Polarimetry of Hot Inflated Jupiters Reveals Their Neptune-like Blue Appearance

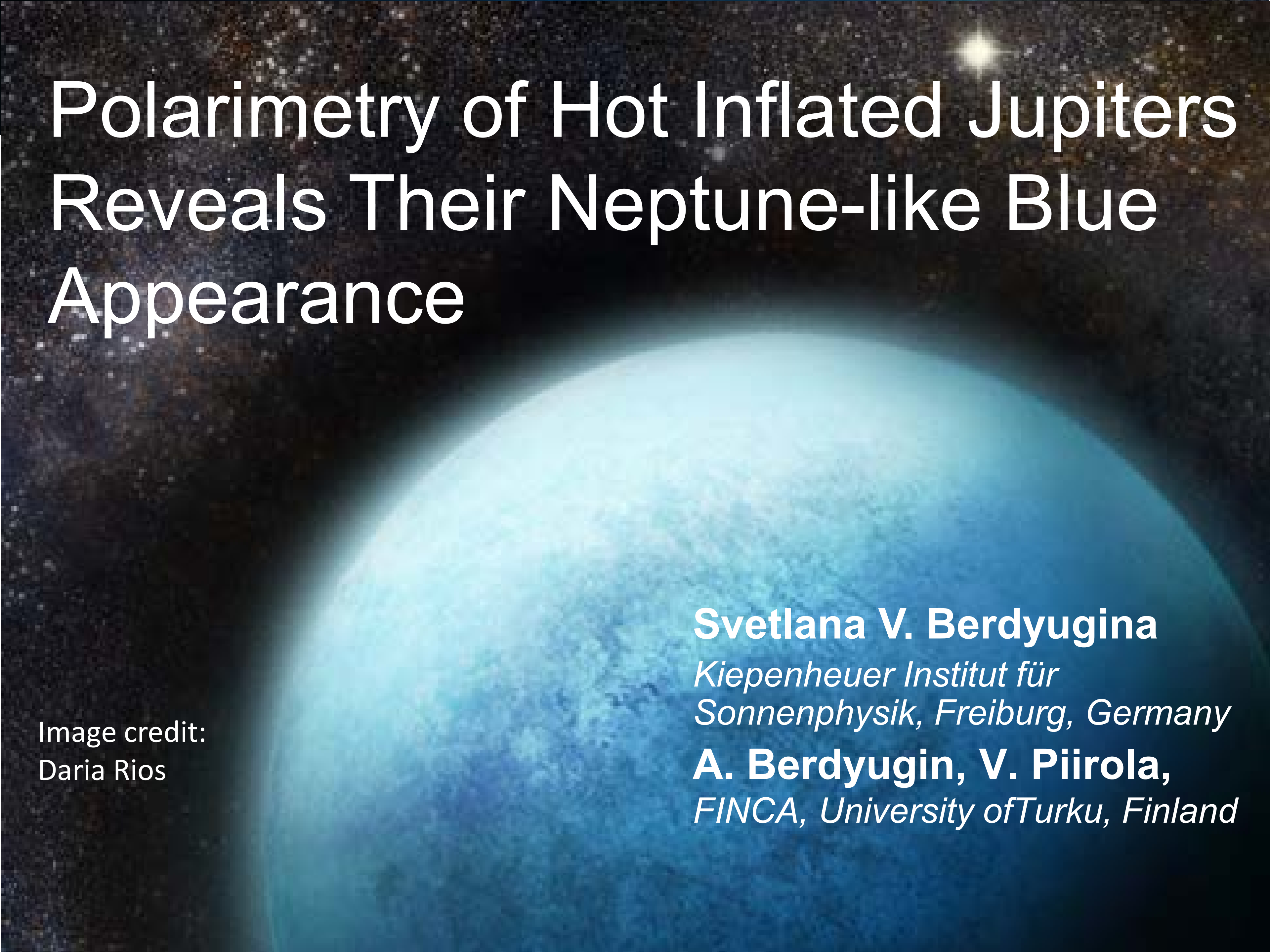

Image credit:
Daria Rios

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FINCA, University ofTurku, Finland

Reflected Light

- Direct probe of planetary atmospheres
- Methods:
  - Spectroscopic signatures:

    Difference between modeled and observed stellar spectrum

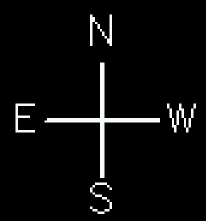
    (Charbonneau et al. 1999, Collier Cameron et al. 1999, 2000, 2002; Leigh et al. 2003ab; Rodler et al. 2008, 2010)
  - Photometric optical secondary eclipses

