Results from a Large Survey of Hot Jupiter Exoplanetary Atmospheres

The Dawn of Comparative Exoplanet Spectroscopy

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European Research Council
UNIVERSITY OF EXETER

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Hot Jupiter ExoSunset Survey
(PI D. Sing)

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Adam Showman	UofA, USA
Heather Knutson	Berkley, USA
Adam Burrows	Princeton, USA
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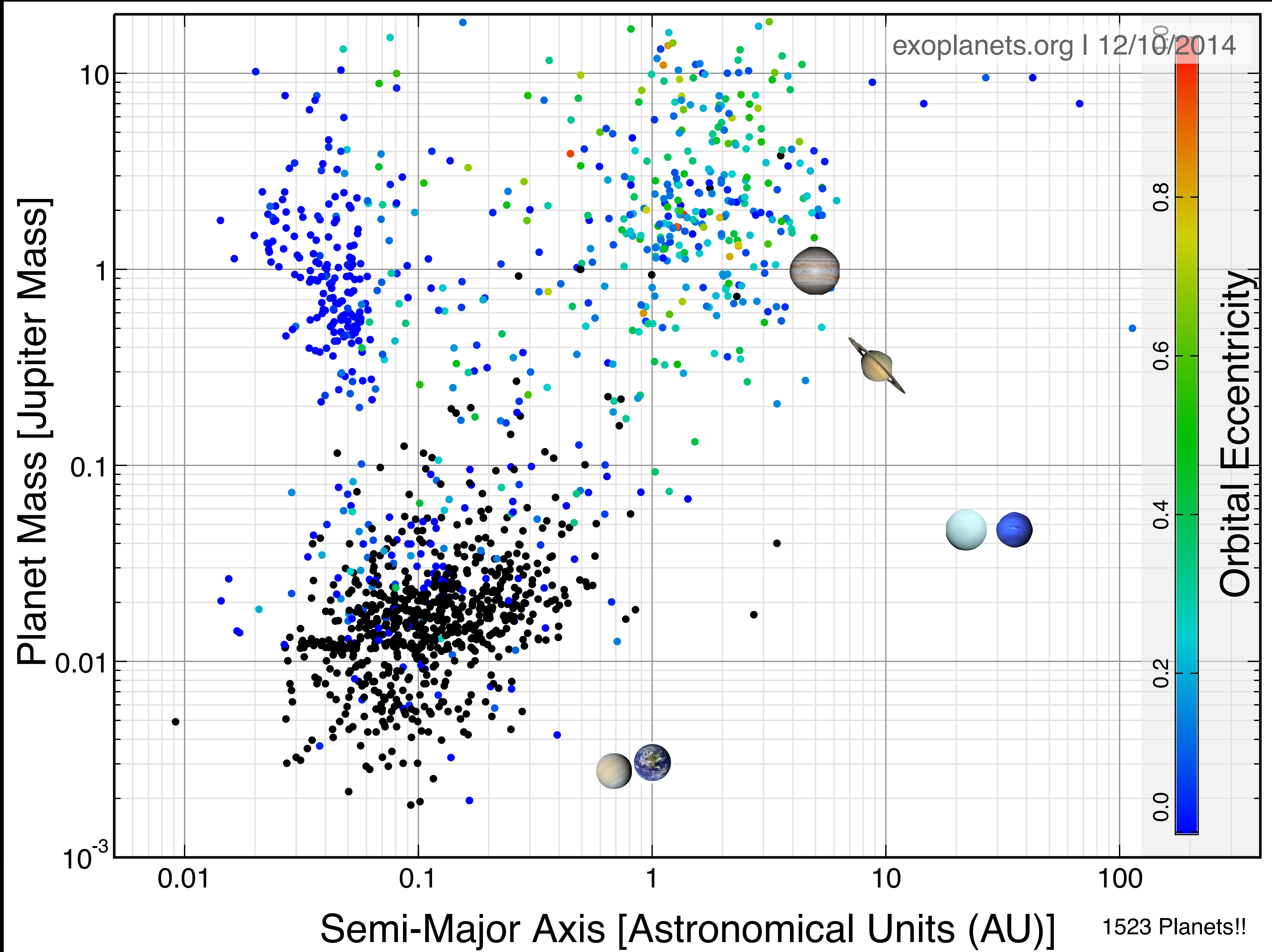
Gibson Neale	ESO

Outline

- Introduction Exoplanets
- Transiting Exoplanet Atmospheres
- Some specific HST survey results
- Comparative Exoplanet Spectroscopy
- What to do next



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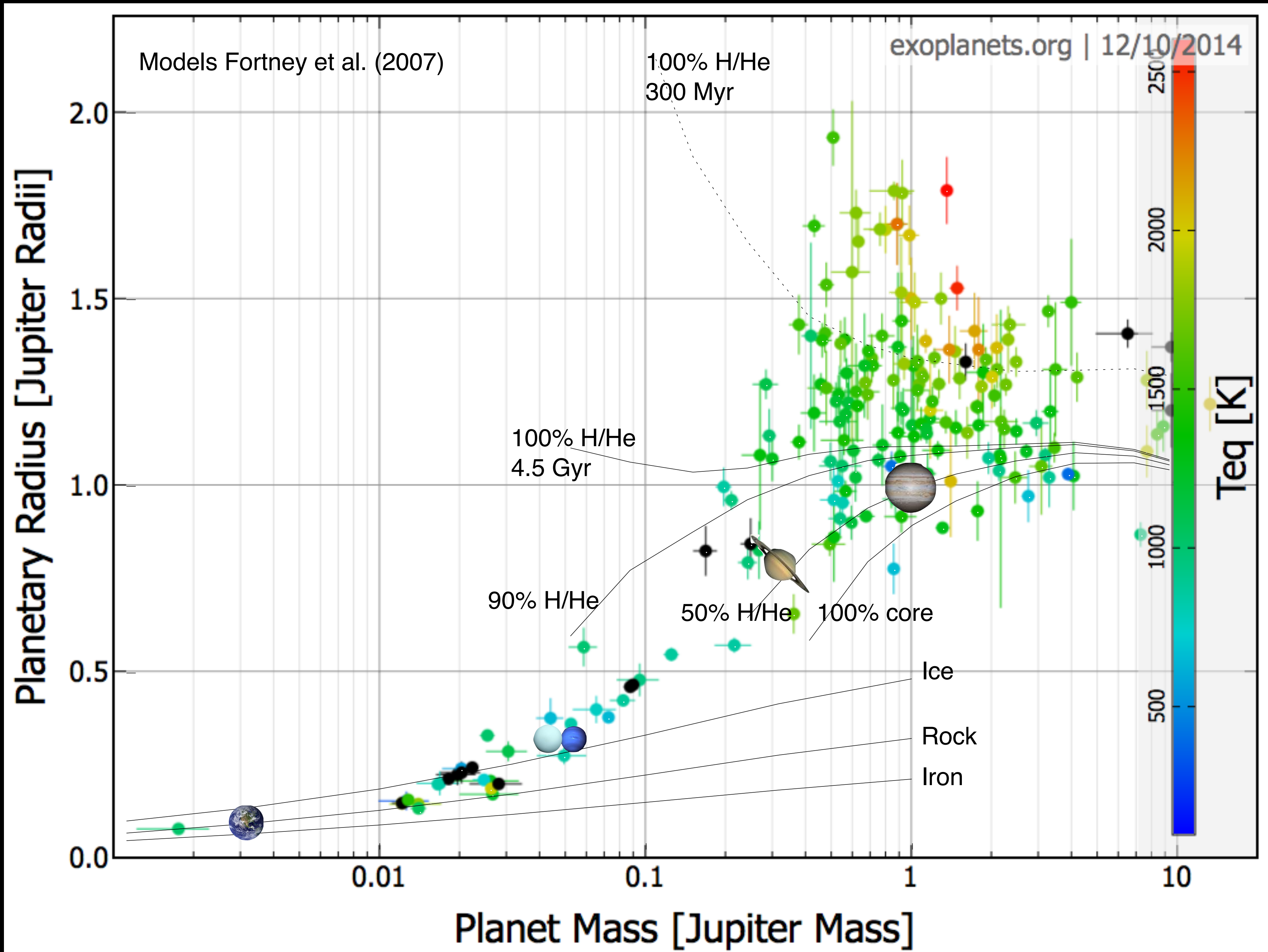

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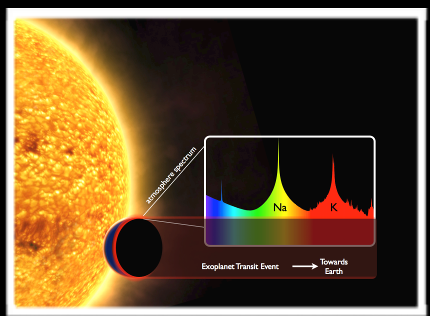
Exoplanet Atmosphere Characterisation

$\hat{t}$ Transits

Close-In Planets

M_{pl}, $R_{pl}(\lambda)$, i, P, a, $Flux_{pl}(\lambda,\Phi)$

Atmo. Composition
Clouds/Hazes
Thermal profile
Stratospheres
Thermospheres
Exospheres
Escape
Dynamics, Winds
Photochemistry

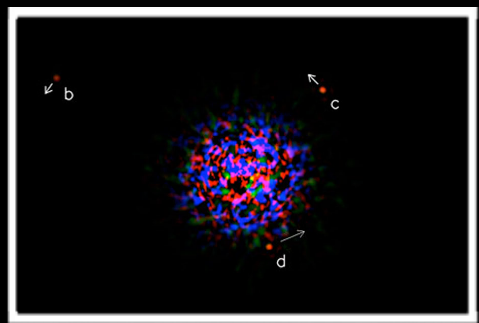


$\hat{x}, \hat{y}$ Direct Imaging

Wide-Separations

$a\sin(i)$, $Flux_{pl}(\lambda)$

Atmo. Composition
Clouds/Hazes
Temperatures
Dynamics
Chemistry

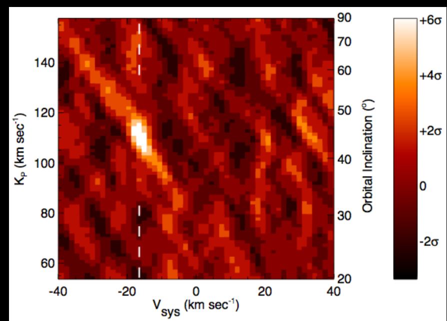


$\hat{\lambda}$ Radial Velocity

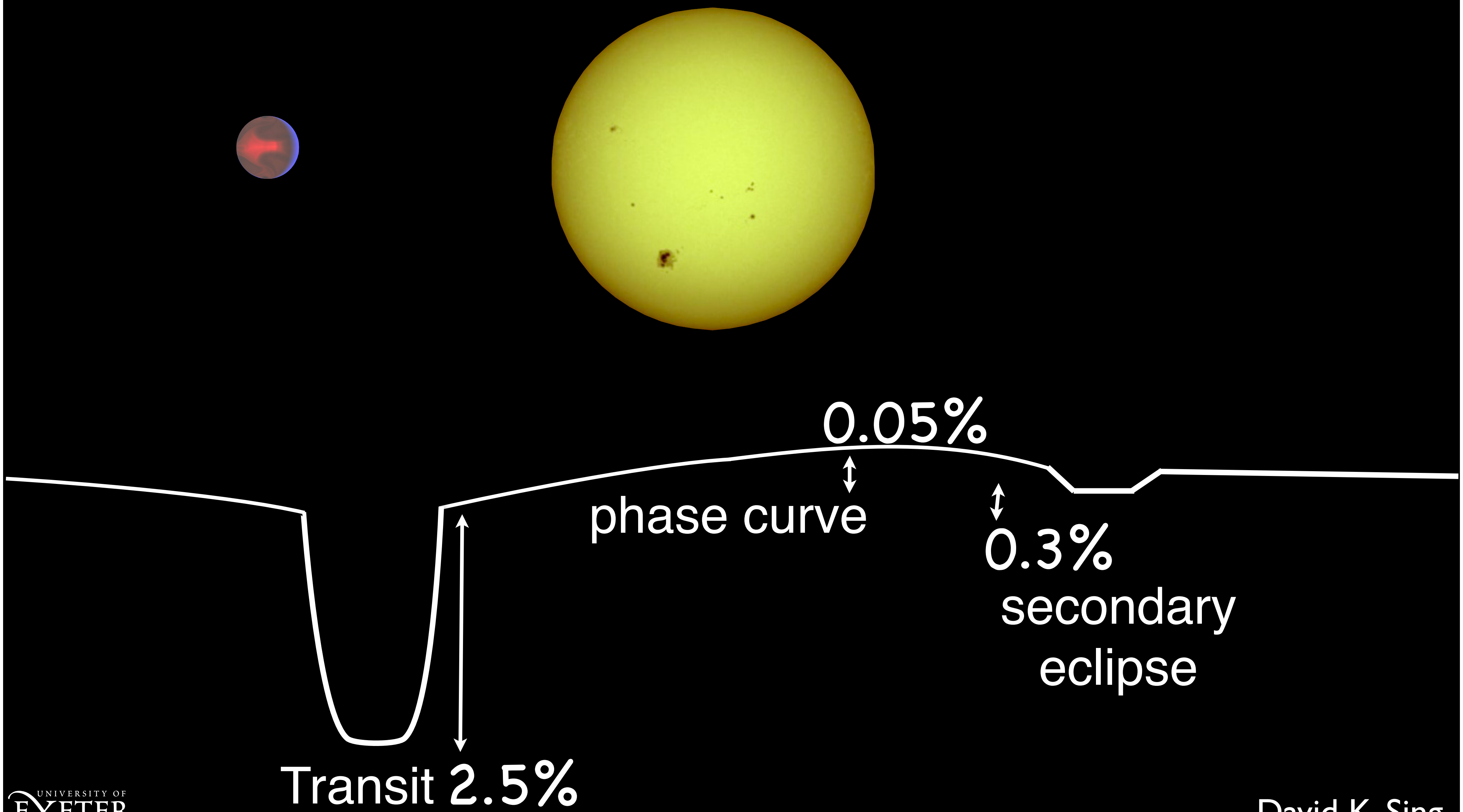
Bright Targets

K_p, M_{pl}, i

Atmo. Composition
Stratospheres
Dynamics, Winds



Transiting Planets



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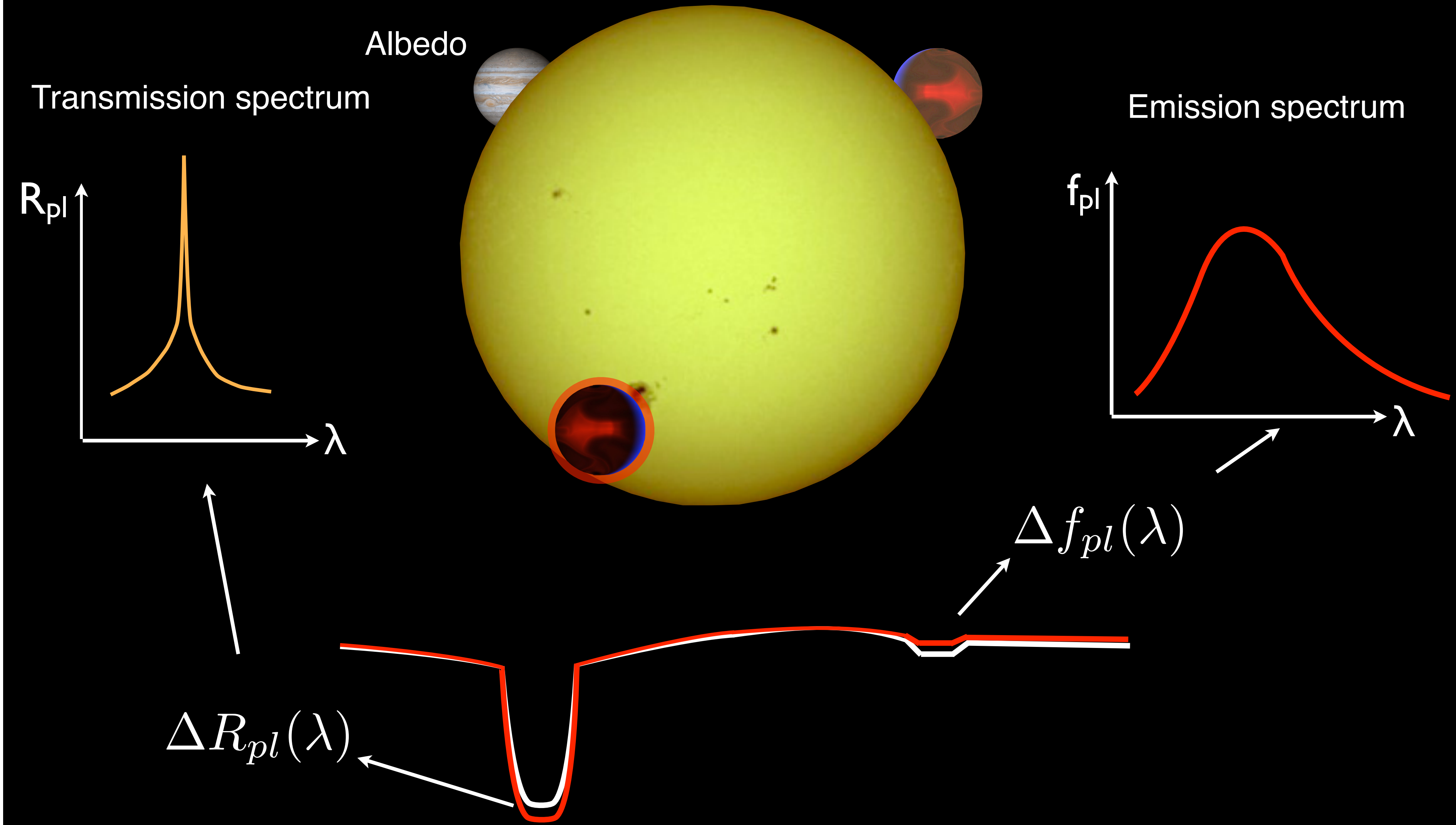
Exoplanet Spectra



