Excursions into inversions: First results from the QUB secondary eclipse campaign

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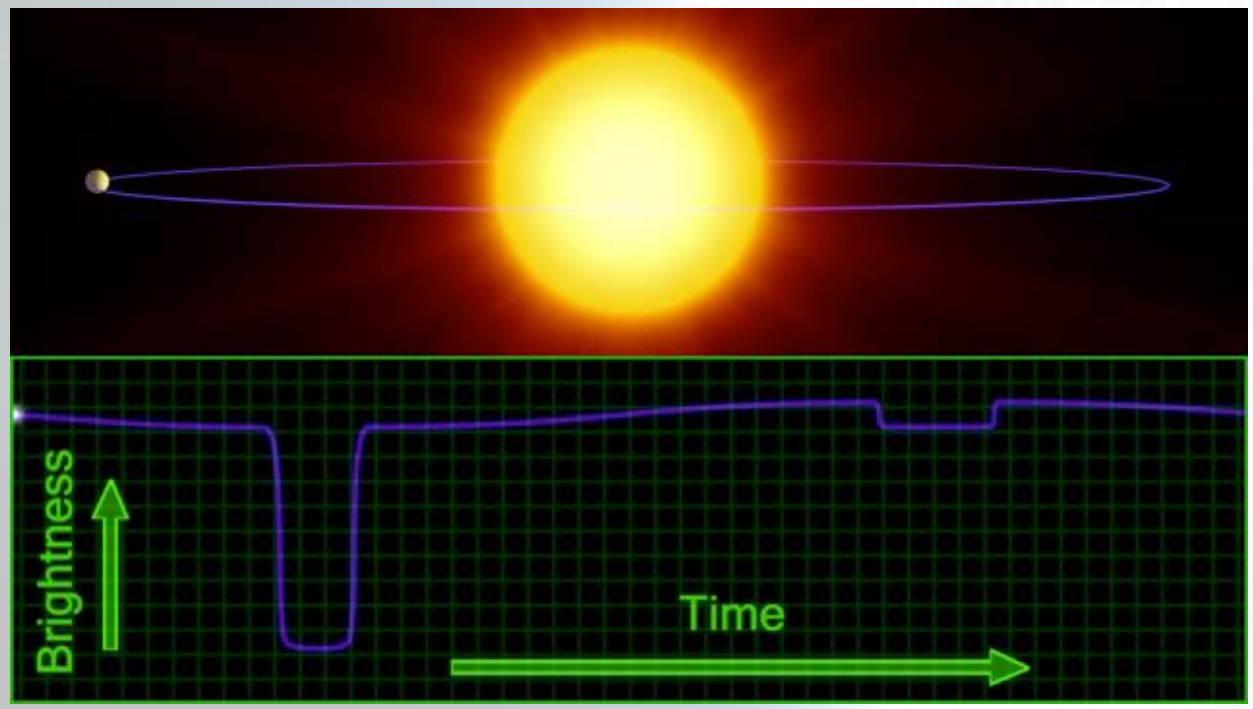
Summary

1. Secondary eclipses of hot Jupiters
2. WASP-12b: storms or systematics?
3. KELT-16b: Initial atmospheric categorisation
4. KELT-9b: Search for reflected light

Hoot Jupiters

Matthew Hooton, Queen's University Belfast

Secondary eclipses of exoplanets

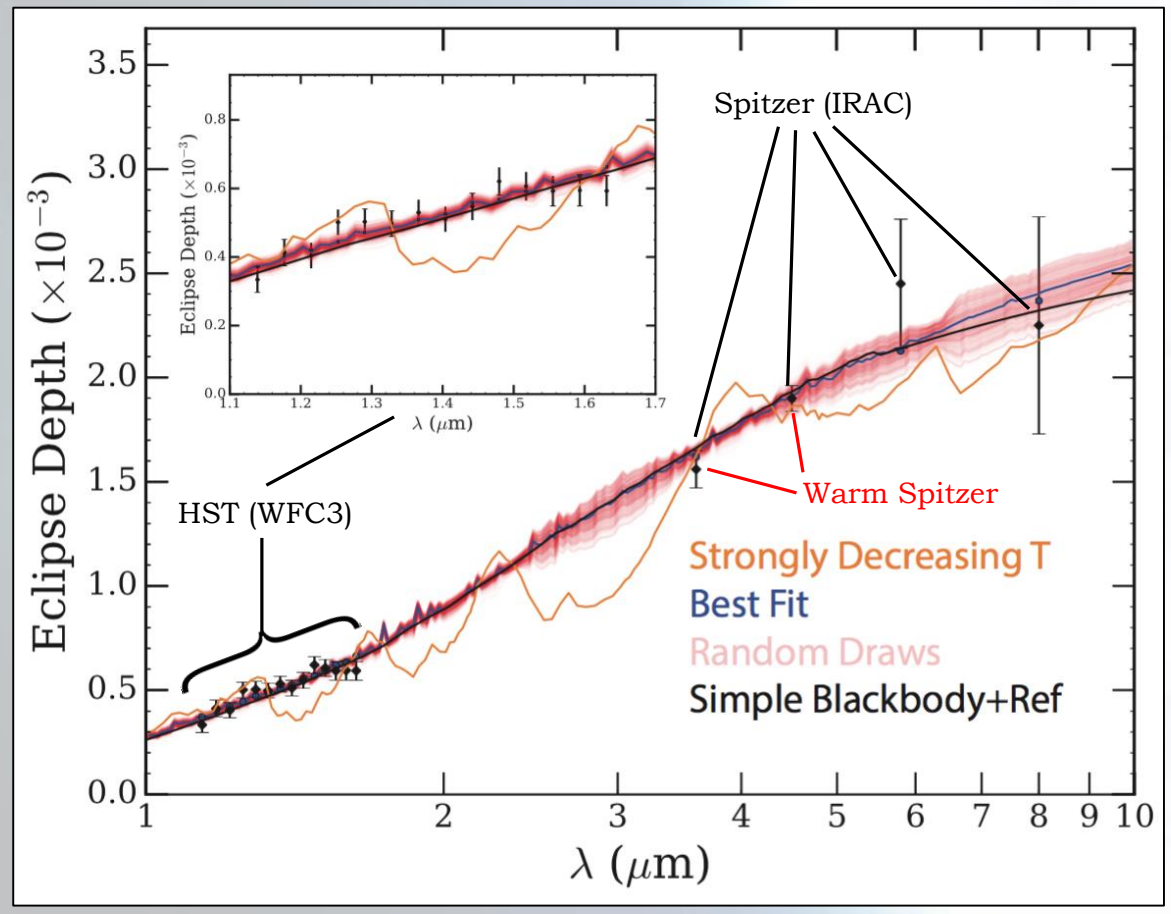


Observing secondary eclipses gives information about:

- Dayside Temperature
- Atmospheric circulation
- Presence of inversion layers
- Atmospheric composition

Graphic credit: NASA

Observations of hot Jupiters



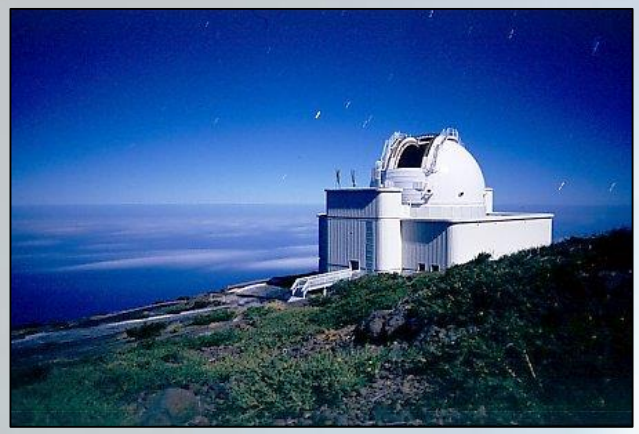
Emission spectrum of HAT-P-7b

- Thermal emission data dominated by HST/WFC3 and (Warm) Spitzer data.
- Routinely leaves us with large gaps in wavelength coverage that are not informing our models.