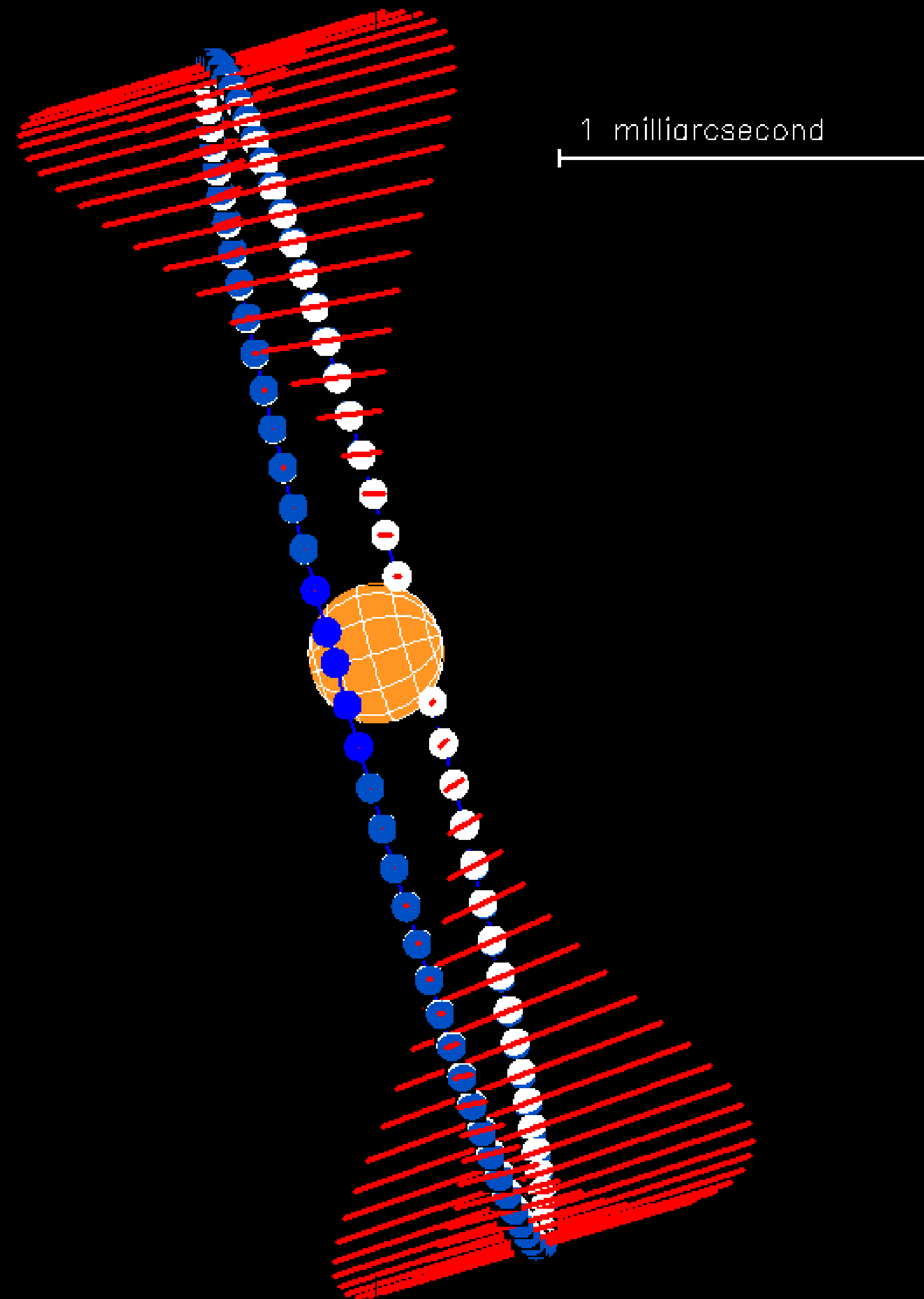
    Difference between observed stellar and star+planet flux

    (Rowe et al. 2008; Snellen et al. 2009, 2010; Alonso et al. 2009, 2010;Christiansen et al. 2010; Kipping & Bakos 2011; Demory et al. 2011; Desert et al. 2011ab; Kipping & Spiegel 2011)
  - Polarimetry

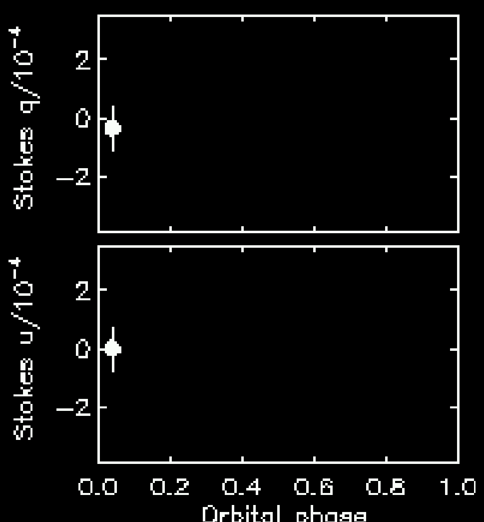
    Intrinsically differential technique offered by nature expands our ability to study exoplanets

    (Hough et al. 2006; Berdyugina et al. 2008, 2011; Wiktorovicz 2009; Lucas et al. 2009)





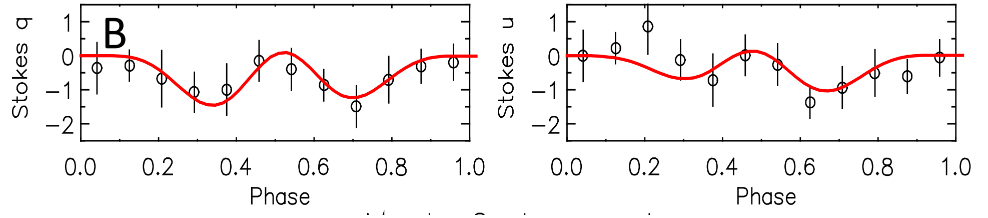
HD189733 (Berdyugina et al. 2008)



