# Overview of Exoplanet Atmospheres and Detection Highlights

## Sagan Workshop 2009

Sara Seager

MIT

# Overview

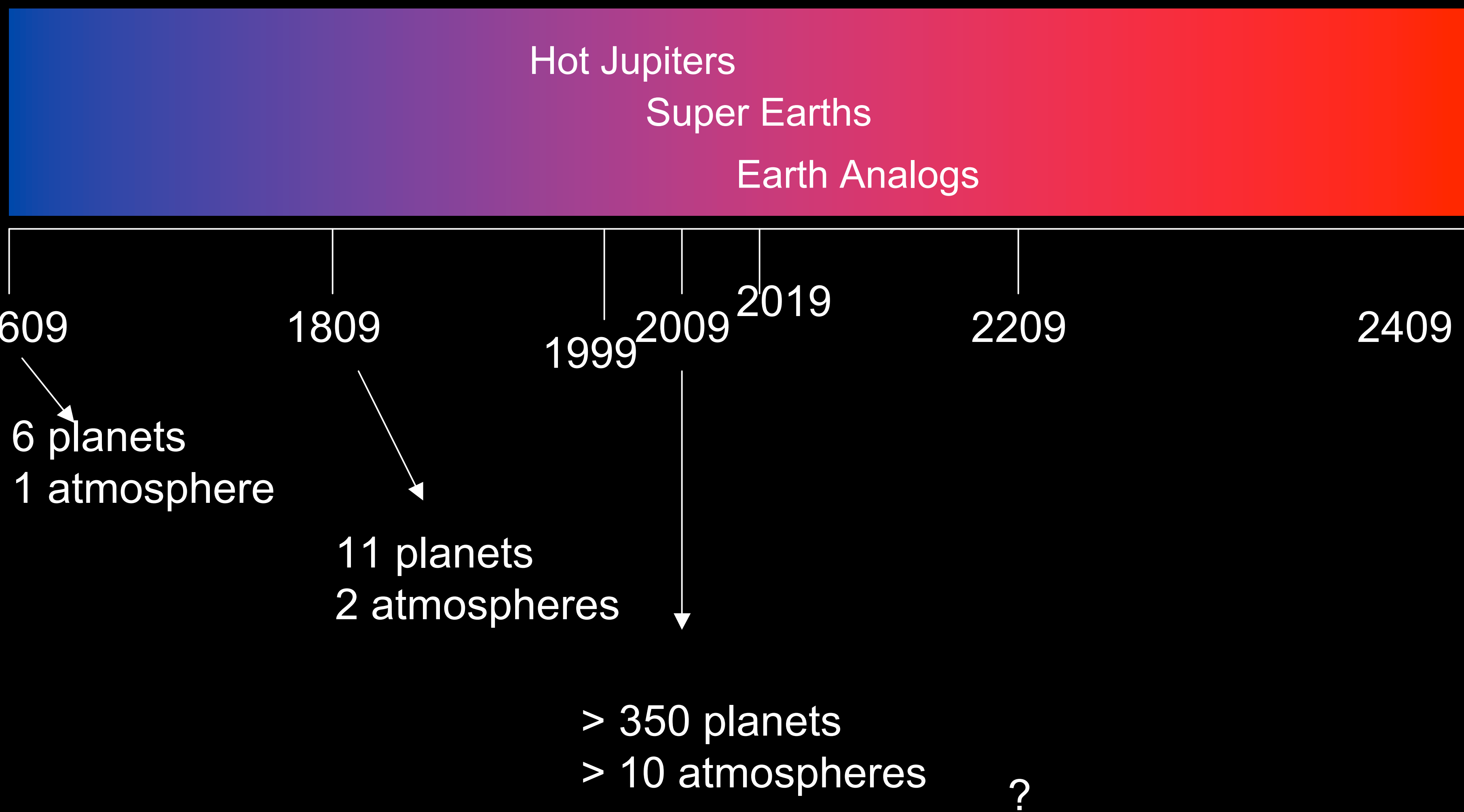
Introduction

Atmospheres 101

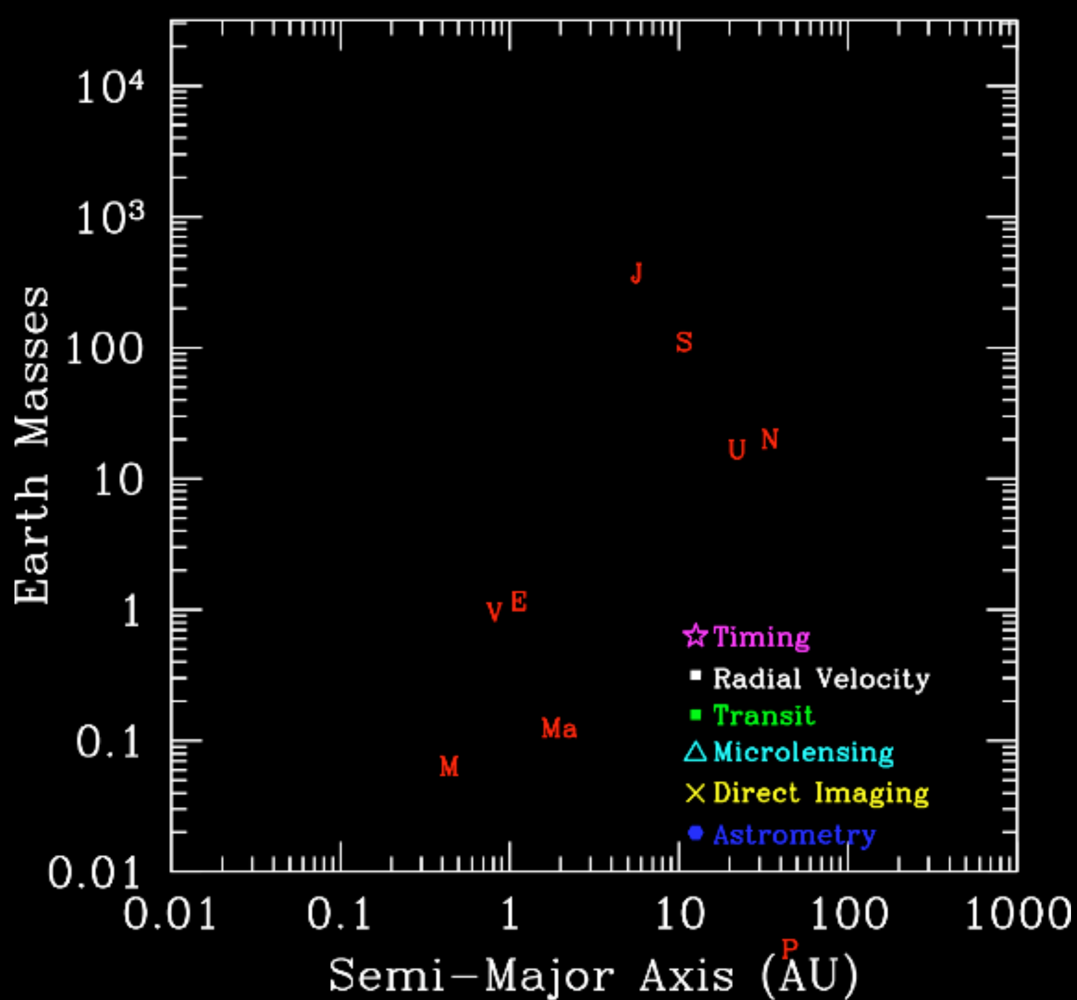
Detection Highlights

Prospects