Mansfield et al. 2018, arXiv:1855:00424

QUB secondary eclipse campaign

2.5m Isaac Newton Telescope (WFC)



2.5m Liverpool Telescope (IO:O)

4.2m William Herschel Telescope (LIRIS & ULTRACAM)

Gemini (GMOS)

VLT (FORS2)

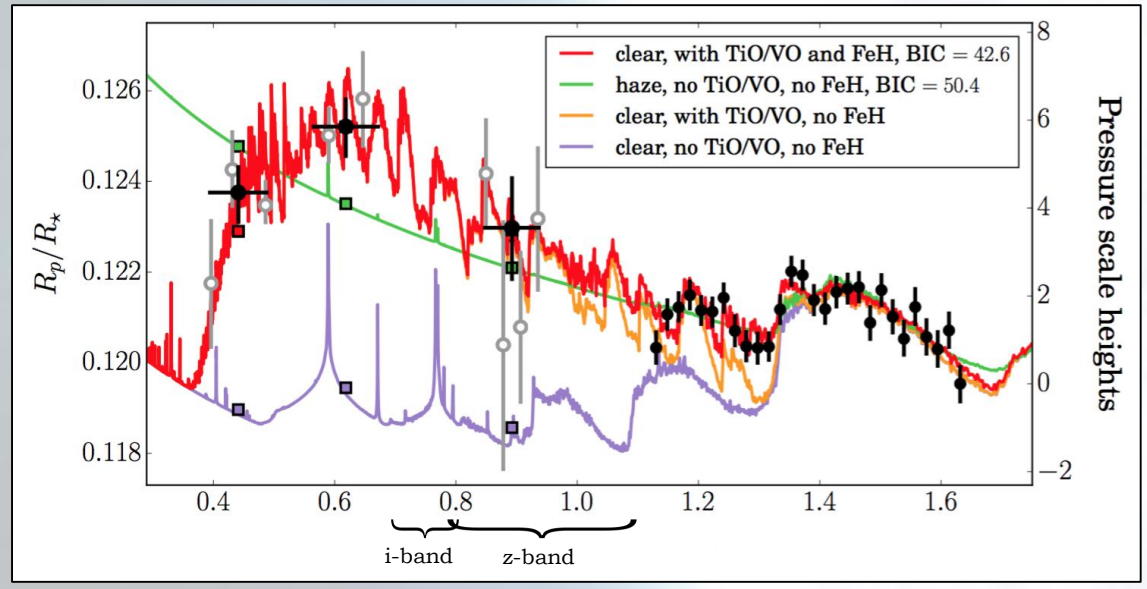
(not to scale)

Acquire photometric and spectral secondary eclipse data, in particular at the following wavelengths:

- K-band
- i- and z- bands
- Optical and NUV (reflected light)

Matthew Hooton, Queen's University Belfast

Secondary eclipses at i- and z-bands

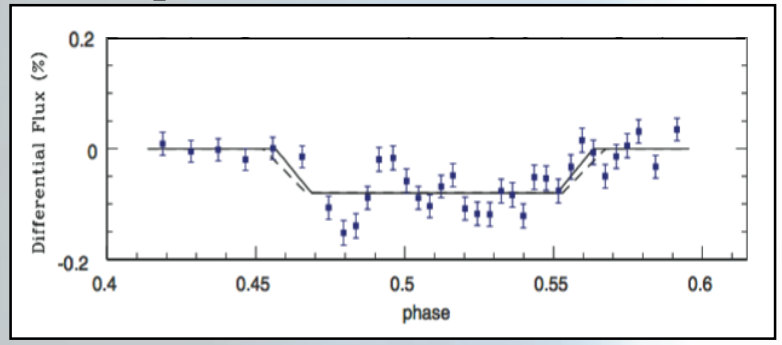
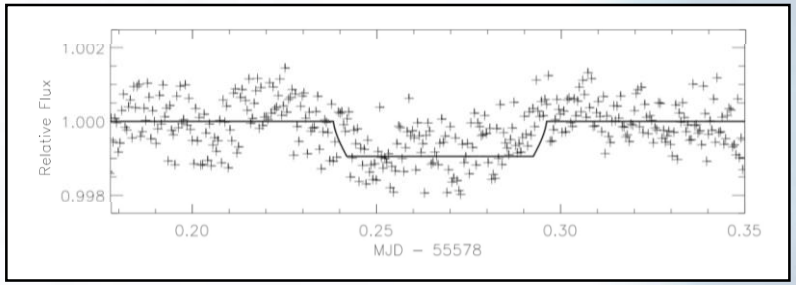
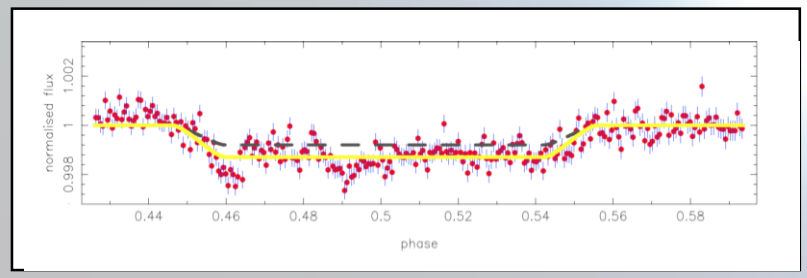
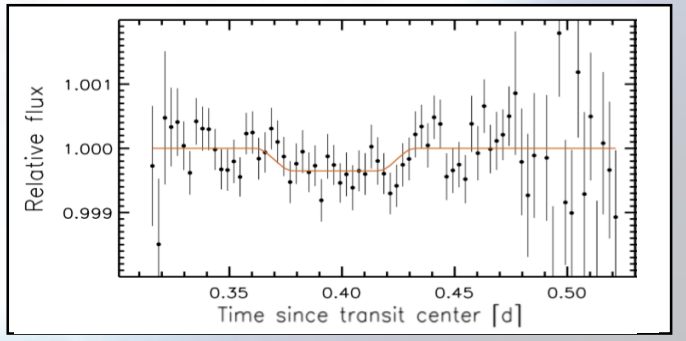


