Studying exoplanets with SOFIA

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14.10.2015

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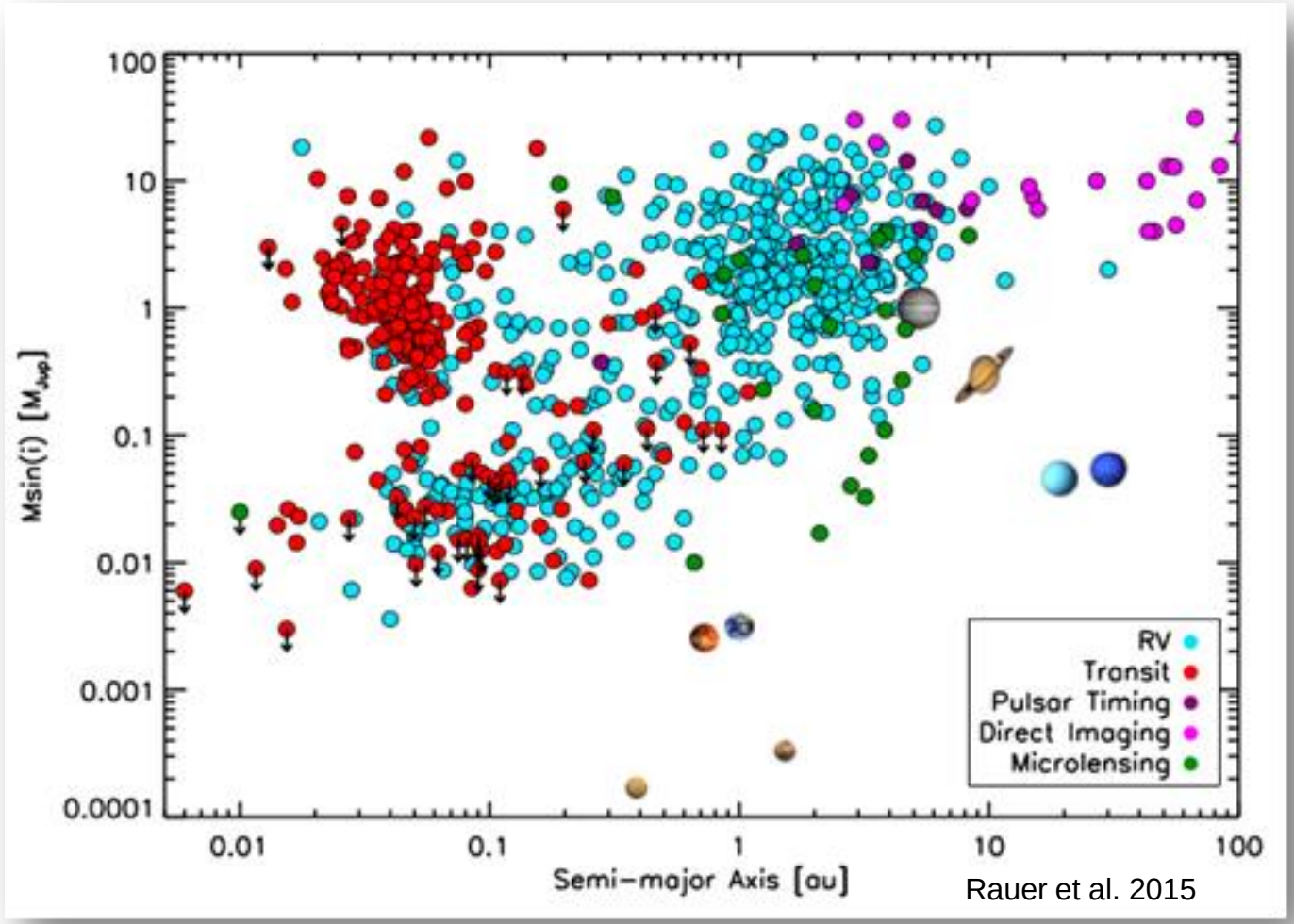
Known Exoplanets

Current status: ~1600 confirmed exoplanets and ~3800 planet candidates
(October 2015; exoplanets.org)



Rauer et al. 2015

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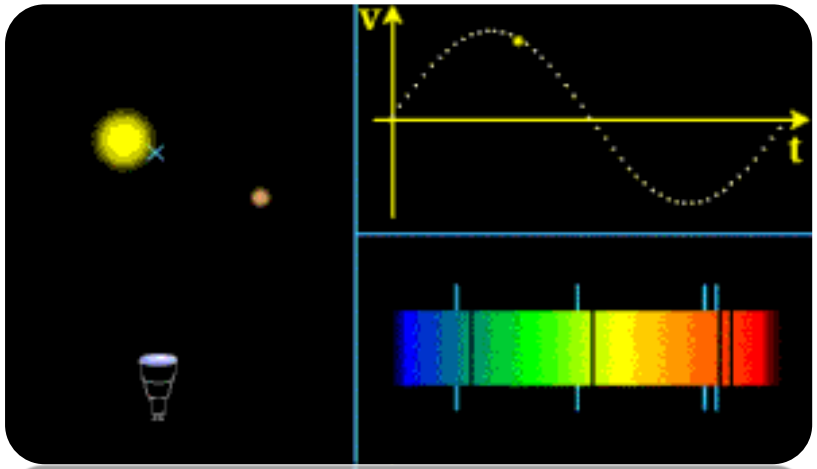
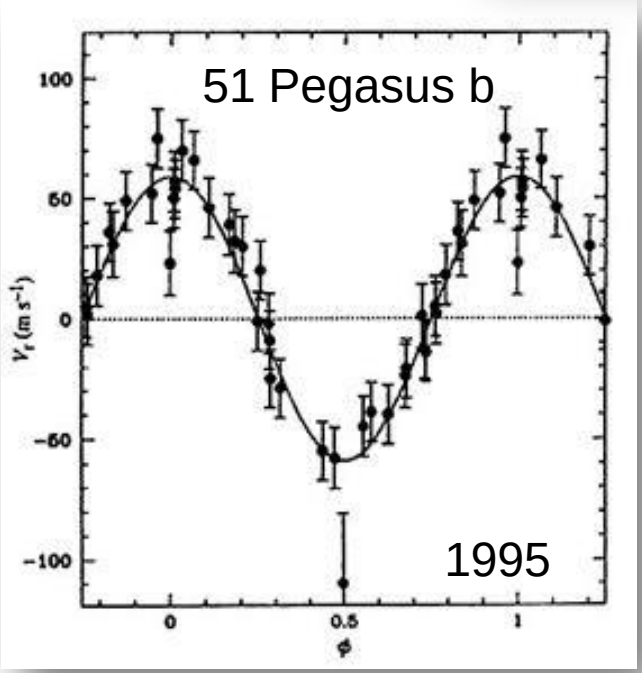
Radial velocity method

Michel Mayor
and
Didier Queloz





→ orbital period and semi-major axis

→ minimum planet mass ***(m sin i)***

- Period: ~4 days
- Semi-major axis: 0.05 AU
- Mass: ~ ½ M_J

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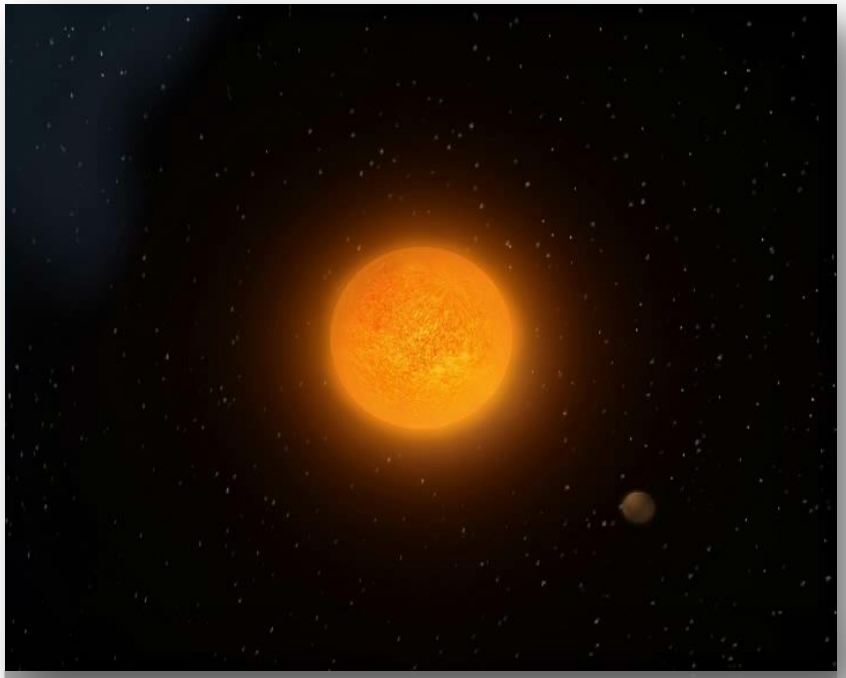
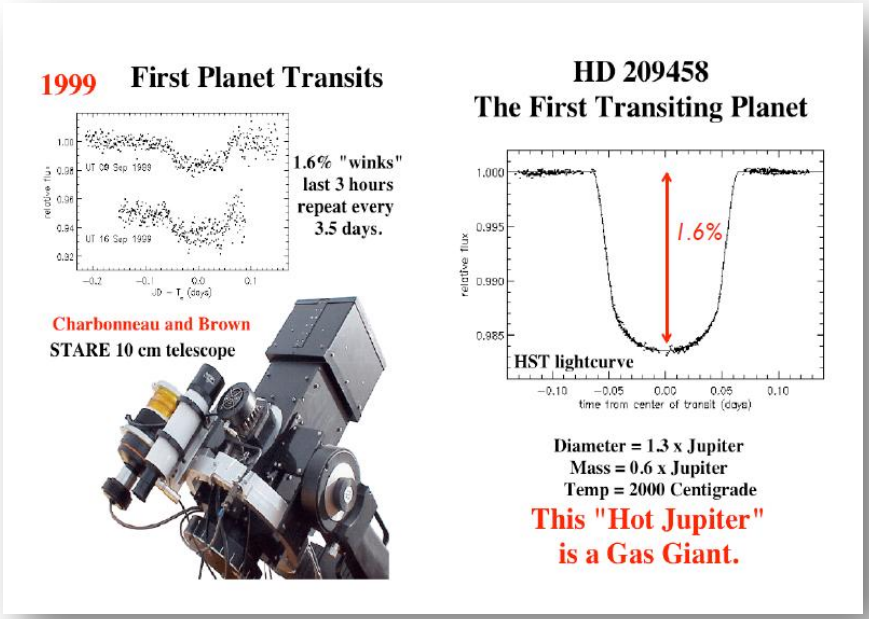
Transit Methode





→ orbital Period and semi-major axis

→ Radius

→ Inclination i

- Period: ~3½ days
- Semi-major axis: 0.05 AU
- Radius: ~1½ R_J

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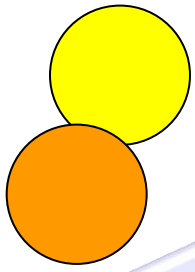
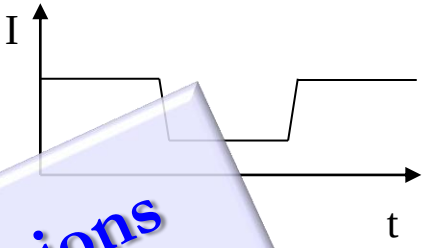
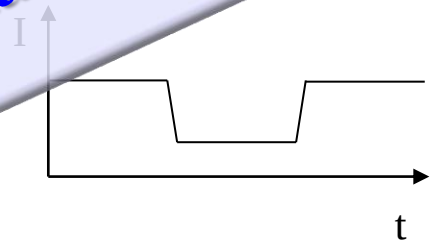
Transit false alarm possibilities

