Extreme Solar Systems III Meeting

Big Island, HI – November/Decemeber, 2015

Meeting Abstracts

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100 – Overview of Observations

100.02 – Doppler spectroscopy: A path to the detection of Earth-twins hosted by nearby solar-type stars

Space missions are the most succesful to detect rocky planets . Nevertheless if we want to detect very low mass planets hosted by nearby (< 30 pcs) solar-type stars, the Doppler spectroscopy remains the most promising technique. However due to the intrinsic variability of stellar atmospheres, it is challenging with that technique to detect Earth-twins in the habitable zone. Thanks to the angular separation between these planets and their host star as well as their luminosity these planetary systems will be the most important targets for future studies.

Author(s): Michel Mayor[1]
Institution(s): *1. Geneva of Geneva*

100.03 – The Architecture of Exoplanetary Systems

The basic geometry of the Solar System -- the shapes, spacings, and orientations of the planetary orbits -- has long been a subject of fascination, and inspiration for planet formation theories. For exoplanetary systems, those same properties have only recently come into focus. I will review our current knowledge about orbital distances and eccentricities, orbital spacings and mutual inclinations in multiplanet systems, the orientation of the host star's rotation axis, and the properties of planets in binary-star systems. I will also discuss the near-term prospects for learning more.

Author(s): Joshua Winn[1]
Institution(s): *1. MIT*

100.04 – Kepler & K2: One spacecraft, Two Missions

This year, we mark twenty years of exploring the diversity of planets and planetary systems orbiting main sequence stars. Exoplanet discoveries spill into the thousands, and the sensitivity boundaries continue to expand. NASA's Kepler Mission unveiled a galaxy replete with small planets and revealed populations that don't exist in our own solar system. The mission has yielded a sample sufficient for computing planet occurrence rates as a function of size, orbital period, and host star properties. We've learned that every late-type star has at least one planet on average, that terrestrial-sized planets are more common than larger planets within 1 AU, and that the nearest, potentially habitable earth-sized planet is likely within 5pc. After four years of continuous observations, the Kepler prime mission ended in May 2013 with the loss of a second reaction wheel. Thanks to innovative engineering, the spacecraft gained a second lease on life and emerged as the ecliptic surveyor, K2. In many regards, K2 is a distinctly new mission, not only by pointing at new areas of the sky but also by focusing on community-driven goals that diversify the science yield. For exoplanets, this means targeting bright and low mass stars -- the populations harboring planets amenable to dynamical and atmospheric characterization. To date, the mission has executed 7 observing campaigns lasting ~80 days each and has achieved a 6-hour photometric precision of 30 ppm. A couple dozen planets have been confirmed, including two nearby (< 50 pc) systems on the watch-list for future JWST campaigns. While Kepler prime is setting the stage for the direct imaging missions of the future, K2 is easing us into an era of atmospheric characterization -- one spacecraft, two missions, and a bright future for exoplanet science.

Author(s): Natalie Batalha[1]
Institution(s): *1. NASA Ames*

100.05 – Direct Imaging and Distant Planets: A Path Towards a Full View of Planet Populations

ost of exo-planets have been found so far by indirect techniques, at separations typically less than 5 AU. Direct imaging offers the possibility to detect and study longer period planets. The few planets found so far, all giants, bring new challenges to the theories of planet formation and evolution. I will review the challenges associated to direct imaging, and the results obtained until today on these distant planets. I will stress on the opportunities offered by the new, extreme AO-fed, high contrasts imagers such as SPHERE and GPI and show the first results obtained with these instruments.
I will also show how coupling imaging and indirect techniques can now help, for the first time, to investigate the population of giant planets, from a fraction up to hundreds of AU of some stars, giving the opportunity to estimate more accurately the frequency of giant planets around stars.
I will finally propose a reasonable, longer term roadmap towards telluric planet imaging with the ELTs.

Author(s): Anne-Marie LAGRANGE[1]
Institution(s): *1. IPAG*

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101 – Radial Velocities

101.01 – Constraints on the Compositions of Small Planets from the HARPS-N Consortium

HARPS-N is an ultra-stable fiber-fed high-resolution spectrograph optimized for the measurement of very precise radial velocities. The NASA Kepler Mission has demonstrated that planets with radii between 1 - 2.5 that of the Earth are common around Sun-like stars. A chief objective of the HARPS-N Consortium is to measure accurately the masses and infer compositions for a sample of these small worlds. Here I report on our conclusions from the first three years. After analyzing the Kepler light curves to vet potential targets, favoring those with asteroseismic estimates of the stellar properties and excluding those likely to show high RV jitter, we lavished attention on our sample: We typically gathered 100 observations per target, which permitted a mass accuracy of better than 20%. We find that all planets smaller than 1.5 Earth radii are rocky, while we have yet to find a rocky planet larger than this size. I report on the resulting constraints on the planetary compositions, including previously unpublished estimates for several worlds. Comparison of the inferred iron-to-rock ratios to the spectroscopically determined abundances of Fe, Mg, and Si in the stellar atmospheres should provide insight into the formation of terrestrial worlds. I address the transition from rocky planets to Neptune-like worlds, noting that our targets are highly irradiated and hence have likely experienced atmospheric mass loss. The K2 and TESS Missions will provide a list of similarly sized planets around much brighter stars, for which the greater apparent brightness will permit us to measure densities of planets at longer orbital periods, where atmospheric escape will be less important.

Author(s): David Charbonneau[1]
Institution(s): *1. Harvard University*

101.02 – Revised Masses and Densities of the Planets around Kepler-10

Determining which small exoplanets have stony-iron compositions is necessary for quantifying the occurrence of such planets and for understanding the physics of planet formation. Kepler-10 hosts the stony-iron world Kepler-10b, and also contains what has been reported to be the largest solid silicate-ice planet, Kepler-10c. Using 220 radial velocities (RVs), including 72 new precise RVs from Keck-HIRES, and 17 quarters of Kepler photometry, we obtain the most complete picture of the Kepler-10 system to date. We find that Kepler-10b ($R_p = 1.47\ R_\oplus$) has mass $3.70 \pm 0.43\ M_\oplus$ and density 6.44 ± 0.73 g cm^{-3}. Modeling the interior of Kepler-10b as an iron core overlaid with a silicate mantle, we find that the core constitutes 0.17 ± 0.11 of the planet mass. For Kepler-10c ($R_p = 2.35\ R_\oplus$) we measure mass $13.32 \pm 1.65\ M_\oplus$and density 5.67 ± 0.70 g cm^{-3}, significantly lower than the mass in Dumusque et al. (2014, $17.2 \pm 1.9\ M_\oplus$). Kepler-10c is not sufficiently dense to have a pure stony-iron composition. Internal compositional modeling reveals that at least 10% of the radius of Kepler-10c is a volatile envelope composed of either hydrogen-helium (0.0027 ± 0.0015 of the mass, 0.172 ± 0.037 of the radius) or super-ionic water (0.309 ± 0.11 of the mass, 0.305 ± 0.075 of the radius). Transit timing variations (TTVs) of Kepler-10c indicate the likely presence of a third planet in the system, KOI-72.X. The TTVs and RVs are consistent with KOI-72.X having an orbital period of 24, 71, 82, or 101 days, and a mass from 1-7 M⊕.

Author(s): Lauren M. Weiss[3], Leslie A. Rogers[3], Howard T. Isaacson[3], Eric Agol[6], Geoffrey W. Marcy[3], Jason F. Rowe[2], David Kipping[1], Benjamin Fulton[5], Jack Lissauer[2], Andrew Howard[5], Daniel Clark Fabrycky[4]
Institution(s): *1. Harvard-Smithsonian Center for Astrophysics, 2. NASA Ames, 3. UC Berkeley, 4. University of Chicago, 5. University of Hawaii, 6. University of Washington*

101.03 – The Automated Planet Finder's detection of a 6-planet system orbiting the bright, nearby star HD219134

The Automated Planet Finder (APF) is the newest facility at Lick Observatory, comprised of a 2.4m telescope coupled with the high-resolution Levy echelle spectrograph. Purpose built for exoplanet detection and characterization, 80% of the telescope's observing time is dedicated to these science goals. The APF has demonstrated 1 m/s radial velocity precision on bright, RV standard stars and performs with the same speed-on-sky as Keck/HIRES when observing M-dwarfs.

The APF has contributed to the detection of four planetary systems in its first two years of scientific operations. Our most recent detection is that of a 6-planet system around the bright (V=5.5), nearby (d=6.5pc), K3V star HD219134. The planets in this system have masses ranging from 3.5 to108 M_{Earth}, with orbital periods from 3 to 2247 days. An independent detection of the inner 4 planets in this system by the HARPS-N team has shown that the 3d planet transits the star, making this system ideal for follow-up observations.

I will discuss the APF's detections to date, highlighting HD219134, as well as the overall performance results of the telescope and our future observing strategy.

Author(s): Jennifer Burt[2], Greg Laughlin[2], Stefano Meschiari[3], Steve Vogt[2], R. Paul Butler[1]
Institution(s): *1. Carnegie Institute of Washington, 2. UC Santa Cruz, 3. University of Texas at Austin*

101.04 – Refining Mass Measurements of Kepler Planets with Keck/HIRES.

We present improved radial velocity mass measurements from Keck/HIRES for exoplanets detected by NASA’s Kepler Mission. Since Kepler’s launch 6 years ago, ~30 planetary systems have been monitored with radial velocities, resulting in measured masses for many planets between 1.0 and 4.0 Earth radii. The resulting planet masses have been used to determine the transition between planets with a rocky interior and those with a lower density interior which requiring significant H/He atmospheres. We provide updated masses and densities for those planets published in Marcy et al (2014) based on two additional observing seasons with HIRES of the Kepler field. These radial velocities also reveal non-transiting planets in systems with previously found transiting planets. One such system has a non-transiting planet with a period between two transiting planets, providing a constraint on the co-planarity of the system. Finally, we provide an updated mass-radius relation, showing the distinction between planets that must have a substantial iron-silicate interior, and those requiring significant contributions from volatiles such as hydrogen and helium.

Author(s): Howard T. Isaacson[1], Geoffrey W. Marcy[1], Andrew Howard[2]
Institution(s): *1. University of California at Berkeley, 2. University of Hawaii*

101.05 – A super-Earth around a solar twin with evidence for planet accretion

Over the last four years we have been carrying out a HARPS radial velocity planet search program aimed at solar twins. Solar twins are a class of stars uniquely suited for high-precision chemical abundance measurements, and the goal of this project is to search for correlations between stellar abundances and planet frequency at a level of sensitivity only solar twins can provide. We recently discovered a 3 Earth mass planet on a 1.8 day orbital period around one of our targets. Our spectroscopic analysis of the host star indicates that it may have accreted planetary material: its chemical abundance pattern has an enhancement in refractory materials and the stellar rotation rate is unusually high for its age, possibly a marker of spin-up. This raises the intriguing possibility that the super-Earth is the core remnant of an accreted hot Jupiter. We present this system as a case study of the power of high-precision host star characterization.

Author(s): Megan Bedell[1]
Institution(s): *1. University of Chicago*

101.06 – Hot Jupiters with companions: results of the long-term CORALIE survey

For twenty years hot Jupiters have been challenging planet formation theories. While in-situ formation has rapidly been rejected, the giant planets migration mechanisms are still not well understood. Disc migration is probably the dominant scenario but it cannot explain the observed population of hot Jupiters. Dynamical models involving the influence of an additional planetary or stellar companion through scattering or Kozai-Lidov mechanisms could also explain planetary migration. Their role needs to be characterised.

High eccentricity migration mechanisms are triggered by the presence of an additional object. Knutson et al. (2014) searched for planetary companions to hot Jupiters and deduced that half of them had a giant planetary companion.

We have performed our own independent search for companions of hot Jupiters. Since 2007, we have monitored the Southern WASP confirmed planets with the high-resolution echelle spectrograph CORALIE. Our sample includes more than 100 targets, including 90 that have been followed for more than three years. Our results slightly differ from those of Knutson et al. (2014).

I will present the results of this survey regarding the statistics of companions of hot Jupiters. I will compare our detections with the planetary occurrence rates as well as with the binary stars occurrence rates. I will describe the correlations between the presence of a companion and the properties of the hot Jupiter.

Author(s): Marion Neveu Van Malle[2], Didier Queloz[1], Amaury H.M.J. Triaud[3], Damien Segransan[2], Stéphane Udry[2], Francesco Pepe[2]
Institution(s): *1. Cambridge University, 2. Geneva Observatory, 3. University of Toronto*

101.07 – Statistics of Long-Period Gas Giant Planets in Known Planetary Systems

We conducted a Doppler survey at Keck combined with NIRC2 K-band AO imaging to search for massive, long-period companions to 123 known exoplanet systems with one or two planets detected using the radial velocity (RV) method. Our survey is sensitive to Jupiter mass planets out to 20 AU for a majority of the stars in our sample, and we report the discovery of eight new long-period planets in addition to 20 RV trends at 3 sigma significance indicating the presence of an outer companion beyond 5 AU. We combined our RV observations with AO imaging to determine the range of allowed masses and orbital separations for these companions and fit this population with a power law in mass and semi-major axis. We estimate the total occurrence rate of companions in our sample, and find that hot and warm gas giants inside 1 AU are more likely to have an outer companion than cold gas giants. We also find that planets with an outer companion have higher than average eccentricities than their single counterparts, suggesting that dynamical interactions between planets may play an important role in these systems.

Author(s): Marta Levesque Bryan[1], Heather Knutson[1], Andrew Howard[6], Henry Ngo[1], Konstantin Batygin[1], Justin Crepp7, Benjamin Fulton[6], Sasha Hinkley5, Howard T. Isaacson4, John Asher Johnson[2], Geoffrey W. Marcy4, Jason Wright3
Institution(s): *1. Caltech, 2. Harvard University, 3. Penn State University, 4. University of California Berkeley, 5. University of Exeter, 6. University of Hawaii, 7. University of Notre Dame*

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102 – Transiting Planets I

102.01 – A rocky planet transiting a nearby low-mass star

Results from Kepler indicate that M dwarfs host, on average, at least 1.4 planets between 0.5 and 1.5 Earth radii per star. Yet, the closest small planets known to transit M dwarfs have been too distant to allow Doppler measurements of their masses or spectroscopic studies of their atmospheres. Here, we announce a new planet discovered by the MEarth-South observatory, an Earth-size planet transiting an M dwarf that is only 12 pc away. The density of the planet, determined from radial velocity observations with HARPS, is consistent with an Earth-like rock/iron composition. With an equilibrium temperature of 530K (assuming a Bond albedo of 0.3), this planet is cooler than most other rocky planets with measured densities. Although too hot to be habitable, it is cool enough that it may have retained a substantial atmosphere over its lifetime. Thanks to the star's proximity and its diminutive size of only 1/5th the radius of the Sun, this new world likely provides the first opportunity for our community to spectroscopically examine the atmosphere of a terrestrial exoplanet. We estimate that JWST could secure high signal-to-noise spectra of the planet's atmosphere, both in transmission during transit and in emission at secondary eclipse.

Author(s): Zachory K. Berta-Thompson5, Jonathan Irwin[1], David Charbonneau[1], Elisabeth R. Newton[1], Jason Dittmann[1], Nicola Astudillo-Defru[8], Xavier Bonfils[6], Michael Gillon9, Emmanuel Jehin9, Antony Stark[1], Brian Stalder[2], Francois Bouchy4, Xavier Delfosse[6], Thierry Forveille[6], Christoph Lovis[8], Michel Mayor[8], Vasco Neves7, Francesco Pepe[8], Nuno Santos3, Stéphane Udry[8], Anael Wunsche[6]
Institution(s): *1. Harvard-Smithsonian Center for Astrophysics, 2. Institute for Astronomy, 3. Instituto de Astrofísica e Ciências do Espaço, 4. Laboratoire d'Astrophysique de Marseille, 5. MIT, 6. Univ. Grenoble Alpes, 7. Universidade Federal do Rio Grande do Norte, 8. Université de Genéve, 9. Université de Liège*

102.02 – Securing the Extremely Low-Densities of Low-Mass Planets Characterized by Transit Timing Variations

Transit timing variations (TTVs) provide an excellent tool to characterize the masses and orbits of dozens of small planets, including many at orbital periods beyond the reach of both Doppler surveys and photoevaporation-induced atmospheric loss. Dynamical modeling of these systems has identified low-mass planets with surprisingly large radii and low densities (e.g., Kepler-79d, Jontof-Hutter et al. 2014; Kepler-51, Masuda 2014; Kepler-87c, Ofir et al. 2014). Additional low-density, low-mass planets will likely become public before ESS III (Jontof-Hutter et al. in prep). Collectively, these results suggest that very low density planets with masses of 2-6 M_{Earth} are not uncommon in compact multiple planet systems. Some astronomers have questioned whether there could be an alternative interpretation of the TTV observations. Indeed, extraordinary claims require extraordinary evidence.

While the physics of TTVs is rock solid, the statistical analysis of Kepler observations can be challenging, due to the complex interactions between model parameters and high-dimensional parameter spaces that must be explored. We summarize recent advances in computational statistics that enable robust characterization of planetary systems using TTVs. We present updated analyses of a few particularly interesting systems and discuss the implications for the robustness of extremely low densities for low-mass planets. Such planets pose an interesting challenge for planet formation theory and are motivating detailed theoretical studies (e.g., Lee & Chiang 2015 and associated ESS III abstracts).

Author(s): Eric B Ford[1]
Institution(s): *1. Penn State*

102.03 – The Occurrence of Compact Multiples Orbiting Mid-M Dwarf Stars

Various investigations of exoplanet occurrence indicate that short-period planets are common around M dwarf stars. However, not all M dwarfs are equal, with mid-to-late type M dwarfs being significantly smaller, fully convective, and showing different activity phenomena when compared to early-type M dwarf stars. Accurate exoplanet statistics for mid-to-late M dwarfs is much more challenging owing to the few systems surveyed with adequate precision to detect small planets. Using data from NASA's Kepler Mission, we confirmed and characterized two new exoplanetary systems orbiting mid-M dwarfs: Kepler-445 and Kepler-446. When combined with Kepler-42, and isolating all mid-M dwarf stars observed by Kepler with the precision necessary to detect similar systems, we calculate that one-fifth of mid-M dwarf stars host compact multiples (multiple planets with periods of less than 10 days) for a wide range of metallicities. We suggest that the inferred planet masses for these systems support highly efficient accretion of protoplanetary disk metals by protoplanets orbiting low-mass stars.

Author(s): Philip Steven Muirhead[2], Andrew Mann[6], Andrew Vanderburg3, Timothy Morton4, Adam Kraus[6], Michael Ireland[1], Jonathan Swift5, Gregory Feiden[8], Eric Gaidos7, J Zachary Gazak7
Institution(s): *1. Australian National University, 2. Boston University, 3. Harvard University, 4. Princeton University, 5. The Thacher School, 6. The University of Texas at Austin, 7. University of Hawai'i at Manoa, 8. Upsalla University*

102.04 – The Dynamics of the WASP-47 Planetary System: A Hot Jupiter, Two Additional Planets, and Observable Transit Timing Variations

New data from the K2 mission indicate that WASP-47, a previously known Hot Jupiter host, also hosts two additional transiting planets: a Neptune-sized outer planet and a super-Earth inner companion. The measured period ratios and size ratios for these planets are unusual (extreme) for Hot Jupiter systems. We measure the planetary properties from the K2 light curve and detect transit timing variations, thereby confirming the planetary nature of the outer planet. We performed a large ensemble of numerical simulations to study the dynamical stability of the system and to find the theoretically expected transit timing variations (TTVs). The system is stable provided that the orbital eccentricities are small. The theoretically predicted TTVs are in good agreement with those observed, and we use the TTVs to determine the masses of two planets, and place a limit on the third. The WASP-47 planetary system is important because the companion planets can both be inferred by TTVs and are also detected directly through transit observations. The depth of the Hot Jupiter's transits make ground-based TTV measurements possible, and the brightness of the host star makes it amenable for precise radial velocity measurements. The system thus serves as a Rosetta Stone for understanding TTVs as a planet detection technique. Moreover, this compact set of planets in nearly circular, coplanar orbits demonstrates that at least a subset of Jupiter-size planets can migrate in close to their host star in a dynamically quiet manner. As final curiosity, WASP-47 hosts one of few extrasolar planetary systems that can observe Earth in transit.

Author(s): Fred C Adams4, Juliette C Becker[1], Andrew Vanderburg[1], Saul Rappaport[2], Hans Martin Schwengeler 3
Institution(s): *1. Harvard-Smithsonian Center for Astrophysics, 2. MIT, 3. Planet Hunters, 4. University of Michigan*

102.05 – Analytic formulae for transit timing variations of planets

Gravitational interactions between planets in transiting exoplanetary systems lead to variations in the times of transit (TTVs) that are diagnostic of the planetary masses and the dynamical state of the system. I will present analytic formulae for TTVs which can be applied to planetary systems with nearly circular orbits which are not caught in a mean motion resonance. The formulae relate physical parameters, like masses and orbital elements, to direct TTV observables, including shape, amplitude, and timescales. Importantly, the formulae highlight which components of TTVs break degeneracies to allow for unique measurements of planet masses and eccentricities. Additionally, modeling of TTV data using our analytic formulae can be nearly 4 orders of magnitude faster compared with n-body integration. For a number of Kepler systems with TTVs, I will show that our formulae lead to accurate mass and orbital element measurements without full dynamical analyses involving direct integration of the equations of motion. The analytic formulae may ultimately allow for a homogenous analysis of the TTVs (or lack thereof) of many multi-planet systems.

Author(s): Katherine Michele Deck[1], Eric Agol[2]
Institution(s): *1. Caltech, 2. University of Washington*

102.06 – Measurements of *Kepler* Planet Masses and Eccentricities from Transit Timing Variations: Analytic and N-body Results

Several *Kepler* planets reside in multi-planet systems where gravitational interactions result in transit timing variations (TTVs) that provide exquisitely sensitive probes of their masses of and orbits. Measuring these planets' masses and orbits constrains their bulk compositions and can provide clues about their formation. However, inverting TTV measurements in order to infer planet properties can be challenging: it involves fitting a nonlinear model with a large number of parameters to noisy data, often with significant degeneracies between parameters. I present results from two complementary approaches to TTV inversion: Markov chain Monte Carlo simulations that use N-body integrations to compute transit times and a simplified analytic model for computing the TTVs of planets near mean motion resonances. The analytic model allows for straightforward interpretations of N-body results and provides an independent estimate of parameter uncertainties that can be compared to MCMC results which may be sensitive to factors such as priors. We have conducted extensive MCMC simulations along with analytic fits to model the TTVs of dozens of *Kepler* multi-planet systems. We find that the bulk of these sub-Jovian planets have low densities that necessitate significant gaseous envelopes. We also find that the planets' eccentricities are generally small but often definitively non-zero.

Author(s): Sam Hadden[1], Yoram Lithwick[1]
Institution(s): *1. Northwestern University*

103 – Transiting Planets II

103.01 – Latest Results From the K2 M Dwarf Program

Small stars and small planets are ubiquitous in the Galaxy. Planets smaller than ~2.5 Earth radii occur more frequently than any other type of planet; stars with masses below ~0.4 Solar masses are the most common type of star. Nonetheless we know much less about the formation, evolution, interior composition, atmospheric makeup, and population trends of M dwarf planetary systems than we do for planets orbiting Sunlike stars. Our team has made major progress in identifying and validating new planet candidates discovered by NASA's K2 mission, especially including many planets orbiting M dwarfs. I will review our discoveries and their system architectures in the first five K2 fields, and describe how we are already finding many excellent candidates for ongoing & future followup studies with RV spectrographs (to measure planetary masses) and HST, Spitzer, and/or JWST (to measure atmospheric composition).

Author(s): Ian Crossfield[1]
Institution(s): *1. UA/LPL*

103.02 – Discovery and characterization of small planets from K2

In 2014, the Kepler Telescope was repurposed for a new "K2" mission, searching for transiting planets in ~14 fields along the ecliptic, for 80 days each. We are conducting a follow-up program to detect and characterize K2 planets to better understand small planet diversity. I present the detection and confirmation of over 150 transiting planets, mostly sub-Neptune-size, in the first five K2 fields. This includes more than a dozen multi-planet systems, many of which are bright enough for spectroscopic follow-up to measure planet masses via radial velocities (RVs). I report preliminary masses and densities of planets in a few of these new multi-planet systems, constrained by Keck HIRES RVs. Continued RV follow-up will probe the compositional diversity of small planets, examining the degree to which environmental factors (e.g. stellar properties, incident flux, system architectures) sculpt the planet mass-radius diagram.

Author(s): Evan Sinukoff4, Andrew Howard4, Ian Crossfield3, Erik Petigura[1], Joshua Schlieder[2]
Institution(s): *1. Caltech, 2. NASA Ames, 3. University of Arizona, 4. University of Hawaii at Manoa*

103.03 – Follow-up of K2 planet candiates with the LCOGT network

K2 has proven to be an outstanding successor to the Kepler mission. It has already revealed dozens of new planet candidates, and unlike those found by the primary mission, many of these systems' host stars are sufficiently bright to allow extensive follow-up observations. This is especially important since each of the K2 observing campaigns are only ~80 days long, leaving the community with the discovery of exciting new systems but often not enough time coverage to enable a thorough characterization of these systems.

We are leading a large effort to observe K2 transiting planet candidates with the LCOGT telescope network. LCOGT's longitudinal coverage, multiple identical telescopes per site and automated queue observing make it an ideal facility for fast, high-precision and multi-color follow-up. Our program focuses on specific aspects of K2 follow-up for which the network is especially powerful: period determination for candidates with fewer than three K2 transits; transit timing variation monitoring to measure planetary masses, orbital parameters and to search for additional planets in multiple systems; and multi-color photometry to vet planet candidates and carry-out preliminary atmospheric spectroscopy.

We will present new results for a selection of systems observed so far through this program. These include K2-19, a multi-planet system extremely close to 3:2 resonance and experiencing transit timing variations with amplitudes as large as one hour; EPIC201702477, a long-period planet with only two K2 transits; WASP-47, a system hosting a hot Jupiter and two K2-discovered small planets; and EPIC201637175b, a disintegrating rocky planet.

Our program demonstrates that LCOGT is uniquely positioned to be the primary ground-based photometric follow-up resource for K2 exoplanet discoveries, but also for the numerous bright systems that will result from the TESS mission. LCOGT photometry complements ongoing radial velocity and atmospheric spectroscopy efforts to reveal a more complete picture of the bright, nearby exoplanet systems discovered by these missions.

Author(s): Diana Dragomir[7], Daniel Bayliss[5], Knicole Colón[4], William Cochran[9], George Zhou[2], Timothy Brown[3], Avi Shporer[1], Nestor Espinoza[6], Benjamin Fulton[8]
Institution(s): *1. Caltech, 2. Harvard, 3. Las Cumbres Observatory Global Telescope, 4. NASA Ames, 5. Observatoire de Geneve, 6. Pontificia Universidad Católica de Chile , 7. University of Chicago, 8. University of Hawaii, 9. University of Texas*

103.04 – NGTS, a new transit search facility in operation in the Southern sky

NGTS is an automated wide field transit survey designed and built to detect transiting Neptune size planet on bright K dwarfs stars. NGTS first light was obtained in summer 2015. First preliminary results as well as details simulations of the survey expectation will be presented during this talk.
Bright K dwarfs stars are targets of special interest to look for transiting planets and gather information about planetary structure and the nature of atmospheric composition of exoplanets. Planetary transit to be detected by NGTS will provide us with a unique target sample for further characterization by HARPS, VLT, and later JWST. Interesting synergies with TESS may be found as well on the coolest stars of the sample (M stars).

Author(s): Didier Queloz[1]
Institution(s): *1. Cambridge*

103.05 – Kepler-223: A Resonant Chain of Four Sub-Neptune Planets

The Kepler mission has revealed an abundance of pairs of planets in the same system which often lie near, but not exactly on, resonance. Understanding how and when they entered a resonance and were removed from it has implications for their birthplaces and planetary structure. Here we characterize Kepler-223 (KOI-730), an outstanding example of a system of small planets in resonance. We perform TTV, photodynamic, stability, and migration analyses to determine the system's most likely current parameters and resonant state. Its four sub-Neptune planets form a chain linked by 4:3, 3:2, and 2:1 resonances that cause measurable dynamical effects and imply a disk-migration origin. Tidal dissipation in the planets or wide-scale instability may eventually transform resonant chains of planets like Kepler-223 into the more common type of architecture.

Author(s): Sean M Mills[2], Daniel Clark Fabrycky[2], Cezary Migaszewski[4], Eric B Ford[1], Erik Petigura[3], Howard T. Isaacson[3]
Institution(s): *1. The Pennsylvania State University, 2. The University of Chicago, 3. University of California at Berkeley, 4. University of Szczecin*

103.06 – Kepler-80 and the Frequency of STIPs

At ESS-II, Kepler and detailed radial velocity surveys had confirmed that systems of multiple, small, close-in planets were relatively common, but there was a order of magnitude difference between the estimated frequency of STIPs from Kepler (~5%, Lissauer, Ragozzine et al. 2011) and the frequency from RV surveys (~50%, Mayor et al. 2011). Continued Kepler observations are providing insight into the properties of this new population, now called STIPs (Systems with Tightly-packed Inner Planets), both through individually interesting systems and through a large ~homogeneous population. Kepler-80 (KOI-500) is an important system due to its still-unique extreme three-body resonance configuration and its relatively compact configuration. I will present a full dynamical TTV analysis of this system including densities for the four outer planets. We will also discuss the statistical evidence for whether Kepler-80 and similar extremely-tightly-packed systems could be considered a separate population from the STIPs. Radial Velocity surveys have not detected any of these extremely-tightly-packed systems (~4 planets with periods within a factor of ~3), so with the masses from our TTV analysis, we investigate the ability of radial velocity surveys to detect such systems. We find that it is extremely difficult in practice to correctly disentangle the signals for all five planets of Kepler-80 due to the low-SNR amplitudes and similar frequencies involved (even for circular orbits with no resonance effects). STIPs will, to some degree, inherit this propensity for RV measurements to miss planets with similar periods; this has potentially important effects on the completeness estimates for RV surveys of STIPs. We address current results and present a roadmap for investigating the frequency of such systems in more detail using the Planetary System Simulator (SysSim), an extension of the population analysis of Lissauer, Ragozzine, et al. 2011.

Author(s): Darin Ragozzine[1], Mariah Macdonald[1], Eric B Ford[2]
Institution(s): *1. Florida Institute of Technology, 2. Penn State*

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104 – Direct Imaging Poster Session

104.01 – Direct imaging and spectroscopic characterization of habitable planets with ELTs

While the ~1e10 reflected light contrast between Earth-like planets and Sun-like stars is extremely challenging to overcome for ground-based telescopes, habitable planets around lower-mass stars can be "only" a 10 million times fainter than their host stars. Thanks to the small angular resolution offered by upcoming extremely large telescopes (ELTs) and recent advances in wavefront control and coronagraphic techniques, direct imaging and spectroscopic characterization of habitable planets will be possible around nearby M-type stars. Deep (~1e-8) contrast can be achieved by combining (1) sensitive fast visible light wavefront sensing (extreme-AO) with (2) kHz speckle control in the near-IR and (3) high efficiency coronagraphy. Spectroscopy will measure abundances of water, oxygen and methane, measure the planet rotation period, orbit, and identify main surface features through time-domain spectrophotometry.
The Subaru Coronagraphic Extreme AO (SCExAO) system is a technology precursor to such a habitable planet imager for ELTs, and is currently under active development. By combining small inner working angle coronagraphy, visible-WFS based extreme-AO and fast speckle control, it will include the key elements of a future ELT system able to image and characterize habitable planets. We describe a technical plan to evolve SCExAO into a habitable planet imager for the Thirty Meter Telescope (TMT), which is aimed at providing such scientific capability during the 2020 decade, and inform the design, deployment and scientific operation of a more capable Extreme-AO instrument.

Author(s): Olivier Guyon[2], Nemanja Jovanovic[1], Julien Lozi[1]
Institution(s): *1. Subaru Telescope, 2. University of Arizona*

104.02 – Results from SPOTS: The Search for Planets Orbiting Two Stars

A large number of direct imaging surveys for exoplanets have been performed in recent years, which have yielded the first directly imaged planets and provided constraints on the prevalence and distribution of wide planetary systems. However, these surveys generally focus on single stars, hence binaries and higher-order multiples have not been studied to the same level of scrutiny. This motivated the initiation of the SPOTS survey, which is an ongoing direct imaging study encompassing 67 close binaries in total, performed first with VLT/NACO and now with VLT/SPHERE. The study is the first to systematically study the distribution of wide planets in multiple systems, and may yield the first image on any circumbinary planet altogether. Here, we will describe the layout of the survey, the follow-up of planetary candidates in the sample, and the detection of novel features in a newly resolved circumbinary disk which may indicate the presence of one or two unseen planetary companions.

Author(s): Ruben Asensio Torres[2], Christian Thalmann[1], Markus Janson[2]
Institution(s): *1. ETH Zürich, 2. Stockholm University*

104.03 – SCExAO: the most complete instrument to characterize exoplanets and stellar environments

The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) instrument, currently under development for the Subaru

Telescope, optimally combines state-of-the-art technologies to directly study exoplanets and stellar environments at the diffraction limit, both in visible and infrared light (0.6 to 2.4 um). The instrument already includes an ultra-fast visible pyramid wavefront sensor operating at 3.5 kHz, a 2k-actuator deformable mirror, a set of optimal coronagraphs that can work as close as 1 l/D, a low-order wavefront sensor, a high-speed speckle control, and two visible interferometric modules, VAMPIRES and FIRST. Stability of the wavefront correction has already been demonstrated on sky, and SCExAO is already producing scientific results. After the integration of the Integral Field Spectrograph (IFS) CHARIS and a Microwave Kinetic Inductance Detector (MKID) in 2016, SCExAO will be one of the most powerful and effective tools for characterizing exoplanets and disks.

Author(s): Julien Lozi[2], Olivier Guyon[2], Nemanja Jovanovic[2], Garima Singh[2], Danielle Doughty[2], Prashant Pathak[2], Sean Goebel[1], Tomoyuki Kudo[2]
Institution(s): *1. Institute for Astronomy, 2. National Astronomical Observatory of Japan*

104.04 – The SEEDS High-Contrast Imaging Survey: Exoplanet and Brown Dwarf Survey for Nearby Young Stars Dated with Gyrochronology and Activity Age Indicators

The SEEDS campaign has successfully discovered and characterized exoplanets, brown dwarfs, and circumstellar disks since it began in 2009, via the direct imaging technique. The survey has targeted nearby young stars, as well as stars associated to star-forming regions, the Pleiades open cluster, moving groups, and debris disks. We selected the nearby young stars that have been dated with age indicators based on stellar rotation periods (i.e., gyrochronology) and chromoshperic/coronal activities. Of these, nearly 40 were observed, with ages mainly between 100 and 1000 Myr and distances less than 40 pc. Our observations typically attain the contrast of ~6 x 10^{-6} at 1'' and better than ~1 x 10^{-6} beyond 2'', enabling us to detect a planetary-mass companion even around such old stars. Indeed, the SEEDS team reported the discovery that the nearby Sun-like star GJ 504 hosts a Jovian companion GJ 504b, which has a mass of 3-8.5 Jupiter masses that is inferred according to the hot-start cooling models and our estimated system age of 100-510 Myr. The remaining observations out of the selected ~40 stars have resulted in no detection of additional planets or brown dwarf companions. Meanwhile, we have newly imaged a low-mass stellar companion orbiting the G-type star HIP 10321, for which the presence of companion was previously announced via radial velocity technique. The astrometry and radial velocity measurements are simultaneously analyzed to determine the orbit, providing constraints on the dynamical mass of both objects and stellar evolution models. Here we summarize our direct imaging observations for the nearby young stars dated with gyrochrolorogy and activity age indicators. Furthermore, we report the analysis for the HIP 10321 system with the imaged low-mass companion.

Author(s): Masayuki Kuzuhara[6], Motohide Tamura7, Kris Helminiak5, Kyle Mede7, Timothy Brandt[2], Markus Janson4, Ryo Kandori3, Tomoyuki Kudo5, Nobuhiko Kusakabe[1], Jun Hashimoto[1]
Institution(s): *1. Astronomical Biology Center, 2. Institute of Advanced Study, 3. National Astronomical Observatory of Japan, 4. Stockholm University, 5. Subaru Telescope, 6. Tokyo Institute of Technology, 7. University of Tokyo*

104.05 – Intensity of Hydrogen Line Emission from Accreting Gas-Giant Planets

Planets have been thought to form in circumstellar gaseous disks. Indeed, a number of young stars surrounded by such disks have been already detected. Recently, there are some reports on detection of gap-like structure in circumstellar disks, which suggests that there are forming massive protoplanets embedded in the disks. A challenging issue is how to find forming planets in circumstellar disks directly. In this study, we investigate whether detectable emission occurs from accreting gas-giant planets.

In a circumstellar disk, once a solid core becomes massive enough, it captures the surrounding disk gas gravitationally in a runaway manner. Since the disk gas accretion occurs much faster than angular momentum loss, a circumplanetary disk is formed in the mid-plane of the circumstellar disk. Recent three-dimensional hydrodynamic simulations by Tanigawa et al. (2012) revealed that the gas flowed from the cicumstellar disk to the circumplanetary disk not horizontally but vertically. According to those simulations, the disk gas falls onto the circumplanetary disk at a speed comparable to the free fall speed, and the local gas temperature reaches up to tens of thousands of kelvin because of shock heating near the planet.

Thus, the presence of an accreting gas giant planet may be found by observation of the radiative emission from such hot gas in the circumplanetary disk, which we quantify in this study. In particular, we focus on the intensity of line emission from hydrogen. We have simulated the post-shock gas flow with non-equilibrium chemical reaction and electron transition. Then, we have found that the intensity of some hydrogen lines is proportional to the number density of the surrounding circumstellar disk gas and square of the planet mass, so the protoplanet's hydrogen-line emission is less intense by a few orders of magnitude relative to the protostar's emission under some realistic conditions. Also, the duration time is comparable to the dissipation time of the disk gas (i.e., several hundred thousand years). Thus, we conclude that an accreting gas giant planet is detectable via hydrogen-line emission observation, provided the planet is massive enough or the density of the disk gas is high enough.

Author(s): Yuhiko Aoyama[1], Takayuki Tanigawa[2], Masahiro Ikoma[1]
Institution(s): *1. The University of Tokyo, 2. University of Occupational and Environmental Health*

104.06 – PSF subtraction to search for distant Jupiters with SPITZER

In the course of the search for extrasolar planets, a focus has been made towards rocky planets very close (within few AUs) to their parent stars. However, planetary systems might host gas giants as well, possibly at larger separation from the central star. Direct imaging is the only technique able to probe the outer part of planetary systems. With the advent of the new generation of planet finders like GPI and SPHERE, extrasolar systems are now studied at the solar system scale. Nevertheless, very extended planetary systems do exist and have been found (Gu Ps, AB Pic b, etc.). They are easier to detect and characterize. They are also excellent proxy for close-in gas giants that are detected from the ground. These planets have no equivalent in our solar system and their origin remain a matter of speculation. In this sense, studying planetary systems from its innermost to its outermost part is therefore mandatory to have a clear understanding of its architecture, hence hints of its formation and evolution. We are carrying out a space-based survey using SPITZER to search for distant companions around a well-characterized sample of 120 young and nearby stars. We designed an observing strategy that allows building a very homogeneous PSF library. With this library, we perform a PSF subtraction to search for planets from 10" down to 1". In this poster, I will present the library, the different algorithms used to subtract the PSF, and the promising detection sensitivity that we are able to reach with this survey. This project to search for the most extreme planetary systems is unique in the exoplanet community. It is also the only realistic mean of directly imaging and subsequently obtaining spectroscopy of young Saturn or Jupiter mass planets in the JWST-era.

Author(s): Julien Rameau[6], Etienne Artigau[6], Frédérique Baron[6], David Lafrenière[6], Rene Doyon[6], Lison Malo3, Marie-Eve Naud[6], Philippe Delorme4, Markus Janson5, Loic Albert[6], Jonathan Gagné[2], Charles Beichman[1]
Institution(s): *1. Caltech, 2. Carnegie Institute, 3. CFHT, 4. IPAG, 5. Stockholm University, 6. Université de Montréal, iREx*

104.07 – MKIDs for Direct Imaging of Exoplanets

Microwave Kinetic Inductance Detectors (MKIDs) are single photon counting, energy resolving detectors applicable from the optical through near-IR. MKIDs are especially interesting for exoplanet direct imaging due to their read noise free, high speed, energy resolved near-IR photon counting in reasonably large formats. The first MKID instrument, ARCONS, has been taking data on the Palomar 200" for several years. There are currently two UVOIR MKID instruments fully funded and under construction for direct imaging of planets, DARKNESS for the Palomar coronagraphs and MEC for Subaru's SCExAO. Operating an MKID camera behind these coronagraphs will allow an effective 2 kHz frame rate with minimal latency, allowing fast real-time nulling of atmospheric speckles. Simulations show this could improve contrast ratios by up to a factor of 100. In this this talk I will discuss the current state of these cameras as well as their expected scientific yield. In particular, MEC with SCExAO on Subaru may be capable of detecting Jupiter analogs in reflected light within the next 2 years.

Author(s): Benjamin A. Mazin5, Seth Meeker5, Matthew Strader5, Paul Szypryt5, Alex Walter5, Clint Bockstiegel5, Giulia Collura5, Dimitri Mawet[2], Rebecca Jensen-Clem[2], Olivier Guyon4, Nemanja Jovanovic4, Rebecca Oppenheimer[1], Eugene Serabyn3
Institution(s): *1. AMNH, 2. Caltech, 3. JPL, 4. Subaru Observatory, 5. University of California Santa Barbara*

104.08 – A Method for Selecting M dwarfs with an Increased Likelihood of Unresolved Ultra-cool Companionship

Locating ultra-cool companions to M dwarfs is important for constraining low-mass formation models, the measurement of sub-stellar dynamical masses and radii, and for testing ultra-cool evolutionary models. We present an optimised method for identifying M dwarfs which may have unresolved ultra-cool companions. We construct a catalogue of 440,694 candidates, from WISE, 2MASS and SDSS, based on optical and near-infrared colours and reduced proper motion. With strict reddening, photometric and quality constraints we isolate a sub-sample of 36,898 M dwarfs and search for possible mid-infrared M dwarf + ultra-cool dwarf candidates by comparing M dwarfs which have similar optical/near-infrared colours (chosen for their sensitivity to effective temperature and metallicity). We present 1,082 M dwarf + ultra-cool dwarf candidates for follow-up. Using simulated ultra-cool dwarf companions to M dwarfs, we estimate that the occurrence of unresolved ultra-cool companions amongst our M dwarf + ultra-cool dwarf candidates should be at least four times the average for our full M dwarf catalogue. We discuss possible contamination and bias and predict yields of candidates based on our simulations.

[Paper submitted to MNRAS 2015-08-17]

Author(s): Neil James Cook[1], David J Pinfield[1], Federico Marocco[1]
Institution(s): *1. University of Hertfordshire*

104.09 – WEIRD : Wide orbit Exoplanet search with InfraRed Direct imaging

We currently do not know what does the emission spectrum of a young 1 Jupiter-mass planet look like, as no such object has yet been directly imaged. Arguably, the most useful Jupiter-mass planet would be one that is bound to a star of known age, distance and metallicity but which has an orbit large enough (100-5000 UA) that it can be studied as an "isolated" object. We are therefore searching for the most extreme planetary systems. We are currently gathering a large dataset to try to identify such objects through deep [3.6] and [4.5] imaging from SPITZER and deep seeing-limited J (with Flamingos 2 and WIRCam) and z imaging (with GMOS-S and MegaCam) of all 181 known confirmed members of a known young association (<120 Myr) within 70pc of the Sun. Our study will reveal distant planetary companions, over the reveal distant PMCs up to 5000 AU. AU separation range, through their distinctively red z-J and [4.5]-[3.6] colors. The sensitivity limits of our combined Spitzer+ground-based program will allow detection of planets with masses as low as 1 Mjup with very low contamination rates. Here we present some preliminary results of our survey. This approach is unique in the community and will give us an overview of the architecture of the outer part of planetary systems that were never probed before. Our survey will provide benchmark young Saturn and Jupiter for imaging and spectroscopy with the JWST

Author(s): Frédérique Baron[6], Etienne Artigau[6], Julien Rameau[6], David Lafrenière[6], Loic Albert[6], Marie-Eve Naud[6], Jonathan Gagné3, Lison Malo4, Rene Doyon[6], Charles Beichman[2], Philippe Delorme[1], Markus Janson5
Institution(s): *1. Institut de Planétologie et d'Astrophysique de Grenoble, 2. California Institute of Technology, 3. Carnegie Institution for Science, 4. CFHT, 5. Stockholm University, 6. Université de Montréal*

104.10 – Imaging Discovery of a Low-Mass Companion Around HR 3549

We report the discovery of a low-mass companion to HR 3549 , an A0V star surrounded by a debris disk with a warm excess detected by WISE. We imaged the companion at the Very Large Telescope with NAOS-CONICA in the L-band in January 2013 and January 2015. The companion is at a projected separation of 80 AU and position angle of 157◦ . Our age estimate for this object corresponds to a mass in the range 15-80 M J , spanning the brown dwarf regime, and so HR 3549 b is another recent addition to the growing list of brown dwarf desert objects with extreme mass ratios.

Author(s): Karl Stapelfeldt4, Dimitri Mawet[1], Trevor David[1], Michael Bottom[1], Sasha Hinkley5, Deborah Padgett4, Bertrand Mennesson3, Eugene Serabyn3, Farisa Y. Morales3, Jonas Kuhn[2]
Institution(s): *1. California Institute of Technology, 2. ETH Department of Physics, 3. Jet Propulsion Laboratory, 4. NASA Goddard Space Flight Center, 5. University of Exeter*

104.11 – Exoplanet Imaging in the Thermal Infrared

Self-luminous exoplanets emit the majority of their light in the thermal infrared (3-5 microns), which besides making the region interesting in its own right, implies that less contrast is necessary to detect them against the bright glare of their host stars. I will present LBT/LMIRcam thermal infrared photometry of a handful of directly imaged planets, and explain how that photometry constrains atmospheric models. Additionally, I will present first-light images from ALES, the world's first integral field spectrograph capable of spectroscopically characterizing exoplanets from 3-5 microns.

Author(s): Andy Skemer[1]
Institution(s): *1. UC Santa Cruz*

104.12 – Investigating the Atmospheric Properties of the Young Exoplanet HD 95086 b

We present the results of a Gemini Planet Imager (GPI) investigation into the atmospheric properties of the young and extremely red planetary-mass companion HD 95086 b. Combining a new low-resolution K1 (1.95 - 2.20 μm) spectrum of this object obtained with GPI, with literature H and L' photometry, we are able to place the best constraints to-date on the near- to thermal-infrared spectral energy distribution of this 5 Jupiter mass planet. Based on a comparison to public model grids, the SED is best fit by a low-surface gravity (log (g)~3.0-3.5) and low temperature (Teff = 850-1200K), with the temperature strongly dependent on the treatment of clouds and dust within the model atmosphere. We also compare the SED of HD 95086 b to that of other planetary-mass companions—both those found around other Sco-Cen members (e.g. 1RXS J1609 b and HD 106906 b), and those around older stars (e.g. HR 8799 bcd)—and to field L- and T-dwarfs. Using an empirical K-K1 color correction, we demonstrate that, while having a similar H-K1 color to HR 8799 bcde and 2M 1207, HD 95086 b has an extremely red K1-L' color, indicative of a significantly higher level of photospheric dust. These results demonstrate the diversity of the atmospheric properties of imaged planetary-mass companions, and provide useful empirical constraints for the continued development of models of low-temperature atmospheres.

Author(s): Robert De Rosa[2], Julien Rameau[3], Laurent Pueyo[1], Jason Wang[2]
Institution(s): *1. STScI, 2. UC Berkeley, 3. Université de Montréal, iREx*

104.13 – Towards a Comprehensive Set of Atmosphere and Evolution Models from Brown Dwarfs, to Gas Giants, to Sub-Neptunes

High signal-to-noise spectral observations of the thermal emission of brown dwarfs have been routinely achieved for 20 years, and for extrasolar gas giant planets for nearly 10 years. JWST may allow for the detection of emission for exo-Neptune-class planets at large orbital separations. Given these large and growing databases of spectra, there is a need for a large suite of state-of-the-art models for comparison with these data. These H/He dominated atmospheres span a range of nearly 2000 in mass and perhaps a similar range in atmospheric metallicity. In addition, for all of these classes of planets, the radiative-convective atmosphere serves as a bottleneck for interior cooling, so an understanding of the atmosphere is essential to understand thermal evolution. Here we present our initial plans for a large grid of atmosphere models, over a range of Teff from 200 K to 2400 K, log g from 2.5 to 5.5, metallicities from 0.1 to 300X solar, across a range of cloud parametrizations, vertical mixing efficiencies, and C/O ratios. For brown dwarfs and for metal-enriched giant planets, these atmospheres will be coupled to thermal evolution in a self-consistent manner. Here we present some initial calculations for the atmospheric structure and emitted spectra for the metal-enriched "planetary" portion of the grid, from 10X to 300X solar.

Author(s): Jonathan J. Fortney[3], Mark Marley[2], Caroline Morley[3], Channon Visscher[1], Roxana Lupu[2], Richard Freedman[2]
Institution(s): *1. Dordt College, 2. NASA Ames Research Center, 3. University of California, Santa Cruz*

104.14 – Measuring the spin of the directly imaged sub-stellar companion GQ Lupi b

Recently we measured for the first time the spin rotation of an extra-solar planet. The famous planet beta Pictoris b was found to spin much faster than any planet in our solar system, which is in line with the idea that massive planets spin more rapidly. Interestingly, field brown dwarfs do not seem to follow this relation, which may indicate that an object's spin is closely linked to its formation mechanism.

Here we present the spin measurement of the sub-stellar companion GQ Lupi b, which has an uncertain mass in the range separating extrasolar planets and brown dwarfs. The young T-Tauri system was observed for an hour with the CRIRES instrument at the VLT with a spectral resolving power of 100000, positioning the slit to both contain the host star and the companion separated from the host by 0.7 arcseconds. We find GQ Lupi b to be a slow rotator with a projected rotational velocity of 6.0 pm 0.8 km/s, possibly due to the ultra-young companion still being in the process of accreting material and angular momentum.

Author(s): Henriette Schwarz[2], Matteo Brogi[3], Remco de Kok[2], Jayne Birkby[1], Ignas Snellen[2]
Institution(s): *1. Harvard-Smithsonian Center for Astrophysics, 2. Leiden University, 3. University of Colorado*

104.15 – Spectra of Aurorae in Exoplanet Atmospheres

Aurorae have been observed on an object at the end of the stellar main sequence, many times brighter than any produced on Earth or the solar system planets (Hallinan et al 2015). This provokes the question of whether exoplanets have aurorae, and whether their aurorae can be detected. In order to address this question, we apply an ion-neutral chemical kinetics and transport model to a model atmospheric temperature profile for a hypothetical directly imaged giant gas planet. We consider beams of 500 eV and 10 keV auroral electrons and their effect on the upper atmospheric chemistry. The chemical profiles that result from these calculations are applied to a radiative transfer model in order to predict the effect aurorae have on the optical and infrared spectra of giant gas planets. We will also comment on whether hydrogen anions would have a sufficient column to explain the Planck curve optical spectrum observed by Hallinan et al (2015).

Author(s): Paul Brandon Rimmer[4], Christiane Helling[4], Caroline Morley[2], Stuart Littlefair[3], Gregg Hallinan[1]
Institution(s): *1. Caltech, 2. University of California Santa Cruz, 3. University of Sheffield, 4. University of St Andrews*

104.17 – Effects of latent heating on driving atmospheric circulation of brown dwarfs and directly imaged giant planets

Growing observations of brown dwarfs (BDs) and directly imaged extrasolar giant planets (EGPs), such as brightness variability and surface maps have provided evidence for strong atmospheric circulation on these worlds. Previous studies that serve to understand the atmospheric circulation of BDs include modeling of convection from the interior and its interactions with stably stratified atmospheres. These models show that such interactions can drive an atmospheric circulation, forming zonal jets and/or vortices. However, these models are dry, not including condensation of various chemical species. Latent heating from condensation of water has previously been shown to play an important role on driving the zonal jets on four giant planets in our solar system. As such, condensation cycles of various chemical species are believed to be an important source in driving the atmospheric circulation of BDs and directly imaged EGPs. Here we present results from three-dimensional simulations for the atmospheres of BDs and EGPs based on a general circulation model that includes the effect of a condensate cycle. Large-scale latent heating and molecular weight effect due to condensation of a single species are treated explicitly. We examine the circulation patterns caused by large-scale latent heating which results from condensation of silicate vapor in hot dwarfs and water vapor in the cold dwarfs. By varying the abundance of condensable vapor and the radiative timescale, we conclude that under normal atmospheric conditions of BDs (hot and thus with relatively short radiative timescale), latent heating alone by silicate vapor is unable to drive a global circulation, leaving a quiescent atmosphere, because of the suppression to moist instability by downward transport of dry air. Models with relatively long radiative timescale, which may be the case for cooler bodies, tend to maintain an active hydrological cycle and develop zonal jets. Once condensation happens, storms driven by moist instability can extend vertically over several pressure scale heights, reaching the photospheres and being able to induce flux variabilities — helping to explain patchy clouds inferred from near-IR light curves and inferred surface map of BDs.

Author(s): Xianyu Tan[1], Adam P Showman[1]
Institution(s): *1. University of Arizona*

104.19 – BASS-Ultracool : A Survey for Isolated Analogs of Methane Exoplanets

I will present BASS-Ultracool, a new survey to identify isolated cold, late L and T-type members of young moving groups. These objects have masses below 10 MJup and physical properties similar to those of exoplanets identified with the direct-imaging method. The discovery of such isolated planetary-mass objects will allow us to characterize their atmospheres with unprecedented signal-to-noise and spectroscopic resolution due to the absence of a host star. They will serve as benchmarks to understand cold exoplanets such as the recently discovered 51 Eri b.

I will also present how the prototype version of the BASS-Ultracool survey has already identified the first isolated T-type member of a nearby moving group SDSS J1110+0116, which is a young 10-12 MJup T5.5 member of the ~150 Myr-old AB Doradus moving group. This object is an isolated and slightly cooler version of the previously identified T3.5 AB Doradus member GU Psc b.