Transmission spectrum of WASP-121b

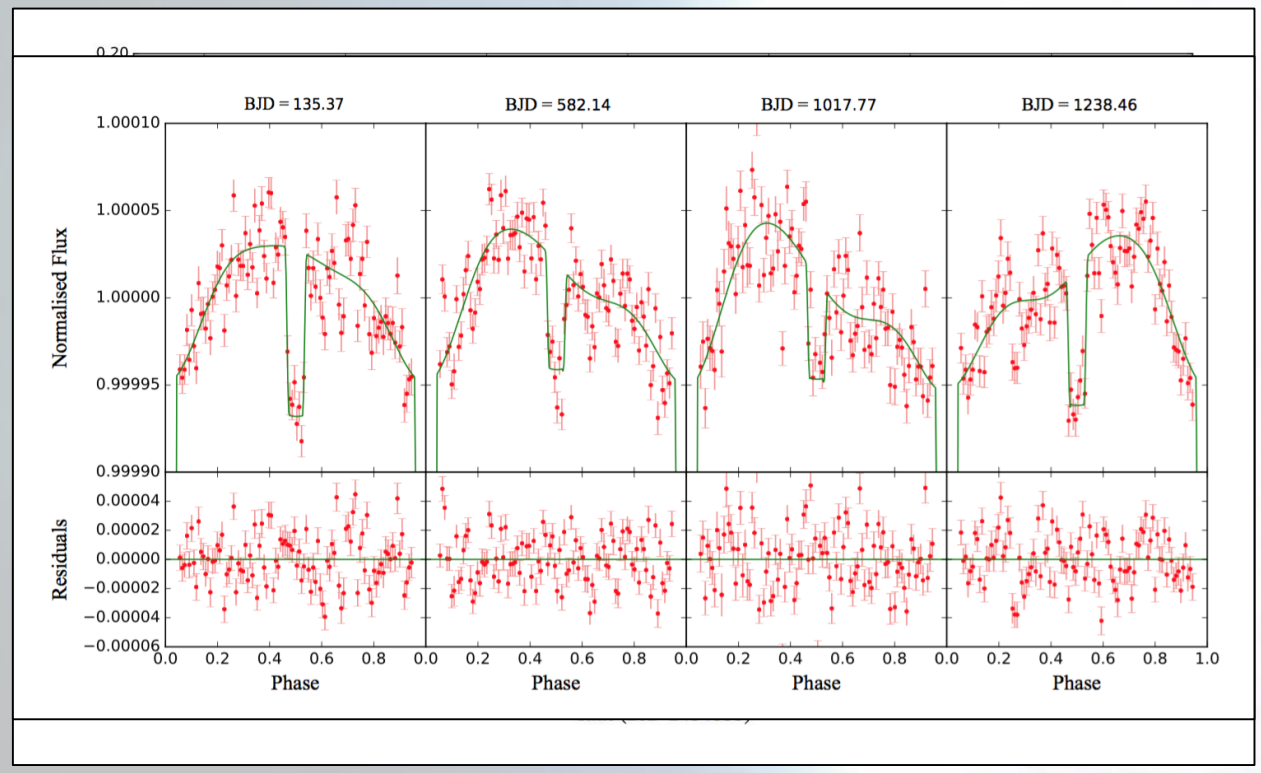
- TiO and VO compounds thought to be responsible for temperature inversions.
- TiO/VO features dominate this window.
- Very sensitive to the precise temperature of the emitting layers.
- A good measure of the C/O ratio.

Evans, Gibson et al. 2016, ApJL, 822, L4

z-band eclipses: results

WASP-12b		WASP-19b	
Eclipse	Depth (mmag)	Eclipse	Depth (mmag)
López-Morales et al. 2010 	0.82 ± 0.15	Burton, Watson, Gibson et al. 2012 	0.88 ± 0.19
Föhring et al. 2014 	1.30 ± 0.13	Lendl et al. 2013 	0.352 ± 0.116

The variable atmosphere of HAT-P-7b



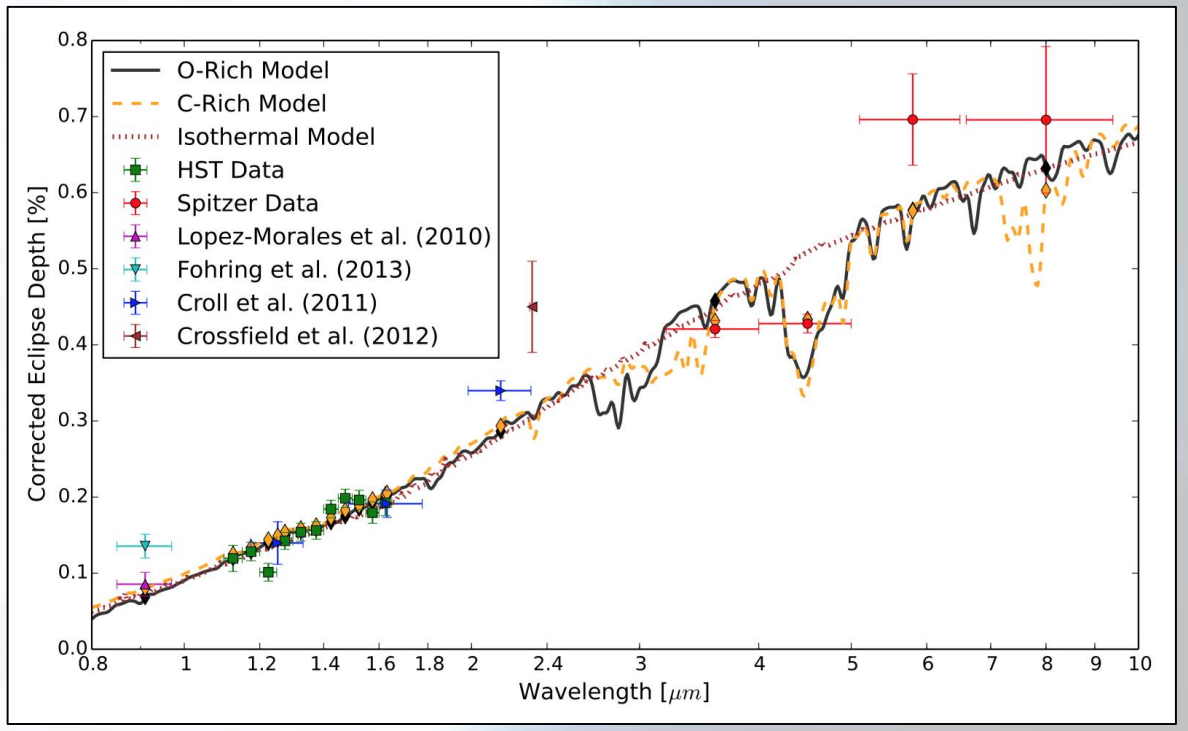
4 years of Kepler data showing the changing offset between the peak of thermal emission and the secondary eclipse for HAT-P-7b.

- Temporal variations in dayside emission and reflection seen for HAT-P-7b
- Changing offset between mid-eclipse and peak flux observed indicates peak brightness shifting about substellar point.
- Suggested that this is due to changing windspeeds, leading to variable cloud coverage and a changing energy balance.

Armstrong, De Mooij et al. 2016, Nat. Astron., 1, 4

WASP-12b

WASP-12	
Spectral Type	G0
Mass	1.35 $M_\odot$
Radius	1.599 $R_\odot$
T_{eff}	6300 K
WASP-12b	
Mass	1.404 M_J
Radius	1.736 M_J
Density	0.268 ρ_J
Period	1.09 days
T_{eq}	2533 K