* Grazing eclipse of binaries



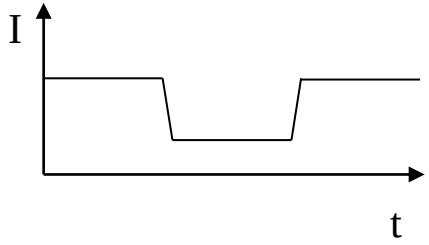


* Transit of brown dwarf

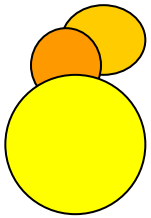


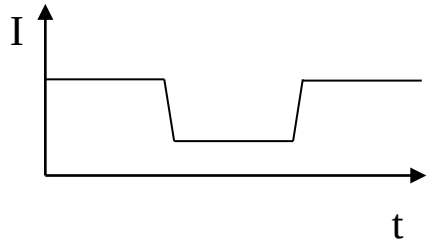
→ Need for follow-up confirmations

* Stellar spots



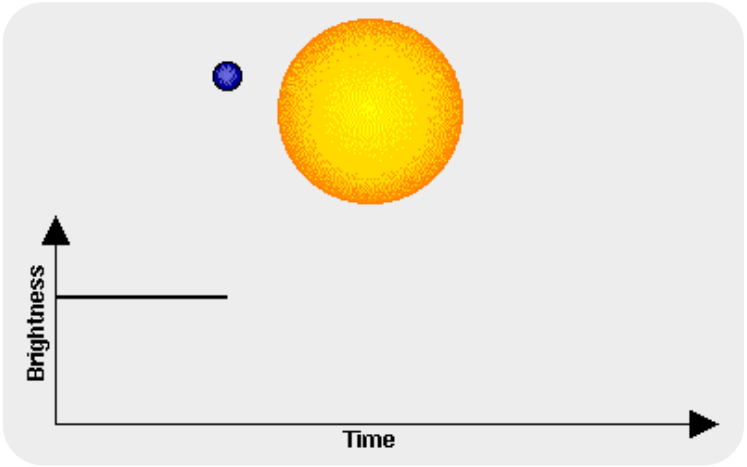
* Binary system in background





Exoplanet Detection methods

Transit Method

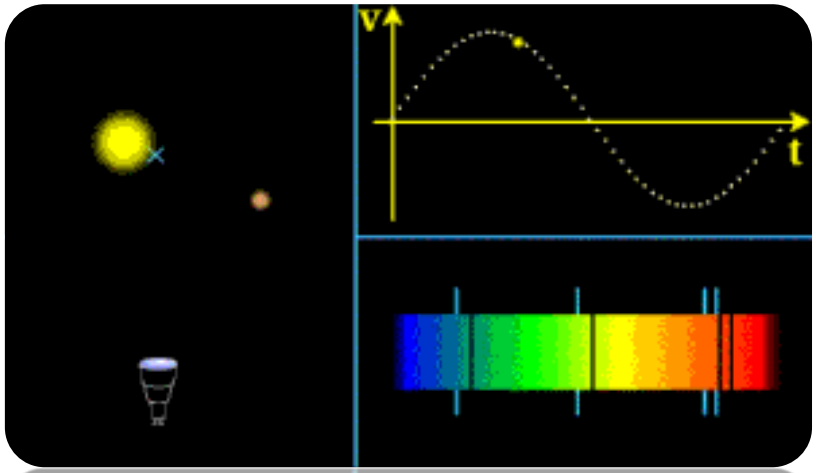


→ Orbit parameters

→ Orbital inclination, ***i***

→ Planet radius

Radial velocity method



→ Orbital parameters

→ Minimum planet mass, ***m* sin *i***

True planet mass and mean density

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Our Solar System

and its planets are NOT the general rule

- Small planets ≠> rocky, large planets ≠> gaseous
- Small planets ≠> close-in, large planets ≠> far out
- New class of planets not existent in our solar system

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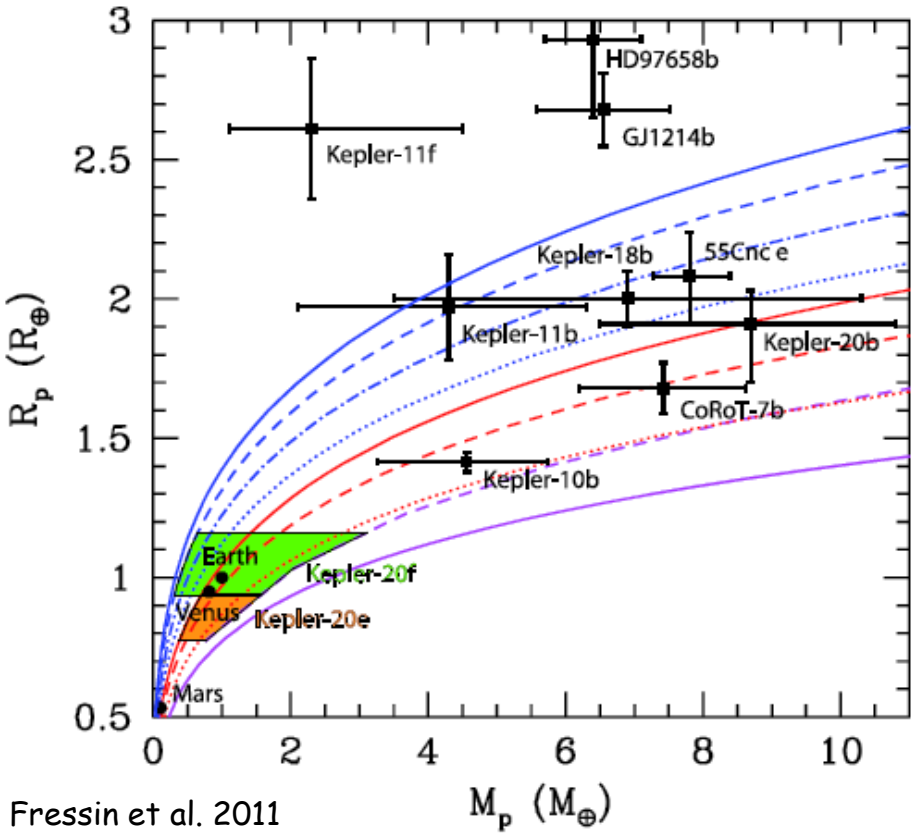
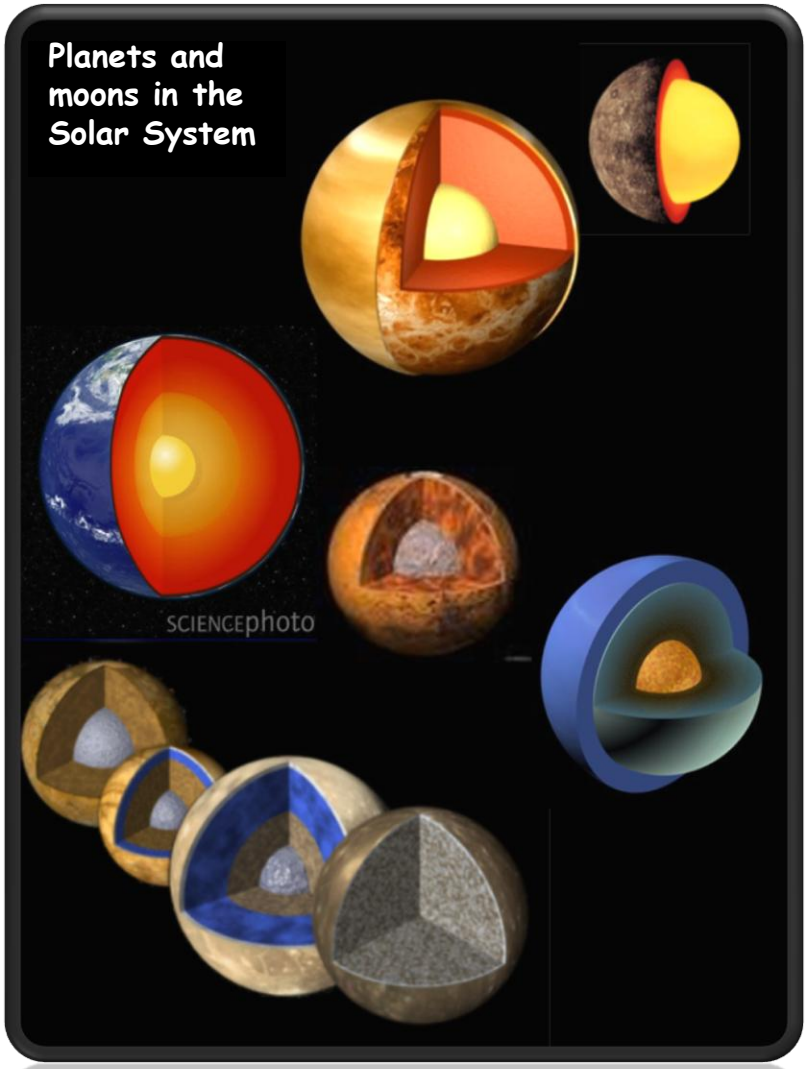
Planet diversity



Fressin et al. 2011



Degeneracy between the mass and bulk composition and a possible atmosphere in theoretical models

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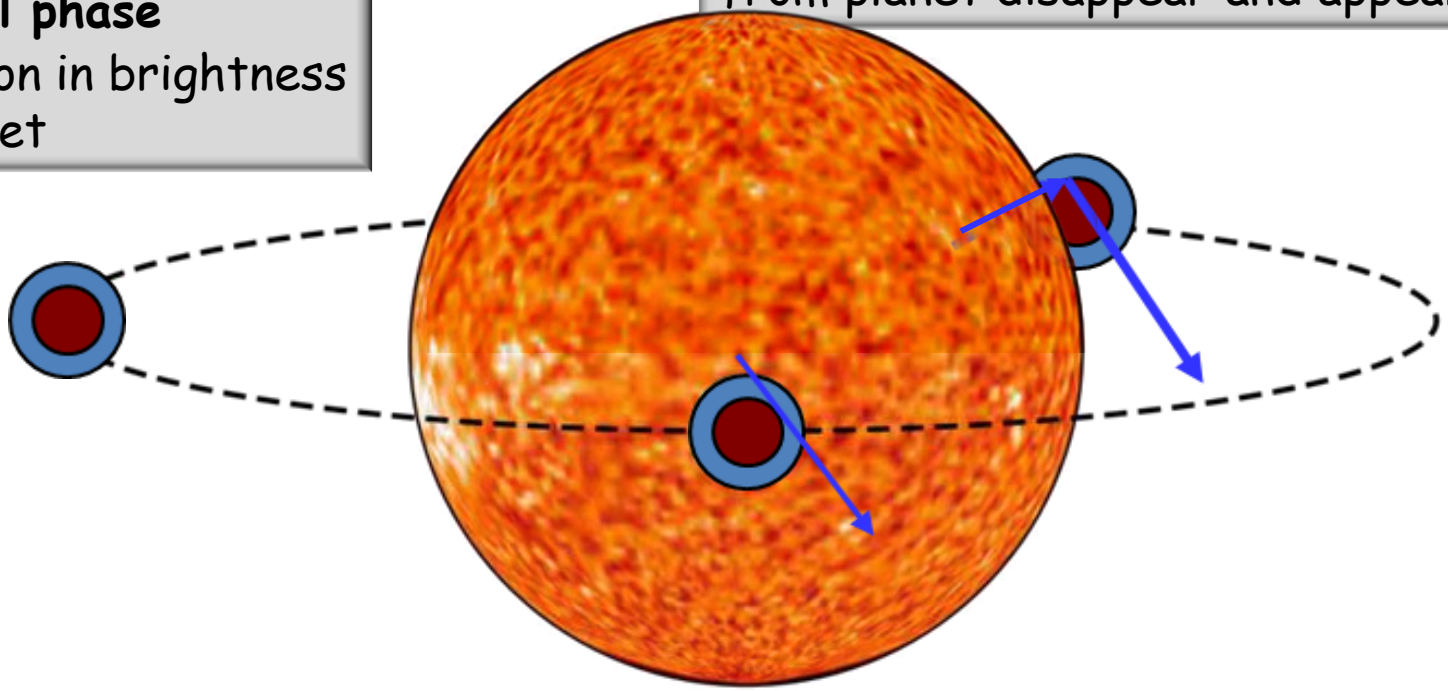
Exoplanet atmosphere characterization

Secondary Eclipse (Occultation)
Thermal radiation and reflected light from planet disappear and appear again

Orbital phase
variation in brightness of planet



Primary Eclipse (Transit)
Radiation from star transmitted through the planets atmosphere

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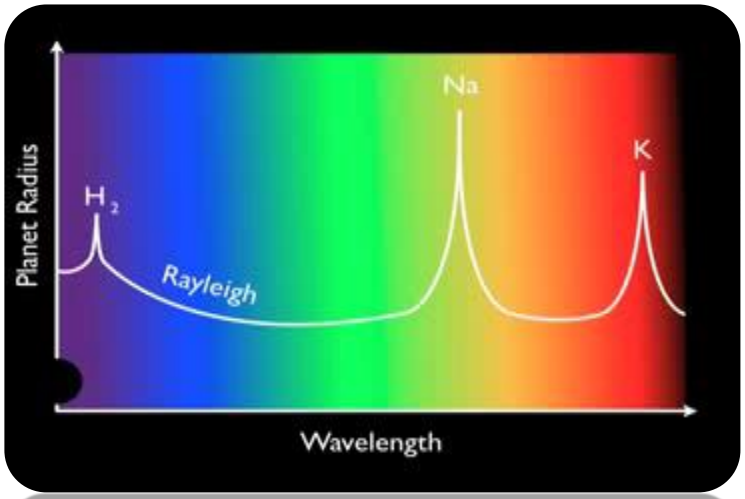
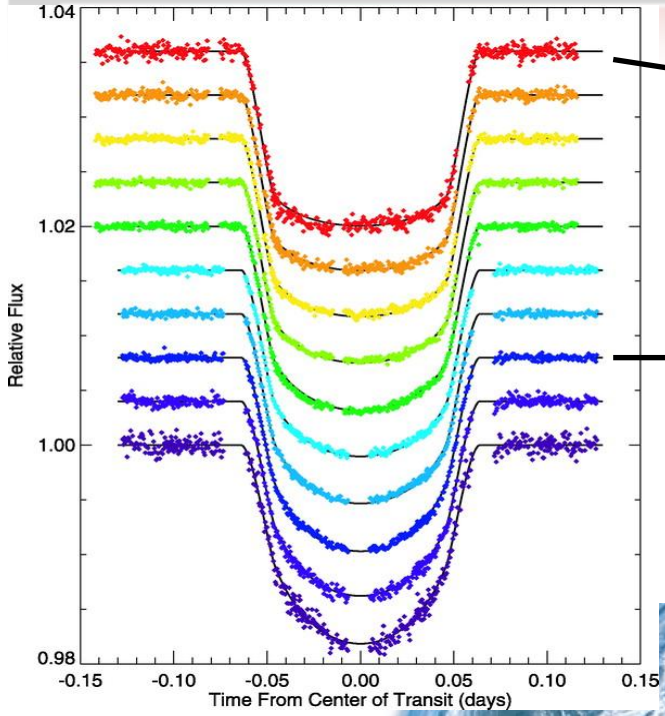
Characterizing Exoplanet Atmospheres with Transit-Spectrophotometry