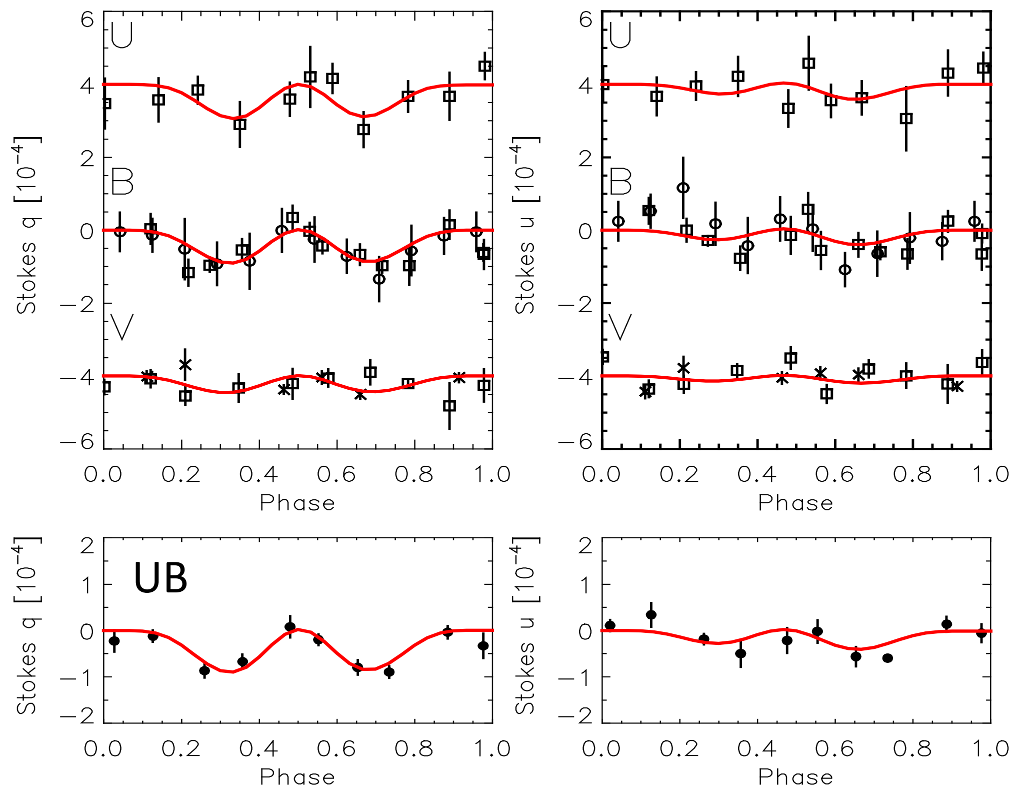
First Detection: HD189733b

- **Transiting hot Jupiter**
  - mass 1.15 M_J
  - period 2.2 d
  - semimajor axis 0.03 AU
- **B band** (440nm, **DiPol**, KVA60) *(Berdyugina et al. 2008)*
  - 93 nightly measurements (3h), Stokes *q* & *u*
  - Individual errors ~$(1\text{-}2)\cdot10^{-4}$
  - Error of binned data ~$5\cdot10^{-5}$
- **UBV** (360,440,550nm, **TurPol**, NOT) *(Berdyugina et al. 2011a)*
  - 35 nightly measurements(3-4h), Stokes *q* & *u*
  - 29 standard stars for calibration: ~$(1\text{-}2)\cdot10^{-5}$
  - Individual errors ~$(2\text{-}4)\cdot10^{-5}$
  - Error of binned data ~$1\cdot10^{-5}$
- Monte Carlo error analysis
- Max amplitude $9\times10^{-5} \pm 10^{-5}$

(Berdyugina et al. 2008)



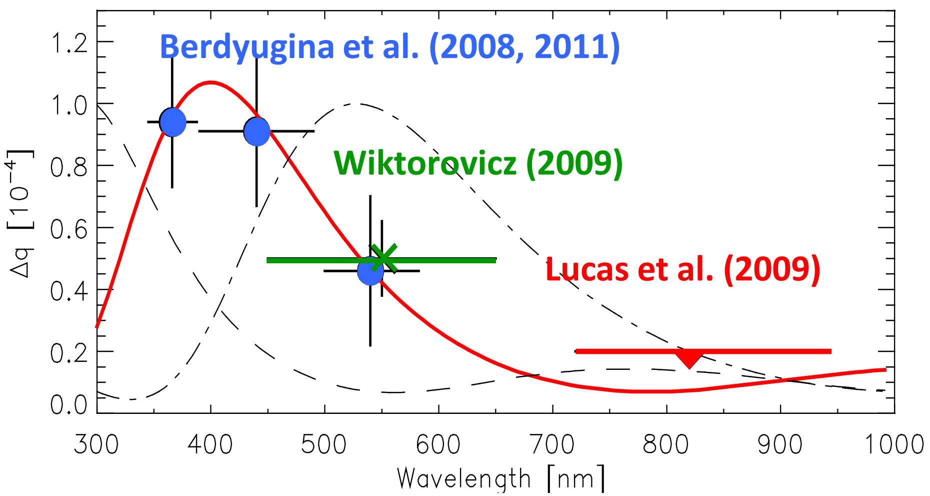
(Berdyugina et al. 2011a)

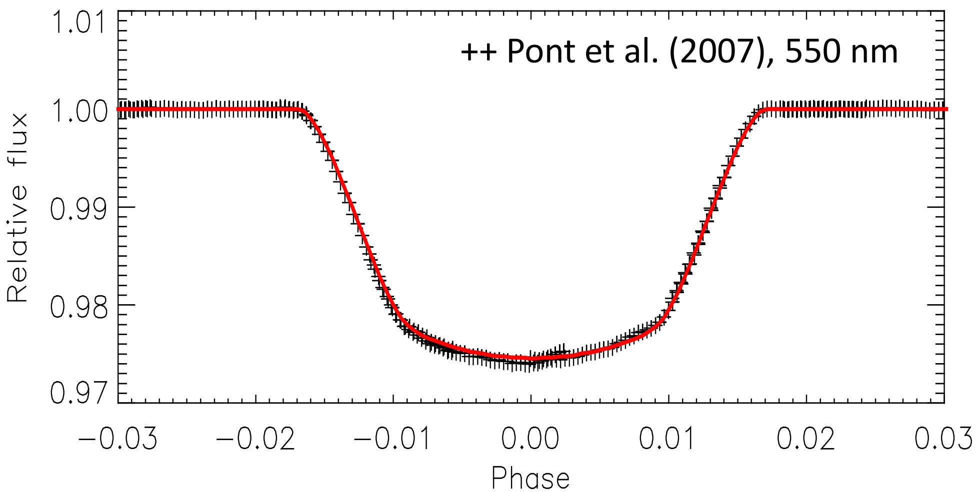


Model with Condensates: HD189733b

- Polarimetry and transit data fit with one model
- Semi-empirical model
  - Rayleigh scattering: H, H_2, He, CO, H_2O, CH_4, e^-, $MgSiO_3$ (Lecavelier des Etangs et al. 2008)
  - Absorption: H, H^-, H_2^-, H_2^+, He, He^-, metals
  - High-altitude condensate layer (haze) with 20-30nm particles
  - $R_{\tau=1}/R_J(U) \sim 1.19 \pm 0.24 \rightarrow$ Scat
  - $R_{\tau=1}/R_J(B) \sim 1.18 \pm 0.10 \rightarrow$ Scat (in agreement with Sing et al. 2011)
  - $R_{\tau=1}/R_J(V) < 0.75 \pm 0.20 \rightarrow$ Abs
  - $R_{\tau=1}/R_J(RI) < 0.43 \rightarrow$ Abs