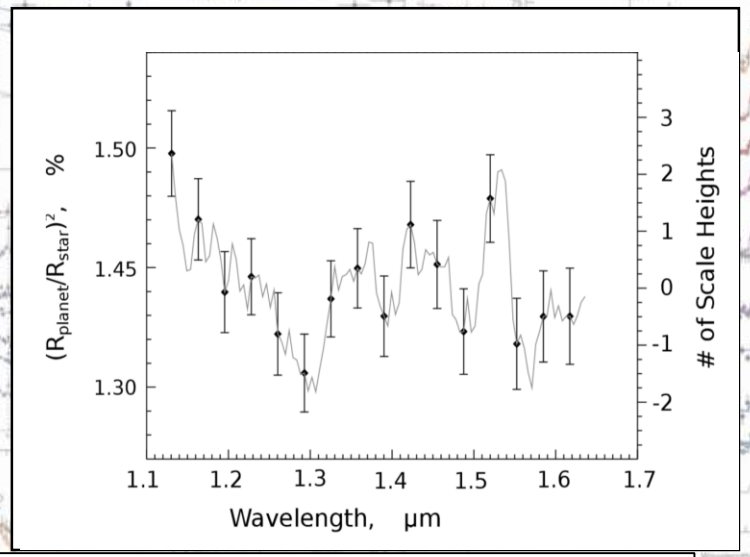
Emission spectrum of WASP-12b

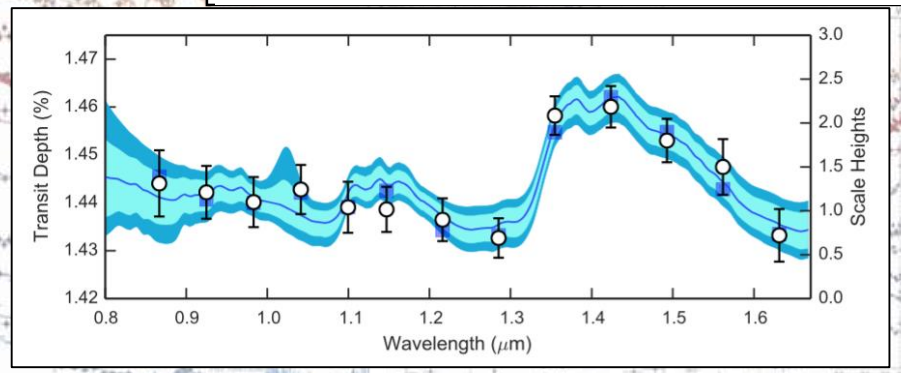
Hebb et al. 2009, ApJ, 693, 1920

Stevenson et al. 2014, ApJ, 791, 36

WASP-12b: transmission spectra

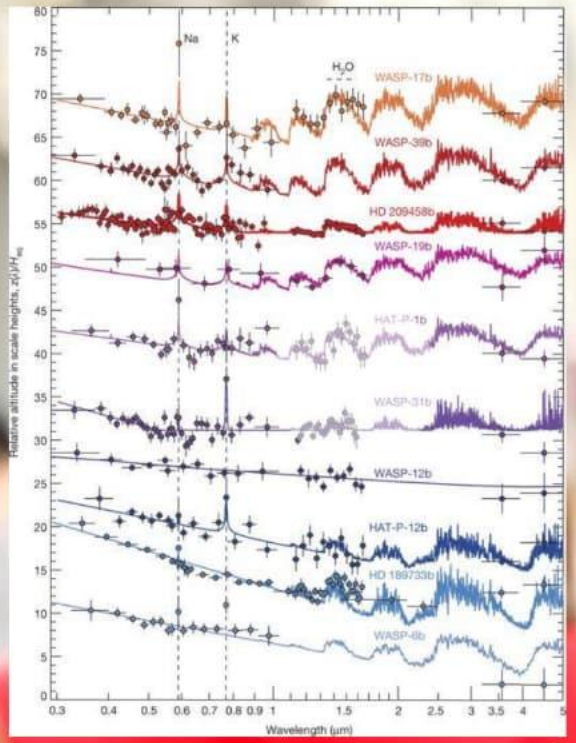
Swain et al. 2013, Icarus, 225, 432





Kriedberg et al. 2015, ApJ, 814, 66

- Swain et al. (2013) found a low amplitude water feature in WASP-12b's transmission spectrum.
- Sing et al. (2015) suggested that this could be due winds transporting clouds from the nightside to the terminator.
- Kriedberg et al. (2015) detected a water feature at 7σ, consistent with solar abundances.



OTHER TRANSMISSION SPECTRA

EXOPLANET SCIENTISTS

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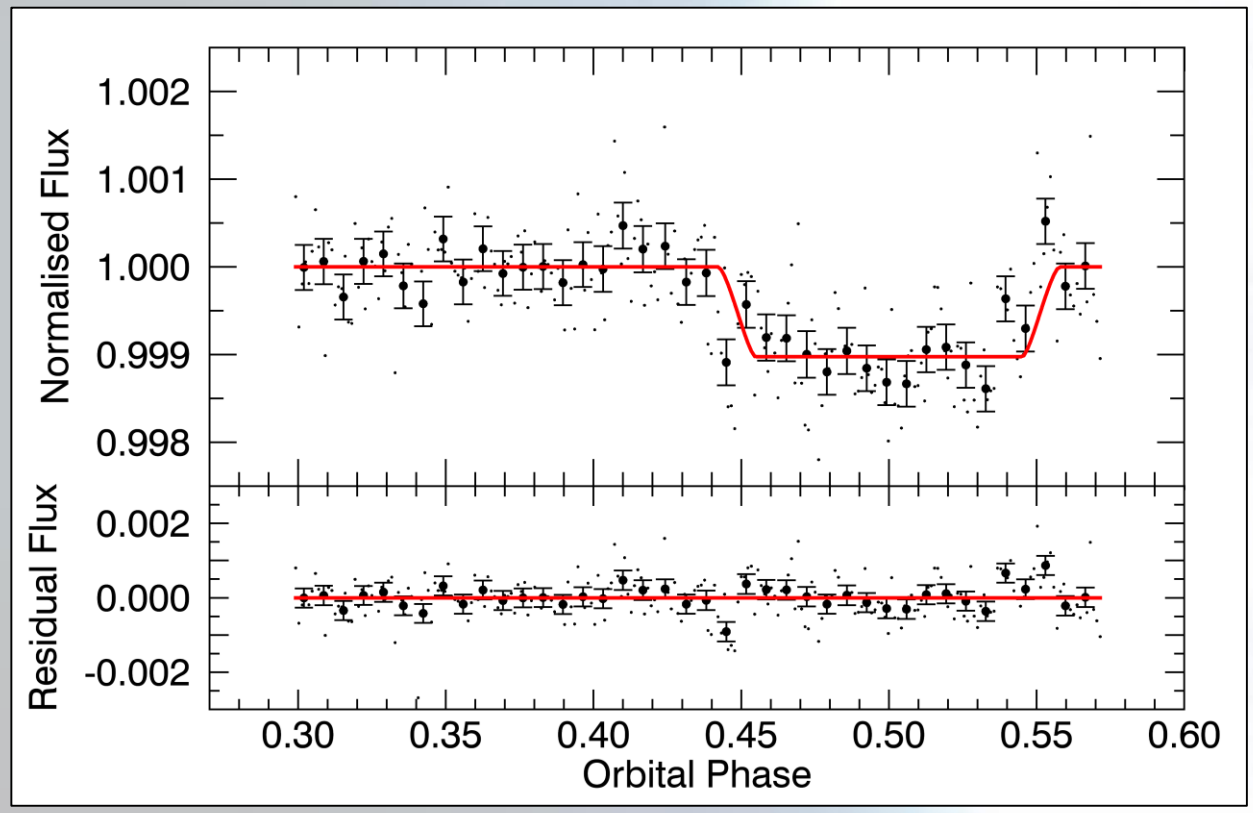
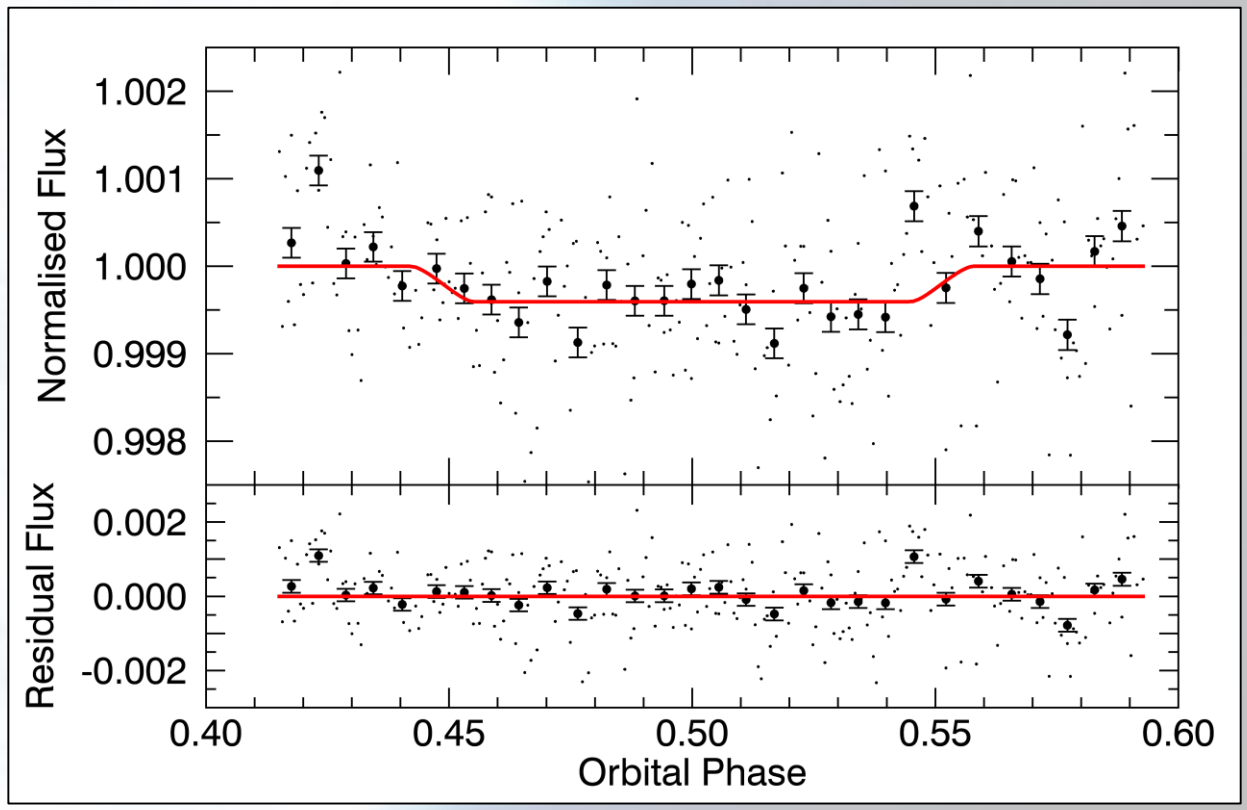
WASP-12b: i-band observations