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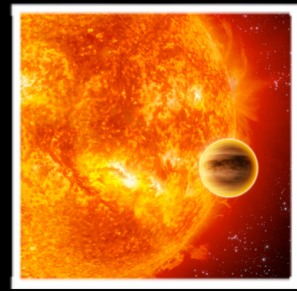
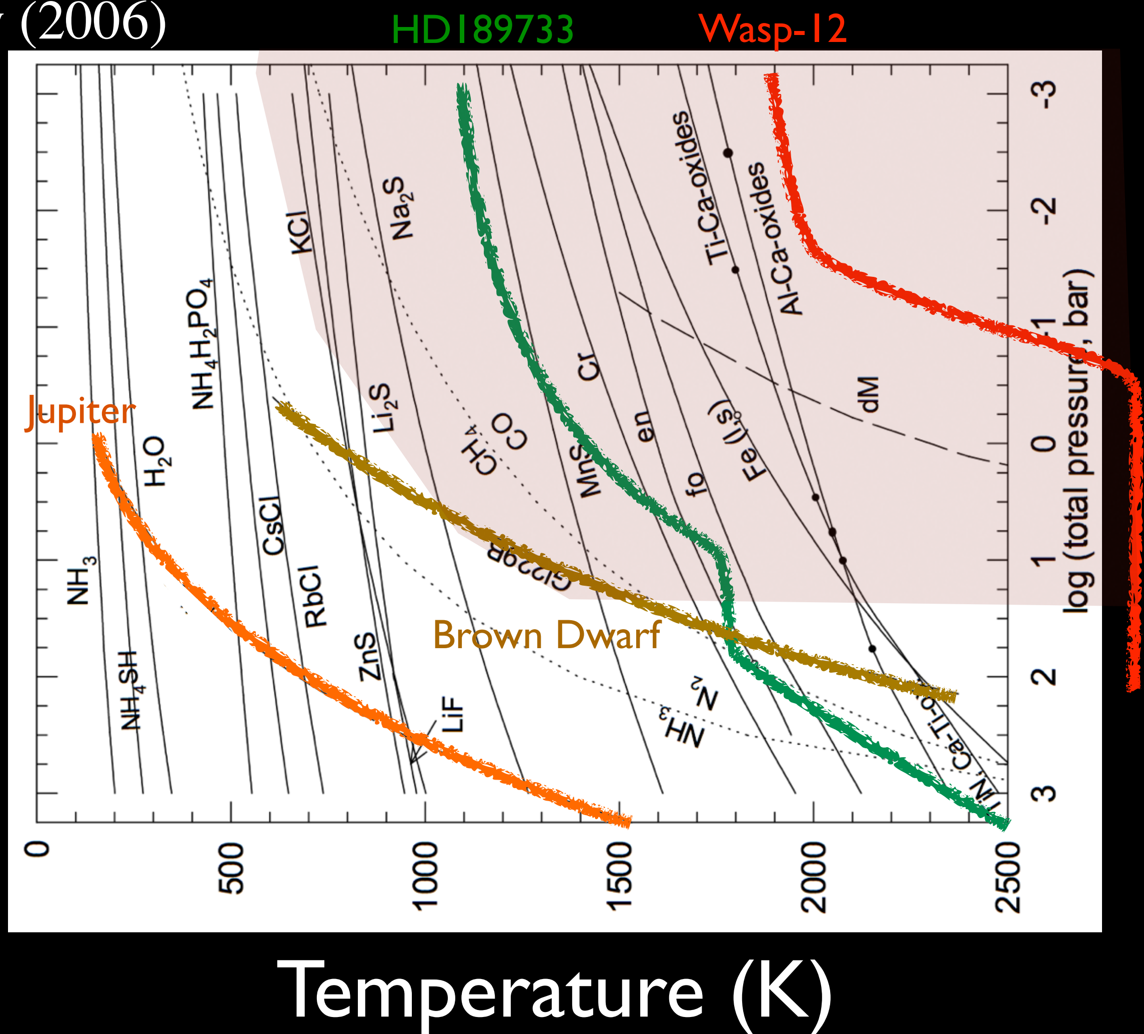
Hot Jupiter models

What might these planets look like?



Lodders & Fegley (2006)



Early Atmosphere Models

Solar Composition

Chemical Equilibrium

Radiative Transfer

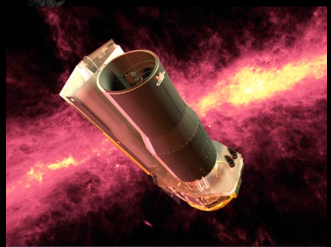
H_2 Na K
H_2O - Dominant
CO - hotter atmospheres
CH_4 - cooler atmospheres

TiO - **Thermal Inversion Layers**
Clouds - likely depending on T-P profiles

Transiting Exoplanet Atmospheres Timeline

2002 04 05 08 09 11 14

STIS | STIS & WFC3



cryogenic | warm

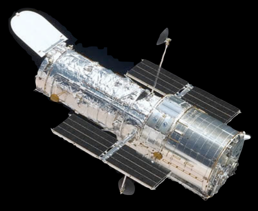
HR Phot MOS

Transiting Planets: 1 — 10 — 100

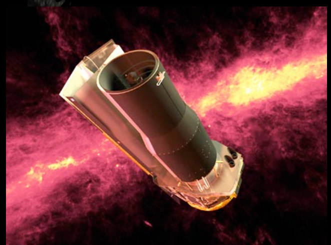
Spectra for... |——— 209/189 era———> |—— survey era—>

Transiting Exoplanet Atmospheres
209/189 era

	2002	04	05	08	09	11	14



STIS — STIS & WFC3



cryogenic — warm

HR — Phot — MOS

\# Transiting Planets: 1 — 10 — 100

Spectra for... |———— 209/189 era————> |—— survey era—>

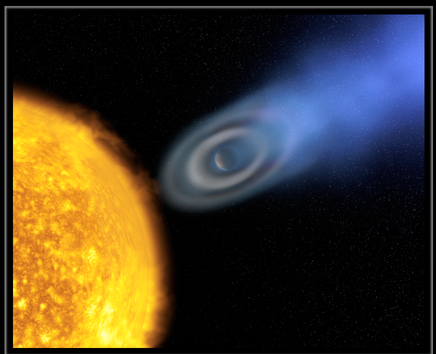
‘209 and ‘189

Almost everything we know about hot Jupiters has come from these *two* planets.

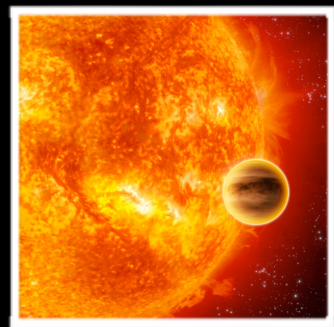
Prototype HJs ??

transit + emission+ phase curve spectroscopy is ‘highly’ constraining

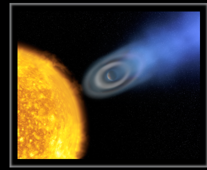
very few planets can be measured with all 3



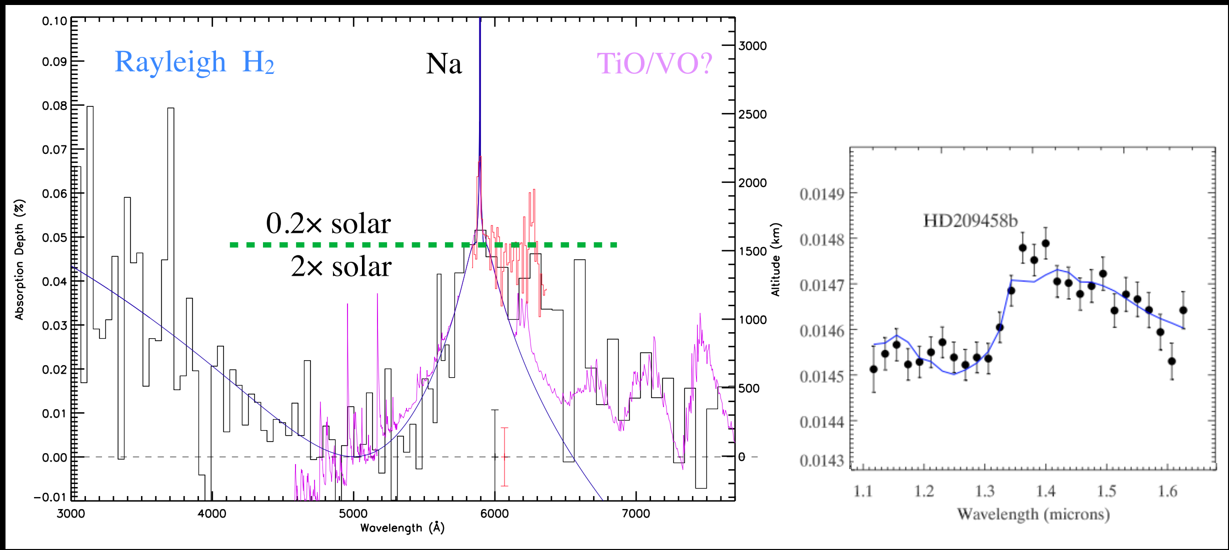
... the current summary?



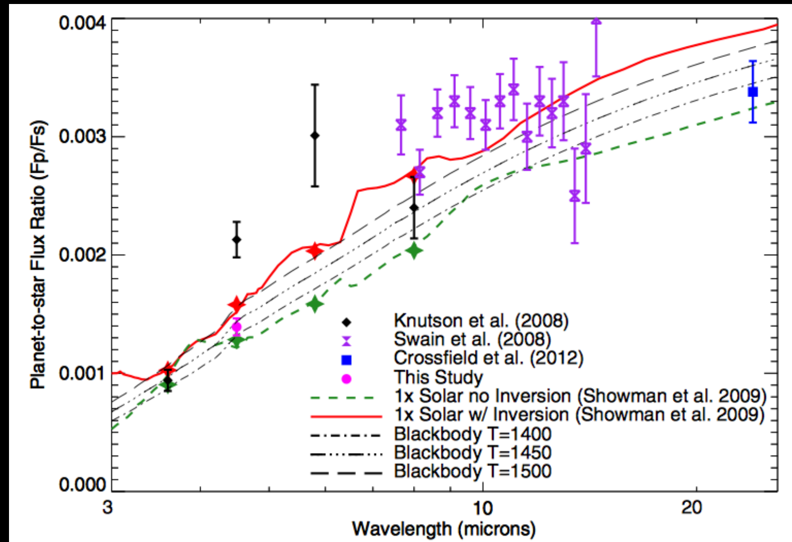
HD 209458b: our first characterised exoplanet

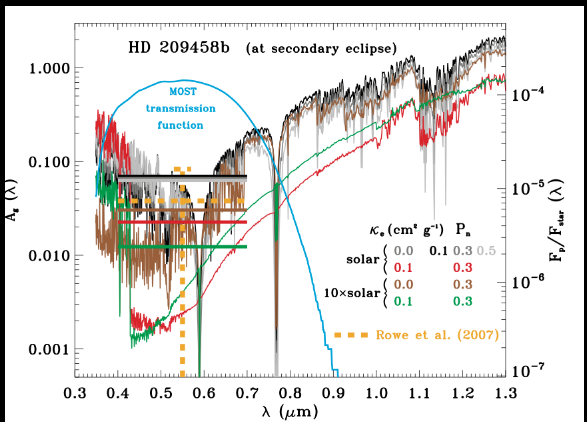


Transmission



Emission





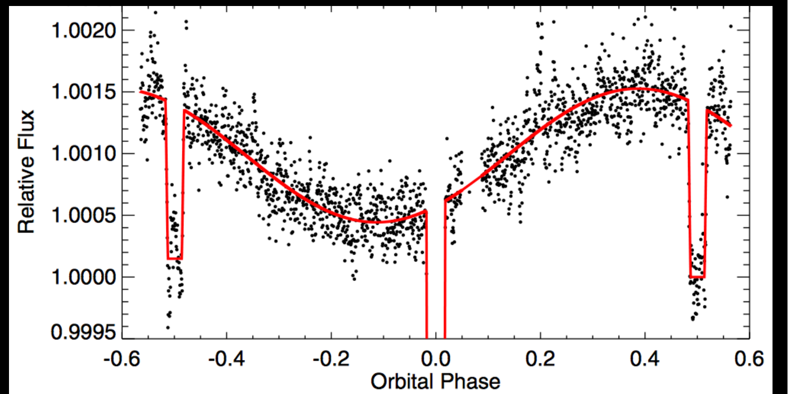
Albedo

Na, H2O, CO, Rayleigh

Low albedo - few %

Possible?? Stratosphere

Likely Thermosphere



Phase Curve

Charbonneau et. al. (2002)
Sing et al. ('08a,'08b)
Desert et al. (2009)
Agol et al. (2010)
Lecavelier et al. (2008)
Rowe et al. (2008)

Burrows et al. (2008)
Crossfield et al. (2012)
Knutson et al. ('07,'08)
Deming et al. (2013)
Vidal-Madjar (2011)
Zellem et al. (2014)

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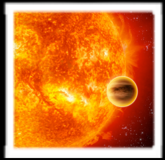
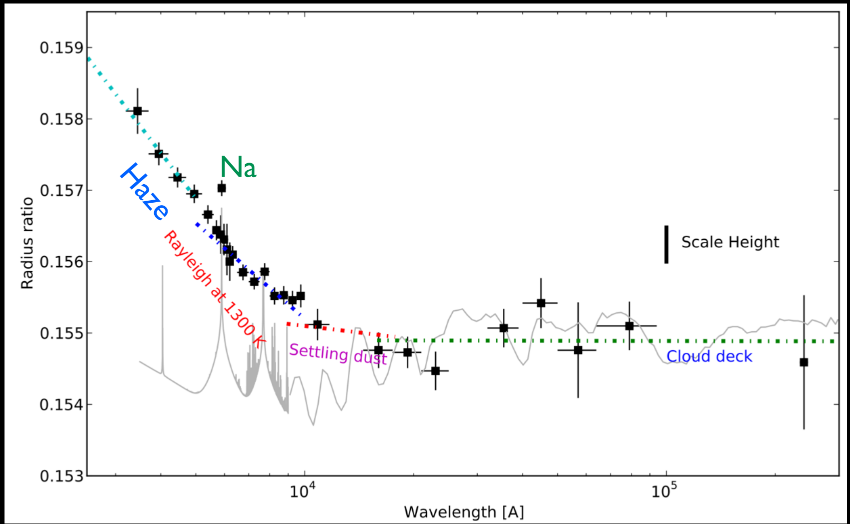
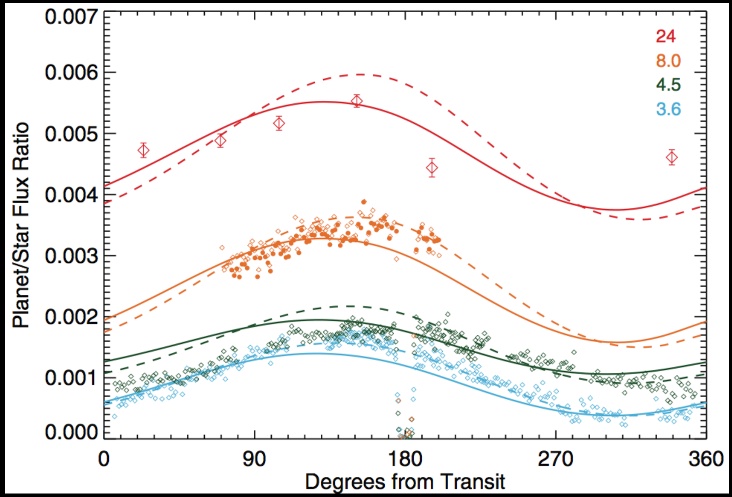
HD 189733b: our best characterised exoplanet



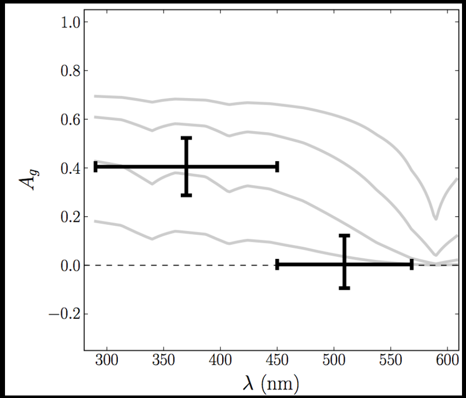
Transmission



Phase Curve



Albedo



Optical Haze

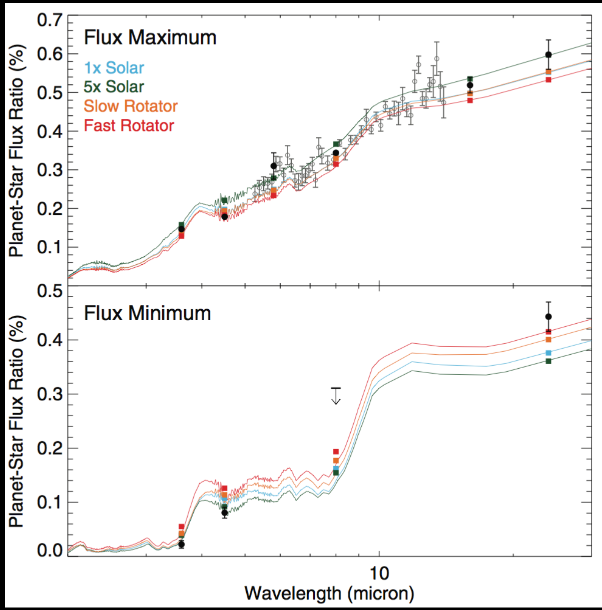
'blue planet'

offset Hot Spot - 'Jets'

Na, Hα, H_2O and CO present

Efficient heat re-distribution

Emission



Charbonneau et al. (2008)
Grillmair et al. (2007)
Knutson et al. ('07,'09,'12)
Pont et al. ('07, '13)
Sing et al. ('09, '12)
de Kok et al. (2013)

Birkby et al. (2013)
Desert et al. ('09,'11)
Agol et al. (2010)
Gibson et al. ('11,'12)
Huitson et al. (2012)
Evans et al. (2013)

Jensen et al. (2012)
Redfield et al. (2008)
McCullough (2014)

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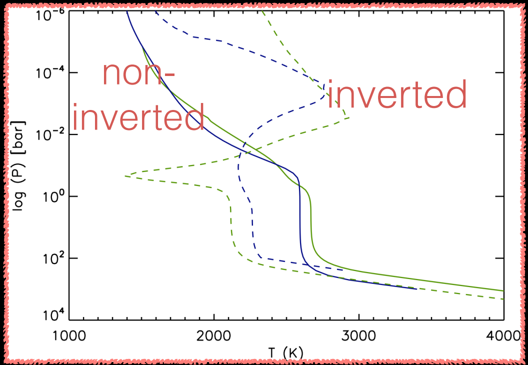
Major Science Q's



- Thermal Structure
  Stratospheres? Day/Night?