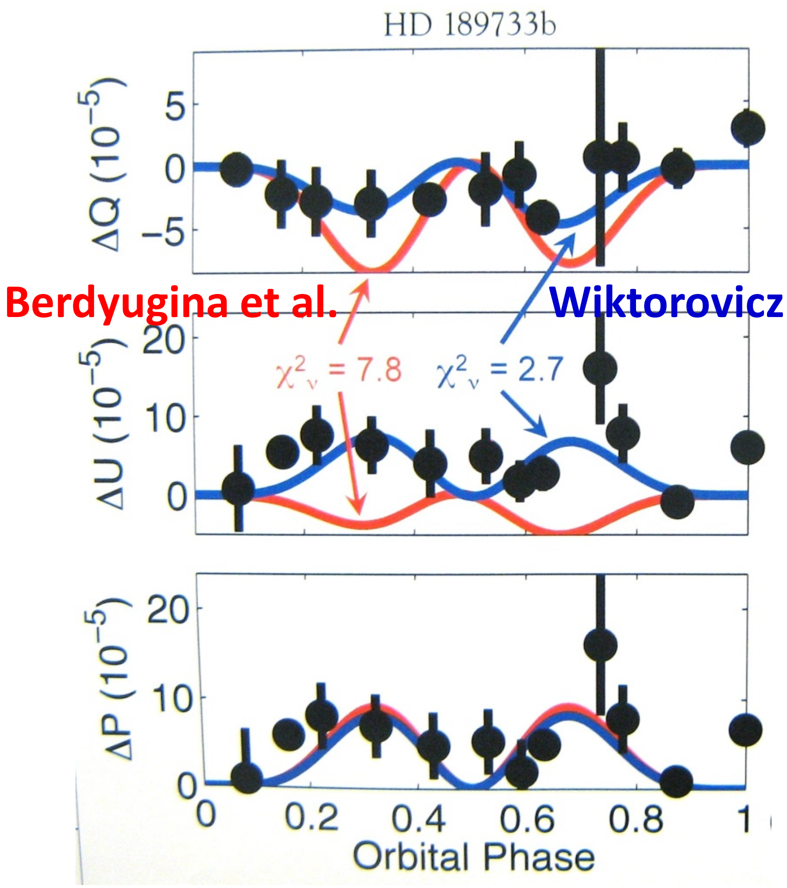
(*Berdyugina 2011*, arXiv:1011.0751)





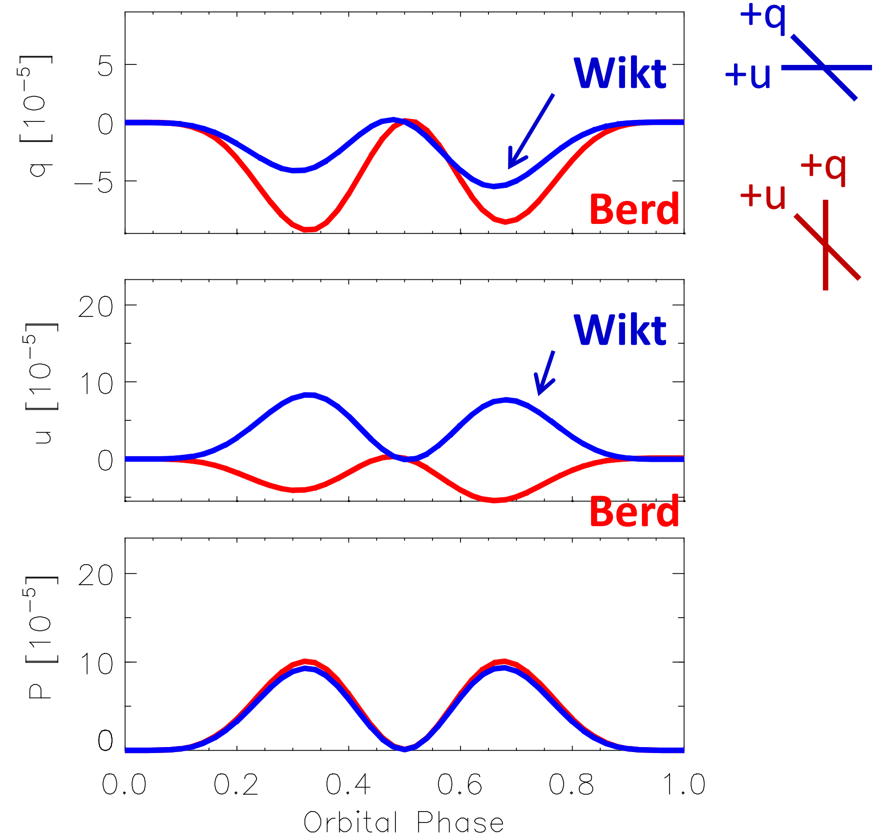
HD189733b: New data

- Wiktorovicz (poster):
  Passband? Calibration?



- Simple rotation by 45°!

$$\begin{pmatrix} Q \\ U \end{pmatrix}_{\text{Wikt\_rot}} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} Q \\ U \end{pmatrix}_{\text{Wikt}}$$