INT/WFC Jan 15 2017



1.01 ± 0.18 mmag

LT/IO:O Jan 20 2018

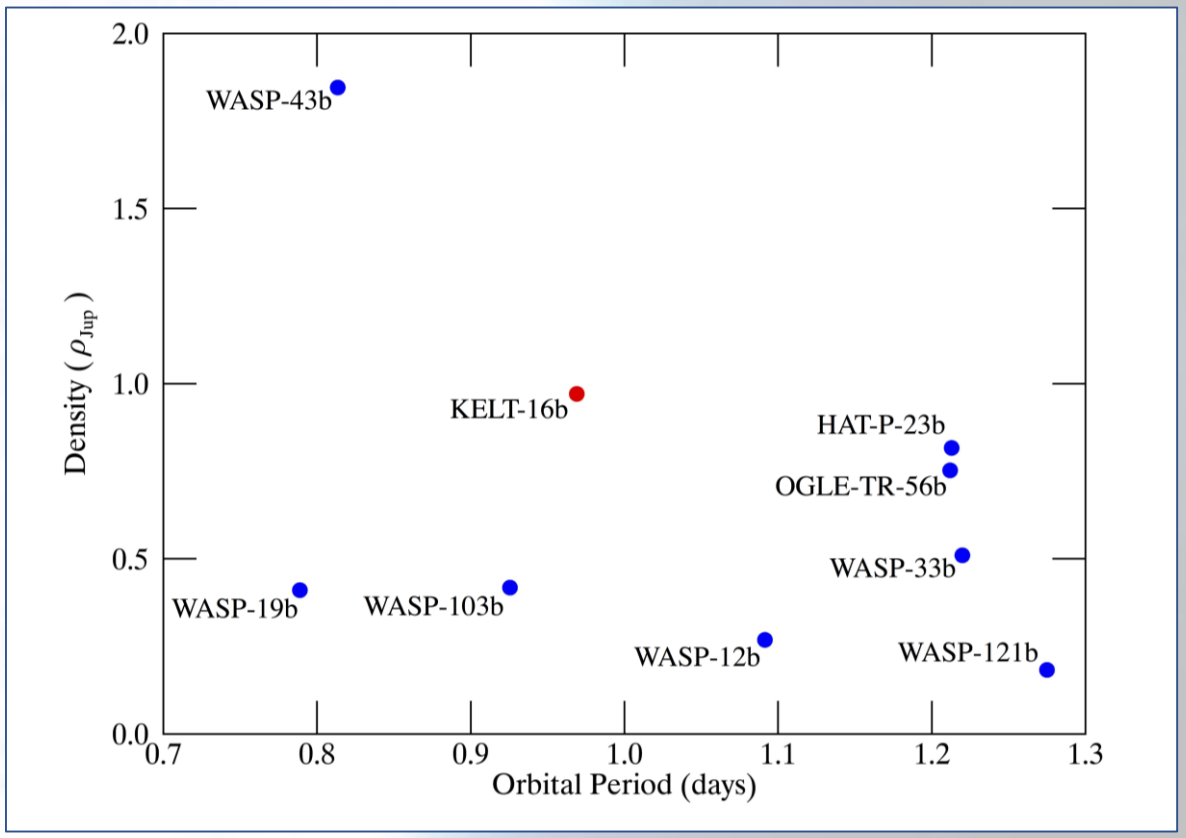


0.52 ± 0.24 mmag

Hooton et al. 2018, in prep

KELT-16b

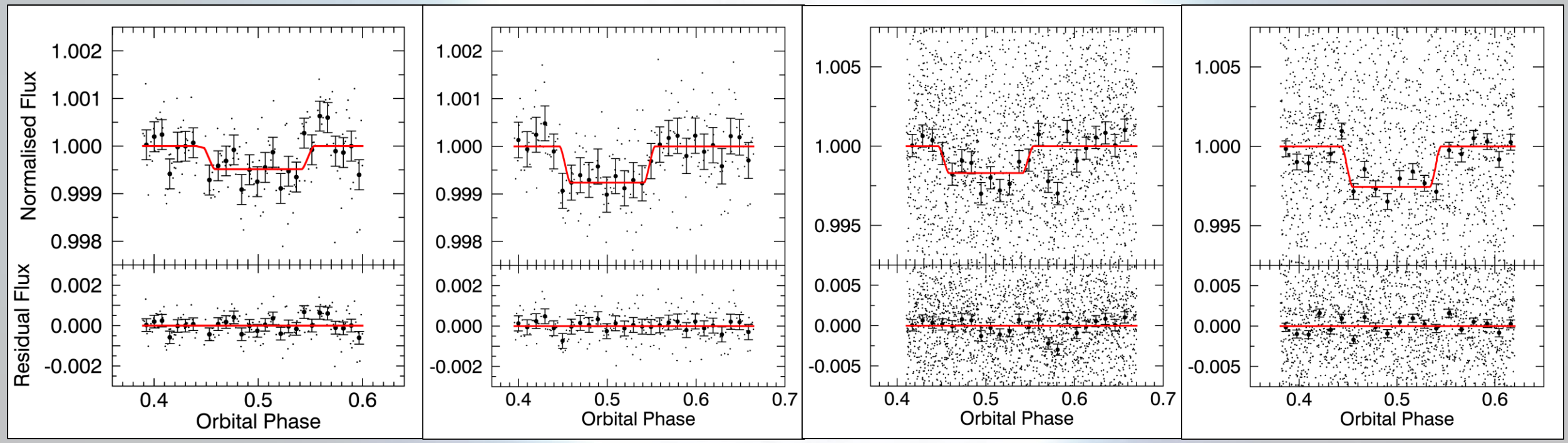
KELT-16	
Spectral Type	F7V
Mass	1.211 $M_\odot$
Radius	1.36 $R_\odot$
T_{eff}	6236 K
KELT-16b	
Mass	2.75 M_J
Radius	1.415 M_J
Density	0.971 ρ_J
Period	0.97 days
T_{eq}	2450 K