- Composition & Abundances
  H_2O? Chem? Formation?

- Clouds & Hazes?

… and many more

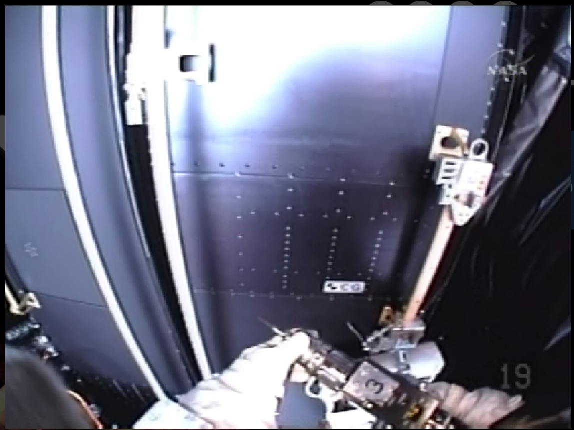
Transiting Exoplanet Atmospheres
survey era

9 | 11 | 14

STIS & WFC3

warm

HR | Phot | MOS



Transiting Planets — 100

Spectra for.. —> |—— survey era—>

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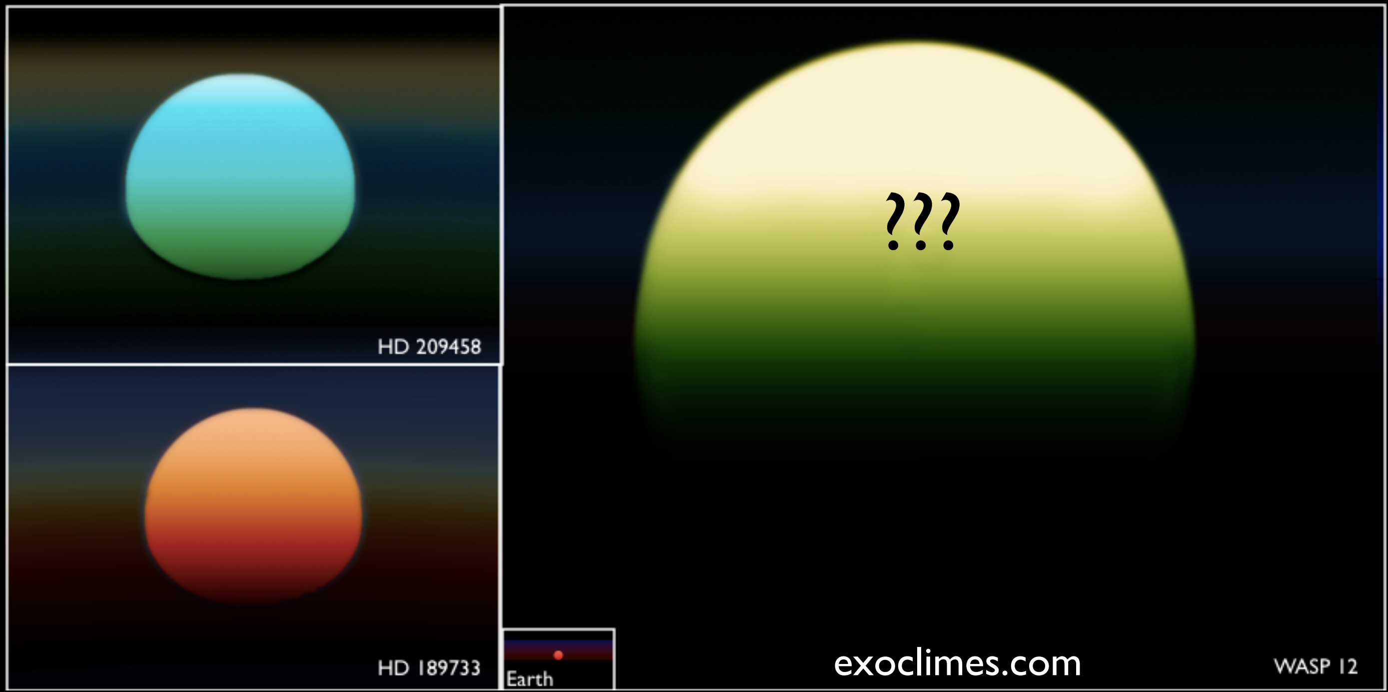
Exploring the Family Album



ExoSunset portraits rendered from real transmission spectra

- HST is now PREEMINENT Exoplanet Observatory

  Ultra High S/N, UV-Optical-NIR spectra (20ppm)

- Comparative Exoplanet Spectroscopy

- Somewhat empty buzzword for a long time... potential to learn A LOT about planets

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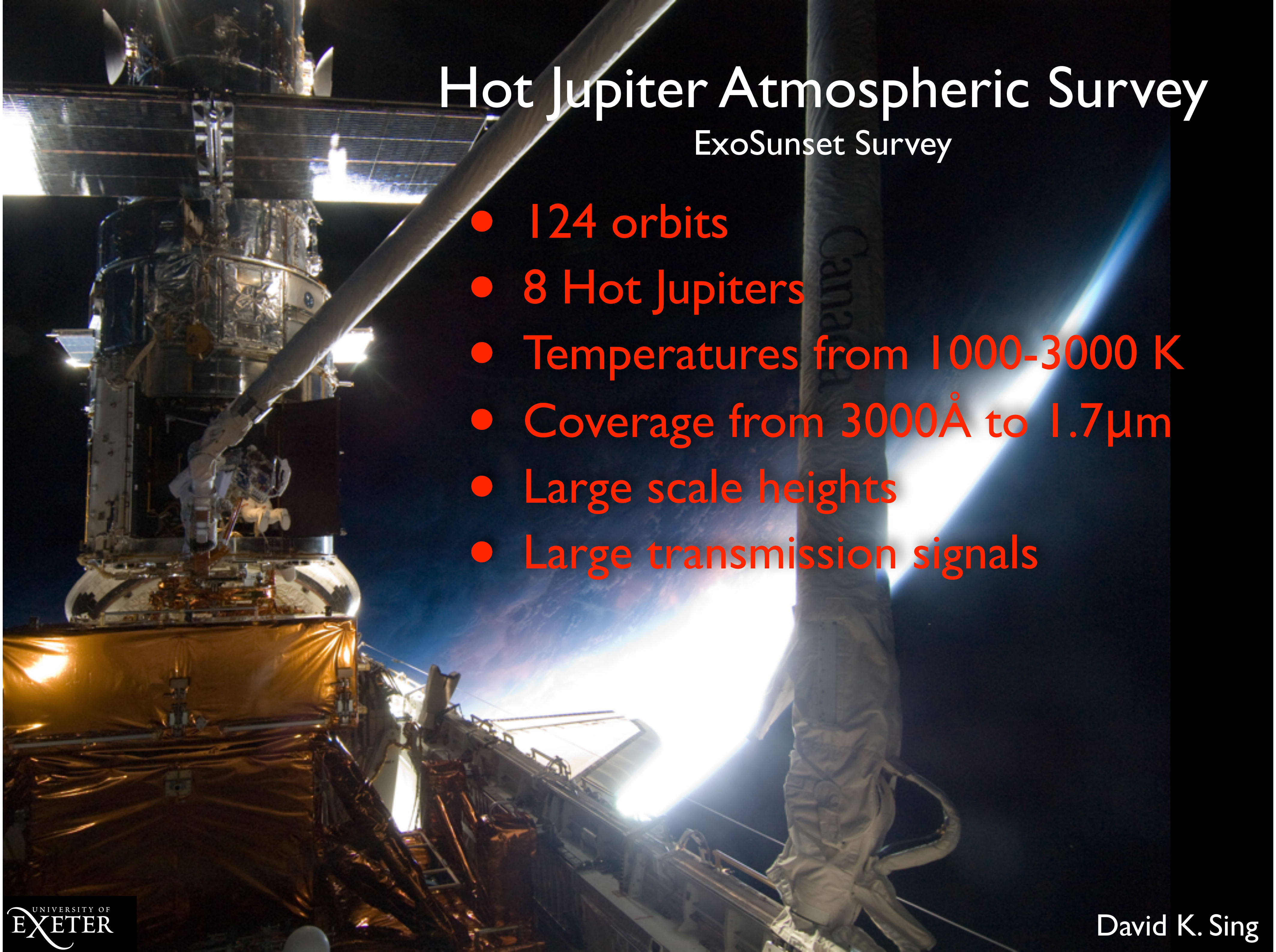

Hot Jupiter Atmospheric Survey

ExoSunset Survey

- 124 orbits
- 8 Hot Jupiters
- Temperatures from 1000-3000 K
- Coverage from 3000Å to 1.7μm
- Large scale heights
- Large transmission signals

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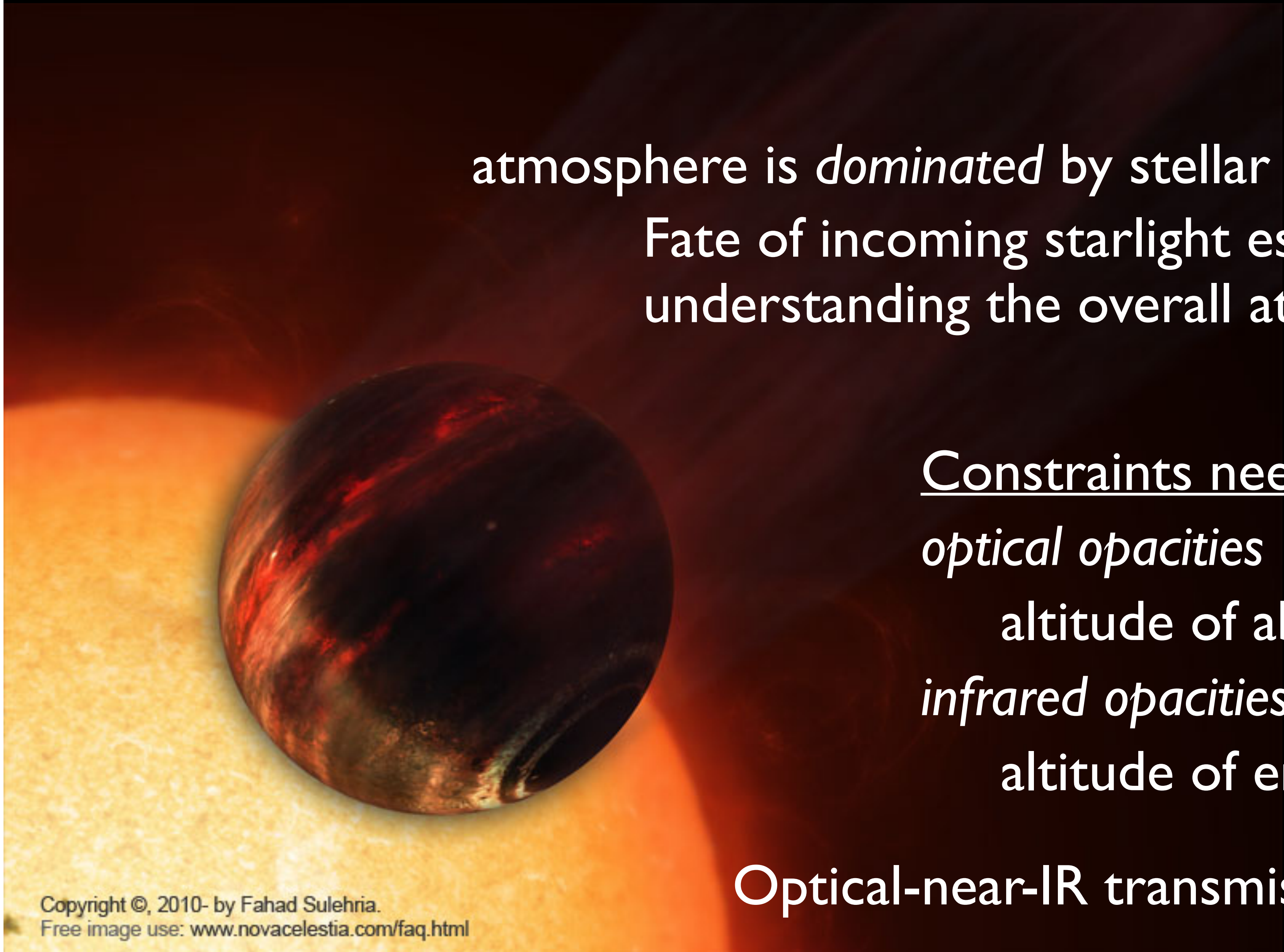
Hot Jupiter Atmospheric Survey

Key H-J Fact: hot Jupiters really are *HOT* (up to 3000 K)



atmosphere is *dominated* by stellar irradiation

Fate of incoming starlight essential to understanding the overall atmosphere

<u>Constraints needed</u>

optical opacities

altitude of absorption

infrared opacities

altitude of emission

Optical-near-IR transmission spectra

Large HST Transmission Spectra Program
PI SING

Science Goals

- Identify Stratosphere Absorbers (TiO, HS)
- Measure & compare abundances
- Hot Jupiter sub-classes
- Clouds & Hazes

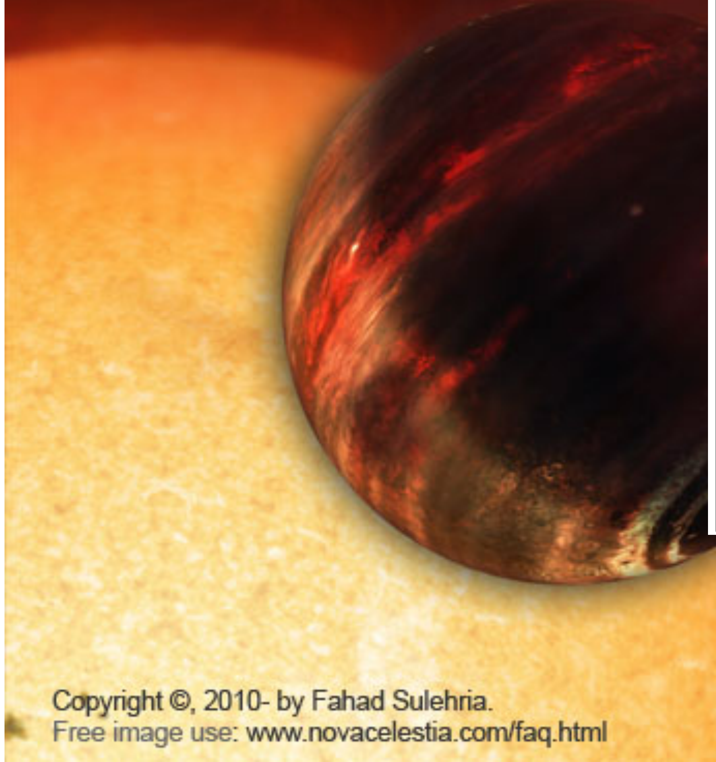


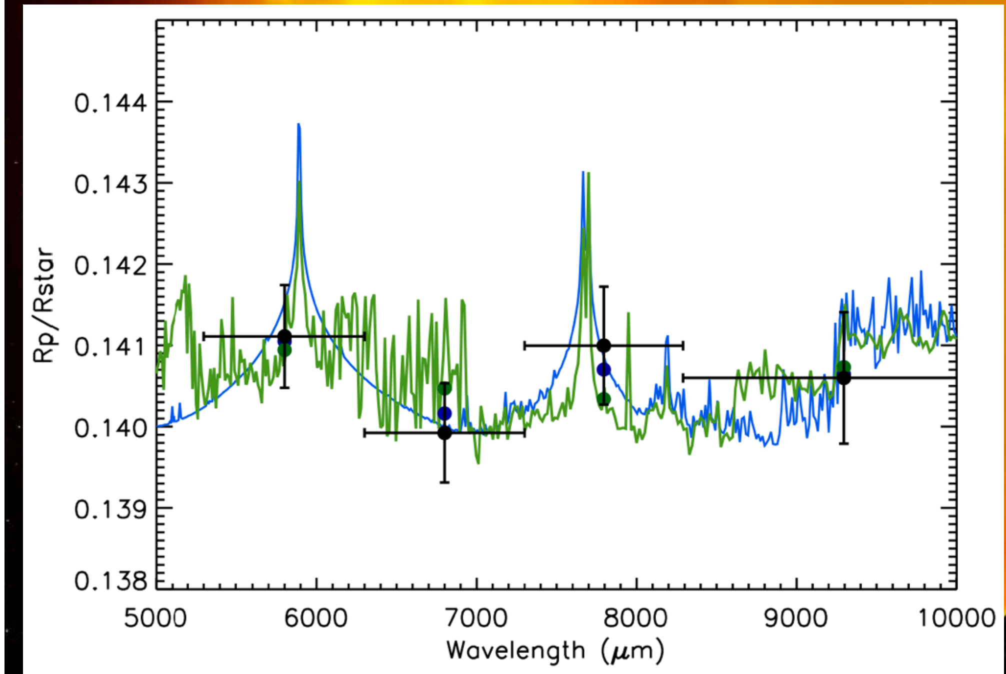
Table 1. Hot-Jupiter Target List (T_{eff} is estimated equilibrium temperature)