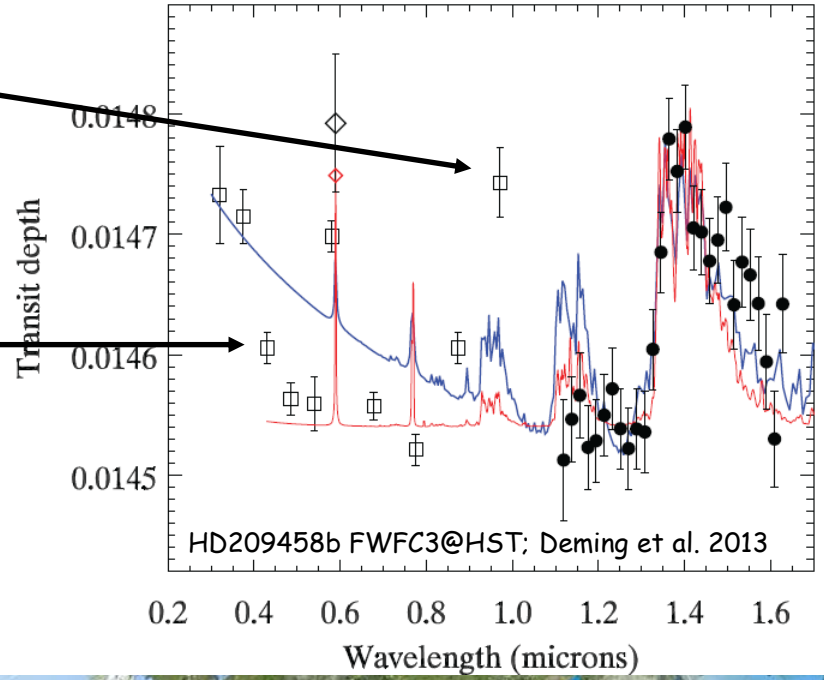


- Atmospheric composition
- Atmospheric structure
  (T/P profile, day/night side heat exchange)
- Formation history

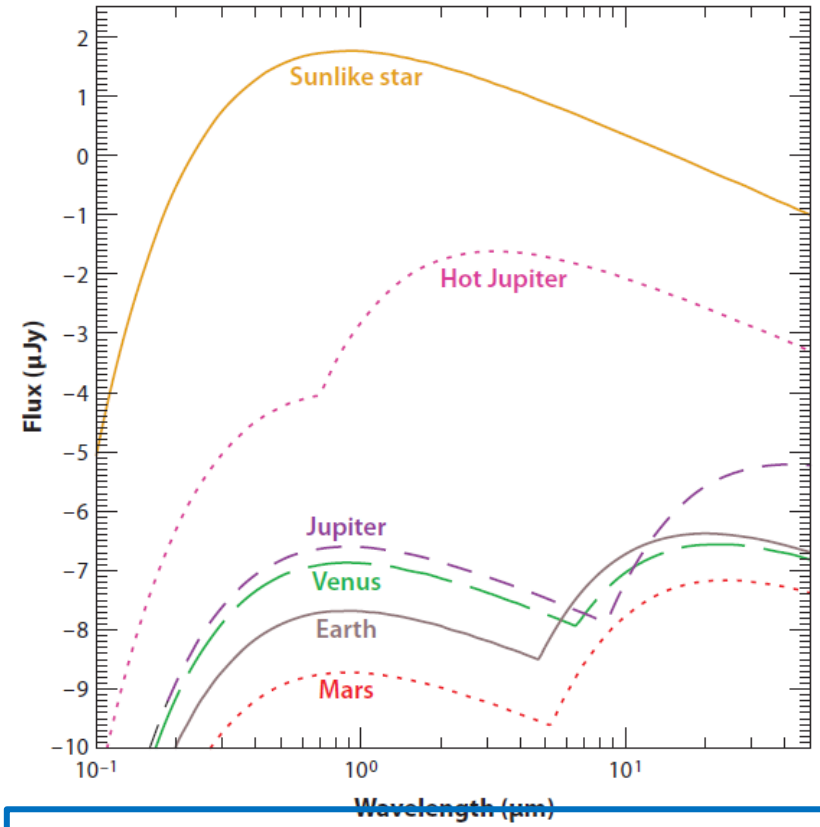
HD 209458b STIS@HST Knutson et al. 2007

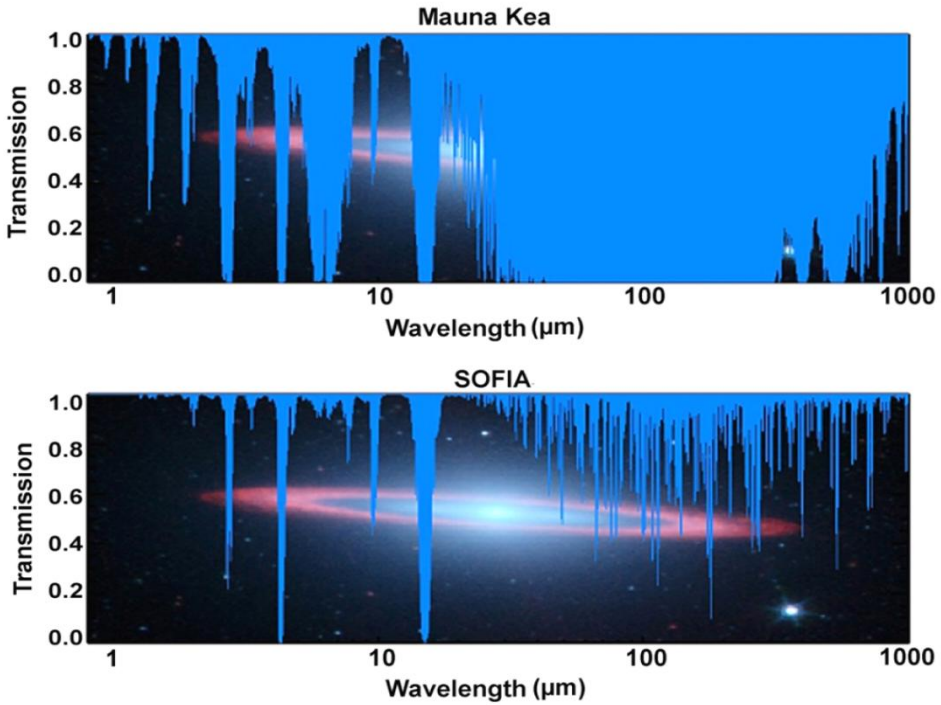


$$\sim \left(\frac{R_p}{R_s}\right)^2$$



SOFIA & Exoplanets



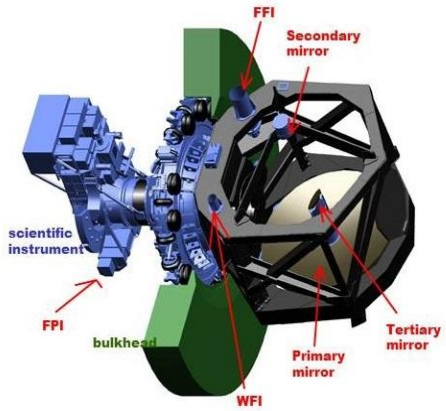


SOFIA

- operates at wavelengths where the planet's black-body temperature peaks and improved contrast ratios star/planet
- operates at low temperatures (240K); therefore the contribution from the thermal background are significantly reduced.
- can observe simultaneously at infrared and optical wavelengths, 'FLIPO' mode, thereby obtaining light curves for a single transit event over a wide range in wavelength

SOFIA Science Instruments

Stratospheric Observatory For Infrared Astronomy



Spectral resolution

10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0

GREAT
CASIMIR
EXES
FLITECAM w/ grisms
FORCAST w/ grisms
FIFI LS
SAFIRE
HIPO
FLITECAM
FORCAST
HAWC

1
10
100
1000

Wavelength [μm]

The best-known Hot Jupiter HD 189733 b

Planet HD 189733b

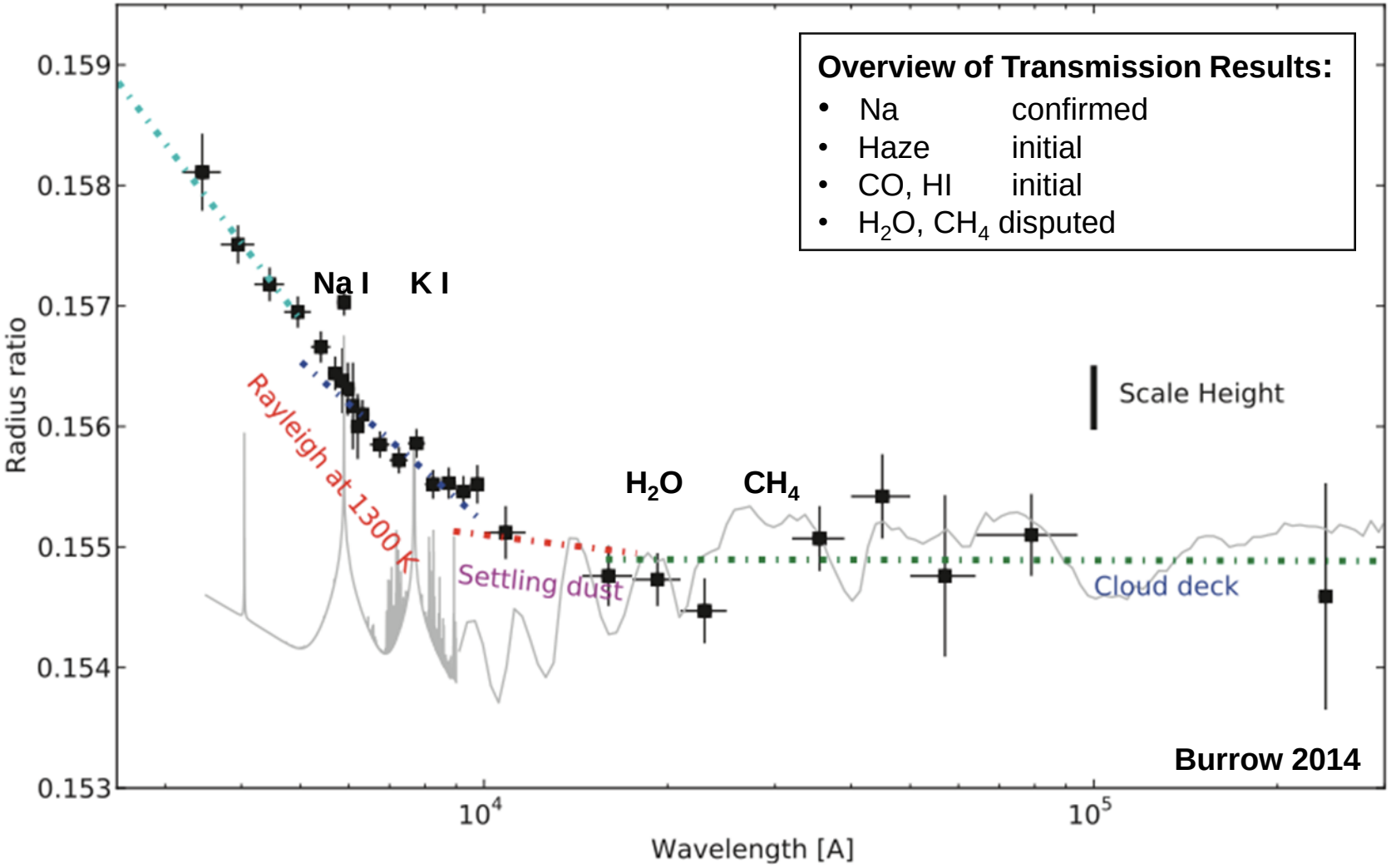
Discovery:	2005 (Bouchy et al)
Mass (*m*):	1.144 ± 0.056 MJ
Radius (*r*):	1.138 ± 0.027 RJ
Dichte (*ρ*):	$0.963\ ^{+0.088}_{-0.079}$ g cm^{-3}
Period (p):	2.21857312 ± 7.6e-07 d
Transit duration (T):	0.0760 ± 0.0017 d
Semi major axis (a):	0.03142 ± 0.00052 au

Host star 189733

Right ascension (*α*):	$20^h\ 00^m\ 43.0^s$
Declination (*δ*):	+ 22°42′ 39″
Magnitude (m_V):	7,67
Distance (d):	19.3 ± 0.2 pc
Spectral type:	K1-K2
Mass (*m*):	0.8 ± 0.4 $M_\odot$
Radius (*r*):	0.805 ± 0.016 $R_\odot$
Temperature (*T*):	4875 ± 43 K
Age:	0,6 Gyr

Hot Jupiter HD 189733 b

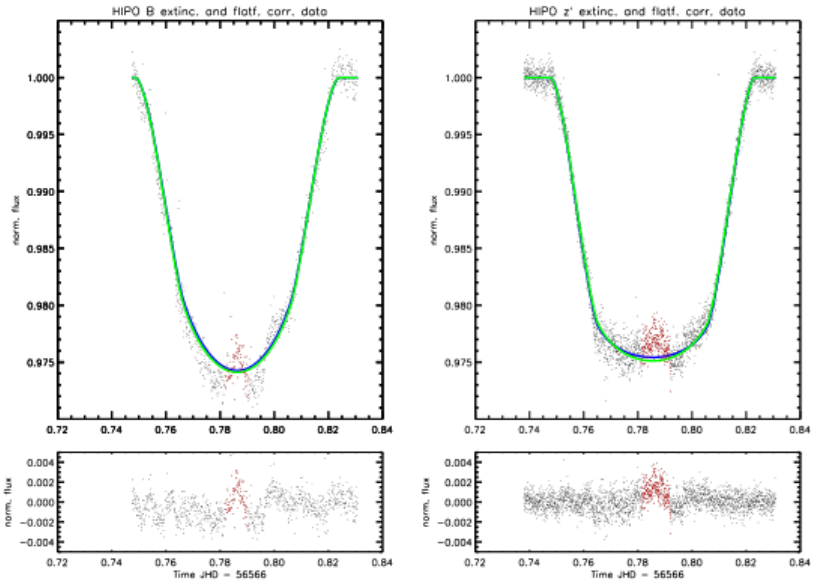
Transmission spectrum of HD 189733b, showing the core of the sodium Na and potassium K lines, and the signature of aerosols