Oberst et al. 2017, AJ, 153, 97

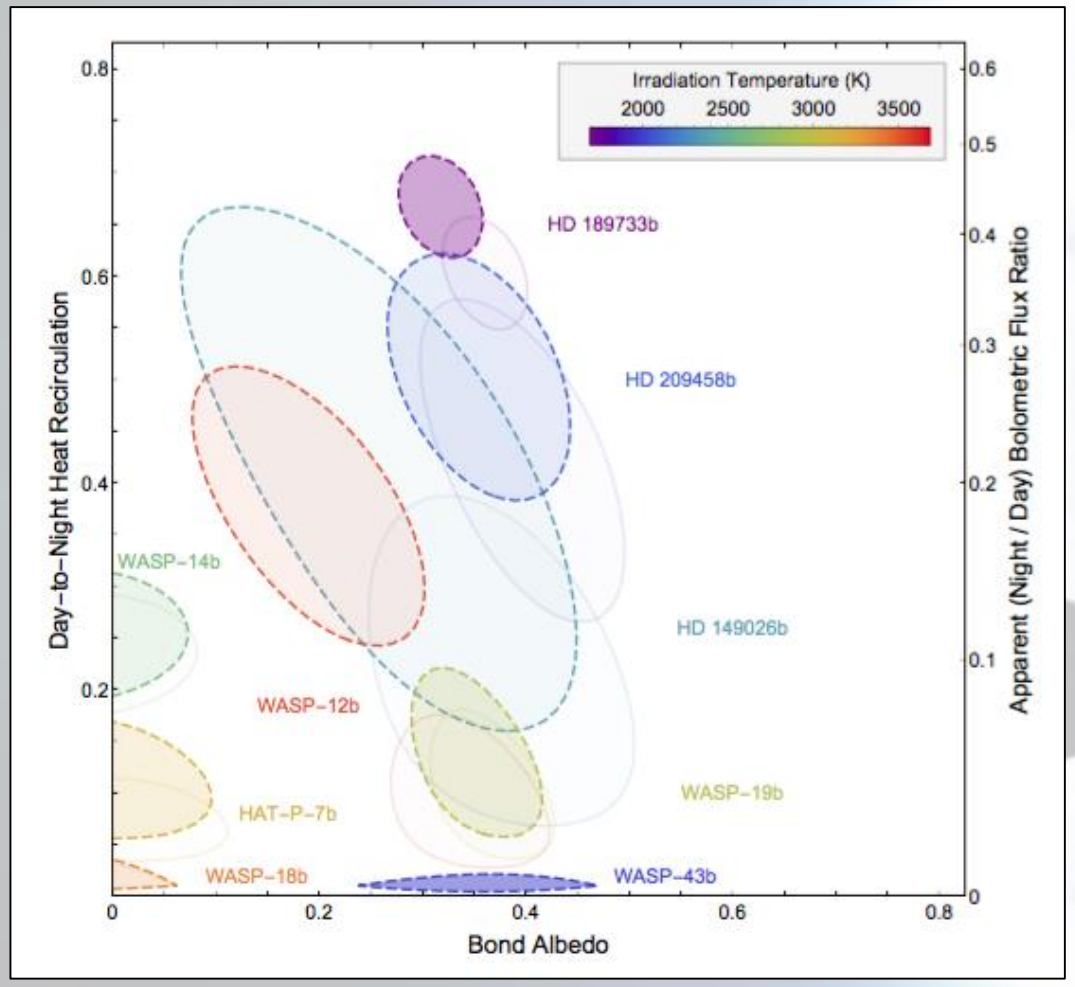
KELT-16b: multi-band observations

INT/WFC Aug 4 2017 | INT/WFC Aug 5 2017 | WHT/LIRIS Aug 9 2017 | WHT/LIRIS Aug 5 2017



i-band: 0.54 ± 0.22 mmag | z-band: 0.78 ± 0.12 mmag | J-band: 1.4 ± 1.1 mmag | K_S-band: 3.1 ± 1.0 mmag