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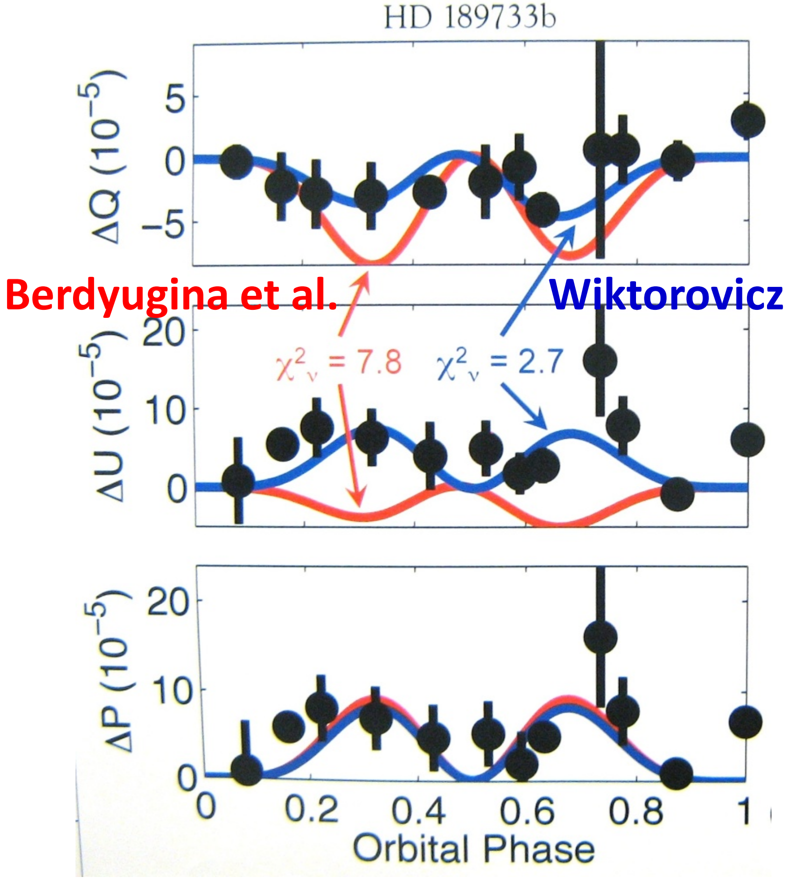

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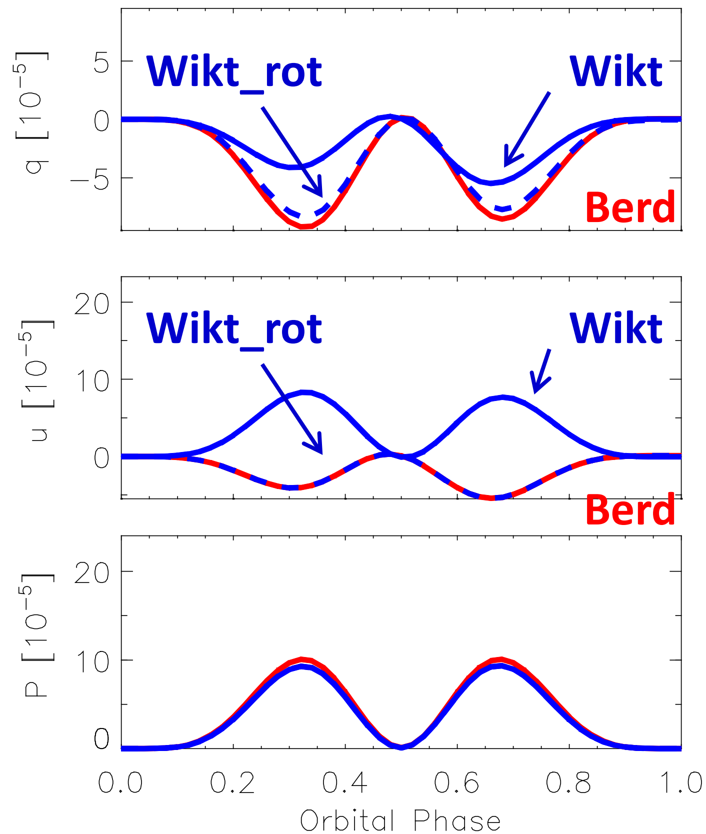
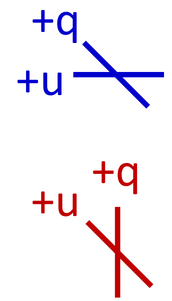
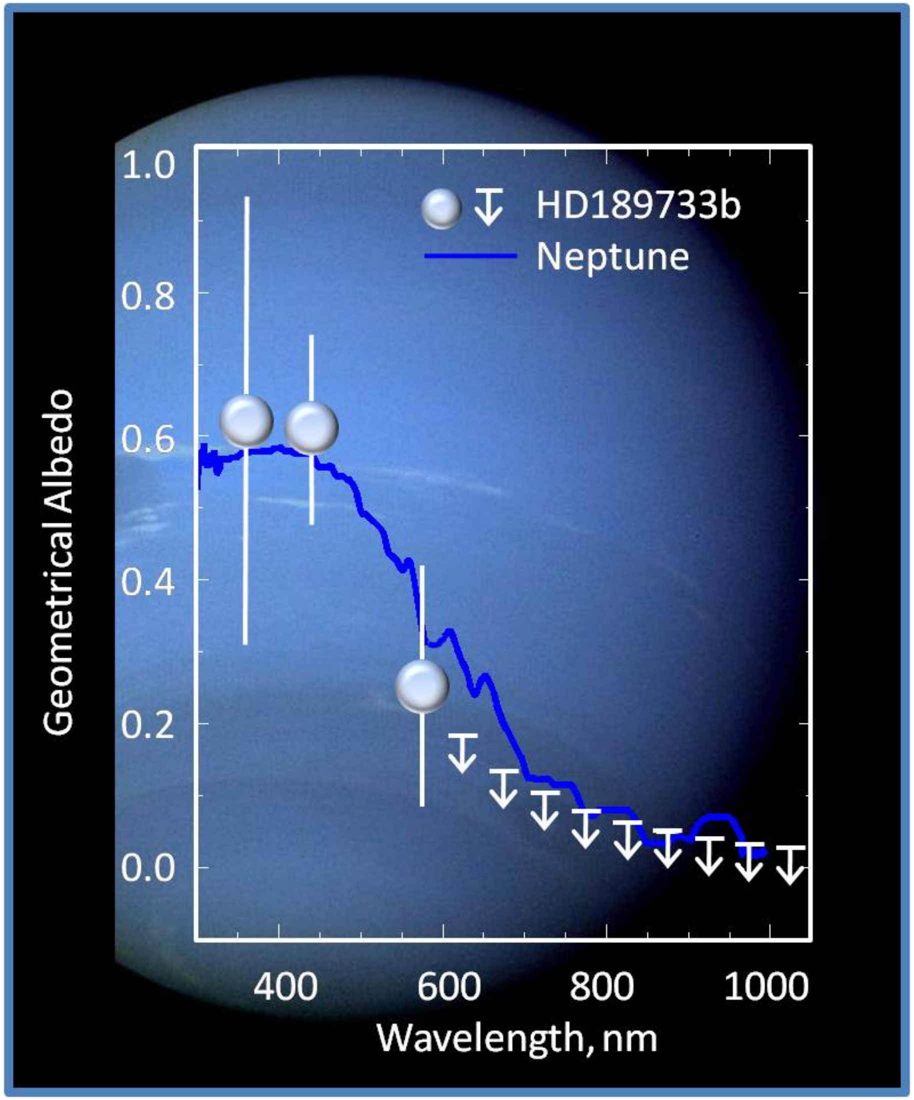