First exoplanet transit observation: HJ HD189733b

Stratospheric Observatory For Infrared Astronomy

- **Examine the presence of a Rayleigh slope in the optical (using HIPO's B & z′ filters)**
- **Examine the existence of H_2O absorption in the NIR (using FLITECAMs 1.85 μm filter)**



Extinction & flat field corrected absolute photometry of HIPO's B (left) and z′ (right) channels before removal of correlated noise

Youtube: Exoplanet observations with SOFIA

Angerhausen et al. 2015

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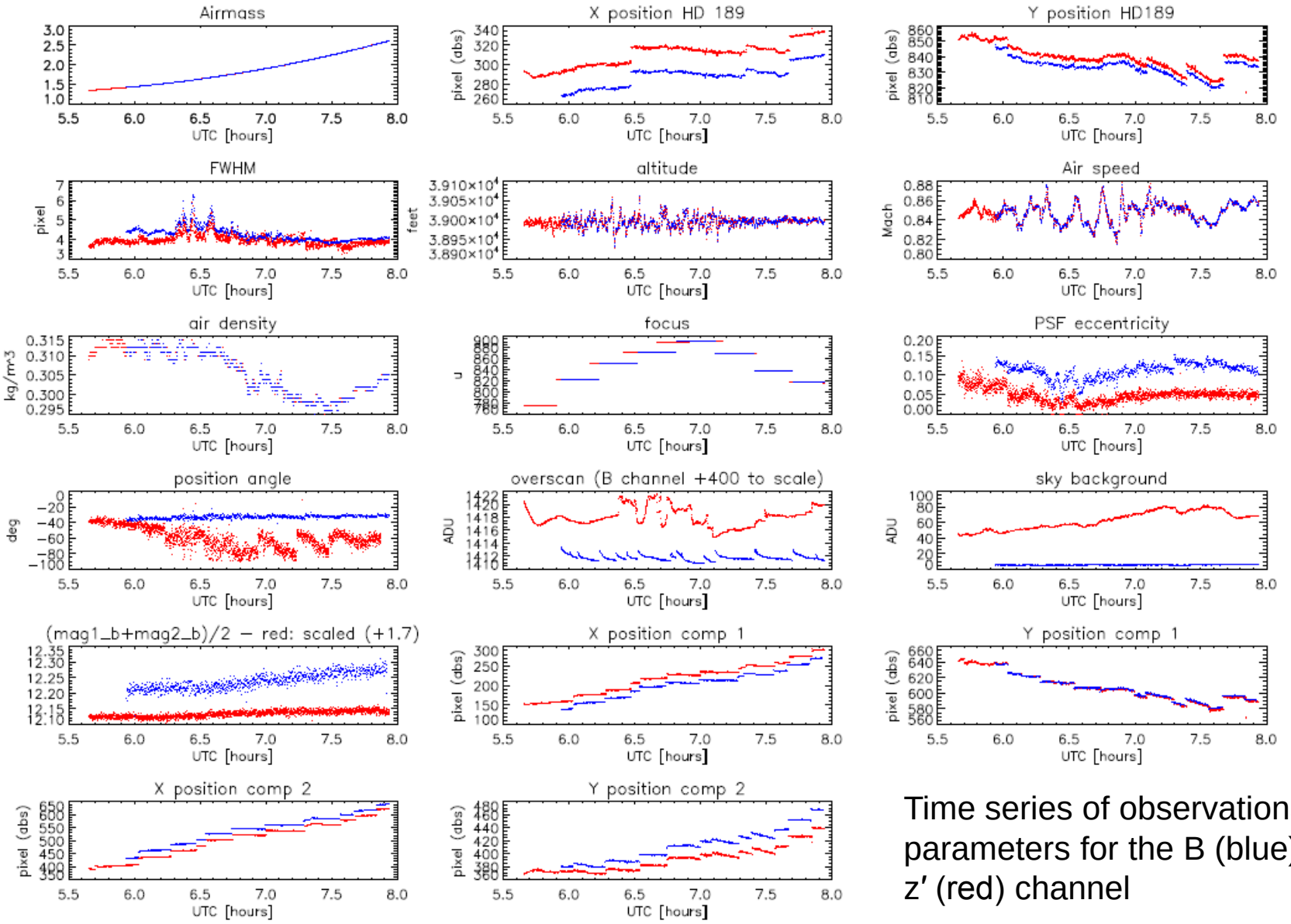
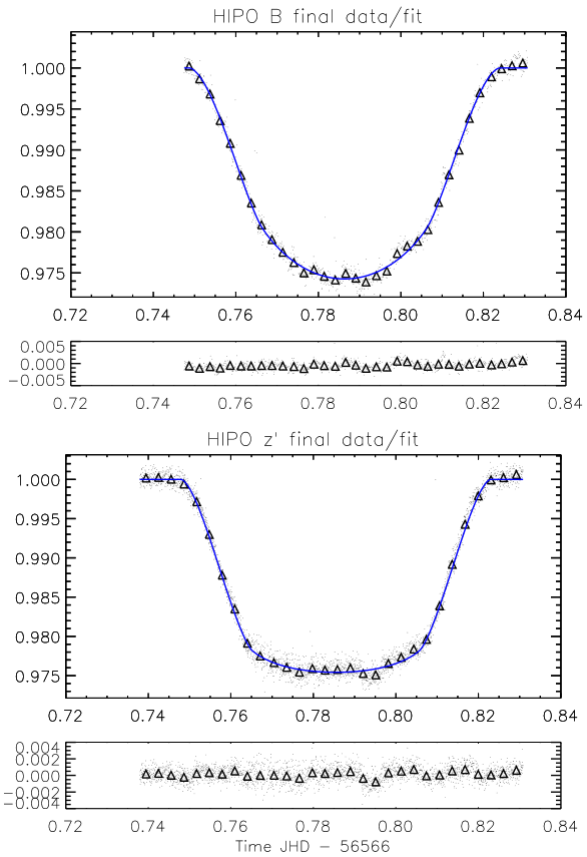
First exoplanet transit observation: HJ HD189733b



Angerhausen et al. 2015

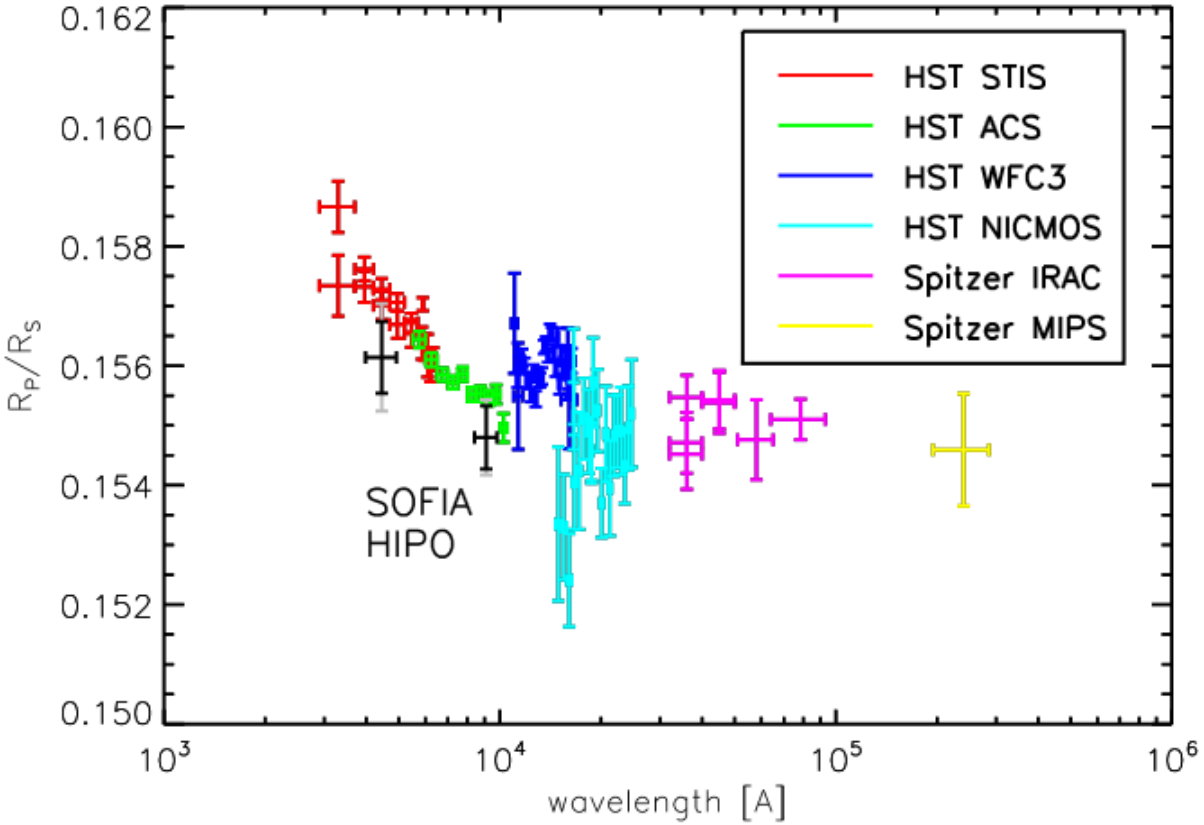
Time series of observational parameters for the B (blue) and z′ (red) channel

First exoplanet transit observation: HJ HD189733b



Final light curve in HIPO B & z'

Transmissionspectrum



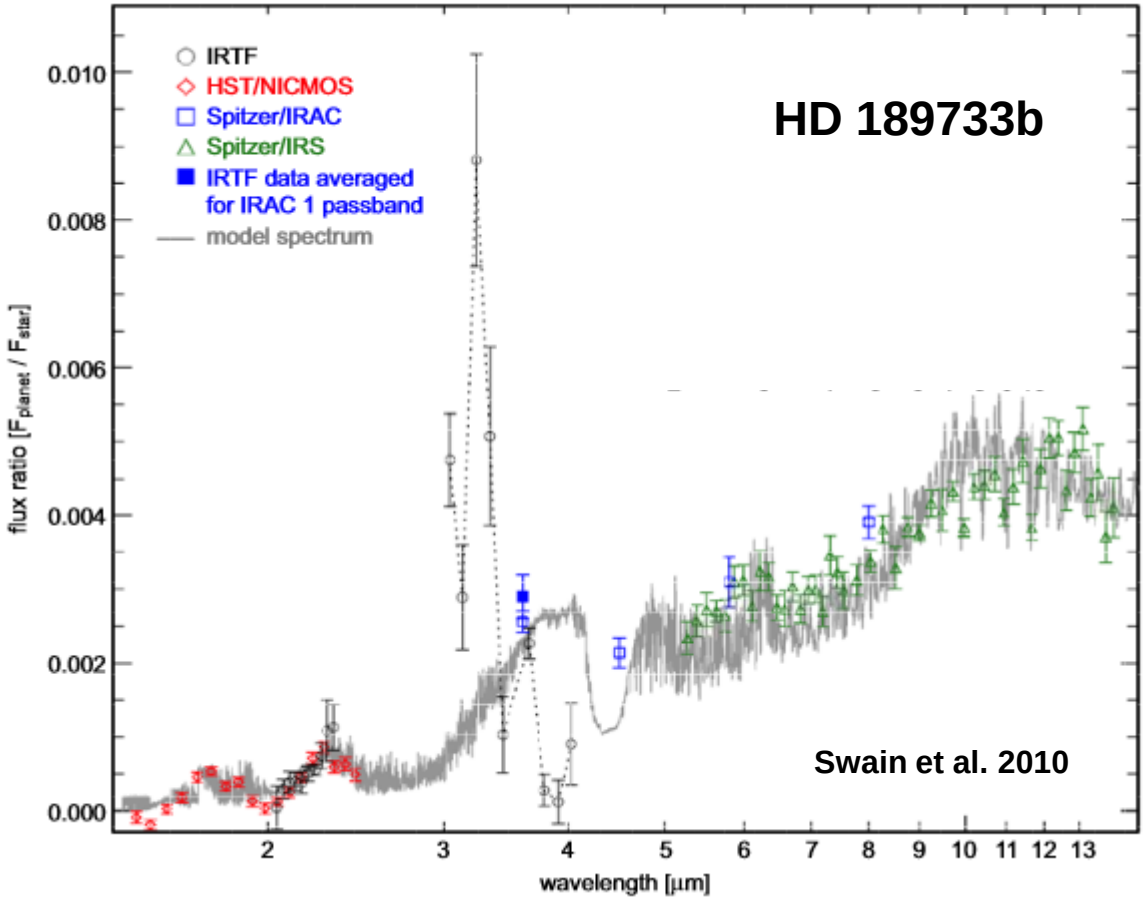
Absolute photometry of a transit of HD 189733b observed by SOFIA/HIPO in the B (445 nm) and z' (905 nm) bands, corrected for extinction, flat field, and correlated noise

Angerhausen et al. 2015

The Origin of non-LTE Emission on Dayside of a hot-Jupiter Exoplanet

- ground-based observations of unexpected strong emission around 3.25 μm
- Non LTE methane CH_4 emission ?
- Take off date Oct. 1, 2015 (PDT)
  PI: Mark Swain, JPL

Emission spectrum



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GJ 1214 - Super Earth or mini-Neptune ?