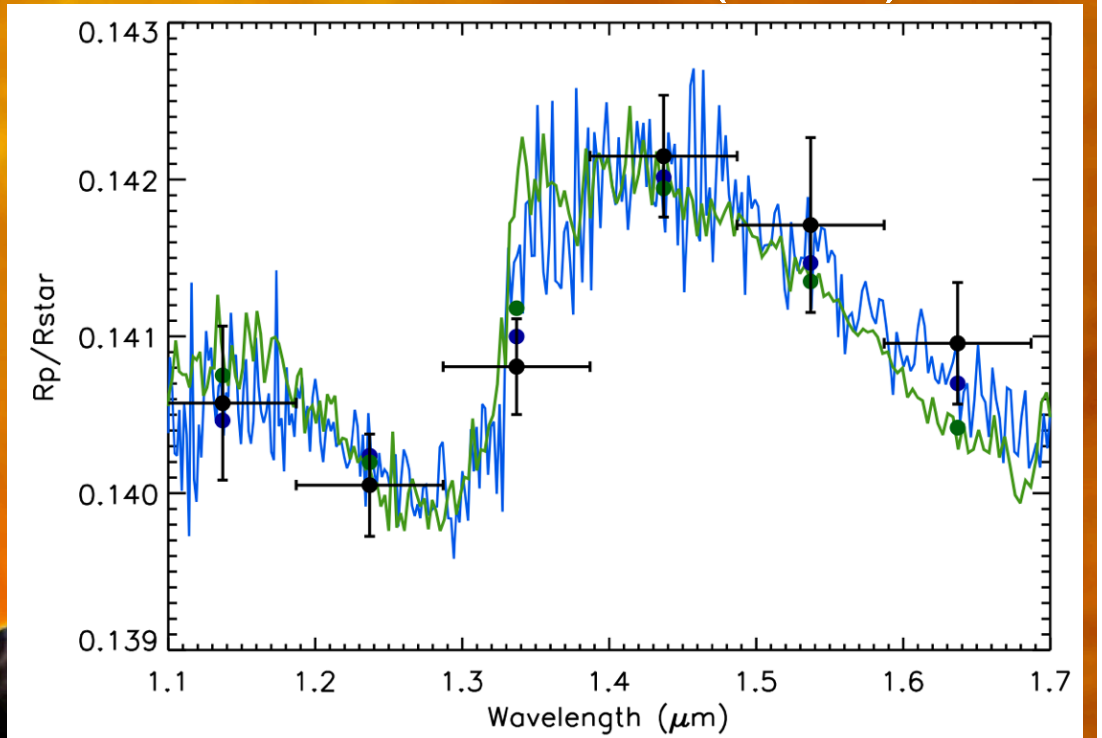
Target	Period (days)	R_{planet} (Jup)	M_{planet} (Jup)	T_{eff} (K)	g (m/s^2)	Irradiation ($ergs/s/cm^2$)	V_{mag}	H (km)
Hat-P-12b	3.21	0.96	0.21	1080	5.7	2.2E+08	12.8	680
Wasp-6b	3.36	1.22	0.50	1340	8.3	5.2E+08	11.9	580
Wasp-39b	4.05	1.27	0.28	1360	4.3	5.00E+08	12.1	1140
Hat-P-1b	4.46	1.20	0.53	1500	9.1	7.3E+08	10.4	580
Wasp-31b	3.4	1.54	0.48	1800	5.02	1.50E+09	11.7	1280
Wasp-17b	3.74	1.74	0.49	1860	4.0	1.9E+09	11.6	1670
Wasp-19b	2.15	1.15	1.31	2319	16.6	4.10E+09	12.3	501
Wasp-12b	1.09	1.79	1.41	2800	11.0	1.0E+10	11.69	930

Results published for Wasp-19b, Wasp-12b, Hat-P-1b

Wasp-19b

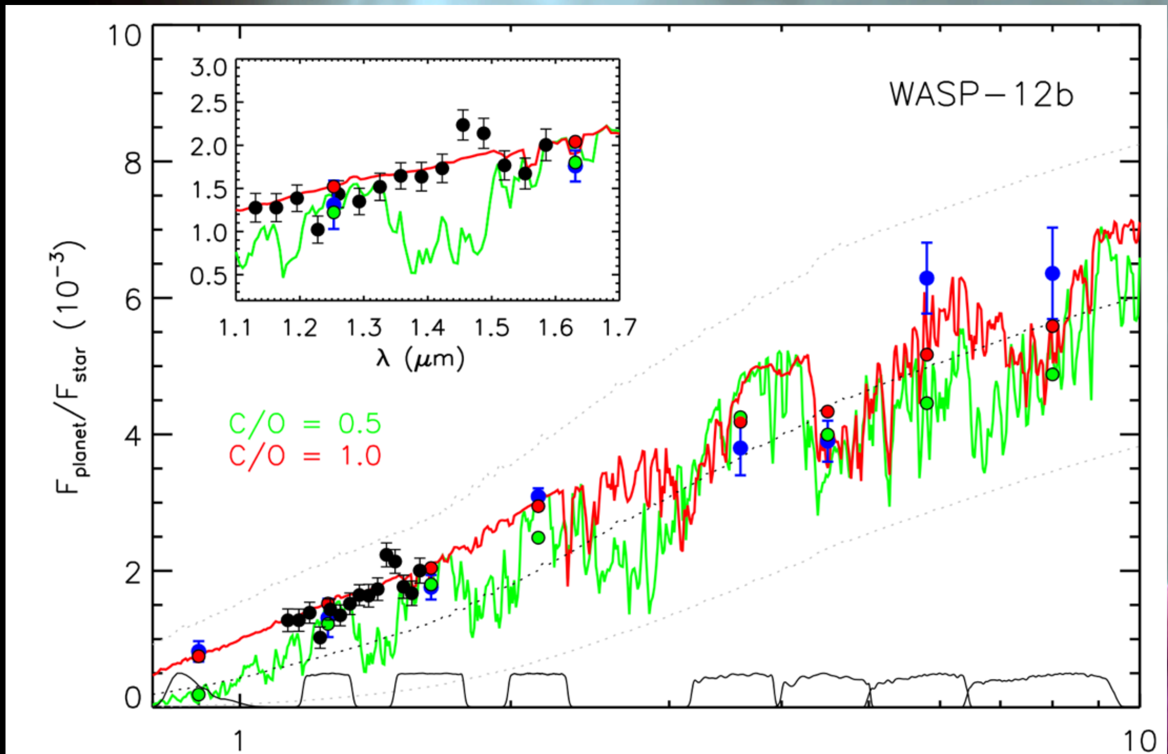
Huitson et al. (2013)





Detect H_2O - amazing consistency with standard models
TiO ruled out despite 2300 K temp
no thermal inversion - activity??
- insufficient mixing??
- high C/O unlikely with H_2O detection

Wasp-12b



Madhusudhan et al. (2012)

One of the hottest (Teq~3200K) at 0.023 AU (3.1R★) from hot (but not active) star.

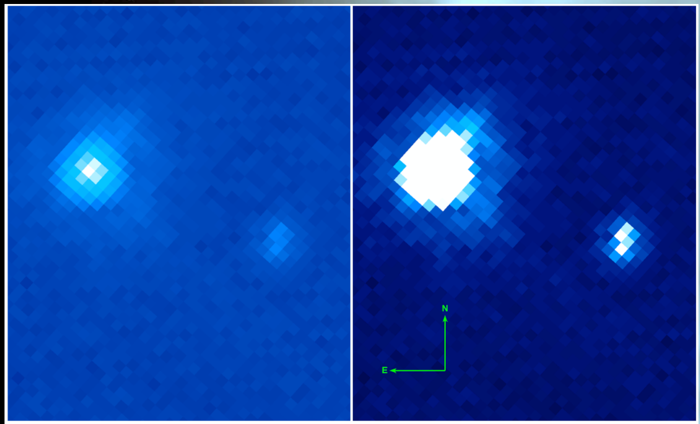
Roche lobe radius ~ 1.24 Rpl !

This is the potential carbon-rich "diamond planet" with C/O > 1, the tidally-disrupting planet, the bow-shock planet.

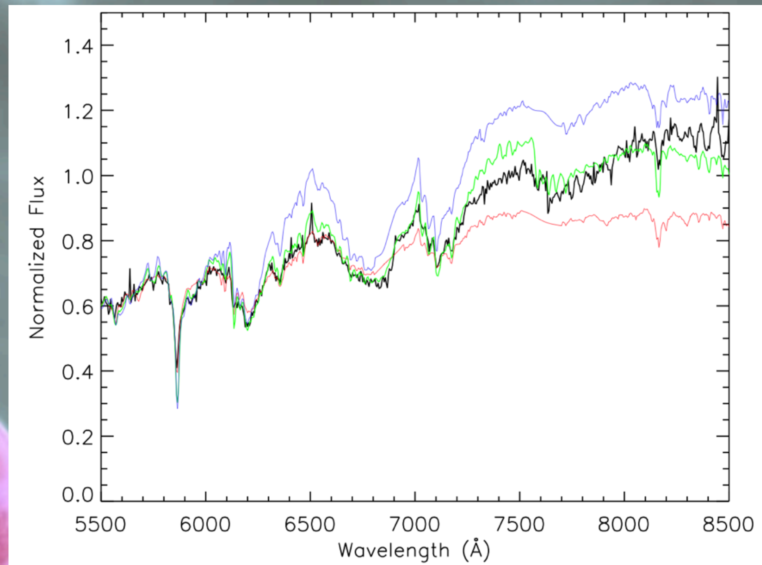
Wasp-12b

Wasp-12 is Triple System

M0V equal mass binary (21 AU separation)
Physically associated with Wasp-12A (450 AU separation)



HST acquisition image

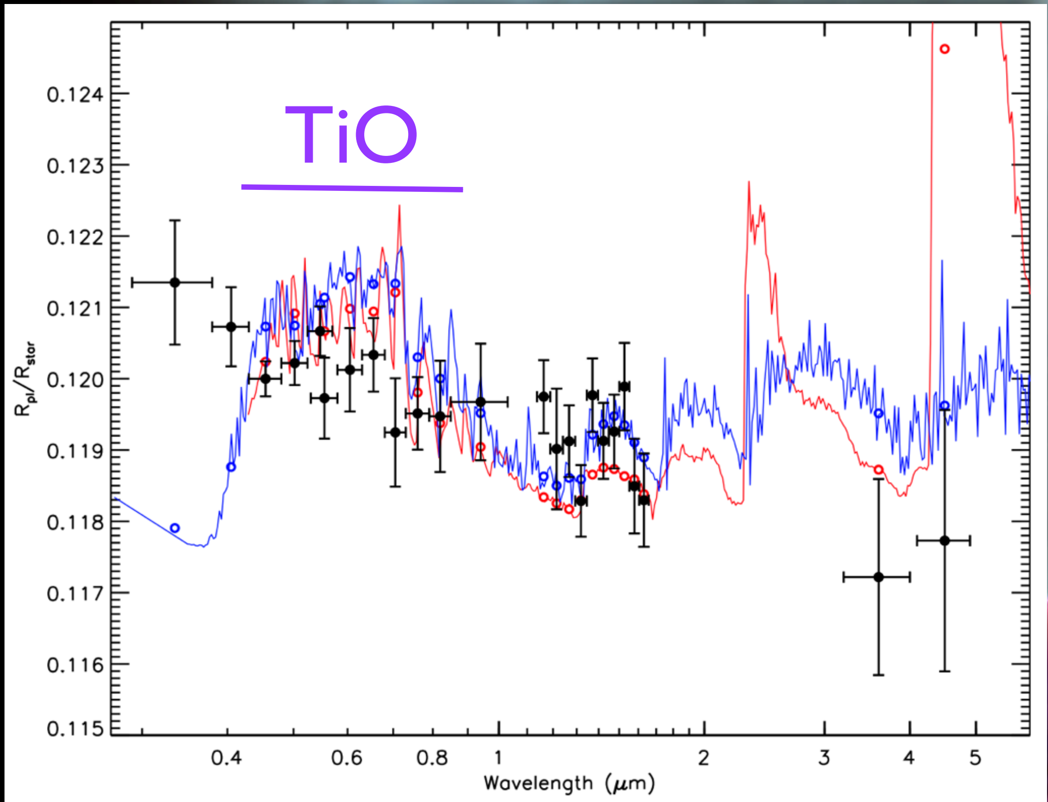


M-dwarf spectral type Teff= 3660 K

Emission spectrum is consistent with Black Body at 3000 K

Bergfors et al. (2011;2013)
Crossfield et al. (2012)
Sing et al. (2013)
Bechter et al. (2013)

Wasp-12b



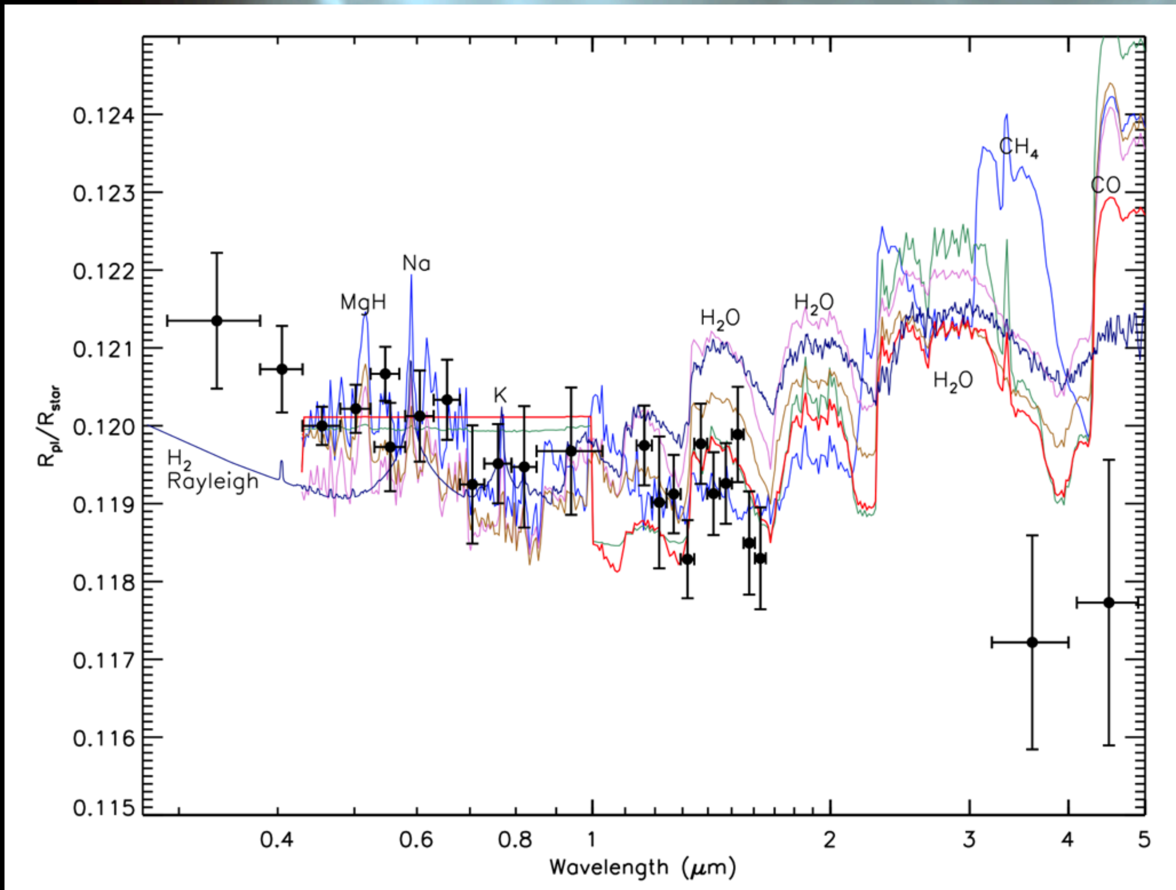
Muted 1.4 μm water-band absorption (already known; Swain et al. 2013)

Optical shows no agreement with CLEAR, solar abundance atmospheric models

TiO ruled out

Sing et al. (2013)

Wasp-12b



Muted/Absent 1.4 μm water-band absorption (already known; Swain et al. 2013; Mandell et al. 2013)

Clear Atmospheric models ruled out (variety of C/O & Metallicities)

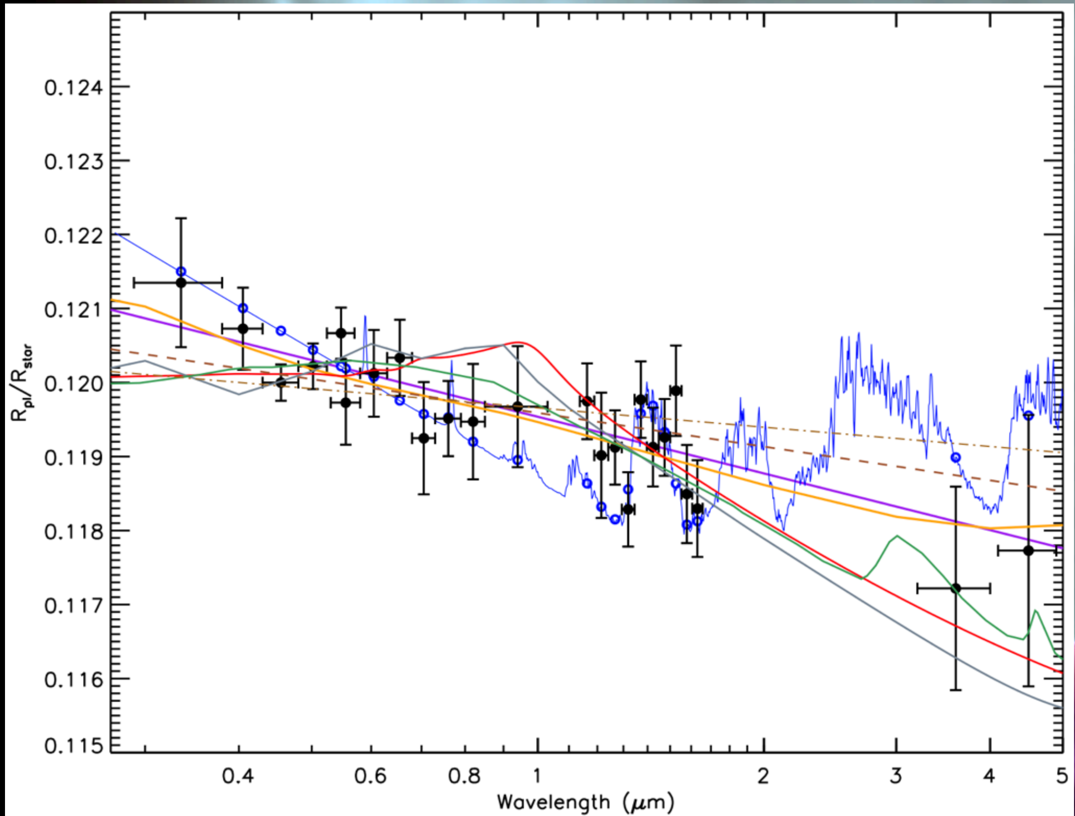
No metal oxides (TiO...)

No metal hydrides (MgH...)