# International Year of Astronomy

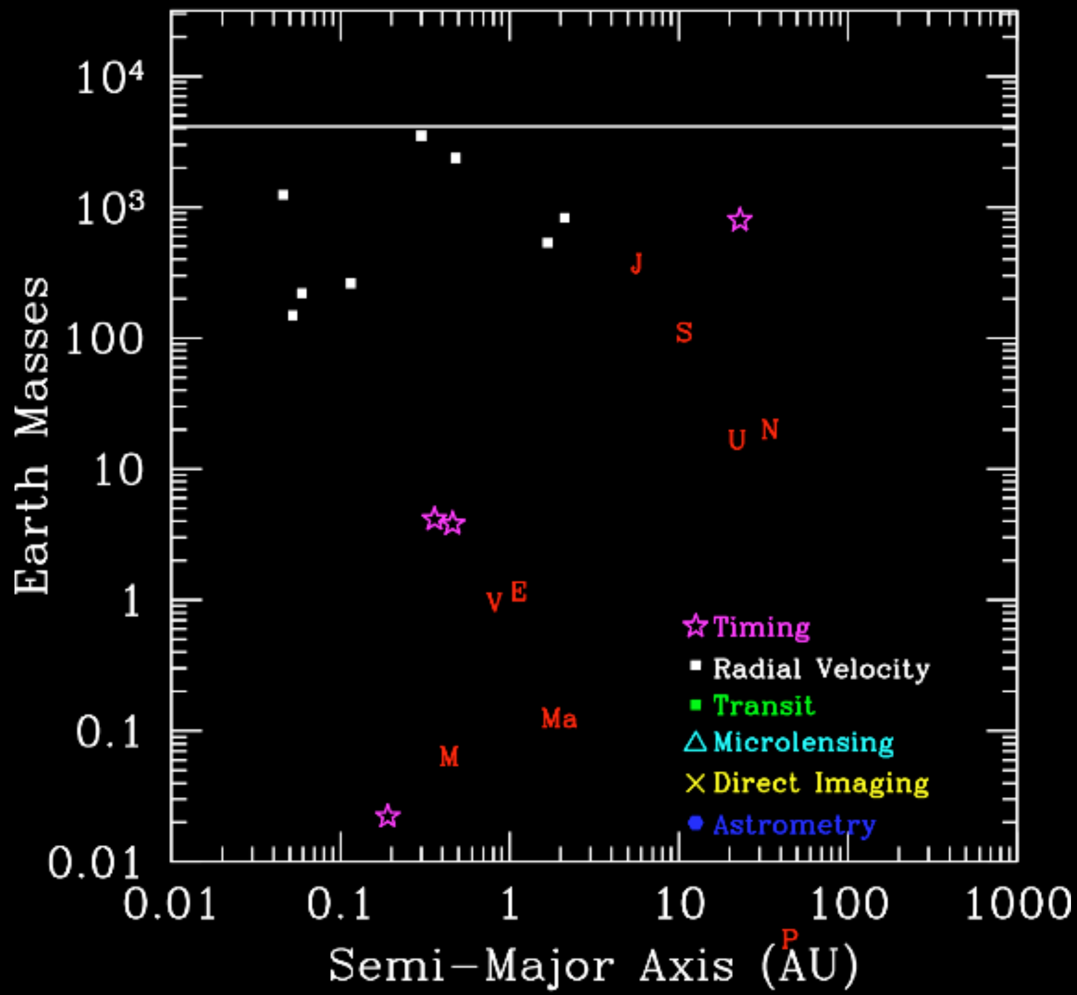


# Known Planets 1985



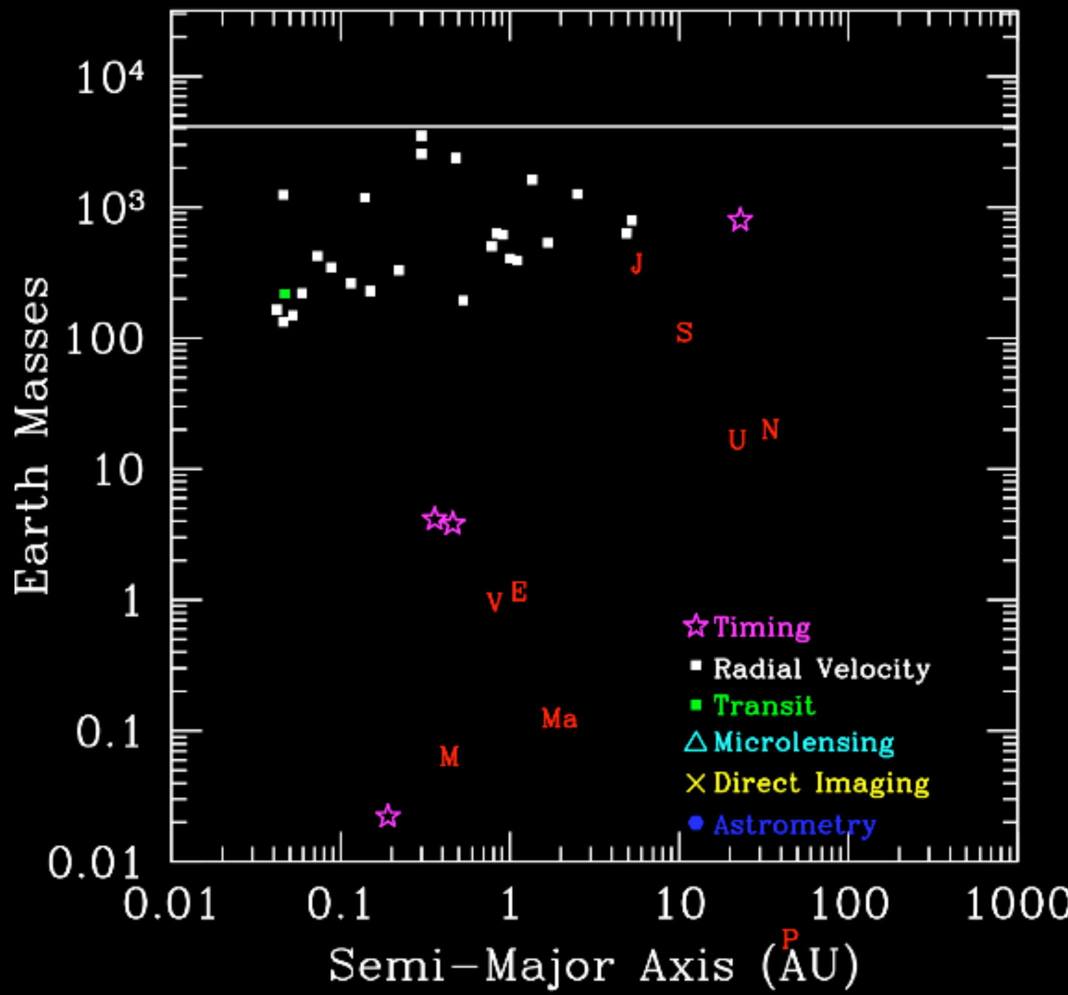

Based on data compiled by J. Schneider

# Known Planets 1995



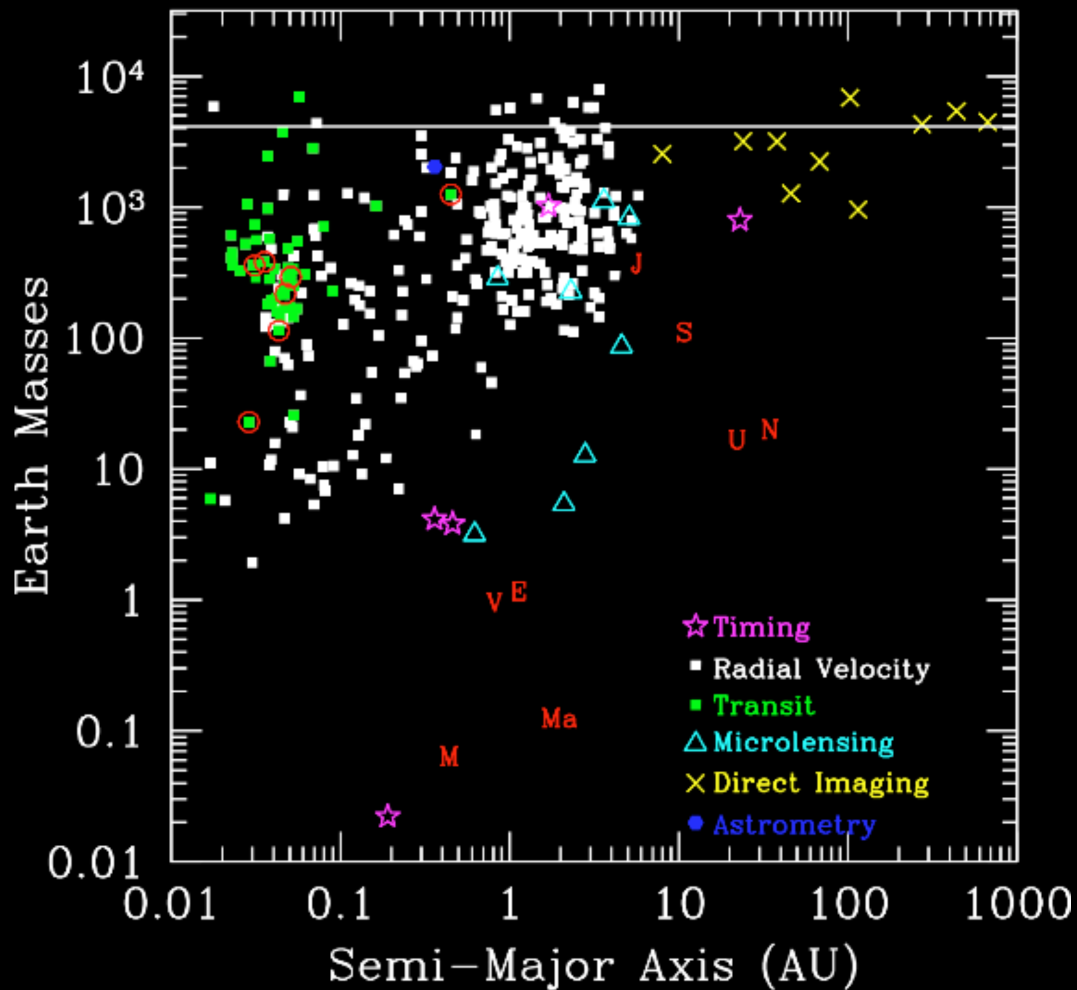

Based on data compiled by J. Schneider