Author(s): Jonathan Gagné3, Jacqueline K. Faherty3, Lison Malo[2], Joseph C. Filippazzo[1], Adam J. Burgasser7, Etienne Artigau5, David Lafrenière5, Rene Doyon5, Emily Bowsher4, Christine P. Nicholls[6]
Institution(s): *1. American Museum of Natural History, 2. Canada-France-Hawaii Telescope, 3. Carnegie Institution of Washington, 4. Columbia University, 5. Institut de Recherche sur les Exoplanètes (iREx), 6. Institute for Astrophysics, University of Vienna, 7. University of California, San Diego*

104.20 – HELIOS-R: An Ultrafast, Open-Source Retrieval Code For Exoplanetary Atmosphere Characterization

Atmospheric retrieval is a growing, new approach in the theory of exoplanet atmosphere characterization. Unlike self-consistent modeling it allows us to fully explore the parameter space, as well as the degeneracies between the parameters using a Bayesian framework. We present HELIOS-R, a very fast retrieving code written in Python and optimized for GPU computation. Once it is ready, HELIOS-R will be the first open-source atmospheric retrieval code accessible to the exoplanet community. As the new generation of direct imaging instruments (SPHERE, GPI) have started to gather data, the first version of HELIOS-R focuses on emission spectra. We use a 1D two-stream forward model for computing fluxes and couple it to an analytical temperature-pressure profile that is constructed to be in radiative equilibrium. We use our ultra-fast opacity calculator HELIOS-K (also open-source) to compute the opacities of CO2, H2O, CO and CH4 from the HITEMP database. We test both opacity sampling (which is typically used by other workers) and the method of k-distributions. Using this setup, we compute a grid of synthetic spectra and temperature-pressure profiles, which is then explored using a nested sampling algorithm. By focusing on model selection (Occam's razor) through the explicit computation of the Bayesian evidence, nested sampling allows us to deal with current sparse data as well as upcoming high-resolution observations. Once the best model is selected, HELIOS-R provides posterior distributions of the parameters. As a test for our code we studied HR8799 system and compared our results with the previous analysis of Lee, Heng & Irwin (2013), which used the proprietary NEMESIS retrieval code. HELIOS-R and HELIOS-K are part of the set of open-source community codes we named the Exoclimes Simulation Platform (www.exoclime.org).

Author(s): Baptiste LAVIE[1]
Institution(s): *1. University of Bern*

104.21 – Weather in an extremely nearby substellar system

At a distance of only 2 pc, the brown dwarf binary WISE J104915.57-531906.1, also known as Luhman 16AB, is the third closest system from the Sun. As the closest substellar objects outside of the solar system, their unusual brightness makes these brown dwarfs of late-L and early-T spectral type a unique laboratory for the study of ultracool atmospheres. Their effective temperatures are very similar to those of directly imaged planets such as the HR8799 planets, and they share many atmospheric properties. Without a bright host star, the brown dwarf atmospheres can be studied in much greater detail. In particular, time-resolved spectroscopic observations have recently started to be used to provide new insights into heterogeneities in the cloud structure of brown dwarfs. Luhman 16B was the first brown dwarf to be mapped with Doppler Imaging, which resulted in a surface map with darker and brighter spots that may relate to different cloud features. We have now obtained spectroscopic time series with HST/WFC3 that allow us to measure the absolute flux changes over a broad wavelength range (0.8 – 1.7 microns) and cover several molecular and atomic absorption features, including for the first time the FeH feature that has been thought to be a good tracer of cloud holes. Because we detect significant variability in both Luhman 16A and B, effectively observing weather on these nearby worlds, we can for the first time directly characterize and compare the heterogeneous cloud structure in a co-eval L/T transition binary. The observations provide important insight into how clouds evolve and disappear across the L/T transition at ~1200 K, and the results are also very relevant for the interpretation of spectra of young directly imaged giant planets.

Author(s): Esther Buenzli[1], Mark Marley[2], Daniel Apai4, Beth Biller5, Ian Crossfield4, Jacqueline Radigan3
Institution(s): *1. ETH Zurich, 2. NASA Ames, 3. Space Telescope Science Institute, 4. University of Arizona, 5. University of Edinburgh*

104.22 – Water abundance retrieval from the near-infrared spectrum of κ And b

Spectral retrieval is a powerful tool for constraining the chemical and physical properties of exoplanet atmospheres from observed spectra, for both transiting objects and for directly imaged substellar companions. However, this approach has been applied to only about a dozen targets, because obtaining an information-rich, high-signal-to-noise exoplanet spectrum is challenging. Determining the chemical composition of the atmosphere of a planet is important, since it has implications on its formation and evolution. We present a spectral retrieval analysis of the near-infrared spectrum of κ And b, observed by Hinkley et al. 2013. κ And b is a massive substellar companion discovered via direct imaging around a young B9 star. We fit our simplified and hence fast atmospheric emission model to the observed spectra using a Markov Chain Monte Carlo algorithm. We estimate the abundance of water and place upper limits on the abundances of carbon dioxide and methane in the atmosphere of the object. We then compare our results to the water abundances of other substellar companions determined using a similar approach.

Author(s): Kamen O. Todorov[1], Michael R. Line3, Jaime Pineda[2], Michael Meyer[1], Sascha Quanz[1], Sasha Hinkley4, Jonathan Fortney3
Institution(s): *1. ETH Zürich, 2. Max Planck Institute for extraterrestrial Physics, 3. UC Santa Cruz, 4. University of Exeter*

105 – Disks and Migration Poster Session

105.01 – Formation of giant planetary systems with consistent eccentricity and inclination damping

We study the orbital evolution of three giant planets in the late stage of the gas disc, extending the previous work of Libert & Tsiganis (2011) on the combined action of disc migration and planet-planet scattering. Our goal is to investigate the influence of the eccentricity and inclination damping due to planet-disc interactions, on the final configurations of planetary systems. We present the results of ~10000 numerical experiments, exploring different initial configurations, planetary mass ratios and disc masses. Our n-body simulations use the damping formulae for eccentricity and inclination provided by the hydrodynamical simulations of Bitsch et al. (2013), and the disc mass is assumed to decrease exponentially. The simulated population reproduces the observed semi-major axis and eccentricity distributions with a very good agreement, except for low initial disc masses. Concerning the inclinations, most of the systems are found with small inclinations (< 10°). Even though many systems enter an inclination-type resonance during the migration phase, the disc damps the inclination in a relatively short time scale, leading the planets back to the midplane. Nevertheless, a significant fraction of the systems end up with high mutual inclinations. The percentages of resonant two- and three-body systems in the population are finally discussed.

Author(s): Anne-Sophie Libert[2], Sotiris Sotiriadis[2], Bertram Bitsch[1], Aurélien Crida3
Institution(s): *1. Lund Observatory, 2. University of Namur, 3. University of Nice-Sophia Antipolis*

105.02 – Adding disk effects to N-body simulations with REBOUNDx: Application to overstability of

resonances in exoplanet pairs
Mean-motion resonances (MMRs) are typically stable configurations for pairs of planets. Given that planets should migrate relative to one another in their natal disk, one might expect to have found most planets locked in such MMRs. The fact that most Kepler planets are *not* observed in MMRs therefore requires an explanation. Goldreich and Schlichting (2014) recently argued that, in fact, due to interactions with the protoplanetary disk, planets below a threshold mass should break out of the strongest MMRs, i.e., the MMRs become *overstable*.

While follow-up work has studied the robustness of this result to varying orbital architectures, we focus on the specific numerical implementation of the disk effects, which translates into differing physical interpretations of the planet-disk interactions. We will present how these physical choices affect the parameter space in which overstability sets in, and how certain choices can generate spurious results. We will then extend our results to general cases of broad applicability, and summarize the merits and pitfalls of these different numerical implementations of perturbations from the protoplanetary disk, particularly in tightly packed systems.

We have packaged these numerical implementations into REBOUNDx, an open-source C and Python package for incorporating planet-disk interactions, as well as additional effects (like post-newtonian corrections), into N-body simulations using REBOUND. We will give a brief demo that highlights its ease of installation and use, as well as its synergy with Python's powerful plotting and scientific analysis libraries.

Author(s): Daniel Tamayo[2], Hanno Rein[2], Alice Chen[2], morgan bennett[1]
Institution(s): *1. Simon Fraser University , 2. University of Toronto at Scarborough*

105.03 – Constraints on Exoplanet System Architectures from Debris Disks

Debris disks are dusty disks around main sequence stars. Terrestrial planets may be forming in young debris disks with ages <100 Myr. Planets in debris disks dynamically sculpt the dust in these systems. Thus, the spatial structure of debris disks could be an indicator of where planets have formed. We present an analysis of several members of the Scorpius-Centaurus OB Association (Sco Cen) that host both debris disks and planets, including HD 95086, HD 106906, and HD 133803. These objects are about 15-17 Myr old. The thermal emission from the debris disks constrains the locations of the dust. The dust is typically interior to the directly imaged planets in the systems. If additional planets reside in these systems, their locations are constrained by the positions of the dust belts. Many debris disk systems in Sco Cen appear to be two-belt systems. The gap between the belts in each system is a likely location for additional planets. The detection of planets in debris disk systems provide clues about the planet formation process, giving insights into where, when and how planets form.

Author(s): Hannah Jang-Condell[8], Christine H Chen[4], Tushar Mittal[6], Erika Nesvold[1], Marc J Kuchner[3], P Manoj[5], Dan Watson[7], Carey M Lisse[2]
Institution(s): *1. Carnegie Institution for Science, 2. Johns Hopkins University Applied Physics Laboratory, 3. NASA Goddard Space Flight Center, 4. Space Telescope Science Institute, 5. Tata Institute of Fundamental Research, 6. University of California, Berkeley, 7. University of Rochester, 8. University of Wyoming*

105.04 – The survival of gas giant planets on wide orbits

It is not known whether gas giant planets on wide orbits form the same way as Jupiter or by fragmentation of gravitationally unstable discs. It has been suggested that giant planets that form on wide orbits in gravitationally unstable discs quickly migrate towards the central star. We simulate the migration of such planets including the effects of gas accretion onto the planet and radiative feedback from the planet, both of which have been ignored in previous studies. We show that a giant planet, which has formed in the outer regions of a protostellar disc, initially migrates towards the central star while accreting gas from the disc. However, the planet eventually opens up a gap in the disc and the migration is essentially halted. At the same time, accretion-powered radiative feedback from the planet, significantly limits its mass growth, keeping it within the planetary mass regime (i.e. below the deuterium burning limit). Giant planets are therefore able to survive as planets (not higher-mass objects, i.e. brown dwarfs) on wide orbits, shaping the environment in which terrestrial planets that may harbour life form.

Author(s): Dimitris Stamatellos[1]
Institution(s): *1. University of Central Lancashire*

105.05 – Constraint of a planet mass from the depth and width of an observed gap on a protoplanetary disk

In a protoplanetary disk, a large planet is able to create the so-called disk gap, which is a low gas density region along the planet's orbit, due to the gravitational interaction between the disc and the planet. The gap formation induced by the giant planet is a possible mechanism to explain the formation of the so-called pre-transition disks with a ring gap structure. If the gap is created by the planet, the gap shape, i.e., the depth and width, would represent the mass and location of the planet. At the present stage, many pre-transition disks have been observed by e.g., ALMA and Subaru telescopes. It is important for us to examine what properties of the planet are constrained from the observed gap if the planet is in the gap.
We derived the relation between the depth of the observed gap and the planet mass in the gap based on the analytical model (Kanagawa et al. 2015a). This relation is a powerful tool to estimate the planet mass from the direct imaging of gaps in protoplanetary disks. We also applied this relation to the image of HL Tau' disk given by a part of the 2014 ALMA long baseline camphene and estimate the planet masses (Kanagawa et al 2015b).
We also performed the numerical hydrodynamic simulation with the FARGO which is well-known code for the rotation disk, and found that the gap width becomes wider with a square root of the planet mass. Using this empirical relation for the gap width, we can also constrain the planet mass from the gap width.
I'll talk about the relation between the gap depth, width and the planet, and the method for estimating the planet mass from the observed image of the disks.

Author(s): Kazuhiro Kanagawa[2], Takayuki Muto[3], Hidekazu Tanaka[2], Takayuki Tanigawa[4], Taku Takeuchi[1]
Institution(s): *1. Tokyo Institute of Technology, 2. ILTS, Hokkaido University, 3. Kogakuin university, 4. University of Occupational and Environmental Health*

105.06 – Using Protoplanetary Disks to Weigh the Youngest Stars and Constrain The Earliest Stages of Stellar Evolution

Mass is the fundamental property that determines the fate of a star. In particular, the masses of young stars are of great relevance to many astrophysical problems, including star and planet formation. We have developed a novel approach that combines spatially resolved sub-millimeter spectral line imaging and optical/near-infrared high resolution spectroscopy to derive the fundamental properties of a young star: mass, temperature, and radius. By applying our technique to a sample of pre-main sequence stars, we are mapping out a dynamically-calibrated Hertzsprung-Russell diagram for the express purpose of evaluating pre-main sequence evolutionary models. Looking forward, ALMA is poised to deliver precise stellar masses in statistically large quantities, enabling a meaningful survey of the fundamental properties of young stars.

Author(s): Ian Czekala[1], Sean Andrews[1], Eric Jensen[2], Keivan Stassun[3], David W Latham[1], David Wilner[1], Guillermo Torres[1]
Institution(s): *1. Harvard-Smithsonian Center for Astrophysics, 2. Swarthmore College, 3. Vanderbilt University*

105.07 – Caught in the act: The quest for forming giant planets still embedded in their parent disk

When, where, and how giant planets form is one of the burning questions in the field of exo-planets. There is little doubt that forming giant planets carve gaps in their parent disks, and many disks with this exact geometry have been observed. However, such gaps can be produced by other processes occurring in protoplanetary disks too, e.g. grain growth or photoevaporation. Observational constraints on planet formation theories have therefore been severly limited by our difficulties to unambiguously identify those disks that are in the process of forming giant planets. Only recently has the direct detection of forming giant planets still embedded in a protoplanetary disk become technically feasible. Indeed around half a dozen protoplanet candidates have been published within the last years. However, several of them are based on Sparse Aperture Masking observations and I will show that most of them are likely to be false positives. In their place, I present new and reliable direct-imaging SPHERE observations of a protoplanetary disk, revealing it to be almost certainly in the process of giant planet formation. This object, and others like it, may allow us for the first time to derive clear empirical constraints on the formation process of giant planets and their effects on the surrounding disk.

Author(s): Matthias R. Schreiber[1]
Institution(s): *1. Universidad Valparaiso*

105.08 – Photo-Reverberation Mapping of a Protoplanetary Accretion Disk around a T Tauri star

Theoretical models and spectroscopic observations of newborn stars suggest that protoplantary disks have an inner "wall", where material is depleted by sublimation and/or magnetospheric accretion. Around T Tauri stars, the size of this disk hole is expected to be on a 0.1-AU scale that is unresolved by current adaptive optics imaging, though some model-dependent constraints have been obtained by near-infrared interferometry. Here we report the first measurement of the inner disk wall around a solar-mass young stellar object, YLW 16B in the ρ Ophiuchi star-forming region, by detecting the light travel time of the variable radiation from the stellar surface to the disk. Consistent time lags were detected on two nights, when the time series in H and K bands were synchronized while the 4.5 µm emission lagged by 74.5 ± 3.2 seconds. Considering the nearly edge-on geometry of the disk, the inner rim should be 0.084 ± 0.004 AU from the protostar on average. This size is likely larger than the range of magnetospheric truncations, but consistent with an optically and geometrically thick disk front at the dust sublimation radius of ~1500 K. The detection of a definite time lag places constraints on the geometry of the disk.

Author(s): Huan Meng[1], Peter Plavchan[1], George Rieke[2]
Institution(s): *1. California Institute of Technology, 2. University of Arizona*

105.09 – Indirect and Direct Signatures of Young Planets in Protoplanetary Disks

Directly finding young planets around protostars is challenging since protostars are highly variable and obscured by dust. However, young planets will interact with protoplanetary disks, inducing disk features such as gaps, spiral arms, and asymmetric features, which are much easier to be detected. Transitional disks, which are protoplanetary disks with gaps and holes, are excellent candidates for finding young planets. Although these disks have been studied extensively in observations (e.g. using Subaru, VLT, ALMA, EVLA), theoretical models still need to be developed to explain observations. We have constructed numerical simulations, including dust particle dynamics and MHD effects, to study planet-disk interaction, with an emphasis on explaining observations. Our simulations have successfully reproduced spiral arms, gaps and asymmetric features observed in transitional disks. Furthermore, by comparing with observations, we have constrained protoplanetary disk properties and pinpoint potential planets in these disks. We will present progress in constructing global simulations to study transitional disks, including using our recently developed Athena++ code with static-mesh-refinement for MHD. Finally we suggest that accreting circumplanetary disks can release an observable amount of energy and could be the key to detect young planets directly. We will discuss how JWST and next generation telescopes can help to find these young planets with circumplanetary disks.

Author(s): Zhaohuan Zhu4, James M. Stone4, Ruobing Dong[1], Roman Rafikov3, Xue-Ning Bai[2]
Institution(s): *1. Berkeley, 2. Harvard-Smithsonian Center for Astrophysics, 3. Institute of Advanced Study, 4. Princeton University*

106 – Future Missions and Instrumentation Poster Session

106.01 – Respective capabilities of affordable Coronagraphs and Interferometers searching for Biosignatures

We describe an analytic model to estimate the capabilities of space missions dedicated to the search for biosignatures in the atmosphere of rocky planets located in the Habitable Zone of nearby stars. Relations between performance and parameters such as mirror diameter, distance to target, stellar properties, are obtained.
Two types of instruments are considered: Coronagraphs observing in the visible, and Nulling Interferometers observing in the thermal infrared. Missions considered as affordable are single-pupil coronagraphs with a 2.4 m primary mirror, and formation flying interferometers with 4 x 0.75 m collecting mirrors with baselines ranging from a few decameters to a few hectometers.
The numbers of accessible planets are calculated as a function of η_{earth}, the mean number of Earth analogues and super-Earths in stellar Habitable Zones.
Based on current estimates, η_{earth}=10% around FGK stars and 20% around M stars, the built-in coronagraph and starshade could study *only ~2.0* relevant planets, and the interferometer *~14*. These numbers are obtained under *the major assumption* that the exozodiacal light around the target stars is not an issue for any of these instruments.
For the coronagraphs, our estimates are in agreement with the values recently published by Stark et al. (2014), but these authors did not consider the case of interferometers.
For the long-term future, building both types of spectroscopic instruments, and using them on the same targets, will be the optimal solution because they provide complementary information. But as a first affordable space mission, *the interferometer looks the more promising in term of biosignature harvest.*

Author(s): Alain M. Leger[1]
Institution(s): *1. IAS*

106.02 – GravityCam: ground-based wide-field high-resolution imaging and high-speed photometry

The image blurring by the Earth's atmosphere generally poses a substantial limitation to ground-based observations. While opportunities in space are scarce, lucky imaging can correct over a much larger patch of sky and with much fainter reference stars. We propose the first of a new kind of versatile instruments, "GravityCam", composed of ~100 EMCCDs, that will open up two entirely new windows to ground-based astronomy: (1) wide-field high-resolution imaging, and (2) wide-field high-speed photometry. Potential applications include (a) a gravitational microlensing survey going 4 magnitudes deeper than current efforts, and thereby gaining a factor 100 in mass at the same sensitivity, which means probing down to Lunar mass or even below, (b) extra-solar planet hunting via transits in galactic bulge fields, with high time resolution well-suited for transit timing variation studies, (c) variable stars in crowded fields, with sensitivity to very short periods, (d) asteroseismology with many bright stars in one pointing, (e) serendipitous occultations of stars by small solar system bodies, giving access to the small end of the Kuiper Belt size distribution and potentially leading to the first detection of true Oort cloud objects, while predicted occultations at high time resolution can reveal atmospheres, satellites, or rings, (f) general data mining of the high-speed variable sky (down to 40 ms cadence).

Author(s): Martin Dominik[10], Craig Mackay[7], Iain Steele[2], Colin Snodgrass[5], Michael Hirsch[3], Uffe Gråe Jørgensen[8], Markus Hundertmark[8], Rafael Rebolo[1], Keith Horne[10], Sarah Bridle[9], Bruno Sicardy[6], Daniel Bramich[4], Khalid Alsubai[4]
Institution(s): *1. Instituto de Astrofísica de Canarias (IAC), 2. Liverpool John Moores University, 3. Max Planck Institute for Intelligent Systems, 4. Qatar Foundation, 5. The Open University, 6. Université Pierre-et-Marie-Curie, 7. University of Cambridge, 8. University of Copenhagen, 9. University of Manchester, 10. University of St Andrews*

106.03 – A laser locked Fabry-Perot etalon with 3 cm/s stability for wavelength calibration of Doppler spectrographs

Superior wavelength calibration is a major component in attaining Doppler precision of 10 cm/s and better with high resolution spectrographs. To achieve this goal, current calibration methods like thorium-argon lamps and iodine cells need to be replaced by more precise techniques. The ideal wavelength calibrator has a grid of densely spaced, narrow lines of equal brightness and works over a wide wavelength range. Laser frequency combs have received much attention recently, but they are complex and costly. We present an alternative method that builds on the success of passively stabilized Fabry-Perot etalons: we actively stabilize the etalon to an atomic transition, which provides an absolute frequency reference. We use saturated absorption laser spectroscopy to detect the hyperfine transitions of rubidium at 780 nm, a well-established frequency standard. Then we tune an etalon parameter (for instance, temperature) to keep one etalon peak coincident with the rubidium transition. Our setup is designed to be simple and robust, adaptable to various etalons, and to work in the infrared as well as the visible spectral range. We achieve a locking precision that is equivalent to a Doppler precision of better than 3 cm/s over any reasonable integration time.

Author(s): Christian Schwab[1], Yulia Gurevich[5], Julian Stuermer[3], Thorsten Fuehrer[2], Steve Lamoreaux[5], Thomas Walther[2], Andreas Quirrenbach[4]
Institution(s): *1. Macquarie University, 2. Technische Universitaet Darmstadt, 3. University of Chicago, 4. University of Heidelberg, 5. Yale University*

106.05 – Overview of the TESS Science Pipeline

The Transiting Exoplanet Survey Satellite (TESS) science pipeline is being developed by the Science Processing Operations Center (SPOC) at NASA Ames Research Center based on the highly successful Kepler science pipeline. Like the Kepler pipeline, the TESS science pipeline will provide calibrated pixels, simple and systematic error- corrected aperture photometry, and centroid locations for all 200,000+ target stars, observed over the 2-year mission, along with associated uncertainties. The pixel and light curve products are modeled on the Kepler archive products and will be archived to the Mikulski Archive for Space Telescopes (MAST). In addition to the nominal science data, the 30-minute Full Frame Images (FFIs) simultaneously collected by TESS will also be calibrated by the SPOC and archived at MAST.

The TESS pipeline will search through all light curves for evidence of periodic transit signals that occur when a planet crosses the disk of its host star. The Data Validation (DV) pipeline component will generate a suite of diagnostic metrics for each transit-like signature discovered, and extract planetary parameters by fitting a limb-darkened transit model to each potential planetary signature. The results of the transit search will be similar in content to the Kepler transit search products (tabulated numerical results, time series products, and pdf reports) all of which will be archived to MAST.

This paper provides an overview of the TESS science pipeline and describes the development of the SPOC remaining before launch in August 2017.

TESS was selected by NASA for launch in 2017 as an Astrophysics Explorer mission.

Author(s): Jon Michael Jenkins[1]
Institution(s): *1. NASA Ames Research Center*

106.06 – The Guest Investigator Program for the Transiting Exoplanet Survey Satellite (TESS)

In June 2015, NASA HQ approved the establishment of a Guest Investigator Program Office for TESS. Through the GI Program, members of the Astronomical Community will be able to apply for observations of new targets with TESS and for funding to support research with both 2-minute cadence postage stamp data and full-frame images (FFIs). In addition, the GI Program office will be responsible for making key software for working with TESS data available to the Community, and will provide long-term support for working with the data. Here, we introduce the GI Program to the K2 Community, describe the organization and roles of the program, and solicit feedback from the Community in how to ensure the greatest effectiveness of the program.

Author(s): Stephen Rinehart[2], Mark Clampin[2], George R. Ricker[1], Sara Seager[1], Joshua Winn[1], Roland Vanderspek[1], David W Latham[3]
Institution(s): *1. MIT, 2. NASA Goddard, 3. SAO*

106.07 – More ESSs with the ELTs: Gas Giants, Habitable Planets and Exomoons

The upcoming 30-m class telescopes will open-up exciting science capabilities, achieving three times better angular resolution, allowing for of wealth of new discoveries to be made of closer in/lower mass planets. While the discovery of young gas giant planets in nearby systems will become daily news with these telescopes, we can expect the Quest for the first picture/characterization of an Earth-like planet to be at its apogee in the 2020s, with the development of dedicated instruments in the NIR and thermal IR for the ELTs; in parallel with space endeavors. Third generation ExAO systems will produce higher SNR planet images of known systems, allowing, for the first time, an in-depth analysis of these worlds, including their surface mapping, and possibly revealing the presence of exomoons.

Author(s): Christian Marois[1]
Institution(s): *1. National Research Council of Canada*

106.08 – ASTERIA: A CubeSat for Exoplanet Transit and Stellar Photometry

We present ASTERIA, a 6U CubeSat demonstrator for exoplanet transit photometry. ASTERIA, currently in development at JPL and due to be launched in mid to late 2016, is a testbed for a two-stage pointing system capable of <10 arcsecond pointing as well as active thermal control. These two features will allow ASTERIA to achieve very high photometric precision (<100 ppm) in a very small and cost effective package. ASTERIA will be used to search for transits of known RV planets as well as perform long duration, high cadence stellar photometry. The stellar photometry data will be used to study flares and stellar activity on a variety of stellar types. This presentation will focus on ASTERIA's science mission.

Author(s): Mary Knapp[1], Sara Seager[1]
Institution(s): *1. Massachusetts Institute of Technology*

106.09 – Technology for radial velocity search and characterisation of exoplanets in the 2020s and beyond

In the past 20 years, radial velocity exoplanet instrumentation has been focussed on a small number of moderate sized (or moderate efficiency) telescopes. I will argue that there are two very different uses for radial velocity in the near future: transit follow-up and low-mass exoplanet detection around relatively nearby stars. For the first of these science goals, targets are relatively distant, and a high eficiency spectrograph on a large telescope is needed, for example the Gemini High-resolution Optical SpecTrograph (GHOST): a stabilised spectrograph fed by an array of multi-mode fibers at the final design stage. For the second of these goals, stellar noise due to pulsations, convective cells and activity provide a lower limit to the noise floor achievable for any given temporal sampling. I will argue through simple simulations that an array of small telescopes with precise spectrographs making a very large number of measurements is a much more effective way to detect the smallest exoplanets than instrumentation on large telescopes. I will describe the first results from the Replicable High-Resoluition Exoplanet and Asteroseismology (RHEA) spectrograph designed for 0.25 to 0.5m telescopes, which has single-epoch measurement uncertainties at the 1 m/s level and a total whole cost for detecting the smallest exoplanets that is significantly lower than medium to large telescope concepts. RHEA has an eyepiece-sized fast tip/tilt and mode reformatting system that efficiently injects a small array of single-mode fibers, feeding a <0.5m sized stabilised inexpensive spectrograph. I will show preliminary performance results from both stars and laboratory tests that verify the precision, and will discuss pathways to turn this into a broader community project.

Author(s): Michael Ireland[1], Tobias Feger[2], Joao Bento[1], Adam Rains[1]
Institution(s): *1. Australian National University, 2. Macquarie University*

106.10 – The NASA Exoplanet Exploration Program

The NASA Exoplanet Exploration Program (ExEP) is chartered to implement the NASA space science goals of detecting and characterizing exoplanets and to search for signs of life. The ExEP manages space missions, future studies, technology investments, and ground-based science that either enables future missions or completes mission science. The exoplanet science community is engaged by the Program through Science Definition Teams and through the Exoplanet Program Analysis Group (ExoPAG). The ExEP includes the space science missions of Kepler, K2 , and the proposed WFIRST-AFTA that includes dark energy science, a widefield infrared survey, a microlensing survey for outer-exoplanet demographics, and a coronagraph for direct imaging of cool outer gas- and ice-giants around nearby stars. Studies of probe-scale (medium class) missions for a coronagraph (internal occulter) and starshade (external occulter) explore the trades of cost and science and provide motivation for a technology investment program to enable consideration of missions at the next decadal survey for NASA Astrophysics. Program elements include follow-up observations using the Keck Observatory, which contribute to the science yield of Kepler and K2, and include mid-infrared observations of exo-zodiacal dust by the Large Binocular Telescope Interferometer which provide parameters critical to the design and predicted science yield of the next generation of direct imaging missions. ExEP includes the NASA Exoplanet Science Institute which provides archives, tools, and professional education for the exoplanet community. Each of these program elements contribute to the goal of detecting and characterizing earth-like planets orbiting other stars, and seeks to respond to rapid evolution in this discovery-driven field and to ongoing programmatic challenges through engagement of the scientific and technical communities.

Author(s): Douglas M Hudgins[2], Gary H Blackwood[1], John S Gagosian[2]
Institution(s): *1. Jet Propulsion Laboratory, 2. NASA Headquarters*

106.12 – Status of the James Webb Space Telescope and its Capabilities for Exoplanet Observations

The James Webb Space Telescope (JWST) is a large aperture, infrared telescope planned for launch in 2018. JWST is a facility observatory that will address a broad range of science goals covering four major themes: First light and Re-Ionization, the Assembly of Galaxies, the Birth of Stars and Protoplanetary Systems, and Planetary Systems and the Origins of Life. With a 6.5 meter diameter mirror it will be the largest space telescope ever flown, and is the first cryogenic telescope to incorporate passive cooling, achieved by means of a large sunshade, to reach its ~40 K operating temperature. JWST has a complement of four science instruments that offer a range of capabilities for exoplanet imaging and transit imaging and spectroscopy. I will present an overview of the observatory design, highlight recent progress towards integration, testing, and science operations. I will also discuss JWST's launch and commissioning timeline. Finally, I will present the capabilities of JWST to conduct programs which address the observations of exoplanets.

Author(s): Mark Clampin[1]
Institution(s): *1. GSFC*

107 – Habitability Poster Session

107.01 – From snowball to moist greenhouse: the climatological evolution of Earth-analog planets simulated with a 3D climate system model

The host star imposes a primary control on terrestrial planet climate. Both the spectral energy distribution and the main sequence lifetime vary as a function of stellar type. Here we present recent results from three-dimensional climate system models describing the evolutionary sequence of Earth-analog planets throughout their habitable lifetimes. Climatological evolution is traced from snowball to moist greenhouse, representing the conventional end-member states of the habitable zone. For Earth the habitable period would have been tantalizingly short, if not for geological and biological regulation of greenhouse gases. Without active carbon cycling, an early snowball could not have been broken until late in Earth's history. Abrupt solar driven deglaciation would soon be followed by the onset of the water vapor greenhouse feedback and a moist greenhouse climate, leaving little over 1 billion years of habitable surface conditions. Around bluer stars, the habitable period for terrestrial planets is constricted further due to their reduced main sequence lifetimes and thus more rapid brightening. Planets with long-lived habitable periods are most likely found around stars redder than the Sun due to their more gradual brightening.

Author(s): Eric T Wolf[2], Ravi Kopparapu3, Jacob Haqq-Misra[1], Owen Brian Toon[2]
Institution(s): *1. Blue Marble Space Institute of Science, 2. Laboratory for Atmospheric and Space Physics, 3. NASA Goddard Space Flight Center*

107.03 – Titania may produce abiotic oxygen atmospheres on habitable exoplanets

The search for habitable exoplanets in the Universe is actively ongoing in the field of astronomy. The biggest future milestone is to determine whether life exists on such habitable exoplanets. In that context, oxygen in the atmosphere has been considered strong evidence for the presence of photosynthetic organisms. In this paper, we show that a previously unconsidered photochemical mechanism by titanium (IV) oxide (titania) can produce abiotic oxygen from liquid water under near ultraviolet (NUV) lights on the surface of exoplanets. Titania works as a photocatalyst to dissociate liquid water in this process. This mechanism offers a different source of a possibility of abiotic oxygen in atmospheres of exoplanets from previously considered photodissociation of water vapor in upper atmospheres by extreme ultraviolet (XUV) light. Our order-of-magnitude estimation shows that possible amounts of oxygen produced by this abiotic mechanism can be comparable with or even more than that in the atmosphere of the current Earth, depending on the amount of active surface area for this mechanism. We conclude that titania may act as a potential source of false signs of life on habitable exoplanets.

Reference:
Narita N. et al.,
Scientific Reports **5**, Article number: 13977 (2015)
http://www.nature.com/articles/srep13977

Author(s): Norio Narita[2], Takafumi Enomoto[1], Shigeyuki Masaoka[1], Nobuhiko Kusakabe[2]
Institution(s): *1. Institute for Molecular Science, 2. National Astronomical Observatory of Japan*

107.04 – Climate and Habitability of Kepler 452b

The discovery of Kepler 452b marks a milestone of searching for habitable exoplanets. While simple estimation indicates that Kepler 452b is located in the habitable zone of a Sun-like star, the climate state and habitability of Kepler 452b require detailed studies. Using a three-dimensional fully coupled atmosphere-ocean climate model and assuming an aqua-planet, we perform simulations to demonstrate climate states of Kepler 452b for different greenhouse effects and ice-albedo feedbacks. Our simulations show that sea ice can only invade from poles to about 45 degree in latitude for extremely low levels of CO_2 (5 ppmv), and that surface temperature near the equator remains as high as 300 K. For high level of CO_2 (0.2 bars), the exoplanet becomes ice free, and tropical surface temperature reaches about 335 K. The results suggest that Kepler 452b is very close to the inner edge of the habitable zone, and that its climate state can readily reach the runaway greenhouse limit as greenhouse concentration is higher.

Author(s): Yongyun Hu[1], Yuwei Wang[1], Yonggang Liu[1]
Institution(s): *1. Peking University*

107.05 – Atmospheres and Oceans of Rocky Planets In and Beyond the Habitable Zones of M dwarfs

he evolution of M dwarfs during their pre-main-sequence phase causes rocky planets in and beyond the habitable zones these stars to be in the runaway and moist greenhouse states. This scenario has been studied by three groups of researchers recently (Ramirez and Kaltenegger 2014, Tian and Ida 2015, Luger and Barnes 2015), and their consensus is that massive amount of water could have been lost during this time -- early evolution of M dwarfs could have changed the water contents of rocky planets around them, which could strongly influence the habitability of rocky planets around low mass stars. It has been proposed that dense oxygen dominant atmospheres (up to 2000 bars, Luger and Barnes 2015) because of rapid water loss. Is this true? If so, what's the condition for such atmospheres to exist and can they be maintained? On the other hand, what's the likelihood for sub-Neptunes to shrink into habitable planets under such environment? In general how is the habitability of planets around M dwarfs different from those around Sun-type stars? These are the questions we will attempt to address in this work.

Author(s): Feng Tian[1]
Institution(s): *1. Tsinghua University*

107.06 – Effects of Water Amount on the Surface Environment of Terrestrial Planets: High Pressure Ice and Carbon Cycle

Terrestrial planets with several wt% of H_2O in extrasolar planetary systems are theoretically predicted in the habitable zone [Raymond et al., 2004]. Such planets are expected to be covered by an ocean entirely (called as “ocean planets”). Amount of atmospheric CO_2 (P_{CO_2}) is important for surface environment because CO_2 is a strong greenhouse gas. P_{CO_2} is determined by a race between degassing and sink through weathering on carbon cycle. On an ocean planet, seafloor weathering is important because continental weathering can’t work [Abbot et al., 2012]. In addition, ocean planets with large water amount may have high-pressure (HP) ice on the seafloor [Leger et al., 2004]. Since the ocean floor is covered by ice in such case, it has been thought that any weathering processes will not work and P_{CO_2} will be extremely high.

When plate tectonics works, heat flow from oceanic crust decreases with distance from the mid ocean ridge. Therefore, HP ice near the mid ocean ridge will be kept solid-liquid coexistent state at the melting point because of high heat flow. Seafloor weathering works in this region. The seafloor weathering under this condition efficiently works because weathering temperature is kept melting point regardless of surface temperature. Thus, our aim is to clarify the relationship between water amount and surface environment focusing seafloor environment.

We develop a carbon cycle model considering the seafloor weathering. Our major assumptions are following; 1) Earth-sized ocean planets with various water amount, 2) Degassing rate is depended on the total amount of carbon and total carbon inventory is proportional to the surface water amount. We investigated thermal state of HP ice and determined effective weathering region where HP ice is coexistent with water, then we investigated the P_{CO_2} in equilibrium state where degassing and regassing are balanced. As a result, forming of HP ice may cause snowball state due to high weathering rate. When solar incident flux and heat flow from mantle are the present Earth’s value and a ratio of CO_2 / H_2O inventory is carbonaceous chondrite composition, a planet with large ocean which is larger than 90 Earth’s ocean mass lapses into snowball state. It was previously believed that forming of HP ice supports warm climate; rather, forming of HP ice could cause snowball state.

Author(s): Akifumi NAKAYAMA[1], Yutaka Abe[1]
Institution(s): *1. The University of Tokyo*

107.07 – On the Possibility of Habitable, Trojan Planets in the Kepler Circumbinary Planetary Systems

The recent discovery of circumbinary planets with the Kepler space telescope has opened a new direction in the search for habitable planets. Three of the known Kepler circumbinary planets reside in habitable zones: Kepler 16b, Kepler 47c, and Kepler 453b. Although these planets are too large to be habitable, they present the possibility of having habitable, terrestrial-size Trojan planets and/or moons. Although no Trojan planets have yet been detected in any exoplanetary system, theoretical studies suggest Trojan planets can exist in stable orbits in circumbinary planetary systems and can be detected with current and future space telescopes. We have performed more than 1,000 numerical integrations of each of these systems in which we have included an Earth-mass object in a random orbit near one of the two Lagrangian points in the habitable zone. We present the results of these integrations and further discuss their implications for the formation and evolution of these particular systems. We also report on the detectability of Earth-mass Trojan planets via transits or transit timing variations.

Author(s): Jeffrey Sudol[2], Nader Haghighipour[1]
Institution(s): *1. University of Hawai'i-Manoa, 2. West Chester University*

107.08 – Spectra for Small Volatile Molecules for Potential Exoplanet Biosignature Gases

With thousands of exoplanets discovered orbiting nearby stars, the community anticipates that next-generation telescopes will have the capability to detect a few habitable planets and possibly find signs of life via biosignature gases in the atmosphere. We propose that life on another world could produce a large variety of gases. If a significant quantity of certain volatile molecule is produced, it could be considered as a biosignature gas. We have collected existing spectra for over 1000 volatile molecules from searching dozens of existing on-line databases. We present representative spectra for different classes of molecules, and discuss differences within each class. We highlight gases that, based on atmospheric lifetimes, might be observable if produced in abundance and offer an observational “triage” strategy.

Author(s): Zhuchang Zhan[1], Sara Seager[1], William Bains[1], Laura Eckman[1], Anshula Gandhi[1], Zifan Lin[1], Mihkel Pajusalu[1], Janusz Petkowski[1], Lizhou Sha[1]
Institution(s): *1. MIT*

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108 – Hot Jupiters and Star-Planet Interactions Poster Session

108.01 – The architecture of the multi-planet system of υ And: υ And b - a super-inflated hot Jupiter in a

cosmic ping-pong game

The gas giant Upsilon Andromeda b (υ And b) was one of the first discovered exoplanets. This planet orbits around a bright, similar to the Sun star only 13.5 parsecs away from us. υ And b is also the innermost planet of a confirmed three-planet system, all of them non-transiting. As with all non-transiting planets, their exact masses and sizes are unknown, with their orbital inclination being the key parameter to unveil those values. Astrometric measurements have placed constraints to the orbital inclinations of the two outer planets in this system, indicating that we look almost 'face-on' on the system (McArthur et al. 2010). However, the orbital inclination for the innermost planet remained unknown.

Photometric monitoring of υ And b orbit at infrared wavelengths has revealed significant brightness changes between the day-side and the night-side of the planet (Crossfield et al. 2010). The amplitude of those brightness variations depends on the orbital inclination of the planet and on its radius, therefore we can tightly constrain the size of the planet if its inclination is known.

Here we present the measurement of the orbital inclination for the innermost planet υ And b, 23 deg, obtained by monitoring the Doppler shift of carbon monoxide (CO) lines on the atmospheric day-side of the planet with Keck/NIRSPEC. From this measurement we establish a planet mass of 1.7 times the mass of Jupiter and a minimum planet radius of 1.8 times the size of Jupiter. This result reveals that υ And b is likely to be one of the most inflated giant planets discovered to date. In addition, the observed strong CO absorption suggests an atmosphere with temperature uniformly decreasing towards higher altitudes, which suggests the absence of an atmospheric thermal inversion (Rodler et al. 2015).

Author(s): Florian Rodler[1]
Institution(s): *1. Max-Planck Institute for Astronomy*

108.02 – Architectural Insights into the Origin of Hot Jupiters

The origin of Jupiter-mass planets with orbital periods of only a few days is still uncertain. This problem has been with us for 20 years, long enough for significant progress to have been made, and also for a great deal of "lore" to have accumulated about the properties of these planets. Among this lore is the widespread belief that hot Jupiters are less likely be in multiple giant planet systems than longer-period giant planets. We will show that in this case the lore is not supported by the best data available today: hot Jupiters are no more or less likely than warm or cool Jupiters to have additional Jupiter-mass companions. In contrast to the expectation from the simplest models of high-eccentricity migration, the result holds for Jupiter-mass companions both inside and outside of the water-ice line. This support the importance of disk migration for the origin of short-period giant planets.

Author(s): Kevin C Schlaufman[1], Joshua Winn[2]
Institution(s): *1. Carnegie Observatories, 2. Massachusetts Institute of Technology*

108.03 – Ohmic Inflation of Hot Jupiters: an Analytical Approach

Many giant exoplanets in close orbits have observed radii which exceed theoretical predictions.
One suggested explanation for this discrepancy is heat deposited deep inside the atmospheres of these hot Jupiters.
We present an analytical model for the evolution of such irradiated, and internally heated gas giants, and derive scaling laws for their cooling rates and radii.
We estimate the Ohmic dissipation resulting from the interaction between the atmospheric winds and the planet's magnetic field, and apply our model to Ohmically heated planets.
Our model can account for the observed radii of many inflated planets, but not the most extreme ones.
We show that Ohmically heated planets have already reached their equilibrium phase and they no longer contract.
We show that it is possible to re-inflate planets, but we confirm that re-heating timescales are longer by about a factor of 30 than cooling times.

Author(s): Sivan Ginzburg[1], Re'em Sari[1]
Institution(s): *1. The Hebrew University*

108.04 – Tidal Forces Cannot Explain Planets Close to 2:1 Mean Motion Resonance

Many planet pairs lie just wide of first-order mean motion resonances (MMRs), and tidal forces have been frequently proposed to explain these pileups. We contribute to this ongoing discussion by calculating an optimistic theoretical estimate on the minimum initial eccentricity required by Kepler planets to explain the current observed spacing, and compliment these calculations with N-body simulations. In particular, 27 Kepler near-resonant systems we're investigated, and we found that the initial eccentricities required to explain the observed spacings are unreasonable from simple dynamical arguments. Furthermore, our numerical simulations revealed that only two systems (out of 27) could be successfully explained using tidal forces alone.

We find the main hurdle preventing tides from effectively migrating planets away from MMR is "resonant tugging", an effect which conspires against the migration of resonant planets away from the 2:1 MMR, requiring planets to have even higher initial eccentricities in order to explain the current Kepler distribution.

Overall, we find that tides alone cannot explain planets close to 2:1 MMR, and additional mechanisms are required to explain these systems.

Author(s): Ari Silburt[1], Hanno Rein[1]
Institution(s): *1. University of Toronto*

108.05 – The impact of stellar activity on X-ray and UV transits

X-ray and UV observations of transiting exoplanets have revealed the presence of extended atmospheres around a number of systems. At high energies, stellar radiation is absorbed high up in the planetary atmosphere, making X-ray and UV observations a potential tool for investigating the upper atmospheres of exoplanets. However, at these high energies, stellar activity can dramatically impact the observations. At short wavelengths the star appears limb-brightened, and active regions appear as bright features on the stellar disk. These will impact both the transit depth and shape, affecting our ability to measure the true planet-to-star radius ratio.

I will show results of simulate exoplanet transit light curves using Solar data obtained in the soft X-ray and UV by NASA's Solar Dynamics Observatory to investigate the impact of stellar activity at these wavelengths. By using a limb-brightened transit model coupled with disk resolved Solar images in the X-ray, extreme- and far-UV I will show how both occulted and unocculted active regions can mimic an inflated planetary atmosphere by changing the depth and shape of the transit profile. I will also show how the disk integrated Lyman-alpha Solar irradiance varies on both short and long timescales and how this variability can impact our ability to recover the true radius ratio of a transiting exoplanet.

Finally, I will present techniques on how to overcome these effects to determine the true planet-to-star radius in X-ray and UV observations.

Author(s): Joe Llama[2], Evgenya Shkolnik[1]
Institution(s): *1. Lowell Observatory, 2. University of St Andrews*

108.06 – Towards a new model of atmospheric tides: from Venus to super-Earths

Tides can strongly affect the evolution of the spin of planets. Super-Earths presenting a solid core and an atmosphere are submitted to both gravitational tides caused by bodies' mutual gravitational interactions and thermal tides resulting from stellar insolation.

Thermal tides are particularly important for planets in the habitable zone where they drive the tidal response of the atmosphere (Correia & Laskar 2008). They play a key role for the equilibrium states of the spin, as in the case of Venus (Correia & Laskar 2004) and of exoplanets (e.g. the numerical simulations by Leconte & al. 2015). Given the complex mechanisms involved in thermal tides, analytic models are essential to understand the dependence of the perturbation on the physics on the atmosphere and the tidal frequency. The one proposed in the 60's by Lindzen and Chapman explains well thermal tides in the asymptotic regime of fast rotators but presents a singularity near synchronization. We will present a new analytic approach that generalizes these early works to all regimes of tidal perturbations. This model describes the mechanisms of tidal waves generated in the atmosphere by both gravitational and thermal tides. The tidal torque is computed as a function of the frequency of the forcing and agrees very well with results obtained by direct numerical simulations using General Circulation Models.

Author(s): Pierre Auclair-Desrotour[2], Jacques Laskar[2], Stéphane Mathis[1]
Institution(s): *1. CEA, 2. Paris Observatory*

108.07 – Mass Transfer Stability of Hot Jupiters at Their Roche Limit

Many exoplanets have been detected in orbits close to their Roche limit. Through tidal dissipation, it is expected that their orbits will decay, initiating mass transfer via Roche lobe Overflow (RLO). Previous studies have looked at the RLO evolution of these planets, suggesting a Neptune or Earth mass remnant will remain after concluding mass transfer. However, a critical assumption entering such calculations is that the RLO mass transfer of these systems is stable. We present numerical calculations using smoothed-particle hydrodynamics to investigate the details of this mass transfer.

Author(s): Joshua Fixelle[1], Jason Hwang[1], Francesca Valsecchi[1], Fred Rasio[1]
Institution(s): *1. Northwestern*

108.08 – Nonlinear tides in giant planets

Tidal interactions between short-period planets and their host stars can play an important role in the evolution of planetary orbits and stellar and planetary spins. For example, the observational preponderance of circular orbits among the shortest-period planets, with orbital periods shorter than about ten days, relative to those with wider orbits, is thought to be explained by tidal dissipation inside these planets. I will review recent work and present new results on the nonlinear evolution of tidal flows in rotating planets, which aims to understand the mechanisms responsible for tidal dissipation from first principles. I will describe the results of global hydrodynamical simulations of the elliptical instability, as well as the tidal excitation of inertial waves in a planet with a core, focusing on the role of nonlinear fluid effects. The importance of these mechanisms in explaining observations will be discussed.

Author(s): Adrian J Barker[1]
Institution(s): *1. University of Cambridge*

108.09 – Planets in extreme magnetic environments

Interactions between stars and planets in very close-in systems include irradiation, tidal and magnetic effects, the relative amplitudes of which depend on the system parameters. The extent of magnetic interactions, however, is only poorly known since the magnetic fields of the parent star itself is barely characterized. In this presentation, I will review the recent efforts made to measure and characterize the magnetic fields of star hosting close-in planets, in order to provide quantitative constraints in the studies of star-planet interactions.
We have been using the spectropolarimeters CFHT/ESPaDOnS and TBL/NARVAL to assess the our ability to detect the circular polarization of several dozens planet-host stars, and to map the large-scale magnetic topology of a sub-sample of these stars. The detection of magnetic fields as low as a few Gauss is possible around relatively bright, solar-like stars. After hot-Jupiter systems, we got interested in systems with smaller planets in close orbits. Several applications of these magnetic topologies have already been used in theoretical analyses of the star-planet interactions, that we will briefly review. Perspectives for this work include further observing programs and more detailed theoretical representations.

Author(s): Claire Moutou[1]
Institution(s): *1. CFHT*

108.10 – Sating a Voracious Appetite: The Tidal Interaction of Close-in Planets with their Host Stars

Transit observations of the apparent angle between the stellar spin and the vector normal to the planetary orbital plane suggest that cool stars are preferably aligned systems even as hot stars exhibit a large range of obliquities. In addition, as was demonstrated recently by Mazeh et al., the distribution of planet periods as a function of mass exhibits a dearth of sub-Jupiter--mass planets at < 4 days periods, with the boundary of the sparsely populated region in phase space having a roughly conical shape. We suggest that both of these seemingly disparate features are manifestations of the tidal interaction between close-in planets and their host stars. We attribute the dichotomy in the obliquity properties to the effect of an early population of hot Jupiters that got stranded near the inner edge of a primordially misaligned protoplanetary disk and subsequently (on a timescale < 1 Gyr) ingested by the host star. The relative magnitudes of the stellar spin and planetary orbital angular momenta at the time of ingestion determined whether the hot Jupiter could realign the host; this did not happen in the case of hot stars because of inefficient magnetic braking and a comparatively high moment of inertia. We interpret the dearth of intermediate-mass planets at short periods by considering the tidal evolution of planets that arrive on highly eccentric orbits at later (> 1 Gyr) times and become circularized at radii of a few times the Roche limit.

Author(s): Titos Matsakos[1], Arieh Königl[1]
Institution(s): *1. University of Chicago*

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109 – Orbital Dynamics and Planet-Planet Interactions Poster Session

109.01 – Exoplanetary System Dynamics: Planetary Multiplicity and Mass Effects

Recently numerous systems consisting of multiple exoplanets have been discovered. Using a dataset of 375 systems (500 planets) discovered by the radial velocity method and 365 systems (899 planets) containing planet candidates found by the Kepler Mission, we investigate the dependence of the dynamical structure of planetary systems on their multiplicity and the masses of the member planets. We classify the planetary system by three parameters: planetary multiplicity, planetary mass, and the evolutionary stage of the central star. We normalize planetary masses by the mass of the central star and divide the planets into small and large categories by a cut at 10^{-4}. The central star is classified into main-sequence or giant according to its evolutionary stage. We focus on the angular momentum deficit (AMD) of the systems and the orbital separation between adjacent planets normalized by their Hill radii. We find that in all categories the system AMD decreases with increasing multiplicity. This suggests that in order for multiple systems to be stable, each planet's orbit must be relatively circular. In addition, we find that the distribution of orbital eccentricities of the massive planets and low-mass planets differs. In particular, only high-mass planets have eccentricities larger than 0.4. In the low-mass systems around main sequence stars, we find that the orbital separation decreases with increasing multiplicity. In addition, the orbital separation around main-sequence stars is wider than that around giants. Furthermore, the minimum orbital separation is about 6.4 for non-resonant pairs. This paper presents the statistical properties of the dynamical structure of multiple planetary systems and discusses their formation.

Author(s): Mari Isoe[1], Eiichiro Kokubo[1], Edwin Turner[2]
Institution(s): *1. National Observatory of Japan, 2. Princeton University*

109.02 – Long-Term Stability of Planets in the Alpha Centauri System

The α Centauri system is billions of years old, so planets are only expected to be found in regions where their orbits are long-lived. We evaluate the extent of the regions within the α Centauri AB star system where small planets are able to orbit for billion-year timescales, and we map the positions in the sky plane where planets on stable orbits about either stellar component may appear. We confirm the qualitative results of Wiegert & Holman (Astron. J. 113, 1445, 1997) regarding the approximate size of the regions of stable orbits of a single planet, which are larger for retrograde orbits relative to the binary than for prograde orbits. Additionally, we find that mean motion resonances with the binary orbit leave an imprint on the limits of orbital stability, and the effects of the Lidov-Kozai mechanism are also readily apparent. Overall, orbits of a single planet in the habitable zones near the plane of the binary are stable, whereas high-inclination orbits are short-lived. However, even well within regions where single planets are stable, multiple planet systems must be significantly more widely-spaced than they need to be around an isolated star in order to be long-lived.

Author(s): Jack Lissauer[1], Billy Quarles[1]
Institution(s): *1. NASA Ames Research Center*

109.03 – Secular Dynamics of STIPs and Observable Consequences

We analyze the secular dynamics of Systems with Tightly-packed Inner Planets (STIPs) to determine if the planetary orbits can achieve large mutual inclinations while remaining stable. Analogues of Kepler 11 and Kepler 90 are explored in detail, as well as ensembles of hypothetical five-planet STIPs. In all cases, we map the secular resonance structure with and without the presence of outer perturbers. We find that some planets in a given STIP can acquire large inclinations due to secular resonances. These systems can remain stable, effectively producing two orbital planes for the planetary system. This can cause at least a moderate (~20 deg) stellar obliquity relative to orbital planes, impacting the observability of the entire STIP, as only one of the planes can be observed by transits at a time. Eccentricity resonances also play a large role in reducing the multiplicity of a STIP, leading merging collisions.

Author(s): Agueda Paula Granados-Contreras[1], Aaron Boley[1]
Institution(s): *1. University of British Columbia*

109.04 – Formation of Close-in Super-Earths by Giant Impacts: Effects of Initial Eccentricities and Inclinations of Protoplanets

Recent exoplanet observations are revealing the eccentricity and inclination distributions of exoplanets. Most of observed super-Earths have small eccentricities ~ 0.01 - 0.1 and small inclinations ~ 0.03 rad (e.g., Fabrycky et al., 2014). These distributions are results of their formation processes. N-body simulations have been used to investigate accretion of close-in super-Earths (e.g., Hansen & Murray 2012, Ogihara et al. 2015). Hansen & Murray (2013) showed that the averaged eccentricity of close-in super-Earths formed through giant impacts in gas-free and no planetesimal environment is around 0.1. In the giant impact stage, the eccentricities and inclinations are pumped up by gravitational scattering and damped by collisions. Matsumoto et al. (2015) found that the eccentricity damping rate by a collision depends on the eccentricity and inclination and thus affects the eccentricity and inclination of planets. We investigate the effect of initial eccentricities and inclinations of protoplanets on eccentricities and inclinations of planets. We perform N-body simulations with systematically changing initial eccentricities and inclinations of protoplanets independently. We find that the eccentricities and inclinations of planets barely depend on the initial eccentricities of protoplanets although the collision timescale is changed. This means that initial eccentricities of protoplanets are well relaxed through scattering and collisions. On the other hand, the initial inclinations of protoplanets affect the inclination of planets since they are not relaxed during the giant impact stage. Since the collisional timescale increases with inclinations, protoplanets with high inclinations tend to interact longer until they collide with each other. As a result, planets get large eccentricities, and the number of planets becomes small. The observed eccentricities and inclinations of super-Earths can be reproduced by giant impacts of protoplanets with inclinations ~ 10^{-3} -10^{-2} rad.