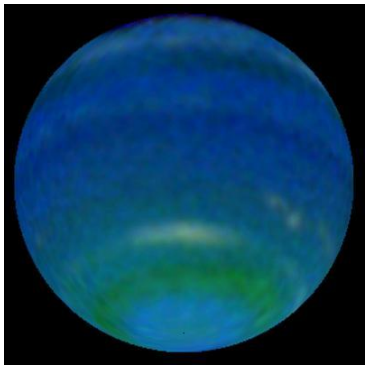
Planet GJ 1214 b

Discovery:	2009 (Charbonneau et al)
Mass (*m*):	6.55 ± 0.98 $M_{\oplus}$
Radius (*r*):	2.678 ± 0.13 $R_{\oplus}$
Dichte (ρ):	1.870 ± 0.400 g cm^{-3}
Period (p):	1.58040456 ± 1.6×10^{-7} d
Transit duration (T):	~ 52 min
Semi major axis (a):	0.01411 au

Host star GJ 1214

Right ascension (α):	$17^{h}\ 15^{m}\ 18.942^{s}$
Declination (δ):	+04° 57′ 49.69″
Magnitude (m_V):	14.71 ± 0.03
Distance (d):	13.0 ± 0.9 pc
Spectral type:	**d**M 4.5
Mass (*m*):	0.157 $M_{\odot}$
Radius (*r*):	$0.2064^{+0.0086}_{-0.0096}$ $R_{\odot}$
Temperature (*T*):	3,026 ± 130 K
Age:	6 Gyr

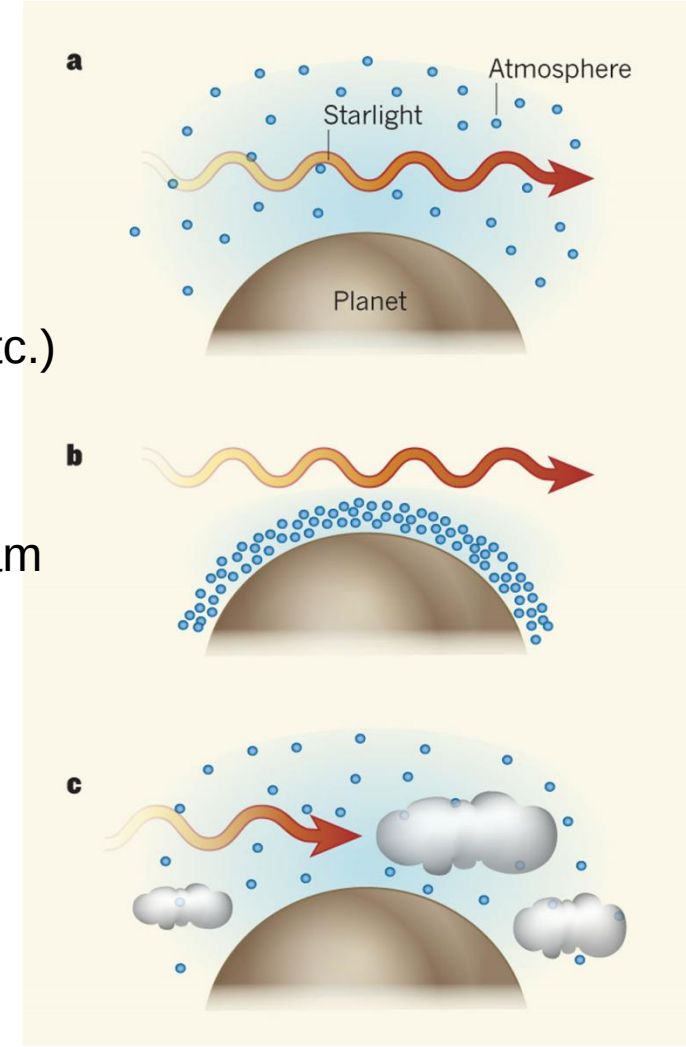
Possible Compositions of GJ 1214b



a. “Mini-Neptune” Scenario:
- Rock / ice interior + hydrogen-dominated atmosphere
- (mostly H_2+ trace H_2O, CH_4, etc.)

b. Water World Scenario:
- Mostly H_2O - ice interior + steam atmosphere

c. Clouds Scenario
- Rock / ice interior + hydrogen-dominated atmosphere
- Clouds



(Rogers & Seager, 2010; Nettelmann et al. 2011)

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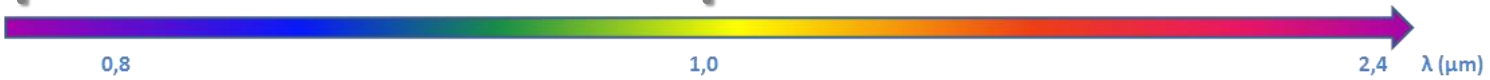
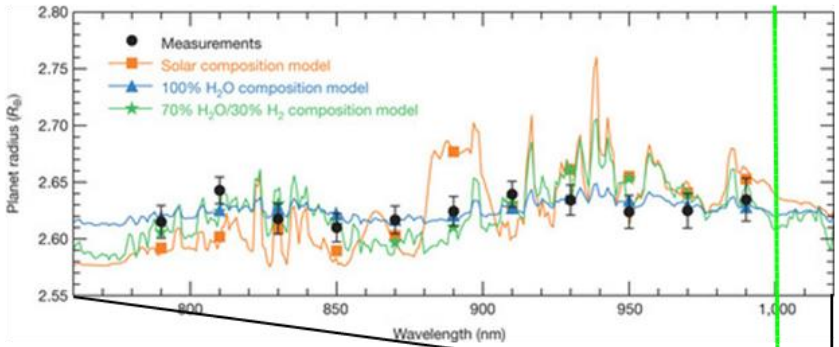
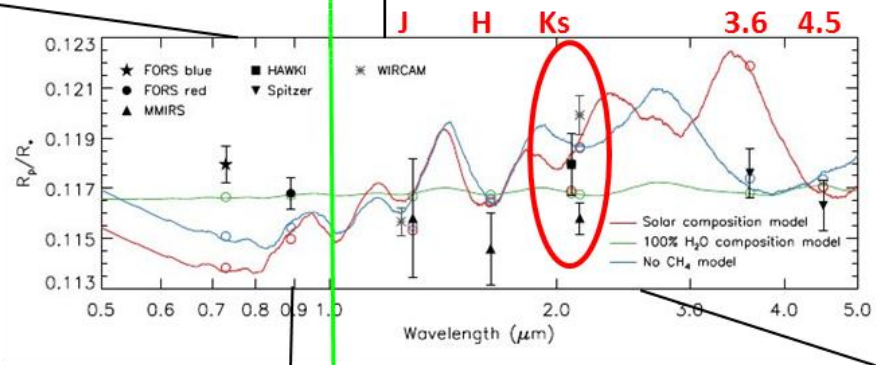
Determining the composition of GJ1214b's atmosphere: Super-Earth or Mini-Neptune



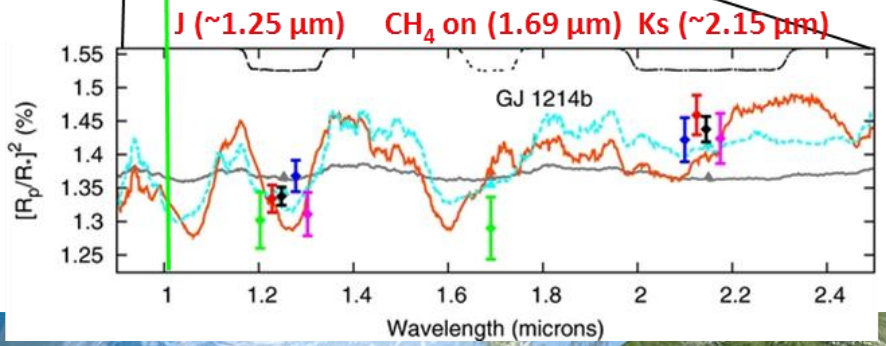


Bean et al. 2010
(VLT/FORS2)



Bean et al. 2011
(VLT/FORS)
(MMIRS)

Miller-Ricci Kempton et al. 2011,
Crossfield et al. 2011 (KECK)



Croll et al. 2011
(CFHT/ WIRCam)

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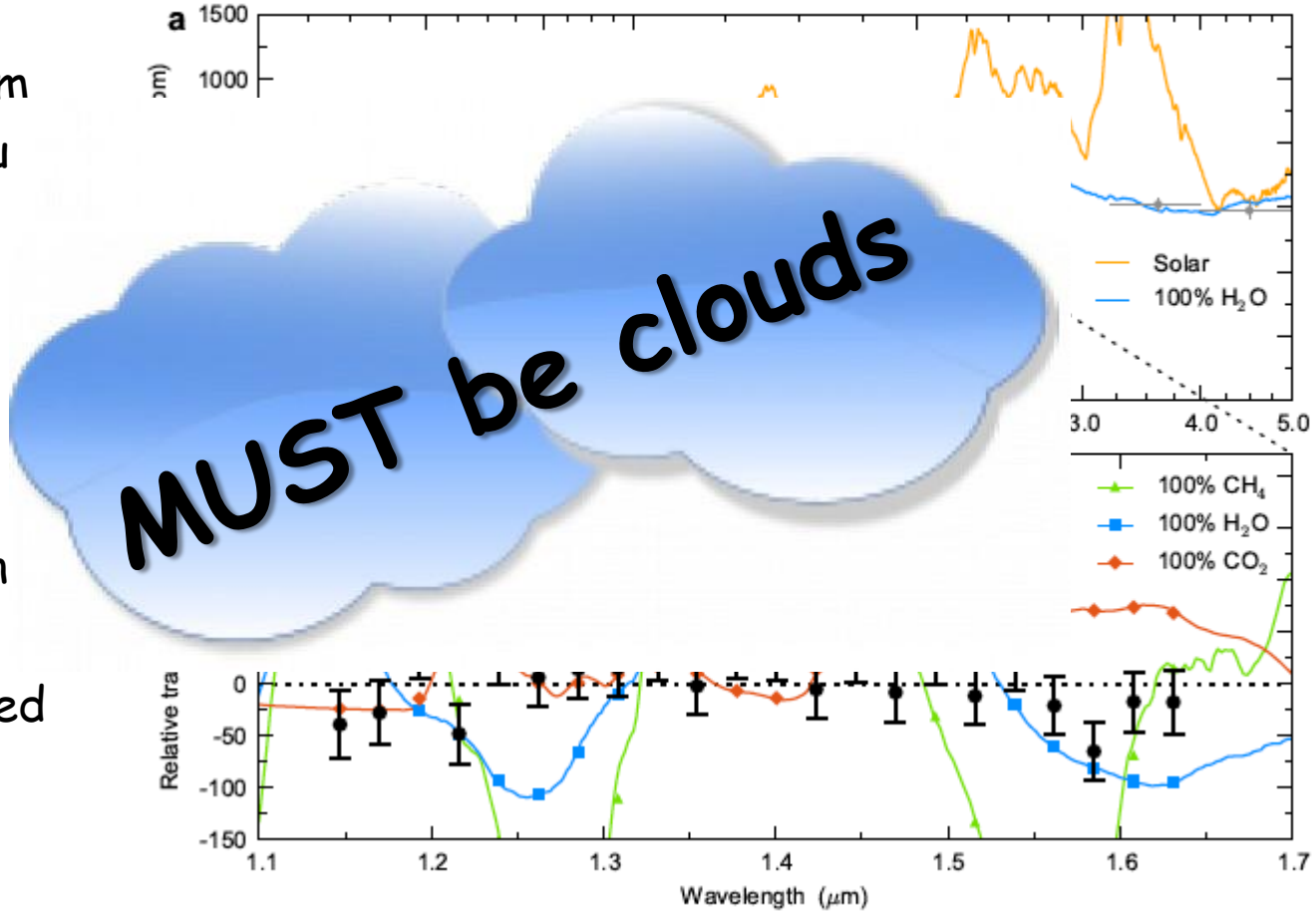
Determining the composition of GJ1214b's atmosphere: Super-Earth or Mini-Neptune

- Featureless spectrum
  → high-mean molecu weight atmosphere clouds

- Different high-mean molecular weight atmospheres are ruled out



Kreidberg et al.2014, WFC3@HST

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GJ 1214b – Super-Earth or Mini-Neptune?