# Known Planets 1999




Based on data compiled by J. Schneider

# Known Planets 2009




Based on data compiled by J. Schneider

# Overview

Introduction

Atmospheres 101

Detection Highlights

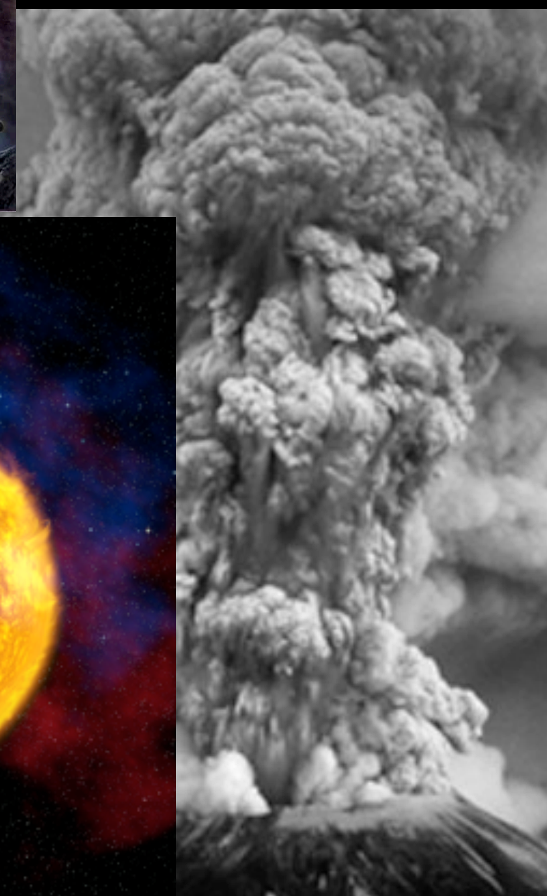
Prospects

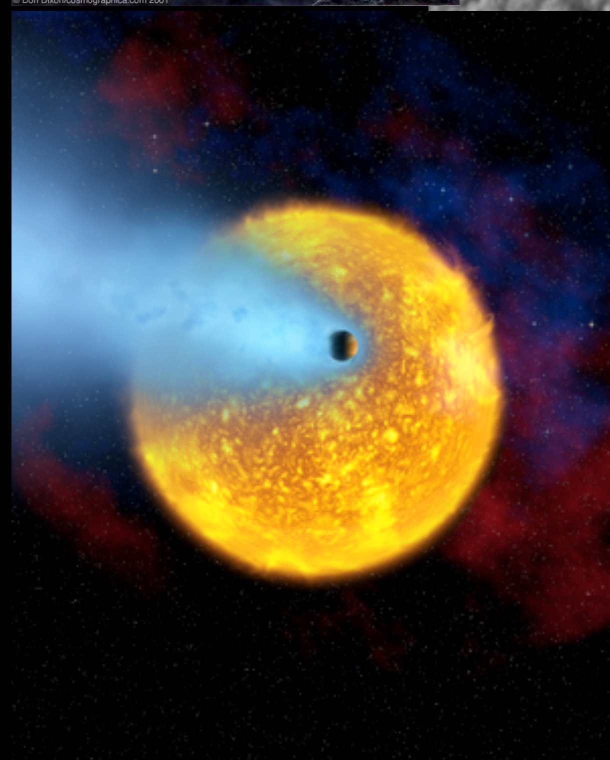
# Where do Atmospheres Originate?


