Picturing the Extreme
Planetary Systems Revealed through Direct Imaging

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SETI Institute, Mountain View

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Extreme Solar Systems II

Collaborators: James Graham, Mike Fitzgerald, Mark Clampin, Bruce Macintosh, Matt Kenworthy, Eugene Chiang, Erik Mamajek, Ansgar Reiners, Andreas Seifahrt, Stefan Dreizler, The GPI Team
**Discovery Space:** Outer portions of planetary systems (long periods), A star (MS) planets, very young planets, face-on planets

![Plot from Bruce Macintosh, James Graham & GPI Team](Image)
Direct imaging: remarkable progress & surprises too

GQ Lup 2M1207 AB Pic

GQ Lup 2M1207 AB Pic

J1609  Fomalhaut  HR 8799  Beta Pic
Lafreniere et al. 2008  Kalas et al. 2008  Marois et al. '08,'10  Lagrange et al. 2009
Extreme separations

2M1207b: 55 AU from a BD host

Fomalhaut b: 119 AU from an A star
Visible light: Fomalhaut
Orbital motion: Fomalhaut, HR 8799, β Pic and GQ Lup

What is a planet? Formation matters?

Direct detection planet candidates

<table>
<thead>
<tr>
<th>Host</th>
<th>SpT</th>
<th>Distance (pc)</th>
<th>Separation (AU)</th>
<th>Mass (M_J)</th>
<th>Age (Myr)</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Fomalhaut</td>
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Starting in 2011:
Gemini Planet Imager
And SPHERE
Mass estimate depends on models & age determination

How do planet form?
Hot Start vs. Cold Start

Ages?

Marley et al 2007
Too extreme to be a “planet”? 

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**OBJECTS IN UNEXPECTED ORBITS**

It has become apparent during recent announcements of images of exoplanets that circumstantial arguments are causing some scientists to reject the objects’ planetary status. The objects found so far have at least several Jupiter masses (Neuhäuser et al. 2005) and are seen 50–100 AU from their stars [or in one case, from a brown dwarf (Chauvin et al. 2005)]. Some astronomers reject these objects as planets because their distance from their host stars suggests that they may not have formed in the standard scenario (which is not thought to operate rapidly enough out there to beat the short lifetime of gas disks). They are being called “sub-brown dwarf binaries,” and similar names.

Basri & Brown 2006
"This process of drag-mediated gravitational focusing leads to fast growth, rendering core accretion plausible out to distances at which directly imaged planets have been observed."
Extreme Atmospheres, or Planetary Rings/Disks?

THE PLANETARY MASS COMPANION 2MASS 1207–3932B: TEMPERATURE, MASS, AND EVIDENCE FOR AN EDGE-ON DISK

Subhanjoy Mohanty,¹ Ray Jayawardhana,² Nuria Huéldamo,³ and Eric Mamajek¹

¹University of Arizona, ²University of Vermont, ³University of Wisconsin–Milwaukee
Non-local equilibrium chemistry (non-LCE)
Intermediate clouds (ICM)
Low $T_{\text{eff}}$ (1000 K), High N(CO) for 2M1207b

"The primary lesson... is that atmospheric clouds and chemistry can dramatically alter the spectral shape and potentially lead to errors in effective temperature as great as 50%.”

Barman et al. 2011

For HR 8799, see 2011 papers by Madhusudhan et al., Currie et al., Barman et al.

See Poster by Robert King et al.
Extreme Atmospheres, or Planetary Ring/Disks?

- Detected at optical wavelengths (HST ACS & STIS)
- Not detected at infrared wavelengths (Gemini & Keck)
- Age is 400 Myr instead of 200 Myr? (Eric Mamajek)
- Optical light is reflected from circumplanetary rings?

$T_{\text{eff}} = 400 \text{ K}, M = 1.7 – 3.5 \text{ M}_J$

Kalas et al 2008
Why is Fomalhaut b optically bright?

Circumplanetary disk
Kalas et al. 2008
Planet + 16 - 35 $R_p$ rings
For comparison, Callisto at $\sim 27$ Jupiter radii

or

Irregular Satellite Cloud

see also

A Ringed Earthlike Planet

See also poster by Megan Shabram
Observations

1984
1998
2004
2007+

Many EXTREME debris disks
Planet-Disk dynamics give constraints on planet masses & orbital properties

Theory

1700

Fitzgerald talk
Tuesday
Extreme Dynamics

- Is Beta Pic b responsible for the warp?
- If so, why is the planet plane inclined 5° away from the main disk midplane?

Okamoto et al. 2005
Extreme Adaptive Optics

Southern Hemisphere: Gemini Planet Imager
VLT/SPHERE

Northern Hemisphere: Palomar 1640
Subaru HiCIAO+SCEXAO
Large Binocular Telescope

General Properties:
1) Extreme Strehl ratios, better than 85% at H
2) Extreme contrast; $\Delta H > 15$ mag at 0.5” radius

Observations beginning 2012
Need “extremely” bright host stars (9th mag or brighter)
Extreme Adaptive Optics Systems
2012 - 2015

Gemini Planet Imager

When: Mid - 2012
Where: Gemini South
Who: PI Bruce Macintosh
How: High-order AO with coronagraphy
What: 0.9 – 2.4 μm, m_I < 9 mag stars, polarimetry, R~100 spectroscopy

Direct Detections
Add 100+ rows from GPI and SPHERE results, also SEEDS, 1640, LBT, JWST

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GPIES: GPI Exoplanet Survey

Talk by James Graham (Tuesday), Poster by Jeff Chilcote et al.
890 hours awarded for a 600 star planet survey
PI Bruce Macintosh (LLNL)

Expected detection rate: 4% - 8% (cold vs. hot start)
or 25-50 exoplanets

Current Keck AO

GPI

Marois et al. 2011
Direct imaging: Lessons being learned

- Most are >5 Jupiter masses in the 1-100 Myr age range, with 8 – 300 AU separations, often including debris disks.

- Flux & spectra anchor planet formation & atmosphere models, such as hot-start vs. cold-start, GI vs. core-accretion, chemistry, clouds, etc.

- Astrometry yields orbit estimates → planet masses given from dynamics, independently from atmosphere models.

- Surveys using GPI, SPHERE, 1640, Subaru, LBT, JWST, etc. will transition the field from individual discoveries to statistically significant samples.
Many more results at the conference!

• Debris disks and their relationship to exoplanets
  – Jenny Patience et al. (poster), Debbie Padgett et al. (poster), Mike Fitzgerald et al. (oral, Tues PM), Karl Stapelfeldt (oral, Tues PM), Amaya Moro-Martín et al. (oral, Fri. AM), Torsten Lohne et al. (oral, Fri. AM), Rebekah Ilene Dawson (oral, Wed. AM), Etienne Morey (poster), Mark Booth (poster)

• Recent Direct Imaging Surveys
  – Eric Nielsen et al. (oral, Tues PM), Zahed Wahhaj (poster), Ray Jayawardhana et al. (oral, Tues PM), Markus Janson (poster), Arthur Vigan (poster), Heidi Karhonen et al. (poster), Sloane Wiktorowicz (poster)

• Planets in protoplanetary disks
  – Jane Greaves et al. (oral, Tues PM), Adam Kraus (poster)

• HR 8799
  – Quinn Konapacky et al. (oral, Tues PM), Sasha Hinkley et al. (poster)