No Na or K

Sing et al. (2013)

Wasp-12b



Best fits Mie scattering Al_2O_3
T=1000-3100 K

Rayleigh scattering good fit - but needs a low Temp of 880 K

Variety of cloudy/hazy models are acceptable fits

- Aerosols needed for Transmission (Sub-micron)
- Helps explain Modest albedo (A_B=25%)
- Helps explain black body emission spectrum

Sing et al. (2013)

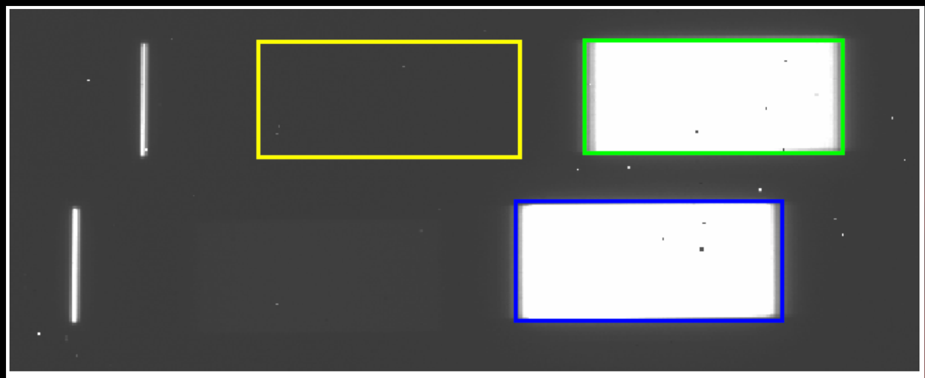
HST WFC3

A near-IR Revolution for Transiting Exoplanets

- Spacial-scan drastically increases duty cycle
- Much higher S/N per image
- Systematics are common-mode, relative transit depths preserved (easy to reliably remove, no complex controversial de-trending required)

Hat-P-1A

Hat-P-1B



0th

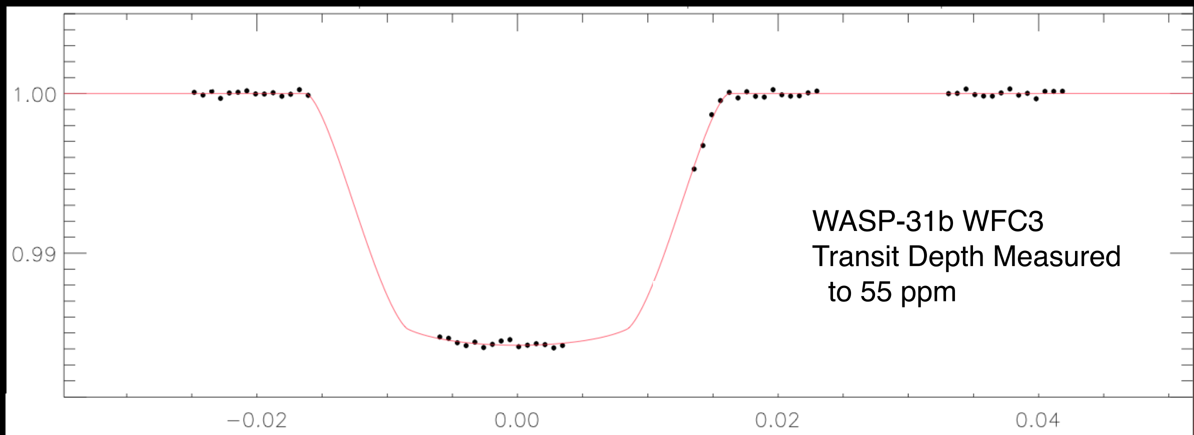
1st

telescope slews in cross-dispersion direction during exposure

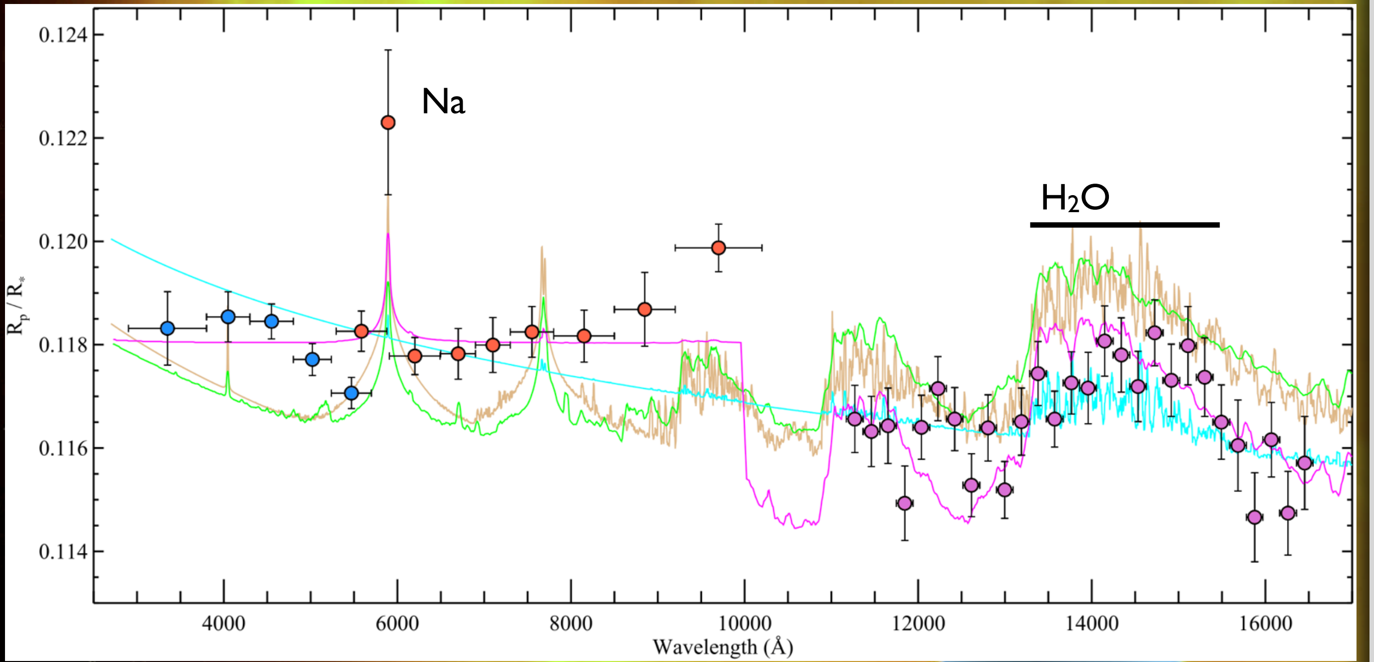
HST WFC3

A near-IR Revolution for Transiting Exoplanets

Kepler-like quality IR Spectroscopy
- Fully resolved H_2O
- multiple exoplanets
- transmission & emission



Hat-P-1b



Strong water

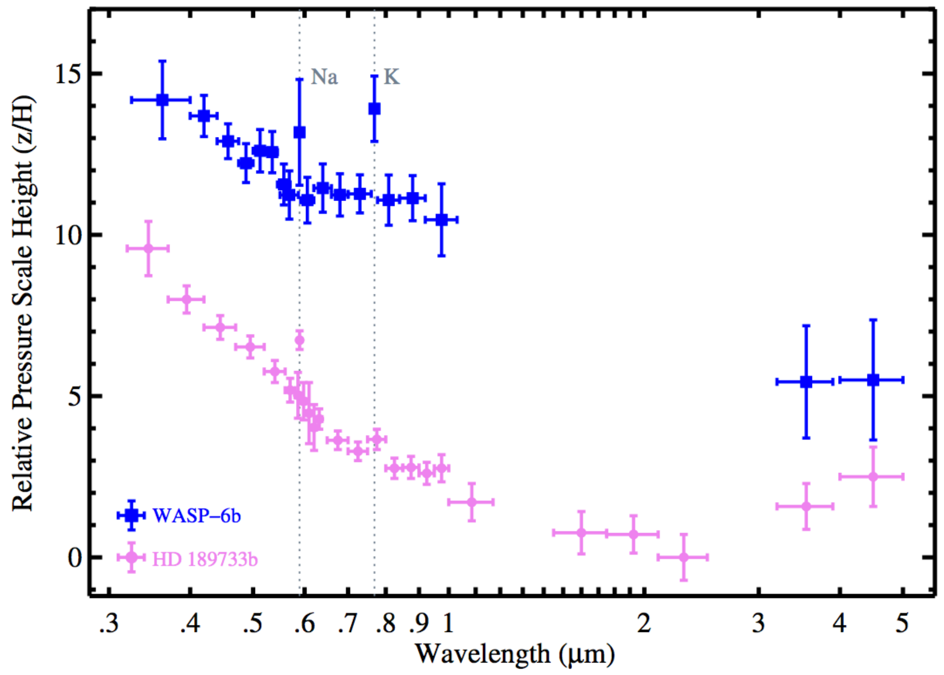
Strong Na vs. models
ξ_Na/ξ_H20 = x1000 solar.

Detect large optical radii from extra absorber (added to some models)

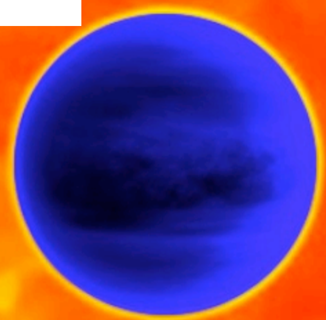
Resembles HD209458b in some aspects (Na, H_2O, no K)

Wakeford et al. (2013)
Nikolov et al. (2013)

WASP-6b: A Hazy exoplanet similar to HD189733b ?!



Property	WASP-6	HD 189733
$T_{\rm eff}$, K	5375 ± 65	5050 ± 50
$\log g$, cm s^{-2}	4.61 ± 0.07	4.61 ± 0.03
[Fe/H], dex	-0.20 ± 0.09	-0.03 ± 0.05
P, day	3.361	2.219
a, AU	0.042	0.031
e	0	0
g	8.71 ± 0.01	21.5 ± 1.2
$T_{\rm eq}$	1145 ± 23	1191 ± 20
H, km	492	199



Rayleigh Scattering by a Haze (6.7-σ)

Very low IR low/obscured H2O?

Narrow Alkali
K - likely

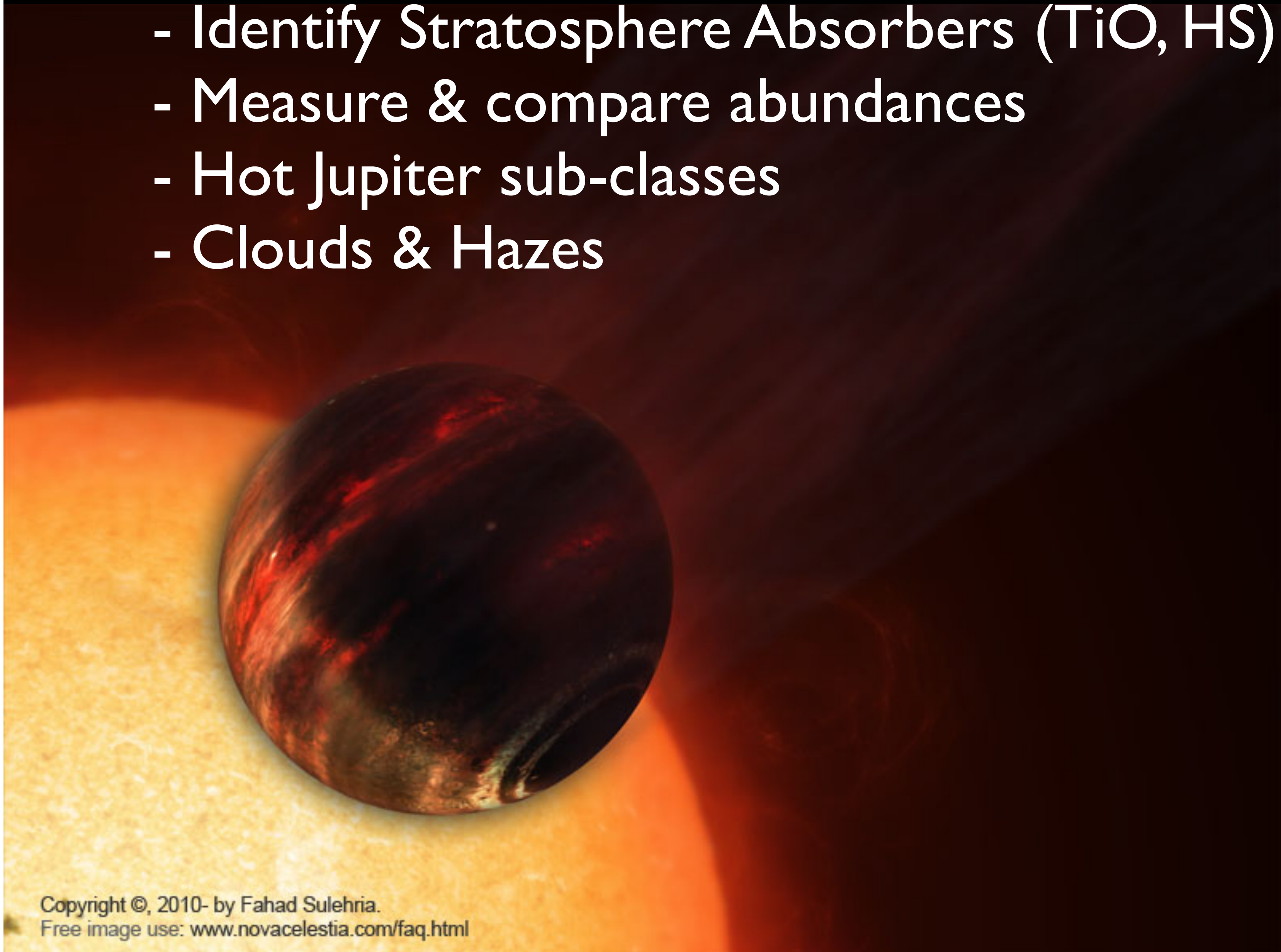
similar bulk parameters as '189 (except *g*)

Nikolov et al. (2014, arXiv)

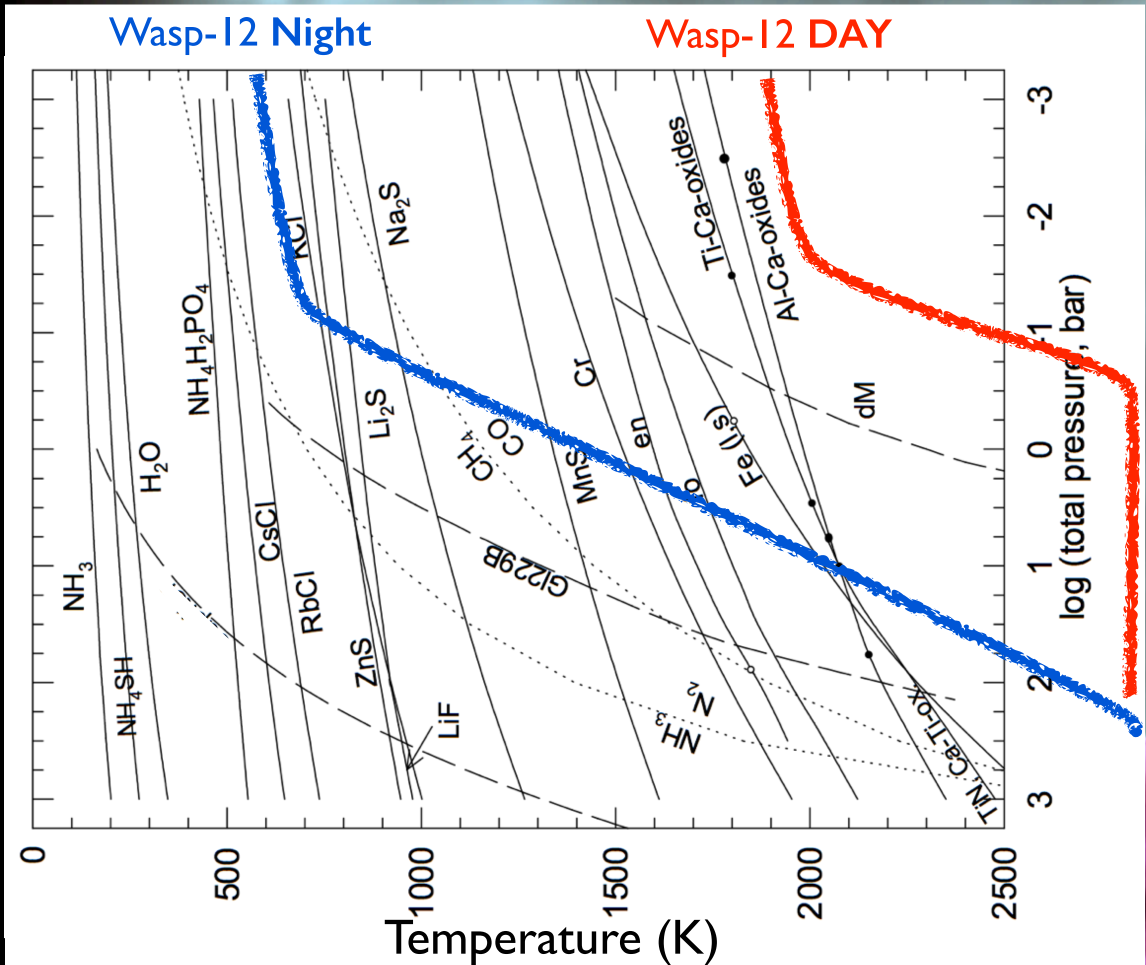
Large HST STIS/WFC3 Optical-NIR Program

<u>Science Goals</u>

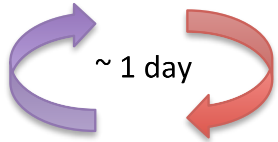
- Identify Stratosphere Absorbers (TiO, HS)
- Measure & compare abundances
- Hot Jupiter sub-classes
- Clouds & Hazes



Night-Side Cold Traps on hot Jupiters



day-to-night (condensation)
cold trap?



night-to-day transport and uplifting of finer grains (large effective Kzz) ?

Is this cold-trapping the TiO?