HD189733b: Geometrical albedo

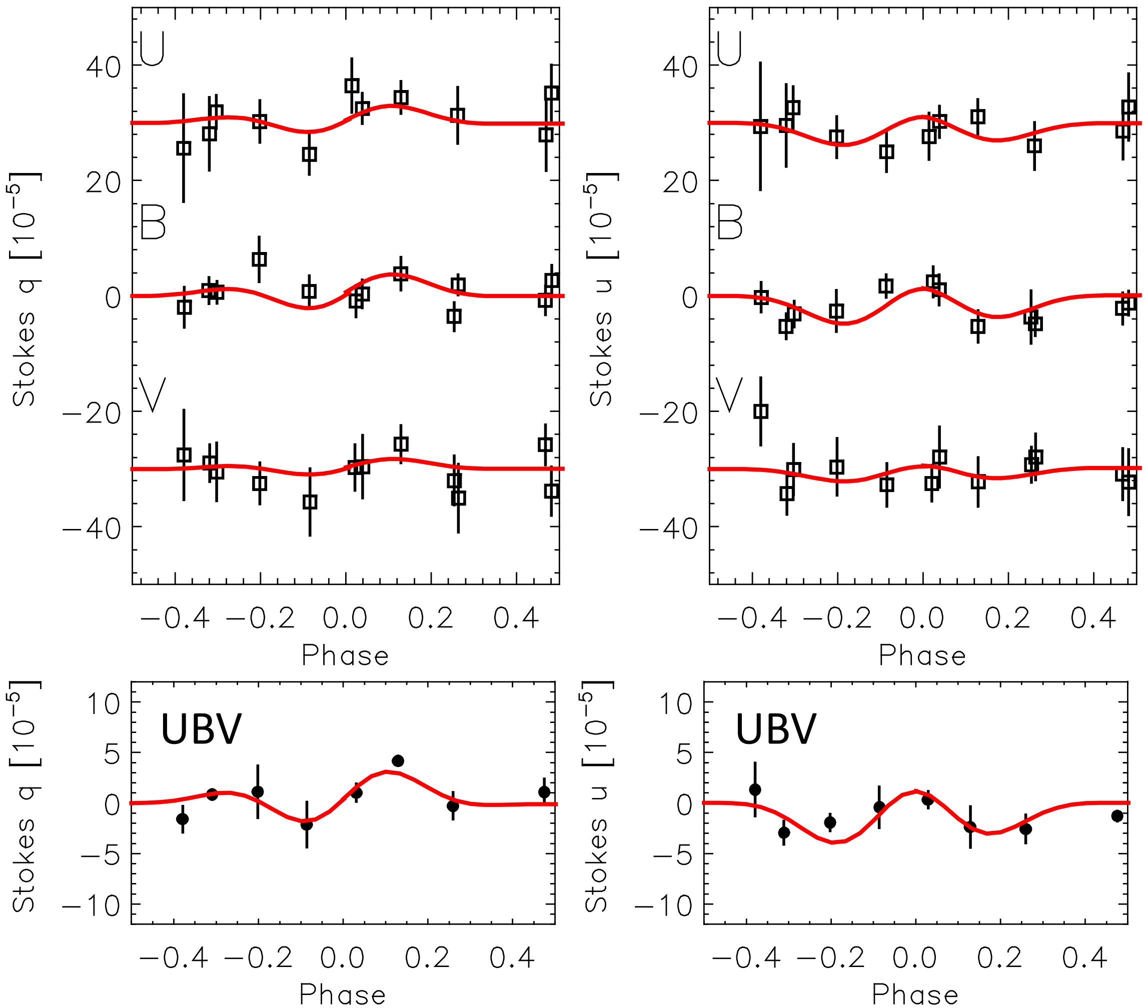
- Strong function of λ
  0.61 at 400 nm,
  0.28 at 550 nm,
  <0.2 at 600 nm
  <0.1 at >800 nm
- Similar to that of Neptune
  - blue: Rayleigh and Raman scattering on H_2
  - red: absorption by molecules
- Blue Planet



υ And b: Polarimetry

(Berdyugina et al. 2011b, arXiv:1109.3116)

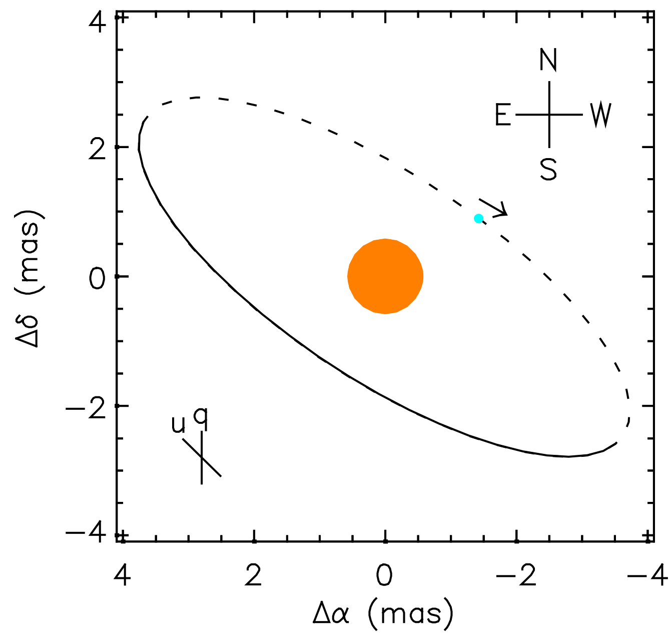
- **Non-transiting**
  - mass >0.69 M_J
  - period 4.6 d
  - semimajor axis 0.06 AU
- **UBV bands** (360, 440, 550 nm)
  - 35 nightly measurements(2-3h), Stokes *q* & *u*
  - 13 standard stars for calibration: ~$(1\text{-}2)\cdot 10^{-5}$
  - Individual errors ~$(2\text{-}4)\cdot 10^{-5}$
  - Instr. polariz. ~$1\cdot 10^{-5}$
  - Mean error of binned data = $0.7\cdot 10^{-5}$
- Monte Carlo error anal.
- Average amplitude UBV: $5\pm0.5(0.7)\text{x}10^{-5}$