Optical & NIR spectro-photometry with FLIPO

HIPO

Blue: 0.3-0.6 µm

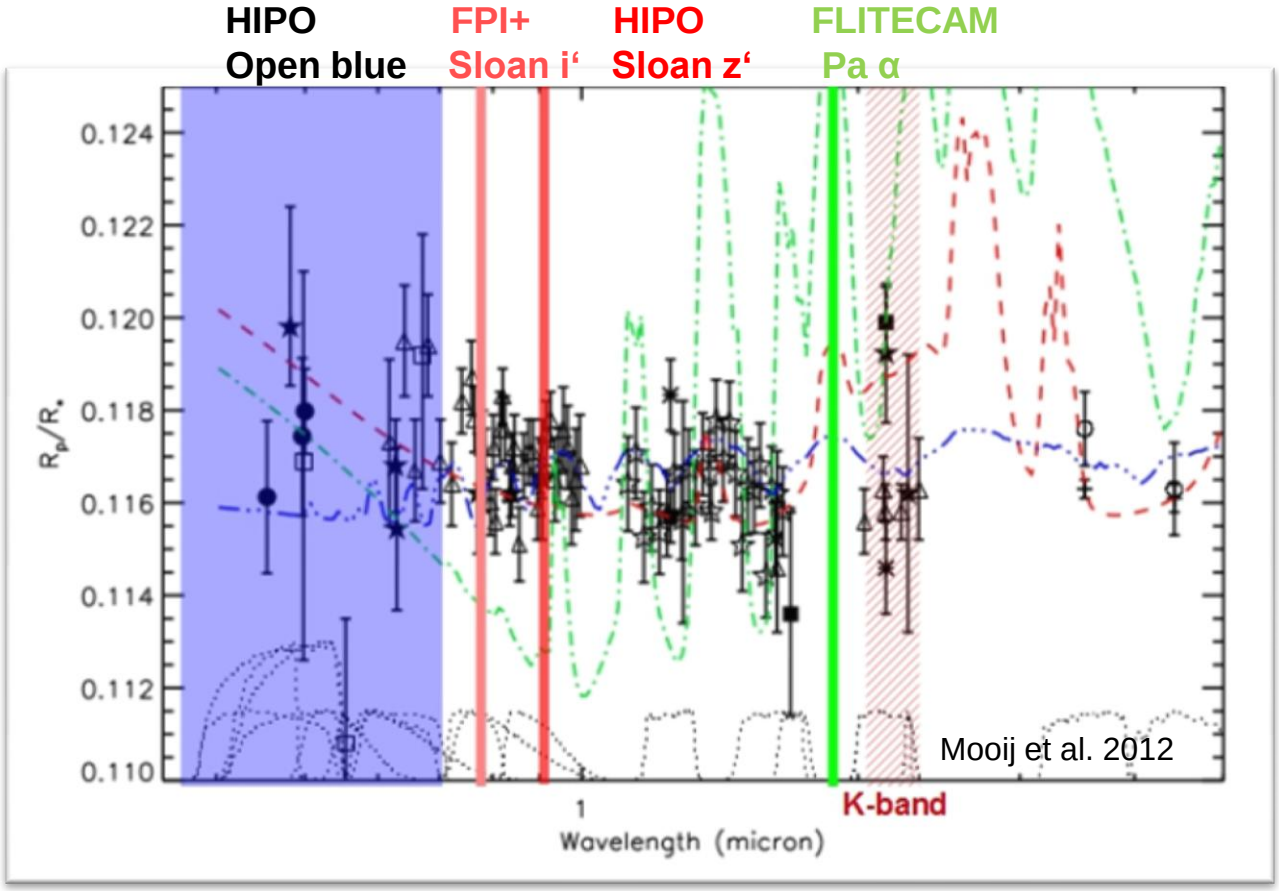
z': 0.9 µm

FPIplus

i': 0.8 µm

FLITECAM

Pa α cont: 1.9 µm



SOFIA: crucial wavelength region not observable from the ground: FLITECAM *Paschen a cont* 1.90 µm close to Ks band where contradictory data was obtained

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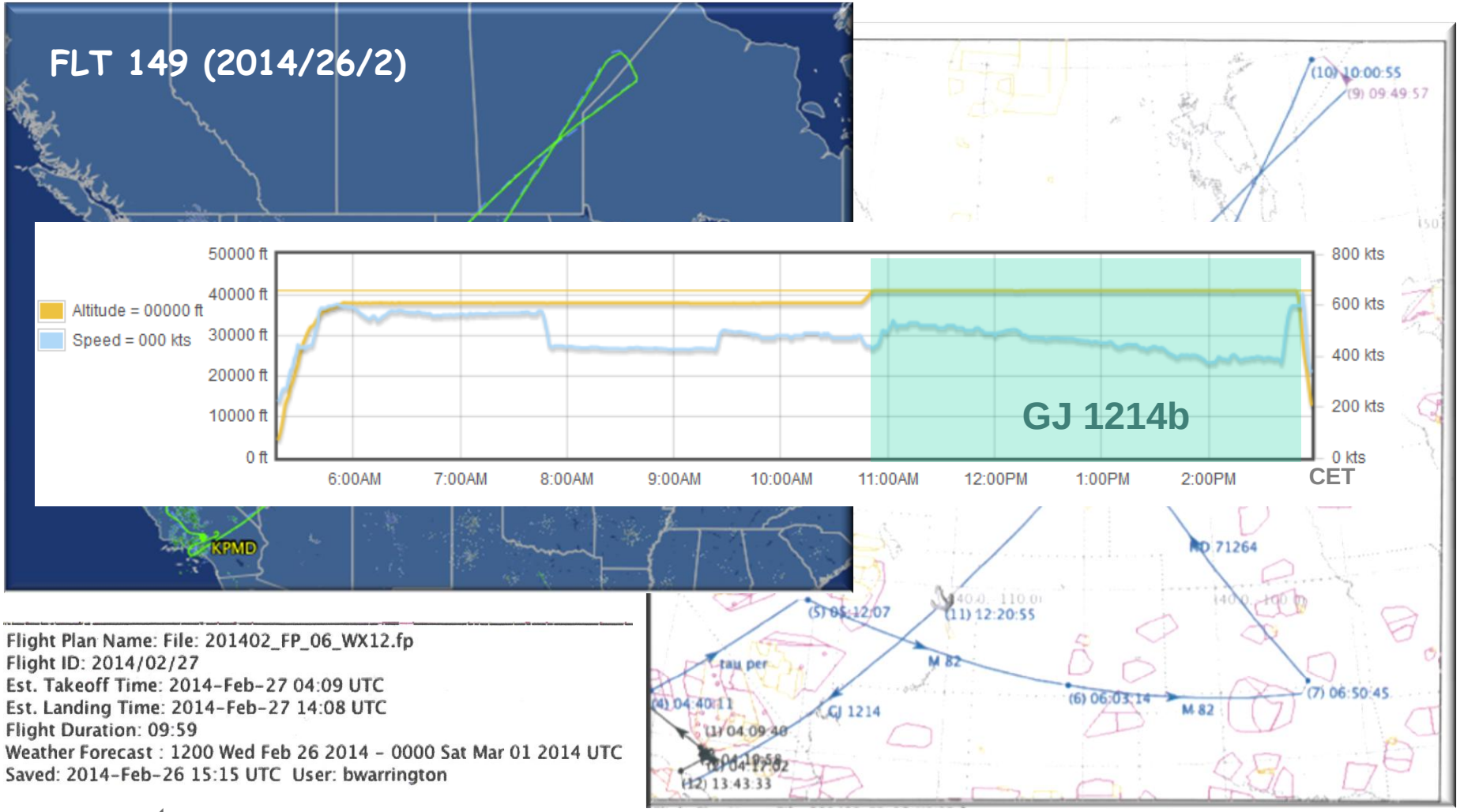
GJ 1214b – Super-Earth or Mini-Neptune?

Stratospheric Observatory For Infrared Astronomy



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Flight ID: 2014/02/27
Est. Takeoff Time: 2014-Feb-27 04:09 UTC
Est. Landing Time: 2014-Feb-27 14:08 UTC
Flight Duration: 09:59
Weather Forecast : 1200 Wed Feb 26 2014 - 0000 Sat Mar 01 2014 UTC
Saved: 2014-Feb-26 15:15 UTC User: bwarrington

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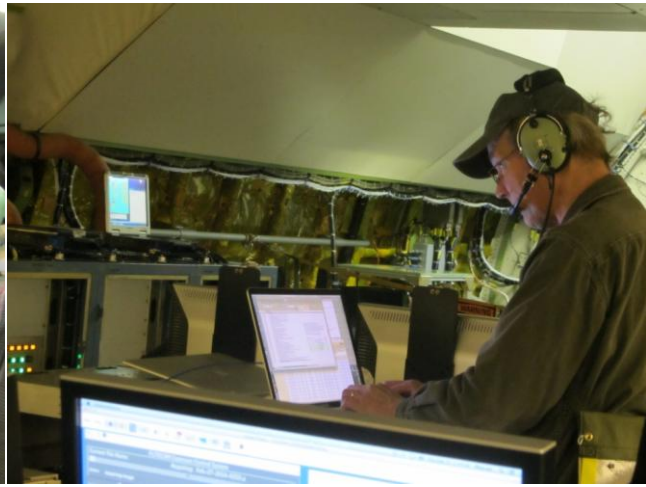
FLT 149 (2/26/14) - People@work

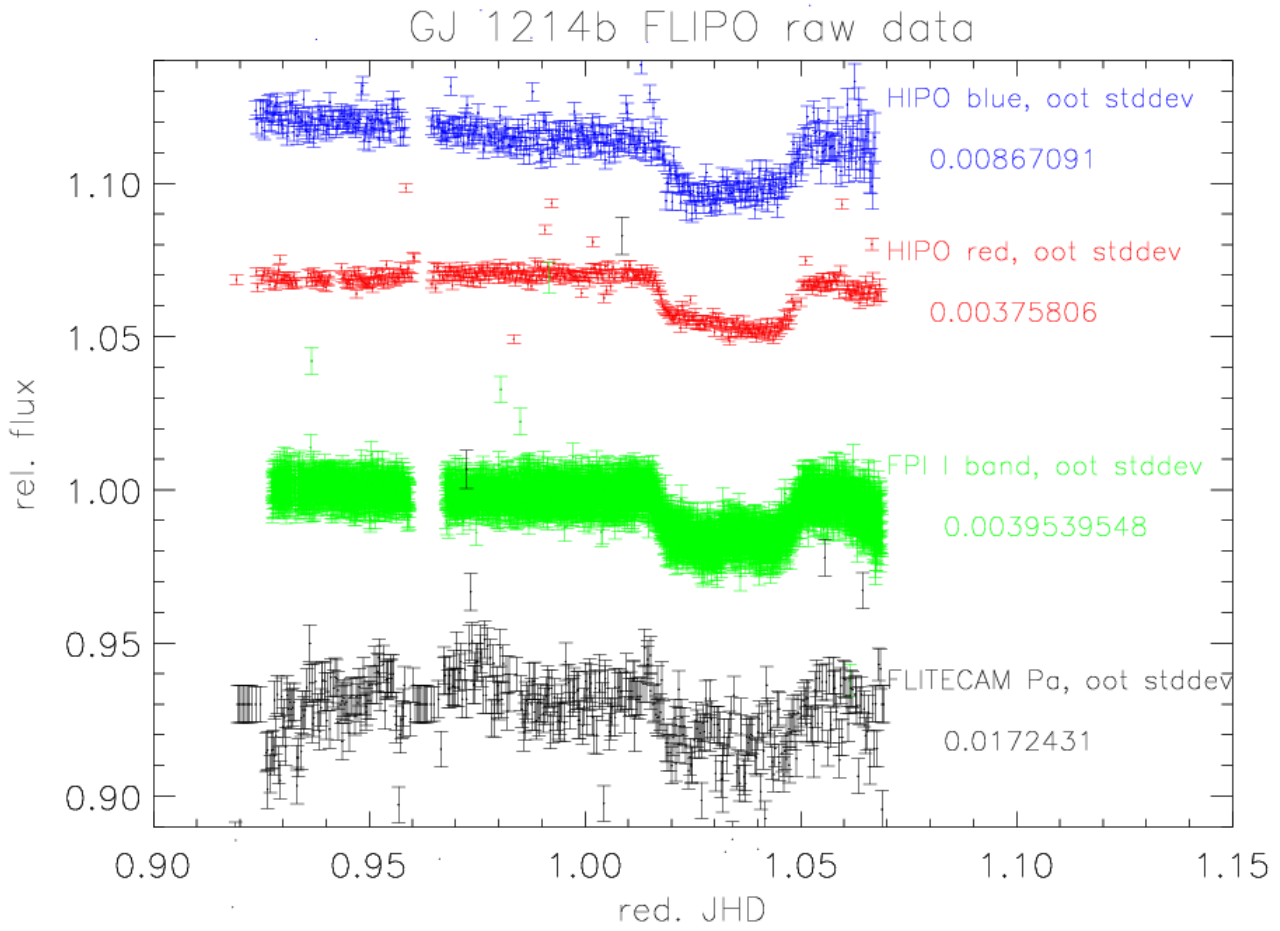
SOFIA
Stratospheric Observatory For Infrared Astronomy



GJ 1214 b raw data

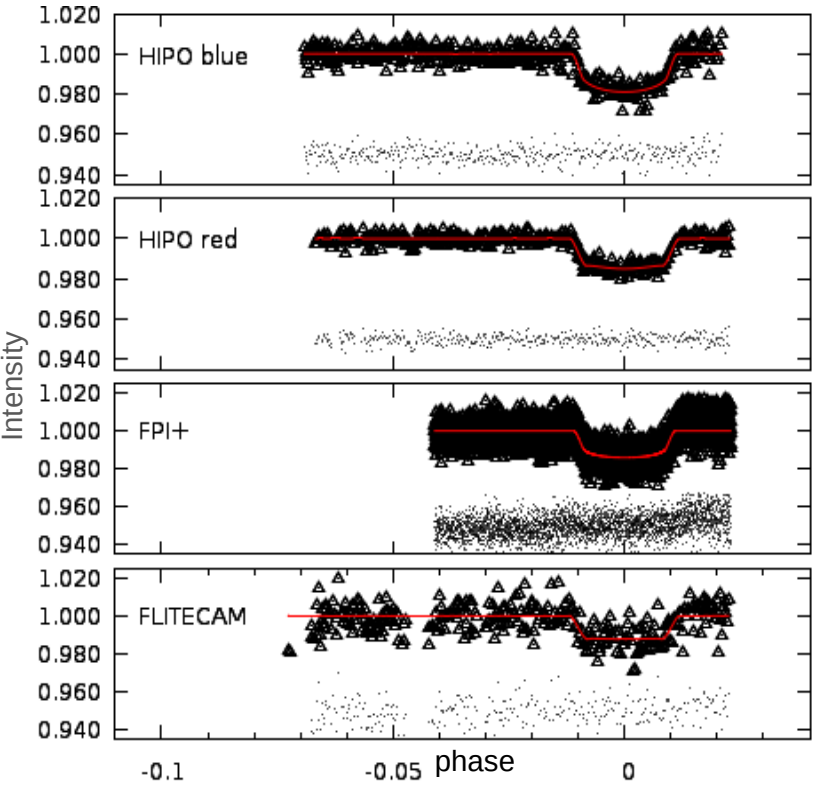
FLT 149 (2/26/14)