Author(s): Yuji Matsumoto[1], Eiichiro Kokubo[1]
Institution(s): *1. National Astronomical Observatory of Japan*

109.05 – GENGA: a GPU code for planet formation and planetary system evolution

We present GENGA, a GPU code designed and optimised for (exo)planetary formation - and orbital evolution simulations. The use of the parallel computing power of GPUs allows GENGA to achieve a significant speedup compared to other N-body codes. GENGA runs about 30 – 50 times faster than the Mercury code. GENGA can be used with three different computational modes: The main mode permits to integrate a N-body system with up to 8192 fully interacting planetesimals, orbiting a central mass.
The test particle mode can include up to 1 million massless bodies in the presence of massive planets or protoplanets. The third mode allows the parallel integration of up to 100000 samples of small exoplanetary systems with different parameters. With this functionality, GENGA can be used in a variety of applications in planetary and exoplanetary science. Possible applications of GENGA are: the late stage of terrestrial planet formation, study core accretion models for gas giants in the presence of planetesimals, simulate the evolution of asteroids and asteroid families, find stable configurations of exoplanetary systems to restrict the detected orbital parameters, and many more.
Since such simulations can often take billions of time steps to complete, or require the cover of a very large parameter space, it makes it necessary to use a highly optimised code, running on the today's most efficient hardware. As a bonus, the use of GPUs allows a real time visualisation of the simulations on the screen.
In our presentation we will give an overview of the possibilities of the code and discuss the newest results and applications of GENGA. The code is published as open source software under https://bitbucket.org/sigrimm/genga.

Author(s): Simon Lukas Grimm[1], Joachim Stadel[1]
Institution(s): *1. University of Zürich*

109.06 – Evolution of angular-momentum-losing exoplanetary systems - Revisiting Darwin stability

The dynamical evolution of planetary systems, after the evaporation of the accretion disk, is the result of the competition between tidal dissipation and the net angular momentum loss of the system. In the case of multiple systems, gravitational interaction between planets must also be taken into account. However, even focusing on single companion systems, the description of the diversity of orbital configurations, and correlations between parameters of the observed system, (e.g. in the case of hot Jupiters) is still limited by our understanding of tidal dissipation and its interplay with magnetic braking.

Using energy considerations only, I will present a new characterisation of the tidal equilibrium that is valid when the total angular momentum of the system is not conserved. This implies a remarkably different evolution of the planet's semi-major axis depending on the properties of the stellar host. I apply this theory to a sample of planetary systems and discuss their evolution using a particularly simple graphic approach that generalizes the classic Darwin tidal diagrams. This can help constraining theories of tidal dissipation and testing models of planetary formation. This kind of studies rely on the determination of stellar raddi, masses and ages. Major advances will thus be obtained with the results of the PLATO 2.0 mission, selected as the next M-class mission of ESA's Cosmic

Vision plan, that will allow the complete characterization of host stars using asteroseismology.

Author(s): Cilia Damiani[2], Antonino-Francesco Lanza[1]
Institution(s): *1. INAF - Osservatorio Astrofisico di Catania, 2. Université Paris-Sud*

109.07 – Oort Cloud Asteroids: From one extreme of the Solar System to the other

The record of planetary migration is written in the dynamics of the small bodies they leave in their wake. One such case is the production of the Oort cloud, where scattering by planets injected planetesimals into this long-lived population, which today retains a record of where and when the scattering occured. We use N-body simulations to show that for a static, collisionless solar system history, ~4% of the Oort cloud objects should have formed within 2.5 au of the Sun, and hence be ice-free rock-iron bodies. If we assume that these Oort cloud asteroids have the same size distribution as their cometary counterparts, the Large Synoptic Survey Telescope should find roughly a dozen Oort cloud asteroids during 10 years of operations. Collisional evolution can substantially change this fraction from the static case, reducing the asteroid fraction of the Oort cloud by as much as two orders of magnitude. We perform additional simulations of Solar system histories with significant planet migration, modelled on the `Nice Model' and `Grand Tack' scenarios, and find they can produce very different asteroid fractions in the Oort cloud population, thus retaining a record of the Solar system's dynamical history in the present day small body populations.

Author(s): Andrew Brian Shannon[2], Alan P. Jackson[1], Dimitri Veras3, Mark Wyatt[2]
Institution(s): *1. Arizona State University, 2. University of Cambridge, 3. University of Warwick*

109.08 – How to simulate the most extreme planetary systems

The most interesting planetary systems are often also the most difficult ones to simulate numerically. In extrasolar planetary systems, one encounters binary systems, highly eccentric orbits and marginal stability much more often than in the Solar System. I present a new toolkit that allows everyone to simulate such extreme planetary systems with ease. In particular, I present two new N-body integrators, the symplectic WHFast and 15th-order IAS15 integrator. These algorithms are, for the first time ever, capable of simulating systems down to machine precision over a billion year timescale. I also explain how to incorporate additional forces due to migration, tides and general relativity. I present several systems for which these new methods have already been applied and discuss the physical implications for planet formation.

Author(s): Hanno Rein[1]
Institution(s): *1. University of Toronto*

109.09 – "Slimplectic" Integrators: Variational Integrators for General Nonconservative Dynamics

Symplectic integrators are widely used for long-term integration of conservative astrophysical problems due to their ability to preserve the constants of motion; however, they cannot in general be applied in the presence of nonconservative (e.g. dissipative) interactions. Here we present the “slimplectic” integrator, a new type of numerical integrator that shares many of the benefits of traditional symplectic integrators yet is applicable to general nonconservative systems. We utilize a fixed-time-step variational integrator formalism applied to the recently developed principle of stationary nonconservative action. As a result, the generalized momenta and energy (Noether current) evolutions are well-tracked. Slimplectic integrators are well-suited for integrations of systems where nonconservative effects play an important role in the long-term dynamical evolution. As such they are particularly appropriate for cosmological or celestial N-body dynamics problems where nonconservative interactions, e.g., PR drag, gas interactions, or dissipative tides, can play an important role

Author(s): David Tsang[1]
Institution(s): *1. University of Maryland*

109.10 – Eccentricity of small exoplanets

Solar system planets move on almost circular orbits. In strong contrast, many massive gas giant exoplanets travel on highly elliptical orbits, whereas the shape of the orbits of smaller, more terrestrial, exoplanets remained largely elusive. This is because the stellar radial velocity caused by these small planets is extremely challenging to measure. Knowing the eccentricity distribution in systems of small planets would be important as it holds information about the planet's formation and evolution. Furthermore the location of the habitable zone depends on eccentricity, and eccentricity also influences occurrence rates inferred for these planets because planets on circular orbits are less likely to transit. We make these eccentricity measurements of small planets using photometry from the Kepler satellite and utilizing a method relying on Kepler's second law, which relates the duration of a planetary transit to its orbital eccentricity, if the stellar density is known.

I present a sample of 28 multi-planet systems with precise asteroseismic density measurements, which host 74 planets with an average radius of 2.6 R_earth. We find that the eccentricity of planets in these systems is low and can be described by a Rayleigh distribution with sigma = 0.049 +- 0.013. This is in full agreement with solar system eccentricities, but in contrast to the eccentricity distributions previously derived for exoplanets from radial velocity studies. I further report the first results on the eccentricities of over 50 Kepler single-planet systems, and compare them with the multi-planet systems. I close the talk by showing how transit durations help distinguish between false positives and true planets, and present six new planets.

Author(s): Vincent Van Eylen[1], Simon Albrecht[1]
Institution(s): *1. Aarhus University*

109.11 – Survival of extrasolar giant planet moons in planet-planet scattering

Planet-planet scattering is the best candidate mechanism for explaining the eccentricity distribution of exoplanets. Here we study the survival and dynamics of exomoons under strong perturbations during giant planet scattering. During close encounters, planets and moons exchange orbital angular momentum and energy. The most common outcomes are the destruction of moons by ejection from the system, collision with the planets and the star, and scattering of moons onto perturbed but still planet-bound orbits. A small percentage of interesting moons can remain bound to ejected (free-floating) planets or be captured by a different planet. Moons' survival rate is correlated with planet observables such as mass, semi-major axis, eccentricity and inclination, as well as the close encounter distance and the number of close encounters. In addition, moons' survival rate and dynamical outcomes are predetermined by the moons' initial semi-major axes. The survival rate drops quickly as moons' distances increase, but simulations predict a good chance of survival for the Galilean moons. Moons with different dynamical outcomes occupy different regions of orbital parameter space, which may enable the study of moons' past evolution. Potential effects of planet obliquity evolution caused by close encounters on the satellites’ stability and dynamics will be reported, as well as detailed and systematic studies of individual close encounter events.

Author(s): YU CIAN HONG[1], Jonathan Lunine[1], Phillip Nicholson[1], Sean Raymond[2]
Institution(s): *1. Cornell University, 2. Observatoire de Bordeaux*

109.12 – Predicting Precession Rates from Secular Dynamics for Extra-solar Multi-planet Systems

Considering the secular dynamics of multi-planet systems provides substantial insight into the interactions between planets in those systems. Secular interactions are those that don't involve knowing where a planet is along its orbit, and they dominate when planets are not involved in mean motion resonances. These interactions exchange angular momentum among the planets, evolving their eccentricities and inclinations. To second order in the planets' eccentricities and inclinations, the eccentricity and inclination perturbations are decoupled. Given the right variable choice, the relevant differential equations are linear and thus the eccentricity and inclination behaviors can be described as a sum of eigenmodes. Since the underlying structure of the secular eigenmodes can be calculated using only the planets' masses and semi-major axes, one can elucidate the eccentricity and inclination behavior of planets in exoplanet systems even without knowing the planets' current eccentricities and inclinations. I have calculated both the eccentricity and inclination secular eigenmodes for the population of known multi-planet systems whose planets have well determined masses and periods and have used this to predict what range of pericenter precession (and nodal regression) rates the planets may have. One might have assumed that in any given system the planets with shorter periods would have faster precession rates, but I show that this is not necessarily the case. Planets that are 'loners' have narrow ranges of possible precession rates, while planets that are 'groupies' can have a wider range of possible precession rates. Several planets are expected to undergo significant precession on few-year timescales and many planets (though not the majority of planets) will undergo significant precession on decade timescales.

Author(s): Christa Van Laerhoven[1]
Institution(s): *1. University of Toronto*

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110 – Other Topics Poster Session

110.01 – Solar Systems at Last

Planet host stars, the Sun among them, will eventually evolve into giants, through the Planetary Nebula phase to finally end their lives as white dwarfs. Planets will be engulfed along the giant phases, evaporated during the Planetary Nebula phase, and possibly destabilized when the star enters the white dwarf cooling track. A large number of planets will eventually be destroyed and there is a lot to be learned from that. The conditions on the planet surface of those that survive are expected to be modified as well as the result of the evolution of the star. I will discuss the new limits that the theoretical studies allow us to set on the survival and habitability of planets as the star runs out of its hydrogen fuel and the possibilities for the formation of second generation planets. Finally, I will present new results on the real consequences that the presence and destruction of these Extreme Solar systems have in the evolution of stars.

Author(s): Eva Villaver[1]
Institution(s): *1. Universidad Autonoma de Madrid*

110.02 – A Study on Planetary Atmospheric Circulations using THOR

The large variety of planetary parameters observed leads us to think that exoplanets may show a large range of possible climates. It is therefore of the uttermost importance to investigate the influence of astronomical and planetary bulk parameters in driving the atmospheric circulations. In the solar system the results from planetary spacecraft missions have demonstrated how different the planetary climate and atmospheric circulations can be. The study of exoplanets will require probing a far wider range of physical and orbital parameters than the ones of our neighbor planets. For this reason, such a study will involve exploring an even larger diversity of circulation and climate regimes. Our new atmospheric model, THOR, is intended to be extremely flexible and to explore the large diversity of planetary atmospheres.

THOR is part of the Exoclimes Simulation Platform, and is a project of the Exoplanet and Exoclimes Group (see www.exoclime.org). THOR solves the complex atmospheric fluid equations in a rotating sphere (fully compressible – nonhydrostatic system) using an icosahedral grid. The main advantages of using our new platform against other recent exoplanet models is that 1) The atmospheric fluid equations are completely represented and no approximations are used that could compromise the physics of the problem; 2) The model uses for the first time in exoplanet studies, a specific icosahedral grid that solves the pole problem; 3) The interface is user friendly and can be easily adapted to a multitude of atmospheric conditions; 4) By using GPU computation, our code greatly improves the typical code running time.

We will present and discuss the first detailed results of our simulations, more specifically of two benchmark tests that are a representative sample of the large range of exoplanetary parameters: Earth-like conditions (the Held-Suarez test) and a tidally locked hot-Jupiter. THOR has successfully passed these tests and is able to determine the main mechanisms driving the circulation in the simulated planets. From the 3D numerical simulations we found that some hot-Jupiters atmospheres can sustain multiple dynamical steady states. The results also suggest the presence of a new mechanism that transports heat from the upper to the lower atmosphere. The presence and impact of this mechanism in the global temperature will be discussed in this presentation.

Author(s): João Mendonça[1], Luc Grosheintz[1], Simon Lukas Grimm[1], Kevin Heng[1]
Institution(s): *1. University of Bern*

110.04 – The Distribution of Plants on Habitable Planet around M-dwarfs

Previous studies show that habitable exoplanets around M dwarfs may have two climate patterns, an eyeball climate pattern and a striped-ball climate pattern, depending on the spin-orbit period ratio. The two climate patterns are included into the DNDC (denitrification-decomposition) model, which is modified to accommodate the climate and stellar light conditions different than those on the Earth, to investigate the growth of plants on the corresponding planets. The pattern of plant distribution correlates well with the climate pattern, which is consistent with the close link between plant growth and climate.

Author(s): Duo Cui[1]
Institution(s): *1. Center for earth science system*

110.05 – Supergranular Convection

Observation of the Solar photosphere through high resolution instruments have long indicated that the surface of the Sun is not a tranquil, featureless surface but is beset with a granular appearance. These cellular velocity patterns are a visible manifestation of sub- photospheric convection currents which contribute substantially to the outward transport of energy from the deeper layers, thus maintaining the energy balance of the Sun as a whole.
Convection is the chief mode of transport in the outer layers of all cool stars such as the Sun (Noyes,1982). Convection zone of thickness 30% of the Solar radius lies in the sub-photospheric layers of the Sun. Here the opacity is so large that heat flux transport is mainly by convection rather than by photon diffusion. Convection is revealed on four scales. On the scale of 1000 km, it is granulation and on the scale of 8-10 arcsec, it is Mesogranulation. The next hierarchial scale of convection , Supergranules are in the range of 30-40 arcsec. The largest reported manifestation of convection in the Sun are 'Giant Cells'or 'Giant Granules', on a typical length scale of about 108 m.
'Supergranules' is caused by the turbulence that extends deep into the convection zone. They have a typical lifetime of about 20hr with spicules marking their boundaries. Gas rises in the centre of the supergranules and then spreads out towards the boundary and descends.
Broadly speaking supergranules are characterized by the three parameters namely the length L, the lifetime T and the horizontal flow velocity vh . The interrelationships amongst these parameters can shed light on the underlying convective processes and are in agreement with the Kolmogorov theory of turbulence as applied to

large scale solar convection (Krishan et al .2002 ; Paniveni et. al. 2004, 2005, 2010).

References:
1) Noyes, R.W., The Sun, Our Star (Harvard University Press, 1982)
2) Krishan, V., Paniveni U., Singh , J., Srikanth R., 2002, MNRAS, 334/1,230
3) Paniveni , U., Krishan, V., Singh, J., Srikanth, R., 2004, MNRAS, 347, 1279-1281
4) Paniveni , U., Krishan, V., Singh, J., Srikanth, R., 2005, Solar Physics, 231, 1-10
5) Paniveni , U., Krishan, V., Singh, J., Srikanth, R., 2010, MNRAS, 402, Issue 1, 424-428

Author(s): Paniveni Udayashankar[1]
Institution(s): *1. NIEIT*

110.06 – Discovery of four new low-mass white-dwarf companions in the Kepler data

We report the discovery of four new short-period eclipsing systems in the Kepler light curves, consisting of an A-star primary and a low-mass white-dwarf (WD) secondary (dA+WD) - KIC 4169521, KOI-3818, KIC 2851474 and KIC 9285587. These add to the 6 Kepler, and 19 non-Kepler, previously known short-period eclipsing dA+WD binaries.
The discoveries were made through searching the light curves of bright Kepler stars for BEaming, Ellipsoidal and Reflection (BEER) modulations that are consistent with a compact companion, using the BEER search algorithm. This was followed by inspection of the search top hits, looking for eclipsing systems with a secondary eclipse deeper than the primary one, as expected for a WD that is hotter than the primary star. Follow-up spectroscopic radial-velocity (RV) observations confirmed the binarity of the systems. We derive the systems' parameters through analyses of the light curves' eclipses and phase modulations, combined with RV orbital solutions and stellar evolution models.
The four systems' orbital periods of 1.17-3.82 days and WD masses of 0.19-0.22 Msun are similar to those reported for the previously known systems. These values are consistent with evolution models of such systems, that undergo a stable mass transfer from the WD progenitor to the current A star.
For KIC 4169521 we derive a bloated WD radius of 0.09 Rsun that is well within the WD radius range of 0.04-0.43 Rsun of the known systems. For the remaining three systems we report WD radii of 0.026-0.035 Rsun, the smallest WD radii derived so far for short-period eclipsing dA+WD binaries.
As suggested before, the previously known systems, together with KIC 4169521, all with hot and bloated WD secondaries, represent young systems probably at a proto-WD, or initial WD cooling track stage. The other three new systems - KOI-3818, KIC 2851474, and KIC 9285587, are probably positioned further along the WD cooling track, and extend the known population to older systems with cooler and smaller WD secondaries.

Author(s): Simchon Faigler3, Ilya Kull3, Tsevi Mazeh3, Flavien Kiefer3, David W. Latham[1], Steven Bloemen[2]
Institution(s): *1. Harvard-Smithsonian Center for Astrophysics, 2. Radboud University, 3. Tel-Aviv University*

110.07 – Lithium depletion and the star age connection

It is known that lithium is destroyed in the inner layers of a star via proton capture (^{7}Li(p, α)α) at temperatures near to 2.5 * 10^6 K. Due to the fact that Li burning happens when the element is transported to the innermost and hotter regions through convective motions of the star, Li abundance studies offers an excellent opportunity to understand the extent of the mixing processes within and below the stellar convective zone. Thus, for a better understanding of the inner stars regions, this study aims to observe correlations between lithium abundances, stellar age, masses and planets occurrence for various solar twins aged between 0.7 and 8.8 Gyr.

The sample consists of 21 solar twins measured in the HARPS spectrograph with spectral resolution R≈115.000 and signal to noise ratio from 400 to 2400. The lithium abundance were obtained by spectral synthesis of the line 6707.75 Å with the aid of MOOG code.

The results indicate a strong correlation between age and Li abundances in the stars of this sample and a non-connection between lithium abundances and the presence of planets.

Author(s): Marília Gabriela C. C. Carlos[1]
Institution(s): *1. Universidade de São Paulo*

110.08 – Analysis of Repeatability and Reliability of Warm IRAC Observations of Transiting Exoplanets

Extracting information about thermal profiles and composition of the atmospheres of transiting exoplanets is extremely challenging due to the small differential signal of the atmosphere in observations of transits, secondary eclipses, and full phase curves for exoplanets. The relevant signals are often at the level of 100 ppm or smaller and require the removal of significant instrumental systematics in the two infrared instruments currently capable of providing information at this precision, WFC3 on HST and IRAC aboard the Spitzer Space Telescope. For IRAC, the systematics are due to the interplay of residual telescope pointing variation with intra-pixel gain variations in the moderately undersampled camera. There is currently a debate in the community on the reliability of repeated IRAC observations of exoplanets particularly those in eclipse from which inferences about atmospheric temperature and pressure profiles can made. To assess the repeatability and reliability of post-cryogenic observations with IRAC, the Spitzer Science Center in conjunction with volunteers from the astronomical community has performed a systematic analysis of the removal of systematics and repeatability of warm IRAC observations. Recently, a data challenge consisting of the measurement of ten secondary eclipses of XO-3b (see Wong et al. 2014) and a complementary analysis of a synthetic version of the XO-3b data was undertaken. We report on the results of this data challenge. Five different techniques were applied to the data (BLISS mapping [Stevenson et al. (2012)], kernel regression using the science data [Wong et al. (2015)] and calibration data [Krick et al. (2015)], pixel-level decorrelation [Deming et al. (2015)], ICA [Morello et al. (2015)] and Gaussian Processes [Evans et al. (2015)]) and found consistent results in terms of eclipse depth and reliability in both the actual and synthetic data. In addition, each technique obtained the input eclipse depth in the simulated data within the stated measurement uncertainty. The reported uncertainties for each measurement approach the photon noise limit. These findings generally refute the results of Hansen et al. (2014) and suggest that inferences about atmospheric properties can be reasonably made using warm IRAC data. Application of our test methods to future observations using JWST (in particular the MIRI instrument) will be discussed.

Author(s): Sean J Carey[1], Jessica Krick[1], James Ingalls[1]
Institution(s): *1. Caltech*

110.09 – Evidence for Reflected Light from the Most Eccentric Known Exoplanet

Planets in highly eccentric orbits form a class of objects not seen within our Solar System. The most extreme case known amongst these objects is the planet orbiting HD 20782, with an orbital period of 597 days and an eccentricity of 0.96. Here we present new data and analysis for this system as part of the Transit Ephemeris Refinement and Monitoring Survey (TERMS). New radial velocities acquired during periastron provide incredible accuracy for the planetary orbit and astrometric results that show the companion is indeed planetary in nature. We obtained MOST photometry during a predicted periastron passage that shows evidence of phase variations due to reflected light from the planet. The extreme nature of this planet presents an ideal case from which to test theories regarding the formation of eccentric orbits and the response of atmospheres to extreme changes in flux.

Author(s): Stephen Kane[1]
Institution(s): *1. San Francisco State University*

111 – Planetary Atmospheres - Close-In and Transiting Gas Giants Poster Session

111.02 – Dayside-Nightside Temperature Differences in Hot Jupiter Atmospheres

The infrared phase curves of low-eccentricity transiting hot Jupiters show a trend of increasing flux amplitude, or increasing day-night temperature difference, with increasing equilibrium temperature. Here we utilize atmospheric circulation modeling and analytic theory to understand this trend, and the more general question: what processes control heat redistribution in tidally-locked giant planet atmospheres? We performed a wide range of 3D numerical simulations of the atmospheric circulation with simplified forcing, and constructed an analytic theory that explains the day-night temperature differences in these simulations over a wide parameter space. Our analytic theory shows that day-night temperature differences in tidally-locked planet atmospheres are mediated by wave propagation. If planetary-scale waves are free to propagate longitudinally, they will efficiently flatten isentropes and lessen day-night temperature differences. If these waves are damped, the day-night temperature differences will necessarily be larger. We expect that wave propagation in hot Jupiter atmospheres can be damped in two ways: by either radiative cooling or frictional drag. Both of these processes increase in efficacy with increasing equilibrium temperature, as radiative cooling is directly related to the cube of temperature and magnetically-induced (Lorentz) drag becomes stronger with increasing partial ionization and hence temperature. We find that radiative cooling plays the largest role in damping wave propagation and hence plays the biggest role in controlling day-night temperature differences. As a result, day-night temperature differences in hot Jupiter atmospheres decrease with increasing pressure and increase with increasing stellar flux. One can apply this result to phase curve observations of individual hot Jupiters in multiple bandpasses, as varying flux amplitudes between wavelengths implies that different photospheric pressure levels are being probed. Namely, a larger flux amplitude in one waveband than the band-averaged value implies a relatively low photospheric pressure and hence high abundance of the absorber in that waveband. This effect has been seen for both HD 189733b and WASP-14b, where the 3.6 micron flux amplitude is larger than the 4.5 micron flux amplitude, which constrains the relative abundances of methane and carbon monoxide and hence the C/O ratio in these atmospheres.

Author(s): Thaddeus D Komacek[1], Adam P Showman[1]
Institution(s): *1. University of Arizona*

111.03 – A transition in the cloud composition of hot Jupiters atmospheres

Over a large range of equilibrium temperatures clouds seem to dominate the transmission spectrum of Hot Jupiters atmospheres and no trend allowing the classification of these objects have yet emerged. Recently observations of the light reflected by Hot Jupiters atmospheres shed a new light on the cloud distribution on the dayside of these planets : for a handful of planets clouds are more abundant on the western than on the eastern side of the dayside hemisphere and, more importantly, this asymmetry depends on the equilibrium temperature of the planet.
Here we use a grid of 3D global circulation models to show that a single cloud species is unable to explain the recent Kepler observations. The cloud asymmetry on the dayside is a strong function of the condensation temperature of the cloud species which allow us to determine the composition of the clouds present in these planets. We show that a transition between silicate clouds and sulfide clouds appear at equilibrium temperatures of 1600*K*. A mechanism such as the presence of a deep cold trap is necessary to explain this transi- tion. Furthermore, we show that the western limb temperature is always cold, independently of the equilibrium temperature of the planet, allowing cloud particles to form even in the most irradiated planets as seen in the observations.
Our results provide the first evidence for a transition in the cloud species of hot Jupiters similar to the L/T Brown Dwarf transition. We showed that inhomogeneous dayside and limbs cloud coverage are expected what should affect the retrieved molecular abundances from emission and transmission spectra of these planets.

Author(s): Vivien Parmentier3, Fortney Jonathan3, Adam P Showman[2], Mark Marley[1], Caroline Morley3
Institution(s): *1. NASA Ames, 2. University of Arizona, 3. University of California Santa Cruz*

111.04 – Exploring biases in exoplanet spectroscopy retrievals

Spectra from the atmospheres of transiting planets and imaged planets are now being routinely achieved. The interpretation of these spectra gives us a window into the physics and chemistry of these atmospheres, as well as a better understanding of planet formation. Over the past several years retrievals of exoplanet spectra have been used to obtain chemical abundances and thermal structures, along with assessments of uncertainties on these quantities. However, any potential biases inherent in these methods have yet to be fully explored. The atmospheres we observe are inherently three-dimensional (3D) structures that feature gradients in temperatures and chemical abundances, as well as hot spots, cold spots, storms, and cloud patchiness. How well does the assumption of retrieving 1D hemispheric average conditions represent the true state of a 3D atmosphere? Can we be led astray? Answering these questions are important today, and will only become more important as data quality improves. Using a descendent of the CHIMERA retrieval code, here I present the results of how retrievals perform on more complex scenarios. We start with the emitted spectrum from the average of two pressure-temperature profiles, one warmer, one colder, and move on to more sophisticated, but still realistic, scenarios. Our work makes use of a new code we have developed to construct spectra from arbitrary 3D model atmospheres.

Author(s): Ying Feng[2], Jonathan Fortney[2], Michael R. Line[1], Caroline Morley[2]
Institution(s): *1. NASA Ames Research Center, 2. UC Santa Cruz*

111.05 – HELIOS: A new open-source radiative transfer code

I present the new open-source code HELIOS, developed to accurately describe radiative transfer in a wide variety of irradiated atmospheres. We employ a one-dimensional multi-wavelength two-stream approach with scattering. Written in Cuda C++, HELIOS uses the GPU's potential of massive parallelization and is able to compute the TP-profile of an atmosphere in radiative equilibrium and the subsequent emission spectrum in a few minutes on a single computer (for 60 layers and 1000 wavelength bins).
The required molecular opacities are obtained with the recently published code HELIOS-K [1], which calculates the line shapes from an input line list and resamples the numerous line-by-line data into a manageable k-distribution format. Based on simple equilibrium chemistry theory [2] we combine the k-distribution functions of the molecules H_2O, CO_2, CO & CH_4 to generate a k-table, which we then employ in HELIOS.
I present our results of the following: (i) Various numerical tests, e.g. isothermal vs. non-isothermal treatment of layers. (ii) Comparison of iteratively determined TP-profiles with their analytical parametric prescriptions [3] and of the corresponding spectra. (iii) Benchmarks of TP-profiles & spectra for various elemental abundances. (iv) Benchmarks of averaged TP-profiles & spectra for the exoplanets GJ1214b, HD189733b & HD209458b. (v) Comparison with secondary eclipse data for HD189733b, XO-1b & Corot-2b.
HELIOS is being developed, together with the dynamical core THOR and the chemistry solver VULCAN, in the group of Kevin Heng at the University of Bern as part of the Exoclimes Simulation Platform (ESP) [4], which is an open-source project aimed to

provide community tools to model exoplanetary atmospheres.
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[1] Grimm & Heng 2015, ArXiv, 1503.03806
[2] Heng, Lyons & Tsai, Arxiv, 1506.05501
Heng & Lyons, ArXiv, 1507.01944
[3] e.g. Heng, Mendonca & Lee, 2014, ApJS, 215, 4H
[4] exoclime.net

Author(s): Matej Malik[1], Luc Grosheintz[1], Simon Lukas Grimm[1], João Mendonça[1], Daniel Kitzmann[1], Kevin Heng[1]
Institution(s): *1. University of Bern*

111.06 – The Impact of Non-Uniform Cloud Cover on Transit Transmission Spectra

Clouds play a substantial role in sculpting transit transmission spectra as they tend to mute or entirely mask spectral features. Many investigations have treated clouds as globally uniform with a single "1D" structure. However, we have learned from albedo phase curves (e.g., Kepler 7) that cloud coverage can be spatially inhomogeneous across the planetary disk. Non-uniform cloud coverage is also supported by brown dwarf variability observations which suggest the presence of "patchy clouds". We also see non-uniform cloud coverage within our own solar system planets (e.g., belts and zones on Jupiter, ITCZ on earth etc.). Given the mounting evidence for spatially variable cloud coverage, it is prudent that we at least explore the role that non-uniform cloud coverage can have on transit transmission spectra. In this investigation we demonstrate how non-uniform cloud coverage on the terminator can influence transit transmission spectra and the potential biases incurred if non-uniform cloud coverage is not taken into account in spectral retrievals. For instance, a high altitude opaque cloud covering the entire morning terminator, along with a perfectly clear evening terminator can mimic a high mean molecular weight transmission spectrum in a hot Jupiter. Finally, we present the impact that non-uniform cloud coverage may have on transit light curves.

Author(s): Michael Line[1], Vivien Parmentier[2]
Institution(s): *1. Hubble Postdoctoral Fellow, 2. Sagan Postdoctoral Fellow*

111.07 – Microphysics of Exoplanet Clouds and Hazes

Clouds and hazes are ubiquitous in the atmospheres of exoplanets. However, as most of these planets have temperatures between 600 and 2000 K, their clouds and hazes are likely composed of exotic condensates such as silicates, metals, and salts. We currently lack a satisfactory understanding of the microphysical processes that govern the distribution of these clouds and hazes, thus creating a gulf between the cloud properties retrieved from observations and the cloud composition predictions from condensation equilibrium models. In this work we present a 1D microphysical cloud model that calculates, from first principles, the rates of condensation, evaporation, coagulation, and vertical transport of chemically mixed cloud and haze particles in warm and hot exoplanet atmospheres. The model outputs the equilibrium number density of cloud particles with altitude, the particle size distribution, and the chemical makeup of the cloud particles as a function of altitude and particle mass. The model aims to (1) explain the observed variability in "cloudiness" of individual exoplanets, (2) assess whether the proposed cloud materials are capable of forming the observed particle distributions, and (3) examine the role clouds have in the transport of (cloud-forming) heavy elements in exoplanet atmospheres.

Author(s): Peter Gao[1], Björn Benneke[1], Heather Knutson[1], Yuk Yung[1]
Institution(s): *1. California Institute of Technology*

111.08 – Evidence for the Directly-Detected Thermal Emission Spectrum of HD 88133 b

Most studies of exoplanetary atmospheres to date have been of the sample of close-in gas giant planets transiting their host stars. These works have detected a multitude of important atmospheric constituents in diverse systems, but are limited in that their methods prove ineffective for the exoplanets which do not transit their host stars and only provide low-resolution data for those which do transit. A few recent studies have targeted the thermal emission spectra of non-transiting exoplanets with high-resolution, near-infrared spectroscopy. These groups have been able to successfully detect water vapor, carbon monoxide, and high altitude winds in the atmospheres of the brightest and closest non-transiting gas giants. This approach treats the planet and its host star as a spectroscopic binary, and here we apply it to six epochs of NIRSPEC *L* band observations of the HD 88133 system. By observing the star and planet at multiple epochs and for long integration times, we build up the signal of the hot gas giant's atmosphere compared to the host star's spectrum. We then perform a principle component analysis to remove the contribution of the Earth's atmosphere to the observed spectra. Finally, we use a cross-correlation analysis to tease out the spectra of the host star and HD 88133 b to determine its orbit and atmospheric composition. We present the preliminary results from our cross-correlation analysis of the hot Saturn HD 88133 b.

Author(s): Danielle Piskorz[1], Geoffrey Blake[1], Björn Benneke[1], Nathan Crockett[1], Katherine Kaufman[1], Alexandra Lockwood[1], Travis Barman5, Chad Bender3, John Carr4, John Asher Johnson[2]
Institution(s): *1. California Institute of Technology, 2. Harvard University, 3. Pennsylvania State University, 4. U.S. Naval Research Lab, 5. University of Arizona*

111.09 – THOR: an open-source exo-GCM

In this talk, I will present THOR, the first fully conservative, GPU-accelerated exo-GCM (general circulation model) on a nearly uniform, global grid that treats shocks and is non-hydrostatic. THOR will be freely available to the community as a standard tool.

Unlike most GCMs THOR solves the full, non-hydrostatic Euler equations instead of the primitive equations. The equations are solved on a global three-dimensional icosahedral grid by a second order Finite Volume Method (FVM). Icosahedral grids are nearly uniform refinements of an icosahedron. We've implemented three different versions of this grid. FVM conserves the prognostic variables (density, momentum and energy) exactly and doesn't require a diffusion term (artificial viscosity) in the Euler equations to stabilize our solver. Historically FVM was designed to treat discontinuities correctly. Hence it excels at resolving shocks, including those present in hot exoplanetary atmospheres.

Atmospheres are generally in near hydrostatic equilibrium. We therefore implement a well-balancing technique recently developed at the ETH Zurich. This well-balancing ensures that our FVM maintains hydrostatic equilibrium to machine precision. Better yet, it is able to resolve pressure perturbations from this equilibrium as small as one part in 100'000. It is important to realize that these perturbations are significantly smaller than the truncation error of the same scheme without well-balancing. If during the course of the simulation (due to forcing) the atmosphere becomes non-hydrostatic, our solver continues to function correctly.

THOR just passed an important mile stone. We've implemented the explicit part of the solver. The explicit solver is useful to study instabilities or local problems on relatively short time scales. I'll show some nice properties of the explicit THOR. An explicit solver is not appropriate for climate study because the time step is limited by the sound speed. Therefore, we are working on the first fully implicit GCM. By ESS3, I hope to present results for the advection equation.

THOR is part of the Exoclimes Simulation Platform (ESP), a set of open-source community codes for simulating and understanding the atmospheres of exoplanets. The ESP also includes tools for radiative transfer and retrieval (HELIOS), an opacity calculator (HELIOS-K), and a chemical kinetics solver (VULCAN). We expect to publicly release an initial version of THOR in 2016 on www.exoclime.org.

Author(s): Luc Grosheintz[2], João Mendonça[2], Roger Käppeli[1], Simon Lukas Grimm[2], Siddhartha Mishra[1], Kevin Heng[2]
Institution(s): *1. Swiss Federal Institute of Technology (ETH), 2. University of Bern*

111.10 – Modelling the Global Cloud Cover of HD 189733b

Context.
Each rain droplet on Earth contains a microscopic condensation seed of sand or ash at its center, leading to more efficient water droplet formation than supersaturated vapour alone. Similarly, in hot Jupiter atmospheres, the formation of seed particles from the gas phase allows the condensation of solid mineral compounds such as Iron, Quartz and Enstatites. Recent observations of the atmosphere on HD 189733b suggest that clouds form in its atmosphere. Clouds have a large effect on the local thermodynamic and chemical properties of the atmosphere. The different thermodynamic conditions on the dayside and nightside will result in locally different cloud structures.

Aims.
Inspired by mineral cloud modelling efforts for Brown Dwarf atmospheres, we present spatially varying kinetic cloud model structures for HD 189733b. We investigate the resulting cloud properties at the dayside, nightside and terminator regions of the planet.

Methods.
We apply a 2-model approach, using results from a 3D radiative-hydrodynamic (RHD) simulation of the atmosphere of HD 189733b and our kinetic cloud formation model. 1D T_{gas}-p_{gas} profiles at the equator and +45 latitude covering the dayside, nightside and terminator regions of the simulation were chosen as input for the cloud formation model. Effective medium theory and Mie theory are applied to calculate the wavelength dependent opacity of the cloud materials.

Results.
We present results of the local cloud properties such as number density, size, composition and opacity at the chosen locations. The mean grain size varies between nm at the cloud deck to mm sizes at the cloud base. Cloud particle sizes in the upper atmosphere were found to be one order of magnitude larger on the dayside compared to the nightside. More efficient nucleation of cloud particles on the nightside leads to larger number densities compared to the dayside. The solid composition of cloud particles throughout the atmosphere is dominated by a combination of Silicate-Oxides (~70%) with a significant fraction of Iron (~15%) content. Iron grains dominate at higher temperature regions such as the cloud base. We show that the gas phase can be depleted of elements by several orders of magnitude due condensation of material onto grains. Our results suggest that the thermodynamic conditions on HD 189733b are suitable for efficient cloud formation and that the majority of the atmosphere is covered in thick mineral clouds.

Author(s): Graham Kim Huat Lee3, Christiane Helling3, Ian Dobbs-Dixon[1], Diana Juncher[2]
Institution(s): *1. NYU Abu Dhabi, 2. University of Copenhagen, 3. University of St Andrews*

111.11 – Extended Pre-Transit Structures and the Exosphere Detected for HD189733b in Optical Hydrogen Balmer Line Absorption

We present two separate observations of HD189733b in the three strongest hydrogen Balmer lines (H-alpha, H-beta, and H-gamma), with HiRES on Keck I that show definitive in-transit absorption, confirming the detection with the HET by Jensen et al. (2012), as well as, significant pre-transit absorption. Recently, pre-transit absorption in UV metal transitions of the hot Jupiter exoplanets HD 189733b and WASP12-b have been interpreted as being caused by material compressed in a planetary bow shock, however our observations are the first to densely time-sample and redundantly detect these extended planetary structures. While our first observations (obtained in 2013 and presented in Cauley et al. 2015), were consistent with a bow shock, our subsequent observation taken in August 2015 show pre-transit absorption but with a pattern that is inconsistent with the 2013 model. Instead, the observations indicate significant variability in the strength and timing of the pre-transit absorption. We also find differences in the strength of the in-transit exospheric absorption as well. These changes could be indicative of variability in the extreme stellar wind properties found at just 8 stellar radii, which could drive the extended atmospheric interaction between star and planet. The pre-transit absorption in 2013 was first observed 65 minutes prior to transit (corresponding to a linear distance of ~7 planetary radii), although it could have started earlier. The pre-transit signal in 2015, which is well sampled, is first detected 165 minutes prior to transit (a linear distance of ~17 planetary radii). The line shape of the pre-transit feature and the shape of the time series absorption provide the strongest constraints on the morphology and physical characteristics of extended structures around the exoplanet. The absorption strength observed in the Balmer lines indicates an optically thick, but physically small, geometry. If part of this extended structure is a bow shock mediated by a planetary magnetosphere, these measurements present an opportunity to measure the exoplanetary magnetic field strength, an elusive property that is crucial to evaluating the habitability of the planet.

Author(s): Seth Redfield4, P. Wilson Cauley4, Adam G. Jensen[2], Travis Barman[1], Michael Endl3, William Cochran3
Institution(s): *1. University of Arizona, 2. University of Nebraska at Kearney, 3. University of Texas, 4. Wesleyan University*

111.12 – Transmission spectral properties of clouds for hot Jupiter exoplanets

Clouds play an important role in the atmospheres of planetary bodies. It is expected that, like all the planetary bodies in our solar system, exoplanet atmospheres will also have substantial cloud coverage, and evidence is mounting for clouds in a number of hot Jupiters. To better characterise planetary atmospheres, we need to consider the effects these clouds will have on the observed broadband transmission spectra. Here we examine the expected cloud condensate species for hot Jupiter exoplanets and the effects of various grain sizes and distributions on the resulting transmission spectra from the optical to infrared, which can be used as a broad framework when interpreting exoplanet spectra. We note that significant infrared absorption features appear in the computed transmission spectrum, the result of vibrational modes between the key species in each condensate, which can potentially be very constraining. While it may be hard to differentiate between individual condensates in the broad transmission spectra, it may be possible to discern different vibrational bonds, which can distinguish between cloud formation scenarios, such as condensate clouds or photochemically generated species. Vibrational mode features are shown to be prominent when the clouds are composed of small sub-micron sized particles and can be associated with an accompanying optical scattering slope. These infrared features have potential implications for future exoplanetary atmosphere studies conducted with JWST, where such vibrational modes distinguishing condensate species can be probed at longer wavelengths.

Author(s): Hannah Ruth Wakeford[1], David Kent Sing[2]
Institution(s): *1. NASA Goddard Space Flight Center, 2. University of Exeter*

111.13 – An open-source chemical kinetics network: VULCAN

I will present VULCAN, an open-source 1D chemical kinetics code suited for the temperature and pressure range relevant to observable exoplanet atmospheres. The chemical network is based on a set of reduced rate coefficients for C-H-O systems. Most of the rate coefficients are based on the NIST online database, and validated by comparing with thermodynamic equilibrium codes (TEA, STANJAN). The difference between the experimental rates and those from the

thermodynamical data is carefully examined and discussed. For the numerical method, a simple, quick, semi-implicit Euler integrator is adopted to solve the stiff chemical reactions, within an operator-splitting scheme for computational efficiency.
Several test runs of VULCAN are shown in a hierarchical way: pure H, H+O, H+O+C, including controlled experiments performed with a simple analytical temperature-pressure profiles, so that different parameters, such as the stellar irradiation, atmospheric opacities and albedo can be individually explored to understand how these properties affect the temperature structure and hence the chemical abundances. I will also revisit the "transport-induced-quenching" effects, and discuss the limitation of this approximation and its impact on observations. Finally, I will discuss the effects of C/O ratio and compare with published work in the literature.

VULCAN is written in Python and is part of the publicly-available set of community tools we call the Exoclimes Simulation Platform (ESP; www.exoclime.org). I am a Ph.D student of Kevin Heng at the University of Bern, Switzerland.

Author(s): Shang-Min Tsai[2], James Lyons[1], Kevin Heng[2]
Institution(s): *1. Arizona State University, 2. University of Bern*

111.14 – Refining Techniques for the Spectroscopic Detection of Reflected Light from Exoplanets

The detection of reflected light from exoplanets provides a direct measure of planetary mass as well as a powerful probe of atmospheric composition and albedo. However, close-in giant planets which provide the largest planet-to-star flux ratios are dim in the optical. With contrasts at the level of 10^-5, the direct detection of these present a severe technical challenge to current instruments, and require both large aperture telescopes for high signal-to-noise ratio observations, and a stabilized spectrograph for stable instrument profiles. Leveraging the heritage and stability of the HARPS spectrograph, Martins et al (2015) recently published evidence of a direct detection of the historic exoplanet 51 Peg b, using the stellar mask cross-correlation technique. We attempt to expand upon their results with independent spectral and CCF reductions, using a two-template cross-correlation technique that can potentially be tuned to match the planetary signal and probe models of the albedo. By cross-correlating against a spectrum rather than a mask, we access the full information content in the lines, but must ensure proper telluric correction to mitigate the possibility of overwhelming the small planetary signal with terrestrial features. We are on the verge of confidently recovering planetary albedos for close-in giant planets, while also refining predictive and analytical tools that will come into their full capability with the arrival of the next generation of planet characterizing instruments, such as ESPRESSO on VLT and HIRES on E-ELT.

Author(s): Arpita Roy[1], Chad Bender[1], Suvrath Mahadevan[1]
Institution(s): *1. The Pennsylvania State University*

111.15 – Reigniting the Debate: First Spectroscopic Evidence for Stratospheres In Hot Jupiters

Hot Jupiters represent an extreme end of the exoplanet distribution: they orbit very close to their host stars, which subjects them to an intense heating from stellar radiation. An inverted temperature structure (i.e. a stratosphere) was an early observable prediction from atmospheric models of these planets, which demonstrated that high-temperature absorbers such as TiO and VO could reprocess incident UV/visible irradiation to heat the upper layers of the atmosphere.

Evidence for such thermal inversions began with the first secondary eclipse measurements of transiting hot Jupiters taken with the IRAC camera on Spitzer, offering the chance to physical processe at work in the atmospheres of hot exoplanets. However, these efforts have been stymied by recent revelations of significant systematic biases and uncertainties buried within older Spitzer results, calling into question whether or not temperature inversions are actually present in hot Jupiters.

We have recently published spectroscopy of secondary eclipses of the extrasolar planet WASP-33b using the Wide Field Camera 3 (WFC3) on the Hubble Space Telescope, which allow us to constrain the temperature structure and composition of its dayside atmosphere. WASP-33b is one of the most highly irradiated hot Jupiters discovered to date and orbits a relatively inactive A star, making it an excellent candidate for eclipse spectroscopy at NIR wavelengths (1.1 – 1.7 µm). We find that a fit to combined data from HST, Spitzer and ground-based photometry can rule out models without a temperature inversion; additionally, we find that our measured spectrum displays excess in the measured flux toward short wavelengths that is best explained as emission from TiO.

This discovery re-opens the debate on the presence and origin of stratospheres in hot Jupiters, but it also confirms that the combination of HST spectroscopy and a robust analysis of Spitzer and ground-based photometry can conclusively detect thermally inverted atmospheres. In this talk I will present the theoretical underpinnings of temperature inversions in hot Jupiters, discuss the current state of observational evidence including our results for WASP-33b, and describe a path forward for how we can leverage future measurements of exoplanet atmospheric temperature structure to inform our understanding of the composition and formation of exoplanets.

Author(s): Avi M. Mandell4, Korey Haynes[1], Nikku Madhusudhan3, Drake Deming5, Heather Knutson[2]
Institution(s): *1. Astronomy Magazine, 2. Caltech, 3. Cambridge University, 4. NASA GSFC, 5. University of Maryland*

111.16 – Molecules on the night-side of a non-transiting Hot Jupiter

Detecting molecules in the atmospheres of Hot Jupiters is possible using high dispersion spectroscopy (R~100,000). At this resolution, the many absorption lines of a molecule can be individually resolved, and their Doppler shifts can be determined by cross-correlating high dispersion observations with a model template of the planet spectrum. Since the Doppler shift of Hot Jupiters are large and rapidly varying, the planet lines can be disentangled from the stellar and telluric lines, which are static. This technique has been used successfully to detect water and CO in the day-sides of Hot Jupiter atmospheres, even in those that do not transit their host star (e.g. Brogi et al., Nature 486, 502, 2012). Detections of molecules on Hot Jupiters using high dispersion spectroscopy are not only limited to the day-side, unlike secondary eclipse measurements. As long as there are notable absorption lines in the planet's night-side spectrum it should be as easy to detect molecules on the day-side as it is on the night-side (de Kok et al., A&A 561, A150, 2014). Here we will present the first attempt to detect molecules on the night-side of a non-transiting planet. For this planet (HD 179949b) we have previously detected water vapour and carbon monoxide absorption on the day-side (Brogi et al., A&A 565, A124, 2014), and we will compare the results from both datasets to gain information about the heat distribution from the day-side to the night-side, and the potential presence of clouds. Preliminary analysis shows tentative detections of molecules on the night-side of HD 179949b.

Author(s): Remco de Kok3, Matteo Brogi4, Jayne Birkby[1], Henriette Schwarz[2], Ignas Snellen[2]
Institution(s): *1. Harvard/CfA, 2. Leiden Observatory, 3. SRON Netherlands Institute for Space Research, 4. University of Colorado*

111.17 – Characterizing exoplanet atmospheres with the 10.4m GTC telescope: New results from the world's largest optical telescope

Exoplanet transit spectroscopy of hot Jupiters has given us the first detailed glimpses of the complex physical characteristics that govern these objects. These highly irradiated planets with their extended atmospheres lend themselves as excellent targets for probing their compositions, temperature-pressure profiles and the vertical abundance distributions.

We have explored the atmospheres of several hot Jupiters using the 10.4m GTC telescope together with unique tunable filters capable of precision narrowband photometry at specific wavelengths. Using the worlds largest optical telescope we have been able to detect and characterise specific atmospheric features at higher resolutions than can be obtained with the Hubble Space Telescope. This is important as atmospheric signatures could be missed if the resolution is not sufficiently high.

In this talk I will present a summary of the exoplanet atmospheres characterised with the GTC telescope. I will also present new results obtained by combining Kepler and GTC data to study the low-albedo atmosphere of TrES-2b.

Author(s): Paul Anthony Wilson[2], Tom Evans[3], David Kent Sing[3], Nikolay Nikolov[3], Alain Lecavelier des Etangs[2], Knicole Colón[1]
Institution(s): *1. NASA Ames Research Center, 2. Paris Institute of Astrophysics (IAP), 3. University of Exeter*

111.18 – Exoplanet observations with GTC

Our group is presently conducting an observational campaign, using the 10-meter Gran Telescopio Canarias (GTC), to obtain the transmission spectrum of several exoplanets during a transit event. The GTC instrument OSIRIS is used in its long-slit spectroscopic mode, covering the spectral range of 520-1040 nm, and observations are taken using a set of custom-built slits of various, broad, widths. We integrate the stellar flux of both stars in different wavelength regions producing several light curves and fit transit models in order to obtain the star-to-planet radius ratio Rp/Rs across wavelength. A Markov Chain Monte Carlo (MCMC) Bayesian approach is used for the transit fitting. We will show that with our instrumental setup, OSIRIS has been able to reach precisions down to 250 ppm (WASP-48b, V=11.06 mag) for each color light curve 10 nm wide, in a single transit. And accuracies of the order of 500ppm can be obtained for objects with V=16. Central transit timing accuracies have been measured down to 6 seconds. Here, we will present refined planet parameters, the detection of planet color signatures, and the transmission spectra of a set of know and unpublished transiting exoplanets. We will also discuss the capabilities and limitations of GTC with current and future instrumentation, and the role of GTC as tool for the follow up of faint exoplanet targets.

Author(s): Enric Pallé[1]
Institution(s): *1. Instituto de Astrofisica de Canarias*

111.19 – Climate models of exoplanets with simplified radiative transfer and scattering

We present a set of general circulation models (GCM) for tidally locked hot Jupiters, with simplified radiative transfer and scattering in the optical and infrared. To quantify the effects of scattering, we study climatology plots, T-P profiles, optical and infrared phase curves.
We show that it is possible to obtain an estimation of the shape and peak offset of the optical phase curve from the GCM output. Moreover, westward shifts of the optical phase curves is a generic feature of our models, although the degree of the offset depends on scattering parameters and aerosol composition.

Author(s): Maria Oreshenko[1], Kevin Heng[1]
Institution(s): *1. University of Bern*

111.20 – Transmission Spectroscopy of HAT-P-32Ab with GTC/OSIRIS

I will present one of the latest results of our GTC exoplanet transit spectroscopy survey. Over the last years our group has obtained ground-based optical (538 nm - 918 nm) spectrophotometric transit observations for several hot Jupiters including HAT-P-32Ab using the OSIRIS (Optical System for Imaging and low Resolution Integrated Spectroscopy) instrument at the Spanish 10-meter telescope GTC.
I will discuss the source, nature and proper correction of instrument specific systematic noise we found to affect our data. After its correction, we were able to yield high quality results with a precision between 482 and 1703 ppm depending on the wavelength channel. We measure a flat optical transmission spectrum for HAT-P-32Ab, consistent with the results of Gibson et al. (2013, MNRAS, 436, 2974) obtained with GMOS at Gemini-North. This independent reproduction of consistent results re-establishes faith in the reliability of ground-based transmission spectroscopy and emphasizes the high potential of OSIRIS at the GTC as a tool to complement current and future space-based observations.

Author(s): Lisa Nortmann[1], Enric Pallé[2], Felipe Murgas[4], Stefan Dreizler[1], Nicolas Iro[3], Antonio Cabrera-Lavers[2]
Institution(s): *1. Institut für Astrophysik, Universität Göttingen, 2. Instituto de Astrofísica de Canarias, 3. Meteorologisches Institut, Universität Hamburg, 4. Univ. Grenoble Alpes, IPAG*

111.21 – Exploring the diversity of exoplanet atmospheres from the ground with the ACCESS Survey

One of the most exciting possibilities enabled by transiting exoplanets is to measure their atmospheric properties through the technique of transmission spectroscopy: the variation of the transit depth as a function of wavelength due to starlight interacting with the atmosphere of the exoplanet. Motivated by the need of optical transmission spectra of exoplanets, we recently launched the Arizona-CfA-Católica Exoplanet Spectroscopy Survey (ACCESS), which aims at studying the atmospheres of ~20 exoplanets ranging from super-Earths to hot-Jupiters in the entire optical atmospheric window using ground-based facilities from both northern and southern hemispheres. In this talk, I will present the survey and its first results using Magellan/IMACS data, focusing on the lessons learned and future prospects of the survey.

Author(s): Nestor Espinoza[4], Andres Jordan[4], Daniel Apai[5], Mercedes Lopez-Morales[2], Benjamin Rackham[5], Nikole K Lewis[3], Jonathan Fraine[6], Ryan Diaz-Pérez[2], Florian Rodler[2], Robert Wells[2], David Osip[1]
Institution(s): *1. Carnegie, OCIW, 2. Harvard-Smithsonian Center for Astrophysics, 3. Massachusets Institute of Technology, 4. Pontificia Universidad Catolica de Chile, 5. University of Arizona, 6. University of Maryland College Park*

111.22 – Spitzer IRAC Sparsely Sampled Phase Curve of the Exoplanet WASP-14b

Motivated by a high Spitzer IRAC oversubscription rate, we present a new technique of randomly and sparsely sampling phase curves of hot jupiters. Snapshot phase curves are enabled by technical advances in precision pointing as well as careful characterization of a portion of the central pixel on the array. This method allows for observations which are a factor of roughly two more efficient than full phase curve observations, and are furthermore easy to insert into the Spitzer observing schedule. We present our pilot study from this program using the exoplanet WASP-14b. Data of this system were taken both as a sparsely sampled phase curve as well as a staring mode phase curve. Both datasets as well as snapshot style observations of a calibration star are used to validate this technique. By fitting our WASP-14b phase snapshot dataset, we successfully recover physical parameters for the transit and eclipse depths as well as amplitude and maximum and minimum of the phase curve shape of this slightly eccentric hot jupiter. We place a limit on the potential phase to phase variation of these parameters since our data are taken over many phases over the course of a year. We see no evidence for eclipse depth variations over a 3.5 year baseline in a comparison with literature values.