http://abyss.uoregon.edu/~js/ast121/lectures/lec14.html

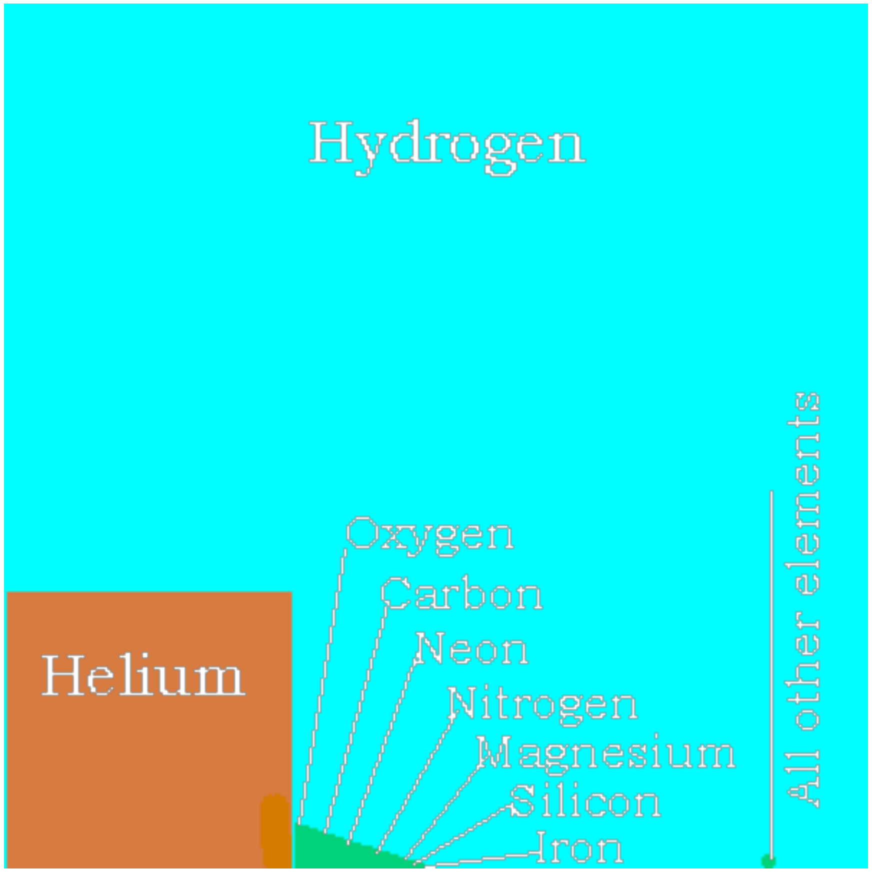
# Atmosphere = Sources vs. Sinks

- Sources
  - Giant planet
    - Gravitational capture of solar nebula gases (expect ratios in approx. solar proportions)
  - Terrestrial planet
    - Outgassing during/after accreting rocky planetesmials
- Sinks
  - Giant planet
    - None. Retain all primordial gases
  - Terrestrial planets:
    - Atmospheric escape
    - Sequester in oceans
    - Gas/surface interactions