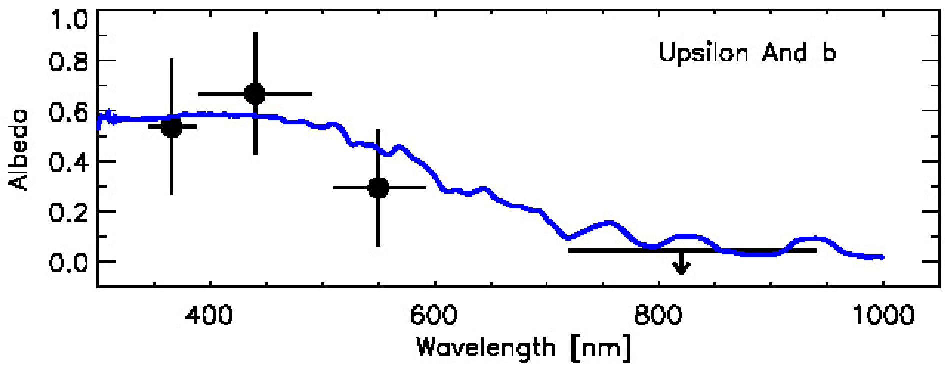


υ And b: Properties

- Inclination: 111° ± 11°
- Mass: 0.74 ± 0.07 M_J
- Radius: 1.36 ± 0.20 R_J
- Density: 0.36±0.08 g/cm^3
- Gravity: ~1000 cm/c^2
- ω=279°±14°, Ω=236°±12°
- Apsidal resonance with planets c and d
- Albedo:
  - 0.53 at 360 nm,
  - 0.67 at 440 nm,
  - 0.3 at 550 nm
  - <0.04 at 800nm (Hough et al.)
- Rayleigh scattering, similar to Neptune blue appearance

(Berdyugina et al. 2011b, , arXiv:1109.3116)