Author(s): Jessica Krick[1]
Institution(s): *1. IPAC*

111.23 – Testing Atmospheric Circulation Theories with Multi-Wavelength Phase-Curve Observations of WASP-43b

Interpretation of published Spitzer phase-curve observations suggest a temperature dependence in hot Jupiters' heat redistribution efficiencies. Planets with equilibrium temperatures below ~2000 K typically exhibit less-extreme day-night temperature contrasts, with the one exception being WASP-43b. The conclusion that WASP-43b has inefficient heat redistribution originates from our HST/WFC3 spectroscopic phase-curve measurements and may yet agree with the current view if there is a strong wavelength dependence. We will present new Spitzer phase-curve observations of WASP-43b at 3.6 and 4.5 microns that test this theory. Additionally, using the combined WASP-43b datasets, we will compare thermal and chemical abundance constraints from the day- and night-side emission spectra and discuss the implications of any inconsistencies.

Author(s): Kevin Stevenson3, Jacob Bean3, Michael R. Line[1], Jonathan Fortney[1], Jean-Michel Desert4, Laura Kreidberg3, Adam P Showman[2], Tiffany Kataria5
Institution(s): *1. UC Santa Cruz, 2. University of Arizona, 3. University of Chicago, 4. University of Colorado, 5. University of Exeter*

111.24 – Biases and degeneracies in the retrieval of exoplanetary atmospheres through transit spectroscopy

Over the past decades transit spectroscopy has become one of the pioneering methods to study exoplanetary atmospheres. With the increasing number of observations, and the advent of new ground and spaced based instruments, it is now crucial to find the most optimal and objective methodologies to interpret these data, and understand the information content they convey.

Nowadays, spectral retrievals are the industry standard used to characterise exoplanetary atmospheres. Thanks to the use of fast line-by-line forward models and Bayesian frameworks, an accurate mapping of the parameter space can be easily obtained. However, the forward models used in these retrieval often contain many simplifying assumptions. In this conference, we will present a new study on the biases that these simplifications cause on the retrieved model parameters. We will show under which conditions these become significant, and how they can be overcome.

Using the most sophisticated photochemical models in the literature, we compute, for a few typical planets, synthetic exoplanetary spectra. The same spectra are then retrieved using TauREx, a new line-by-line radiative transfer atmospheric retrieval framework for exoplanet spectroscopy (Waldmann et al. 2015). In a study that is first of its kind, we investigate how the most common assumptions used in the forward models affect the retrieved model parameters, and how these biases can lead to inaccurate conclusions. Understanding the biases and degeneracies in our retrievals, and in which observing conditions they arise, is proving crucial, especially considering the advent of new instruments, such as the JWST.

Author(s): Marco Rocchetto[1], Ingo Peter Waldmann[1]
Institution(s): *1. University College London*

111.25 – HST hot Jupiter transmission spectral survey: The atmospheric circulation of a large hot Jupiter sample

Even as we move towards characterizing smaller and cooler exoplanets, hot Jupiters continue to be the best transiting planets for probing the atmospheric properties of exoplanets and refining current theory. Here we present results from a comprehensive atmospheric circulation study of nine transiting hot Jupiters that probe a wide range of planetary properties, including orbital distance, rotation rate, mass, radius, gravity and stellar insolation. We utilize these circulation models to aid in the interpretation of transmission spectra obtained using the Space Telescope Imaging Spectrograph (STIS) and Wide Field Camera 3 (WFC3) as a part of a large Hubble Space Telescope (HST) transmission spectral survey. These observations have shown a range of spectral behavior over optical and infrared wavelengths, suggesting diverse cloud and haze properties in their atmospheres. Our "grid" of models recovers trends shown in other parametric studies of hot Jupiters, particularly increased day-night temperature contrast with increasing equilibrium temperature and equatorial superrotation. Furthermore, we show that three-dimensional variations in temperature, particularly across the western and eastern terminators and from the equator to the pole, can vary by hundreds of Kelvin. This can result in vastly different cloud properties across the limb, which can lead to variations in transmission spectra. Finally, we comment on prospects with the James Webb Space Telescope (JWST) to further characterize hot Jupiters out to longer wavelengths.

Author(s): Tiffany Kataria5, David Kent Sing5, Nikole K Lewis[2], Jonathan Fortney4, Mark Marley[1], Adam P Showman3
Institution(s): *1. NASA Ames Research Center, 2. Space Telescope Science Institute, 3. University of Arizona, 4. University of California at Santa Cruz, 5. University of Exeter*

111.26 – Hot Exoplanet Atmospheres Resolved with Transit Spectroscopy

The field of exoplanet atmospheres is booming thanks to (low-resolution) space-borne spectrographs and high-resolution (narrow-ranged) NIR spectrographs on ground-based 8m-class telescopes. Atmospheres are important because they are our observing window on the physical, chemical, and evolutionary processes occurring on exoplanets. Transiting exoplanets are the best suitable targets for atmospheric studies. Observing a transit in different filters or with a spectrograph reveals the transmission spectrum of the planet atmosphere. More than one decade of such observations allowed the exploration of these remote words by detecting some constituents of their atmospheres, but revealing also the presence of scattering hazes and clouds in several exoplanets preventing the detection of major chemical constituents at low to medium resolution even from space.
Transit observations from the ground with stabilised high-resolution spectrograph, such HARPS, have key roles to play in this context. Observation of the hot-jupiter HD 189733b with HARPS allow the detection of sodium in the planet atmosphere. The high-resolution transmission spectra allowed to probe a new region high in the atmosphere and revealed rapid winds and a heating thermosphere. This new use of the famous planet hunter turned HARPS into a powerful exoplanet characterisation machine. It has the precision level of the Hubble Space Telescope, albeit at 20 higher resolution.

A survey of a large set of known hot transiting exoplanets with HARPS and later with ESPRESSO will allow the detection of key tracers of atmospheric physics, chemistry, and evolution, above the scattering haze layers known to dominate low-resolution visible spectra of exoplanets.
Such observation, in total sinergy with other technics, will rmly establish stabilised, high-resolution spectrographs on 4m telescopes as corner-stones for the characterisation of exoplanets. This is instrumental considering the upcoming surveys (NGTS,K2, CHEOPS, TESS, PLATO) that will deliver hundreds of exoplanets amenable to atmospheric characterisation.

Author(s): Aurélien Wyttenbach[1], David Ehrenreich[1]
Institution(s): *1. Geneva University*

111.27 – Race to the Top: Transiting Brown Dwarfs and Hot Jupiters

There are currently twelve known transiting brown dwarfs, nine of which orbit single main-sequence stars. These systems give us one of the only ways in which we may directly measure the masses and radii brown dwarfs, which in turn provides strong constraints on theoretical models of brown dwarf interiors and atmospheres. In addition, the transiting brown dwarfs allow us to forge a link between our understanding of transiting hot Jupiters, and our understanding of the field brown dwarf population. Comparing the two gives us a unique avenue to explore the role and interaction of surface gravity and stellar irradiation in the atmospheres of sub-stellar objects. It also allows us to leverage the detailed spectroscopic information we have for field brown dwarfs to interpret the broadband colors of hot Jupiters. This provides us with insight into the L/T transition in brown dwarfs, and the atmospheric chemistry changes that occur in hot Jupiter atmospheres as they cool. I will discuss recent observational results, with a particular focus on the transiting brown dwarf KELT-1b, and suggest how more of these important systems may be discovered in the future.

Author(s): Thomas G. Beatty[1]
Institution(s): *1. Penn State*

111.28 – Spatially resolved winds on an exoplanet

We will present evidence that the atmosphere of the hot Jupiter HD 189733b has a strong eastward motion, with red-shifted absorption detected on the leading limb of the planet and blue-shifted absorption on the trailing limb. Our results are based on a time-resolved model of the sodium transmission spectrum measured with the HARPS spectrograph. The model includes limb darkening and stellar rotation, and it accounts implicitly for the Rossiter-McLaughlin effect.

Our results can be understood as a combination of tidally locked planetary rotation and an eastward equatorial jet. The equatorial jet has long been predicted in atmospheric circulation models, and it helps to explain Spitzer maps of the dayside thermal emission of HD 189733b that show the hottest point of the planetary atmosphere offset to the east of the substellar point. In addition to testing atmospheric circulation models, our results demonstrate the feasibility of studying weather systems on distant planets.

Author(s): Tom Michael Louden[1], Peter Wheatley[1]
Institution(s): *1. University of Warwick*

111.29 – Simulations of Hot Jupiter-Stellar Wind Hydrodynamic Interaction

Gas giant exoplanets orbiting at close distances to the parent star are subjected to large radiation and stellar wind fluxes. In this talk I will discuss hydrodynamic simulations of the planetary upper atmosphere and interaction with the stellar wind carried out to understand the possible flow regimes and how they affect the Lyman α transmission spectrum and light curve. Charge exchange reactions are included to explore the role of energetic atoms as compared to thermal particles. Simulations were carried for a range of gas binding parameters in order to understand the flow geometry, and how the geometry is reflected by the lightcurve and transit depth. Results for scattering of Lyman alpha radiation outside of transit will also be discussed.

Author(s): Phil Arras[1]
Institution(s): *1. University of Virginia*

111.30 – Secondary eclipses of hot-Jupiters from the Anglo Australian Telescope

Secondary eclipses measure the day-side brightness temperatures of hot-Jupiters. Secondary eclipses measured at multiple photometric bands build up the spectral colours of these planets. We present a set of eclipse observations from the 3.9m Anglo-Australian Telescope, with the aim of building up an empirical understanding of hot-Jupiter atmospheres. From these observations, we can begin to assemble near-infrared colour-magnitude diagrams of hot-Jupiters. Statistical analyses of the eclipse sample have the potential to reveal the presence of clouds, global heat redistribution properties, and the diversity of hot-Jupiter atmospheres.

Author(s): George Zhou[1]
Institution(s): *1. Harvard-Smithsonian Center for Astrophysics*

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112 – Planet Detection - Other Poster Session

112.01 – Measuring the Mass of Free-Floating Planets with K2

Campaign 9 of the K2 mission (K2C9) will begin April next year, and presents us with our first and likely only opportunity to measure the masses of the large population of free-floating planets found by gravitational microlensing surveys. I will describe the plans for the campaign, including the unprecedented need for wide-field ground-based observations, and the innovative techniques that are being developed to work in crowded fields with Kepler's large pixels. Finally I will discuss what we can expect to learn from K2C9 and future microlensing surveys for free-floating planets.

Author(s): Matthew Penny[1]
Institution(s): *1. The Ohio State University*

112.02 – Using K2 To Find Free-floating Planets

K2's Campaign 9 (K2C9) will conduct a several square-degree microlensing survey toward the Galactic bulge to detect exoplanets simultaneously from the ground and from space. The ~0.5 AU baseline between K2 and the Earth during C9 will facilitate satellite parallax measurements for hundreds of microlensing events, some with planetary signatures, allowing for the determination of the mass of and distance to the lens systems. For short timescale events, with durations of ~1 day, a determination of the parallax will identify that the cause is in fact a very low-mass object, i.e., a free-floating planet. Subsquent high-resolution NIR photometric follow-up can then distinguish between a planet that is widely separated from but gravitationally bound to a host star and one that is truly free-floating.

Author(s): Calen Henderson[1]
Institution(s): *1. JPL/Caltech*

112.03 – The rotation of nearby M dwarfs and implications for exoplanet discovery

Stellar rotation and its associated activity signals can mimic the radial velocity signatures of orbiting planets. Rotation is both mass- and age-dependent; and despite the prevalence of low-mass stars, few have measured rotation periods. The MEarth Project is a transiting planet survey looking for Earths and Super Earths around mid-to-late M dwarfs (<0.33 Rsun) within 33 pc of the Sun, with observatories in the northern and southern hemispheres. Using the MEarth planet-search data, we measured photometric periods ranging from 0.1 to 150 days for approximately 500 mid-to-late M dwarfs. We used galactic kinematics to estimate the ages of the stars with detected rotation periods. We find that mid M dwarfs in the field are slowly-rotating, with periods of approximately 100 days at 5 Gyr. We consider late-type stars at 5 Gyr and show where stellar rotation may impact the discovery of habitable planets. The slow rotation rates and close-in habitable zones of mid M dwarfs indicate that rotation-induced signals are unlikely to interfere with the detection of habitable planets around these stars. We present a catalog of photometric rotation periods and non-detections for the 2300 stars that have been observed by MEarth. The MEarth target list comprises the brightest and nearest low-mass stars and is the sample of M dwarfs best suited for the discovery and atmospheric characterization of habitable planets. We highlight the subset that, based on their photometric rotation, is well-suited as targets for the upcoming generation of radial velocity surveys dedicated to low-mass stars, including SPIROU, CARMENES, and HPFS.

Author(s): Elisabeth R. Newton[2], Jonathan Irwin3, David Charbonneau[2], Andrew A. West[1], Zachory K. Berta-Thompson4, Jason Dittmann[2]
Institution(s): *1. Boston University, 2. Harvard University, 3. Harvard-Smithsonian Center for Astrophysics, 4. Massachusetts Institute of Technology*

112.04 – The Case for Exoplanet Surveys at Radio Wavelengths

Motivated by the bright and phenomenologically-rich auroral radio bursts observed in the Solar System, astronomers have been attempting to detect exoplanets at radio wavelengths since before the discovery of 51 Peg b. While the first efforts were admittedly optimistic, long-wavelength radio arrays are finally achieving sensitivities comparable to the expected signal, and the pace of investment has been quickening as groups compete to make the first conclusive detection of radio emission from an exoplanet. I describe current survey efforts and their potential payoff: radio observations can yield measurements of otherwise inaccessible quantities such as rotation periods and magnetic moments, the latter being particularly relevant to habitability and star/planet interactions. I argue that the under-construction Hydrogen Epoch of Reionization Array, HERA, will be a particularly powerful instrument in these studies.

Author(s): Peter K. G. Williams[1], Edo Berger[1]
Institution(s): *1. Harvard-Smithsonian Center for Astrophysics*

112.05 – *Kepler* beaming binaries radial velocity follow-up with WIYN/Hydra

High-quality space-based time series photometry reveals the minute photometric modulations induced by orbital motion in short-period binary systems with stellar and substellar secondaries. Those modulations are induced by both gravitational and atmospheric processes. Gravitational processes include the beaming effect (aka Doppler boosting) and tidal ellipsoidal distortion, and the atmospheric processes include reflected light and thermal emission by the secondary atmosphere. Therefore, non-eclipsing (non-transiting) systems are detectable using photometry alone. The availability of Kepler data for a large sample of stars combined with the sensitivity to non-eclipsing systems (which are at least an order of magnitude more common than eclipsing systems) has the potential of transforming the Kepler survey into the equivalent of a radial velocity survey of a large sample of stars. This allows detecting intrinsically rare systems, where traditional approaches, e.g., radial velocity and transit surveys, are highly inefficient. Those include systems where the companion is a brown-dwarf or a massive planet, or even a white dwarf. As this approach is still in its infancy, we are carrying out radial velocity follow-up of Kepler photometric detections, to confirm the nature of the system and accurately measure the orbit and the companion's mass. Here we present our results from an radial velocity campaign with the WIYN/Hydra multi-fiber spectrograph, where we used 26 nights during the 2014 and 2015 Kepler observing seasons to observe five Hydra one-degree diameter fields within the Kepler field. Our list of targets includes 131 Kepler beaming binaries, and we used additional fibers to observe 85 Kepler eclipsing binaries and 31 Kepler Objects of Interest (KOIs). A detailed comparison between the photometrically predicted companion's mass and the mass measured through radial velocities will improve our understanding of this young approach, and will support similar projects using data from current and future space-based time series photometry missions including K2, TESS, and PLATO. Our primary long term goal is to characterize the so-called brown-dwarf desert - a paucity of short-period companions in the brown-dwarf mass range, orbiting G- and K-type stars - and see how its characteristics depend on the primary spectral type.

Author(s): Avi Shporer[1], Keivan Stassun3, Simchon Faigler[2], Tabetha Boyajian5, Tsevi Mazeh[2], Lev Tal-Or[2], Andrej Prsa4
Institution(s): *1. JPL, 2. Tel Aviv University, 3. Vanderbilt University, 4. Villanova University , 5. Yale University*

112.06 – K-Stacker, a new way of detecting and characterizing exoplanets with high contrast imaging instruments

This year, a second generation of coronagraphs dedicated to high-contrast direct imaging of exoplanets is starting operations. Among them, SPHERE, installed at the focus of the UT3 Very Large Telescope, reaches unprecedented contrast ratios up to 10^{-6} -10^{-7}, using eXtreme Adaptive Optics and the Angular Differential Imaging (ADI) technics. In this paper, we present a new method called Keplerian-Stacker that improves the detection limit of high contrast instruments like SPHERE, by up to a factor of 10. It consists of observing a star on a long enough period to let a hypothetical planet around that star move along its orbit. Even if in each individual observation taken during one night, we do not detect anything, we show that it is possible, using an optimization algorithm, to re-center the images according to keplerian motions (ex: 10-100 images taken over a long period of typically 1-10 years) and detect planets otherwise unreachable. This method can be used in combination with the ADI technics (or possibly any other high contrast data reduction method) to improve the Signal to Noise Ratio in each individual image, and to further improve the global detection limit. It also directly provides orbital parameters of the detected planets, as a by-product of the optimization algorithm.

Author(s): Herve Le Coroller[2], Mathias Nowak[2], Luc Arnold[1], Kjetil Dohlen[2], Thierry Fusco[2], Jean-François Sauvage[2], Arthur Vigan[2]
Institution(s): *1. Observatoire de Haute-Provence, 2. Pytheas/CNRS*

112.07 – A Census of Habitable Planets around Nearby stars?

One day or another, a spectroscopic mission will be launched searching for biosignatures in the atmospheres of Earth-like planets, i.e. planets located in the Habitable Zone (HZ) of their stars and hopefully rocky. This could be done blindly, the expensive spectroscopic mission searching for the candidates before performing their spectroscopy. According to a clear tendency in the *Kepler* data, the mean number of Earth-like planets, η_{Earth}, around the *Kepler* stars is rather low (10% - 20%). It makes this approach pretty inefficient, most of the stars studied (90% - 80%) having no such planets, and the corresponding mission time being essentially lost. This is more severe when the random position of planets on their orbits is taken into account. An exhaustive census of these planets around the nearby stars, the only ones accessible to the mission, appears desirable priorly to its launch.
Up to now, the detection of low mas planets in the HZ of their stars by the Radial Velocity technique is limited to stars with very low activity (~ 2% of F,G,K stars). The detection by transits is limited by the low probability the randomly oriented orbits, few of them leading to a transit (0.5% for solar-type stars). On the other hand, ultra accurate astrometry is less sensitive to stellar activity and could detect Earth-like planets around most of the nearby solar-type stars.
We present the project of a space mission, Theia+, that could do the job and measure the masses and orbits of these planets, a key piece of information to derive a possible statement about the likelihood of the actual presence of life on a planet. Other capabilities of the mission regarding Dark Matter, Very Compact Object, Cosmology, and Stellar Formation is also rapidly mentioned.

Author(s): Alain M. Leger[1]
Institution(s): *1. IAS*

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113 – Planet Detection - Radial Velocities Poster Session

113.01 – RAFT I: New planetary candidates from archival FEROS spectra

I will present initial results from our RAFT program (Reanalysis of Archival FEROS specTra) that was published in MNRAS (Soto et al. 2015, MNRAS, 451, 3131S). This project was motivated by the strikingly different conclusions several authors have arrived at after analyzing radial velocities measured using the FEROS spectrograph, throwing some doubt on the validity of a number of planet detections. We have reanalyzed the stars HD 11977, HD 47536, HD 70573, HD 110014 and HD 122430, all of which are claimed to have at least one planetary companion, and I will discuss the results from this work. In particular, we confirmed the existence of planets around HD 11977, HD 47536 and HD 110014, we found no evidence of the second planet candidate around HD 47536, nor any companions orbiting HD 122430 and HD 70573, and finally, we discovered a second planet orbiting HD 110014. These results confirm that very metal-poor stars down to [Fe/H] ~ -0.7 dex, can indeed form giant planets given the right conditions.

Author(s): Maritza Gabriela Soto[1]
Institution(s): *1. Universidad de Chile*

113.02 – HARPS-N and SOPHIE joint follow-up of Kepler close-in planetary candidates

Radial velocity follow-up is mandatory to establish the nature of most of the transiting planet candidates detected with Kepler, then to characterize them and in particular to measure their mass and eccentricity. We started follow-up programs with the spectrograph HARPS-N that benefit from our SOPHIE observations on Kepler Objects of Interest. Our HARPS-N programs mainly aim at extending the SOPHIE results toward Kepler planetary candidates having lower masses, smaller radii, and/or fainter host stars. Up to now, they allowed the identification of several false positives and the characterization of 7 new planets, i.e. about half the number of transiting planets characterized with HARPS-N since its installation. Most of them are in parameters domain with a sparse number of known objects.

Author(s): Guillaume Hebrard[1]
Institution(s): *1. Institut d'astrophysique de Paris*

113.03 – Extreme Precision Environmental Control for Next Generation Radial Velocity Spectrographs

Extreme radial velocity precisions of order 10cm/s will enable the discoveries of Earth-like planets around solar-type stars. Temperature and pressure variations inside a spectrograph can lead to thermomechanical instabilities in the optics and mounts, and refractive index variations in both the optical elements as well as the surrounding air. Together, these variations can easily induce instrumental drifts of several tens to hundreds of meters per second. Enclosing the full optical train in thermally stabilized high-vacuum environments minimizes such errors. In this talk, I will discuss the Environmental Control System (ECS) for the Habitable Zone Planet Finder (HPF) spectrograph: a near infrared (NIR) facility class instrument we will commission at the Hobby Eberly Telescope in 2016. The ECS will maintain the HPF optical bench stable at 180K at the sub milli-Kelvin level on the timescale of days, and at the few milli-Kelvin level over months to years. The entire spectrograph is kept under high-quality vacuum ($<10^{-6}$ Torr), and environmental temperature fluctuations are compensated for with an actively controlled radiation shield outfitted with custom feedback electronics. High efficiency Multi-Layer Insulation (MLI) blankets, and a passive external thermal enclosure further isolate the optics from ambient perturbations. This environmental control scheme is versatile, suitable to stabilize both next generation NIR, and optical spectrographs. I will show how we are currently testing this control system for use with our design concept of the Extreme Precision Doppler Spectrograph (EPDS), the next generation optical spectrograph for the WIYN 3.5m telescope. Our most recent results from full-scale stability tests will be presented.

Author(s): Gudmundur K Stefansson[1], Fred Hearty[1], Eric Levi[1], Paul Robertson[1], Suvrath Mahadevan[1], Chad Bender[1], Matt Nelson[2], Samuel Halverson[1]
Institution(s): *1. Pennsylvania State University, 2. University of Virginia*

113.04 – Improve Radial Velocity Precision with Better Data Analysis Tools

The synergy between Kepler and the ground-based radial velocity (RV) surveys have made numerous discoveries of low-mass exoplanets, opening the age of Earth analogs. However, Earth analogs such as Kepler 452-b require a much higher RV precision (~ 10 cm/s) than the achievable with current instruments (~ 1 m/s) and understanding of stellar photosphere. This presentation will cover some of the instrumental and data issues that are currently hindering us from achieving the sub 1 m/s precision, as well as remedies and ways forward with future RV instruments. Highlights of our work include: (1) how telluric contamination affects RV precision and how to "telluric-proof" a Doppler pipeline; (2) how errors in the deconvolved stellar reference spectrum can mimic the signal of a super-Earth on a ~1 year orbit; (3) the battle with imperfections in the iodine reference spectra and how an ultra-high resolution (R ~ 500,000) echelle spectrum can help; (4) and a new RV extraction code in Python which incorporates MCMC and Gaussian Processes. This research is based on radial velocity data taken with iodine cell calibrators using Keck/HIRES and HET/HRS.

Author(s): Sharon Xuesong Wang[1], Jason Wright[1], Ming Zhao[1]
Institution(s): *1. Penn State University*

113.05 – Determining the Mass of Kepler-78b With Nonparametric Gaussian Process Estimation

Kepler-78b is a transiting planet that is 1.2 times the radius of Earth and orbits a young, active K dwarf every 8 hours. The mass of Kepler-78b has been independently reported by two teams based on radial velocity measurements using the HIRES and HARPS-N spectrographs. Due to the active nature of the host star, a stellar activity model is required to distinguish and isolate the planetary signal in radial velocity data. Whereas previous studies tested parametric stellar activity models, we modeled this system using nonparametric Gaussian process (GP) regression. We produced a GP regression of relevant Kepler photometry. We then use the posterior parameter distribution for our photometric fit as a prior for our simultaneous GP + Keplerian orbit models of the radial velocity datasets. We tested three simple kernel functions for our GP regressions. Based on a Bayesian likelihood analysis, we selected a quasi-periodic kernel model with GP hyperparameters coupled between the two RV datasets, giving a Doppler amplitude of 1.86 ± 0.25 m s^{-1} and supporting our belief that the correlated noise we are modeling is astrophysical. The corresponding mass of $1.87 +0.27-0.26$ $M_\oplus$ is consistent with that measured in previous studies, and more robust due to our nonparametric signal estimation. Based on our mass and the radius measurement from transit photometry, Kepler-78b has a bulk density of $6.0+1.9-1.4$ g cm^{-3}. We estimate that Kepler-78b is 32±26% iron using a two-component rock-iron model. This is consistent with an Earth-like composition, with uncertainty spanning Moon-like to Mercury-like compositions.

Author(s): Samuel K Grunblatt[1], Andrew Howard[1], Raphaëlle Haywood[2]
Institution(s): *1. University of Hawaii, 2. University of St Andrews*

113.07 – Early Results from Dharmar Planet Survey

The Dharma Planet Survey (DPS) with the TOU optical spectrograph at the 2m AST (soon at the dedicated robotic 50inch on Mt. Lemmon) is designed to detect and characterize sub-Jovian planets with high cadence (100 RVs per target) and high Doppler precision (~1-2 m/s) at the orbital region (~100-450 days) uncovered by previous RV surveys. The ultimate goal is to detect potentially habitable super-Earths to independently measure $\eta_\oplus$ and provide high priority targets for future space direct-imaging missions (such as *WFIRST-AFTA* and *LUVOIR surveyor)* to identify possible biomarkers supporting life (Ge et al. 2014). It will initially search for and characterize low mass planets around 100 nearby bright FGK dwarfs (25 late F, 50 G dwarfs and 25 K dwarfs with V<7 and within 25 pc) in 2016-2018, observe more targets and continue to monitor targets with linear trends after 2018. This poster presents our survey plan and early results.

Author(s): Bo Ma[2], Jian Ge[2], Sirinrat Sithajan[2], Scott Powell[2], Frank Varosi[2], Michael Williamson[1], Matt Muterspaugh[1], Rory Barnes3, Mickey Singer[2]
Institution(s): *1. TSU, 2. University of Florida, 3. WSU*

113.08 – The Rossiter-McLaughlin effect of planets transiting M-dwarfs, and its impact on planet detection in Doppler surveys

A major endeavour in recent exoplanetary science is to detect potentially habitable, Earth-like planets around nearby stars. The upcoming SPIRou (Le SpectroPolarimètre Infra-Rouge) Legacy Survey is one such initiative and is optimized for the detection of such exoplanets around cool M-dwarfs via the radial velocity method. If a planetary transit occurs, radial velocity observations made in-transit will be subject to an anomalous signal due to the occultation of the differentially Doppler shifted stellar limbs; the so-called Rossiter-McLaughlin (RM) effect. Using the SPIRou Legacy Survey as a test case, we assess the impact of the RM effect on unevenly sampled Doppler survey data. Firstly, the stellar spectra taken during a Doppler survey, along with an assumed planetary mass-radius relationship, can be used to estimate the likelihood of a planetary transit. This is useful for target-selection of stars with potentially transiting exoplanets. However, if not properly accounted for in models of the stellar Doppler shift, the anomalous RM effect can result in 20-30% loss in planet detection rate. This significant loss can be easily remedied by our proposed simple process of iteratively re-sampling the timeseries and searching for periodicities. For the subset of the anticipated SPIRou planet population that is hidden by the RM effect, our algorithm is capable of recovering planets with the same efficiency as in the absence of the RM effect thus negating its effect.

Author(s): Ryan Cloutier[2], Amaury H.M.J. Triaud[1], Kristen Menou[1]
Institution(s): *1. Centre for Planetary Sciences, 2. University of Toronto*

113.09 – Searching for rocky planets using correlated noise models and multi-instrument radial velocity data sets

The search for rocky planets orbiting the nearest stars to the Sun is a quest that, at the present time, is well suited to the search for planets by precision radial velocity measurements. However, recent studies have shown how the presence of correlated noise in the data can mask low-amplitude Doppler signals or introduce false-positives. We have been searching for these elusive low-amplitude signals by applying correlated noise models and studying ways to limit the impact of this noise on the Doppler measurements. I will discuss some of the outcomes of this work, including recent results for some Doppler interesting stars that exhibit evidence for very low amplitude signals at the few m/s level e.g. HD41248. The combined analysis of data from the instruments HARPS, PFS, HiRES, UCLES, and CHIRON was employed in this analysis, and I will elaborate on how each of these data sets complement the presence or not of the detected signals.

Author(s): James Stewart Jenkins[1]
Institution(s): *1. Universidad de Chile*

113.10 – The APF Fifty: A Robotic Search for Earth's Nearest Neighbors

With the Automated Planet Finder (APF) telescope, we are conducting a Doppler survey of a magnitude-limited sample of 51 nearby, chromospherically inactive, G and K dwarfs. This APF-50 survey is sensitive to planets with masses as low as 2–3 times the mass of the Earth and will measure small planet occurrence in the solar neighborhood. We expect to measure details of the planet mass function and to identify the nearby stars hosting low-mass planetary systems that will be the likely targets of follow-up measurements. We employ the robotic APF telescope to monitor the stars at high cadence for the duration of the survey. It builds on the Eta-Earth Survey at Keck Observatory, but with improved Doppler precision due to the high observing cadence and a larger number of measurements. We will measure the occurrence rate and mass function of small planets in our local neighborhood using the new planets discovered by the APF-50 survey and the set of planets already known to orbit stars in our sample. Combining the mass function from this survey with the size distribution from Kepler, we will probe the density and core mass properties of super-Earths to inform formation theories of the galaxy's most abundant planets.

Author(s): Benjamin Fulton[1], Andrew Howard[1], Lauren M. Weiss[2], Evan Sinukoff[1], Geoffrey W. Marcy[2], Howard T. Isaacson[2], Lea Alyse Hirsch[2]
Institution(s): *1. Institute for Astronomy, University of Hawaii, 2. University of California, Berkeley*

113.11 – Precise Doppler Monitoring of K2 Planets with Magellan/PFS

Planets in the size range between Earth and Neptune are poorly understood. Is there a critical size below which they are always rocky? Are they sometimes layered with thick hydrogen-helium atmospheres? Could there be "water worlds" with thick water-vapor atmospheres? Answering these questions requires a larger sample of small planets for which the mass, radius, and atmospheric scale height can all be measured. We are using K2 data to identify small transiting planets with host stars bright enough to be suitable for precise spectroscopy. Here we present Doppler observations with the Magellan Planet Finding Spectrograph, which have enabled us to measure the masses of several small planets. Among the systems we have studied are WASP-47, which hosts a hot Jupiter with two smaller close companions, and EPIC-201505350, a two planet system in 3:2 mean-motion resonance.

Author(s): Fei Dai[1]
Institution(s): *1. MIT*

114 – Planet Detection - Transits Poster Session

114.01 – A Big Data Analytics Pipeline for the Analysis of TESS Full Frame Images

We present a novel method for producing a catalogue of extra-solar planets and transients using the full frame image data from TESS. Our method involves (1) creating a fast Monte Carlo simulation of the TESS science instruments, (2) using the simulation to create a labeled dataset consisting of exoplanets with various orbital durations as well as transients (such as tidal disruption events), (3) using supervised machine learning to find optimal matched filters, Support Vector Machines (SVMs) and statistical classifiers (i.e. naïve Bayes and Markov Random Fields) to detect astronomical objects of interest and (4) "Big Data" analysis to produce a catalogue based on the TESS data. We will apply the resulting methods to all stars in the full frame images. We hope that by providing libraries that conform to industry standards of Free Open Source Software we may invite researchers from the astronomical community as well as the wider data-analytics community to contribute to our effort.

Author(s): Matthew Wampler-Doty[1], John Pierce Doty[1]
Institution(s): *1. Noqsi Aerospace, Ltd.*

114.02 – Unreliable Populations: A Classification of Types of Unreliability in Kepler Exoplanet Catalogs

Exoplanet occurrence rate estimates based on Kepler data suffer from the problem of reliability: Objects in the catalog may be due to false alarms (FAs), spurious detections of non-transit-like signals; or false positives (FPs), detection of transit-like signals that are not due to planets orbiting the observed star. The computation of the true occurrence rate requires knowledge of the rate of FPs and FAs, which can be very difficult to determine on a planet-by-planet basis, particularly at the low signal levels expected in the Earth-Sun analog regime. Some occurrence rate estimates treat reliability as a population, assuming that the reliability rate depends on planet period and radius.

We present a classification of types of FAs and FPs in terms of their underlying cause. These include astrophysical FPs such as eclipsing binaries (grazing or blended) and FAs due to stellar variability. We give particular emphasis to instrumental FAs, which can be due to a variety of causes. Our classification emphasizes that different classes of FAs, and to a lesser extent FPs, can be strongly dependent on position or time of observation. For example, the likelihood of background eclipsing binary FPs depends strongly on Galactic latitude. Some types of instrumental FAs occur only on particular locations on the focal plane or at particular observation times such as near strong instrument thermal transients. These dependencies imply that care should be taken when treating FP/FA rates as functions of only planet period and radius.

The Kepler mission provides various reliability diagnostics at the Exoplanet Archive. We discuss how these diagnostics relate to our classification scheme, and find that while FPs are well covered, instrumental FAs have poor coverage. At low signal-to-noise ratios these diagnostics provide little information, so the reliability rate for small planets in long-period orbits is less well known and may be high. We describe upcoming studies by the Kepler team that will measure the rate of several types of instrumental FAs.

Author(s): Steve Bryson[1], Fergal Mullally[2]
Institution(s): *1. NASA Ames Research Center, 2. SETI Institute*

114.03 – Multi-object Spectroscopy Reduction Challenges

Here we present multiple observations of the primary transits of bright exoplanets with visible-wavelength multi-object spectroscopy. Multi-object spectroscopy allows simultaneous observations of both the exoplanet host star and one or more comparison stars. Ideally, the comparison star measures errors, such as airmass variations and telescope jitter. The hypothesis is that these errors can then be divided out from target star to achieve higher SNR and improve estimation of the small transit signal. However we find that the astrophysical signal can change depending on selection of comparison star, typically on the ~0.1% level. For example, small bumps during in-transit portion of the lightcurve indicative of star spots appear when using one check star but not the other. Our analysis suggests that comparison and target stars do not necessarily share same the systematics due to differing pixel properties across the detector. We conclude that one cannot blindly use a comparison star to remove systematics. Using our small sample we explore and compare multiple reduction methods to find the true underlying astrophysical signal.

Author(s): Robert Thomas Zellem[2], Kyle Pearson3, Ismael Mireles[1], Mark R. Swain[2]
Institution(s): *1. California Institute of Technology, 2. Jet Propulsion Laboratory - California Institute of Technology, 3. Northern Arizona University*

114.04 –
KELT-10b and KELT-11b: Two Sub-Jupiter Mass Planets well-Suited for Atmospheric Characterization in the Southern Hemisphere

The Kilodegree Extremely Little Telescope (KELT) project is a photometric survey in both the northern and southern hemispheres for transiting planets around bright stars (8 < V < 11), and has discovered 15 planets to date. Of these, several possess unique characteristics that make them especially well suited for study of planet atmospheres. Here, I present the first two discoveries from the KELT-South survey. KELT-10b is an inflated transiting sub-Jupiter mass planet (0.68 MJ) around a V=10.7 early G-star. It has the 3rd deepest transit (1.4%) in the southern hemisphere for a star V < 12.5, making it a great target for transmission spectroscopy. KELT-11b is a highly inflated transiting Saturn mass planet (0.22 MJ) orbiting one of the brightest planet-hosting stars in the southern hemisphere. Interestingly, KELT-11b's host star is a clear sub-giant star (log(g) ~ 3.7). I will discuss their impact for atmospheric characterization. For example, the highly inflated nature of the KELT-11b planet provides the ability to study a sub-Jupiter atmosphere at very low planetary gravity, while the sub-giant nature of its host star allows us to study the effects of post main sequence evolution of a host star on a hot Jupiter.

Author(s): Joseph E. Rodriguez[1]
Institution(s): *1. Vanderbilt University*

114.05 – Spin-Orbit Misalignment of Two-Planet-System KOI-89 Via Gravity Darkening

We investigate the potential causes of spin-orbit misalignment in multiplanetary systems via two-planet-system KOI-89. We focus on this system because it can experimentally constrain the outstanding hypotheses that have been proposed to cause misalignments. Using gravity darkening, we constrain both the spin-orbit angles and the angle between the planes of the orbits. Our best-fit model shows that the 85-day-orbit and 208-day-orbit planets are misaligned from the host star's rotation axis by 72° ± 3° and 73° (+11 -5°), respectively. From these results, we limit KOI-89's potential causes of spin-orbit misalignment based on three criteria: agreement with KOI-89's fundamental parameters, the capability to cause extreme misalignment, and conformance with mutually aligned planets. Our results disfavor planet-embryo collisions, chaotic evolution of stellar spin, magnetic torquing, coplanar high-eccentricity migration, and inclination resonance, limiting possible causes to star-disk binary interactions, disk warping via planet-disk interactions, Kozai resonance, planet-planet scattering, or internal gravity waves in the convective interior of the star.

Author(s): Jonathon Ahlers[1], Jason W Barnes[1], Rory Barnes[2]
Institution(s): *1. University of Idaho, 2. University of Washington*

114.06 – High Precision Photometry for the K2 Mission

The two reaction wheel K2 mission brings new challenges for the data reduction processes. We developed a reduction pipeline for extracting high precision photometry from the K2 dataset and we use this pipeline to generate light curves for the K2 Campaign 0 super-stamps and K2 Campaign 1 target pixel dataset. Key to our reduction technique is the derivation of global astrometric solutions from the target stamps from which accurate centroids are passed on for high precision photometry extraction. We also implemented the image subtraction method to reduce the K2 Campaign 0 super-stamps containing open clusters M35 and NGC2158. We extract target light curves
for sources from a combined UCAC4 and EPIC catalogue -- this includes not only primary targets of the K2 Mission, but also other stars that happen to fall on the pixel stamps.
Our astrometric solutions achieve a median residual of ~0.127". For bright stars, our best 6.5 hour precision for raw light curves is ~20 parts per million (ppm). For our detrended light curves, the best 6.5 hour precision achieved is ~15 ppm. We show that our detrended light curves have fewer systematic effects (or trends, or red-noise) than light curves produced by other groups from the same observations. We highlight the measurements of rotation curves using the K2 light curves of stars within open cluster M35 and NGC2158.

Author(s): Xu Huang[1], Melinda Soares-Furtado3, Kaloyan Penev3, Joel Hartman3, Gaspar Bakos 3, Waqas Bhatti 3, Istvan Domsa[2], Miguel de Val-Borro3
Institution(s): *1. Dunlap Institute for Astronomy & Astrophysics, 2. Hungarian Astronomical Association, 3. Princeton University*

114.07 – Searching for circumbinary planets with CB-BLS

Transiting circumbinary planets (CBP) produce transit signals that are neither periodic not constant in duration or depth. These complications contribute to the low number of detected transiting CBP (nine published in total so far), and limited detection to systems that exhibit transits that are relatively deep, i.e. giant planets with individually-significant transit events. On the other hand, planets around single stars taught us that small planets far outnumber larger planets; consequently the ability to detect small CBPs is of the essence in order to correctly describe CBP demographics. Unfortunately, all currently known transiting CBP were detected either by eye or by some ad-hoc technique that has nothing to do with the 3-body dynamics of CBPs (e.g. QATS, Carter & Agol 2013) limiting their detection power.

CB-BLS (Ofir 2008) is an algorithm for the detection of transiting CBPs that was proposed well before the first transiting CBP was detected (Doyle et al 2011) but was unfortunately not used thus far. CB-BLS was further evolved since its introduction; it is now optimally sensitive and general, it can detect transit signals that are not individually significant, and it has relatively well-understood statistical properties that allow placing limits on non-detections. As a test for its competence we show it to blindly detect all currently known transiting CBPs, including these in eccentric and/or inclined and/or very long planetary orbits that failed other techniques.

We currently run a thorough search for CBPs in the Kepler dataset using CB-BLS. On top of presenting CB-BLS and it capabilities, we will give an update on the search's status and preliminary results.

Author(s): Aviv Ofir[1]
Institution(s): *1. Weizmann Institute of Science*

114.08 – XO-6b: A transiting hot Jupiter around a fast rotating star

Orbital properties of hot Jupiters depend on the temperature and rotation rate of their host stars. These observed correlations provide some of the very few constraints on their dynamical evolution. However, almost all the objects available to such studies orbit around relatively slow rotators, with stellar rotation periods usually several times larger than the orbital periods. Because of the apparent dearth of hot Jupiters around fast rotators, the dynamical evolution of these systems is largely unconstrained. Here, we report the discovery of XO-6b, a hot Jupiter orbiting a fast rotating and bright F5 star (Teff = 6605 K, Vsini = 45 km/s, V = 10.25). This transiting hot Jupiter system is one of the very few with a stellar rotation period smaller than the planet orbital period (Prot < 1.41 d, Porb = 3.77 d), and adds to the sample of hot Jupiters around hot stars with a measured obliquity. We present the system parameters extracted from photometric follow-up and Rossiter-McLaughlin measurements. This system provides an additional constraint to dynamical and tidal models in their promising attempt of explaining the dynamical evolution of close-in giant planets, and will allow to extend the emerging picture to planets orbiting fast rotating stars.

Author(s): Nicolas Michael Crouzet[11], Peter McCullough[9], Pilar Montañés-Rodríguez[5], Ignasi Ribas[4], Vincent Bourrier[10], Alain Lecavelier des Etangs[3], Guillaume Hebrard[3], Enrique Garcia-Melendo[4], Enrique Herrero[4], Francesc Vilardell[4], Jerry Foote[12], Bruce Gary[2], Paul Benni[8], Matthieu Conjat[7], Magali Deleuil[6], Laetitia Akhenak[3], Joe Garlitz[1], Doug Long[9]
Institution(s): *1. Elgin Observatory, 2. Hereford Arizona Observatory, 3. Institut d'Astrophysique de Paris, CNRS, 4. Institut d'Estudis Espacials de Catalunya, 5. Instituto de Astrofísica de Canarias, 6. Laboratoire d'Astrophysique de Marseille, CNRS, 7. Observatoire de la Cote d'Azur, 8. Paul Benni Observatory, 9. Space Telescope Science Institute, 10. Universite de Geneve, 11. University of Toronto, 12. Vermillion Cliffs Observatory*

114.09 – A Year-by-Year Analysis of Transiting Exoplanet Detectability Using LSST

The Large Synoptic Survey Telescope (LSST) will generate light curves for approximately 1 billion stars over the course of its ten year initial mission. The majority of LSST light curves will contain about 1000 data points (so-called regular cadence) while select fields will have light curves with 10000 data points (deep-drilling cadence). Lund et al. (2015) demonstrated that several configurations of exoplanetary systems could be recovered using LSST in areas currently underrepresented in planet searches; i.e. the galactic bulge, the Magellanic clouds, and nearby red dwarfs. A fundamental question in working with LSST data is how time sensitive detection of transient phenomena will affect the rate and type of expected scientific discoveries. Specifically, we aim to examine how quickly significant science results be achievable over the course of LSST's ten year mission. We apply a methodology established in Jacklin et al. (2015) designed to examine hot Jupiter detectability over a range of planetary periods and radii in LSST's ten year light curves. Here, we conduct a similar analysis on a yearly basis in order to examine the change in detectability over the course of the LSST mission. We specifically report on how the LSST yield evolves on a year-by-year basis for the extreme systems, such as planets orbiting very low-mass M-dwarfs in the Milky Way, that we have considered in our previous analyses.

Author(s): Savannah Renee Jacklin[2], Michael B Lund[2], Joshua Pepper[1], Keivan Stassun[2]
Institution(s): *1. Lehigh University, 2. Vanderbilt University*

114.10 – Exploring LSST's Transiting Exoplanet Yield for the Large Magellanic Cloud

The Large Synoptic Survey Telescope (LSST) will observe over half the sky during its ten-year mission, and will provide light curves for around one billion stars between 16th and 24th magnitude in the *ugrizy* bands. The combination of sky coverage and magnitude range will mean that a significant portion of the stars that LSST will observe will be in stellar populations that have rarely been observed by existing transiting planet searches. These new regimes that LSST will explore include Sun-like stars in the Galactic bulge, distant stellar clusters, the Magellanic Clouds, and nearby red dwarfs. We explore the potential yield of transiting exoplanets that LSST will be able to detect in the Large Magellanic Cloud. This presents a first opportunity to detect extragalactic planets.

Author(s): Michael B Lund3, Savannah Renee Jacklin[1], Joshua Pepper[2], Keivan Stassun3
Institution(s): *1. Fisk University, 2. Lehigh University, 3. Vanderbilt University*

114.11 – Target Selection for the TESS Mission

The goal of the TESS mission is to discover small, rocky planets transiting bright stars. To reach that goal, we have constructed a compiled catalog of stars from which to select TESS targets. The catalog contains all dwarf stars in the sky with spectral types F5 and later, and I < 12, along with selected sets of fainter M stars. Provisions are being made to augment the target list with stars that fall outside the nominal spectral type and magnitude limits, and to permit dynamic updating of the catalog to accommodate new survey data being released (e.g. Gaia). I will describe the overall target selection strategy, the current target catalog, and how we intend to further expand and refine the TESS target lists.

Author(s): Joshua Pepper[1], Keivan Stassun[2]
Institution(s): *1. Lehigh University, 2. Vanderbilt University*

114.12 – A Characteristic Transmission Spectrum for WFC3 IR Water Hosting Exoplanet

Using the 19 published Hubble/WFC3 IR exoplanet transmission spectra, we perform a meta-analysis of the spectral modulation due to water. Because of the heterogeneous nature of these data, in which spectral resolution, calibration approach, and observational method vary, we introduce a formalism to de-bias the estimates of spectral modulation. This analysis finds a characteristic transmission spectrum and examines trends for these water-hosting exoplanets.

Author(s): Mark R. Swain[1]
Institution(s): *1. Jet Propulsion Laboratory - California Institute of Technology*

114.14 – Transit Timing Study with Kepler and its synergy with LAMOST

Kepler space telescope has found over 4000 transiting planet candidates. Transit timing is a powerful tool to study these transit planet candidates. The Large Sky Area Multi-Object Fiber Spectroscopic Telescope（LAMOST: http://www.lamost.org) provides mass and radius measurements of the stars thus helps with modeling transit timing. Here, we will show two transit timing techniques, i.e., transit timing variation (TTV) and transit duration (TD), which enable confirming their planetary nature and obtaining insight into their orbital properties by combining Kepler and LAMOST.

Author(s): Jiwei Xie[2], Subo Dong[1], Zhaohuan Zhu4, A-Li Luo3, Ji-Lin Zhou[2]
Institution(s): *1. KIAA-PKU, 2. Nanjing University, 3. NAOC, 4. Princeton University*

114.15 – A Catalog of Transit Timing Posterior Distributions for all Kepler Planet Candidate Transit Events

Kepler has ushered in a new era of planetary dynamics, enabling the detection of interactions between multiple planets in transiting systems for hundreds of systems. These interactions, observed as transit timing variations (TTVs), have been used to find non-transiting companions to transiting systems and to measure masses, eccentricities, and inclinations of transiting planets. Often, physical parameters are inferred by comparing the observed light curve to the result of a photodynamical model, a time-intensive process that often ignores the effects of correlated noise in the light curve. Catalogs of transit timing observations have previously neglected non-Gaussian uncertainties in the times of transit, uncertainties in the transit shape, and short cadence data. Here, I present a catalog of not only times of transit centers, but also posterior distributions on the time of transit for every planet candidate transit event in the Kepler data, developed through importance sampling of each transit. This catalog allows one to marginalize over uncertainties in the transit shape and incorporate short cadence data, the effects of correlated noise, and non-Gaussian posteriors. Our catalog will enable dynamical studies that reflect accurately the precision of Kepler and its limitations without requiring the computational power to model the light curve completely with every integration. I will also present our open-source N-body photodynamical modeling code, which integrates planetary and stellar orbits accounting for the effects of GR, tidal effects, and Doppler beaming.

Author(s): Benjamin Tyler Montet[1], Juliette C Becker3, John Asher Johnson[2]
Institution(s): *1. California Institute of Technology, 2. Harvard University, 3. University of Michigan*

114.16 – The TTV inverse problem

I will present a simple-to-use analytical method for solving the transit timing variation inverse problem.

Author(s): Rosemary Mardling[1]
Institution(s): *1. Monash University*

114.17 – Planetary system architectures as sculpted from binary-disk interactions

Recent years have seen a flurry of ideas attempting to explain the widespread misalignment between stellar spin axes and the orbital planes of their hosted planets. One such hypothesis is so-called disk-torquing, whereby stellar companions gravitationally tilt protoplanetary disks out of alignment with their host stars. This mechanism is capable of dynamically exciting the entire observed range of spin-orbit misalignments. However, a frequent criticism is that systems of mutually inclined planets do not follow from this scenario. Here, we will address these concerns, revealing the under-appreciated richness of planetary architectures that naturally arise out of the disk-torquing framework.

Author(s): Christopher Spalding[1], Konstantin Batygin[1]
Institution(s): *1. California Institute of Technology*

114.18 – Formation of Misaligned Planetary Systems: Primordial Spin-Disk Misalignment

Significant stellar obliquities have been observed in many exoplanetary systems containing hot Jupiters, including some coplanar multiplanet systems. It is traditionally assumed that planet migration in protoplanetary disks leads to aligned planetary orbital axis and stellar spin axis. This may not be the case because the disk
itself may be misaligned with the protostar, for several reasons: (1) Since star formation takes place in a turbulent medium, the accreting gas assembled onto a protoplanetary disk may have a varying direction of angular momentum; (2) Magnetic star-disk interaction may produce a misalignment torque between the stellar spin and the disk; (3) Perturbation from a binary companion can change the orientation of the disk. We critically examine these mechanisms for generating primordial spin-disk misalignments. The importance of star-disk-binary interactions and the possibility of secular spin-orbit resonance in producing large stellar obliquities will be emphasized. The effects and uncertainties involving the dynamics of warped disks and star-disk magnetic interactions will be discussed. Possible observational constraints and tests on primordial misalignments will also be discussed, including the observed correlation between the stellar obliquity and effective temperature.

Author(s): Dong Lai[1]
Institution(s): *1. Cornell University*

114.19 – Validation and Characterization of Planets around Hot Stars with Doppler Tomography

Hot, rapidly rotating stars are not amenable to observations with typical radial velocity techniques due to their wide, rotationally broadened spectral lines. This prevents radial velocity follow-up of transiting planet candidates around these stars, as well as radial velocity Rossiter-McLaughlin observations to determine the alignment of the planetary orbit relative to the stellar spin. An alternative approach is to use Doppler tomography, where we spectroscopically resolve the line profile distortion during the transit due to the Rossiter-McLaughlin effect. This also allows the measurement of the trajectory of the planet across the stellar disk, relative to the projected stellar rotation axis. We are using Doppler tomography to both validate planet candidates around rapidly-rotating stars and to measure the spin-orbit misalignments of candidate and confirmed planets. Doppler tomography is one of the few techniques that can validate transiting planet candidates around rapidly rotating A and early F stars. Our program has already yielded results on some of the most extreme planets known, including the measurement of the spin-orbit misalignment of Kepler-13 Ab and the detection of the nodal precession of the hot Jupiter WASP-33 b. We present the latest results from this program, and highlight the potential for Doppler tomography to contribute to our knowledge of planet formation and migration and the planetary systems around massive stars.

Author(s): Marshall Johnson[1], William Cochran[1]
Institution(s): *1. University of Texas at Austin*

114.20 – KOI2138.01: First of the Intermediate-Period Spin-Orbit Aligned Super-Earths

The relative angle between a planet's orbital angular momentum vector and its parent star's rotational angular momentum vector -- the planet's spin-orbit alignment -- bears the fingerprint of the planet's origin and orbital evolution. We will show that a gravity-darkening determination of the spin-orbit alignment for KOI2138.01 shows alignment with its parent star. With a radius of 2.1 R_{Earth}, KOI2138.01 is only the second super-Earth with a measured spin-orbit alignment, after misaligned 55 Cancri e. Furthermore, with an orbital period of 23.55 days KOI2138.01 orbits beyond the influence of tides, implying that its observed alignment is likely primordial. KOI2138.01 may thus represent the tip of an iceberg of solar-system like terrestrial and super-terrestrial planets, with periods longer than 10 days orbiting near their stars' equatorial planes.

Author(s): Jason W Barnes[1], Jonathon Ahlers[1]
Institution(s): *1. University of Idaho*

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115 – Planet Formation and Interior Structure Modeling Poster Session

115.01 – The Physics of Planetesimal Formation

Planetesimals are the precursors to planets, and understanding their formation is an essential step towards developing a complete

theory of planet formation. For small solid particles (e.g., dust grains) to coagulate into planetesimals, however, requires that these particles grow beyond centimeter sizes; with traditional coagulation physics, this is very difficult. The streaming instability, which is a clumping process akin to the pile-up of cars in a traffic jam, generates sufficiently high solid densities that the mutual gravity between the clumped particles eventually causes their collapse towards planetesimal mass and size scales. Exploring this transition from dust grains to planetesimals is still in its infancy but is extremely important if we want to understand the basics of planet formation. Here, I present a series of high resolution, first principles numerical simulations of potoplanetary disk gas and dust to study the clumping of particles via the streaming instability and the subsequent collapse towards planetesimals. These simulations have been employed to characterize the planetesimal population as a function of radius in protoplanetary disks. The results of these simulations will be crucial for planet formation models to correctly explain the formation and configuration of solar systems.

Author(s): Jacob Simon[1], Philip Armitage[3], Andrew Youdin[2], Rixin Li[2]
Institution(s): *1. Southwest Research Institute (SwRI), 2. University of Arizona, 3. University of Colorado*

115.02 – The diversity of planetary system from formation/composition population synthesis models

Extrasolar planetary systems show an extreme diversity in mass and orbital architecture. Explaining this diversity is one of the key challenges for theoretical models and requires understanding the formation, composition and evolution of planetary systems from the stage of the protoplanetary disk up to the full mature planetary system. Such an effort needs the development of end-to-end, necessarily simplified, formation models used in a population synthesis approach. We present in this contribution such planetary system formation and composition models. Our planetary system formation models include the following effects: planetary growth by capture of solids and gas, protoplanetary disk structure and evolution, planet-planet and planet-disk interactions. In addition, we compute the composition of the solids and gas in the protoplanetary disk and their evolution with time. The formation and composition models allow therefore the determination of the composition of planets in terms of refractory elements (Mg, Si, Fe, etc...) as well as volatile compounds (water, CO_2, CO, NH_3, etc...), in a way that is self-consistent with the formation process of the different members of the planetary system. We will show the results of these formation/composition models, and will compare the diversity of observed and synthetic planetary systems. Considering the solar system, we will show how different formation scenarios translate into different planetary compositions. Finally, we will demonstrate how the simultaneous determination of mass and radius of a statistical number of warm to cold earth to neptune mass bodies at different ages can be used to constrain the composition (in particular the volatile content) of planets, and how the same observations (mass, radius, period) can be used in order to select planets that are best suited for follow-up habitability studies.