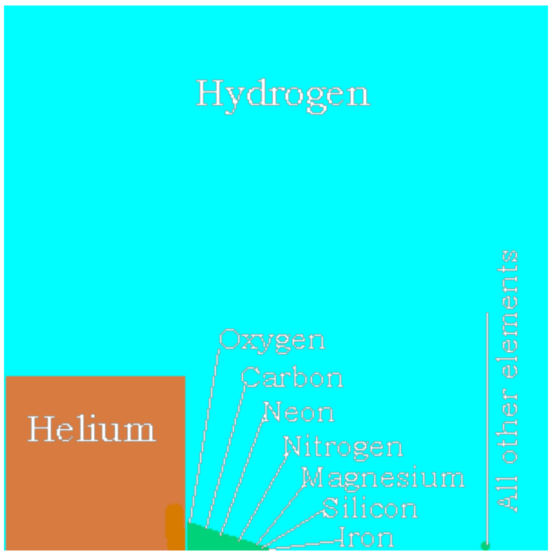



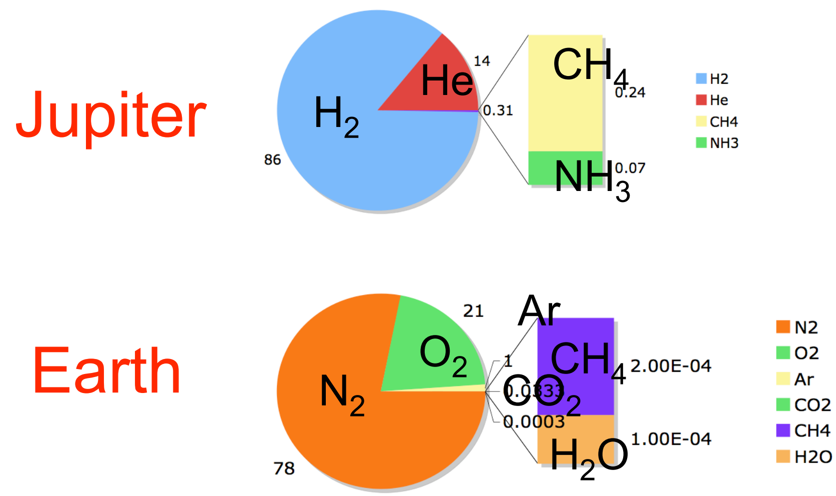


# Atmospheric Composition



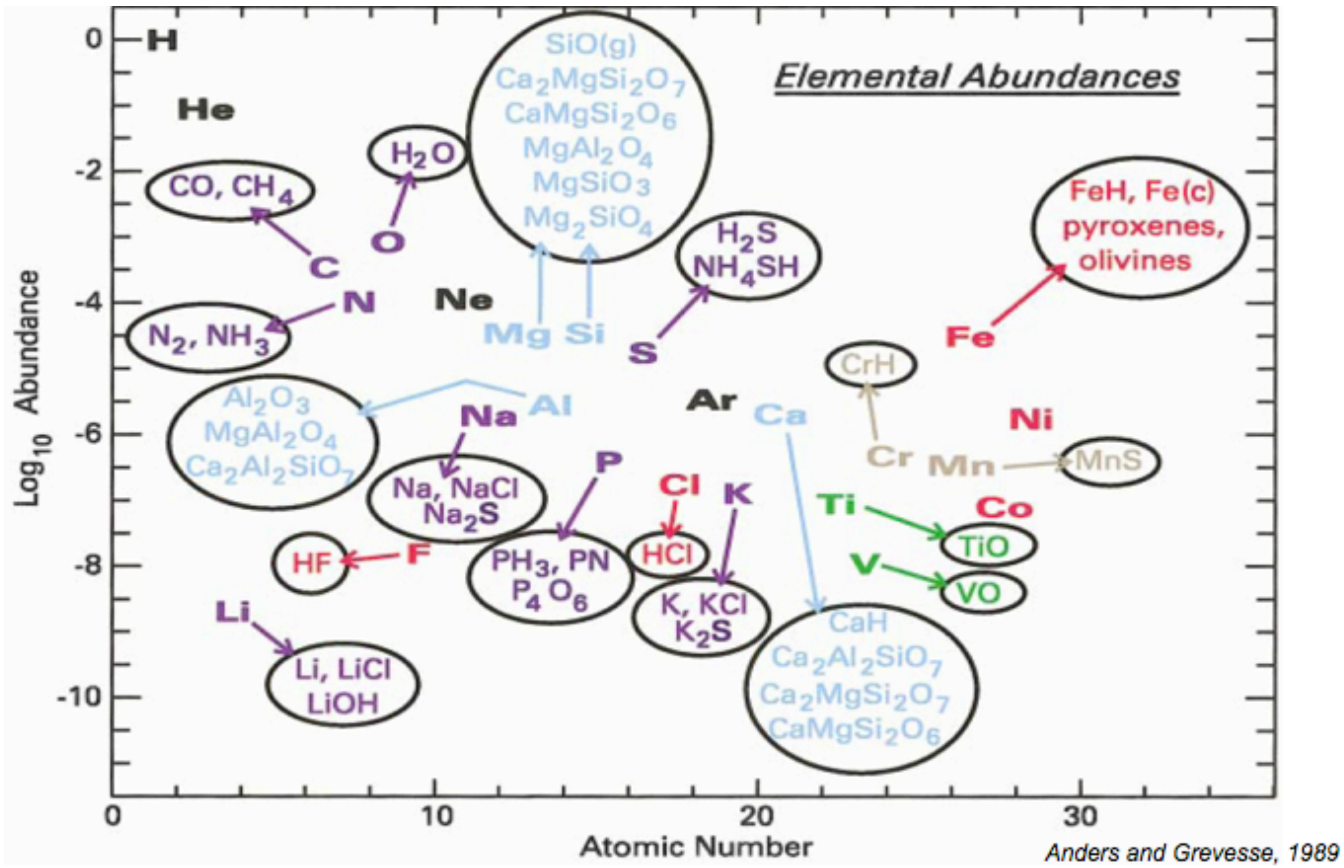
# Atmospheric Composition



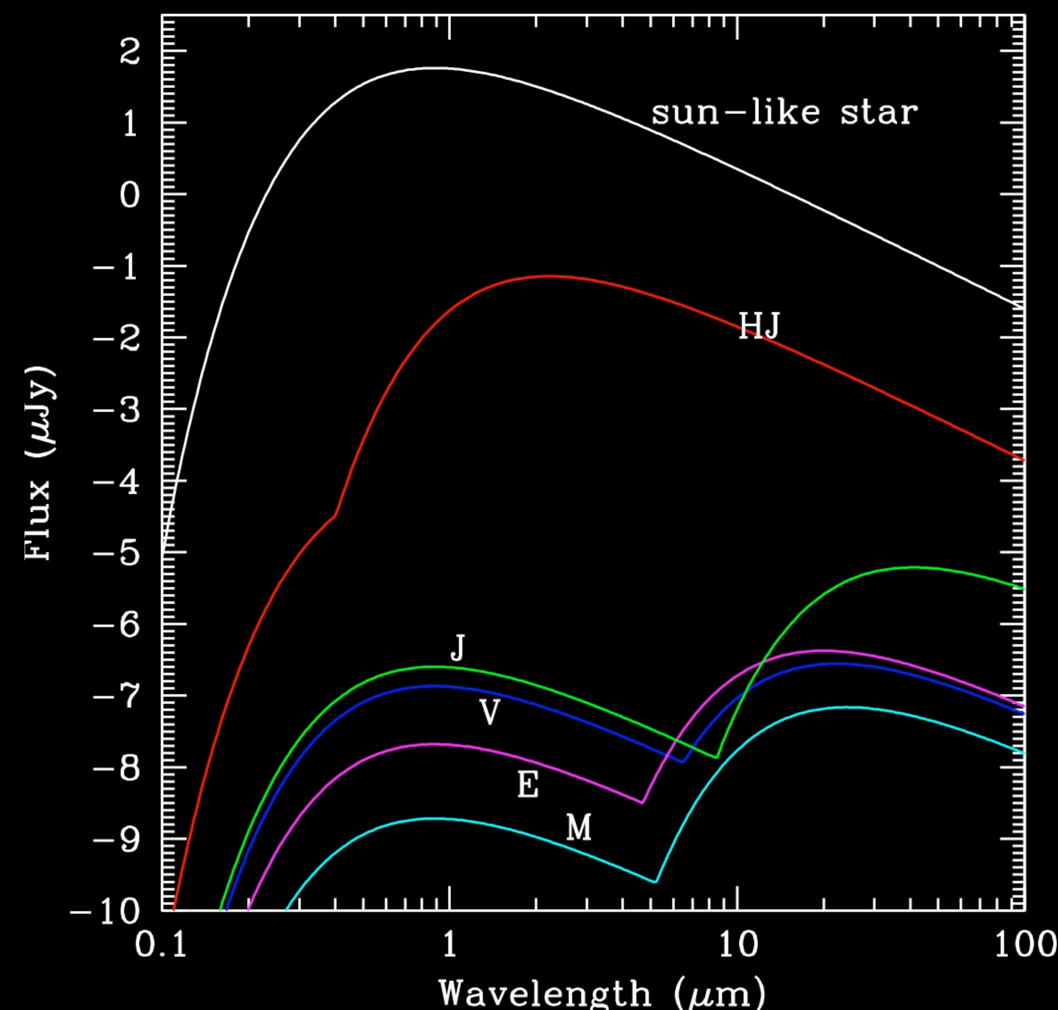

- Jupiter's atmosphere is "primordial", containing the gases it was born with
- Earth's atmosphere has suffered loss of H and He

# Atmosphere Composition




From K. Stanek

# Planet-Star Flux Ratios




Solar System at 10 pc

Seager 2003

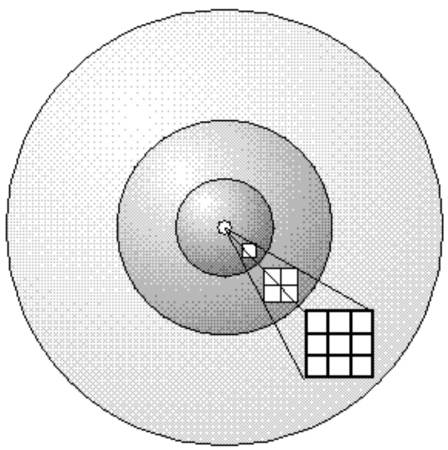
# Planet-Star Flux Ratio at Earth

- $F_p(\nu)$ is the flux at the planet surface
- $F_{p\oplus}(\nu)$ is the planet flux at Earth

$$F_{p,\oplus}(\nu) = F_p(\nu)\left(\frac{R_p}{D_\oplus}\right)^2$$

$$F_{*,\oplus}(\nu) = F_*(\nu)\left(\frac{R_*}{D_\oplus}\right)^2$$

$$\frac{F_{p,\oplus}(\nu)}{F_{*,\oplus}(\nu)} = \frac{F_p(\nu)}{F_*(\nu)}\frac{R_p^2}{R_*^2}$$



Inverse square law

# Thermal Emission Flux Ratio

- Planet-to-star flux ratio
- Black body flux
- Take the ratio

- Approximation for long wavelengths
- Final flux ratio
- Thermal emission is typically at infrared wavelengths

$$\frac{F_{p,\oplus}(\nu)}{F_{*,\oplus}(\nu)} = \frac{F_p(\nu)}{F_*(\nu)} \frac{R_p^2}{R_*^2}$$

$$F(\nu) = \pi B(\nu, T)$$

$$\frac{F_{p,\oplus}(\nu)}{F_{*,\oplus}(\nu)} = \frac{B(\nu, T_p)}{B(\nu, T_*)} \frac{R_p^2}{R_*^2}$$

$$\frac{h\nu}{kT} << 1; B(\nu, T) \approx \frac{kT}{h\nu} \frac{2h\nu^3}{c^2}$$

$$\frac{F_{p,\oplus}(\nu)}{F_{*,\oplus}(\nu)} = \frac{T_p}{T_*} \frac{R_p^2}{R_*^2}$$

# Scattered-Light Flux Ratio

- Planet-to-star flux ratio

$$\frac{F_{p,\oplus}(\nu)}{F_{*,\oplus}(\nu)} = \frac{F_p(\nu)}{F_*(\nu)} \frac{R_p^2}{R_*^2}$$

- Black body flux

$$F_*(\nu) = \pi B_*(\nu,T)$$

- Scattered stellar flux

$$F_p(\nu) = A_g(\nu) F_*(\nu) \left(\frac{R_*}{a}\right)^2 = A_g(\nu)\pi B_*(\nu,T)\left(\frac{R_*}{a}\right)^2$$

- Take the planet-to-star flux ratio

$$\frac{F_{p,\oplus}(\nu)}{F_{*,\oplus}(\nu)} = A_g(\nu)\pi B(\nu,T_*)\left(\frac{R_*}{a}\right)^2 \frac{1}{\pi B(\nu,T_*)} \frac{R_p^2}{R_*^2}$$

- Scattered flux is usually at visible-wavelengths for planets

$$\boxed{\frac{F_{p,\oplus}(\nu)}{F_{*,\oplus}(\nu)} = A_g(\nu)\left(\frac{R_p}{a}\right)^2}$$