But there are many many unknowns…

(Spiegel et al. 2009;
Parmentier, Showman& Lian 2013)

Sing et al. (2013)
Huitson et al. (2013)

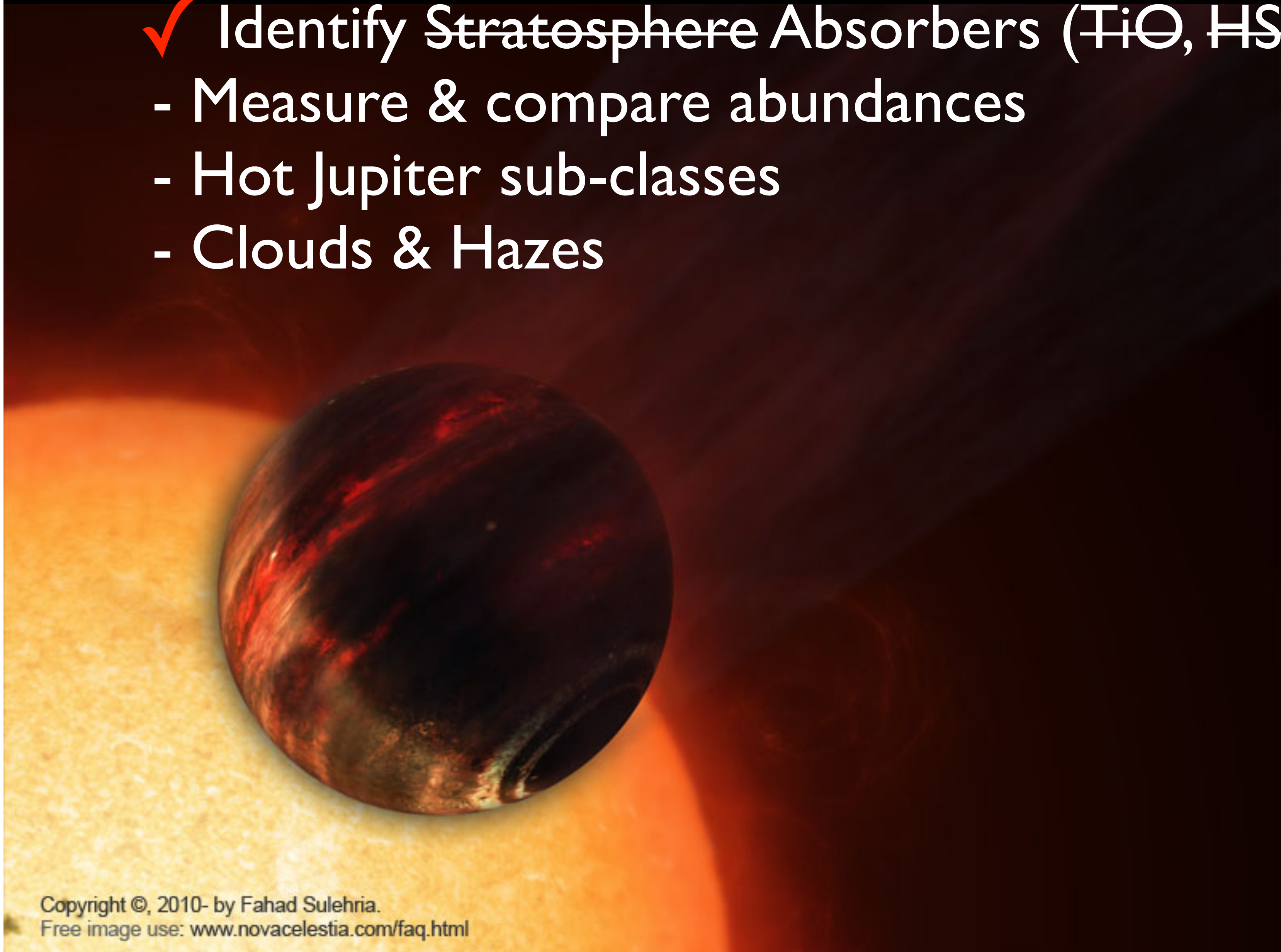
- NO TiO in HOT planets Wasp-12b, 19b, or 17b
- May not see TiO in for ANY hot Jupiters
- No TiO Stratospheres HS ruled out too

Large HST STIS/WFC3 Optical-NIR Program

<u>Science Goals</u>

✓ Identify ~~Stratosphere~~ Absorbers (~~TiO~~, ~~HS~~)

- Measure & compare abundances
- Hot Jupiter sub-classes
- Clouds & Hazes



Large HST STIS/WFC3 Optical-NIR Program

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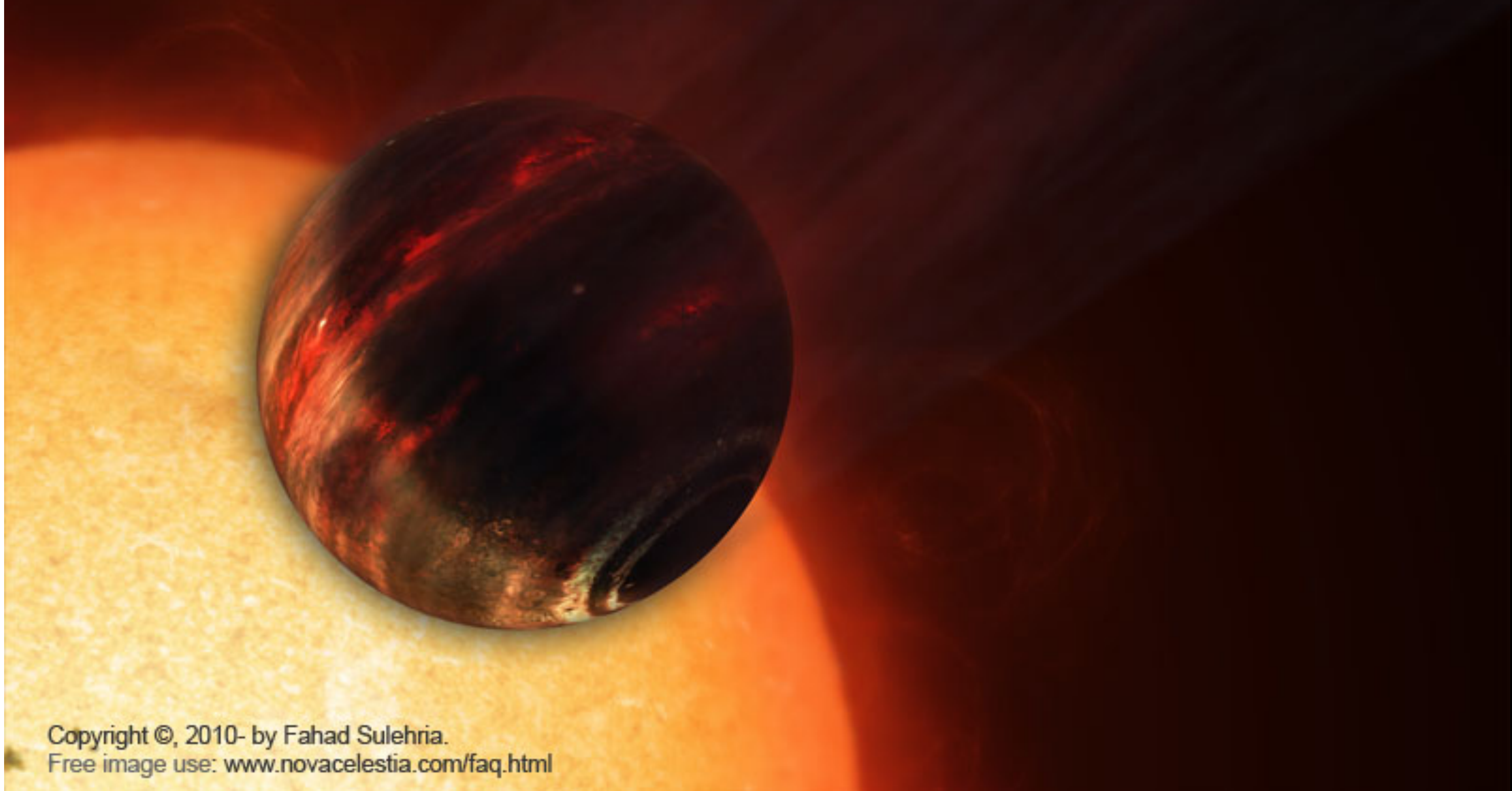
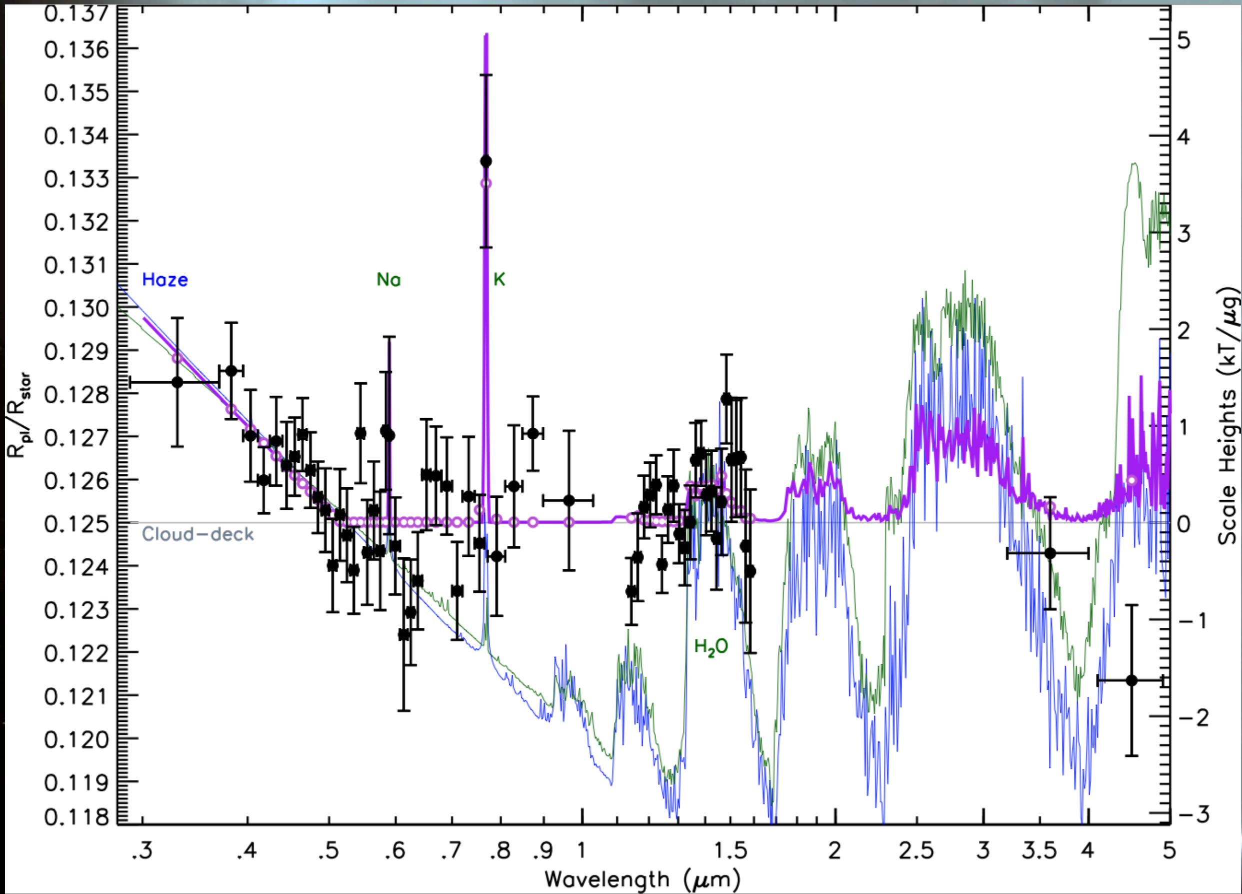


WASP-31b: Cloudy Hazy & Potassium
A heavily Clouded but not 'flat' exoplanet



Rayleigh Scattering by a Haze (4-σ)

Cloud-Deck Covers H_2O

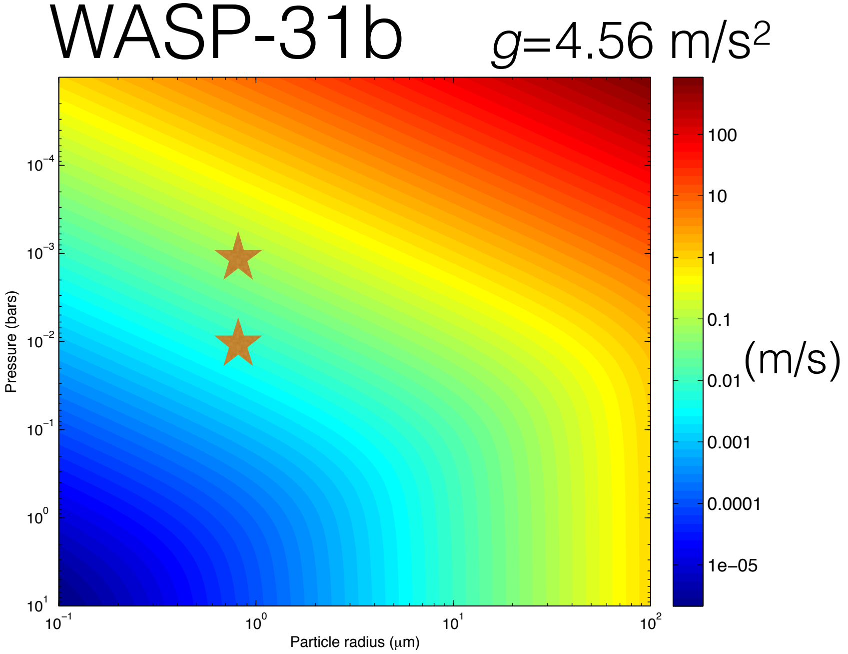
Detect Potassium (4-σ) but not Na!

10 mbar - no alkali press broad.
1 mbar - No H_2O

Na/K < 1 ?!
ln[Na/K] = - 3.3±2.8
solar is +3

Sing et al. (2015)

WASP-31b: Cloudy Hazy & Potassium
Can Clouds/Hazes be sustained at high altitudes??



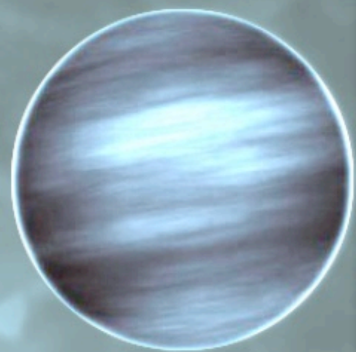
Downward settling velocity for silicates requires:

$K_{zz} \sim 10^{-4}\ m^2\ s^{-1}$ at 10 mbar

$K_{zz} \sim 10^{-5}\ m^2\ s^{-1}$ at 1 mbar

10 mbar - no alkali broad.
1 mbar - No H_2O
~1 micron size

Parmentier et al. (2013)
3D GCM of
HD 209458b
estimates effective diffusivity
WASP-31 similar Temp



$K_{zz} \sim 10^{-5}\ m^2\ s^{-1}$ at 10 mbar

$K_{zz} \sim 10^{-6}\ m^2\ s^{-1}$ at 1 mbar

Sing et al. (2015)

It appears physically plausible that the circulation will be sufficiently strong to mix particles upward to 1–10 mbar

Large HST STIS/WFC3 Optical-NIR Program

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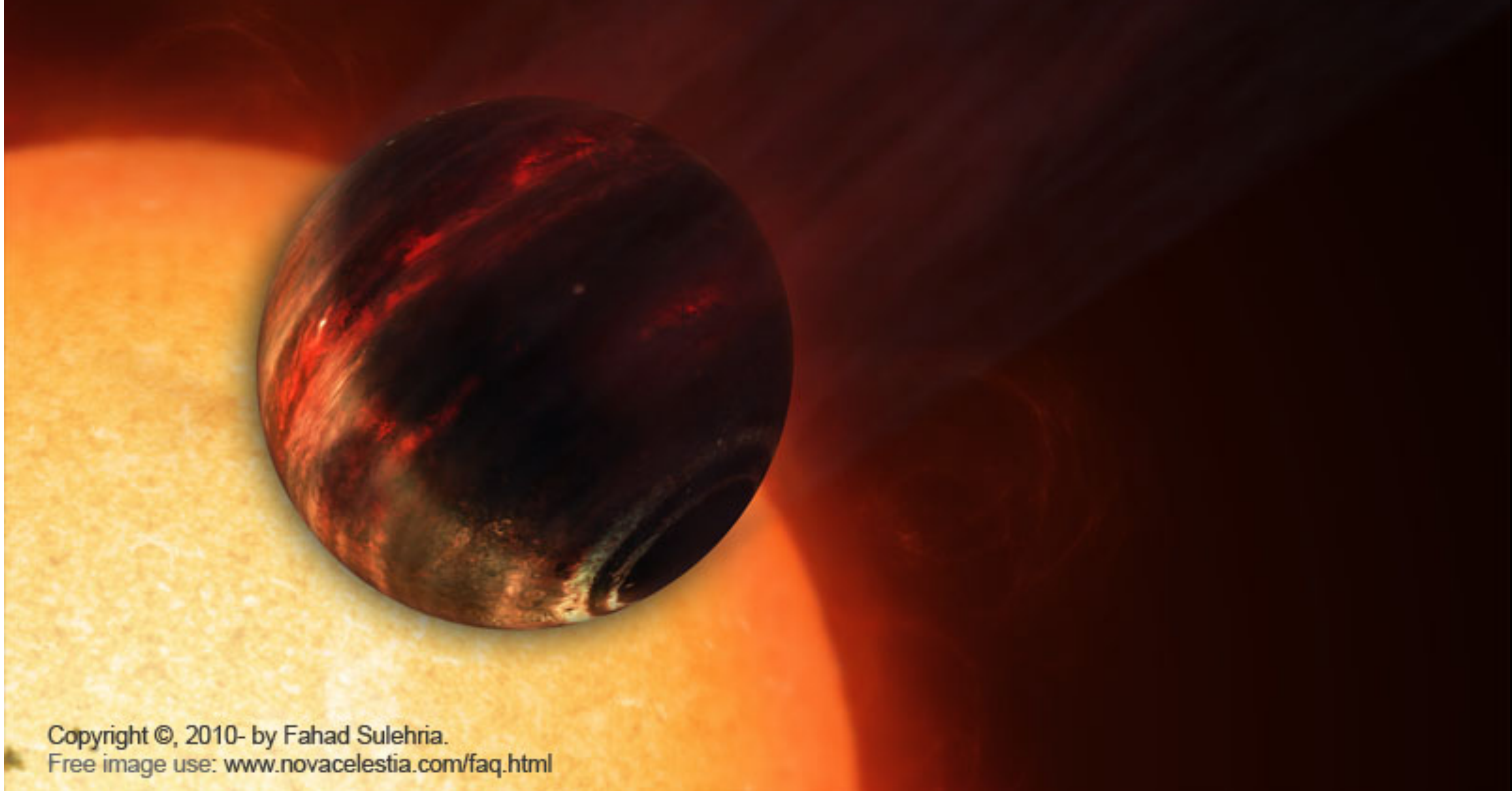
- Hot Jupiter sub-classes
- Clouds & Hazes