Author(s): Yann Alibert[1], amaury thiabaud[1], ulysses marboeuf[1], david swoboda[1], willy benz[1], klaus mezger[1], ingo leya[1]
Institution(s): *1. University of Bern*

115.03 – C/O and Snowline Locations in Protoplanetary Disks: The Effect of Radial Drift and Viscous Gas Accretion

The C/O ratio is a defining feature of both gas giant atmospheric and protoplanetary disk chemistry. In disks, the C/O ratio is regulated by the presence of snowlines of major volatiles at different distances from the central star. We explore the effect of radial drift of solids and viscous gas accretion onto the central star on the snowline locations of the main C and O carriers in a protoplanetary disk, H_2O, CO_2 and CO, and their consequences for the C/O ratio in gas and dust throughout the disk. We determine the snowline locations for a range of fixed initial particle sizes, in both an active and a passive disk. We find that grains with sizes ~0.5 cm < s < ~7 m for a passive disk and ~0.001 cm < s < ~7 m for an active disk desorb at a size-dependent location in the disk, which is independent of the particle's initial position. The snowline radius decreases for larger particles, up to sizes of ~7 m. Compared to a static disk, we find that radial drift and gas accretion move the H_2O and CO_2 snowlines inwards by up to 60 %, and the CO snowline by up to 50 %. We thus determine an inner limit on the snowline locations when radial drift and gas accretion are accounted for.

Author(s): Ana-Maria Piso[1]
Institution(s): *1. Harvard University*

115.04 – Looking at the cooler hosts - accurate metallicity determination of M dwarfs with and without planets

M dwarfs constitute 70% of the stars in the local Galaxy and are becoming attractive targets in the search for Earth-sized planets and planets within the habitable zone. With our research we aim to extend the current understanding of planet formation theory and explore the planet – host metallicity correlation for these cooler hosts.

Unlike their solar-type counterparts, the metallicity of M dwarfs is difficult to determine. Their low surface temperature results in plenty of diatomic and triatomic molecules in the photospheric layers. Especially in the optical wavelength region these molecules give rise to a forest of millions of weak lines, making accurate spectroscopy nearly impossible. Previous studies of M dwarfs have therefore established different metallicity calibrations using photometric colors or spectral indices. But these methods exclude the possibility of detailed chemical analysis. High-resolution spectrographs operating in the infrared have recently opened up a new window for investigating M dwarfs. In the infrared the number of molecular transitions is greatly reduced, allowing an accurate continuum placement, and a large number of unblended atomic lines are available. This enabled us to use similar methods as is standard for warmer solar-like stars, and determine the overall metallicity through synthetic spectral fitting.

In the first part of our work we used high-resolution spectra taken in the J band (1100-1400nm) with the CRIRES spectrograph, VLT, to verify our method internally and externally by analyzing both components in several M+FGK binaries. In the second part of this study we are analyzing 20 single M dwarfs to achieve a good coverage of effective temperature and metallicity, where our sample covers subtypes M0-M6 and estimated metallicites ranging from +0.8 to -0.8 dex. With these data we aim to derive the to-date most accurate relationship between photometric colors and metallicity for M dwarfs. We will present the current status of our work and give an overview of the future potential of high-resolution infrared spectroscopy for M dwarf planet hosts.

Author(s): Sara Lindgren[1], Ulrike Heiter[1]
Institution(s): *1. Department of Physics and Astronomy, Uppsala University*

115.05 – Terrestrial Planet Formation around Low-Mass Stars: Effect of the Mass of Central Stars

The Kepler space telescope has detected several thousand planets and candidates.
Their central stars are mainly FGK-type stars.
It is difficult to observe M-stars by using visible light since M-stars have their peak radiation in the infrared region.
However, recently there are several survey projects for planets around M-stars such as the InfraRed Doppler (IRD) survey of the Subaru telescope.
Therefore it is expected that the number of planets around M-stars will increase in the near future.
The habitable zone of M-stars is closer to the stars than that of G-stars.
For this reason, the possibility of finding habitable planets is expected to be higher.

Here we study the formation of close-in terrestrial planets by giant impacts of protoplanets around low-mass stars by using N-body simulations.
An important parameter that controls formation processes is the ratio between the physical radius of a planet and its Hill radius, which decreases with the stellar mass.
We systematically change the mass of the central stars and investigate its effects on terrestrial planet formation.
We find that the mass of the maximum planet decreases with the mass of central stars, while the number of planets in the system increases.
We also find that the orbital separation of adjacent planets normalized by their Hill radius increases with the stellar mass.

Author(s): Shoichi Oshino[1], Yuji Matsumoto[1], Eiichiro Kokubo[1]
Institution(s): *1. National Astronomical Observatory of Japan*

115.06 – Triggered fragmentation in self-gravitating discs: forming fragments at small radii

We perform three dimensional radiation hydrodynamical simulations to understand the formation and evolution of planets in young self-gravitating discs. We explore how the disc material responds to the presence of a planet by considering the movement of mass in it following its initial fragmentation. We find that the radial velocity of the gas in some parts of the disc increases by up to a factor of ≈10 after the disc fragments, compared to before. While the movement of mass occurs in both the inward and outward directions, the inwards movement can cause the inner spirals of a self-gravitating disc to become sufficiently dense such that they can fragment. We find that the formation of a fragment in the outer disc, and resulting dynamical disc behaviour, can potentially trigger the formation of a second fragment at smaller radii. This suggests that the dynamical behaviour of fragmented discs may cause subsequent fragmentation to occur at smaller radii than initially expected, but only *after* an initial fragment has formed in the outer disc.

Author(s): Farzana Meru[1]
Institution(s): *1. University of Cambridge*

115.07 – A Collisional Origin for the Coexistence of Volatile-Poor Super-Earths and Mini-Neptunes in the Proximity of Their Host Stars

The Kepler mission has revealed the prevalence of volatile-rich/poor low-mass planets in the proximity of host stars. Several post-formation processes have hitherto been proposed for explaining the origin of volatile inventory of those planets: a mass loss via a stellar XUV irradiation and Parker wind, degassing of accreted material, and in-situ accumulation of the disk gas. However, the compositional dissimilarity between neighboring planets on adjacent orbits such as Kepler-36 and Kepler-11 systems is puzzling for the three processes. We consider the possibility of a collisional origin for the coexistence of volatile-poor super-Earths and mini-Neptunes in a tightly-packed system.We performed three-dimensional hydrodynamic simulations of giant impacts on a super-Earth with a H/He atmosphere. A high-speed collision can strip off most of the original H/He atmosphere, as we expected. A hot and inflated planet after the giant impact cools down so slowly that a prolonged lifetime of the extended post-impact atmosphere enhances mass loss via a Parker wind and subsequent hydrodynamic escape driven by a stellar XUV irradiation. We also found that a low-speed head-on collision results in the appearance of a positive-compositional gradient deep inside the planet which leads to an inefficient heat transport via double-diffusive convection, whereas a high-speed one can homogenize a distribution of heavy elements above the core.

Author(s): Yasunori Hori[2], Shang-fei Liu3, Douglas NC Lin3, Eric Asphaug[1]
Institution(s): *1. Arizona State University, 2. National Astronomical Observatory of Japan, 3. University of California, Santa Cruz*

115.08 – Formation of Jupiter-mass planets from hydrodynamic simulations -- the role of the circumplanetary disk in the accretion process

In the era of observing young planetary systems with growing planets, it is necessary to study planet formation with numerical simulations to provide predictions for observations and also to update planet formation models. In this talk we are going to summarize a PhD thesis on the topic of accretion of giant planets with hydrodynamic simulations.
One of the main problems with the core accretion formation model is that it predicts a runaway growth phase for the giant planets at the last stages of the formation process, which would indicate a presence of an unseen population of super-giants. We performed isothermal and radiative hydrodynamic simulations in 3D on a Jupiter-mass planet in an MMSN disk to simulate the fastest part of the runaway growth for our Jupiter. This massive planet can form a circumplanetary disk around it, which can limit the accretion in this late stage of planet formation, and is the focus point of our study. We have found that the 90% of the accreted gas by the planet is coming from the vertical direction, from the top layers of the circumstellar disk falling through the planetary gap, in an inflow hitting the circumplanetary disk and directly the planet as well. We will show that this vertical influx is part of a feedback loop -- a meridional circulation -- between the circumstellar and circumplanetary disks.
We have also revisited the question of circumplanetary disk formation. Planets which are massive enough to open gaps (above ~Saturn's mass) were believed to form circumplanetary disk, while planets below this mass threshold were only capable to form an envelope. We will prove that the planetary surface temperature is also playing a large role in this question. We carried out a series of simulations with various planetary surface temperatures, and found that in the hottest case even a Jupiter-mass planet, which was capable to open a planetary gap, cannot form a circumplanetary disk, only an envelope, similarly to small mass planets. We will show the quantitative differences between the envelope and disk cases which have implications on the satellite formation and for the future observations of circumplanetary disks/envelopes around giant planets as well.

Author(s): Judit Szulagyi[1], Alessandro Morbidelli[1], Frederic Masset[2], Elena Lega[1], Aurelien Crida[1], Tristan Guillot[1]
Institution(s): *1. Observatoire de la Cote d'Azur, 2. Universidad Nacional Autónoma de México*

115.09 – Observations vs theory: from metallicity correlations of exoplanets and debris discs to HL Tau

Boley et al (2010) and Nayakshin (2010) proposed Tidal Downsizing (TD), a new hypothesis for forming all types of planets. Gas fragments born by gravitational disc instability at ~ 100 AU migrate inwards rapidly, with some becoming hot Jupiters. Grain sedimentation inside the fragments makes rocky cores. These cores are future Earths and Super Earths, leaved behind when most of the migrating fragments are tidally disrupted.

TD can now be tested against data in detail thanks to a numerical population synthesis model (Nayakshin and Fletcher 2015). TD scenario is fundamentally different from Core Accretion (CA), with sub-Saturn planets and debris discs born in gas fragment disruptions, and not vice versa. I therefore find robust observational differences between CA and TD despite uncertainties inherent in any population synthesis. Here I use metallicity correlations of all sorts to test the model. In TD, the only population that correlates with metallicity (Z) of the host strongly is that of moderately massive gas giants interior to a few AU from the host. Super-Earths and debris discs correlate in mass but not in numbers with Z; very massive gas giants, brown dwarfs and directly imaged gas giants are neutral to Z. Fragment self-destruction by core feedback explains simultaneously the core mass function roll-over at ~20 Earth masses, the rapid formation of suspected planets in HL Tau, and the paucity of directly imaged gas giants. Debris discs and gas giants do not correlate in TD, as observed.

I argue that TD does a better job in accounting for many of the observed properties of exoplanets and planetary debris than CA. I finish with observational predictions that can distinguish TD from Core Accretion in the near future.

Author(s): Sergei V Nayakshin[1]
Institution(s): *1. University of Leicester*

115.10 – Do C/O > 1 main-sequence stars build carbon planets?

The existence of rocky yet carbon-dominated planets is predicated on a C-dominated (rather than O-dominated) nebular birthplace. Planet-forming stars with unusually high C/O > 0.8 could provide such a favourable environment. Therefore the highest C/O ratios in potential host stars is of interest, as it has a direct impact on the frequency of C-dominated planetary systems.

Interestingly, C/O > 1 main-sequence stars are relatively common, and have distinctive optical spectra dominated by strong molecular carbon features. These dwarf carbon (dC) stars are even more numerous than carbon giants, but their origins may be fundamentally tied to binarity -- where the C/O ratio is increased by C-rich material accreted from an AGB star (now a white dwarf). We are undertaking a survey of dC stars to measure their binary fraction, and to ascertain if any C/O > 1 stars are single and thus favourable to C-rich planet formation.

We present first results from our ongoing search for radial velocity companions to dC stars. Multi-epoch observations of 22 systems show clear RV variability for > 70% of targets, suggesting that most, if not all, dC stars are in binary systems. The presence of a formerly more massive companion suggests their C/O > 1 is an enhancement via mass transfer, and not primordial. If correct, C/O > 1 stars may host oxygen-dominated (possibly circumbinary) planets, significantly reducing the Galactic real estate available for carbon planets.

Author(s): Carolina Bergfors[1], Jay Farihi[1]
Institution(s): *1. University College London*

115.11 – N-body simulations of planet formation: understanding exoplanet system architectures

Observations have demonstrated the existence of a significant population of compact systems comprised of super-Earths and Neptune-mass planets, and a population of gas giants that appear to occur primarily in either short-period (<10 days) or longer period (>100 days) orbits. The broad diversity of system architectures raises the question of whether or not the same formation processes operating in standard disc models can explain these planets, or if different scenarios are required instead to explain the widely differing architectures. To explore this issue, we present the results from a comprehensive suite of N-body simulations of planetary system formation that include the following physical processes: gravitational interactions and collisions between planetary embryos and planetesimals; type I and II migration; gas accretion onto planetary cores; self-consistent viscous disc evolution and disc removal through photo-evaporation. Our results indicate that the formation and survival of compact systems of super-Earths and Neptune-mass planets occur commonly in disc models where a simple prescription for the disc viscosity is assumed, but such models never lead to the formation and survival of gas giant planets due to migration into the star. Inspired in part by the ALMA observations of HL Tau, and by MHD simulations that display the formation of long-lived zonal flows, we have explored the consequences of assuming that the disc viscosity varies in both time and space. We find that the radial structuring of the disc leads to conditions in which systems of giant planets are able to form and survive. Furthermore, these giants generally occupy those regions of the mass-period diagram that are densely populated by the observed gas giants, suggesting that the planet traps generated by radial structuring of protoplanetary discs may be a necessary ingredient for forming giant planets.

Author(s): Gavin Coleman[1], Richard Nelson[1]
Institution(s): *1. Queen Mary University of London*

115.12 – Final Masses of Giant Planets II: Jupiter Formation in a Gas-Depleted Disk

Firstly, we study the final masses of giant planets growing in protoplanetary disks through capture of disk gas, by employing an empirical formula for the gas capture rate and a shallow disk gap model, which are both based on hydrodynamical simulations. The shallow disk gaps cannot terminate growth of giant planets. For planets less massive than 10 Jupiter masses, their growth rates are mainly controlled by the gas supply through the global disk accretion, rather than their gaps. The insufficient gas supply compared with the rapid gas capture causes a depletion of the gas surface density even at the outside of the gap, which can create an inner hole in the protoplanetary disk. Our model can also predict how deep the inner hole is for a given planet mass. Secondly, our findings are applied to the formation of our solar system. For the formation of Jupiter, a very low-mass gas disk with a few or several Jupiter masses is required at the beginning of its gas capture because of the non-stopping capture. Such a low-mass gas disk with sufficient solid material can be formed through viscous evolution from an initially ~10AU-sized compact disk with the solar composition. By the viscous evolution with a moderate viscosity of $\alpha \sim 10^{-3}$, most of disk gas accretes onto the sun and a widely spread low-mass gas disk remains when the solid core of Jupiter starts gas capture at $t \sim 10^7$ yrs. The depletion of the disk gas is suitable for explaining the high metallicity in giant planets of our solar system. A very low-mass gas disk also provides a plausible path where type I and II planetary migrations are both suppressed significantly. In particular, we also show that the type II migration of Jupiter-size planets becomes inefficient because of the additional gas depletion due to the rapid gas capture by themselves.

Author(s): Takayuki Tanigawa[2], Hidekazu Tanaka[1]
Institution(s): *1. ILTS, Hokkaido University, 2. UOEH*

115.13 – Planetesimal Formation through the Streaming Instability

The streaming instability is a promising mechanism to circumvent the barriers in direct dust growth and lead to the formation of planetesimals, as demonstrated by many previous studies. In order to resolve the thin layer of solids, however, most of these studies were focused on a local region of a protoplanetary disk with a limited simulation domain. It remains uncertain how the streaming instability is affected by the disk gas on large scales, and models that have sufficient dynamical range to capture both the thin particle layer and the large-scale disk dynamics are required.

We hereby systematically push the limits of the computational domain up to more than the gas scale height, and study the particle-gas interaction on large scales in the saturated state of the streaming instability and the initial mass function of the resulting planetesimals. To overcome the numerical challenges posed by this kind of models, we have developed a new technique to simultaneously relieve the stringent time step constraints due to small-sized particles and strong local solid concentrations. Using these models, we demonstrate that the streaming instability can drive multiple radial, filamentary concentrations of solids, implying that planetesimals are born in well separated belt-like structures. We also find that the initial mass function of planetesimals via the streaming instability has a characteristic exponential form, which is robust against computational domain as well as resolution. These findings will help us further constrain the cosmochemical history of the Solar system as well as the planet formation theory in general.

Author(s): Chao-Chin Yang[1], Anders Johansen[1], Urs Schäfer[1]
Institution(s): *1. Lund University*

115.14 – Pebble Accretion Rates for Planetesimals: Hydrodynamics Calculations with Direct Particle Integration

The formation and growth of planetesimals are fundamental to planet building. However, in our understanding of planet formation, there are a number of processes that limit the formation of planetesimals such as particle bouncing, fragmentation, and inward radial drift due to gas drag. Such processes seemingly make growth beyond mm to cm sizes difficult. In this case, the protoplanetary disk may become rich in pebble-sized solids as opposed to km-sized planetesimals. If a small number of large planetesimals do manage to form, then gas-drag effects can allow those seeds to efficiently accrete the abundant pebbles from the nebula and grow to planet sizes. We present self-consistent hydrodynamic simulations with direct particle integration and gas-drag coupling to evaluate the rate of planetesimal growth due to pebble accretion. We explore a range of particle sizes and nebular conditions using wind tunnel numerical experiments.

Author(s): Anna Hughes[1], Aaron Boley[1]
Institution(s): *1. University of British Columbia*

115.15 – The Effect of Giant Planets on Terrestrial Planet Formation

The giant planets in the Solar System likely played a defining role in shaping the properties of the Earth and other terrestrial planets during their formation. Observations from the Kepler spacecraft indicate that terrestrial planets are highly abundant. However, there are hints that giant planets a few AU from their stars are relatively uncommon based on long baseline radial velocity searches. It therefore seems reasonable to assume that many terrestrial planets lack a Jupiter-like companion. We use a recently developed, state-of-the-art N-body model that allows for collisional fragmentation to perform hundreds of numerical simulations of the final stages of terrestrial planet formation around a Sun-like star -- with and without giant outer planets. We quantify the effects that outer giant planet companions have on collisions and the planet accretion process. We focus on Earth-analogs that form in each system and explore how giant planets influence the relative frequency of giant impacts occurring at late times.

Author(s): Thomas Barclay[1], Elisa Quintana[1]
Institution(s): *1. NASA Ames Research Center*

115.17 – A Moderate Migration Scenario to form the Terrestrial Planets

The early solar system contained a gas-dominated protoplanetary disk that could cause the migration of the giant planets. This migration can be in the form of a two-stage migration, including an inward and then outward migration. One of the current favored theories, the Grand Tack theory, states that Jupiter migrates in to 1.5 AU, creating a planetesimal disk truncated at 1 AU to then form the terrestrial planets during the subsequent outward migration of Jupiter. There are reasons to believe that such a large movement by Jupiter may be impractical, namely the disk would need to be massive and long-lived. An exploration of migration parameters that involve smaller migration distances and shorter timescales can shed light on whether such extreme displacements are necessary for the formation of the solar system. We examine more moderate migration simulations, where Jupiter starts near the conjectured location of the ice line and migrates a moderate radial distance inward for a variety of distances and times. After the inward migration, Jupiter moves outwards to its final orbital configuration today. We find that the planetesimal disk need not be truncated at 1 AU to form planets with similar characteristics to those in the solar system. We vary the number and mass of planetesimals in the disk to see how this affects the characteristics of the forming terrestrial planets. We find a number of scenarios that provide systems of terrestrial planets similar to those in the solar system. We thus propose an alternative to the Grand Tack theory where Jupiter's migration is less extreme than proposed in the Grand Tack theory.

Author(s): Zoe Robin Todd[1], Steinn Sigurdsson[2]
Institution(s): *1. Harvard University, 2. Pennsylvania State University*

115.18 – Calculating Internal Structure and Mass-Radius Relationships of Rocky Exoplanets

We present a code (ExoPlex) we have written to calculate the internal structures and mass-radius relationships of rocky exoplanets. Existing codes described in the literature consider only a limited range of compositions for the core and mantle, and they generally assume that mineral phases are always present as a single high-pressure polymorph. These restrictions arise from the need to specify material properties, such as bulk modulus, at every depth in the planet, which requires knowledge of the phases present. Existing codes also neglect the effects of temperature on material properties, assuming values attained in the low-temperature limit. Our code circumvents these problems. We specify a stoichiometry for the core and for the mantle, we find the pressure at depth by integrating the equation of hydrostatic equilibrium, and we assume adiabatic temperature gradients in the mantle and in the core. We then supply pressure, temperature, and composition as inputs to the PerpleX software package that calculates the mineral phases present in thermodynamic equilibrium, and their material properties. This allows us to explore mass-radius relationships across a wide range of compositional and mineralogical parameter space. We discuss preliminary results.

Author(s): Steve Desch[1], Alejandro Lorenzo[1], Byeongkwan Ko[1]
Institution(s): *1. Arizona State University*

115.19 – The Metallicity of Giant Planets

Unique clues about the formation processes of giant planets can be found in their bulk compositions. Transiting planets provide us with bulk density determinations that can then be compared to models of planetary structure and evolution, to deduce planet bulk metallicities. At a given mass, denser planets have a higher mass fraction of metals. However, the unknown hot Jupiter "radius inflation" mechanism leads to under-dense planets that severely biases this work. Here we look at cooler transiting gas giants (Teff < 1000 K), which do not exhibit the radius inflation effect seen in their warmer cousins. We identified 40 such planets between 20 M_Earth and 20 M_Jup from the literature and used evolution models to determine their bulk heavy-element ("metal") mass. Several important trends are apparent. We see that all planets have at least ~10 M_Earth of metals, and that the mass of metal correlates strongly with the total mass of the planet. The heavy-element mass goes as the square root of the total mass. Both findings are consistent with the core accretion model. We also examined the effect of the parent star metallicity [Fe/H], finding that planets around high-metallicity stars are more likely to have large amounts of metal, but the relation appears weaker than previous studies with smaller sample sizes had suggested. We also looked for connections between bulk composition and planetary orbital parameters and stellar parameters, but saw no pattern, which is also an important result. This work can be directly compared to current and future outputs from planet formation models, including population synthesis.

Author(s): Daniel P Thorngren[1], Jonathan Fortney[1]
Institution(s): *1. UC Santa Cruz*

115.20 – Probing the Conductivity, Composition, and Differentiation of Ultra-short-period Super-Earths with Magnetized Host Stars.

The omnipresence of super Earths around nearby stars stimulates the quest to characterize their internal structure. In addition to the average density and atmospheric composition, we show that the mantle conductivity and composition can be determined for a class of short- period super Earths which magnetically interact with their host stars. As an example, we analyze the observed properties of Kepler-78b to place limits on its Ohmic dissipation rate and to estimate the electric conductivity in its mantle. We show that its surface is primarily composed of molten/condensed rock on the day/night sides and its iron may have differentiated to its core.

Author(s): Douglas NC Lin[1]
Institution(s): *1. University of California, Santa Cruz*

116 – Planets around Compact Objects Poster

Session

116.01 – A new evolved planetary system with water-rich debris: the tip of the iceberg?

The detection of metals in white dwarf atmospheres, with a composition resembling that of Solar system asteroids, is unmistakable evidence for recent or ongoing accretion of planetary debris. We present the spectral analysis of SDSS J1242+5226, which is one of the most heavily metal-polluted white dwarfs. We detect atmospheric traces of hydrogen and eight metals, notably including oxygen. The chemical signature exhibited by the metal abundances matches the building blocks of formed planets. The excess of oxygen with respect to other trace metals, and the large hydrogen mass that we measure, suggest the likely accretion of water-rich exo-planetary debris, making this star the second of its kind. Accumulation of hydrogen with increasing cooling age, in this and other white dwarfs, exceeds the equivalent content in water-ice and hydrated minerals within the Solar system asteroid Ceres. This evidence suggests that water-rich asteroids may be common around other stars.

Author(s): Roberto Raddi[1]
Institution(s): *1. University of Warwick*

116.02 – C/O ratios in extrasolar planetesimals

The wide range of densities found in small exoplanets imply a variety of possible compositions and interior structures. In particular, some models predict that protoplanetary discs with C/O>0.8 may form carbon-dominated planets. The only way to directly test such predictions are studies of evolved planetary systems at white dwarfs. Analysis of planetesimal debris in white dwarf atmospheres provides a unique insight into the chemical compositions of extrasolar planets, which cannot be observed at main-sequence systems. Thus far, such studies have predominantly focused on individual objects. However, the growing sample of abundance studies now allows conclusions to be derived regarding the overall chemical abundances of (solid) exoplanet precursors in a statistically significant sample of systems. Here, we present measurements of the C/O ratio in the debris of planetesimals at 16 white dwarfs observed with the Hubble Space Telescope. These data allow us to constrain the occurrence frequency of carbon-dominated planets. We find no evidence for such carbon planets, with C/O<0.8 by number in all 16 systems.

Author(s): David John Wilson[3], Boris Gaensicke[3], Jay Farihi[1], Detlev Koester[2]
Institution(s): *1. University College London, 2. University of Kiel, 3. University of Warwick*

116.03 – Substellar companions to sdB stars

I will present the updated status of an ongoing program with Harps-N@TNG, aimed at detecting new substellar companions to sdB stars in close/ intermediate orbits (0.1 d <~ P <~ 100 d) with masses down to ~30 M_Earth. Moreover I will present the situation of the sdB pulsator V391Peg and its putative planet when 6 more years of photometric data are considered.

Author(s): Roberto Silvotti[1]
Institution(s): *1. INAF*

116.04 – A Search for Rocky Planets in Close Orbits around White Dwarfs

The search for transiting habitable exoplanets has broadened to include several types of stars that are smaller than the Sun in order to increase the observed transit depth and hence the atmospheric signal of the planet. Of all current spectral types, white dwarfs are the most favorable for this type of investigation. The fraction of white dwarfs that possess close-in rocky planets is unknown, but several large angle surveys of stars have the photometric precision and cadence to discover at least one if they are common. Ultraviolet observations of white dwarfs may allow for detection of molecular oxygen or ozone in the atmosphere of a terrestrial planet. We use archival Hubble Space Telescope data from the Cosmic Origins Spectrograph to search for transiting rocky planets around UV-bright white dwarfs. In the process, we discovered unusual variability in the pulsating white dwarf GD~133, which shows slow sinusoidal variations in the UV. While we detect no planets around our small sample of targets, we do place stringent limits on the possibility of transiting planets, down to sub-lunar radii. We also point out that non-transiting small planets in thermal equilibrium are detectable around hotter white dwarfs through infrared excesses, and identify two candidates.

Author(s): John Debes[1], Phoebe Sandhaus[1], Justin Ely[1]
Institution(s): *1. Space Telescope Science Institute*

116.07 – The first velocity space image of a planetary debris disc orbiting a white dwarf

Since the first ESS meeting, dusty debris discs at white dwarfs have been firmly established as signposts of evolved planetary systems. We have identified a small number of systems where the circumstellar dust is accompanied by gas. The emission lines from these gaseous components are tracers of dynamic activity in these remnant planetary environments, and provide unparalleled insight into the formation and evolution of the debris discs, and into the properties of the parent planetesimals.

Here we present the twelve years of spectroscopy of the prototypical gas disc at SDSS J1228+1040, revealing a spectacular long-term evolution in the morphology of the emission line profiles. Using Doppler tomography, we constructed an image of the gaseous disc in velocity space, and show that the observations are consistent with the precession of a fixed intensity pattern on a period of 27 ± 3 years. We speculate that the underlying cause of this dynamical activity is either a young, not fully circularised disc, or a perturbation of a previously stable and quiescent disc.

Author(s): Christopher James Manser[1]
Institution(s): *1. University of Warwick*

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117 – Planets in and around Binary Stars Poster Session

117.01 – Planets or Pretense?: The Search for Substellar Objects around Post Common Envelope Binaries

Many believe post-common envelope binary systems (PCEBs), consisting of a white dwarf and a close main-sequence companion, host a unique class of planetary system. Given the well known age and history of the host binary stars, these systems have the potential to provide new insights into the evolution of planetary systems. However, the existence of the planets should be treated with some skepticism as their presence has so far been inferred only by the indirect method of eclipse timing variations. This method has proved somewhat flawed, as many of the claimed planetary systems have been found dynamically unstable, and others have dramatically failed when confronted with more recent high-precision times. It is therefore of the utmost importance that complementary observations be performed to test the planetary hypothesis, and we have recently performed two such pioneering observations:
1. We use SPHERE on the VLT to image the PCEB V471 Tau. A circumbinary companion to this PCEB has been predicted for more than 30 years with eclipse timings, but only recently has a direct detection become technically possible.
2. We use ALMA to search for dusty material around the young PCEB NN Ser. The planetary model for NN Ser is one of the most convincing, and these planets would likely be present alongside considerable dusty material, now detectable thanks to the sensitivity of ALMA.
I will present the results of these two important observations and discuss their far-reaching implications for the existence and charactistics of planetary systems around PCEBs.

Author(s): Adam Hardy[1], Matthias R. Schreiber[1], Steven Parsons[1], Claudio Caceres[1], Hector Canovas[1]
Institution(s): *1. Universidad de Valparaiso*

117.02 – Planets around post-common envelope binaries

The timing method enables to search planets in extreme conditions, e.g. as companion to pulsars or as planets in post-common envelope binaries (PCEB). In both cases, the planetary systems have experience a dramatic evolution of the primary star.

Eclipse time variations in PCEBs with white dwarfs and subdwarf-B stars as primaries have been interpreted as signatures from circumbinary planets and planetary systems. Several of these interpretations have been questioned later on, either due to dynamical instability of the proposed planetary systems or due to non-detection of the proposed companions. We will give an overview of our long-term monitoring of PCEB systems and the modelling in terms of Keplerian and Newtonian planetary orbits in order to assess the circumbinary planet scenario for these systems. We discuss the implications for the first-generation or second-generatoin planet scenario for these potential planets around these evolved stars.

Author(s): Stefan Dreizler[1], Klaus Beuermann[1], Frederic Hessman[1], Tim-Oliver Husser[1]
Institution(s): *1. University Goettingen*

117.03 – New Evidence for Planets on S-type Orbits in Close Binary Systems

We present evidence for two Jovian planets orbiting the evolved giant stars 39 Cygni and HR 2877, based on more than 10 years of high-precision Doppler data taken at the Lick Observatory. Both stars are the primary components of compact binary systems, and thus these systems provide important clues on how planets could form and remain stable in S-type orbit around a star under the strong gravitational influence from a close stellar companion. We investigate large sets of orbital fits for both systems by applying systematic χ^2
grid-search techniques coupled with self-consistent dynamical fitting. We also perform long-term dynamical simulations to constrain the permitted orbital configurations. We find that 39 Cygni is accompanied
by a low-mass star having nearly circular orbit at a_B > 7.5 AU. The planet orbiting the primary is well separated ($a_b \sim$ 1.6 AU) from the secondary and thus the system is generally stable. HR 2877 has a
stellar companion of at least $0.6 M_\odot$ on a highly eccentric orbit with $e_b \sim$ 0.7. The binary semimajor axis is $a_B \sim$ 13.6 AU, but the pericentre distance is only 3.7 AU leading to strong
interactions with the planet, which is at $a_b \sim$ 1.1 AU. If the binary and the planet in this system have prograde and aligned coplanar orbits, there are only narrow regions of stable orbital solutions. For this system we also test dynamical models with the planet having a retrograde orbit, and we find that in this case the system is fully stable in a large set of orbital solutions. Only a handful of S-type planetary candidates in compact binary systems are known in the literature, and the 39 Cygni and HR 2877 systems are significant additions to the sample.

Author(s): Trifon Trifonov[2], Man Hoi Lee[2], Sabine Reffert[1], Andreas Quirrenbach[1]
Institution(s): *1. Landessternwarte, Zentrum für Astronomie der Universität Heidelberg, 2. The University of Hong Kong*

117.04 – No circumbinary planets transiting the short-period Kepler binaries --- a possible fingerprint of a third star

The Kepler mission has yielded the discovery of eight circumbinary systems, all found around eclipsing binaries with periods greater than 7 d. This is longer than the typical eclipsing binary period found by Kepler, indicating a dearth of planets around the closest binaries. In this paper we suggest that this dearth may be explained by the presence of a distant stellar tertiary companion for all or most short-period binaries, which shrunk the inner binary orbit by the process of Kozai cycles and tidal friction. Such a mechanism has been implicated for producing most binaries with periods below 7 d. We show that the geometry and orbital dynamics of these evolving triple-star systems are highly restrictive for a circumbinary planet, which is subject itself to Kozai modulation, on one hand, and can shield the two inner stars from their Kozai cycle and subsequent shrinking, on the other hand. Only small planets on wide and inclined orbits may form, survive and allow for the inner binary shrinkage. Those are difficult to detect.

Author(s): Tsevi Mazeh[1], David Martin3, Daniel Clark Fabrycky[2]
Institution(s): *1. Tel Aviv University, 2. University of Chicago, 3. University of Geneva*

117.05 – Proxima Centauri's Influence on Planet Formation in Alpha Centauri

It is likely that the nearby M dwarf Proxima Centauri is in a loosely bound orbit around the Alpha Centauri binary and that the system formed as a more tightly-bound triple but evolved to its current state. We quantify how this evolution would have affected the protoplanetary disks around the stars, and characterize the size and location of planets that may be found there. These three stars are our closest neighbors, and thus present an excellent opportunity for detailed observations of any planets they may harbor, so it is particularly important to understand this system as thoroughly as possible. In addition, it gives us additional insight into planet formation in multistellar systems, which contain a large fraction of potential planet host stars.

Author(s): Rachel J Worth[1], Steinn Sigurdsson[1]
Institution(s): *1. The Pennsylvania State University*

117.06 – The Impact of Self-Gravity on Planet and Disc Evolution in the Kepler-16, 34 and 35 Circumbinary Systems

We present results from 2D hydrodynamic simulations of circumbinary discs, and the evolution of embedded planetary cores, with application to the Kepler-16, 34 and 35 systems. These cover a range of binary mass and orbital properties, but all share a common planetary architecture, with the planet lying close to the critical stability limit. This position also lies in the vicinity of the theoretical disc cavity edge created through tidal interaction with the host binary. Understanding what affects the evolution of the circumbinary disc is vital to explaining the final orbital configuration; we have undertaken simulations examining the role of the inner disc boundary conditions as well as the impact of self-gravity. Planetary cores are inserted into these evolved discs, simulating cores that have formed in the outer disc and migrated inwards, with the aim of recreating the observed Kepler circumbinary planetary systems. The choice of inner boundary condition has a clear impact on the disc structure and the evolution of protoplanetary cores. We find significant structure in massive self-gravitating discs, suggesting that younger circumbinary discs could be hostile environments for planetary formation and migration, out to larger radii than previously found.

Author(s): Matthew M Mutter[1], Arnaud Pierens[2], Richard Nelson[1]
Institution(s): *1. Queen Mary University of London, 2. Université de Bordeaux*

117.07 – Constraints on the frequency of circumbinary planets in wide orbits

In the past decade, an increasing amount of effort has been spent on studying the formation and evolution of planets in the environment of binary host star systems (see e.g. the book “Planets in Binaries”, Haghighipour 2010). The Exoplanets.org database (Wright et al. 2011) lists several confirmed planets that have been found in binary systems to date. All of these discoveries have been made with indirect detection methods such as Doppler

spectroscopy or transit photometry methods, which are heavily biased towards planets with short orbital periods and, therefore, favor circumstellar ('s-type') configurations around individual components of wide binary systems. Despite this bias, the Kepler spacecraft has discovered seven planets in circumbinary ('p-type') orbits encompassing tight binary systems, hinting at the existence of an extensive unseen population of circumbinary planets.
Direct imaging, on the other hand, is a powerful planet detection technique particularly well suited to planets on wide orbits, which complements the limited parameter space of the indirect detection methods. However, such surveys have typically rejected binary systems from their target sample, leaving the population of wide-orbit planets in such systems largely unexplored. To address this, the SPOTS project (Search for Planets Orbiting Two Stars; Thalmann et al. 2014) is conducting the first dedicated direct imaging survey for circumbinary planets.
In this talk I will present the results of a statistical analysis of the combined body of existing high contrast imaging constraints on circumbinary planets carried on to complement the results of our ongoing survey.

Author(s): Mariangela Bonavita[5], Christian Thalmann[3], Silvano Desidera[4], Arthur Vigan[1], Gael Chauvin[2], Beth Biller[5]
Institution(s): *1. Aix Marseille Université, 2. Institut de Planétologie et d'Astrophysique de Grenoble, UJF, CNRS, 3. Institute for Astronomy - ETH , 4. Osservatorio Astronomico di Padova - INAF, 5. University of Edinburgh*

117.08 – Stellar Multiples Among the KOIs

We examine high-resolution follow-up imaging data for 84 KOIs with stellar companions detected within 2". These stars were observed in the optical using speckle interferometry (Gemini/DSSI or WIYN/DSSI) and/or in the near-infrared with adaptive optics imaging (Keck/NIRC2, Palomar/PHARO, or Lick/IRCAL), and all have imaging results in at least two filters. Their companions are all unresolved in the Kepler images, and fall on the same pixel of the Kepler detector; thus the planet radii calculated for planet candidates in these systems are subject to upward revision due to contamination of the target star's light by the stellar companion. We calculate updated planet radii for these 84 planet candidates, assuming the planet orbits the brighter of the two stars. We also use isochrone models and distance estimates to assess the likelihood that the companion is bound. This analysis complements galaxy models that determine the probability of a chance alignment of a background star for each system (Everett et al., in prep.). Together, these data allow us to isolate a sub-population of Kepler planets and planet candidates that reside in physical binary systems, for comparison to the wider Kepler planet population.

Author(s): Lea Alyse Hirsch[6], Mark Everett[4], David Ciardi[2], Elise Furlan[2], Elliott Horch[5], Steve Howell[3], Johanna Teske[1], Geoffrey W. Marcy[6]
Institution(s): *1. Carnegie Institution for Science, 2. IPAC, 3. NASA Ames, 4. NOAO, 5. Southern Connecticut State University, 6. UC Berkeley*

117.09 – A triple origin for the lack of tight coplanar circumbinary planets around short-period binaries

Detection of transiting circumbinary planets is more tractable around short-period binaries. However, sofar, no such binaries have been found with orbits shorter than 7 days. Short-period main sequence binaries have been suggested to form in triple systems, through a combination of secular Kozai-Lidov cycles and tidal friction (KLCTF). Here, we show that coplanar circumbinary transiting planets are unlikely to exist around short-period binaries, due to triple evolution. We use secular analysis, N-body simulations and analytic considerations as well as population synthesis models to characterize their overall properties. We find that the existence of a circumbinary planet in a triple is likely to produce one of the following outcomes. (1) Sufficiently massive planets in tight and/or coplanar orbits around the inner binary can partially or completely quench the KL evolution, `shielding' the inner binary from the secular effects of the tertiary, and not allowing the KLCTF process to take place. In this case, the inner binary will not shrink to become a short-period binary. (2) KL evolution is not quenched and it drives the planetary orbit into high eccentricities, giving rise to an unstable configuration, in which the planet is most likely ejected from the system. (3) KL evolution is not quenched, but the planet survives the KLCTF evolution and the formation of the short-period binary; the planet orbit is likely to be much wider than the currently observed inner binary orbit, and is likely to be inclined in respect to the binary orbit, as well as eccentric. These outcomes lead to two main conclusions: (1) it is unlikely to find a (massive) planet on a tight and coplanar orbit around a short-period main-sequence binary, and (2) the frequency, masses and orbits of non-coplanar circumbinary planets in short-period binaries are constrained by their secular evolution.

Author(s): Adrian Hamers[2], Hagai B Perets[1], Simon Portegies Zwart[2]
Institution(s): *1. Israel Institute of Technology, 2. Leiden University*

117.10 – Discovery of Low Mass Binary with Super Jupiter Companion

Transit and radial velocity surveys have been prolific in detecting ~2000 confirmed planets to date. While few directly imaged planets have detected, such systems provide a unique scientific opportunity to probe exoplanets at larger angular separation, younger ages, and study their atmospheres. We present new L- and M-band AO observations, obtained with IRCS on Subaru, of a super Jupiter companion orbiting a cool dwarf. We show that the central object is likely a binary, thereby making this system the first likely directly imaged planetary mass companion surrounding a low mass binary system.

Author(s): Evan Anthes Rich[4], John P Wisniewski[4], Jun Hashimoto[4], Timothy Brandt[2], Masayuki Kuzuhara[3], Motohide Tamura[1]
Institution(s): *1. National Astronomical Observatory of Japan, 2. Tohoku University, 3. Tokyo Institute of Technology, 4. University of Oklahoma*

117.11 – Formation and Evolution of Circumbinary Planets, and the Apparent Lack of CPBs Around Short-Period Binaries

The success of the *Kepler* space telescope in detecting planets in circumbinary orbits strongly suggests that planet formation around binary stars is robust and planets of a variety of sizes and orbital configurations may exist in such complex environments. Accurate modeling of *Kepler* data has also indicated that some of these planets orbit their central binaries in close proximity to the boundary of orbital stability. This finding, combined with the unsuccessful attempts in forming circumbinary planets (CBPs) close to the orbital stability limit has lent strong support to the idea that almost all currently known CBPs have formed at large distances and undergone substantial radial migration. A survey of the currently known CBPs further indicates that these planets are mainly Neptune-mass and there seems to be a lack of planets of Jupiter-mass or larger in P-type orbits. Furthermore, an examination of the observational data obtained by the *Kepler* telescope seems to suggest an absence of CBPs around short-period binaries. Finally, recent detections of episodic transits in the two newly discovered circumbinary systems, Kepler 413b and Kepler 453b, as well as the discovery of *Kepler* non-transiting CBPs, (please see the abstract by Fabrycky et al) have indicated that in general, the orbits of planets and their host binaries are not co-planar. We present a new model for the formation and evolution of CBPs in which the migration of CBPs has been studied for low and high eccentricity binaries, and for different values of binary period. Results of our extensive hydrodynamical simulations show that planet-disk interaction in low-eccentricity binaries can account for the migration of CBPs and the proximity of their final orbits to the boundary of stability. In eccentric binaries, the situation is, however, more complex and in order to explain the final orbital architecture of the system, other factors such as planet-planet interaction have to be taken into account. We show that planet-

planet interaction can also explain the existence of non-transiting CBPs. Results of our simulations using binaries with different orbital periods indicate that the stoppage of planet migration around short-period binaries is not as efficient as that around binaries with larger separations implying that CBPs around short period binaries might have collided with their host binaries.

Author(s): Nader Haghighipour[1]
Institution(s): *1. University of Hawaii-Manoa*

117.12 – Stability of habitable exomoons of circumbinary planets

Among the currently known Kepler circumbinary planets, three, namely Kepler-453b, Kepler-16b, and Kepler-47c are in the binary habitable zone (HZ). Given the large sizes of these planets, it is unlikely that they would be habitable. However, similar to the giant planets in our solar system, these planets may have large moons, which orbit their host planets while in the HZ. These exomoons, if exist, present viable candidates for habitability. As a condition for habitability, the planet-moon system has to maintain its orbital stability for long time. Usually, the empirical formula by Holeman & Wiegert (1999) is used as a measure of orbital stability in circumbinary systems. However, this formula was obtained by assuming planets to be test particles and therefore does not include possible perturbation of the planet on the binary. In this work, we present results of more realistic calculations of stability of circumbinary planets where the interactions between planets and their central binaries are taken into account. We map the region of stability, which in this case will be specific to each system, and determine the range of the orbital parameters of the moons for which their orbits will be long-term stable.

Author(s): Suman Satyal3, Nader Haghighipour[1], Billy Quarles[2]
Institution(s): *1. University of Hawaii-Manoa, 2. University of Nebraska Kearney, 3. University of Texas at Arlington*

117.13 – A Measure of Stellar Binarity Among Kepler Target Stars

The dynamical interactions between stars in binary systems create a complex environment for planet formation and evolution. The Kepler mission offers an opportunity to compare binary stars with, and without, detections of inner transiting exoplanets. Kepler stars with no planet detections can act as a control sample in an effort to discover if inner planet formation in binary systems is a rare occurrence. We build a control sample of ~700 serendipitously observed targets from Robo-AO images of Kepler Objects of Interest (KOIs), while also targeting a specific control dataset with parameters matched to an initial dataset of ~300 KOIs. We find that the binary fraction of KOIs, and the control sample with no detected planets, match to within 1-σ. Our findings do not suggest that inner transiting exoplanets are rare in binary systems for this sample.

Author(s): Larissa Nofi[2], Christoph Baranec[2], Andrew Howard[2], Reed Riddle[1], Nicholas Law3, Carl Ziegler3
Institution(s): *1. California Institute of Technology, 2. University of Hawaii, 3. University of North Carolina at Chapel Hill*

118 – Population Statistics and Mass-Radius Relations Poster Session

118.01 – Extremes of Population Estimated from Kepler Observations

The extremes of exoplanet population (0.5 to 16 Earth radii, 0.5 to 512 days period) are estimated from Kepler observations by comparing the observed numbers of planets at each radius and period against a simulation that accounts for the probability of transit and the estimated instrument sensitivity. By assuming that the population can be modeled as a function of period times a function of radius, and further assuming that these functions are broken power laws, sufficient leverage is gained such that the well-measured short-period extreme of the planet distribution can effectively be used as a template for the less-well sampled long-period extreme. The resulting population distribution over this full range of radius and period provides a challenge to models of the origin and evolution of planetary systems.

Author(s): Wesley A Traub[1]
Institution(s): *1. Jet Propulsion Laboratory*

118.02 – The Starchive: An open access, open source archive of nearby and young stars and their planets

Historically, astronomers have utilized a piecemeal set of archives such as SIMBAD, the Washington Double Star Catalog, various exoplanet encyclopedias and electronic tables from the literature to cobble together stellar and exo-planetary parameters in the absence of corresponding images and spectra. As the search for planets around young stars through direct imaging, transits and infrared/optical radial velocity surveys blossoms, there is a void in the available set of to create comprehensive lists of the stellar parameters of nearby stars especially for important parameters such as metallicity and stellar activity indicators. For direct imaging surveys, we need better resources for downloading existing high contrast images to help confirm new discoveries and find ideal target stars. Once we have discovered new planets, we need a uniform database of stellar and planetary parameters from which to look for correlations to better understand the formation and evolution of these systems. As a solution to these issues, we are developing the Starchive - an open access stellar archive in the spirit of the open exoplanet catalog, the Kepler Community Follow-up Program and many others. The archive will allow users to download various datasets, upload new images, spectra and metadata and will contain multiple plotting tools to use in presentations and data interpretations. While we will highly regulate and constantly validate the data being placed into our archive the open nature of its design is intended to allow the database to be expanded efficiently and have a level of versatility which is necessary in today's fast moving, big data community. Finally, the front-end scripts will be placed on github and users will be encouraged to contribute new plotting tools. Here, I will introduce the community to the content and expected capabilities of the archive and query the audience for community feedback.

Author(s): Angelle Tanner[2], Chris Gelino[1], Mario Elfeki [2]
Institution(s): *1. IPAC, 2. Mississippi State University*

118.03 – Searching for variations in planet populations over time

Simulations predict that exoplanets are often engulfed by their host star or ejected from multiple planet systems due to planet-planet scattering. Planet-loss events are more common in the few millions of years immediately after formation, but are expected to continue over billion-year timescales. In addition, planet migration models predict that old stars host hot Jupiters more commonly than young stars. Both of these effects will be observable with Kepler, K2 and TESS data, provided we can constrain stellar ages with enough precision. Recent developments in our understanding of the age-rotation relations allow us to, for the first time, search for trends in the number of planets per star, and the rate of hot Jupiters, as a function of host star age in the Kepler and K2 data. Additionally, we will compare planet populations in different K2 fields, hoping to gain further understanding of the impact of stellar age on the structure of planetary systems. I will describe exactly how we can exploit the enormously rich data sets provided by Kepler, K2 and TESS to detect trends in the exoplanet population over time.

Author(s): Ruth Angus[1]
Institution(s): *1. University of Oxford*

118.05 – Architectures of Kepler Planet Systems with Approximate Bayesian Computation

The distribution of period normalized transit duration ratios among Kepler's multiple transiting planet systems constrains the distributions of mutual orbital inclinations and orbital eccentricities. However, degeneracies in these parameters tied to the underlying number of planets in these systems complicate their interpretation. To untangle the true architecture of planet systems, the mutual inclination, eccentricity, and underlying planet number distributions must be considered simultaneously. The complexities of target selection, transit probability, detection biases, vetting, and follow-up observations make it impractical to write an explicit likelihood function. Approximate Bayesian computation (ABC) offers an intriguing path forward. In its simplest form, ABC generates a sample of trial population parameters from a prior distribution to produce synthetic datasets via a physically-motivated forward model. Samples are then accepted or rejected based on how close they come to reproducing the actual observed dataset to some tolerance. The accepted samples form a robust and useful approximation of the true posterior distribution of the underlying population parameters. We build on the considerable progress from the field of statistics to develop sequential algorithms for performing ABC in an efficient and flexible manner. We demonstrate the utility of ABC in exoplanet populations and present new constraints on the distributions of mutual orbital inclinations, eccentricities, and the relative number of short-period planets per star. We conclude with a discussion of the implications for other planet occurrence rate calculations, such as eta-Earth.

Author(s): Robert C Morehead[1], Eric B Ford[1]
Institution(s): *1. The Pennsylvania State University*

118.06 – The Metallicities of the Closest M-dwarfs, the Optimal Hosts for Terrestrial Exoplanets

Characterizing terrestrial exoplanets and their atmospheres requires finding the planetary systems for which the host star is both small (to increase the signal size) and close (to increase the photon count rate). Effectively, this means that the mid-to-late M dwarfs within 20 parsecs of the Sun are the best targets. There is an ongoing debate on whether the probability that a star hosts a small planet is correlated with its metallicity. This question is particularly acute for the lowest mass stars where total disk mass and metal content is much lower. Recent spectroscopic work has identified metallicity calibrations in the near-infrared; however, gathering such a spectrum for every M dwarf within 20 parsecs in infeasible. Previous attempts at calibrating photometric metallicity relations have been limited by two factors: the lack of parallax distance measurements and accurate optical magnitudes. Here we present results from the MEarth Project addressing both issues. We measured the trigonometric parallaxes of northern, nearby mid-to-late M-dwarfs. We also calibrated the MEarth photometric system and provide optical magnitudes to 1802 nearby M dwarfs with a precision of 1.5%. We use these results to derive a color-magnitude-metallicity relation across the mid-to-late M dwarf spectral sequence that is calibrated by the nIR spectroscopic metallicity measurements to a precision of 0.1 dex; we find that the median metallicity for a volume limited sample within 20 parsecs of the Sun is [Fe/H] = -0.03. Our catalog of estimated distances, magnitudes, and metallicities is intended to equip the community with the tools to determine whether stellar metallicity correlates with planet formation as the planetary systems around these objects are uncovered. We are currently extending our results to a 4-band calibration of these stars in the Sloan photometric system aimed at identifying a universal color-color metallicity relation grounded in spectroscopic measurements.

Author(s): Jason Dittmann[1], Jonathan Irwin[1], David Charbonneau[1], Elisabeth R. Newton[1]
Institution(s): *1. Harvard Smithsonian, CfA*

119 – Super-Earths and Mini-Neptunes Poster Session

119.01 – Consolidating and Crushing Exoplanets: Did It Happen Here?

Kepler revealed the common existence of tightly packed super Earth systems around solartype stars, existing entirely inside the orbit of
our Venus. Those systems must be stable for the ages of their host stars (~10^9 years); their formation mechanism must provide interplanet spacings that permit longterm stability. If one postulates that most planetary systems form with tightlypacked inner planets, their current absence in some systems could be explained by the collisional destruction of the inner system after a period of metastability. We posit that our Solar System also originally had a system of multiple planets interior to the orbit of Venus. This would resolve a known issue
that the energy/angular momentum of our innerplanet system is best explained by accreting the current terrestrial planets from a disk
limited to 0.71.1 AU; in our picture the disk material closer to the Sun also formed planets, but they have since been destroyed. By studying
the orbital stability of systems like the known Kepler systems, we demonstrate that orbital excitation and collisional destruction could be
confined to just the inner parts of the system. In this scenario, Mercury is the final remnant of the inner system's destruction via a violent multicollision (and/or hitandrun disruption) process. This would provide a natural explanation for Mercury's unusually high eccentricity and orbital inclination; it also fits into the general picture of longtimescale secular orbital instability, with Mercury's current orbit being unstable on 5 Gyr time scales. The common decade spacing of instability time scales raises the intriguing possibility
that this destruction occurred roughly 0.6 Gyr after the formation of our Solar System and that the lunar cataclysm is a preserved record of
this apocalyptic event that began when slow secular chaos generated orbital instability in our former superEarth
system.

Author(s): Brett Gladman[2], Kathryn Volk[1]
Institution(s): *1. The University of Arizona, 2. University of British Columbia*

119.02 – Formation of Kepler multis, and period-ratio asymmetry near mean motion resonances

NASA's Kepler space mission has detected numerous multi-transiting planetary candidate systems. Near-resonant planet pairs show large asymmetric offsets from integer period ratios corresponding to major resonances. We have studied whether such asymmetries can naturally arise during the formation of multiplanet systems and as a function of the initial distribution of solid objects in the protoplanetary disk. We have carried out simulations of the growth of planetesimals and planetary embryos in protoplanetary disks with different surface density profiles and studied the frequency of the occurrence of planet period-ratio asymmetries. We have found that random fluctuations in the disk density profile can relax the requirement of unusually massive disks for the creation of the Kepler multies. We present the results of our study and their implications as a model for explaining the near-resonance pile-ups observed in many Kepler multi-planet systems.

Author(s): Nader Haghighipour[2], Sourav Chatterjee[1]
Institution(s): *1. Northwestern University, 2. University of Hawaii*

119.03 – Dynamics and Collisional Evolution of Closely Packed Planetary Systems

High multiplicity Kepler systems (referred to as Kepler Multis) are often tightly packed and may be on the verge of instability. Many of the currently observed Kepler systems could be remnants of even more tightly packed systems that underwent instabilities. We use numerical simulations to study the dynamical instabilities and planet-planet interactions in a synthetically-generated sample of closely-packed, high-multiplicity systems, using Kepler-11 as a guide. We find that most realizations are unstable, resulting in orbit crossings and, eventually, collisions and mergers. We compare the systems that emerge from dynamical instabilities to the observed Kepler sample (after applying observational corrections) and propose possible observable signatures of these instabilities. We carefully examine the evolution of the planet-planet collisions seen in our dynamical integrations using a smoothed-particle hydrodynamics code, StarSmasher, and find that the results clearly deviate from the sticky-spheres approximation used in many N-body simulations. We present several representative collision calculations and describe in detail the collisional evolution and possible observable signatures.