# Transmission Flux Ratio

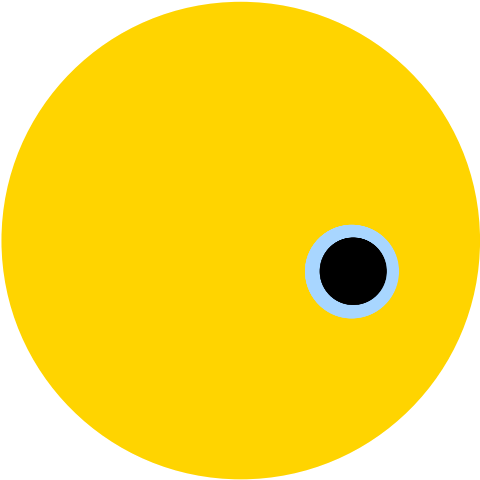
$$\frac{F_{\text{in transit}} - F_{\text{out of transit}}}{F_{\text{out of transit}}} = \frac{F_{*,\oplus}\pi R_*^2 - F_{*,\oplus}\left(\pi R_*^2 - \pi R_p^2 - \text{atmosphere}\right)}{F_{*,\oplus}\pi R_*^2}$$

$$\text{atmosphere} \approx \frac{\pi\left(R_p + 5H\right)^2 - \pi R_p^2}{R_*^2}$$

$$H << R_p$$

$$\text{atmosphere} \approx \pi\left(R_p^2 - 10R_pH + 25H^2\right) \approx \pi\left(R_p^2 - 10R_pH\right)$$

$$\frac{F_{\text{in transit}} - F_{\text{out of transit}}}{F_{\text{out of transit}}} \approx \frac{10R_pH}{R_*^2}$$

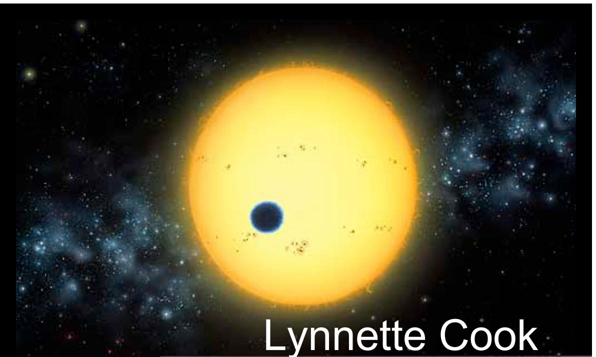


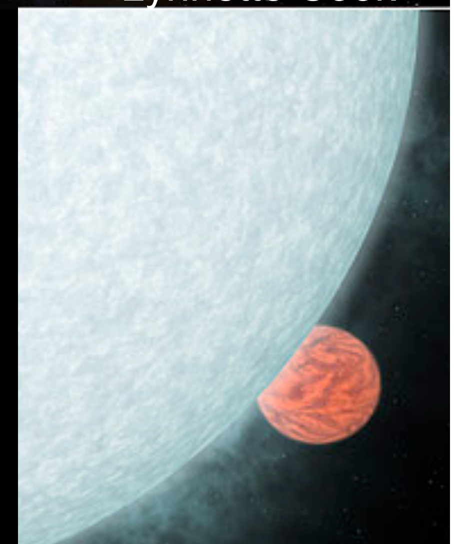
# Hot Jupiter Planet-Star Flux Ratios

- Transit $[R_p/R_*]^2 \sim 10^{-2}$
  - Transit radius -> planet size
- Thermal Emission $T_p/T_*(R_p/R_*)^2 \sim 10^{-3}$
  - Emitting atmosphere $\tau \sim 2/3$
  - Temperature and $\nabla T$
  - Thermal phase curve
- Transmission Spectra $atm/R_*^2 \sim 10^{-4}$
  - Upper atmosphere
  - Exosphere (0.05-0.15)
- Reflection $A_g[R_p/a]^2 \sim 10^{-5}$
  - Albedo
  - Reflected light phase curve
  - Polarization
  - Scattering atmosphere