Light reflected from hot Jupiters

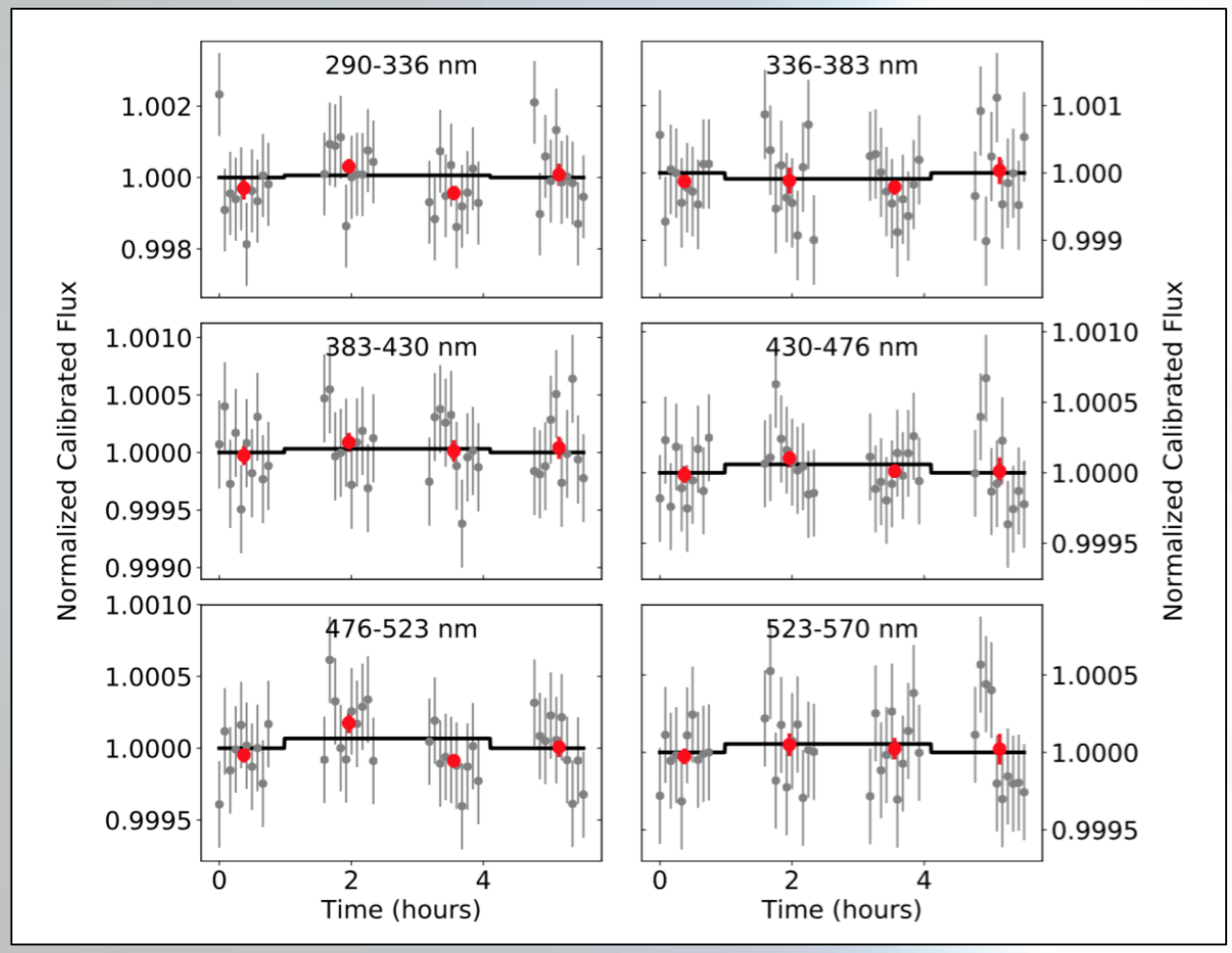


Predicted Bond Albedos for a range of hot Jupiters

- Thermal emission measurements from a range of hot Jupiters suggest that they should have low-moderate Bond albedos.
- This suggests that for some targets, secondary eclipses in the optical and UV should be detectable with current instrumentation.

Schwartz et al. 2017, ApJ, 850, 2

Light reflected from hot Jupiters



UV and optical eclipses of WASP-12b with HST/STIS

- HST/STIS observations could not find a secondary eclipse signal in 6 bins across the optical and NUV.
- Found that $A_g < 0.064$ at 97.5% confidence level.

Bell et al. 2017, ApJ, 847, 1

Light reflected from hot Jupiters

THE VERY LOW ALBEDO OF AN EXTRASOLAR PLANET:
MOST[1] SPACE-BASED PHOTOMETRY OF HD 209458

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WASP-104B IS DARKER THAN CHARCOAL

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Mon. Not. R. Astron. Soc. **417,** L88–L92 (2011)

Detection of visible light from the darkest world★

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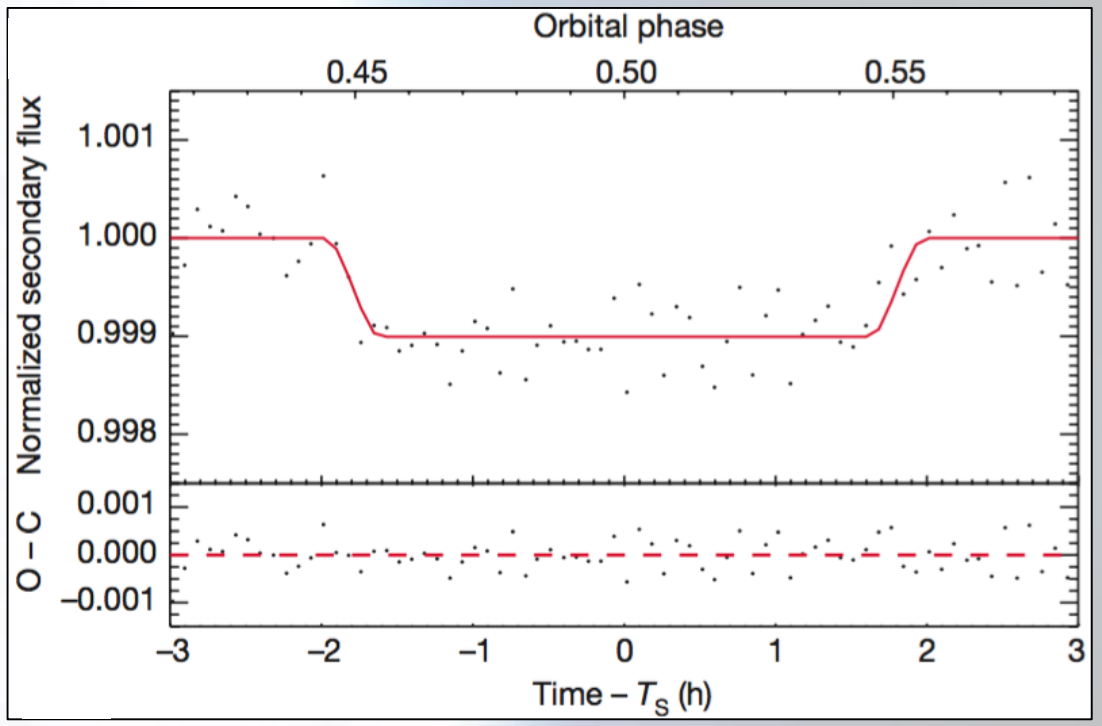
THE VERY LOW ALBEDO OF WASP-12B FROM SPECTRAL ECLIPSE OBSERVATIONS WITH *HUBBLE*

Taylor J. Bell,[1,*] Nikolay Nikolov,[2] Nicolas B. Cowan,[1,3,*] Joanna K. Barstow,[4] Travis S. Barman,[5] Ian J. M. Crossfield,[6] Neale P. Gibson,[7] Thomas M. Evans,[2] David K. Sing,[2] Heather A. Knutson,[8] Tiffany Kataria,[9] Joshua D. Lothringer,[5] Björn Benneke,[10] and Joel C. Schwartz[1,3,*]

KELT-9b

KELT-9	
Spectral Type	B9.5-A0
Mass	2.52 $M_\odot$
Radius	2.362 $R_\odot$
T_{eff}	10170 K
KELT-9b	
Mass	2.88 M_J
Radius	1.891 M_J
Density	0.426 ρ_J
Period	1.48 days
T_{eq}	4045 K

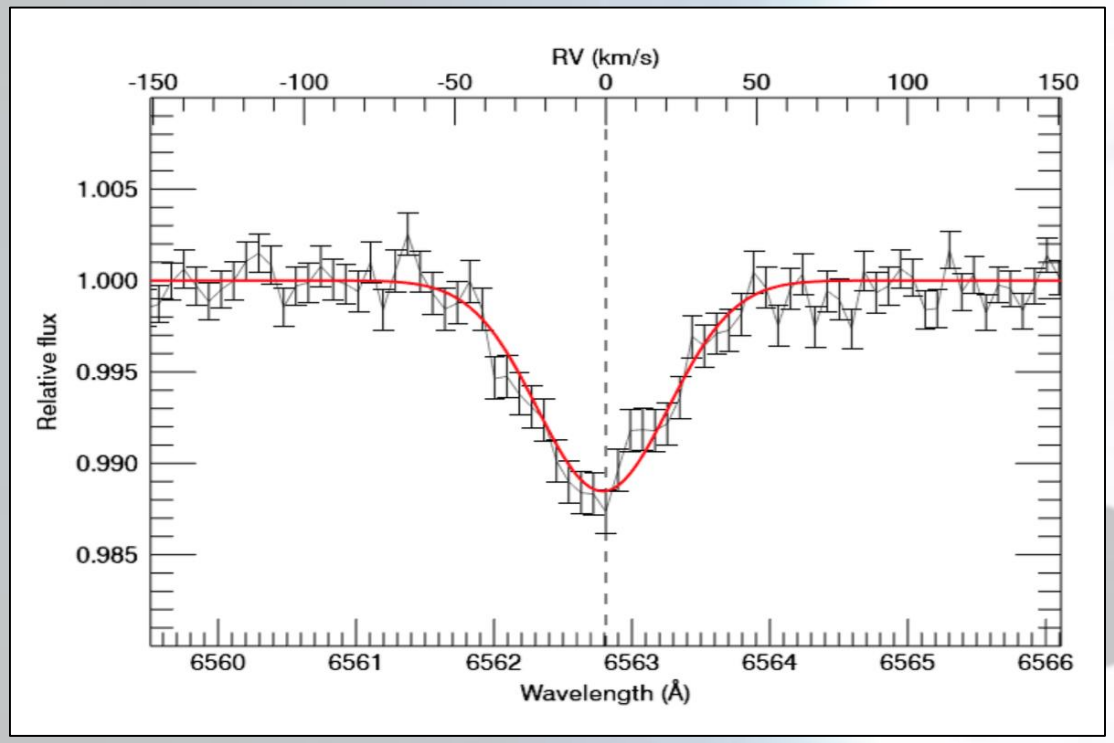


F_{ecl} – 1 mmag (z'-band)