Author(s): Jason Hwang[1], Fred Rasio[1], Jason Steffen[1]
Institution(s): *1. Northwestern University*

119.04 – What Can the Habitable Zone Gallery Do For You?

The Habitable Zone Gallery (www.hzgallery.org) came online in August 2011 as a service to the exoplanet community that provides Habitable Zone (HZ) information for each of the exoplanetary systems with known planetary orbital parameters. The service includes a sortable table, a plot with the period and eccentricity of each of the planets with respect to their time spent in the HZ, a gallery of known systems which plot the orbits and the location of the HZ with respect to those orbits, and orbital movies. Recently, we have added new features including: implementation of both conservative and optimistic HZs, more user-friendly table and movies, movies for circumbinary planets, and a count of planets whose orbits lie entirely within the system's HZ. Here we discuss various educational and scientific applications of the site such as target selection, exploring planets with eccentric or circumbinary orbits, and investigating habitability.

Author(s): Dawn M Gelino[1], Stephen Kane[2]
Institution(s): *1. NASA Exoplanet Science Institute, Caltech, 2. San Francisco State University*

119.06 – CARMENES: First Results from the CAHA 3.5m Telescope

CARMENES (Calar Alto high-Resolution search for M dwarfs with Exo-earths with Near-infrared and optical Echelle Spectrographs) is a next-generation instrument currently undergoing commissioning at the 3.5m telescope at the Calar Alto Observatory. It has been developed by a consortium of eleven Spanish and German institutions (see also Quirrenbach et al. 2010; 2012; 2014). CARMENES will conduct a 600-night exoplanet survey targeting ~300 M dwarfs. An important and unique feature of the CARMENES instrument is that it consists of two separate échelle spectrographs, which together cover the wavelength range from 0.55 to 1.7 μm at a spectral resolution of R = 82,000. The spectrographs are fed by fibers from the Cassegrain focus of the telescope.

The main scientific objective of the CARMENES project is to carry out a survey of late-type main sequence stars with the goal of detecting low-mass planets in their habitable zones (HZs). In the focus of the project are very cool stars later than spectral type M4 and moderately active stars. We aim at being able to detect a $2M_\oplus$ planet in the HZ of an M5 star. A long-term radial velocity precision of $1 ms^{-1}$ per measurement will permit to attain such goals. For stars later than M4 ($M < 0.25M_\odot$), such precision will yield detections of super-Earths of $5M_\oplus$ and smaller inside the entire width of the HZ. The CARMENES survey will thus provide a comprehensive overview of planetary systems around nearby Northern M dwarfs. By reaching into the realm of Earth-like planets, it will provide a treasure trove for follow-up studies probing their habitability.

Quirrenbach, A., Amado, P.J., Mandel, H., et al. (2010). *CARMENES: Calar Alto high-Resolution search for M dwarfs with Exo-earths with Near-infrared and optical Echelle Spectrographs*. In *Ground-based and airborne instrumentation for astronomy III*. Eds. McLean, I.S., Ramsay, S.K., & Takami, H., SPIE 773513
Quirrenbach, A., Amado, P.J., Seifert, W., et al. (2012). *CARMENES. I: Instrument and survey overview*. In *Ground-based and airborne instrumentation for astronomy IV*. Eds. McLean, I.S., Ramsay, S.K., & Takami, H., SPIE 84460R
Quirrenbach, A., Amado, P.J., Caballero, J.A., et al. (2014). *CARMENES instrument overview*. In *Ground-based and airborne instrumentation for astronomy V*. Eds. Ramsay, S.K., McLean, I.S., & Takami, H., SPIE 91471F

Author(s): Andreas Quirrenbach[1], CARMENES Consortium[1]
Institution(s): *1. Landessternwarte Heidelberg*

119.07 – Effects of Bulk Composition on the Atmospheric Dynamics on Close-in Exoplanets

Depending on the metallicity of the protoplanetary disk and processes such as gas accretion during planetary formation and atmospheric loss during planetary evolution, the atmospheres of sub-Jupiter-sized planets could exhibit a variety of bulk compositions. Examples include hydrogen-dominated atmospheres like Jupiter, more metal-rich atmospheres like Neptune, carbon dioxide, water vapor, nitrogen, and other heavy molecules as exhibited by terrestrial planets in the solar system. In this study we systematically investigate the effects of atmospheric bulk compositions on temperature and wind distributions for tidally locked sub-Jupiter-sized planets such as super-Earths and mini-Neptunes, using an idealized three-dimensional general circulation model (GCM). Composition—in particular, the molecular mass and specific heat—affect the sound speed, gravity wave speeds, atmospheric scale height, and Rossby deformation radius, and therefore in principle can exert significant controls on the atmospheric circulation, including the day-night temperature difference and other observables.

We performed numerous simulations exploring a wide range of molecular masses and molar specific heats. The effect of molecular weight dominates. We found that a higher-molecular-weight atmosphere tends to have a larger day-night temperature contrast, a smaller eastward phase shift in the thermal light curve, and a narrower equatorial super-rotating jet that occurs in a deeper atmosphere. The zonal-mean zonal wind is smaller and more prone to exhibit a latitudinally alternating pattern in a higher-molecular-weight atmosphere. If the vertical temperature profile is close to adiabatic, molar specific heat will play a significant role in controlling the transition from a divergent flow in the upper atmosphere to a jet-dominated flow in the lower atmosphere.

In order to understand the systematic behavior and capture the underlying physics, we present analytical theories to explain aspects of the simulations relevant for several important observables on tidally locked exoplanets, such as the day-night temperature difference, thermal phase shift and root-mean-square of the wind speed. Our analytical predictions are quantitatively compared with our numerical simulations and may provide potential indicators for determining the atmospheric compositions in future observations.

Author(s): Xi Zhang[2], Adam P Showman[1]
Institution(s): *1. University of Arizona, 2. University of California Santa Cruz*

119.08 – Spektral Fingerprint and UV environment of Habitable Planets

The fingerprint of a habitable planets changes with star type, stellar activity,and geological time. The changes determines if habitability can be detected on such planets, both in transmission and by direct imaging. We'll discuss the latest results and prioritization of planets for follow up observations with upcoming telescopes.

Author(s): Lisa Kaltenegger[1]
Institution(s): *1. Carl Sagan institute Cornell*

119.09 – KOI 6705: Extreme Behavior at an Extremum of the Exoplanet Size Distribution

The latest Kepler catalog includes an M dwarf system which hosts what may be one of the smallest known exoplanets, KOI 6705.01. This candidate planet has an orbital period of 0.995 d and a transit depth of only ~100 ppm. Our spectra confirm the host star to be an M3-4 dwarf with Teff=3300 K and a solar metallicity. A comparison to nearby M dwarf calibrators yields a radius of 0.29 Rsun and M_K = 7.2, yielding a distance of 70~pc. The star's space motion, apparent 50 d rotation period, and lack of Hα emission suggest it is an older member of the thin disk population. There is no evidence of contaminating background stars in a UKIRT J-band image or a 1951 POSS-I image in which the proper motion of the star reveals the background sky. Combining a model of the Galactic stellar population with constraints from imaging and the lack of significant Kepler image centroid motion during transits, we estimate a prior probability that there is a background star (i.e. eclipsing binary) that could produce the transit signal to be <1.5e-4. We find no other threshold crossing events with the same ephemeris as 6701.01 that would indicate an instrumental false positive, and by examining the positions and magnitudes of stars in the Kepler Input Catalog on the CCDs we rule out or limit the possibilities of antipodal reflection in the telescope optics, electronic cross-talk between CCDs in the same module, or "bleeding" of signal between stars on the same CCD column. We fit the transit light curve with a prior on stellar density and revise the transit depth to 0.0077 +/- 0.0005, and the planet radius to 0.24 Rearth, about the size of the Moon. However, the transit duration is 2.7 hours, requiring a highly eccentric orbit with an unphysically small periastron. Moreover, the transit is absent or much shallower in the first two years of data and fits fails to converge with that subset. We propose two explanations for this enigma: KOI 6701.01 is a planet exhibiting transit timing variation with two time-scales; one much shorter than 90 days which "blurs" the transits over an observation quarter, making the transit duration appear longer, and one longer than 90 days which modulates the amplitude of the first variation and sometimes renders the transit signal undetectable. Alternatively, the "planet" has a much larger cross section analogous to the "disintegrating" planets KIC 12557548b and EPIC 201637175b.

Author(s): Eric Gaidos[1], Andrew Mann[2]
Institution(s): *1. University of Hawaii, 2. University of Texas*

119.10 – The "true" radius of hot sub-Neptune planets and a theoretical way to estimate their minimum mass

We applied hydrodynamic modelling to the close-in sub-Neptune CoRoT-24b (M<5.7 MEarth; R~3.7 REarth; 5-days orbit). Because of its high temperature and low surface gravity, we obtained an unphysical mass-loss rate, three orders of magnitude higher than the maximum possible value given by the energy limited escape formula. The observed transit radius must therefore be caused by Mie scattering and we conclude that the transit radius overestimates the "true" planet radius by about 50%. Similar differences between planet and transit radii will be present for most of the sub-Neptune planets already discovered by Kepler and foreseen to be found by future missions. These findings have dramatic implications, e.g. in the determination of the mass-radius relation for low-mass planets and for planet population synthesis studies. This kind of analysis allows one to constrain the minimum mass of hot sub-Neptunes. The Kepler satellite revealed that low-mass planets are ubiquitous in the Galaxy, but the majority of the Kepler host stars is too faint to be followed-up with radial velocity measurements. Our findings will be able to partly overcome this problem.

Author(s): Luca Fossati[1], Helmut Lammer[1], Nikolai Erkaev[2], Ines Juvan[1]
Institution(s): *1. Austrian Academy of Sciences, 2. Russian Academy of Sciences*

119.11 – The effect of the condensation of ice materials in the atmosphere on the thermal evolution of ice giants

Though Uranus and Neptune are similar in mass and radius, the former is significantly fainter than the latter. As previous theoretical studies of thermal evolution of the ice giants demonstrated, the faintness of Uranus is not explained by simple three-layer models that are composed of a H/He-dominated envelope, an ice mantle and a rocky core. Namely, the observed effective temperature of Uranus is lower than theoretically predicted (e.g., Fortney et al., 2011; Nettelmann et al., 2013). Since the speed of the thermal evolution is determined by how efficiently the planetary atmosphere radiates energy, the atmospheric structure is important. If the atmosphere contains ice materials such as water, ammonia and methane, those materials have been condensed and removed from the atmosphere during the cooling. In this study, we quantify the impact of the condensation of ice components in the atmosphere on the thermal evolution, which previous studies ignore, to explain the current luminosity of Uranus. To do so, we simulate the thermal cooling of ice giants, based on three layer models with a relatively ice-component-rich, H/He-dominated atmosphere on top of a water mantle that surrounds a rocky core. We demonstrate that the effect of the condensation makes the timescale of the thermal cooling of the planet shorter by an order of magnitude than in the case without condensation. Such accelerated cooling is shown to be fast enough to explain the current faintness of Uranus. We also discuss what caused the difference in current luminosity between Uranus and Neptune.

Author(s): Kenji Kurosaki[1], Masahiro Ikoma[1]
Institution(s): *1. The University of Tokyo*

119.12 – Equilibrium and Disequilibrium Chemistry in Evolved Exoplanet Atmospheres

It has been found that sub-Neptune-sized planets, although not existing in our Solar System, are ubiquitous in our interstellar neighborhood. This revelation is profound because, due to their special sizes and proximity to their host stars, Neptune- and sub-Neptune-sized exoplanets may have highly evolved atmospheres. I will discuss helium-dominated atmospheres as one of the outcomes of extensive atmospheric evolution on warm Neptune- and sub-Neptune-sized exoplanets. Due to depleted hydrogen abundance, the dominant carbon and oxygen species may not be methane or water on these evolved planets. Equilibrium and disequilibrium chemistry models are used to compute the molecular compositions of the atmospheres and their spectral features. Applications to GJ 436 b and other Neptune- and sub-Neptune-sized exoplanets will be discussed. As the observations to obtain the spectra of these planets continue to flourish, we will have the opportunity to study unconventional atmospheric chemical processes and test atmosphere evolution theories

Author(s): Renyu Hu[1]
Institution(s): *1. Jet Propulsion Laboratory*

119.13 – Buildup of Abiotic Oxygen and Ozone in Atmospheres of Temperate Terrestrial Exoplanets

The last two decades have seen a rapid increase in the detection and characterization of exoplanets. A focus of future missions will be on the subset of transiting, terrestrial, temperate exoplanets as they are the strongest candidates to harbor life as we know it.

An important bioindicator for life as we know it is the existence of significant amounts of oxygen, and its photochemical byproduct ozone, in the exoplanet's atmosphere. However, abiotic processes also produce oxygen and ozone, and the amount of oxygen abiotically produced in an atmosphere will largely depend on other atmospheric parameters. Constraining this parameter space will be essential to avoid 'false positive' detections of life, that is the interpretation of oxygen or ozone as a bioindicator despite being produced abiotically.

Based on 1D radiative-convective model calculations, Wordsworth and Pierrehumbert (ApJL, 2014) recently pointed out that the formation and buildup of abiotic oxygen on water-rich planets largely depends on the amount of non-condensable gases in the atmosphere. The amount of non-condensable gases determines whether an atmosphere will develop a 'cold-trap' (similar to the tropopause on Earth) that contains most of the water in the lower atmosphere and dries out the upper atmosphere. If water vapor is a major constituent of the atmosphere, this cold-trapping is inhibited, leading to a much moister upper atmosphere. Water vapor in the upper atmosphere is photolyzed due to the availability of hard UV radiation, yielding oxygen.

We use a photochemical model coupled to a 1D radiative-convective climate model to self-consistently study this effect in atmospheres with N_2, CO_2 and H_2O as the main constituents. These are typical constituents for secondary, oxidized atmospheres, and they can exist in a wide range of ratios. We calculate the amounts of abiotically produced oxygen and ozone and determine the vertical structure of temperature and constituent mixing ratios for various input parameters. We use a radiative transfer model to study the spectroscopic fingerprint of these atmospheres in transit observations with a focus on the capabilities of the James Webb Space Telescope. We compare these results to spectra of Earth as it would be seen as an exoplanet.

Author(s): Armin Kleinboehl[1], Karen Willacy[1], Andrew James Friedson[1], Mark R. Swain[1]
Institution(s): *1. California Institute of Technology*

119.14 – Intrinsic Lyα Profile Reconstructions of the MUSCLES Low-Mass Exoplanet Host Stars

UV stellar radiation can significantly impact planetary atmospheres through heating and photochemistry, even regulating production of potential biomarkers. Cool stars emit the majority of their UV radiation in the form of emission lines, and the incident UV radiation on close-in habitable-zone planets is significant. Lyα (1215.67 Å) dominates the 912 – 3200 Å spectrum of cool stars, but strong absorption from the interstellar medium (ISM) makes direct observations of the intrinsic Lyα emission of even nearby stars challenging. The MUSCLES *Hubble Space Telescope* Treasury Survey (Measurements of the Ultraviolet Spectral Characteristics of Low-mass Exoplanetary Systems) has completed observations of 7 M and 4 K stars hosting exoplanets (d < 22 pc). We have reconstructed the intrinsic Lyα profiles using an MCMC technique and used the results to estimate the extreme ultraviolet (100 – 911 Å) spectrum. We also present empirical relations between Lyα and chromospheric UV metal lines, e.g., Mg II, for use when ISM absorption prevents direct measurement of Lyα. The spectra presented here will be made publicly available through MAST to support exoplanet atmosphere modeling.

Author(s): Allison A Youngblood[1], Kevin France[1], R. O. Parke Loyd[1]
Institution(s): *1. University of Colorado at Boulder*

119.15 – 3D modeling of clouds in GJ1214b's atmosphere

GJ1214b is a warm mini-Neptune/waterworld and one of the few low-mass exoplanets whose atmosphere is characterizable by current telescopes. Recent observations indicated a flat transit spectrum in near-infrared which has been interpreted as the presence of high and thick condensate clouds of KCl or ZnS or photochemical hazes [1]. However, the formation of such high clouds/hazes would require a strong vertical mixing linked to the atmospheric circulation [2]. In order to understand the transport, distribution and observational implications of such clouds/haze, we studied the atmospheric circulation and cloud formation on GJ1214b for H-dominated and water-dominated atmospheres using the Generic LMDZ GCM.
Firstly, we analyzed cloud-free atmospheres [3]. We showed that the zonal mean meridional circulation corresponds to an anti-Hadley circulation in most of the atmosphere with upwelling at midlatitude and downwelling at the equator. This circulation should strongly impact cloud formation and distribution, leading to a minimum of cloud at the equator. We also derived 1D equivalent eddy diffusion coefficients. The corresponding values should favor an efficient formation of photochemical haze in the upper atmosphere of GJ1214b.
Secondly, we simulated cloudy atmospheres including latent heat release and radiative effects for KCl and ZnS clouds [4]. We analyzed their distribution and their impacts on the thermal structure. In particular, a stratospheric thermal inversion should likely be formed by absorption of stellar radiation by ZnS clouds. We showed that flat transit spectra consistent with HST observations are possible for cloud particle radii around 0.5 microns. Using the outputs of our GCM, we also generated emission and reflection spectra and phases curves.
Finally, our results suggest that primary and secondary eclipses and phase curves observed by JWST should provide strong constraints on the nature of GJ1214b's atmosphere and clouds.

references:
[1] Kreidberg et al. 2014, Nature
[2] Miller-Ricci Kempton et al. 2012, ApJ
[3] Charnay et al., submitted
[4] Charnay et al., submitted

Author(s): Benjamin Charnay[2], Victoria Meadows[2], Jérémy leconte[1], Amit Misra[2], Giada Arnay[2]
Institution(s): *1. LMD, 2. University of Washington*

119.16 – On the Detection of Carbon Monoxide as an Anti-Biosignature in Exoplanetary Atmospheres

Recent works suggest that oxygen can be maintained on lifeless exoplanets in the habitable zones of M dwarfs as the results of photochemical reactions. However, the same photochemical models also predict high concentrations of carbon monoxide (CO) in the corresponding atmospheres. A line-by-line radiative transfer model is used to investigate observation requirements of O_2 and CO. We find that abiotically produced O_2 is detectable at 0.76 µm, in agreement with previous findings. More interestingly CO in the corresponding atmospheres is also detectable at NIR. We suggest that future missions aiming at characterization of exoplanetary atmospheres consider detections of CO as an anti-biosignature.

Author(s): Yuwei Wang[1], Feng Tian[2], Tong Li[1], Yongyun Hu[1]
Institution(s): *1. Peking University, 2. Tsinghua University*

119.17 – Ground-based search for the atmosphere of the super-Earth 55Cnc e.

The star 55Cnc is currently one of the brightest stars in the sky known to host a transiting planet, the super-Earth 55Cnc e. This super-Earth has a density lower than that of the Earth and could potentially have either a significant water fraction or a hydrogen-rich envelope, although the latter is expected to have vaporated.

We will present the first ground-based transit detections of 55Cnc e obtained with the Nordic Optical Telescope on La Palma, and show the status of our follow-up program aimed at searching for its atmosphere at low and high-spectral resolution with telescopes on the ground, including the WHT, NOT, and Subaru.

Author(s): Ernst de Mooij[3], Lisa Esteves[4], Raine Karjalainen[2], Mercedes Lopez-Morales[1], Ray Jayawardhana[5], Chris Watson[3]
Institution(s): *1. Harvard-Smithsonian Center for Astrophysics, 2. Isaac Newton Group of Telescopes, 3. Queen's University Belfast, 4. University of Toronto, 5. York University*

119.18 – The implications of evaporation on close-in, low-mass exoplanets

Exoplanet surveys have shown that one of the dominant planet modes of planet formation produces close-in exoplanets. At very close-in separations the atmospheres of these exoplanets can be heated to temperatures high enough to drive a hydrodynamic wind. I will discuss recent theoretical work characterizing the various regimes of evaporation: e.g. energy-limited vs recombination limited and discuss how evaporating exoplanets evolve through these different regimes. I will show recent 3D-MHD simulations of exoplanet evaporation including realistic ionizing radiative transfer that indicate that the flow is anisotropic and exhibits time-dependent flow features close to the day/night-side transition, which could have interesting observational implications. Finally, I will discuss how planet evaporation will dominant the evolution of close-in exoplanets, and use the evaporation models to statistically infer the plausible evolution histories of the Kepler-36 system, an ideal test of the planet evaporation hypothesis.

Author(s): James Owen[1]
Institution(s): *1. Institute of Advanced Study*

119.19 – Exoplanet Clouds in the Laboratory

The lack of strong spectral features of some exoplanet atmospheres may suggest the presence of a cloud layer and poses great challenges for atmospheric characterization. We aim to address these observations and the challenges by leveraging lab-based terrestrial cloud particle instrumentation as a means of investigating how particles representative of those in exoplanet atmospheres interact with incoming radiation. In the end we hope to achieve two goals - First, to better understand the observable properties of cloud particles in exoplanet atmospheres. Second, to determine how these clouds might directly limit our ability to observe and characterize the atmosphere below.

In this presentation I will discuss the cloud chamber used for this work, how we leverage terrestrial based cloud knowledge, our initial investigation of the light scattered by ammonium nitrate (NH_4NO_3) across temperature and relative humidity dependent phase changes, and future work with suspected exoplanet atmospheric condensates under various atmospheric compositions, pressures, and temperatures.

Author(s): Alexandria Johnson[2], Daniel J Cziczo[2], Sara Seager[2], David Charbonneau[1], Amy J. R. Bauer3
Institution(s): *1. Harvard University, 2. Massachusetts Institute of Technology, 3. TSI Incorporated*

119.20 – Precision retrieval of non-isothermal exo-atmospheres

Spectroscopy of extrasolar planets is as fast moving as it is new. When trying to characterise the atmospheres of these foreign worlds, we are faced with three challenges: 1) The correct treatment of atmospheric opacities at high temperatures, 2) Low signal-to-noise of the observed data, and 3) Large, degenerate parameter spaces.
To advance in the interpretation of exoplanetary atmospheres, one must address these challenges in one coherent framework. This is particularly true for emission spectroscopy, where the need for non-isothermal temperature-pressure profiles significantly increases degeneracies in low signal-to-noise data.

In the light of these challenges, we developed a novel, bayesian atmospheric retrieval suite, Tau-REx (Waldmann et al. 2015a,b). Tau-REx is a full line-by-line emission/transmission spectroscopy retrieval code based on the most complete hot line-lists from the ExoMol project.
For emission spectroscopy, the correct retrieval of the atmosphere's thermal gradient is extremely challenging with sparse and/or low SNR data. Tau-REx implements a novel two-stage retrieval algorithm which allows the code to iteratively adapt its retrieval complexity to the likelihood surface of the observed data. This way we achieve a very high retrieval accuracy and robustness to low SNR data. Using nested-sampling in conjunction with large scale cluster computing, Tau-REx integrates the full Bayesian Evidence, which allows for precise model selection of the exoplanet's chemistry and thermal dynamics.
Precision and statistical rigour is paramount in the measurement of quantities such as the carbon-oxygen ratio of planets which allow insights into the formation history of these exotic worlds.
In this conference I will discuss the intricacies of retrieving the thermal emission of non-isothermal atmospheres and what can be learned from data of current and future facilities.

Author(s): Ingo Peter Waldmann[1], Marco Rocchetto[1]
Institution(s): *1. UCL*

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120 – Young Systems Poster Session

120.01 – Lifetime and Spectral Evolution of a Magma Ocean with a Steam Atmosphere

Detecting molten terrestrial planets in extrasolar systems is of great significance in testing the widely accepted view of their hot origins. Several authors have investigated emergent spectra of hot molten planets for several atmospheric compositions and masses and have revealed that the mass of the atmosphere is a determining factor for their spectral detectability (Miller-Ricci et al. 2009; Lupu et al. 2014).

The mass of the atmosphere, however, would not remain constant during the solidification process of magma oceans: it would grow by degassing from the planetary interior or would escape into space (Elkins-Tanton 2011; Hamano et al. 2013; Lebrun et al. 2013). Furthermore, recent calculations have indicated that the lifetime of magma oceans depends on the initial water inventory and the orbital distance from the host star (Hamano et al. 2013). This suggests the possibility of placing constraints on the initial water inventory based on the observed occurrence rate of hot molten planets by future direct imaging missions.

We present the thermal evolution and emergent spectra of solidifying terrestrial planets along with the formation of steam atmospheres. The lifetime of a magma ocean and its spectra through a steam atmosphere depends on the orbital distance of the planet from the host star. For a Type I planet, which is formed beyond a certain critical distance from the host star, the thermal emission declines on a timescale shorter than approximately 10^6 years. Therefore, young stars should be targets when searching for molten planets in this orbital region.

In contrast, a Type II planet, which is formed inside the critical distance, will emit significant thermal radiation from near-infrared atmospheric windows during the entire lifetime of the magma ocean. The Ks and L bands will be favorable for future direct imaging because the planet-to-star contrasts of these bands are higher than approximately 10^{-7}– 10^{-8}. Our model predicts that, in the Type II orbital region, molten planets would be present over the main sequence of the G-type host star if the initial bulk content of water exceeds approximately 1 wt%.

Author(s): Keiko Hamano3, Hajime Kawahara3, Yutaka Abe3, Masanori Onishi[1], George L. Hashimoto[2]
Institution(s): *1. Kobe University, 2. Okayama University, 3. The University of Tokyo*

120.02 – Chemical signatures of rocky accretion in a young solar-type star

It is well known that newly formed planetary systems undergo processes of orbital reconfiguration and planetary migration. As a result, planets or proto-planetary objects may accrete onto the central star, being fused and mixed into its external layers. If the accreted mass is sufficiently large and the star has a sufficiently thin convective envelope, such events may result in a modification of the chemical composition of the stellar photosphere in an observable way, enhancing it with elements that were abundant in the accreted mass. Recently, the Gaia-ESO Survey observations of the 10-20 Myr old Gamma Velorum cluster have enabled the identification of a star significantly enriched in iron with respect to other cluster members. In this seminar I will present a further investigation of the abundance pattern of this star, showing that its chemical anomaly is not limited to iron, but is also present in all the refractory elements whose abundances are correlated with the condensation temperature. This finding strongly supports the hypothesis of a recent accretion of rocky material.

Author(s): Lorenzo Spina[1]
Institution(s): *1. Universidade Sao Paulo*

120.03 – Sco-Cen as an Astrophysical Exoplanet Laboratory

The Sco-Cen OB association is our nearest region of recently completed star formation. With vast populations of stars with ages ranging from 5-20 Myr, Sco-Cen also contains the majority of PMS sun-like stars in the nearest 200 pc. Sco-Cen offers a glimpse into the state of a group of stars just following formation, providing a rich laboratory for the study of various astrophysical processes, including exoplanet formation and evolution in "age-calibrated" samples. Here we summarize multiple avenues of characterization of the Sco-Cen association that we have been pursuing to improve the current knowledge of the population and stellar group properties of the different regions in Sco-Cen: We have identified ~250 new K/M-type PMS members in the youngest region of Sco-Cen, and completed a large radial velocity follow-up of the B/A/F-type members in the association, in order to robustly exclude all interlopers from the membership lists and create a vetted sample of single stars for exoplanet-searches in the coming year.

Author(s): Aaron Rizzuto[1]
Institution(s): *1. University of Texas at Austin*

120.04 – Tests of the planetary hypothesis for PTFO 8-8695b

The T Tauri star PTFO 8-8695 exhibits periodic fading events that have been interpreted as the transits of a giant planet on a precessing orbit. Here we present three tests of the planet hypothesis. First, we sought evidence for the secular changes in light-curve morphology that are predicted to be a consequence of orbital precession. We observed 28 fading events spread over several years, and did not see the expected changes. Instead we found that the fading events are not strictly periodic. Second, we attempted to detect the planet's radiation, based on infrared observations spanning the predicted times of occultations. We ruled out a signal of the expected amplitude. Third, we attempted to detect the Rossiter-McLaughlin effect by performing high-resolution spectroscopy throughout a fading event. No effect was seen at the expected level, ruling out most (but not all) possible orientations for the hypothetical planetary orbit. Our spectroscopy also revealed strong, time-variable, high-velocity Hα and Ca H & K emission features. All these observations cast doubt on the planetary hypothesis, and suggest instead that the fading events represent starspots, eclipses by circumstellar dust, or occultations of an accretion hotspot.

Author(s): Liang Yu[5], Joshua Winn[5], Michael Gillon[7], Simon Albrecht[1], Saul Rappaport[5], Allyson Bieryla[4], Fei Dai[5], Laetitia Delrez[7], Lynne Hillenbrand[3], Matthew Holman[4], Andrew Howard[9], Chelsea Huang[6], Howard T. Isaacson[8], Emmanuel Jehin[7], Monika Lendl[7], Benjamin Tyler Montet[4], Philip Steven Muirhead[2], Roberto Sanchis-Ojeda[8], Amaury H.M.J. Triaud[10]
Institution(s): *1. Aarhus University, 2. Boston University, 3. California Institute of Technology, 4. Harvard-Smithonian Center for Astrophysics, 5. Massachusetts Institute of Technology, 6. Princeton University, 7. Université de Liège, 8. University of California at Berkeley, 9. University of Hawaii, 10. University of Toronto*

120.05 – Search for Exoplanets around Young Stellar Objects by Direct Imaging

SEEDS project, exploring exoplanets and protoplanetary disks with Subaru/HiCIAO, has observed about 500 stars by Direct Imaging from 2009 Dec to 2015 Apr. Among these targets we explore around Young Stellar Objects (YSOs; age ≦ 10Myr) which often have the protoplanetary disks where planets are being formed in order to detect young exoplanets and to understand the formation process. We analyzed 66 YSOs (about 100 data in total) with LOCI data reduction. We will report the results (companion candidates and detection limit) of our exploration.

Author(s): Taichi Uyama[3], Motohide Tamura[3], Jun Hashimoto[1], Masayuki Kuzuhara[2]
Institution(s): *1. Astrobiology Center, 2. Tokyo Institute of Technology, 3. Univ. of Tokyo*

120.06 – ALMA Observations of the Nascent Debris System in HD141569: A unique testbed for planet formation and disk evolution

HD 141569 is a unique ~5 Myr transition disk that can give powerful insight into the planet formation process and early debris disk evolution. This B9.5 Ve pre-MS star (99 pc) is surrounded by an extensive disk with spiral-like structure at large stellar separations, as observed in scattered light images. The disk's morphology could be the result of interactions with planets and/or two companion stars. Using our 0."38 resolution ALMA observations, we spatially and kinematically resolve substantial CO (3-2) gas that extends from close to the star to past 100 AU. In addition, we have 870 μm continuum emission that we identify as an inner debris disk. The mm grains of this inner region are associated with a tenuous gas component, potentially making the inner system akin to older gas-rich debris disks. In contrast, the gas in the outer disk is likely from the disk's formation. HD141569 may be observed during a short-lived but common phase of evolution, during which the gas from the protoplanetary disk is being cleared by, e.g., photoevaporation, while the nascent debris disk provides a new source of low-density gas. Based on our observations, we present mass estimates for the inner debris disk, as well as a dynamical mass measurement for the star. In addition, we will discuss how HD 141569 compares to other transition disks and gas-rich systems and how it can be used as a test-bed for the clearing stages of planet formation.

Author(s): Jacob Aaron White[4], Aaron Boley[4], Meredith Hughes[5], Eric B Ford[3], Matthew Payne[2], David Wilner[2], Stuartt Corder[1]
Institution(s): *1. ALMA Science Center, 2. Harvard, 3. Pennsylvania State University, 4. University of British Columbia, 5. Wesleyan*

120.08 – Evolution of gas in debris discs

A non negligible quantity of gas has been discovered in an increasing number of debris disc systems. ALMA high sensitivity and high resolution is changing our perception of the gaseous component of debris discs as CO is discovered in systems where it should be rapidly photodissociated. It implies that there is a replenishment mechanism and that the observed gas is secondary. Past missions such as Herschel probed the atomic part of the gas through O I and C II emission lines. Gas science in debris discs is still in its infancy, and these new observations raise a handful of questions concerning the mechanisms to create the gas and about its evolution in the planetary system when it is released. The latter question will be addressed in this talk as a self-consistent gas evolution scenario is proposed and is compared to observations for the peculiar case of β Pictoris.

Our model proposes that carbon and oxygen within debris discs are created due to photodissociation of CO which is itself created from the debris disc dust (due to grain-grain collisions or photodesorption). The evolution of the carbon atoms is modelled as viscous spreading, with viscosity parameterised using an α model. The temperature, ionisation fraction and population levels of carbon are followed with a PDR model called Cloudy, which is coupled to the dynamical viscous α model. Only carbon gets ionised due to its lower ionisation potential than oxygen. The carbon gas disc can end up with a high ionisation fraction due to strong FUV radiation field. A high ionisation fraction means that the magnetorotational instability (MRI) is very active, so that α is very high. Gas density profiles can be worked out for different input parameters such as the α value, the CO input rate, the location of the input and the incoming radiation field. Observability predictions can be made for future observations, and our model is tested on β Pictoris observations. This new gas evolution model fits the carbon and CO observations in β Pic and gives a self-consistent scenario that might be at play in all debris discs...

Author(s): Quentin Kral[1], Mark Wyatt[1], Jim Pringle[1]
Institution(s): *1. University of Cambridge*

120.09 – New circumstellar disk candidates around young low mass stars and brown dwarfs

It is now common knowledge that circumstellar disks are signposts of past or ongoing planetary system formation. Their presence and their properties, in relation to those of their host star, also bear valuable information about the process of star formation itself. To address these questions, we started a project to uncover new circumstellar disks around newly identified low mass star and brown dwarf candidates in nearby young kinematic associations. Being near the stellar/substellar mass boundary, these hosts - and their potential disks - are particularly interesting to study both star and planet formation. We used a least squares approach to fit synthetic spectra to the observed photometric data of each star, covering from 0.8 µm up to 22 µm, and then identified candidates showing a significant excess compared to the best fits. We then carefully looked at the data for these candidates to filter out those biased by contaminants or other artefacts. We ended up with a list of 4 young stars and brown dwarfs strongly suspected of being surrounded by a disk. Here we will present our search method and some properties of our newly identified disk-bearing candidates.

Author(s): Anne Boucher3, David Lafrenière3, Jonathan Gagné2, Lison Malo1, Rene Doyon3
Institution(s): *1. Canada-France-Hawaii Telescope, 2. Carnegie Institute for Science, 3. Institut de Recherche sur les Exoplanètes (iREx)*

120.10 – Extrasolar comets : dynamics and composition

Extrasolar comets, or exocomets, are detected using transit spectroscopy in young planetary systems.

Spectroscopic observations of β Pictoris revealed a high rate of transits, allowing statistical analysis of exocomets populations. Using more than 1,000 archival spectra, we obtained a sample of several hundreds of signatures of exocomets transiting the disk of the parent star. Statistical analysis of the observed properties of these exocomets allowed the identification of two populations with different physical and dynamical properties. One family consists of exocomets producing shallow absorption lines at high radial velocities (>40 km/s), which can be attributed to old exhausted comets trapped in a mean motion resonance with a massive planet, possibly β Pic b. The second family consists of exocomets which produce deep absorption lines at low radial velocities (~ 15 km/s), which could be related to the recent fragmentation of one or a few parent bodies.

Most recently, our last HST/COS observations of β Pic yielded the first detection of exocomets in the far-UV. Several new species were detected for the first time in exocomets, including HI, CII, NI, OI and all the ionization states of Si. Measuring the abundance of the key species such as Hydrogen, Carbon, Nitrogen and Oxygen in evaporating exocomets allows us to trace the condensation and evaporation processes present in the late stages of planetary formation. Moreover, the measured radial velocities of these exocomets are consistent with the two dynamical populations previously identified. Most importantly, correlations between the dynamical properties and abundances seems to show up. In short, these two families of exocomets have different dynamical properties, and their origin could be determined by studying their chemical composition. I will present the latest results on that subject, and provide an overview of other systems for which signatures of exocomets have been observed.

Author(s): Alain Lecavelier des Etangs[1], Paul Anthony Wilson[1], Flavien Kiefer[1]
Institution(s): *1. IAP-CNRS*

120.11 – Probing Terrestrial Planet Formation by Witnessing Large Collisions in Extreme Debris Disks

The Kepler results indicate that many young planetary systems build terrestrial planets. The most dramatic phases of this process are thought to be oligarchic and chaotic growth, roughly up to ages of 200 million years, when violent collisions occur between bodies of sizes up to proto-planets. Such events should be marked by the production of huge amounts of debris, including clouds of dust, as has been observed in some of the extreme debris disks (young stars with high fractional dust luminosity and prominent solid-state features in the mid-infrared). The newly discovered variable emission from extreme debris disks provides a unique opportunity to learn about asteroid-sized bodies in young exoplanetary systems and to explore planetesimal collisions and their aftermaths during the era of terrestrial- planet-building.

We have a on-going Spitzer program to monitor a dozen of young, dusty debris systems to investigate the incidence, nature, and evolution of these impacts through time-domain observations. I will highlight recent results from time-series monitoring of a 35 Myr-old disk around ID8 in NGC 2547, and discuss future directions for the study of the detailed process of large impacts in the era of terrestrial planet formation using space facilities.

Author(s): Kate Su[1]
Institution(s): *1. University of Arizona*

120.12 – Bringing "The Moth" to Light: A Planet-Perturbed Disk Scenario for the HD 61005 System

The HD 61005 debris disk ("The Moth") is notable for its unusual swept-back "wing" morphology, brightness asymmetries, dust ring offset, and a cleared region inside of ~50 AU. Here we present Gemini Planet Imager data that reveal this disk in scattered light down to Jupiter-like separations of <10 AU. Complementary W.M. Keck NIRC2/AO J,H,K imaging shows the disk's outer regions with high angular resolution. Based on these data, we propose a new explanation for the disk's features: that of an unseen planet on an inclined, eccentric orbit perturbing the disk material. To test this scenario, we used secular perturbation theory to construct 3-D dust distributions that informed 2-D scattered-light models, which we then compared with the data via an MCMC analysis. We found that the best-fit models reproduced morphological disk features similar to those observed, indicating that the perturber scenario is plausible for this system.

Author(s): Thomas M. Esposito[1], Michael P. Fitzgerald[2], James R. Graham[1], Paul G. Kalas[1], Max Millar-Blanchaer3, Jason Wang[1]
Institution(s): *1. UC Berkeley, 2. UCLA, 3. University of Toronto*

120.13 – Resolving the HD 106906 Disk with the Gemini Planet Imager

We present the first direct detection of the debris disk around the young star HD 106906 using the Integral Field Unit on the Gemini Planet Imager (GPI). In addition to our detection of the inner warm component in the near infrared, we also recovered the cold outer region of the disk in the optical using archival HST/ACS data. The GPI observations show a near edge-on disk with a central cleared region at ~50 AU, and an outer extent >500 AU. The HST data show the outer regions are highly asymmetric, resembling the “needle" morphology seen for the HD 15115 debris disk. The GPI images do not show the strong asymmetry seen in the HST data. The star HD 106906 has an ~11 Mjup planetary mass companion with a projected separation of 650 AU, which poses questions about the formation mechanisms for such a distant companion. We compared the literature photometry measurements of the companion to theoretical models and measure a redder than expected color which might suggest the presence of a disk around the companion as well. The H-band spectroscopy data was used to place constraints on the presence of further Jupiter-mass companions closer in to the star.

Author(s): Abhijith Rajan[1], Paul G. Kalas5, Jennifer Patience[1], Jason Wang5, Max Millar-Blanchaer9, Michael P. Fitzgerald[6], Christine H Chen3, Ruobing Dong5, James R. Graham5, Bruce Macintosh4, Ruth Murray-Clay7, Brenda Matthews[2], Julien Rameau[8], Christian Marois[2]
Institution(s): *1. Arizona State University, 2. National Research Council of Canada Herzberg, 3. Space Telescope Science Institute, 4. Stanford University, 5. University of California, Berkeley, 6. University of California, Los Angeles, 7. University of California, Santa Barbara, 8. University of Montreal, 9. University of Toronto*

120.14 – Herschel Imaging of Debris Disks: Resolved Planet-Bearing Disks and a Planet-Disk Correlation

We will present Herschel images from a far-IR survey of known planet-bearing systems. Among the systems with detectable debris disks, 15 such disks are spatially resolved, with radii of ~100 AU. Although this orbiting material is well separated from any radial-velocity-discovered planets in the same system, we nevertheless find a strong correlation between inner planets and outer disks, with disks around planet-bearing stars tending to be much brighter than those not known to have planets.

Author(s): Geoffrey Bryden[1]
Institution(s): *1. JPL*

120.15 – Herschel-Resolved Outer Belts of Two-Belt Debris Disks--Evidence of Icy Grains

We present dual-band Herschel/PACS imaging for 57 main sequence stars (42 A-type and 15 solar-type) with previously known warm dust (Twarm ~200K) detected and characterized by Spitzer. About half of the star-disk systems in our sample have spectral energy distributions (SEDs) that suggest two-ring disk architectures that mirror that of the asteroid-Kuiper belt geometry of our own solar system. The Herschel observations at 70 and/or 100 micron spatially resolve the cold/outer dust component for 18 two-belt debris systems (15 for the first time; 10 are also resolved at 160 micron), finding evidence of planetesimals at >100 AU, i.e. larger size than assumed from a simple blackbody fit to the SED. By breaking the degeneracy between the grain properties and the dust's radial location, the resolved images help constrain the grain size distribution and hint at the dust's composition for each system. Based on the combined Spitzer/IRS+MIPS (5 to 70 micron), the Herschel/PACS (70 and/or 100 and 160 micron) dataset, and under the assumption of idealized spherical grains, we find that the majority of resolved cold/outer belts of star+disk systems are well fit with a mixed ice/rock composition, rather than pure rocky grains. In the absence of spectral features for ice, we find that the behavior of the continuum can help constrain the composition of the grains well (of icy nature and not pure rocky material) given the Herschel-resolved locations of the cold/outer dust belts. We have also begin to identify the presence of candidate companions via Keck direct imaging, which may be interacting with the observed dust.

Author(s): Farisa Y. Morales[1], Geoffrey Bryden[1], Michael W. Werner[1], Karl Stapelfeldt[2]
Institution(s): *1. Jet Propulsion Laboratory, 2. NASA Goddard Space Flight Center*

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200 – Ultrashort Periods and Planet-Star Interactions

200.01 – A giant cloud of hydrogen escaping the warm Neptune-mass planet GJ 436b

Exoplanets in extreme irradiation environments, close to their parent stars, could lose some fraction of their atmospheres because of the extreme irradiation. Atmospheric mass loss has been observed during the past 12 years for hot gas giants, as large (~10%) ultraviolet absorption signals during transits. Meanwhile, no confident detection have been obtained for lower-mass planets, which are most likely to be significantly affected by atmospheric escape. In fact, hot rocky planets observed by Corot and Kepler might have lost all of their atmosphere, having begun as Neptune-like. The signature of this loss could be observed in the ultraviolet, when the planet and its escaping atmosphere transit the star, giving rise to deeper and longer transit signatures than in the optical. I will report on new Hubble observations of the Neptune-mass exoplanet GJ 436b, around which an extended atmosphere has been tentatively detected in 2014. The new data reveal that GJ 436b has huge transit depths of 56.3±3.5% in the hydrogen Lyman-alpha line, far beyond the 0.69% optical transit depth, and even far beyond mass loss signatures observed at the same wavelength from more irradiated gas giants. We infer from this repeated observations that the planet is surrounded and trailed by a large exospheric cloud of hydrogen, shaped as a giant comet, much bigger than the star. We estimate a mass-loss rate, which today is far too small to deplete the atmosphere of a Neptune-like planet in the lifetime of the parent star, but would have been much greater in the past. This 16-sigma detection opens exciting perspectives for the atmospheric characterization of low-mass and moderately-irradiated exoplanets, a large number of which will be detected by forthcoming transit surveys.

Author(s): David Ehrenreich[1]
Institution(s): *1. University of Geneva*

200.03 – Evaporating atmospheres: from Hot-Jupiters to warm-Neptunes

Atmospheric escape has first been detected through transit observations of massive hot Jupiters like HD209458b and HD189733b. Absorption signatures in the Lyman-alpha line of their host stars have been attributed to comet-like tails of escaping neutral hydrogen, blown away by the stellar radiation pressure or stellar wind interactions. The recent detection of a giant exosphere surrounding the warm Neptune GJ 436 b has shed new light on the evaporation of close-in planets, revealing that moderately irradiated, low-mass exoplanets could make exceptional targets for studying this mechanism and its impact on exoplanets. In this talk, I will show the role played by stellar radiation pressure on the structure of GJ436b exosphere and its transmission spectrum, highlighting its differences with the known evaporating hot Jupiters. Furthermore, while the three observations performed in the Lyman-α line of GJ 436 show repeatable transit variations, the spectra observed at each of epoch display specific features that require additional physics. I will present preliminary results as for the origin of this temporal variability.

Author(s): Vincent Bourrier[1], David Ehrenreich[1]
Institution(s): *1. Geneva Observatory*

200.04 – Re-inflated Warm Jupiters around Red Giants: A New Test for Models of Hot Jupiter Inflation

Ever since the discovery of the first transiting hot Jupiter, models have sought to explain the anomalously large radii of highly irradiated gas giants. We now know that the size of the hot Jupiter radius anomaly scales strongly with a planet's level of irradiation and numerous models have since been developed to help explain these inflated radii. In general however, these models can be grouped into two broad categories: 1) models that directly inflate planetary radii by depositing a fraction of the incident irradiation in the convective interior and 2) models that simply slow a planet's radiative cooling allowing it to retain more heat from formation and thereby delay contraction. Here we propose a new test to distinguish between these two classes of models, by examining the post-main sequence radius evolution of gas giants with moderate orbital periods of ~10-30 days. If hot Jupiter inflation actively deposits heat in a planets interior then current and upcoming transit surveys should uncover a new population of "re-inflated" gas giants around post main sequence stars.

Author(s): Eric D Lopez[2], Fortney Jonathan[1]
Institution(s): *1. University of California, Santa Cruz, 2. University of Edinburgh*

200.05 – Evolution of Giant Planets Close to the Roche Limit

Two formation models have been proposed to explain hot Jupiters' tight orbits. These could have migrated inward in a disk (disk migration), or they could have formed via tidal circularization of an orbit made highly eccentric following gravitational interactions with a companion (high-eccentricity migration). I will show how current observations coupled with a detailed treatment of tides can be used to constrain both hot Jupiter formation and tidal dissipation theories.

Eventually, stellar tides will cause the orbits of many hot Jupiters to decay down to their Roche limit. Using a detailed binary mass transfer model we show how a hot Jupiter undergoing a phase of Roche-lobe overflow (RLO) leads to lower-mass planets in orbits of a few days. The remnant planets have a rocky core and some amount of envelope material, which is slowly removed via photo-evaporation at nearly constant orbital period; these have properties resembling many of the observed super-Earths and sub-Neptunes. For these remnant planets we also predict an anti-correlation between mass and orbital period; very low-mass planets in ultra-short periods cannot be produced through this type of evolution.

Author(s): Francesca Valsecchi[1]
Institution(s): *1. Northwestern University*

200.06 – Exo-Mercury Analogues and the Roche Limit for Close-Orbiting Rocky Planets

The origin of Mercury's enhanced iron content is a matter of ongoing debate. The characterization of rocky exoplanets promises to provide new independent insights on this topic, by constraining the occurrence rate and physical and orbital properties of iron-enhanced planets orbiting distant stars. The ultra-short-period transiting planet candidate KOI-1843.03 (0.6 Earth-radius, 4.245 hour orbital period, 0.46 Solar-mass host star) represents the first exo-Mercury planet candidate ever identified. For KOI-1843.03 to have avoided tidal disruption on such a short orbit, Rappaport et al. (2013) estimate that it must have a mean density of at least 7g/cc and be at least as iron rich as Mercury. This density lower-limit, however, relies upon interpolating the Roche limits of single-component polytrope models, which do not accurately capture the density profiles of >1000 km differentiated rocky bodies. A more exact calculation of the Roche limit for the case of rocky planets of arbitrary composition and central concentration is needed. We present 3D interior structure simulations of ultra-short-period tidally distorted rocky exoplanets, calculated using a modified version of Hachisu's self-consistent field method and realistic equations of state for silicates and iron. We derive the Roche limits of rocky planets as a function of mass and composition, and refine the composition constraints on KOI-1843.03. We conclude by discussing the implications of our simulations for the eventual characterization of short-period transiting planets discovered by K2, TESS, CHEOPS and PLATO.

Author(s): Leslie A. Rogers[2], Ellen Price[1]
Institution(s): *1. Harvard University, 2. University of California, Berkeley*

200.07 – Signatures for Dynamical evolution of short period M-dwarf planets

Recently, planetary systems containing sub-Neptune-sized planets with semimajor axes less than the Mercury--Sun separation have been discovered around a wide range of stars. We show that there are several significant differences between M- and G-dwarf close-in sub-Neptune planets. We find that a significant precent of close-in M-dwarf planets reside interior to the star's estimated protoplanetary disk edge, unlike G-dwarf planets. Presumably these planets had to be brought in, after the disk was evaporated, by a dynamical mechanism. This should resulted in large eccentric planets, furthermore, those planets with extreme eccentricities may have circularized to a tight orbit. However, we also find that the eccentricity distribution of M-dwarf is significantly suppressed around the e~0 and for e>0.4 while the G-dwarfs eccentricity distribution covers the entire range. We suggest that tidal evolution, after a scattering event, in both stars plays an important role in shaping these distributions. Because M-dwarfs spands more time in pre-main sequence phase tides operate for longer timescales, which can contribute to damping the large eccentricities. However, tidal forces are proportional to the mass of the star, and as such they are less efficient for M-dwarf planet and do not result in circularization.

Author(s): Smadar Naoz[2], Bao-Minh Hoang[2], Gongjie Li[1], John Asher Johnson[1]
Institution(s): *1. Harvard University, 2. University of California, Los Angeles*

201 – Dynamical Evolution

201.02 – Spin-orbit coupling and the production of misaligned hot Jupiters via Lidov-Kozai oscillations

Many hot Jupiter systems exhibit misalignment between the orbital axis of the planet and the spin axis of its host star. While this misalignment could be primordial in nature, a large fraction of hot Jupiters are found in systems with distant stellar companions, and thus could have undergone Lidov-Kozai (LK) oscillations and acquired their misalignment dynamically. Here we present a study of the effect of spin-orbit coupling during LK oscillations, and the resulting spin-orbit misalignment angle distributions. We show that spin-orbit coupling induces complex, often chaotic, behavior in the spin axis of the host star, and that this behavior depends significantly on the mass of the planet and the properties of the host star (mass and spin history). We develop a semi-analytical framework that successfully explains most of the possible stellar spin behaviors. We then present a comprehensive population synthesis of hot Jupiters created via the LK mechanism, and discuss their possible observable signatures.

Author(s): Natalia I Storch[1], Kassandra R Anderson[2], Dong Lai[2]
Institution(s): *1. California Institute of Technology, 2. Cornell University*

201.03 – Are Tidal Effects Responsible for Exoplanetary Spin-Orbit Alignment?

Obliquities of planet-hosting stars may be clues about the formation of planetary systems. Previous observations led to the hypothesis that for close-in giant planets, spin-orbit alignment is enforced by tidal interactions. Here, we examine two potential problems with this hypothesis. First, Mazeh and coworkers recently used a new technique -- based on the amplitude of starspot-induced photometric variability -- to conclude that spin-orbit alignment is common even for relatively long-period planets, which would not be expected if tides were responsible. We re-examine the data and find a statistically significant correlation between photometric variability and planetary orbital period, which is at least qualitatively consistent with tidal interactions. Second, Rogers and Lin argued against a particular theory for tidal realignment by showing that initially retrograde systems would fail to be re-aligned, in contradiction with the observed prevalence of prograde systems. We present a simple model that overcomes this problem by taking into account the dissipation of inertial waves and the equilibrium tide, as well as magnetic braking. Thus, we find both problems to be less serious than they first appeared, although the tidal model still has shortcomings.

Author(s): Gongjie Li[1], Joshua Winn[2]
Institution(s): *1. Harvard, 2. MIT*

201.04 – Features in the Architectures of Exoplanet Systems

Data from NASA's Kepler mission allow for new and innovative studies of the distributions of planetary orbits and sizes. These distributions have important implications for our understanding of planet formation. I present the results of recent studies of the architectures of Kepler systems where a number of intruiguing features are manifest. Specifically, there is a notable lack of nearby companions to short-period planets and there is a significant excess of planet pairs with an orbital period ratio near 2.2. These features currently lack an explanation, yet may yield important insights into the late stages of planet formation and the subsequent dynamical evolution of the system. I also present results and anlysis of dynamical simulations of dynamical instability in closely-packed planetary systems. These simulations show an important invariance in the timescale to instability with respect to the orbital distance of the planets.

Author(s): Jason Steffen[2], Jason Hwang[1], David Rice[1]
Institution(s): *1. Northwestern University, 2. University of Nevada, Las Vegas*

201.05 – Planetesimal Scattering and its Implications for the Period-Ratio Distribution of Kepler Planet Pairs

Period ratios of most adjacent planet pairs in Kepler's multiplanet systems seem random. However, there is a clear excess and dearth of systems just exterior and interior to major mean motion resonances, respectively. We show that dynamical interactions between initially resonant planet pairs and planetesimals in a planetesimal disk can naturally produce the observed asymmetric abundances in period ratios of near-resonant pairs for a wide variety of planet and planetesimal disk properties (Chatterjee & Ford 2015). We further extend this study to include planet pairs initially *not* in resonance. We will present our key results from this large suite of simulations. We will also discuss implications of planetesimal scattering for the observable properties of these planets including their TTV signal and mass-radius properties as a result of planetesimal accretion.

Author(s): Sourav Chatterjee[1], Seth O Krantzler[3], Eric B Ford[4], Elizabeth Tasker[2], Fred Rasio[1]
Institution(s): *1. CIERA-Northwestern University, 2. Hokkaido University, 3. Northwestern University, 4. Penn State*

201.06 – Orbital Stability of Multi-Planet Systems: Behavior at High Masses

We explore the relationships between planet separation, mass, and stability timescale in high mass multi-planet systems containing planet masses and multiplicities relevant for planetary systems detectable via direct imaging. Extrapolating empirically derived relationships between planet mass, separation, and stability timescale derived from lower mass planetary systems misestimate the stability timescales for higher mass planetary systems by more than an order of magnitude at close separations near the two body Hill stability limit. We also find that characterizing critical separations in terms of period ratio produces a linear relationship between log-timescale and separation with the same slope for planet-star mass ratios comparable to or exceeding Jupiter’s, but this slope steepens for lower mass planetary systems. We discuss possible mechanisms for instability that result in this behavior including perturbing adjacent planet pairs into an overlap regime between 1st and sometimes 2nd order mean motion resonances.