Enabled by a differential measurement

Seager et al. 2005



# Overview

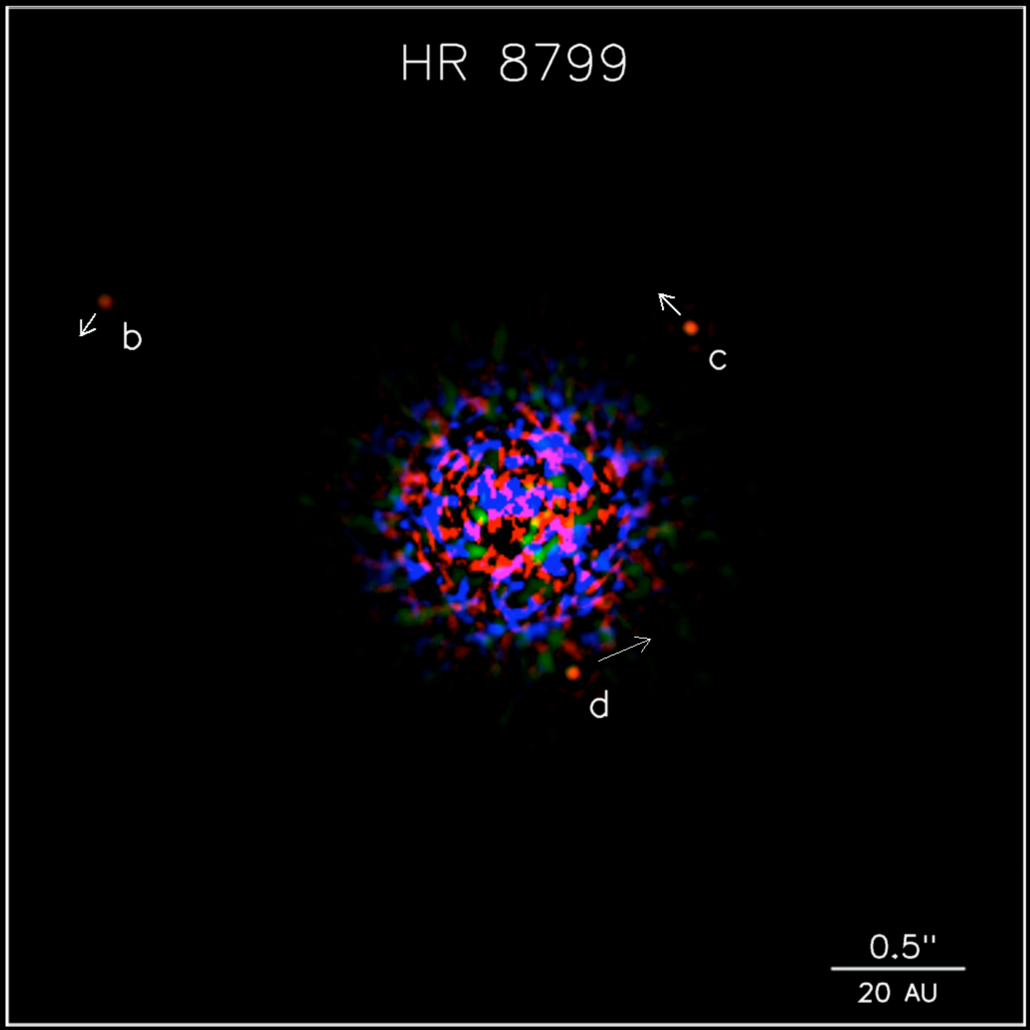
Introduction

Atmospheres 101

Detection Highlights

Prospects

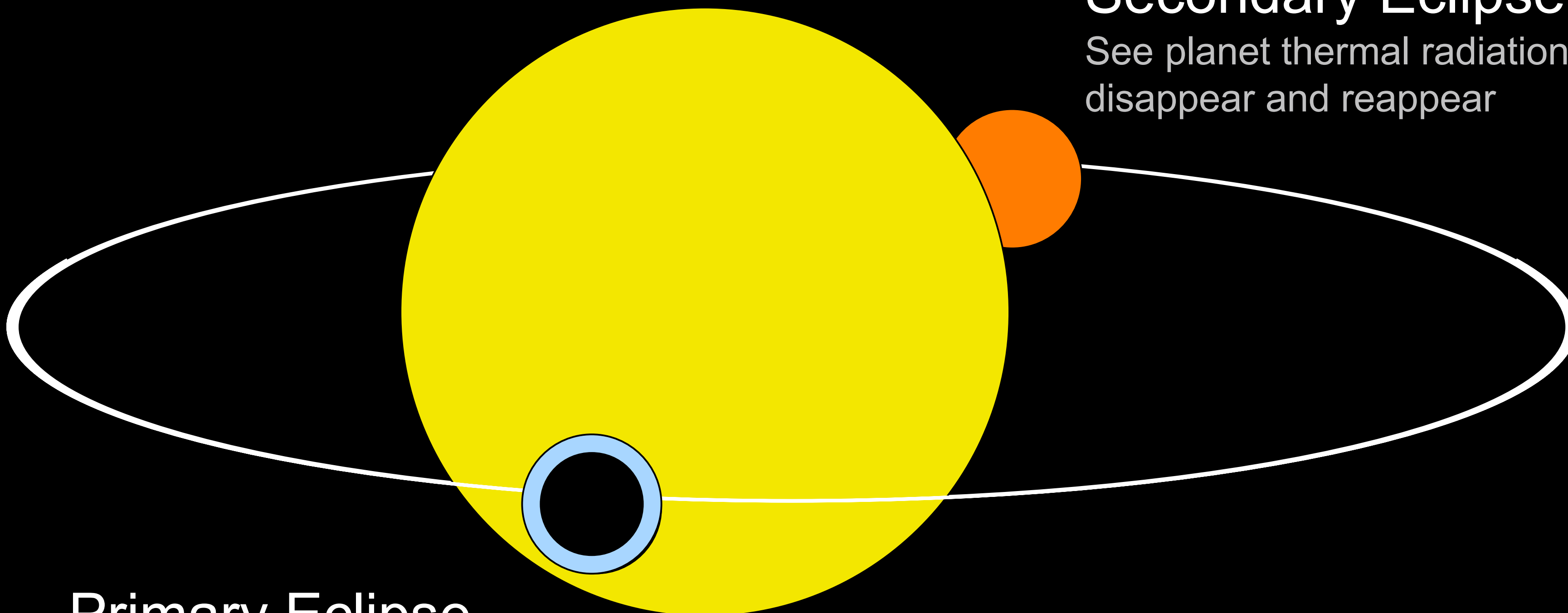
# 1) Direct Imaging




Marois, Macintosh, Doyon et al. 2008


Search
for other earths
© National Geographic
used with permission

# 2) Transiting Exoplanets



## Secondary Eclipse

See planet thermal radiation disappear and reappear

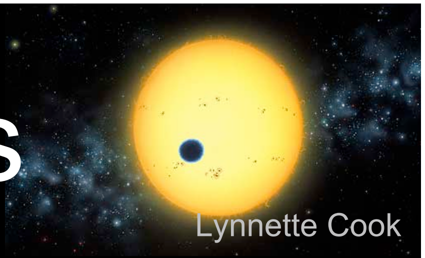
## Primary Eclipse

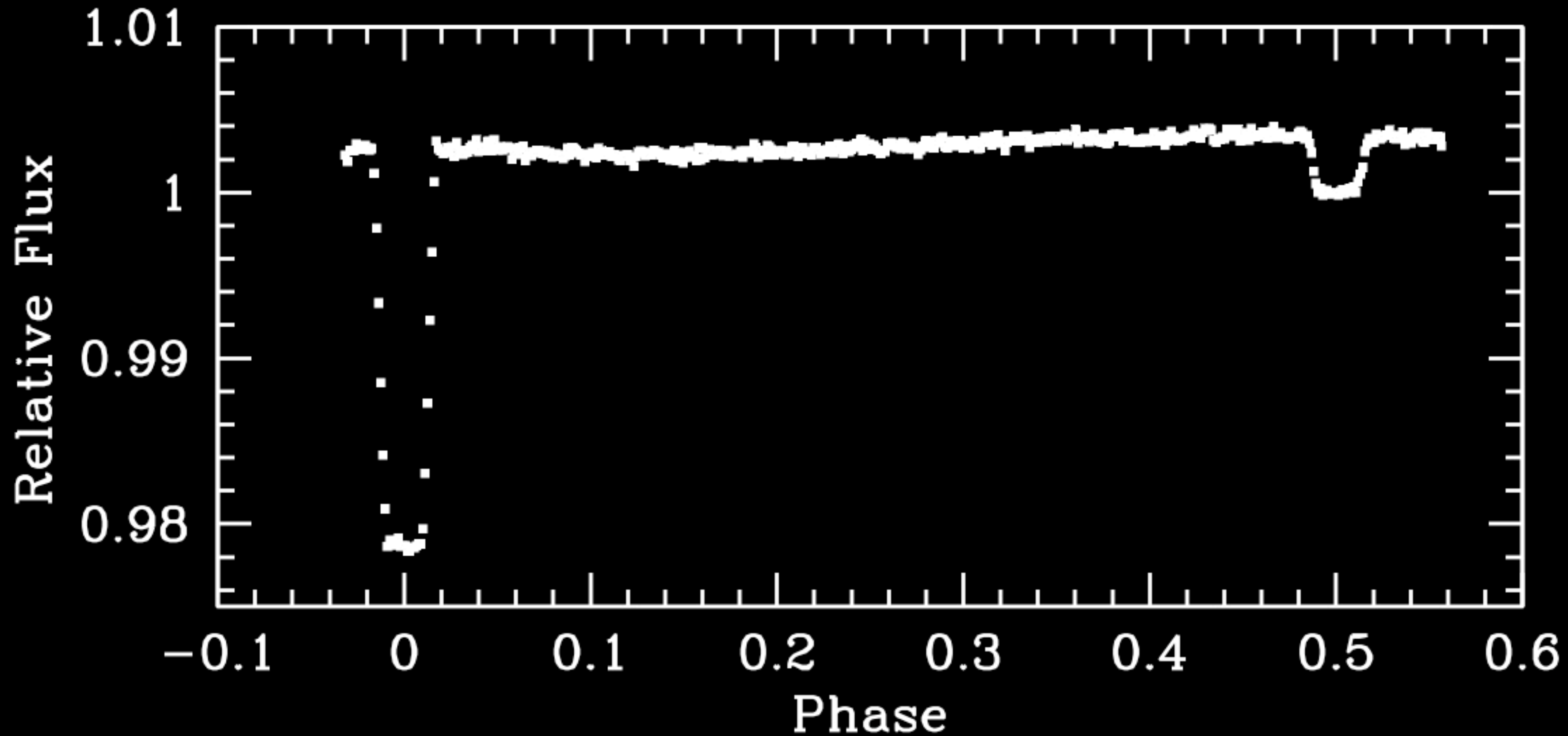
Measure size of planet

See star's radiation transmitted through the planet atmosphere

Learn about atmospheric circulation from thermal phase curves