Large HST Transmission Spectra Program

All 10 Hot Juipters Have Detected Atmospheric Features

Comparative Exoplanet Atmospheric Studies

Name	PHYSICAL PARAMETERS T_{eq} K	g m/s^2	R_p Rj	M_p Mj	Per days	T_{eff} K	Fe/H	R_{hk}	v_{horiz} km/s	Tau_{adv} days	Tau_{set} x10^8 sec	Atmospheric Results Haze/Clouds	Na	K	H_2O	NUV slope	Name
Wasp-12b	2514	10.91	1.848	1.35	1.05	6300	0.3	-5.5	1.76	0.88	23	✓	–	–	–	✓	Wasp-12b
Wasp-19b	2050	16.61	1.38	1.11	0.78	5500	0.02	-4.6	1.25	0.95	7	–			✓		Wasp-19b
Wasp-17b	1773	4.01	1.93	0.51	3.73	6550	-0.25	-5.53	1	1.66	103	–	✓	–	✓		Wasp-17b
Wasp-31b	1586	5.02	1.36	0.48	3.4	6300	-0.2	-5.4	0.84	1.57	55	✓	–	✓	–	✓	Wasp-31b
HD209458b	1448	9.35	1.36	0.69	3.52	6065	0	-4.97	0.96	1.22	14	–	✓	–	✓	✓	HD209458b
Hat-P-1b	1305	9.08	1.24	0.53	4.46	5980	0.13	-4.98	0.79	1.35	3	–	✓	–	✓	✓	Hat-P-1b
HD189733b	1196	21.41	1.138	1.14	2.218	5040	0.03	-4.51	0.8	1.21	2	✓	✓	–	✓	✓	HD189733b
Wasp-6b	1183	4.3	1.224	0.521	3.36	5450	-0.2	-4.6	0.6	1.74	13	✓	–	~	–	✓	Wasp-6b
Wasp-39b	1117	5.69	1.27	0.28	4.055	5400	-0.12		0.43	2.55	45	–	✓	✓	–	✓	Wasp-39b
Hat-P-12b	958	5.69	0.959	0.21	3.21	4650	-0.29	-5.1	0.32	2.56	20	✓	–	–	–	✓	Hat-P-12b

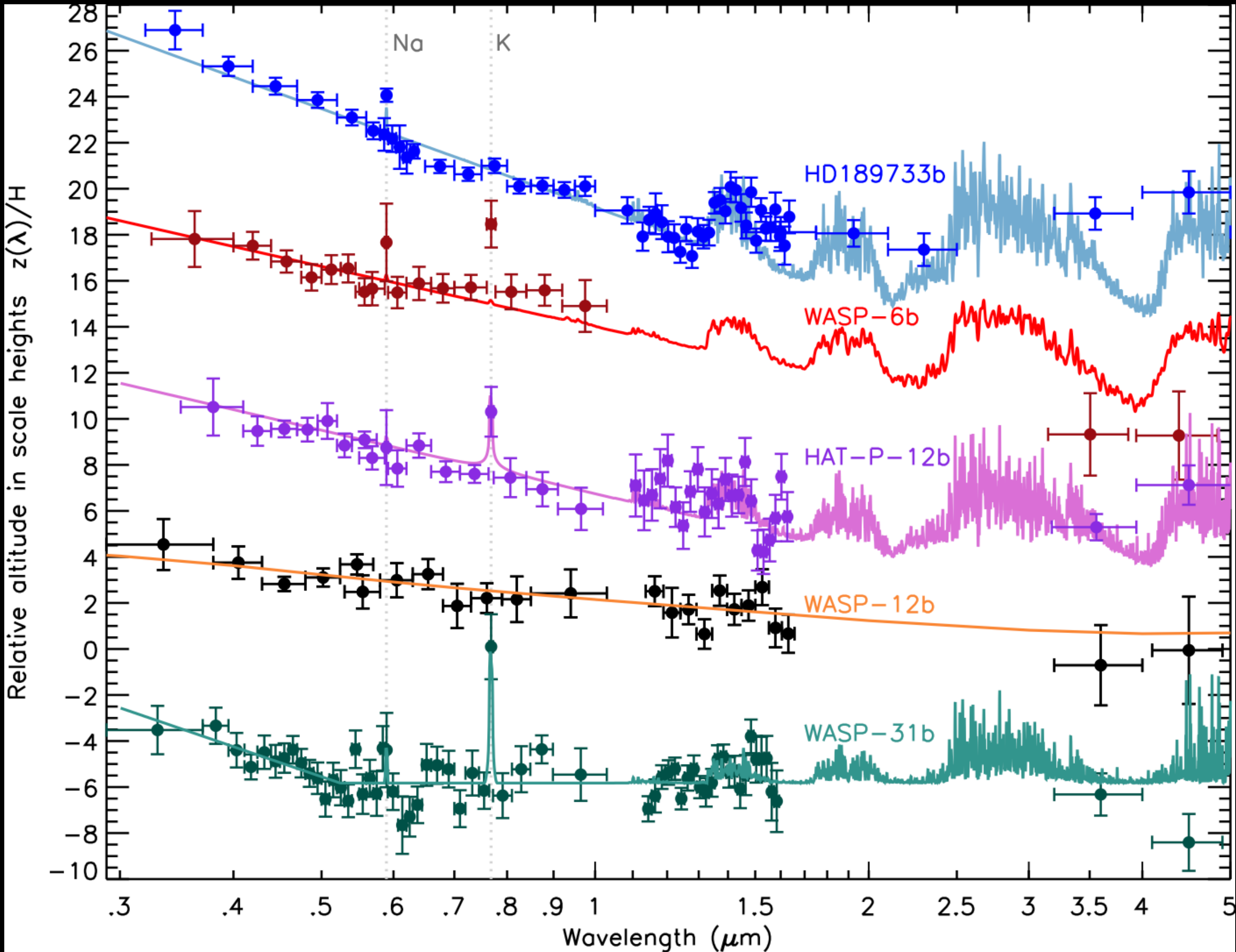
published: Wasp-12, Wasp-19, Hat-P-1, HD189733, Wasp-6, Wasp-31
rest in progress

Largest & Widest Comparison of Exoplanet spectra Ever Assembled

Clouds/Hazes, Na, H_2O are all very common BUT NOT UNIVERSAL

The First Comparitive Exoplanet Spectroscopy

A Family of hazy/cloudy exoplanets



R ~ 50
S/N ~ 5
0.3-5 μm

Large HST Transmission Spectra Program

	PHYSICAL PARAMETERS											Atmospheric Results					
Name	T_{eq} K	g m/s^2	R_p Rj	M_p Mj	Per days	T_{eff} K	Fe/H	R_{hk}	v_{horiz} km/s	Tau_{adv} days	Tau_{set} $x10^{8}$ sec	Haze/Clouds	Na	K	H_2O	NUV slope	Name
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HD209458b	1448	9.35	1.36	0.69	3.52	6065	0	-4.97	0.96	1.22	14	–	✓	–	✓	✓	HD209458b
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Wasp-19b	2050	16.61	1.38	1.11	0.78	5500	0.02	-4.6	1.25	0.95	7	–			✓		Wasp-19b
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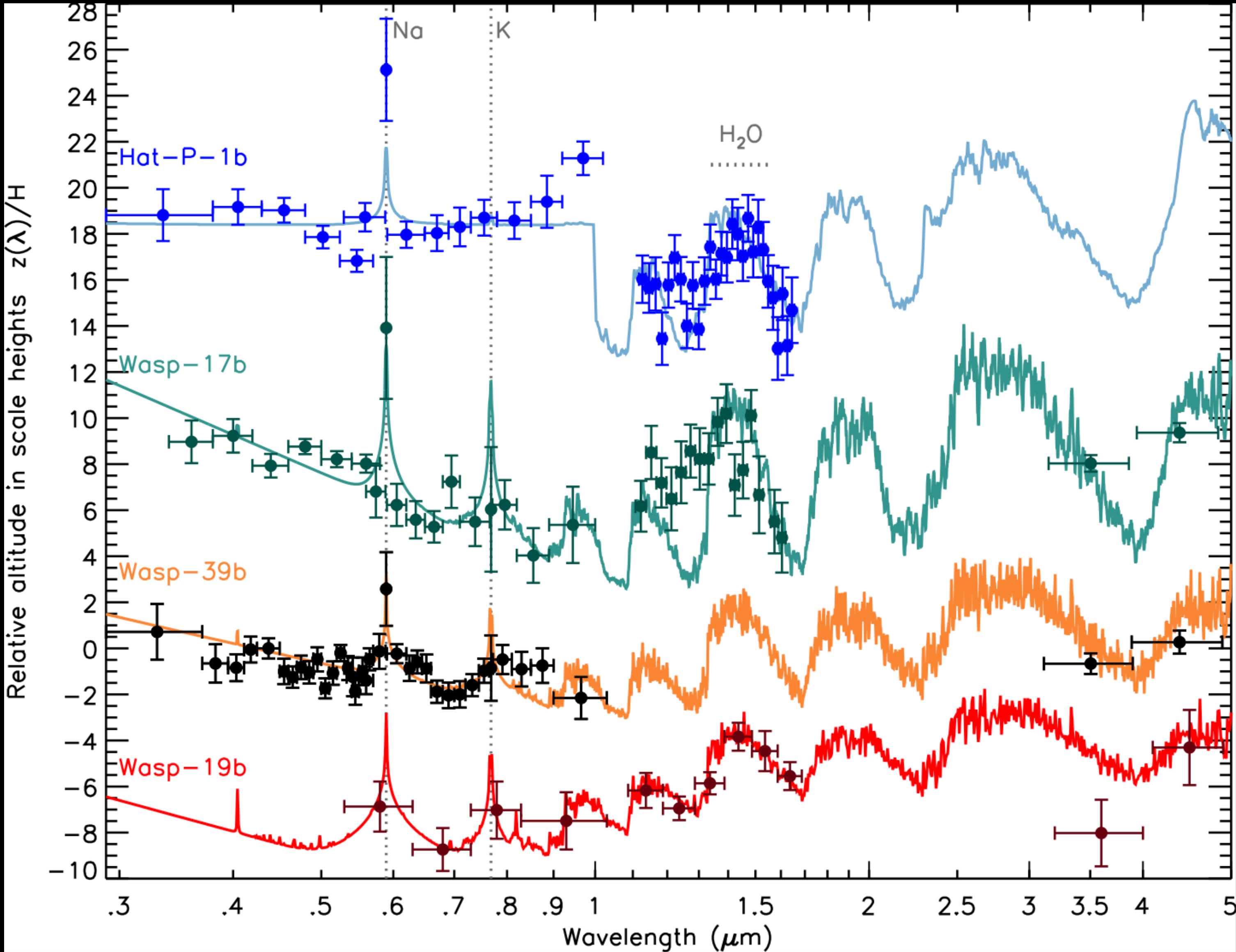
Clear vs. Cloudy Atmospheres *seems* to be a major delimiting factor in HJs

Empirical Relation.

No clear correlations are yet evident.

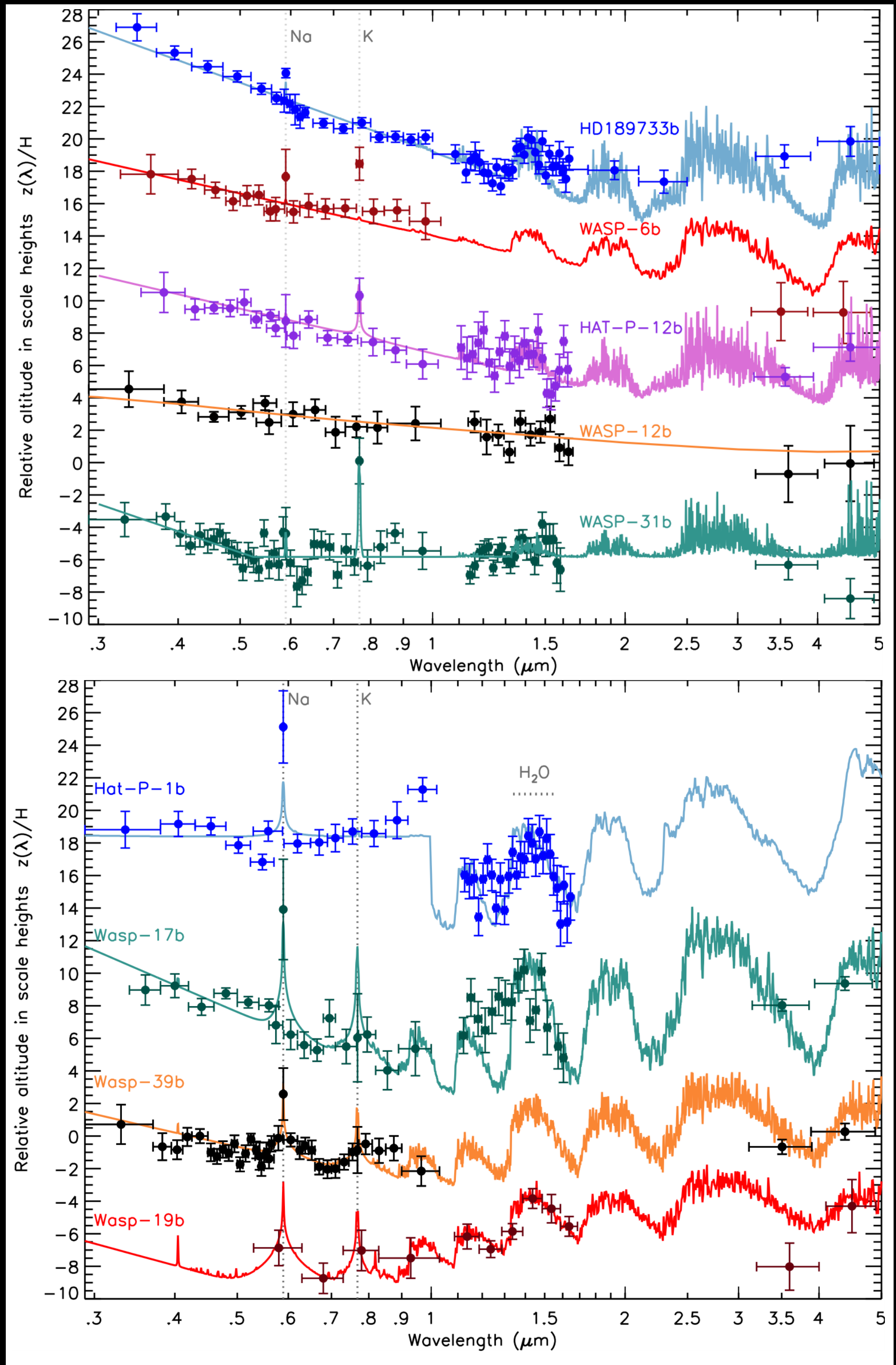
The First Comparitive Exoplanet Spectroscopy

A Family of 'clear atmo.' exoplanets



Can measure H_2O Abundance

The First Comparitive Exoplanet Spectroscopy



Clouds/Hazes a major distinguishing Characteristic of Hot Jupiters

Cover H_2O & Alkali wings

Optical Scattering

But Why? Condensation Chem.?? Photochemistry??

Large Alkali Abundance Variations!?

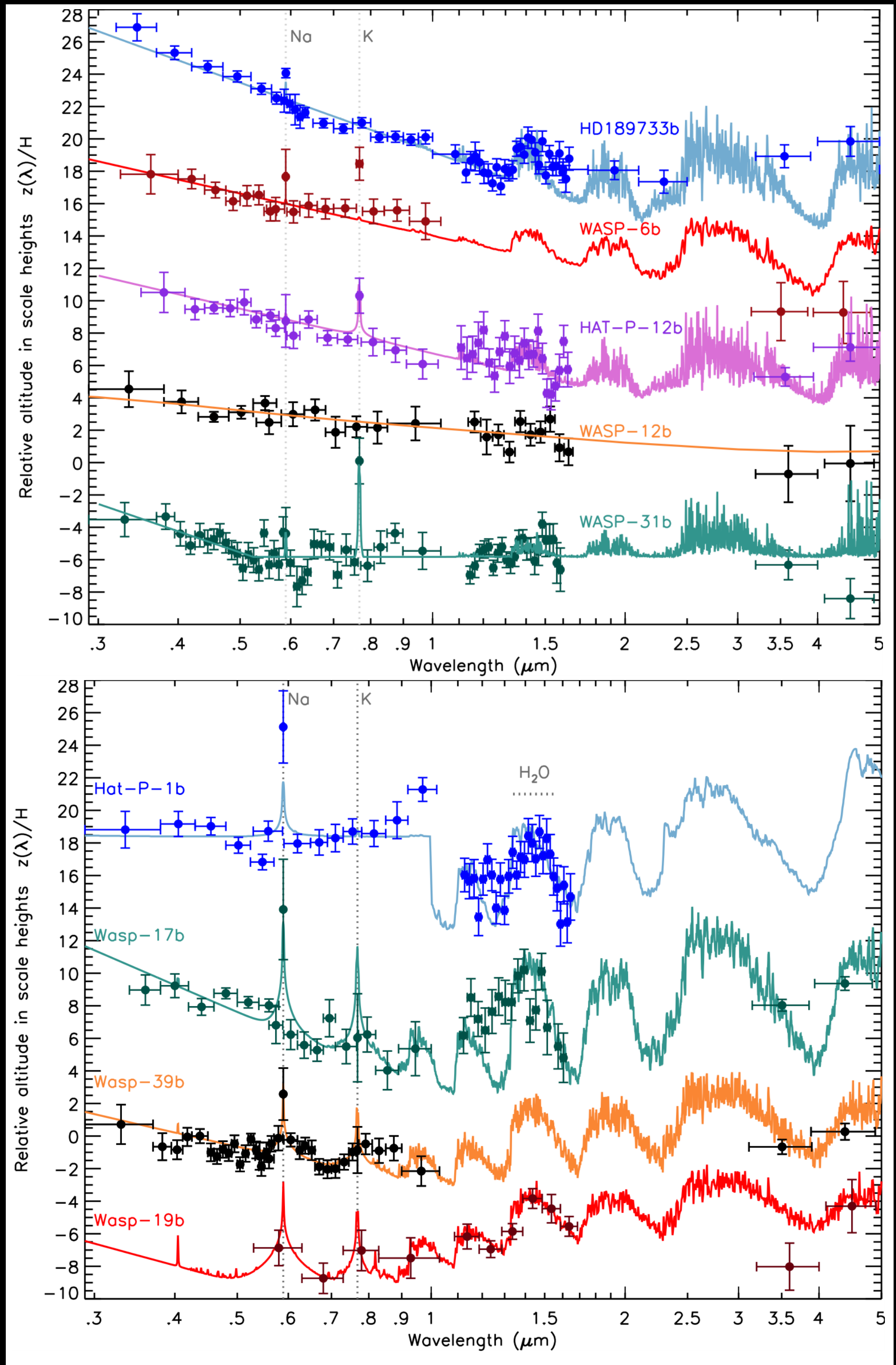
Some Super Solar Na/K

Some Subsolar Na/K ~1 !!