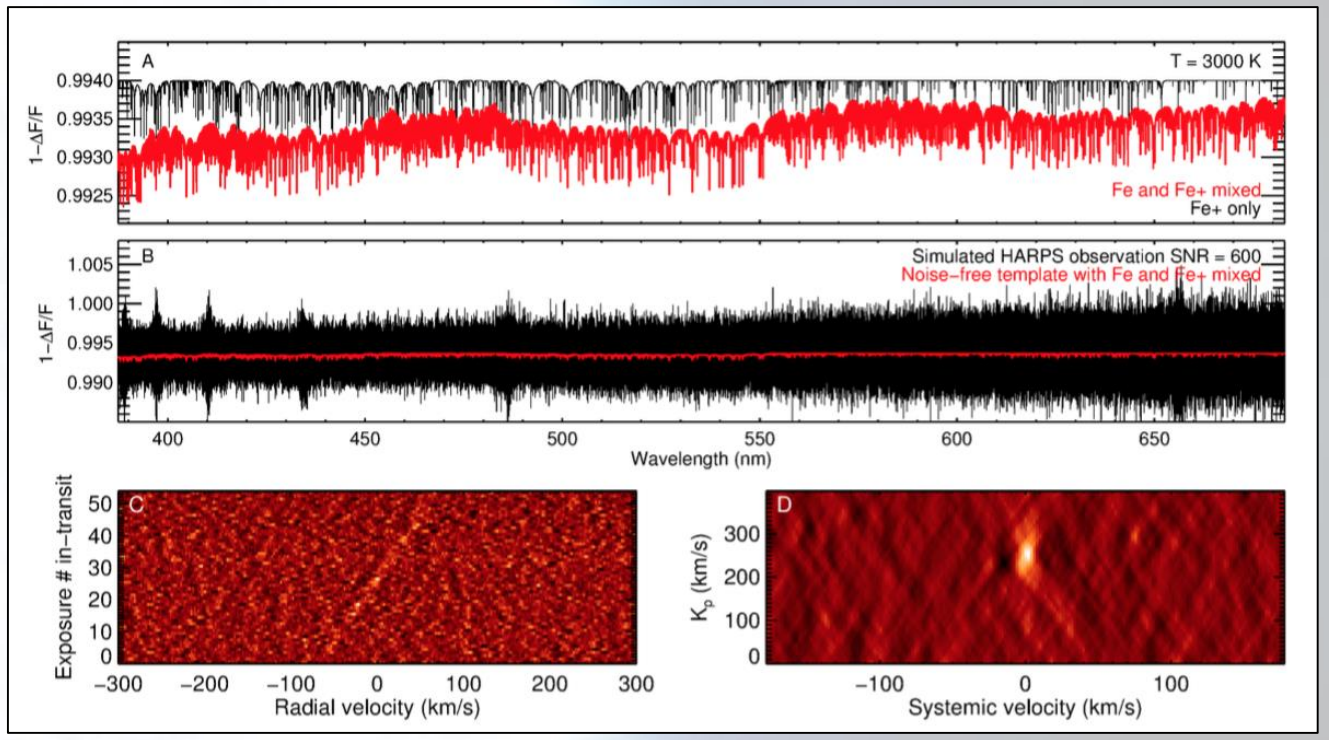
T_{day} – 4,600 K

Gaudi et al. 2017, Nature, 546, 514

KELT-9b



Transmission spectrum of KELT-9b, showing significant absorption at Balmer H_α line



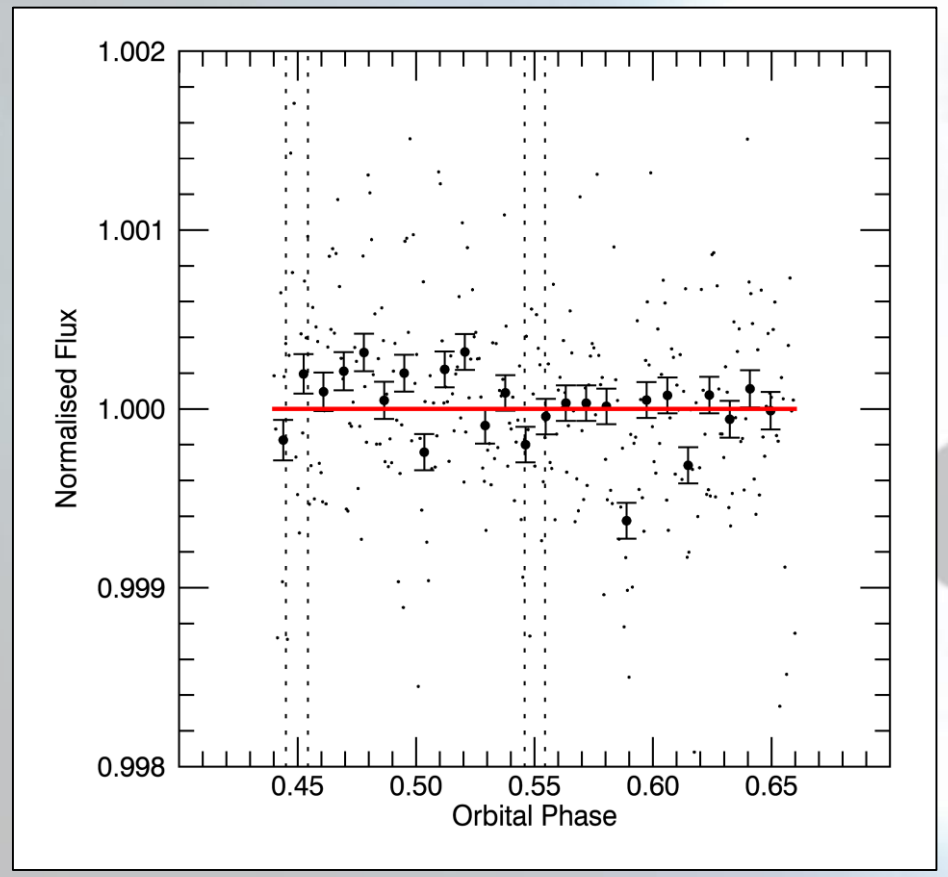
The recovery of a neutral Fe signal using high resolution spectroscopy for a simulated transit observation of KELT-9b with HARPS-N.

Yan & Henning 2018, Nat. Astron., accepted

Kitzmann et al. 2018, ApJ, accepted

KELT-9b: U-band observation

INT/WFC 20170720



Scenario	A_g
No thermal emission (unphysical)	< 0.31
Good dayside-nightside distribution (unlikely)	< 0.23
Bad dayside-nightside distribution (likely)	< 0.16

F_{ecl} < 1.93 mmag (3σ limit)

Hooton et al. 2018, in prep