Author(s): Sarah J. Morrison[1], Kaitlin M Kratter[1]
Institution(s): *1. University of Arizona*

201.07 – Fomalhaut b is Probably Not a Planet: Frequent Collisions within the Fomalhaut Debris Disk

Fomalhaut hosts a beautiful debris disk ring and a directly imaged planet candidate, Fomalhaut b, which seems to continually defy expectations. Originally thought to be a Jovian-mass planet constraining the ring, its unexpected spectral properties and highly eccentric, possibly ring-crossing orbit have completely ruled out that possibility. Many theories have been proposed to explain the weird properties of Fomalhaut b, including a large circumplanetary ring, a system of irregular satellites, and a recent small body collision. We expand on the last theory, discussing our collisional probability simulations of the Fomalhaut debris disk, based on the structure of our Kuiper belt, which show the catastrophic disruption rate of d~100 km bodies in the high-eccentricity scattering component is several per decade. This model paints a picture of the Fomalhaut system as having recently (with ~10-100 Myr) experienced a dynamical instability within its planetary system, which scattered a massive number of planetesimals onto large, high-eccentricity orbits similar to that of Fom b. If Fomalhaut b is indeed a dust cloud produced by such a collision, we should soon see another appear, while Fomalhaut b will expand until it is either resolved or becomes too faint to be seen.

Author(s): Samantha Lawler[1], Sarah Greenstreet[2], Brett Gladman[2]
Institution(s): *1. NRC-Herzberg, 2. University of British Columbia*

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202 – Direct Imaging I

202.01 – The Gemini Planet Imager Exoplanet Survey (GPIES) Campaign Initial Results

The Gemini Planet Imager (GPI) is a next-generation coronagraphic integral field unit with the sensitivity and resolution to detect planetary companions with separations of 0”.2 to 1”.0 around a large set of stars. An 890-hour GPI survey of 600 young, nearby stars commenced in late-2014, and approximately 100 stars have been observed thus far. The central aims of the program are: (1) the discovery of a population of giant planets with orbital radii of 5-50 AU comparable to Solar System gas giant orbits, (2) the characterization of the atmospheric properties of young planetary companions, and (3) the exploration of planet-disk interactions. Initial results from GPI exoplanet observations include the discovery of a new planetary companion to a young F-star; the planet spectrum shows a strong signature of methane absorption, indicating a cooler temperature than previously imaged young planets. An overview of the survey scope, current detection limits, and initial results will be presented.

Author(s): Jennifer Patience[1], Bruce Macintosh[7], James R. Graham[9], Travis Barman[3], Robert De Rosa[9], Quinn Konopacky[10], Mark Marley[4], Christian Marois[5], Eric Ludwig Nielsen[6], Laurent Pueyo[8], Abhijith Rajan[1], Julien Rameau[11], Didier Saumon[2], Jason Wang[9]
Institution(s): *1. ASU, 2. LANL, 3. Lunar and Planetary Lab, 4. NASA Ames, 5. NRC, 6. SETI, 7. Stanford, 8. STScI, 9. UC Berkeley, 10. UCSD, 11. University of Montreal*

202.02 – Astrometric Confirmation and Preliminary Orbital Parameters of the Young Exoplanet 51 Eridani b with the Gemini Planet Imager

The Gemini Planet Imager Exoplanet Survey discovered the young, 2 Jupiter mass planet 51 Eri b based on observations conducted in December 2014 and January 2015. It is the lowest mass extrasolar planet ever detected by direct imaging and shows strong methane absorption, and is at a projected separation of just 13 AU from its host star. We present new astrometry from late 2015 that confirms 51 Eri b is a bound planet and not an interloping brown dwarf. Orbital motion is detected despite monitoring the system for less than a year. We have implemented a computationally efficient Monte Carlo technique for fitting a range of possible orbital motion based on astrometry covering a small fraction of the period and producing distributions of orbital parameters consistent with the measurements. We apply this technique to the astrometry of 51 Eri b and present preliminary orbital parameter distributions of this intriguing planet.

Author(s): Eric Ludwig Nielsen[2], Sarah Blunt[2], Robert De Rosa[5], Quinn Konopacky[6], James R. Graham[5], Bruce Macintosh[4], Franck Marchis[2], Jason Wang[5], Laurent Pueyo[3], Julien Rameau[7], Christian Marois[1]
Institution(s): *1. National Research Council of Canada Herzberg, 2. SETI Institute, 3. Space Telescope Science Institute, 4. Stanford University, 5. UC Berkeley, 6. UC San Diego, 7. Universite de Montreal*

202.03 – Do Photochemical Hazes Cloud the Atmosphere of 51 Eri b?

The first young giant planet to be discovered by the Gemini Planet Imager was the ~ 2MJ planet 51 Eri b. This ~20 Myr old young Jupiter is the first directly imaged planet to show unmistakable methane in H band. To constrain the planet’s mass, atmospheric temperature, and composition, the GPI J and H band spectra as well as some limited photometric points were compared to the predictions of substellar atmosphere models. The best fitting models reported in the discovery paper (Macintosh et al. 2015) relied upon a combination of clear and cloudy atmospheric columns to reproduce the data. In the atmosphere of an object as cool as 700 K the global silicate and iron clouds would be expected to be found well below the photosphere, although strong vertical mixing in the low gravity atmosphere is a possibility. Instead, clouds of Na2S, as have been detected in brown dwarf atmospheres, are a likely source of particle opacity. As a third explanation we have explored whether atmospheric photochemistry, driven by the UV flux from the primary star, may yield hazes that also influence the observed spectrum of the planet. To explore this possibility we have modeled the atmospheric photochemistry of 51 Eri b using two state-of-the-art photochemical models, both capable of predicting yields of complex hydrocarbons under various atmospheric conditions. We also have explored whether photochemical products can alter the equilibrium temperature profile of the atmosphere. In our presentation we will summarize the modeling approach employed to characterize 51 Eri b, explaining constraints on the planet's effective temperature, gravity, and atmospheric composition and also present results of our studies of atmospheric photochemistry. We will discuss whether photochemical hazes could indeed be responsible for the particulate opacity that apparently sculpts the spectrum of the planet.

Author(s): Mark Marley[1], Kevin Zahnle[1], Julianne Moses[2], Caroline Morley3
Institution(s): *1. NASA/Ames Research Center, 2. Space Science Institute, 3. UCSC*

202.04 – Observations of an extreme planetary system

Almost 500 planet host stars are already known to be surrounded by more than one planet. Most of them (except HR8799) are old and all planets were found with the same or similar detection method.
We present an unique planetary system. For the first time, a close in transiting and a wide directly imaged planet are found to orbit a common host star which is a low mass member of a young open cluster. The inner candidate is the first possible young transiting planet orbiting a previously known weak-lined T-Tauri star and was detected in our international monitoring campaign of young stellar clusters. The transit shape is changing between different observations and the transit even disappears and reappears. This unusual transit behaviour can be explained by a precessing planet transiting a gravity-darkened star.
The outer candidate was discovered in the course of our direct imaging survey with NACO at ESO/VLT. Both objects are consistent with a <5 Jupiter mass planet. With ~2.4 Myrs it is among the youngest exoplanet systems. Both planets orbit its star in very extreme conditions. The inner planet is very close to its Roche limiting orbital radius while the outer planet is far away from its host star at a distance of ~660 au. The detailed analysis will provide important constraints on planet formation and migration time-scales and their relation to protoplanetary disc lifetimes. Furthermore, this system with two planets on such extreme orbits gives us the opportunity to study the possible outcome of planet-planet scattering theories for the first time by observations.
I will report on our monitoring and photometric follow-up observations as well as on the direct detection and the integral field spectroscopy of this extreme planetary system.

Author(s): Stefanie Raetz[2], Tobias O. B. Schmidt3, Cesar Briceno4, Ralph Neuhäuser[1]
Institution(s): *1. Astrophysical Institute and University Observatory, 2. ESTEC/ESA, 3. Hamburger Sternwarte, 4. NOAO/CTIO*

202.05 – New SPHERE results on the planetary system around HR8799

Since its discovery in 2008, the multi-planetary system around HR8799 has become a unique testbed for planet formation theories at large orbital radii and the study of non-irradiated planetary atmospheres. We present new SPHERE/IRDIS data in J, H, and K band, for the four planets HR8799bcde with SPHERE/IRDIS and YH-band spectra for planets d and e with SPHERE/IFS. We detect the closest planet HR8799e in J band for the first time. The astrometry gathered for three epochs of observation set new constraints on a hypothetical planet f. We combine the SPHERE photometry and spectra to demonstrate that the 1-5 µm spectral-energy distribution (SED) of the planets e and d can be represented by those of dusty -and young - L7 dwarfs. We show that the two outermost planet SEDs are well reproduced by the spectra of peculiar early-T dwarfs reddened by refractory grain opacities. This demonstrates that the planet peculiar photometric properties are dominated by the effect of dust, and suggests that the planets c, and then b, are less massive that the two innermost ones.

Author(s): Alice Zurlo[2], Mickaël Bonnefoy[1]
Institution(s): *1. IPAG, 2. Universidad Diego Portales*

202.06 – LGS-AO Imaging of Every Kepler Planet Candidate: the Robo-AO KOI Survey

The Robo-AO Kepler Planetary Candidate Survey is observing every Kepler planet candidate host star with laser adaptive optics imaging, to search for blended nearby stars which may be physically associated companions and/or responsible for transit false positives. We will present the results from searching for companions around over 3,000 Kepler planet hosts in 2012-2015. We will describe our first data release covering 715 planet candidate hosts, and give a preview of ongoing results including improved statistics on the likelihood of false positive planet detections in the Kepler dataset, many new planets in multiple star systems, and new exotic multiple star systems containing Kepler planets. We will also describe the automated Robo-AO survey data reduction methods, including a method of using the large ensemble of target observations as mutual point-spread-function references, along with a new automated companion-detection algorithm designed for extremely large adaptive optics surveys. Our first data release covered 715 objects, searching for companions from 0.15" to 2.5" separation with contrast up to 6 magnitudes. We measured the overall nearby-star-probability for Kepler planet candidates to be 7.4+/-1.0%, and we will detail the variations in this number with stellar host parameters. We will also discuss plans to extend the survey to other transiting planet missions such as K2 and TESS as Robo-AO is in the process of being re-deployed to the 2.1-m telescope at Kitt Peak for 3 years and a higher-contrast Robo-AO system is being developed for the 2.2-m UH telescope on Maunakea.

Author(s): Christoph Baranec3, Nicholas Law4, Timothy Morton[2], Carl Ziegler4, Larissa Nofi3, Dani Atkinson3, Reed Riddle[1]
Institution(s): *1. Caltech, 2. Princeton, 3. University of Hawai`i at Manoa, 4. University of North Carolina at Chapel Hill*

203 – Direct Imaging II

203.01 – An Accreting Protoplanet: Confirmation and Characterization of LkCa15b

We present a visible light adaptive optics direct imaging detection of a faint point source separated by just 93 milliarcseconds (~15 AU) from the young star LkCa 15. Using Magellan AO's visible light camera in Simultaneous Differential Imaging (SDI) mode, we imaged the star at Hydrogen alpha and in the neighboring continuum as part of the Giant Accreting Protoplanet Survey (GAPplanetS) in November 2015. The continuum images provide a sensitive and simultaneous probe of PSF residuals and instrumental artifacts, allowing us to isolate H-alpha accretion luminosity from the LkCa 15b protoplanet, which lies well inside of the LkCa15 transition disk gap. This detection, combined with a nearly simultaneous near-infrared detection with the Large Binocular Telescope, provides an unprecedented glimpse at a planetary system during epoch of planet formation. [Nature result in press. Please embargo until released]

Author(s): Katherine Follette[2], Laird Close3, Jared Males3, Bruce Macintosh[2], Stephanie Sallum3, Josh Eisner3, Kaitlin M Kratter3, Katie Morzinski3, Phil Hinz3, Alycia Weinberger[1], Timothy J. Rodigas[1], Andrew Skemer3, Vanessa Bailey[2], Amali Vaz3, Denis Defrere3, eckhart spalding3, Peter Tuthill4
Institution(s): *1. Carnegie DTM, 2. Stanford University, 3. University of Arizona, 4. University of Sydney*

203.02 – Extreme Imaging: Revealing the structure of debris disks on solar systems scales with GPI

A new generation of extreme adaptive optics systems enables an unprecedented exploration of dusty debris disks on solar system scales. Here we review the new science derived from over a dozen debris disks imaged in total intensity and polarized intensity with the Gemini Planet Imager (GPI). These early results typically reveal narrow belts of material with evacuated regions roughly 50 AU in radius and with subtle asymmetries in structure. In many cases, complementary wider field images obtained with the Hubble Space Telescope uncover more extreme asymmetries in the distribution of dust on 100's of AU scales. We will discuss the possible causes of these asymmetries, such as the dynamical upheavals that can occur via internal or external perturbations. In a few cases, a gas giant planet has also been imaged in the system, raising new questions about the possible dynamical co-evolution of exoplanets and debris disks.

Author(s): Paul G. Kalas3, Abhijith Rajan6, Jason Wang3, Max Millar-Blanchaer7, Gaspard Duchene3, Christine H Chen1, Michael P. Fitzgerald4, Jennifer Patience6, Ruobing Dong3, James R. Graham3, Ruth Murray-Clay5, Bruce Macintosh2
Institution(s): *1. Space Telescope Science Institute, 2. Stanford University, 3. UC Berkeley, 4. UCLA, 5. UCSD, 6. University of Arizona, 7. University of Toronto*

203.03 – Resolving the Planetesimal Belt of HR 8799 with ALMA

HR 8799 is well known for being the only star to host multiple planets discovered through direct imaging. HR 8799 also hosts a debris disc first discovered by IRAS. This disc was one of the few resolved by Spitzer showing that dust is present out to a few thousand AU. The Spitzer data also showed that there must be multiple components to the dust both inside and outside the orbits of the planets. Naturally, this system has been a prime target for observations from various telescopes in recent years. We have observed the system with ALMA in band 6 (1340μm), detecting the disc at high resolution. For the first time we resolve the inner edge of the cold planetesimal belt and can determine its inclination at much higher precision than previous observations. I will discuss how these results compare to the previous observations and what these new results can tell us about the planets in the system.

Author(s): Mark Booth3, Andres Jordan3, Antonio Hales1, Simon Casassus4, Bill Dent1, Virginie Faramaz3, Luca Matrà2
Institution(s): *1. ALMA, 2. Cambridge University, 3. Pontificia Universidad Catolica de Chile, 4. Universidad de Chile*

203.04 – Extreme Exoplanet Direct Imaging: New Results with GPI and SCExAO and the Path to Imaging Another Earth

We describe the discovery of a bright, young Kuiper belt-like debris disk around HD 115600, a $\sim$ 1.4--1.5 M$_\mathrm{\odot}$, $\sim$ 15 Myr old member of the Sco-Cen OB Association. Our H-band coronagraphy/integral field spectroscopy from the \textit{Gemini Planet Imager} shows the ring has a (luminosity scaled) semi major axis of ($\sim$ 22 AU) $\sim$ 48 AU, similar to the current Kuiper belt. The disk appears to have neutral scattering dust, is eccentric (e $\sim$ 0.1--0.2), and could be sculpted by analogues to the outer solar system planets. Spectroscopy of the disk ansae reveal a slightly blue to gray disk color, consistent with major Kuiper belt chemical constituents, where water-ice is a very plausible dominant constituent. Besides being the first object discovered with the next generation of extreme adaptive optics systems (i.e. SCExAO, GPI, SPHERE), HD 115600's debris ring and planetary system provides a key reference point for the early evolution of the solar system, the structure and composition of the Kuiper belt, and the interaction between debris disks and planets.

Author(s): Thayne Currie1
Institution(s): *1. NAOJ/Subaru*

203.05 – Direct imaging of the cold jovian (?) companion GJ504b with VLT/SPHERE

In 2008, the Subaru/SEEDS survey reported the direct imaging discovery of a Jovian exoplanet around the Sun-like star GJ 504. With a mass of 3-10 MJup and projected separation of 43.5 AU, this object challenges the core-accretion paradigm. This is the only known nearly mature (age >> 50 Myr) gas giant planet imaged so far. The very low (500 K) estimated temperature of the object makes it a benchmark for the study of the physical and chemical processes at play into the non-irradiated atmospheres of gas giants.

We will present new SPHERE dual-band imaging data on the system gathered from 0.95 to 2.25 microns. The data enable to detect the companion and complete its spectral energy distribution. We use them to refine the effective temperature, surface gravity, and metallicity estimates for the object. This in turns enables to discuss the nature of the companion. We also set constraints on additional companions in the system.

Author(s): Mickaël Bonnefoy1
Institution(s): *1. IPAG*

203.06 – Extreme Planet-Like Systems: Brown Dwarfs at the Exoplanet Mass Boundary

Brown dwarfs have long been the observational anchors for our theoretical understanding of giant gas planets. Recent studies have uncovered a population of nearby young sources that rival the age and mass of many planetary mass companions. From detailed observations, we postulate that objects in this young population have dynamic atmospheres ripe with exotic, thick condensate cloud species that drive extreme photometric and spectroscopic characteristics. In this talk I will review how we are using these so-called exoplanet analogs to establish luminosity, temperature, age, and mass relations for brown dwarf into planetary mass objects.

Author(s): Jacqueline Kelly Faherty1
Institution(s): *1. Carnegie*

203.07 – Plasma processes in cloud-forming exoplanet and brown dwarf atmospheres

The increasing number of observations of cyclotron emission, possible chromospheric emission, and potential aurorae suggests that high energy processes occur also in, or are associated with ultra-cool, cloud-forming atmospheres like in extrasolar planets and brown dwarfs. While a magnetic field is primordial to brown dwarfs and most planets, free charges in form of electrons need to be continuously produced to allow the necessary magnetic coupling for cyclotron emission to occur or for the formation of a chromosphere and possible magnetically driven winds to emerge. This is particularly critical for free floating objects not bathed in the wind of a host or companion star.

We perform a reference study for late M-dwarfs, brown dwarfs and giant gas planets to identify which ultra-cool objects are most susceptible to plasma and magnetic processes. We utilise the Drift-Phoenix model grid where the local atmospheric structure is determined by the global parameters Teff , log(g) and metalicity [M/H]. For this reference study, thermal ionisation is considered only.

Our results show that it is not unreasonable to expect Halfa or radio emission to origin from ultra-cool atmospheres as in particular the rarefied upper parts of the atmospheres can be magnetically coupled
despite having low degrees of thermal gas ionisation. The minimum threshold for the magnetic flux density required for electrons and ions to be magnetised is well above typical values of the global magnetic field of brown dwarfs and giant gas planets. Such atmospheres could therefore drive, e.g., auroral emission without the need for a companion's wind or an outgassing moon. The reference study is based on thermal emission and provides therefore a lower limit for plasma effects in late M-dwarfs, brown dwarfs and giant gas planets. We have shown that non-equilibrium processes like cloud discharges in form of lightning and coronal discharges, high wind speeds and cosmic rays increase the local electron budget substantially.

Author(s): Christiane Helling[1]
Institution(s): *1. University of St Andrews*

300 – Planet Formation

300.01 – Spiral arms in scattered light images of protoplanetary disks

In the past few years, resolved observations with high angular resolution have revealed rich structures in gaseous protoplanetary disks. Among all discoveries, one of the most prominent is the giant double-spiral structure, found in MWC 758, SAO 206462, and HD 100453. The NIR images of these disks taken by Subaru/HiCIAO, VLT/NACO, and VLT/SPHERE showed two spiral arms at tens of AU from the center. The arms are very open with large pitch angles, and are in a nearly m=2 rotational symmetry. Although planets are known to be able to excite density waves in protoplanetary disks, fitting observations with linear theory of the density wave demands unreasonably big scale height in the disk, thus temperature, in order to make the arms as open as observed (and no need to mention the coincidence that they all have two nearly m=2 arms). Using 3D hydro and radiative transfer simulations, we find that a massive perturber (giant planet, brown dwarf, or stellar mass companion) can excite multiple spiral arms in the density structure, and the arms inside the perturber's orbit are very prominent in NIR scattered light images, in striking similarity with observations. Very recently, the perturber was found for the first time in the HD 100453 disk, as a M dwarf companion. This gives us great confidence of our models, and suggests that the double spirals in the other two objects, MWC 758 and SAO 206462, are very likely to be excited in a similar way, by a currently unseen perturber outside the arms. In particular, by measuring the angular distance between the two arms and comparing it with our models, we determine that the perturber in SAO 206462 is about 6 Jupiter mass.

Author(s): Ruobing Dong[1]
Institution(s): *1. UC Berkeley/LBL*

300.02 – Forming the Solar System from Pebbles

In recent years, theories surrounding the formation of small-bodies and planets have been undergoing a radical shift. Particles with stopping times comparable to their orbital times, often called "pebbles" (although they range from sub-centimeter to meter sizes), interact with gaseous protoplanetary disks in very special ways. This allows them to be not only be concentrated, allowing them to gravitationally collapse and directly produce the planetesimal building blocks of planetary systems, but also later be efficiently accreted on to these planetesimals, rapidly producing larger planets. Here we present simulations using the planet formation code LIPAD, which can follow the dynamical evolution of planetary system all the way from pebbles and planetesimals to mature planetary systems. We show how pebble accretion can explain the observed structure of our Solar System, by forming a system of giant planets, ice giants, and a system of terrestrial planets; even providing an explanation the for the low mass of Mars and of the Asteroid Belt.

Author(s): Katherine A. Kretke[1], H. F. Levison[1]
Institution(s): *1. Southwest Research Institute*

300.03 – When worlds collide: How collisions and fragmentation affect terrestrial planet formation

The late stages of terrestrial planet formation are dominated by giant impacts that collectively influence the growth, dynamical stability, composition and habitability of any planets that form. Numerical models designed to explore these late stage collisions have been limited in two major ways. First, nearly all N-body models have assumed that all collisions lead to perfect accretion. Second, many of these studies lack the large number of realizations needed to account for the chaotic nature of these N-body systems. We have recently developed an N-body algorithm, based on the widely-used *Mercury* integration package, that includes a state-of-the-art collision model that allows fragmentation and hit-and-run collisions. Using this new model, we have performed hundreds of simulations of late stage terrestrial planet formation around a Sun-like star with Jupiter and Saturn analogs. We will present these results and compare them to a set of 140 simulations using the standard perfect-accretion model. Over 90% of our fragmentation simulations produced an Earth-analog and we will discuss how we quantify the collisions that led to their formation in order to study their bulk compositions and likelihood of accreting and retaining an atmosphere and oceans.

Author(s): Elisa Quintana[2], Thomas Barclay[2], John Chambers[1], William Borucki[2], Jason F. Rowe[2]
Institution(s): *1. Carnegie Institution, 2. NASA Ames Research Center*

300.04 – Formation of Close-in Terrestrial Planets by Giant Impacts: The Basic Scaling Laws

The recent exoplanet surveys have shown that small close-in planets are more common than hot Jupiters. Most of them are considered as terrestrial (rocky) planets. Thus it becomes increasingly important to generally understand the formation of terrestrial planets. In the standard scenario of terrestrial planet formation, the final stage is the giant impact stage after the dispersal of a gas disk where protoplanets or planetary embryos collide with one another to complete planets. In the present paper, we investigate the in-situ formation of close-in terrestrial planets including super-Earths by giant impacts using N-body simulations. The goal of this project is to obtain the basic scaling laws of close-in terrestrial planet formation as a function of properties of protoplanet systems. We systematically change the system parameters of initial protoplanet systems and investigate their effects on the final planets. We find that in general non-resonant dynamically cold compact systems are formed. The orbits of planets are less eccentric and inclined and the orbital separations of adjacent planets are smaller, compared with those formed in the outer disk. The masses of all planets are almost comparable. These properties are natural outcomes of giant impacts in the inner disk. In the inner disk the ratio of the physical radius to the Hill radius is large, in other words, gravitational scattering is relatively less effective compared with that in the outer disk. Thus protoplanets are less mobile and accretion proceeds relatively locally, which leads to formation of dynamically cold compact systems. The typical mass of the largest planet increases almost linearly with the total mass of protoplanets, while the number of planets per radial width decreases. On average the system angular momentum deficit increases with the total system mass, while the mean orbital separation of adjacent planets decreases.

Author(s): Eiichiro Kokubo[1]
Institution(s): *1. National Astronomical Observatory of Japan*

300.05 – Large-Scale Structures of Planetary Systems

A class of solar system analogs has yet to be identified among the large crop of planetary systems now observed. However, since most observed worlds are more easily detectable than direct analogs of the Sun's planets, the frequency of systems with structures similar to our own remains unknown. Identifying the range of possible planetary system architectures is complicated by the large number of physical processes that affect the formation and dynamical evolution of planets. I will present two ways of organizing planetary system structures. First, I will suggest that relatively few physical parameters are likely to differentiate the qualitative architectures of different systems. Solid mass in a protoplanetary disk is perhaps the most obvious possible controlling parameter, and I will give predictions for correlations between planetary system properties that we would expect to be present if this is the case. In particular, I will suggest that the solar system's structure is representative of low-metallicity systems that nevertheless host giant planets. Second, the disk structures produced as young stars are fed by their host clouds may play a crucial role. Using the observed distribution of RV giant planets as a function of stellar mass, I will demonstrate that invoking ice lines to determine where gas giants can form requires fine tuning. I will suggest that instead, disk structures built during early accretion have lasting impacts on giant planet distributions, and disk clean-up differentially affects the orbital distributions of giant and lower-mass planets. These two organizational hypotheses have different implications for the solar system's context, and I will suggest observational tests that may allow them to be validated or falsified.

Author(s): Ruth Murray-Clay[2], Leslie A. Rogers[1]
Institution(s): *1. UC Berkeley, 2. UC Santa Barbara*

300.06 – Origins of Hot Jupiters, Revisited

Hot Jupiters, giant extrasolar planets with orbital periods less than ~10 days, have long been thought to form at large radial distances (a > 2AU) in protostellar disks, only to subsequently experience large-scale inward migration to the small orbital radii at which they are observed. Here, we propose that a substantial fraction of the hot Jupiter population forms *in situ*, with the Galactically prevalent short-period super-Earths acting as the source population. Our calculations suggest that under conditions appropriate to the inner regions of protostellar disks, rapid gas accretion can be initiated for solid cores of 10-20 Earth masses, in line with the conventional picture of core-nucleated accretion. This formation scenario leads to testable consequences, including the expectation that hot Jupiters should frequently be accompanied by additional planets, reminiscent of those observed in large numbers by NASA's Kepler Mission and Doppler velocity surveys. However, dynamical interactions during the early stages of planetary systems' evolutionary lifetimes tend to increase the mutual inclinations of exterior, low-mass companions to hot Jupiters, making transits rare. High-precision radial velocity monitoring provides the best prospect for their detection.

Author(s): Konstantin Batygin[1], Peter Bodenheimer[2], Greg Laughlin[2]
Institution(s): *1. Caltech, 2. UC Santa Cruz*

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301 – Structure and Evolution

301.01 – Earths, Super-Earths, and Jupiters

We review and add to the theory of how planets acquire atmospheres from parent circumstellar disks. We derive (in real time) a simple and general analytic expression for how a planet's atmosphere grows with time, as a function of the underlying core mass and nebular conditions, including the gas metallicity. Planets accrete as much gas as can cool: an atmosphere's doubling time is given by its Kelvin-Helmholtz time. The theory can be applied in any number of settings --- gas-rich vs. gas-poor nebulae; dusty vs. dust-free atmospheres; close-in vs. far-out distances --- and is confirmed against detailed numerical models for objects ranging in mass from Mars (0.1 Mearth) to the most extreme super Earths (10--20 Mearth). We explain why heating from planetesimal accretion, commonly invoked in models of core accretion, is irrelevant. This talk sets the stage for another presentation, "Breeding Super-Earths and Birthing Super-Puffs".

Author(s): Eugene Chiang[1], Eve J Lee[1]
Institution(s): *1. Berkeley*

301.02 – Internal structures and compositions of giant (exo)planets

One can now attempt to determine the abundances of key species in the atmospheres of exoplanets, in particular hot Jupiters. In parallel, the knowledge of the densities of these exoplanets informs us on their bulk composition in terms of amounts of dense material (rocks and ices) compared to light ones (hydrogen and helium). Linking these constraints seems natural and, intuitively, one would expect dense planets to contain more heavy elements in their atmospheres. However, several physical processes, in particular the formation of a central core, its gradual erosion and the growth of a deep outer radiative zone, could decouple partially or even completely interior and atmospheric composition. The latter will also depend on how heavy elements were delivered to the planet.

Close to us, measurements performed in the atmosphere of Jupiter (and to some extent in Saturn) already provide us with important clues: The high enrichment in carbon coupled to a more modest but significant enrichment in noble gases indicates that solids and gas-species followed different routes. Jupiter obtained its solids probably as a core and via pebble accretion and captured disk gas that had lost part of its hydrogen and helium. The elements originally solid in the disk but fluid in the planetary interior were at least partially mixed upward to account for the present day atmospheric composition.

This simple scenario can be tested. The comparison of bulk and atmospheric compositions of hot Jupiters of different masses will tell us the importance of mixing. Measurements by the Juno spacecraft at Jupiter starting in July 2016 will help us constrain the abundance of water, a key element to understand how the solids were captured.

Author(s): Tristan Guillot[2], Vivien Parmentier3, Mathieu Havel[1]
Institution(s): *1. Columbia University, 2. Observatoire de la Cote d'Azur, 3. UCSC*

301.03 – Breeding Super-Earths and Birthing Super-Puffs in Transitional Disks

The riddle posed by super-Earths (1--4 Earth radii, 2--20 Earth masses) is that they are not Jupiters: their core masses are large enough to trigger runaway gas accretion, yet somehow super-Earths accreted atmospheres that weigh only a few percent of their total mass. We show that this puzzle is solved if super-Earths formed late, as the last vestiges of their parent gas disks were about to clear. This scenario would seem to present fine-tuning problems, but we show that there are none. Ambient gas densities can span many orders of magnitude, and super-Earths can robustly emerge with percent-by-weight atmospheres after ~0.1--1 Myr. We propose that 1) close-in super-Earths form in situ, because their cores necessarily coagulate in gas-poor environments—gas dynamical friction must be weakened sufficiently to allow constituent protocores to cross orbits and merge; 2) super- Earths acquire their atmospheres from ambient wisps of gas that are supplied from a diffusing outer disk. The formation environment is reminiscent of the largely evacuated but still accreting inner cavities of transitional protoplanetary disks. We also 3) address the inverse problem presented by super-puffs: an uncommon class of short- period planets seemingly too voluminous for their small masses (4--10 Earth radii, 2--6 Earth masses). Super-puffs most easily acquire their thick atmospheres as dust-free, rapidly cooling worlds outside ~1 AU where nebular gas is colder, less dense, and therefore less opaque. Unlike super-Earths which can form in situ, super-puffs probably migrated in to their current orbits; they are expected to form the outer links of mean-motion resonant chains, and to exhibit greater water content.

Author(s): Eve J Lee[1], Eugene Chiang[1]
Institution(s): *1. UC Berkeley*

301.04 – Extreme Water: Characterizing Exoplanets with Excess Bulk Water Interiors

A number of planets with radii of 1 - 2.5 Earth radius have measured mean densities that allow more than 20% of their bulk interior to be composed of water. How do planets with solid-state water mantles modulate the fluxes of gases reaching the surface? What should we expect about the composition of their evolved atmospheres? I review theoretical models of the interiors and near-surface layers that constrain the fluxes of major gases (in and out) and resulting atmospheric compositions. The results have implications for observational characterization of rocky versus water planets, when the density alone is not enough, as well as the search for biosignatures and habitability.

Author(s): Dimitar Sasselov[1]
Institution(s): *1. Harvard University*

301.05 – Ohmic Dissipation in Mini-Neptunes

In the quest of characterizing low-mass exoplanets, it is important to consider all sources that may contribute to the interpretation of planetary composition given mass and a radius measurements. While it has been firmly established that inferring the composition of super-Earths and mini-Neptunes suffers from the inherent problem of compositional degeneracy, the effect from ohmic dissipation on these planets and its connection to compositional interpretation has not been studied so far. Ohmic dissipation is arguably the leading theory that aims to explain the large radii seen in highly-irradiated exo-Jupiters. In this study, we determine the strength of ohmic dissipation on mini-Neptunes and its effect on their H/He envelope structure as a function of insolation temperature and planetary mass. We find that ohmic dissipation is strong enough to halt the contraction of mini-Neptunes during their thermal evolution and therefore, inflate their radii in comparison to planets that do not suffer dissipation. This means that the radius of highly irradiated of this class of planets may be explained by the presence of volatiles and ohmic dissipation. In other words, there is a trade-off between ohmic dissipation and H/He content for hot mini-Neptunes.

Author(s): Diana Valencia[2], Michael Pu[1]
Institution(s): *1. Cornell University, 2. University of Toronto*

301.06 – The physical properties of giant exoplanets within 400 days of period

At a time when small planets in the habitable zone are found, not all the questions about giant planets have been answered. For example, their formation, migration and evolution are far from being fully understood. In this context, the Kepler space mission is providing unprecedented constraints to theories by probing transiting giant planets in a wide range of orbital periods. In this talk, we will present the results of a 6-year spectroscopic survey with the SOPHIE spectrograph of the transiting giant-planet candidates detected by Kepler within 400 days of period. First, we will describe the giant-planet candidate sample from the Kepler catalog and our spectroscopic observations which allowed us to screen out more than half of the candidates as false positives. Then, we will present the occurrence rate of giant planets, based on our sample cleaned from fake transiting planets, and compare it with other surveys. Finally, we will discuss the physical properties of the giant transiting planets within 400 days of period and compare them with predictions from planet-synthesis models.

Author(s): Alexandre Santerne[1]
Institution(s): *1. University of Porto*

301.07 – On the expected properties of exomoons

The potential discovery of exomoons is important, as they could provide constraints on their host planets' formation, and large exomoons may represent potentially habitable environments. Detection of exomoons is extremely challenging. However, upper limits on exomoon masses have now been determined for a few dozen planets (Kipping et al. 2015), and additional constraints and/or detections are anticipated in the next several years.

In our solar system, regular satellites are thought to have originated by two main processes: giant impacts and co-accretion. The origin of moons by collisions into solid planets is reasonably well-understood. Depending primarily on the impact angle and the mass of the impactor compared to the target, collisions can produce a broad range of satellite-to-planet mass ratios, M_{sat}/M_p, ranging from tiny moons to relatively massive satellites such as the Moon (M_{sat}/M_p = 0.01; e.g., Canup 2004) and Pluto's Charon (M_{sat}/M_p = 0.12; e.g., Canup 2005). In contrast, the satellite systems of the gas planets in our solar system all have M_{sat}/M_p ~10^{-4}. This similarity is striking given what were presumably different accretion histories for each of these planets. It has been shown that a common satellite system mass ratio results when satellites co-accrete within disks produced by gas and solids inflowing to a planet, with the predicted value of (M_{sat}/M_p) depending rather weakly on the ratio of the disk's gas viscosity parameter to the gas-to-solids ratio in the inflow (Canup & Ward 2006).

The transition between these two modes of origin is unclear, but could reasonably occur once a planet grows large enough to accrete substantial gas through a circumplanetary disk (e.g., M_p ~ 5 to 10 Earth masses; e.g., Machida et al. 2008; 2010). Alternative satellite-forming mechanisms are also possible, e.g., intact capture. However to date, exomoon upper limits appear consistent with expectations based on formation by impact or co-accretion. If exomoons form primarily by these two processes, the most likely hosts of a Mars-sized exomoon would be predominantly solid planets of several Earth masses, or gas giants substantially more massive than Jupiter.

Author(s): Robin Canup[1]
Institution(s): *1. Southwest Research Institute*

400 – Atmospheres I

400.01 – Atmospheric circulation of warm and hot Jupiters: effect of nonsynchronous rotation and stellar irradiation

Efforts to characterize and model extrasolar giant planet (EGP) atmospheres have so far emphasized planets within ~0.05 AU of their stars. Despite this focus, known EGPs now populate nearly a continuum of orbital separations from canonical hot Jupiter values (~0.03-0.05 AU) out to 1 AU and beyond. Unlike typical hot Jupiters, these more distant EGPs will not in general be synchronously rotating and may exhibit a range of rotation rates. In anticipation of observations of this wider population, we here present state-of-the-art atmospheric circulation models including realistic non-grey radiative transfer to explore the dynamical regime that emerges over a broad range of rotation rates and incident stellar fluxes appropriate for warm and hot Jupiters. We find that the circulation resides in one of two basic regimes. The circulation for canonical hot Jupiters exhibits a broad, fast superrotating (eastward) equatorial jet driven by the strong day-night heating contrast, with westward mean flow at high latitudes and large day-night temperature differences. Non-synchronous rotation exerts a significant influence on the jet structure and temperature patterns. Under the less-strongly irradiated conditions appropriate to warm Jupiters, however, the circulation transitions to a vastly different dynamical regime: the day-night heating gradient becomes less important, and baroclinic instabilities emerge as a dominant player, leading to eastward zonal jets in the midlatitudes, with significant equator-to-pole temperature differences, minimal temperature variations in longitude, and, in many cases, weak windflow at the equator. We present infrared (IR) light curves and spectra of these models, which depend significantly on incident stellar flux and rotation rate. This provides a way to identify the regime transition in future observations. In some cases, IR light curves can provide constraints on the rotation rate of nonsynchronously rotating planets.

Author(s): Adam P Showman[2], Nikole K Lewis[1], Jonathan J. Fortney3
Institution(s): *1. Space Telescope Science Institute, 2. University of Arizona, 3. University of California Santa Cruz*

400.02 – A New Angle on Atmosphere Characterization of Giant Exoplanets

Detailed characterization of exoplanets has begun to yield constraints on their atmospheric properties that rival our knowledge of the Solar System planets. These measurements provide unique insight into planet formation and evolution because atmospheres are a rich record of protoplanetary disk chemistry. In this talk, I will present new constraints on hot Jupiter atmospheric composition and thermal structure from two intensive Hubble Space Telescope observational campaigns targeting WASP-12b and WASP-103b. For WASP-12b, we obtained a very precise near-infrared spectrum that exhibits water features at high confidence (>7σ). This detection marks the first spectroscopic identification of a molecule in the planet's atmosphere and implies that it has solar composition, ruling out carbon-to-oxygen ratios greater than unity. For WASP-103b, I will present preliminary results from the new technique of phase-resolved spectroscopy that constrain the planet's temperature structure, dynamics, and energy budget. Taken together, these results highlight the importance of synthesizing multiple observing angles - emission spectroscopy, transmission spectroscopy, and phase curves - to obtain precise, robust constraints on the chemistry and physics of exoplanet atmospheres.

Author(s): Laura Kreidberg[1]
Institution(s): *1. University of Chicago*

400.03 – Measurements of Water Absorption in the Warm Exo-Uranus GJ 3470b

The discovery of short-period planets with masses and radii intermediate between Earth and Neptune was one of the biggest surprises in the brief history of exoplanet science. These "super-Earths" and "sub-Neptunes" are an order of magnitude more abundant than close-in giant planets. Despite this ubiquity, we know little about their typical compositions and formation histories. Spectroscopic transit observations can shed new light on these mysterious worlds by probing their atmospheric compositions. In this talk, we will give an overview of our ongoing 124-orbit (200-hour) Hubble Space Telescope program to reveal the chemical diversity and formation histories of super-Earths. This unprecedented survey will provide the first comprehensive look at this intriguing new class of planets ranging from 1 Neptune mass and temperatures close to 2000K to a 1 Earth mass planet near the habitable zone of its host star. In this talk, I will discuss the scope of the program and present early science results including measurements of water absorption in the atmosphere of the warm exo-Uranus GJ3470b.

Author(s): Björn Benneke[1], Ian Crossfield5, Heather Knutson[1], Peter McCullough3, Joshua Lothringer5, Andrew Howard[6], Caroline Morley4, Jonathan Fortney4, Diana Dragomir[2], Ron Gilliland3
Institution(s): *1. California Institute of Technology, 2. LCOGT, 3. STScI, 4. UC Santa Cruz, 5. University of Arizona, 6. University of Hawaii*

400.04 – Lessons learnt and results from the first survey of transiting exoplanet atmospheres using a multi-object spectrograph

We present results from the first comprehensive survey program dedicated to probing transiting exoplanet atmospheres using transmission spectroscopy with a multi-object spectrograph (MOS). Our three-year survey focused on nine close-in giant planets for which the wavelength dependent transit depths in the visible were measured with Gemini/GMOS. In total, about 40 transits (200 hours) have been secured, with each exoplanet observed on average during four transits. This approach allows for a high spectrophotometric precision (200-500 ppm / 10 nm) and for a unique and reliable estimate of systematic uncertainties. We present the main results from this survey, the challenges faced by such an experiment, and the lessons learnt for future MOS observations and instrument designs. We show that the precision achieved by this survey permits us to distinguish hazy atmospheres from cloud-free scenarios. We lay out the challenges that are in front of us whilst preparing future atmospheric reconnaissance of habitable worlds with multi-object spectrographs.

Author(s): Jean-Michel Desert[1]
Institution(s): *1. University of Colorado*

400.05 – Scorched Planets: Understanding the Structure and Climate of Hot Jupiter Atmospheres

Radial velocity and transit surveys have revealed that hot Jupiters are intrinsically rare in the Galaxy. These extreme examples of extrasolar planets have been the subject of many studies to date, but their formation and evolution are still shrouded in mystery. I will present results from a large ground-based survey to study the atmospheres of hot Jupiters via their secondary eclipses in the near-infrared. Such observations provide us with a direct measurement of thermal emission from a planet's day-side, allowing us to probe the connection between the atmospheric structure and climate deep in their atmospheres, as well as the irradiation from their host star. I will present results obtained for several hot Jupiters using the wide-field camera WIRCam on the 3.6m Canada-France-Hawaii-Telescope (CFHT). The sample of hot Jupiters observed to date in the CFHT survey spans a range of planetary parameters (e.g. temperatures and densities) and also includes several new exotic discoveries from the KELT transit survey, such as a planet in a hierarchical triple stellar system as well as a planet with a very rapidly rotating host star. Results from the CFHT survey will be combined with those from an ongoing survey of hot Jupiter eclipses in the southern hemisphere using the 3.9m Anglo-Australian Telescope as well as an upcoming survey using the 4m Mayall Telescope at Kitt Peak National Observatory. The combined survey will be the largest homogeneous study of this kind to date, and it will provide us with the congruent observations of a significant number of unique planets in eclipse. These observations will ultimately allow a comprehensive statistical analysis of the diversity of hot Jupiter atmospheres via their near-infrared eclipses. In addition, this project will identify legacy targets for comparative exoplanetology using next-generation facilities such as the James Webb Space Telescope.

Author(s): Knicole Colón5, Eder Martioli3, Daniel Angerhausen[6], Joseph E. Rodriguez[10], George Zhou[2], Joshua Pepper4, Keivan Stassun[10], B. Scott Gaudi7, David James[1], Jason Eastman[2], Thomas G. Beatty[8], Daniel Bayliss9
Institution(s): *1. CTIO, 2. Harvard-Smithsonian CfA, 3. Laboratorio Nacional de Astrofisica, 4. Lehigh University, 5. NASA Ames Research Center, 6. NASA Goddard Space Flight Center, 7. The Ohio State University, 8. The Pennsylvania State University, 9. University of Geneva, 10. Vanderbilt University*

400.06 – Exploring Links Between Orbital Dynamics and Atmospheres in Kepler M Dwarf Planetary Systems

The Solar System furnishes the most familiar planetary architecture: many planets, orbiting nearly coplanar to one another. However, the most common planetary systems in the Milky Way orbit much smaller M dwarf stars, and these may present a very different blueprint. The Kepler data set has furnished more than 100 exoplanets orbiting stars half the mass of the sun and smaller. Half of these planets reside in systems with at least one additional planet. The data much prefer a model with two distinct modes of planet formation around M dwarfs, which occur in roughly equal measure. One mode is one very similar to the Solar System in terms of multiplicity and coplanarity, and the other is very dissimilar. Given this so-called "Kepler Dichotomy," we examine the broadband transmission spectra (with data from Kepler and hundreds of hours of Spitzer observations) of dozens of M dwarf planets: half of which reside in one type of planetary system, and half in the other. Although the data set is too small and the observational uncertainty too large to characterize any one system alone, we examine ensemble trends between planetary dynamics and atmospheric content.

Author(s): Sarah Ballard[1]
Institution(s): *1. MIT*

401 – Atmospheres II

401.01 – Seeing Through the Clouds: Thermal Emission and Reflected Light Spectra of Super-Earths with Flat Transmission Spectra

Vast resources have been dedicated to characterizing the handful of planets with radii between Earth's and Neptune's that are accessible to current telescopes. Observations of their transmission spectra have been inconclusive and do not constrain their atmospheric compositions. Of the planets smaller than Neptune studied to date, all have radii in the near-infrared consistent with being constant in wavelength, likely showing that these small planets are consistently enshrouded in thick hazes and clouds. We explore the types of clouds and hazes that can completely obscure transmission spectra and find that very thick, lofted clouds of salts or sulfides in high metallicity (1000× solar) atmospheres create featureless transmission spectra in the near-infrared. Photochemical hazes with a range of particle sizes also create featureless transmission spectra at lower metallicities.

We present a path forward for understanding this class of small planets: by understanding the thermal emission and reflectivity of small planets, we can break the degeneracies and better constrain the atmospheric compositions. Cloudy thermal emission spectra have muted features more like blackbodies, and hazy thermal emission spectra have emission features caused by an inversion layer at altitudes where the haze forms. Analysis of reflected light from warm (~400-800 K) planets can distinguish cloudy planets, which have moderate albedos (A_g=0.05–0.20), from hazy planets, which are very dark (A_g=0.0–0.03). Reflected light spectra of cold planets (~200 K) accessible to a space-based visible light coronagraph may be the key to understanding small planets: they will have high albedos and large molecular features that actually allow them to be more easily characterized than the warmer transiting planets. We suggest a number of complementary observations to characterize super Earths, including transmission spectra of hot (~1000 K) targets, thermal emission spectra of warm targets using the James Webb Space Telescope (*JWST*), and high spatial resolution spectral observations of directly-imaged cold targets in reflected light. These observations may provide rich diagnostics of molecules and clouds in small planets, in contrast to the limited success to date.

Author(s): Caroline Morley5, Jonathan J. Fortney5, Mark Marley3, Kevin Zahnle3, Michael R. Line3, Eliza M.-R. Kempton[1], Nikole K Lewis4, Kerri Cahoy[2]
Institution(s): *1. Grinnell College, 2. MIT, 3. NASA Ames Research Center, 4. Space Telescope Science Institute, 5. UC Santa Cruz*

401.02 – Clouds Composition in Super-Earth Atmospheres: Chemical Equilibrium Calculations

Attempts to determine the composition of super-Earth atmospheres have so far been plagued by the presence of clouds. Yet the theoretical framework to understand these clouds is still in its infancy. For the super-Earth archetype GJ 1214b, KCl, Na_2S, and ZnS have been proposed as condensates that would form under the condition of chemical equilibrium, if the planet's atmosphere has a bulk composition near solar. Condensation chemistry calculations have not been presented for a wider range of atmospheric bulk composition that is to be expected for super-Earth exoplanets. Here we provide a theoretical context for the formation of super-Earth clouds in atmospheres of varied composition by determining which condensates are likely to form, under the assumption of chemical equilibrium. We model super-Earth atmospheres assuming they are formed by degassing of volatiles from a solid planetary core of chondritic material. Given the atomic makeup of these atmospheres, we minimize the global Gibbs free energy of over 550 gases and condensates to obtain the molecular composition of the atmospheres over a temperature range of 350-3,000 K. Clouds should form along the temperature-pressure boundaries where the condensed species appear in our calculations. The super-Earth atmospheres that we study range from highly reducing to oxidizing and have carbon to oxygen (C:O) ratios that are both sub-solar and super-solar, thereby spanning a diverse range of atmospheric composition that is appropriate for low-mass exoplanets. Some condensates appear across all of our models. However, the majority of condensed species appear only over specific ranges of H:O and C:O ratios. We find that for GJ 1214b, KCl is the primary cloud-forming condensate at solar composition, in agreement with previous work. However, for oxidizing atmospheres, where H:O is less than unity, K_2SO_4 clouds form instead. For carbon-rich atmospheres with super-solar C:O ratios, graphite clouds additionally appear. At higher temperatures, clouds are formed from a variety of materials including metals, metal oxides, and aluminosilicates.

Author(s): Eliza M.-R. Kempton[1], Rostom Mbarek[1]
Institution(s): *1. Grinnell College*

401.03 – Rotation and winds of exoplanet HD 189733 b measured with high-resolution transmission spectroscopy

At the dawn of exoplanet science, the first discoveries revealed the existence of giant planets orbiting very close to their parent stars, called hot Jupiters. Early theories suggested that these planets should be tidally locked, although their spin rotation has never been measured directly. On top of rotation, hot Jupiters can show equatorial super-rotation via eastward jet streams and/or high-altitude winds flowing from the day- to the night-side hemisphere. All these patterns broaden and distort the planet spectral lines to an extent that is detectable with measurements at high spectral resolution.
High-dispersion observations have recently excelled in robustly detecting molecules in the atmospheres of transiting and non-transiting hot Jupiters, and in measuring their relative abundances. Here the method is applied to the transmission spectrum of HD 189733 b, a Jupiter-size planet orbiting a K1-2V star in 2.2 days, observed around 2.3μm with CRIRES at the ESO Very Large Telescope. At a spectral resolution of R~100,000, the combined absorption of carbon monoxide and water vapor is detected in the planet spectrum at a confidence level of 7σ. The signal is obtained by cross correlating with theoretical spectra and it is maximized for a planet rotational velocity of $3.5^{+1.1}_{-2.6}$ km/s. This corresponds to a planet rotational period of $1.7^{+4.9}_{-0.4}$ days, consistent with the known orbital period of 2.2 days and therefore with tidal locking. Although planet rotations faster than 1.1 days can be ruled out at high confidence (3σ), sub-synchronous rotational velocities (Vrot < 2.7 km/s) or no-rotation are only marginally excluded (1.2σ). Finally, no significant day-to-night side winds are detected. When compared to the recent detection of sodium Doppler shifted by -8 km/s, this likely implies a strong wind shear between the atmospheric levels probed by these high-dispersion observations and the outermost atmospheric layers where the core of the sodium lines are formed.

Author(s): Matteo Brogi[1]
Institution(s): *1. University of Colorado at Boulder*

401.04 – New frontiers of high-resolution spectroscopy: Probing the atmospheres of brown dwarfs and reflected light from exoplanets

High-resolution spectroscopy (R>25,000) is a robust and powerful tool in the near-infrared characterization of exoplanet atmospheres. It has unambiguously revealed the presence of carbon monoxide and water in several hot Jupiters, measured the rotation rate of beta Pic b, and suggested the presence of fast day-to-night winds in one atmosphere. The method is applicable to transiting, non-transiting, and directly-imaged planets. It works by resolving broad molecular bands in the planetary spectrum into a dense, unique forest of individual lines and tracing them directly by their Doppler shift, while the star and tellurics remain essentially stationary. I will focus on two ongoing efforts to expand this technique. First, I will present new results on 51 Peg b revealing its infrared atmospheric compositional properties, then I will discuss an ongoing optical HARPS-N/TNG campaign (due mid October 2015) to obtain a detailed albedo spectrum of 51 Peg b at 387-691 nm in bins of 50nm. This spectrum would provide strong constraints on the previously claimed high albedo and potentially cloudy nature of this planet. Second, I will discuss preliminary results from Keck/NIRSPAO observations (due late September 2015) of LHS 6343 C, a 1000 K transiting brown dwarf with an M-dwarf host star. The high-resolution method converts this system into an eclipsing, double-lined spectroscopic binary, thus allowing dynamical mass and radius estimates of the components, free from astrophysical assumptions. Alongside probing the atmospheric composition of the brown dwarf, these data would provide the first model-independent study of the bulk properties of an old brown dwarf, with masses accurate to <5%, placing a crucial constraint on brown dwarf evolution models.

Author(s): Jayne Birkby[1], Roi Alonso[2], Matteo Brogi[6], David Charbonneau[1], Jonathan Fortney[5], Sergio Hoyer[2], John Asher Johnson[1], Remco de Kok[4], Mercedes Lopez-Morales[1], Ben Montet[1], Ignas Snellen[3]
Institution(s): *1. Harvard-Smithsonian Center for Astrophysics, 2. Instituto de Astrofisica de Canarias, 3. Leiden Observatory, 4. SRON Netherlands Institute for Space Research, 5. University of California, Santa Cruz, 6. University of Colorado at Boulder*

401.05 – Connecting Young Brown Dwarfs and Directly Imaged Gas-Giant Planets

Direct detections of gas-giant exoplanets and discoveries of young (~10-100 Myr) field brown dwarfs from all-sky surveys are strengthening the link between the exoplanet and brown dwarf populations, given the overlapping ages, masses, temperatures, and surface gravities. In light of the relatively small number of directly imaged planets and the modest associated datasets, the large census of young field brown dwarfs provides a compelling laboratory for enriching our understanding of both classes of objects. However, work to date on young field objects has typically focused on individual discoveries.

We present a large comprehensive study of the youngest field brown dwarfs, comprising both previously known objects and our new discoveries from the latest wide-field surveys (Pan-STARRS-1 and WISE). With masses now extending down to ~5 Jupiter masses, these objects have physical properties that largely overlap young gas-giant planets and thus are promising analogs for studying exoplanet atmospheres at unparalleled S/N, spectral resolution, and wavelength coverage. We combine high-quality spectra and parallaxes to determine spectral energy distributions, luminosities, temperatures, and ages for young field objects. We demonstrate that this population spans a continuum in the color-magnitude diagram, thereby forming a bridge between the hot and cool extremes of directly imaged planets. We find that the extremely dusty properties of the planets around 2MASS J1207-39 and HR 8799 do occur in some young brown dwarfs, but these properties do not have a simple correspondence with age, perhaps contrary to expectations. We find young field brown dwarfs can have unusually low temperatures and suggest a new spectral type-temperature scale appropriate for directly imaged planets.

To help provide a reference for extreme-contrast imaging surveys, we establish a grid of spectral standards and benchmarks, based on membership in nearby young moving groups, in order to calibrate gravity (age) and temperature diagnostics from near-IR spectroscopy. Finally, we use our data to critically examine the possibility that free-floating objects and companions may share different evolutionary histories, thereby complicating the brown dwarf-exoplanet connection.