Solar Na/K = 20

But Why? Condensation Chem.?? Photoionization?? Primordial Abund. ??

The First Comparitive Exoplanet Spectroscopy



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Photoionization??
Primordial Abund. ??

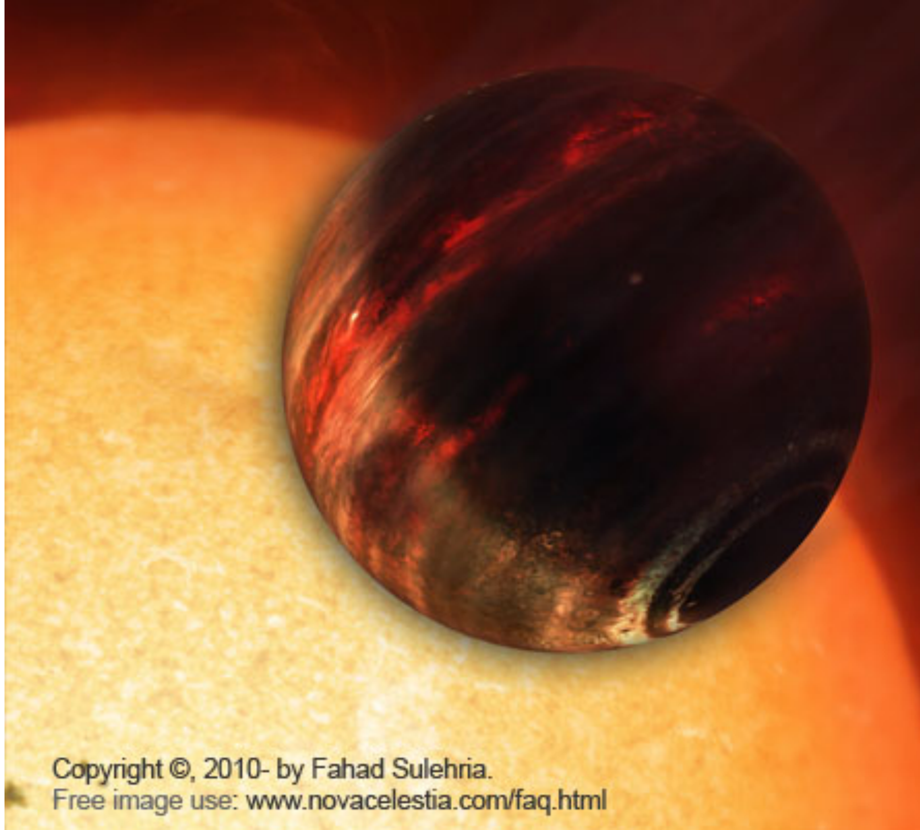
Large HST STIS/WFC3 Optical-NIR Program

Science Goals

- ✓ Identify ~~Stratosphere~~ Absorbers (~~TiO~~, ~~HS~~)
- ✓ Measure & compare abundances (Na/K/H_2O)
- ✓ Hot Jupiter sub-classes
- ✓ Clouds & Hazes

Next...

- Statistically Significant Sample
- Understand Physical Processes
    - Clouds
    - Alkalis abundance
    - H_2O abundance



Still LOTS to do with HST & JWST is coming

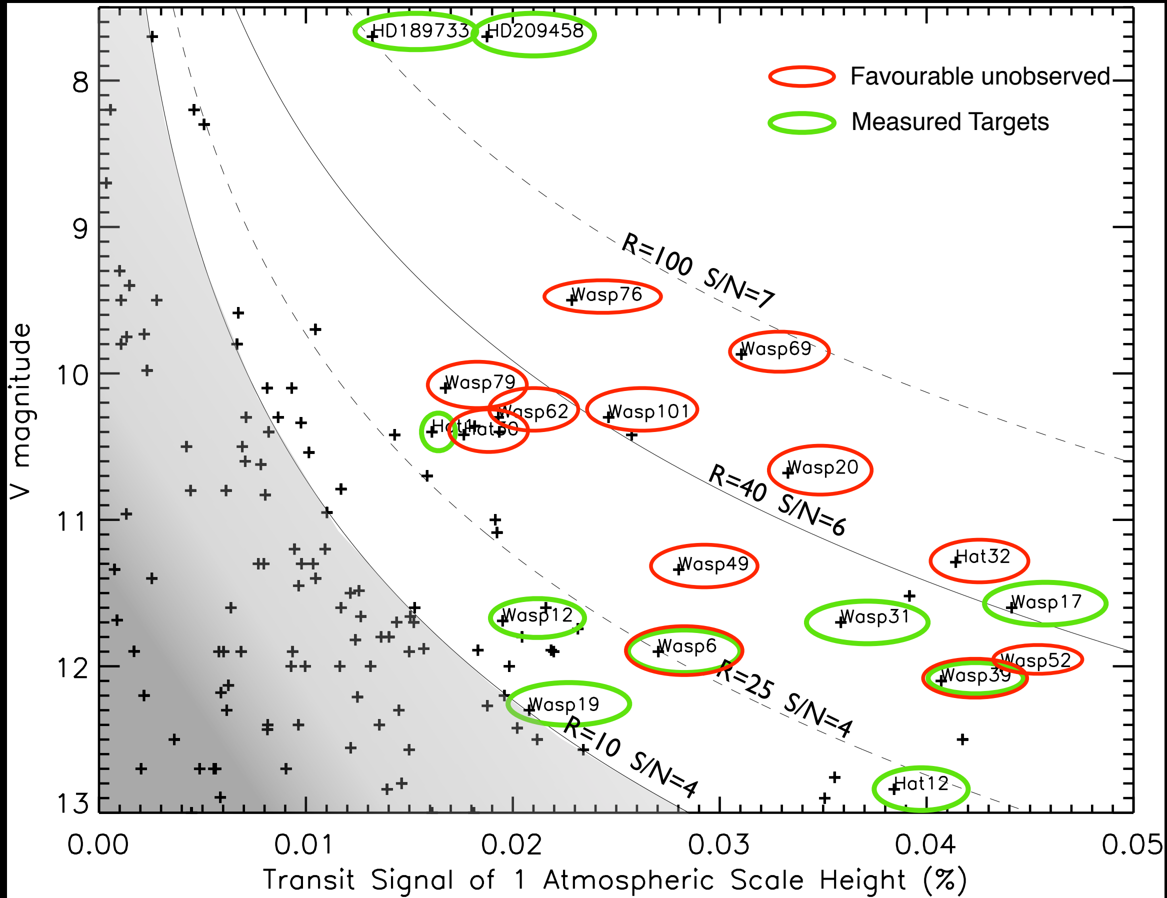
higher photometric signal

Better Because...

- New Discoveries
- Brighter
- Larger atmo. *H*

Resulting in...

- Higher S/N
- Higher Resolution



larger atmosphere signal

Optical to near-IR

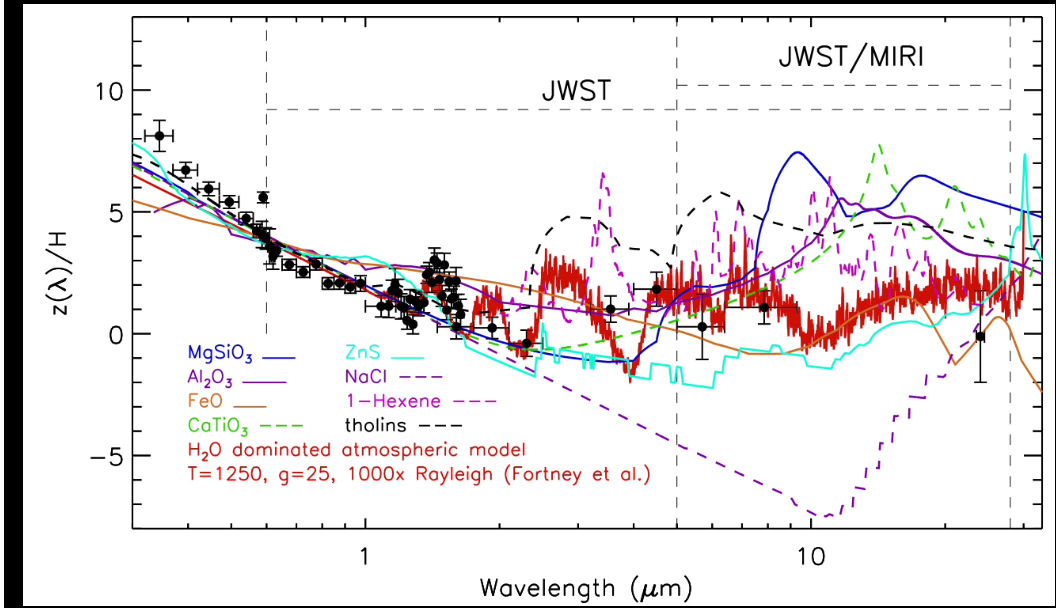
Cycle 19: R~50 S/N~ 5

next: R~75 S/N~ 7

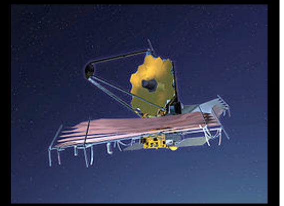
15x photons/transit

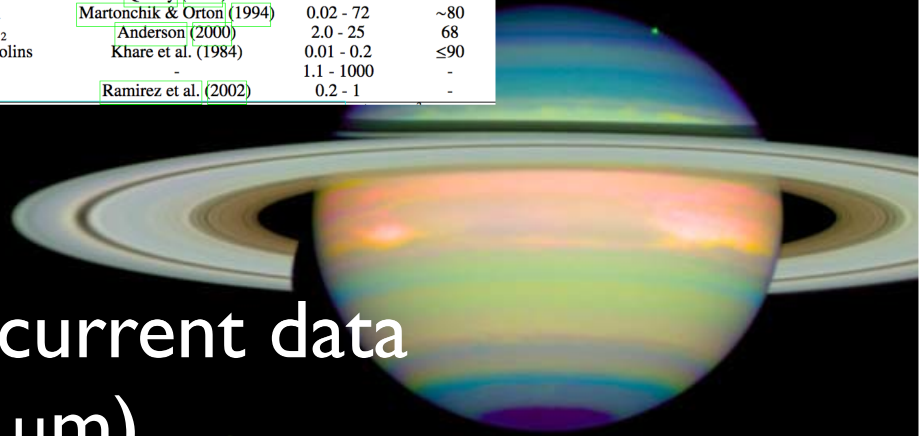
R~150 S/N~ 20

JWST Can Constrain Cloud Species



Condensate	Reference n, k index	λ Range (μm)	Condensation Temperature (K)
SiO_2	Palik (1998)	0.04 - 11	1725
	Andersen et al. (2006)	7 - 28	-
	M. Meinecke (2005)*	6.6 - 10000	-
Al_2O_3	Koike et al. (1995)	0.3 - 150	1677[1]
FeO	Begemann et al. (1995)	10 - 100	1650[4]
	Andersen et al. (2006)	15 - 40	-
$CaTiO_3$	Posch et al. (2003)	2 - 155	1582[1]
Fe_2O_3	M. Meinecke (2005)*	0.1 - 987	1566
Fe_2SiO_4	Day (1981)	8.2 - 35	1443[4]
$MgAl_2O_4$	M. Meinecke (2005)*	1.6 - 270	1397[1]
$FeSiO_3$	Day (1981)	8.2 - 35	1366[4]
Mg_2SiO_4 (Fe–rich)	Henning et al. (2005)	0.2 - 445	1354[1]
Mg_2SiO_4 (Fe–poor)	Zeidler et al. (2011)	0.19 - 800	1354[1]
$MgSiO_3$	Egan & Hilgeman (1975)	0.1 - 0.4	1316[1]
	Dorschner et al. (1995)	0.5 - 80	-
Na_2S	Morley et al. (2012)	0.03 - 73	1176
MnS	Huffman & Wild (1967)	0.1 - 3	1139[2]
TiO_2	Kangarloo (2010a)	0.3 - 1.2	1125[2]
	Kangarloo (2010b)	1.3 - 30	-
NaCl	Palik (1998)	0.04 - 1000	825[3]
KCl	Palik (1998)	0.02 - 200	740[3]
ZnS	Querry (1987)	0.2 - 167	700[5]
CH_4	Martonchik & Orton (1994)	0.02 - 72	~80
C_6H_{12}	Anderson (2000)	2.0 - 25	68
Titan Tholins	Khare et al. (1984)	0.01 - 0.2	≤90
	-	1.1 - 1000	-
	Ramirez et al. (2002)	0.2 - 1	-





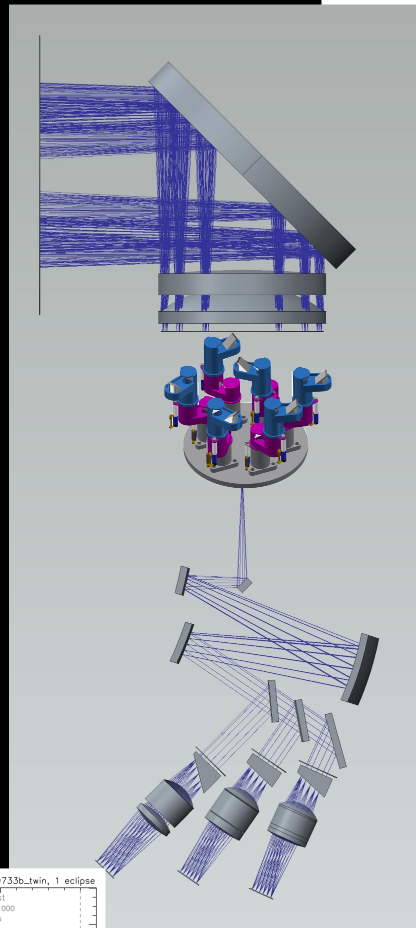
Wakeford & Sing (2014, arXiv)

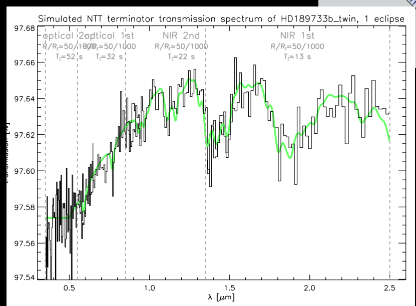
- cloud composition *difficult* with current data
- Vibrational transitions in IR (>3 μm)
- Can constrain basic composition (like brown dwarfs)

- Condensation vs. Photo-Chemistry
  Si-O C-H

Introducing ExoMOS

- Selected for further details by ESO for NTT
- 1st instrument designed for Exoplanet Atmospheric Characterization in Opt+IR
- R~1000, 0.3 to 2.4 um
- Multi-object, 50 ppm, wide field
- Spectra of 100 exoplanets

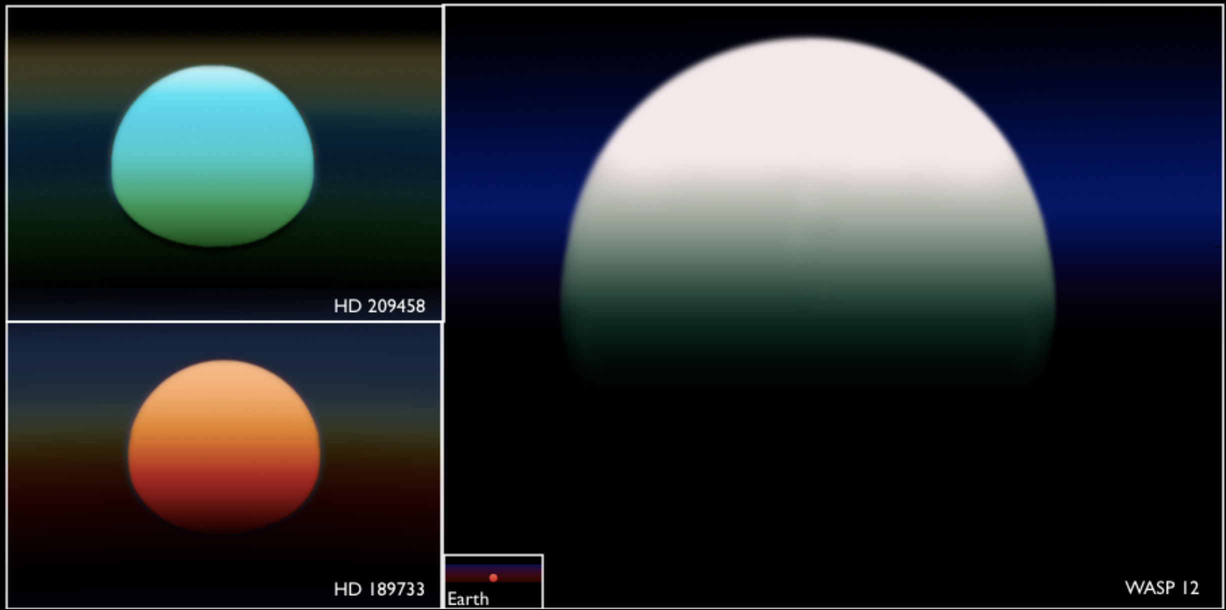


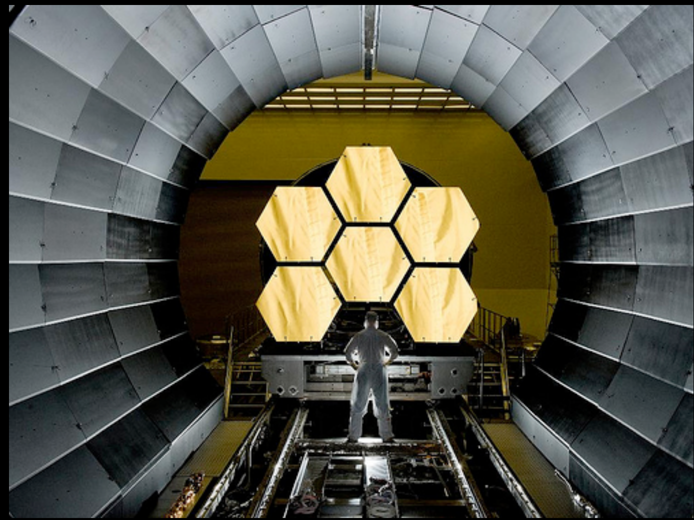


UK, Germany, Switzerland, Netherlands…

Conclusions

HST ExoSunset Survey





jwst.nasa.gov

Now have our first look Comparing Exoplanet Spectra

Powerful way to probe complex physics

Emerging Puzzles concerning Clouds & Metallicity