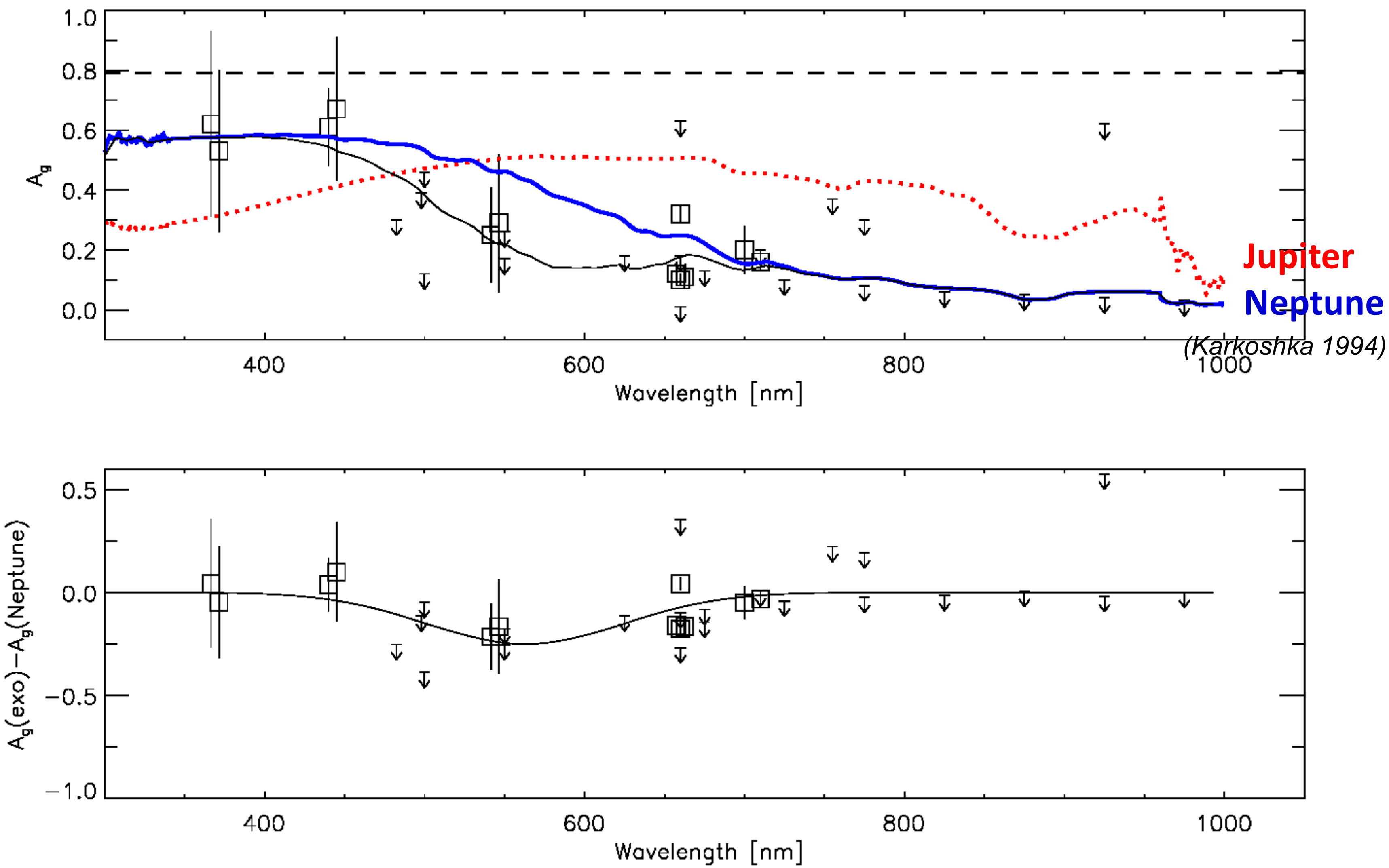


Geometrical Albedo of Hot Jupiters

Planet	A_g	Passband [nm]	R_p [R_J]	M_p [M_J]	ρ [g cm^{-3}]	a [AU]	T_* [K]	R_* [$R_\odot$]	Method$^+$, Reference
HD189733b	0.62±0.31	345–388	1.178	1.138	0.86	0.03142	4980	0.788	Pol, [1]
”	0.61±0.13	390–490							”
”	0.28±0.16	500–583							”
”	<0.26	450–650							Pol, [3]
υ And b	0.53±0.27	345–388	1.35	0.74	0.37	0.059	6212	1.631	Pol, [2]
”	0.67±0.24	390–490							”
”	0.29±0.23	500–490							”
HD209458b	< 0.17	400–700	1.38	0.714	0.34	0.04747	6075	1.146	Ph, [4]
CoRoT-1b	0.20±0.08	400–1000	1.49	1.03	0.39	0.0254	5950	1.11	Ph, [5]
”	<0.2	560–860							Ph, [6]
CoRoT-2b	0.16±0.03	560–860	1.465	3.31	1.31	0.0281	5625	0.902	Ph, [7]
HATP-7b	<0.18	423–897	1.421	1.8	0.78	0.0379	6350	1.84	Ph, [9]
”	<0.13	350–1000							Ph, [8]
TrES-2b	<0.01	423–897	1.169	1.253	0.97	0.03556	5850	1.0	Ph, [10]
TrES-3b	<1.07	550–700	1.305	1.91	1.07	0.0226	5720	0.813	Ph, [11]
”	<0.30	700–850							”
”	<0.62	850–1000							”
Kepler-5b	0.12±0.04	423–897	1.431	2.114	0.90	0.05064	6297	1.793	Ph, [12,13]
Kepler-6b	0.11±0.04	423–897	1.323	0.669	0.36	0.04567	5647	1.391	Ph, [13]
Kepler-7b	0.32±0.03	423–897	1.614	0.433	0.13	0.06246	5933	2.02	Ph, [12,14]
Kepler-8b	<0.63	423–897	1.419	0.60	0.26	0.0483	6213	1.486	Ph, [12]
Kepler-17b	0.10±0.02	423–897	1.31	2.45	1.35	0.02591	5630	1.019	Ph, [15]
τ Boo b	<0.3	466–499	(1.2)$^\times$	>3.9	2.80	0.046	6309	1.331	Sp, [16]
”	<0.39	385–611	(1.2)$^\times$						Sp, [17,20]
”	<0.37	590–920	(1.2)$^\times$						Pol, [21]
HD75289A b	<0.12	400–900	(1.6)$^\times$	>0.42	0.24	0.046	6120	1.25	Sp, [18]
”	<0.46	400–900	(1.2)$^\times$						Sp, [19]

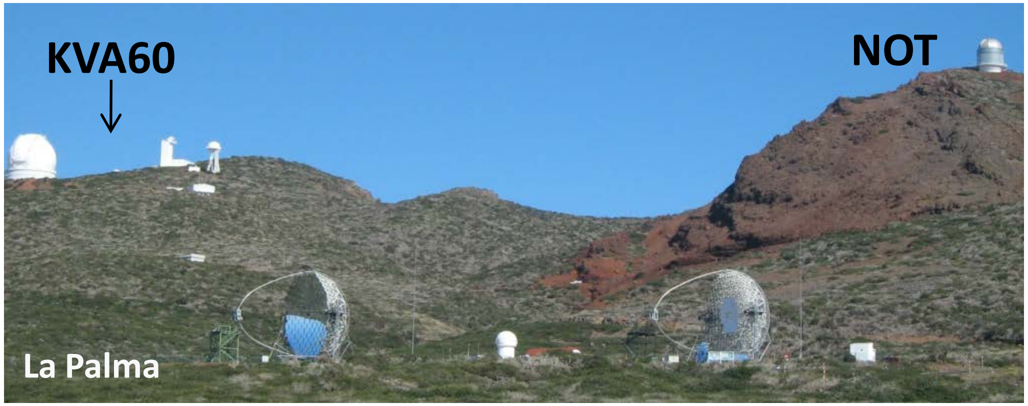
Geometrical Albedo of Hot Jupiters

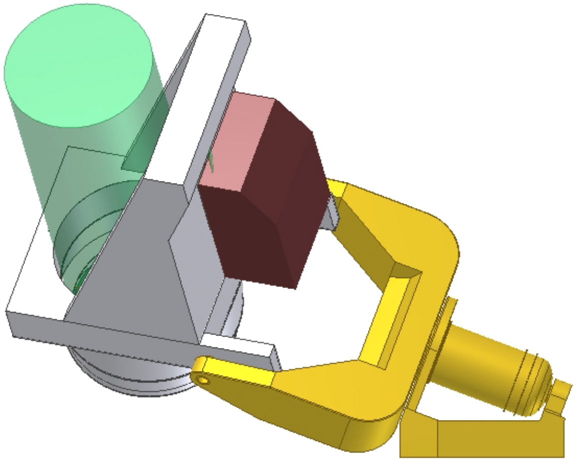
(Berdyugina et al. 2011b)



Polarized Light from Atmospheres of Nearby Extra-Terrestrial Systems

- PLANETS: Dedicated facilities
- Current: La Palma
  - KVA60, DIPol
  - NOT 2.5m, TurPol
- Future: Haleakala
  - H80, DIPol-2 (2011)
  - PLANETS 1.8m, InnoPol (2013)
- Telescope network for polarimetry





Conclusions

- Polarimetry is a differential technique with advantages for direct detection of exoplanets
  - ⇒ composition of the atmosphere, weather pattern, rot. periods, magnetospheres
- Polarimetry provides a detection tool for a much larger sample of exoplanets:
  - ⇒ non-transiting planets
  - ⇒ massive stars, binares
  - ⇒ evolved stars (giants)
- Different instruments provide consistent measurements
- Rayleigh scattering with the strong wavelength dependence dominates the reflected light ⇒ blue planets
- Polarimetry provides new physical insights into atmospheres (albedo, clouds)