Author(s): Michael Liu[2], Trent Dupuy[3], Katelyn Allers[1], Kimberly Aller[2], William Best[2], Eugene Magnier[2]
Institution(s): *1. Bucknell University, 2. University of Hawaii, 3. UT Austin*

401.06 – 1 to 2.4 microns spectrum and orbital properties of the Giant Planet Beta Pictoris b obtained with the Gemini Planet Imager

We present a low-resolution multi-band spectrum of the planetary companion to the nearby young star beta Pictoris using the Gemini Planet Imager (GPI). GPI is designed to image and provide low-resolution spectra of Jupiter sized, self-luminous planetary companions around young nearby stars. While H-band is the primary workhorse for the GPI Exoplanet Survey, the instrument is capable of observing in the near infrared covering Y, J, H, and K bands. These observations of Beta Pic Pictoris b were taken covering multiple bands as part of GPI's verification and commissioning phase in 2013 and 2014. Using atmospheric models along with the H-band data we recently reported an effective temperature of 1600-1700 K and a surface gravity of log (g) = 3.5-4.5 (cgs units). A similar exercise was also carried out by an independent team using the J band data, and did yield similar conclusions. These values agree well with "hot-start" predictions from planetary evolution models for a gas giant with mass between 10 and 12 M Jup and age between 10 and 20 Myr. Here we revisit these conclusions in light of a joint analysis of these two datasets along with the longer wavelength GPI spectrum in K band, and present refined constraints on the atmospheric properties of this giant planet. In addition, we present an updated orbit for Beta Pictoris b based on astrometric measurements taken using commissioning and subsequent monitoring observations, spanning 14 months. The planet has a semi-major axis of 9.2 (+1.5 −0.4) AU, with an eccentricity $e \leq 0.26$. The position angle of the ascending node is Ω=31.75 deg±0.15, offset from both the outer main disk and the inner disk seen in the GPI image. We finally discuss these properties in the context of planet-disk dynamical interactions.

Author(s): Laurent Pueyo[2], Jeffrey Chilcote[6], Max Millar-Blanchaer[6], Travis Barman[5], Michael P. Fitzgerald[4], James R. Graham[3], James Larkin[4], Paul G. Kalas[3], Rebekah dawson[3], Jason Wang[3], Marshall Perrin[2], Dae-Sik Moon[6], Bruce Macintosh[1]
Institution(s): *1. Stanford University, 2. STScI, 3. UC Berkeley, 4. UCLA, 5. University of Arizona, 6. University of Toronto*

401.07 – Near-Infrared Spectroscopy of a Quadruple System Spanning the Stellar to Planetary Mass Regimes

High-contrast imaging surveys are discovering a growing number of brown dwarf companions and giant planets orbiting stars at wide separations between 10-100 AU, but the formation of these objects is poorly understood because multiple routes (disk instability, core accretion plus dynamical scattering, and cloud fragmentation) may contribute to this population. I will describe recent observations of 2M0441+2301 AabBab, a unique young (1-3 Myr) hierarchical quadruple system comprising a low-mass star, two brown dwarfs, and a planetary-mass companion in Taurus. Our near-infrared imaging and spectroscopy with Keck/NIRC2 and OSIRIS confirm the young age, late spectral type (~L1), and low temperature (~1800 K) of the faintest component, 2M0441+2301 Bb. With individual masses of ~200 Mjup, 35 Mjup, 19 Mjup, and 9.8 Mjup, 2M0441+2301 AabBab is the lowest-mass quadruple system known. Its hierarchical orbital architecture and mass ratios imply that it formed from the collapse and fragmentation of a molecular cloud core, demonstrating that planetary-mass companions can originate from a stellar-like pathway analogous to higher-mass quadruple star systems. More generally, cloud fragmentation may be an important formation pathway for the massive exoplanets that are now regularly being imaged on wide orbits.

Author(s): Brendan Bowler[1], Lynne Hillenbrand[1]
Institution(s): *1. Caltech*

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402 – Planets in and around Binaries I

402.01 – Kepler-47: A Three-Planet Circumbinary System

Kepler-47 is the most interesting of the known circumbinary planets. In the discovery paper by Orosz et al. (2012) two planets were detected, with periods of 49.5 and 303 days around the 7.5-day binary. In addition, a single "orphan" transit of a possible third planet was noticed. Since then, five additional transits by this planet candidate have been uncovered, leading to the unambiguous confirmation of a third transiting planet in the system. The planet has a period of 187 days, and orbits in between the previously detected planets. It lies on the inner edge of the optimistic habitable zone, while its outer sibling falls within the conservative habitable zone. The orbit of this new planet is precessing, causing its transits to become significantly deeper over the span of the Kepler observations. Although the planets are not massive enough to measurably perturb the binary, they are sufficiently massive to interact with each other and cause mild transit timing variations (TTVs). This enables our photodynamical model to estimate their masses. We find that all three planets have very low-density and are on remarkably co-planar orbits: all 4

orbits (the binary and three planets) are within ~2 degrees of one another. Thus the Kepler-47 system puts interesting constraints on circumbinary planet formation and migration scenarios.

Author(s): William Welsh[1], Jerome Orosz[1], Billy Quarles[1], Nader Haghighipour[2]
Institution(s): *1. San Diego State University, 2. University of Hawaii Manoa*

402.02 – KIC-5473556: the largest and longest-period Kepler transiting circumbinary planet

We report the discovery of a new Kepler transiting circumbinary planet (CBP). This latest addition to the still-small family of CBPs defies the current trend of short-period CBPs orbiting near the stability limit of binary stars. Unlike the previous discoveries, the planet in the KIC-5473556 system has a very long orbital period (~1100 days) and was at conjunction only twice during the Kepler mission -- making it the longest-period transiting CBP at the time of writing. With a radius of nearly 12 REarth, it is also the largest such planet to date. It produced three transits in the light curve of KIC 5473556, one of them during a syzygy. The planet revolves around an ~11-day Eclipsing Binary consisting of two Solar-mass stars on a slightly inclined to the line of sight, mildly eccentric (ebin = 0.16) orbit. The CBP measurably perturbs the times of the stellar eclipses, allowing us to constrain its mass well. Here we present our spectroscopic and photometric observations of the target, discuss our analysis of the system, and outline the theoretical implications of our discovery.

Author(s): Veselin Kostov[1]
Institution(s): *1. NASA GSFC*

402.03 – The Architecture of Circumbinary Systems

Transiting circumbinary planets, as discovered by *Kepler*, provide unique insight into planet formation and planetary dynamics. These planets are low mass (about Neptune or smaller) and reside close to the stability limit of the binary. The question then becomes nature or nurture? Have circumbinary disks preferentially formed low mass, close in planets, or have dynamical processes sculpted the system into what we observe? We used N-body simulations to explore the impact of planet-planet scattering on the orbital architecture of four planetary populations around both single and binary stars. I will present the similarities and differences in the resultant planet populations. For instance, the final multiplicity is similar between single and binary stars, but planets in binary systems are much more likely to eject than collide. I will address the observable multiplicity and other unique characteristics our simulations have revealed. With this work and future observations, we will be able to better understand the underlying initial planetary distributions around binary stars and the formation mechanisms that allow these systems to form.

Author(s): Rachel Smullen[1], Kaitlin M Kratter[1]
Institution(s): *1. University of Arizona*

402.04 – Orbital Architectures of Planet-Hosting Binary Systems

We present the first results from our Keck AO astrometric monitoring of Kepler planet-hosting binary systems. Observational biases in exoplanet discovery have long left the frequency, properties, and provenance of planets in most binary systems largely unconstrained. Recent results from our ongoing survey of a volume-limited sample of Kepler planet hosts indicate that binary companions at solar-system scales of 20–100 AU suppress the occurrence of planetary systems at a rate of 30–100%. However, some planetary systems do survive in binaries, and determining these systems' orbital architectures is key to understanding why. As a demonstration of this new approach to testing ideas of planet formation, we present a detailed analysis of the triple star system Kepler-444 (HIP 94931) that hosts five Ganymede- to Mars-sized planets. By combining our high-precision astrometry with radial velocities from HIRES and computational dynamical modeling, we discover an unexpected orbital architecture for this multi-planet, triple-star system. Finally, we preview results from our full statistical sample, such as tests of coplanarity between binary and planet orbits in single versus multi-planet systems.

Author(s): Trent Dupuy[6], Kaitlin M Kratter3, Adam Kraus[6], Howard T. Isaacson4, Andrew Mann[6], Michael Ireland[1], Andrew Howard5, Daniel Huber[2]
Institution(s): *1. Australian National University, 2. Sydney Institute for Astronomy, 3. University of Arizona, 4. University of California, Berkeley, 5. University of Hawaii, 6. University of Texas at Austin*

402.05 – The First Cold Circumbinary Planet Found by Microlensing

We present the first cold, circumbinary planet to be discovered by gravitational microlensing. This system consists of a slightly sub-Saturn mass planet orbiting a pair of M-dwarfs with a combined mass of about 0.7 solar masses. Although microlensing is more sensitive to circumbinary planets with orbital parameters near the stability limit, this system has a separation ratio of about 40:1, suggesting that circumbinary planets do not preferentially form near the stabilty limit.

Author(s): David Bennett[1]
Institution(s): *1. University of Notre Dame*

402.06 – More support for the extreme S-type retrograde planet in the spectroscopic binary ν Octantis

ν Octantis is a single-lined spectroscopic binary system consisting of a K-giant primary and a secondary orbiting near 1050 days. Radial velocity observations reveal an additional ~400 day periodicity with a semi-amplitude of 40 m/s. If this signal is planetary in nature, the ν Octantis system would be unique amongst all known exoplanet systems in that long-term stability can only be achieved if the orbit is retrograde with respect to the stellar companions (i.e. mutual inclination ~ 180°).

Spectral line analyses suggest this signal is unlikely to be due to surface activity or pulsations (Ramm 2015). We also rule out an exotic scenario where the secondary itself is a binary.

We report an analysis of 1437 radial velocity measurements taken with HERCULES at the Mt. John Observatory spanning nearly 13 years, 1180 being new iodine iodine-cell velocities (2009-2013). The sensitive orbital dynamics of the two-companion model allow us to constrain the three-dimensional orbital architecture directly from the observations. Posterior samples obtained from an n-body Markov chain Monte Carlo (Nelson et al. 2014) yields a mutual inclination of 158.4 ± 1.2°. None of these are dynamically stable beyond 10^6 years. However, a grid search around the posterior sample suggests that they are in close proximity to a region of parameter space that is stable for at least 10^6 years.

If real, the tight orbital architecture here imposes a considerable challenge for formation of this dynamically extreme system.

Author(s): Benjamin Earl Nelson[2], David Ramm3, Michael Endl4, Fraser Gunn[1], John Hearnshaw3, Pam Kilmartin3, Christoph Bergmann3, Erik Brogt3
Institution(s): *1. Fraser Gunn Astrophotography, 2. Northwestern University, 3. University of Canterbury, 4. University of Texas, Austin*

403 – Planets in and around Binaries II

403.01 – Dynamical Detection of Circumbinary Planets

The Kepler data revealed a population of transiting gas-giant planets orbiting around close binary stars, beginning with Kepler-16, a highlight of the Extreme Solar Systems II meeting. Due to the restrictive geometry requirements of transit detections, this population is highly observationally biased towards coplanarity. However, a third of those planets detectably perturb their host binary's eclipse times, such that they could have been recognized even without transits. Here we announce the detection of three non-transiting planets based on this dynamical technique. Apsidal precession due to the planet makes the primary and secondary eclipse periods differ, and in addition a short-term modulation of the binary's eclipse times reveals the planet's orbital period. Several planetary periods are observed for each system, buttressing the interpretation. Though the method is nearly equally sensitive to all orbital orientations, each planet orbits near its host binary's plane, suggesting this class of planets formed in the circumbinary nebula.

Author(s): Daniel Clark Fabrycky[2], Jerome Orosz[1], William Welsh[1]
Institution(s): *1. San Diego State University, 2. University of Chicago*

403.02 – Constraining Planet Formation Theories with the Detailed Chemical Abundances of Planet-Hosting Wide Binary Stars

We present a detailed chemical abundance analysis of planet-hosting wide binary systems. Each of these binary systems consists of two stars with similar spectral types (ranging from G2V - K2V), and in each system, at least one star hosts a giant planet with an orbital pericenter ~< 0.5 AU. We examine the photospheric abundances of the host stars to determine if they have ingested rocky planetary material as a result of the close-in giant planets scattering inner rocky planets into the star as they migrated to their present-day locations. Using high-resolution, high signal-to-noise echelle spectra, for both stars in each system we derive the chemical abundances ([X/H]) of 15 elements covering a range of condensation temperatures (Tc). For stars in our sample with approximately solar metallicity, the refractory elements (Tc > 900 K) show a positive correlation between [X/H] and Tc. However, for stars with super-solar metallicities, the refractory elements show a slightly negative correlation between [X/H] and Tc. We interpret these results in the context of numerical simulations of giant planet migration that predict the accretion of hydrogen-depleted rocky material by the host star. We demonstrate that a simple model for a solar-metallicity star accreting material with Earth-like composition predicts a positive correlation between [X/H] and Tc, while for a supersolar-metallicity star the model predicts a negative correlation. The stark contrast between the predicted correlations for solar-metallicity and supersolar-metallicity stars may indicate that extracting any chemical signature of rocky planetary accretion is particularly challenging for very metal-rich stars.

Author(s): Claude Ernest Mack[1], Simon Schuler[2], Keivan Stassun3
Institution(s): *1. Leibniz Institute for Astrophysics Potsdam, 2. University of Tampa, 3. Vanderbilt University*

403.03 – Does Planet Formation Influence Whether Binary Stars Are Identical or Fraternal "Twins"?

Disentangling how an individual star's atmospheric composition is affected by the chemistry and transport of disk material, the formation of planets, and its broader position in/motion through the Galaxy during its evolution is difficult. While initially suggested as a sign of accretion of H-depleted material onto the star, the giant planet-metallicity correlation is now established as a mostly primordial effect -- stellar composition affects planet formation. But is it still possible that planet formation may also alter host star composition? Previous studies hinted at a few cases of compositional differences between stars in binary systems, and now high-precision abundance analyses are exploring this possibility in systems known to host planets. I will discuss the important role binary host stars have to play in extending correlations between stellar composition and the presence/type of planets that form, including brand new (not yet published!) results.

Author(s): Johanna Teske[1]
Institution(s): *1. Carnegie Institution for Science*

403.04 – Companion-driven dynamics: Trends in stellar companion fraction and giant exoplanet orbital properties.

Many of the stars in the solar neighborhood are part of multiple star systems, which may affect the formation and subsequent orbital evolution of the planets in these systems. It has been suggested that such interactions might be responsible for hot Jupiter migration and/or the spin-orbit misalignments observed in many hot Jupiter systems. In order to investigate whether stellar companions can explain the present-day properties of the population of hot Jupiters, we carried out a high contrast imaging survey at Keck to determine the frequency of stellar companions around giant planet host stars. Here we present results from surveys of two giant planet populations. First, we present a new expanded sample of 80 stars with transiting hot Jupiters, which confirms and expands on the results from our previous survey. We find that the binary fraction of hot Jupiter host stars is enhanced by approximately a factor of two compared to that of field stars, suggesting that stellar companions may play an important role in these systems. We also find no correlation between misaligned hot Jupiters and the presence of a stellar companion. Second, we present results from a new imaging survey of 146 RV-detected giant planet host stars, including systems with planets at a range of orbital separations, which allow us to search for correlations between stellar multiplicity and the orbital parameters of the inner planets.

Author(s): Henry Ngo[2], Heather Knutson[2], Sasha Hinkley5, Marta Levesque Bryan[2], Justin Crepp7, Eric Bechter7, Konstantin Batygin[2], Andrew Howard[6], John Asher Johnson3, Timothy Morton4, Philip Steven Muirhead[1]
Institution(s): *1. Boston University, 2. California Institute of Technology, 3. Harvard-Smithsonian Center for Astrophysics, 4. Princeton University, 5. University of Exeter, 6. University of Hawaii at Manoa, 7. University of Notre Dame*

403.05 – The Abundance of Circumbinary Exoplanets

Circumbinary planets, planets orbiting around binary stars, represent a new angle of information on planet formation theories, showing us how the different processes that form a planet react to the torque of a central host binary. I will present recently published observational constraints on the occurrence rates and orbital element distributions of circumbinary planets. This work utilises the Kepler dataset of ~2000 eclipsing binaries, along with an independently developed tailored search algorithm, to debias the dataset and find the underlying frequency of these planets. We discover that circumbinary planets have a similar occurrence rate to planets around single stars, but only if they are preferentially coplanar with their host binary. If they are more misaligned, they must be significantly more common. This effect is strong enough that following a reductio ad absurdum argument, we confirm the coplanar preference for these planets. Along with these results, we confirm the previously noted tendency for circumbinary planets to not be found around the closest (P(binary) < ~7 days) host binaries. This last result may be a marker of the binary star formation process.

Author(s): David J Armstrong[1]
Institution(s): *1. University of Warwick*

403.06 – Survival of planets around shrinking stellar binaries

The discovery of transiting circumbinary planets by the Kepler mission suggests that planets can form efficiently around binary stars. None of the stellar binaries currently known to host planets has a period shorter than 7 days, despite the large number of eclipsing binaries found in the Kepler target list with periods shorter than a few days. These compact binaries are believed to have evolved from wider orbits into their current configurations via the so-called Lidov-Kozai migration mechanism, in which gravitational perturbations from a distant tertiary companion induce large-amplitude eccentricity oscillations in the binary, followed by orbital decay and circularization due to tidal dissipation in the stars. We present new results (PNAS 112, 30, p 9264) on the orbital evolution of planets around binaries undergoing orbital decay by this "LK+tide" mechanism. From secular and N-body calculations, we show how planets may survive and become misaligned from their host binary, or may develop erratic behavior in eccentricity, resulting in their consumption by the stars or ejection from the system as the binary decays. Either outcome can explain these planets' elusiveness to detection. Our results suggest that circumbinary planets around compact binaries could still exist, and we offer specific predictions as to what their orbital configurations should be like.

Author(s): Diego Jose Munoz[1], Dong Lai[1]
Institution(s): *1. Cornell University*

500 – Habitability and Biosignatures

500.01 – Towards a List of Molecules as Potential Biosignature Gases for the Search for Life on Exoplanets

Thousands of exoplanets are known to orbit nearby stars. Plans for the next generation of space-based and ground-based telescopes are fueling the anticipation that a precious few habitable planets can be identified in the coming decade. Even more highly anticipated is the chance to find signs of life on these habitable planets by way of biosignature gases. But which gases should we search for? We expand on the search of possible biosignature gases and go beyond those studied so far, which include O_2, O_3, N_2O, and CH_4, as well as secondary metabolites: methanethiol (CH_3SH), dimethyl sulfide ($(CH_3)_2S$), methyl chloride (CH_3Cl), and carbonyl sulfide (CSO).

We present the results of a project to map the chemical space of life's metabolic products. We have constructed a systematic survey of all possible stable volatile molecules (up to N=6 non-H atoms), and identified those made by life on Earth. Some (such as methyl chloride) are made by Earth life in sufficiently substantial quantities to be candidate biosignatures in an Earth-like exoplanet's atmosphere; some, such as stibine (SbH_3), are produced only in trace amounts. Some entire categories of molecules are not made by Earth life (such as the silanes); these and other absences from the list of biogenic volatiles point to functional patterns in biochemical space. Such patterns may be different for different biochemistry, and so we cannot rule out any small, stable molecule as a candidate biosignature gas. Our goal is for the community to use the list to study the chemicals that might be potential biosignature gases on exoplanets with atmospheres and surface environments different from Earth's.

Author(s): Sara Seager[1], William Bains[1], Janusz Petkowski[1]
Institution(s): *1. Massachusetts Institute of Technology*

500.02 – The search for life in our Galaxy: using the solar system planets as benchmarks

Over the past decades a large diversity in planetary systems, accompanied by a large diversity of planetary natures, have been discovered. Nevertheless, despite probable surprises, our knowledge of the solar system planets will be our guidance in the interpretation of the physical properties of extrasolar planet atmospheres. Thus, the solar system offers a unique playground to determine the best observables for such planet characterization. In the past few years, our group has performed observations aimed at retrieving the reflection and transmission spectrum of some of the solar systems planets. These observations include the transmission spectrum of Earth (via a lunar eclipse), the transmission spectrum of Venus (via the transit of Venus in 2012 observed from SOFI) and the transmission spectrum of Jupiter (via a Ganymedes eclipse). Together they have revealed a wealth of new information, such as the detectability of dimer bands (usable as tracers of atmospheric pressure) in earth-like planets, or the signatures of aerosols, hazes and metallic layers in giant planets. Here I am planning to offer a review of the observational setup of these observations, and what they have revealed about Earth, Venus and Jupiter in the context of the search for life in our galaxy

Author(s): Pilar Montañés-Rodríguez3, Enric Pallé3, Manuel Lopez-Puertas2, Beatriz González-Merino3, Enrique Garcia-Melendo1
Institution(s): *1. E.T.S. Ingenieria, Universidad del Pais Vasco, 9 Alameda Urquijo s/n, E-48013 Bilbao, Spain, 2. Instituto de Astrofisica de Andalucia (CSIC), Glorieta de la Astronomia s/n, E-18080 Granada, Spain, 3. Instituto de Astrofisica de Canarias*

500.03 – Determining the Inner Edge of the Habitable Zone Around M and late K-Stars Using 3-D Climate Models

We present preliminary results for the inner edge of the habitable zone (HZ) around M and late K-stars, calculated from state of the art 3-D global climate models, the NCAR Community Atmosphere Model and Flexible Modeling System (FMS) developed by the Geophysical Fluid Dynamics. Both 1-D and 3-D models show that, for a water-rich planet, as the surface temperature increases due to increased stellar radiation, water vapor becomes a significant fraction of the atmosphere. M- and late K-stars have their peak flux in the near-infrared, where water is a strong absorber. Our models have been updated with a new radiation scheme and with H_2O absorption coefficients derived from the most recent line-by-line databases (HITRAN2012 and HITEMP2010). These updates will most likely result in moving the inner edge of the HZ around M and late-K stars further away from the star than previous estimates. The initial targets for survey missions such as K2 and the Transiting Exoplanet Survey Satellite (TESS) will likely be planets near the inner edge of the HZ due to the increased signal-to-noise ratio that results from their proximity to their host star. The James Webb Space Telescope (JWST) *may* be capable of probing the atmospheric composition of terrestrial planets around a nearby M-dwarf. Thus, determining the most accurate inner edge of the HZ around M-dwarf stars is crucial for selecting target candidates for atmospheric characterization and to identify potential biomarkers.

Author(s): Ravi Kopparapu[2], Eric T Wolf5, Jacob Haqq-Misra[1], Yang Jun[4], James Kasting3, Suvrath Mahadevan3, Ryan Terrien3
Institution(s): *1. Blue Marble Space Institute of Science, 2. NASA Goddard Space Flight Center, 3. Pennsylvania State University, 4. University of Chicago, 5. University of Colorado*

500.04 – The unstable CO2 feedback cycle on ocean planets

Ocean planets are volatile rich planets, not present in our Solar System, which are dominated by deep, global oceans. Theoretical considerations and planet formation modeling studies suggest that extrasolar ocean planets should be a very common type of planet. One might therefore expect that low-mass ocean planets would be ideal candidates when searching for habitable exoplanets, since water is considered to be an essential requirement for life. However, a very large global ocean can also strongly influence the climate.

The high pressure at the oceans bottom results in the formation of high-pressure water ice, separating the planetary crust from the liquid ocean and, thus, also from the atmosphere. In our study we, therefore, focus on the CO2 cycle between the atmosphere and the ocean which determines the atmospheric CO2 content. The atmospheric amount of CO2 is a fundamental quantity for assessing the potential habitability of the planet's surface because of its strong greenhouse effect, which determines the planetary surface temperature to a large degree.
In contrast to the stabilising carbonate-silicate cycle regulating the long-term CO2 inventory of the Earth atmosphere, we find that the CO2 cycle on ocean planets is positive and has strong destabilising effects on the planetary climate. By using a chemistry model for oceanic CO2 dissolution and an atmospheric model for exoplanets, we show that the CO2 feedback cycle is severely limiting the potential habitability of ocean planets.

Author(s): Daniel Kitzmann4, Yann Alibert4, Mareike Godolt2, John Lee Grenfell2, Kevin Heng4, Beate Patzer1, Heike Rauer2, Barbara Stracke2, Philip von Paris3
Institution(s): *1. Berlin Institute of Technology, 2. German Aerospace Center (DLR), 3. Univ. Bordeaux LAB, 4. University of Bern*

500.05 – Characterizing Pale Blue Dots Around FGKM Stars

Exoplanet characterization of small rocky worlds will be a main focus in the coming decades. For future telescopes like JWST and UVOIR/HDST, an exoplanet's host star will influence our ability to detect and interpret spectral features, including biosignatures. We present a complete suit of stellar models and a grid of model atmospheres for Earth-like planets at equivalent stages of geological evolution in their HZ for stellar effective temperature from Teff = 2300K to 7000K, sampling the entire FGKM stellar type range. Since M dwarfs are simultaneously the most numerous in the universe, the most active, and the most likely stars to host terrestrial exoplanets, we focus in particular on the range of UV emission possible in each sub M spectral class. The UV emission from a planet's host star dominates the photochemistry and thus the resultant observable spectral features of the planet. Using the latest UV spectra obtained by HST and IUE we model the effect of stellar activity on Earth-like planets. We also model the amount of UV flux reaching the surface for Earth-like planets at various geological epochs ranging from a pre-biotic world through the rise of oxygen and for Earth-like planets orbiting FGKM stars at equivalent stages of evolution. When modeling the remotely detectable spectra of these planets we focus on the primary detectable atmospheric features that indicate habitability on Earth, namely: H2O, CO2, O3, CH4, N2O and CH3Cl. We model spectra of Earth-like planets orbiting our grid of FGKM stars in the VIS/NIR (0.4 – 4 μm) and the IR (5 – 20 μm) range as input for future missions and concepts like UVOIR/HDST and JWST.

Author(s): Sarah Rugheimer4, Lisa Kaltenegger1, Dimitar Sasselov2, Antigona Segura3
Institution(s): *1. Cornell University, 2. Harvard University - CFA, 3. Universidad Nacional Autonoma de Mexico, 4. University of St. Andrews*

500.06 – The High-Energy Radiation Environment of Planets around Low-Mass Stars

Low-mass stars are the dominant planet hosts averaging about one planet per star. Many of these planets orbit in the canonical habitable zone (HZ) of the star where, if other conditions allowed, liquid water may exist on the surface.
A planet's habitability, including atmospheric retention, is strongly dependent on the star's ultraviolet (UV) emission, which chemically modifies, ionizes, and even erodes the atmosphere over time including the photodissociation of important diagnostic molecules, e.g. H2O, CH4, and CO2. The UV spectral slope of a low-mass star can enhance atmospheric lifetimes, and increase the detectability of biologically generated gases. But, a different slope may lead to the formation of abiotic oxygen and ozone producing a false-positive biosignature for oxygenic photosynthesis. Realistic constraints on the incident UV flux over a planet's lifetime are necessary to explore the cumulative effects on the evolution, composition, and fate of a HZ planetary atmosphere.
NASA's Galaxy Evolution Explorer (GALEX) provides a unique data set with which to study the broadband UV emission from many hundreds of M dwarfs. The GALEX satellite has imaged nearly 3/4 of the sky simultaneously in two UV bands: near-UV (NUV; 175–275 nm) and far-UV (FUV; 135–175 nm). With these data these, we are able to calculate the mean UV emission and its level of variability at these wavelengths over critical planet formation and evolution time scales to better understand the probable conditions in HZ planetary atmospheres.
In the near future, dedicated CubeSats (miniaturized satellites for space research) to monitor M dwarf hosts of transiting exoplanets will provide the best opportunity to measure their UV variability, constrain the probabilities of detecting habitable (and inhabited) planets, and provide the correct context within which to interpret IR transmission and emission spectroscopy of transiting exoplanets.

Author(s): Evgenya Shkolnik1, Brittany Miles2, Travis Barman3, Sarah Peacock3
Institution(s): *1. Arizona State University, 2. UCLA, 3. University of Arizona*

501 – Population Statistics and Mass-Radius Relations

501.01 – Terrestrial Planet Occurrence Rates for the Kepler GK Dwarf Sample

I discuss latest results in measuring terrestrial planet occurrence rates using the planet candidates discovered by the Kepler pipeline. For the first time an accurate model for the Kepler pipeline sensitivity to transiting planets is publicly available. My new analysis finds higher planet occurrence rates and a steeper increase in planet occurrence rates toward small planets than previously believed. In addition, I identify the leading sources of systematics that remain impacting Kepler planet occurrence rate determinations, and approaches for minimizing their impact in future studies. This work also sharpens our understanding on the dependence of planet occurrence rates on stellar effective temperature with implications for understanding the planet formation process.

Author(s): Christopher J Burke1
Institution(s): *1. SETI Institute*

501.02 – Prevalence and Properties of Planets from Kepler and K2

Discoveries from the prime Kepler mission demonstrated that small planets (< 3 Earth-radii) are common outcomes of planet formation around G, K, and M stars. While Kepler detected many such planets, all but a handful orbit faint, distant stars, which are not amenable to precise follow up measurements. NASA's K2 mission has the potential to increase the number of known small, transiting planets around bright stars by an order of magnitude. I will present the latest results from my team's efforts to detect, confirm, and characterize planets using the K2 mission. I will highlight some of the progress and remaining challenges involved with generating denoised K2 photometry and with detecting planets in the presence of severe instrument systematics. Among our recent discoveries are the K2-3 and K2-21 planetary systems: M dwarfs hosting multiple transiting Earth-size planets with low equilibrium temperatures. These systems offer a convenient laboratory for studying the bulk composition and atmospheric properties of small planets receiving low levels of stellar irradiation, where processes such as mass loss by photo-evaporation could play a weaker role.

Author(s): Erik Petigura1, Geoffrey W. Marcy4, Andrew Howard5, Ian Crossfield3, Charles Beichman2, Evan Sinukoff5
Institution(s): *1. Caltech, 2. NASA Exoplanet Science Institute, 3. University of Arizona, 4. University of California, Berkeley, 5. University of Hawaii at Manoa*

501.03 – The Occurrence Rate and Composition of Small Planets Orbiting Small Stars

I will describe two investigations of the galactic abundance and properties of small planets orbiting small stars based on data from the Kepler and K2 missions. First, we constrained the planet occurrence rate for early M dwarfs by searching the full four-year Kepler data set using our own planet detection pipeline. We measured a cumulative planet occurrence rate of 2.5 +/- 0.2 planets per M dwarf with periods of 0.5-200 days and planet radii of 1-4 Earth radii. Within a conservative habitable zone based on the moist greenhouse inner limit and maximum greenhouse outer limit, we estimated an occurrence rate of 0.16 (+0.17/-0.07) Earth-size planets and 0.12 (+0.10/-0.05) super-Earths per M dwarf HZ. Second, I will report on ongoing efforts to characterize the population of small planet candidates detected by the K2 mission and discuss how the properties of the small planets orbiting late M dwarfs and K dwarfs compare to those orbiting early M dwarfs. We are gathering near-infrared spectra of the host stars and employing empirical relations (benchmarked to interferometry) to determine their metallicities, temperatures, and radii. The improved stellar properties permit us to constrain better the radii and insolation flux of the planet candidates and search for correlations between stellar and planetary properties. We are also conducting an intensive radial velocity campaign with HARPS-N and HIRES to estimate the masses and densities of the subset of small planet candidates orbiting the brightest low-mass host stars.

Author(s): Courtney D. Dressing[1], David Charbonneau[2], Elisabeth R. Newton[2]
Institution(s): *1. California Institute of Technology, 2. Harvard University*

501.04 – A Probabilistic Mass-Radius Relationship for Sub-Neptune-Sized Planets: Implications for Missions Post-Kepler

The Kepler Mission has discovered thousands of planets with radii between 1 and 4 R_Earth, paving the way for the first statistical studies of the dynamics, formation, and evolution of planets in a size range where there are no Solar System analogs. Masses are an important physical property for these theoretical studies, and yet the vast majority of Kepler planet candidates do not have theirs measured. Therefore, a key practical concern is how to most accurately map a measured sub-Neptune radius to a mass estimate given the existing observations. This issue is also highly relevant to devising the most efficient follow-up programs of future transiting exoplanet detection missions such as TESS. Here we present a probabilistic mass-radius relationship (M-R relation) evaluated within a hierarchical Bayesian framework, which both accounts for the anticipated intrinsic dispersion in these planets' compositions and quantifies the uncertainties on the M-R relation parameters. Assuming that the M-R relation can be described as a power law with a dispersion that is constant and normally distributed, we find that M/M_Earth = 2.7 (R/R_Earth)^1.3 and a scatter in mass of 1.9 M_Earth is the "best-fit" probabilistic M-R relation for the sample of RV-measured transiting sub-Neptunes (R_pl < 4 R_Earth; Wolfgang, Rogers, & Ford, in review). The probabilistic nature of this M-R relation has several advantages: not only does its use automatically account for a significant source of uncertainty in the comparison between planet formation theory and observation, but it can predict the yield of future transit missions' follow-up programs under the observed range of planet compositions at a given radius. We demonstrate the latter with TESS as a case study, building on Sullivan et al. 2015 to provide the RV semi-amplitude distribution predicted by this more general M-R relation and a more detailed treatment of the underlying planet population as derived from Kepler. The uncertainties in the predicted K distribution, which are driven by our derived spread of masses at a given radius, provide an additional consideration for choosing the best RV follow-up target selection strategy.

Author(s): Angie Wolfgang[1], Leslie A. Rogers[2], Eric B Ford[1], Gregory Laughlin3
Institution(s): *1. Pennsylvania State University, 2. University of California, Berkeley, 3. University of California, Santa Cruz*

501.05 – The Mass-Radius-Eccentricity Distribution of Near-Resonant Transiting Exoplanet Pairs Detected by *Kepler*

We characterize the mass-radius-eccentricity distribution of transiting planets near first-order mean motion resonances using Transit Timing Variation (TTV) observations from NASA's *Kepler* mission. *Kepler's* precise measurements of transit times (Mazeh et al. 2014; Rowe et al. 2015) constrain the planet-star mass ratio, eccentricity and pericenter directions for hundreds of planets. Strongly-interacting planetary systems allow TTVs to provide precise measurements of masses and orbital eccentricities separately (e.g., Kepler-36, Carter et al. 2012). In addition to these precisely characterized planetary systems, there are several systems harboring at least two planets near a mean motion resonance (MMR) for which TTVs provide a joint constraint on planet masses, eccentricities and pericenter directions (Hadden et al. 2015). Unfortunately, a near degeneracy between these parameters leads to a posterior probability density with highly correlated uncertainties. Nevertheless, the population encodes valuable information about the distribution of planet masses, orbital eccentricities and the planet mass-radius relationship. We characterize the distribution of masses and eccentricities for near-resonant transiting planets by combining a hierarchical Bayesian model with an analytic model for the TTV signatures of near-resonant planet pairs (Lithwick & Wu 2012). By developing a rigorous statistical framework for analyzing the TTV signatures of a population of planetary systems, we significantly improve upon previous analyses. For example, our analysis includes transit timing measurements of near-resonant transiting planet pairs regardless of whether there is a significant detection of TTVs, thereby avoiding biases due to only including TTV detections.

Author(s): Megan Shabram[1], Daniel Jontof-Hutter[1], Eric B Ford[1]
Institution(s): *1. Penn State*

501.06 – Discovery of A Break in the Exoplanet Mass-Ratio Function beyond the Snow Line

We present the discovery of a break in the exoplanet mass ratio function beyond the snow line from the statistical analysis of microlensing survey data. We find a break and possible peak of the mass ratio function at q ~ 1.e-4. This corresponds to a Neptune mass for a typical 0.5 solar mass host star. Six years of MOA survey data are used to measure the planet frequency as a function of the planet/star mass ratio and separation. The MOA sample includes 1472 well characterized microlensing events, including 22 planetary events and 1 probable planetary event. We calculate the detection efficiency for each event and employ a Bayesian analysis to deal with ambiguities. The measured planet frequency with the MOA data is somewhat lower, but consistent with, previous microlensing results. The break of the mass ratio function is also confirmed with the full microlensing sample using 30 planets. This study implies that Neptunes and failed Jupiter cores are the most common type of planets beyond the snow line. The method we have developed to determine the exoplanet frequency from microlensing survey data can be applied to future exoplanet microlensing surveys, like WFIRST, Euclid, and KMTNet that are expected to dominate the exoplanet microlensing field in the coming decades.

Author(s): Daisuke Suzuki[1], David Bennett[1]
Institution(s): *1. University of Notre Dame*

501.07 – *Kepler* Planet Census Aided by LAMOST

The lack of spectroscopic stellar parameters for the majority of *Kepler* target stars present a major limitation to *Kepler* planet statistics. An ongoing spectroscopic survey of the *Kepler* field has been conducted by the LAMOST telescope in China, and accurate stellar parameters have already been obtained for tens of thousands of *Kepler* targets. I discuss studies using the LAMOST data that lead to new insights into our understanding of *Kepler* planet distributions.

Author(s): Subo Dong[1]
Institution(s): *1. Peking University*

502 – Planets around Evolved Stars and Compact Remnants

502.01 – Planets around Giant Stars: Results from the Lick Survey

We present results from a radial-velocity survey of 373 giant stars at Lick Observatory, which started in 1999. We have detected planets around 15 of these stars; an additional 20 stars host planet candidates. Companions with up to 25 Jupiter masses are rather commonly found around stars with about 2 Solar masses. The frequency of detected planetary companions appears to increase with metallicity. No planets or planet candidates are found around stars with more than 2.7 Solar masses, although our sample contains 113 such stars. We conclude that the occurrence rate of giant planets as a function of Stellar mass peaks around 2 Solar masses. This has important consequences for our understanding of giant planet formation.

The stars 91 Aqr and tau Gem have companions with orbits that are among those with the lowest eccentricities of all known exoplanets, perhaps due to tidal circularization during the RGB phase. If confirmed, this would be the first evidence of planetary orbits modified through stellar evolution.

We have discovered several multiple systems in our sample. An extensive dynamical analysis of the eta Cet system indicates that it contains two massive planets in a 2:1 orbital resonance. The star nu Oph is orbited by two brown dwarf companions in a 6:1 resonance. It is likely that they arrived in this resonance through migration in a circumstellar disk, arguing strongly that objects with more than 20 Jupiter masses can be formed in disks around Herbig Ae stars.

Author(s): Andreas Quirrenbach[1], Sabine Reffert[1], Trifon Trifonov[1], Christoph Bergmann[1], Christian Schwab[1]
Institution(s): *1. Landessternwarte Heidelberg*

502.02 – A Disintegrating Minor Planet Transiting a White Dwarf

Over the past decade, evidence has accumulated suggesting that the photospheres of many white dwarfs are polluted by the remnants of small rocky bodies leftover from the progenitors' planetary systems. The evidence for this scenario is typically indirect and circumstantial. We report observations of a disintegrating minor planet transiting a polluted white dwarf. The transits are 5 minutes long, up to 40% deep, have an asymmetric profile and highly variable transit depths. This system provides strong corroborating evidence for the planet accretion model for white dwarf pollution and lets us watch the destruction of a solar system in real time.

Author(s): Andrew Vanderburg3, John Asher Johnson3, Saul Rappaport5, Allyson Bieryla4, Jonathan Irwin4, John Lewis3, David Charbonneau3, David W Latham4, David Ciardi[1], Laura Schaefer3, David Kipping[2], Ruth Angus3, Jason Eastman4, Jason Wright[6], Nate McCrady[8], Robert Wittenmyer9, Patrick Dufour7
Institution(s): *1. Caltech, 2. Columbia University, 3. Harvard, 4. Harvard-Smithsonian CfA, 5. MIT, 6. Penn State, 7. Universitede Montreal, 8. University of Montana, 9. University of New South Wales*

502.03 – Multiwavelength Transit Observations of the Candidate Disintegrating Planetesimals Orbiting a White Dwarf

At the time of writing of this abstract, an intriguing white dwarf system is shortly to be announced that is believed to be orbited by up to six or more disintegrating, planetesimals in short-period orbits. We report a wealth of multiwavelength, ground-based photometry of this system, and detect multiple transits of up to 30% of the stellar flux. The transits display the variable transit depths and transit profiles featuring longer egresses than ingresses that we have come to associate with disintegrating planets/planetesimals. Our photometry confirms that this white dwarf is indeed being orbited by multiple planetesimals, with at least one object, and likely more, having orbital periods of ~4.5 hours; we are unable to confirm the specific periods that have been reported, thus bringing into question the long-term stability of the planetesimals' orbits. Lastly, our multiwavelength transit photometry allows us to place a limit on the particle size in the cometary tails trailing these planetesimals, helping to determine the mechanism (collisions, tidal disruption, a Parker wind, etc.) that has led to both the cometary tails and the arrival of these planetesimals in such short period orbits.

Author(s): Bryce Croll[1]
Institution(s): *1. Boston University*

502.04 – Water Detected in the Terrestrial Zone of Extreme Solar Systems

Life as we know it requires water in contact with a rocky planetary surface. In the Solar System, water and other volatiles must have been delivered to a dry Earth from planetesimals, where asteroids in the outer main belt and Jupiter-Saturn region are excellent candidates. The first extrasolar analog of these rocky and water-rich planetesimals was reported between ESS II and III (Farihi et al. 2013, Science, 342, 218), and there is now evidence for additional examples. These results imply an underlying population of large, extrasolar planetesimals formed near a snow line, and suggesting a common mechanism for water delivery to habitable exoplanets.

I will present Hubble, Spitzer, and ground-based data that demonstrate the confirmed and likely water-rich nature of exo-asteroids identified in a growing number of white dwarf planetary systems. These extreme solar systems formed and evolved around A-type (and similar) stars -- now firmly retired -- and the asteroid debris now orbits and pollutes the white dwarf with heavy elements, including oxygen in excess of that expected for oxide minerals. The abundance patterns are also carbon-poor, indicating the parent bodies were not icy planetesimals analogous to comets, but instead similar in overall composition to asteroids in the outer main belt.

Importantly, these remnant exoplanetary systems imply architectures similar to the Solar System, where a giant planet exterior to a snow line perturbs rocky asteroids on the interior. Thus, they appear to share basic characteristics with HR 8799, Vega, Fomalhaut, and epsilon Eridani where two disks of debris are separated by giant planet(s), with one belt near the snow line. If such archictectures are as common as implied by polluted white dwarfs, then at least 30% of 1.2-3.0 Msun stars have both the tools and ingredentients for water delivery in their terrestrial planet zones.

Author(s): Jay Farihi[1]
Institution(s): *1. University College London*

502.05 – The final fate of planetary systems

The discovery of the first extra-solar planet around a main-sequence star in 1995 has changed the way we think about the Universe: our solar system is not unique. Twenty years later, we know that planetary systems are ubiquitous, orbit stars spanning a wide range in mass, and form in an astonishing variety of architectures. Yet, one fascinating aspect of planetary systems has received relatively little attention so far: their ultimate fate.

Most planet hosts will eventually evolve into white dwarfs, Earth-sized stellar embers, and the outer parts of their planetary systems (in the solar system, Mars and beyond) can survive largely intact for billions of years. While scattered and tidally disrupted planetesimals are directly detected at a small number of white dwarfs in the form infrared excess, the most powerful probe for detecting evolved planetary systems is metal pollution of the otherwise pristine H/He atmospheres.

I will present the results of a multi-cycle HST survey that has obtained COS observations of 136 white dwarfs. These ultraviolet spectra are exquisitely sensitive to the presence of metals contaminating the white atmosphere. Our sophisticated model atmosphere analysis demonstrates that at least 27% of all targets are currently accreting planetary debris, and an additional 29% have very likely done so in the past. These numbers suggest that planet formation around A-stars (the dominant progenitors of today's white dwarf population) is similarly efficient as around FGK stars.

In addition to post-main sequence planetary system demographics, spectroscopy of the debris-polluted white dwarf atmospheres provides a direct window into the bulk composition of exo-planetesimals, analogous to the way we use of meteorites to determine solar-system abundances. Our ultraviolet spectroscopy is particularly sensitive to the detection of Si, a dominant rock-forming species, and we identify up to ten additional volatile and refractory elements in the most strongly contaminated white dwarfs. The derived bulk abundances unambiguously demonstrate the predominantly rocky nature of the accreted material, with two exceptions where we detect volatile-rich debris. The relative abundance ratios suggest a wide range of parent bodies, including both primitive asteroids and fragments from differentiated planetesimals. The growing number of detailed debris abundances can provide important observational constraints on planet formation models.

Author(s): Boris Gaensicke[1]
Institution(s): *1. University of Warwick*

502.06 – Planetary systems through all stages of stellar evolution

We know that planetary systems around white dwarfs are just as common as those around main sequence stars. However, observations reveal significant gaps in our understanding about how planets, asteroids, comets and pebbles undergo physical and orbital changes as their parent stars evolve off of the main sequence. We have performed full-lifetime (14 Gyr) numerical simulations of multi-planet systems across all phases of stellar evolution, incorporating realistic profiles for stellar mass loss and stellar radius variability, and including test particles and wide binary stellar companions. We demonstrate that closely-packed planetary systems can remain stable throughout the main sequence and for many Gyr during the white dwarf phase before unpacking and triggering scattering events. These events may generate an ever-changing dynamical architecture around the white dwarfs, and perturb planets onto orbits which can be detectable by transit photometry.

Author(s): Dimitri Veras[1]
Institution(s): *1. University of Warwick*

503 – TESS and Other Future Missions

503.01 – The Transiting Exoplanet Survey Satellite (TESS): Discovering New Earths and Super-Earths in the Solar Neighborhood

The Transiting Exoplanet Survey Satellite (TESS) will discover thousands of exoplanets in orbit around the brightest stars in the sky. In its two-year prime survey mission, TESS will monitor more than 200,000 bright stars in the solar neighborhood for temporary drops in brightness caused by planetary transits. This first-ever spaceborne all-sky transit survey will identify planets ranging from Earth-sized to gas giants, around a wide range of stellar types and orbital distances.

TESS stars will typically be 30-100 times brighter than those surveyed by the Kepler satellite; thus, TESS planets will be far easier to characterize with follow-up observations. For the first time it will be possible to study the masses, sizes, densities, orbits, and atmospheres of a large cohort of small planets, including a sample of rocky worlds in the habitable zones of their host stars.

An additional data product from the TESS mission will be full frame images (FFI) with a cadence of 30 minutes or less. These FFI will provide precise photometric information for every object within the 2300 square degree instantaneous field of view of the TESS cameras. These objects will include more than 1 million stars and bright galaxies observed during sessions of several weeks. In total, more than 30 million objects brighter than I=16 will be precisely photometered during the two-year prime mission. In principle, the lunar-resonant TESS orbit could provide opportunities for an extended mission lasting more than a decade, with data rates in excess of 100 Mbits/s.

An extended survey by TESS of regions surrounding the North and South Ecliptic Poles will provide prime exoplanet targets for characterization with the James Webb Space Telescope (JWST), as well as other large ground-based and space-based telescopes of the future.

TESS will issue data releases every 4 months, inviting immediate community-wide efforts to study the new planets, as well as commensal survey candidates from the FFI. A NASA Guest Investigator program is planned for TESS. The TESS legacy will be a catalog of the nearest and brightest main-sequence stars hosting transiting exoplanets, which should endure as the most favorable targets for detailed future investigations.

TESS is targeted for launch in 2017 as a NASA Astrophysics Explorer mission.

Author(s): George R. Ricker[1]
Institution(s): *1. MIT*

503.02 – Opportunities for Community Participation in TESS

Much of the scientific work in support of NASA's TESS mission will be carried out by working groups, composed of members of the TESS Science team and experts from the community. For example, the goal of measuring masses for 50 planets smaller than 4 Earth radii will require extensive efforts by the TESS Follow-up Observing Program (TFOP), both for spectroscopic and photometric reconnaissance observations and for very precise radial velocities needed to determine orbits and planetary masses. These efforts will be coordinated and in many cases carried out by members of the TFOP Working Group. Other key working groups include Simulations, Target Selection, Asteroseismology, Atmospheric Characterization, Habitability, and Non-Exoplanet Science.

A second opportunity for community involvement will be the Guest Investigator program run out of the Goddard Space Flight Center. The plan is for annual calls for proposals to do science other than the primary mission science, with the first call about a year before launch. This program will build on the experience of the highly successful Guest Observer programs for the Kepler and K2 missions.

Author(s): David W Latham[1]
Institution(s): *1. Harvard-Smithsonian Center for Astrophysics*

503.03 – Asteroseismology of Exoplanet-Host Stars in the TESS Era

New insights on stellar evolution and stellar interiors physics are being made possible by asteroseismology, the study of stars by the observation of their natural, resonant oscillations. Throughout the duration of the Kepler mission, asteroseismology has also played an important role in the characterization of host stars and their planetary systems. Examples include the precise estimation of the fundamental properties of stellar hosts, the obliquity determination of planetary systems, or the orbital eccentricity determination via asterodensity profiling. The Transiting Exoplanet Survey Satellite (TESS) will perform a wide-field survey for planets that transit bright host stars. Its excellent photometric precision and long intervals of uninterrupted observations will enable asteroseismology of solar-type stars and their evolved counterparts. Based on existing all-sky simulations of the stellar and planetary populations, we investigate the asteroseismic yield of the mission, placing particular emphasis on the yield of exoplanet-host stars for which we expect to detect solar-like oscillations. This is done both for the cohort of target stars (observed at a 2-min cadence), which will mainly involve low-mass main-sequence hosts, as well as for the cohort of "full-frame image" stars (observed at a 30-min cadence). The latter cohort offers the exciting prospect of conducting asteroseismology on a significant number of evolved hosts. Also, the brightest solar-type hosts with asteroseismology will become some of the best characterized planetary systems known to date. Finally, we discuss the impact of the detected oscillations on the accuracy/precision of the derived properties of the host stars and their planetary systems.

Author(s): Tiago L. Campante5, Mathew Schofield5, William J. Chaplin5, Daniel Huber[6], Jørgen Christensen-Dalsgaard[1], Hans Kjeldsen[1], David W Latham[2], George R. Ricker4, Joshua Winn3
Institution(s): *1. Aarhus University, 2. Harvard-Smithsonian Center for Astrophysics, 3. Massachusetts Institute of Technology, 4. MIT Kavli Institute for Astrophysics and Space Research, 5. University of Birmingham, 6. University of Sydney*

503.04 – The CHEOPS Mission

The CHaracterising ExOPlanet Satellite (CHEOPS) is a joint ESA-Switzerland space mission dedicated to search for exoplanet transits by means of ultra-high precision photometry. It is expected to be launch-ready at the end of 2017.

CHEOPS will be the first space observatory dedicated to search for transits on bright stars already known to host planets. It will have access to more than 70% of the sky. This will provide the unique capability of determining accurate radii for planets for which the mass has already been estimated from ground-based radial velocity surveys and for new planets discovered by the next generation ground-based transits surveys (Neptune-size and smaller). The measurement of the radius of a planet from its transit combined with the determination of its mass through radial velocity techniques gives the bulk density of the planet, which provides direct insights into the structure and/or composition of the body. In order to meet the scientific objectives, a number of requirements have been derived that drive the design of CHEOPS. For the detection of Earth and super-Earth planets orbiting G5 dwarf stars with V-band magnitudes in the range $6 \leq V \leq 9$ mag, a photometric precision of 20 ppm in 6 hours of integration time must be reached. This time corresponds to the transit duration of a planet with a revolution period of 50 days. In the case of Neptune-size planets orbiting K-type dwarf with magnitudes as faint as V=12 mag, a photometric precision of 85 ppm in 3 hours of integration time must be reached. To achieve this performance, the CHEOPS mission payload consists of only one instrument, a space telescope of 30 cm clear aperture, which has a single CCD focal plane detector. CHEOPS will be inserted in a low Earth orbit and the total duration of the CHEOPS mission is 3.5 years (goal: 5 years).

The presentation will describe the current payload and mission design of CHEOPS, give the development status, and show the expected performances.

Author(s): Christopher Broeg[2], willy benz[2], andrea fortier[2], David Ehrenreich[1], Thomas beck[2], Virginie cessa[2], Yann Alibert[2], Kevin Heng[2]
Institution(s): *1. Geneva University, 2. University of Bern*

503.05 – Gaia, PLATO and WEAVE: A Powerful combination for Exoplanet Characterisation

This presentation will describe the powerful linkages between the Gaia and PLATO missions and the potential impact of the WHT's WEAVE multi-object spectrograph in the study of exoplanet populations.

ESA's Gaia mission commenced its nominal operations phase in July 2014. Its first data release is expected summer 2016. Over the course of its (at least) five year mission, it will discover, via their astrometric signatures, upwards of 20,000 massive Jupiter sized long period planets at distances out to several hundred parsecs around all star types. In addition Gaia will discover a significant number of short period hot Jupiters around M stars. This presentation will discuss the form and content of the first Gaia Data Release.

The ESA PLATO mission, planned to launch in 2024, will photometrically observe a million host stars, and will detect, via the transit technique, planets down to Earth masses. PLATO will observe two fields of over 2,000 square degrees for 2 to 3 years each. At least one of these will be in the northern hemisphere. where WEAVE (a new multi object high resolution spectrograph currently under construction for the 4.2m William Herschel Telescope) will have the potential to provide detailed chemical characterisation of the host stars of the Gaia and PLATO exoplanet systems. This will enable insights into, for instance, metallicity of the host star correlations against both massive exoplanets (perhaps confirming current relationships), and lower mass exoplanets.

We note how the rapid exploitation of such a potential WEAVE survey could be achieved, utilising the WEAVE processing systems being developed at the IoA, Cambridge, coupled with efficient interfaces to the Cambridge Gaia and PLATO data processing centres.

Author(s): Nicholas Walton[1]
Institution(s): *1. University of Cambridge*

503.06 – SPIRou -A Near-Infrared Spectropolarimeter @ CFHT

SPIRou is a near-infrared spectropolarimeter and a high-precision velocimeter optimized for both the detection and characterization of terrestrial planets orbiting nearby low-mass stars, and the study of the impact of magnetic field on the star-planet formation. The spectrograph is designed to record the whole near-infrared spectrum simultaneously in either circular or linear polarization and to reach a RV precision of 1 m/s at a resolving power of 75,000. It will be use to carry out the "SPIRou Legacy Survey" targeting two science objectives (habitable terrestrial planet detection & magnetic field impact on star-planet formation) and is intended to provide the community with an extensive, homogenous, well characterized and high-quality data. SPIRou is expected to make a major breakthrough in the field of telluric planets in the habitable zone of cool stars. Once implemented at CFHT in 2017, SPIRou is expected to be used extensively by the astronomical community - supporting in particular space missions such as TESS, JWST and PLATO. In this presentation, I will focus on the impact of the SPIRou future observing programs in the field of exoplanets: 1) the radial-velocity survey, its target selection of cool dwarfs, strategy and expectations; 2) the follow-up characterization of transiting candidates; 3) the search for giant planets around very young stars; 4) the importance of spectropolarimetry to filter out the intrinsic jitter of target stars at the sub m/s level; 5) the anticipated role in preparing further exoplanet characterization missions.

Author(s): Lison Malo[1], Claire Moutou[1], Etienne Artigau3, Xavier Delfosse[2], Jean-François Donati[2], Rene Doyon3, Pascal Fouqué[1], Julien Morin5, Eder Martioli4
Institution(s): *1. Canada-France-Hawaii Telescope, 2. IRAP, 3. iREX, 4. LNA, 5. Universite de Montpellier*

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