Final data set consists of about ~4500 measurements of 25 sec integrations in HIPO blue, HIPO red, FLITECAM and 2.5 sec integrations in FPI+



GJ 1214b – Super-Earth or Mini-Neptune? Preliminary results

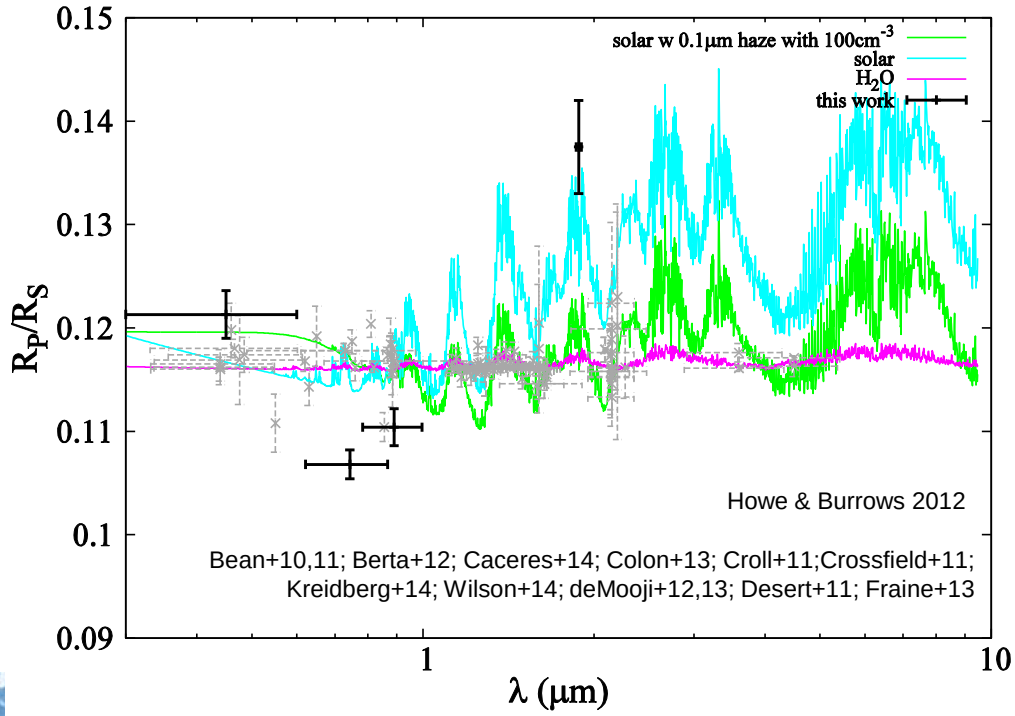
SOFIA
Stratospheric Observatory For Infrared Astronomy



Light curves

Fit results

Parameter	HIPO Blue	HIP Red	FPI	FLITECam
P (d)	**1.58040482**	**1.58040482**	**1.58040482**	**1.58040482**
T_{14} (P)	0.02287±0.0006	0.02317±0.00045	0.02188±0.00038	0.0235±0.0011
Rp/R*	0.1234±0.0042	0.1199±0.0023	0.1083±0.0025	0.1122±0.0037
b (R*)	0.05±0.20	0.05±0.17	0.08±0.17	0.62±0.12
u+	0.63±0.35	0.54±0.31	0.64±0.24	-0.14±048
u-	0.49±0.85	0.58±0.65	0.04±0.63	1.42±0.91
a/R*	16.62	15.42	16.06	12.48



Transmission spectrum

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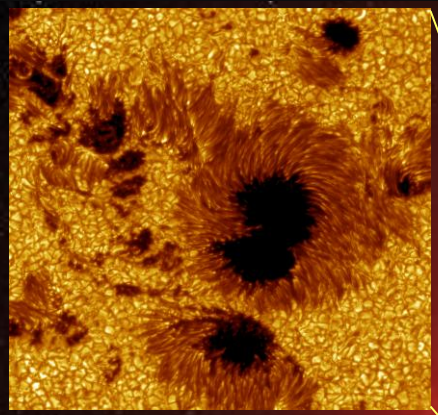
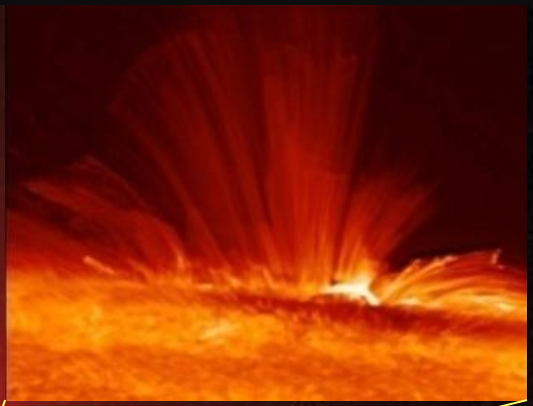
Long-term monitoring of GJ1214s stellar variability

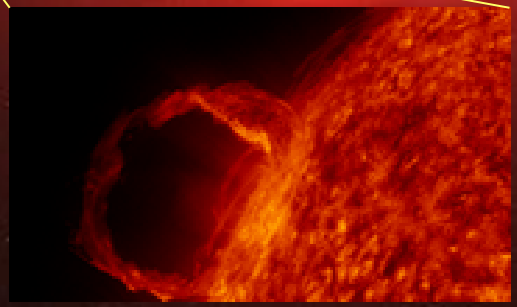


spots

rotation



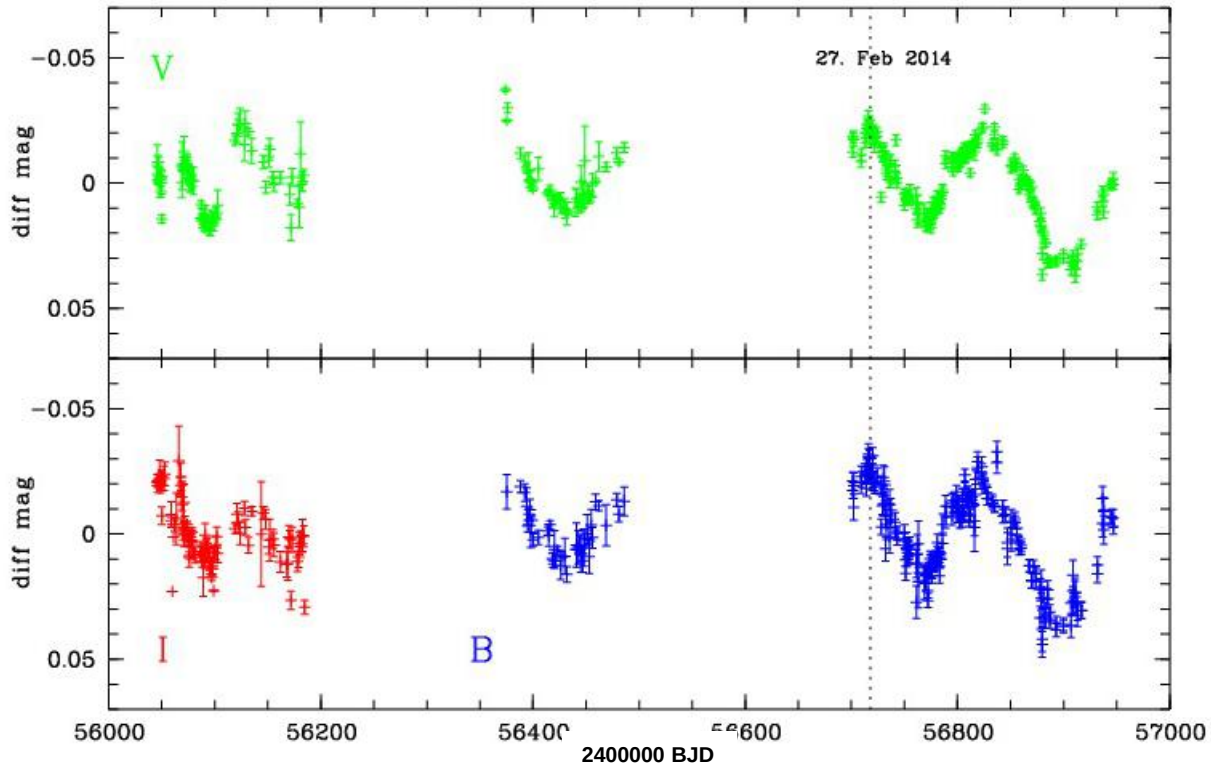
flares



loops

Long term monitoring of GJ 1214: stellar variability

- active star with period of ~80 days (Charbonneau+ ‘09),
  ~44 days (Narita+ ’13); ~120 days tbc (this work)
- stellar spots may mimic Rayleigh slope (Oshagh+ ’14)



M. Mallonn

DLR

Warm Uranus GJ 3470 b

Host star GJ 3470

Right ascension (α):	$07^h\ 59^m\ 06.0^s$
Declination (δ):	+15° 23′ 30″
Magnitude (m_V):	12.27
Distance (d):	30.7 ($^{+1.7}_{-2.1}$) pc
Spectral type:	dM 1.5
Mass (m):	0.539 (± 0.047) $M_\odot$
Radius (r):	0.568 (± 0.037) $R_\odot$
Temperature (T):	3600.0 (± 100.0) K
Age:	1.0 ($^{+0.7}_{-0.7}$) Gyr

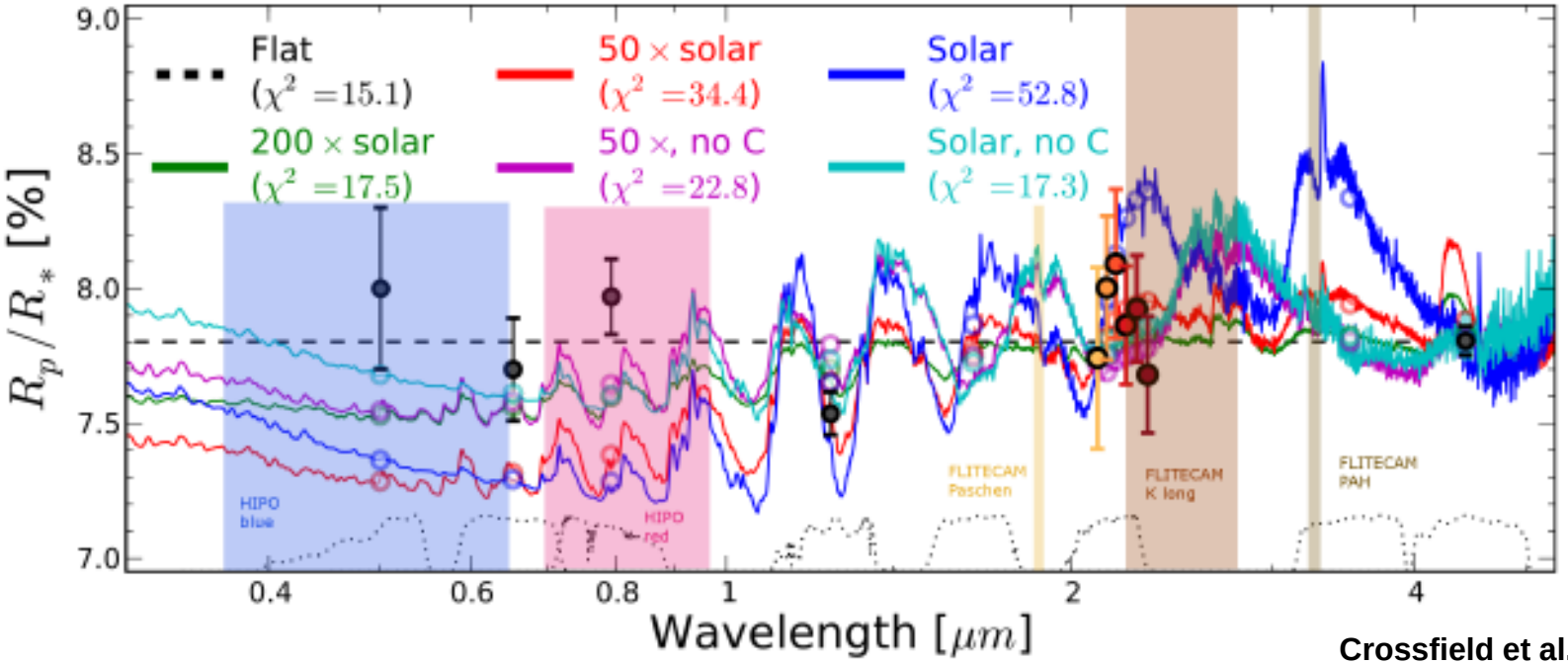
Planet GJ 3470 b

Discovery:	2012 (Bonfiles et al.)
Mass (m):	0.044 (± 0.005) M_J
Radius (r):	0.37 (± 0.05) R_J
Dichte (ρ):	1.07 (± 0.43) g cm^{-3}
Period (p):	3.33671 (± 5e-05) day
Transit duration (T):	~ 113 min
Semi major axis (a):	0.03557 (± 0.001) AU

Transmission spectrum of GJ 3470b

No detection of atmospheric features in the atmospheres (cf. GJ 1214b)

→ Determine its atmospheric structure and composition



Crossfield et al. 2013

- 3 optical channels (HIPO's red, blue filters and additional channel from FPI+)
- 1 infrared channel (FLITECAM 'Paschen alpha cont' filter)

Observation of the primary transit of GJ 3470b

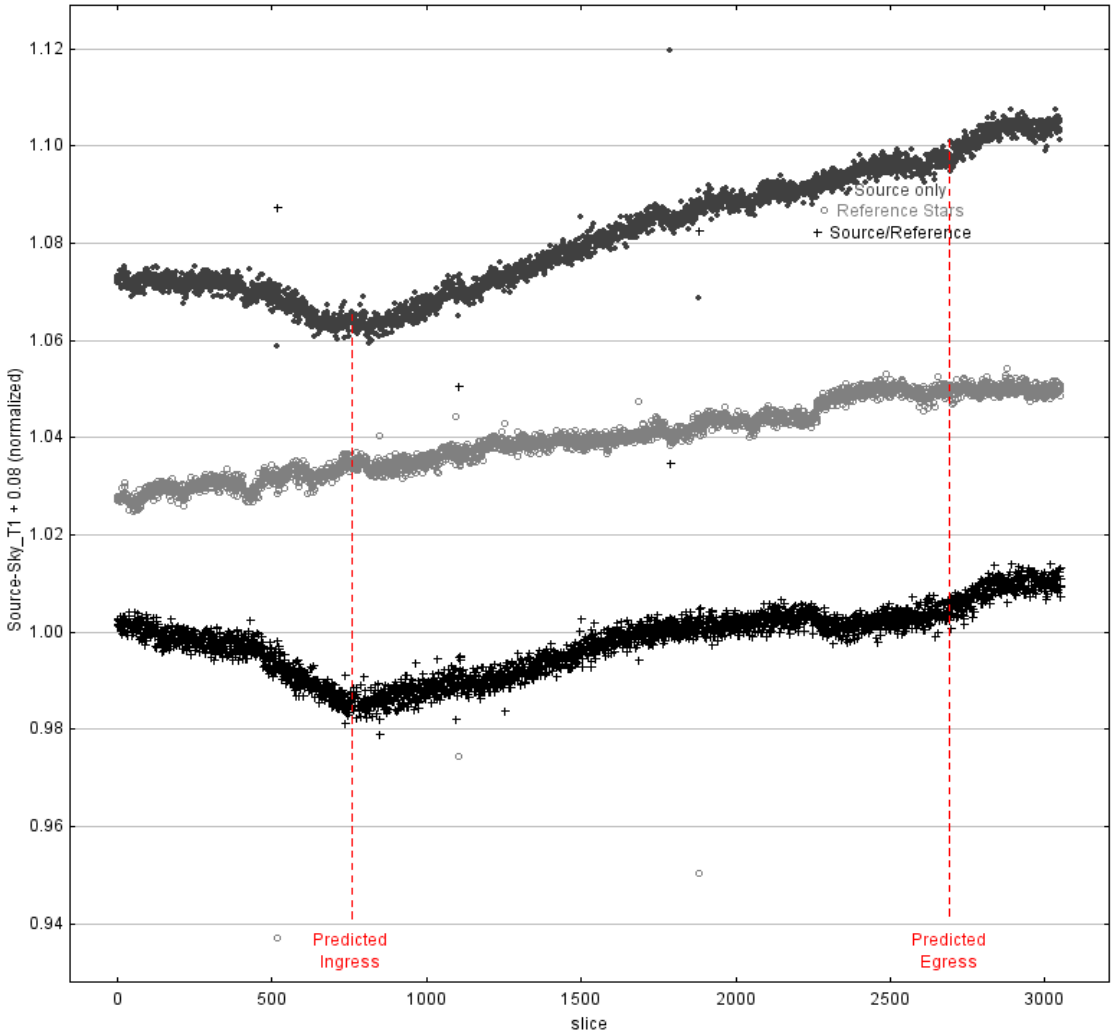
Take off date: 2015/09/29

FPI+ GJ3470b light curve

Top:
signal of the target only

Middle:
signal of the reference star

Bottom:
differential between target and reference star



Do starspots inflate the exoplanet CoRoT-2b ?

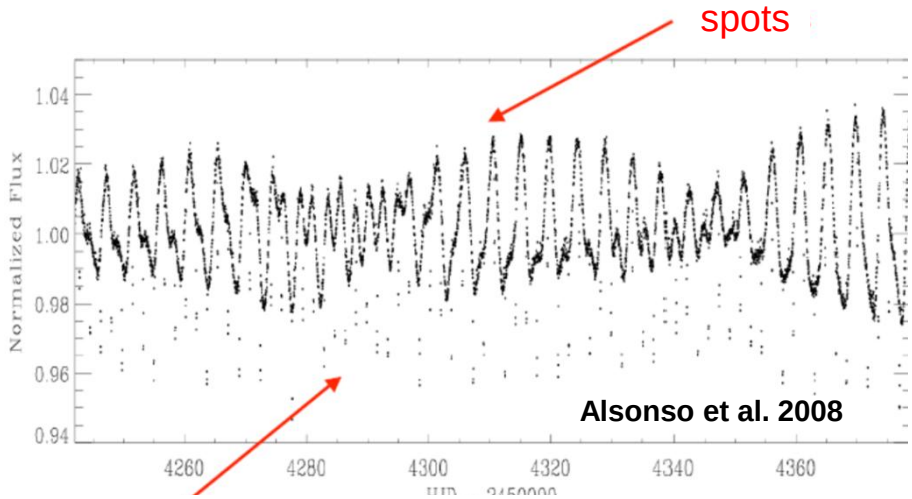
Host star CoRoT 2

Right ascension (α):	$19^h\ 27^m\ 07.0^s$
Declination (δ):	+01° 23′ 03″
Magnitude (m_V):	12.57
Distance (d):	300.0 (± 100.0) pc
Spectral type:	G7V
Mass (m):	0.97 (± 0.06) $M_\odot$
Radius (r):	0.902 (± 0.018) $R_\odot$
Temperature (T):	5575.0 (± 66.0) K
Age:	--

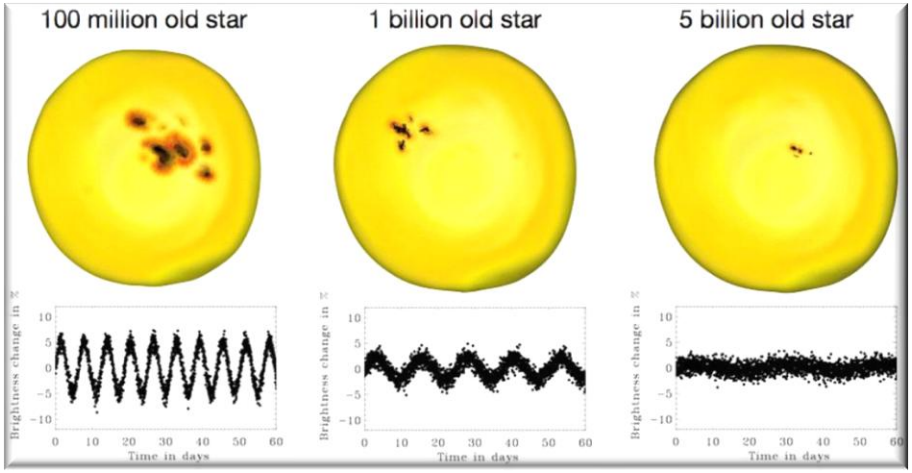
Planet CoRoT 2b

Discovery:	2007 (Alonso et al.)
Mass (m):	3.31 (± 0.16) M_J
Radius (r):	1.465 (± 0.029) R_J
Dichte (ρ):	1,310 (± 0,040) g cm^{-3}
Period (p):	1.7429964 (± 1.7e-06) day
Transit duration (T):	~ 125 min
Semi major axis (a):	0.0281 (± 0.0009) au

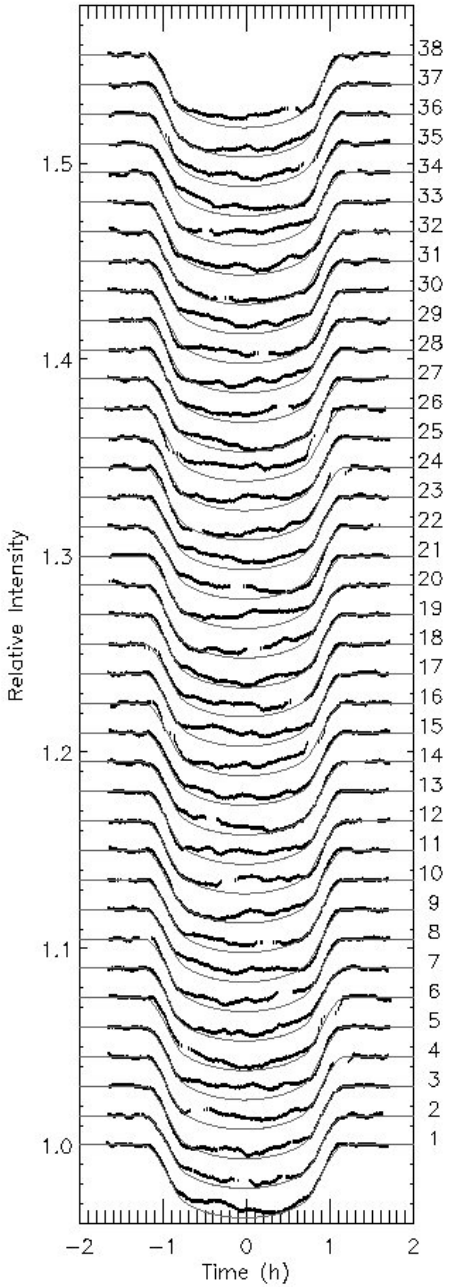
Do starspots inflate the exoplanet CoRoT-2b ?



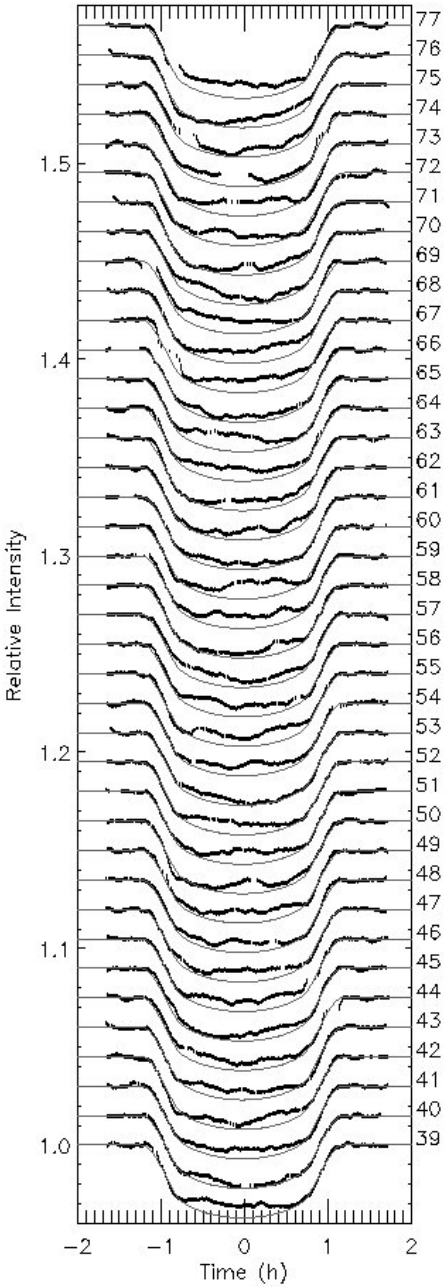
77 transits (134d); P = 1.743 d



older stars rotate slowly & have fewer and smaller spots



Silva-Valio et al. 2010



DLR

A time line of exoplanet characterization

K2

HARPS

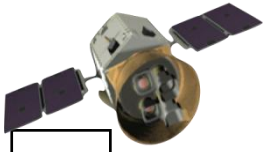
HARPS-N

HIRES

SOPHIE

NGTS

Mearth-S



TESS

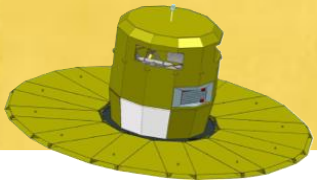
JWST

PLATO 2.0
2024

Now - 2015

2017

2020

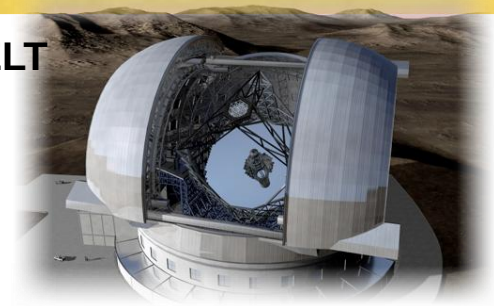


GAIA

"Warm" Spitzer

HST

CHEOPS



E-ELT

M4
Spectroscopy
mission?

ARIEL

New IR spectrographs

2017-2020

Thank you for your attention !

Have a safe flight