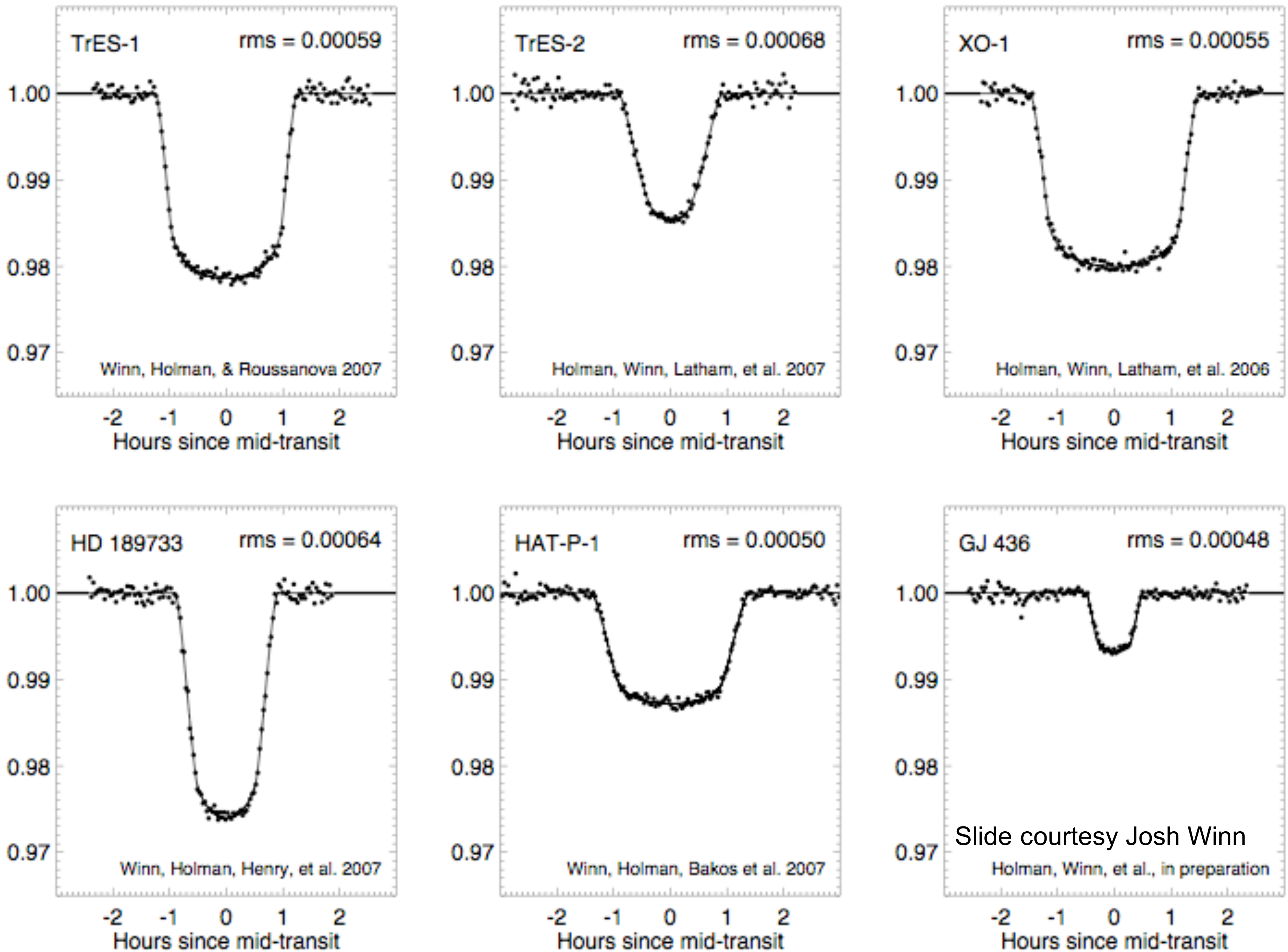
# Transiting Exoplanets



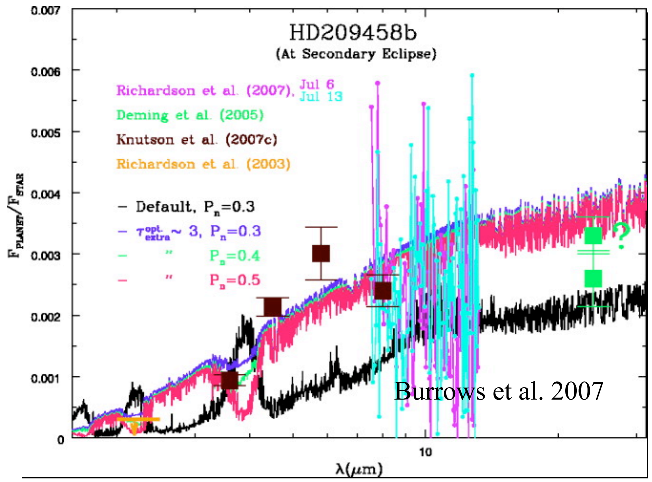




*Spitzer*

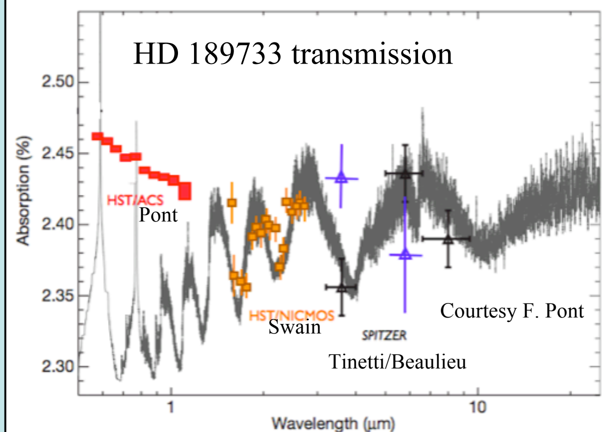
Knutson et al. 2007


TrES-1
rms = 0.00059
Winn, Holman, & Roussanova 2007
TrES-2
rms = 0.00068
Holman, Winn, Latham, et al. 2007
XO-1
rms = 0.00055
Holman, Winn, Latham, et al. 2006
HD 189733
rms = 0.00064
Winn, Holman, Henry, et al. 2007
HAT-P-1
rms = 0.00050
Winn, Holman, Bakos et al. 2007
GJ 436
rms = 0.00048
Holman, Winn, et al., in preparation
1.00
0.99
0.98
0.97
-2
-1
0
1
2
Hours since mid-transit
Slide courtesy Josh Winn

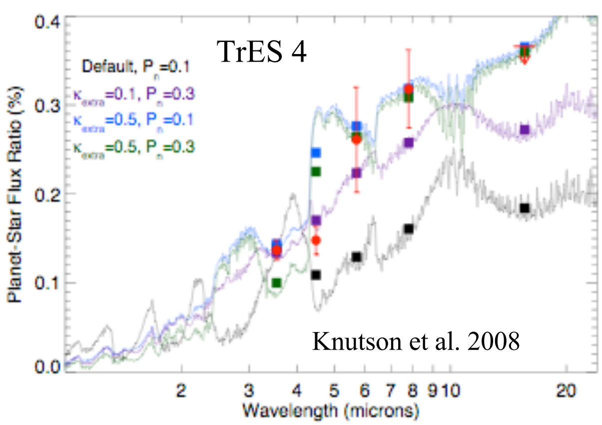
# Exoplanet Atmospheres




TBD




TBD




TBD

TBD

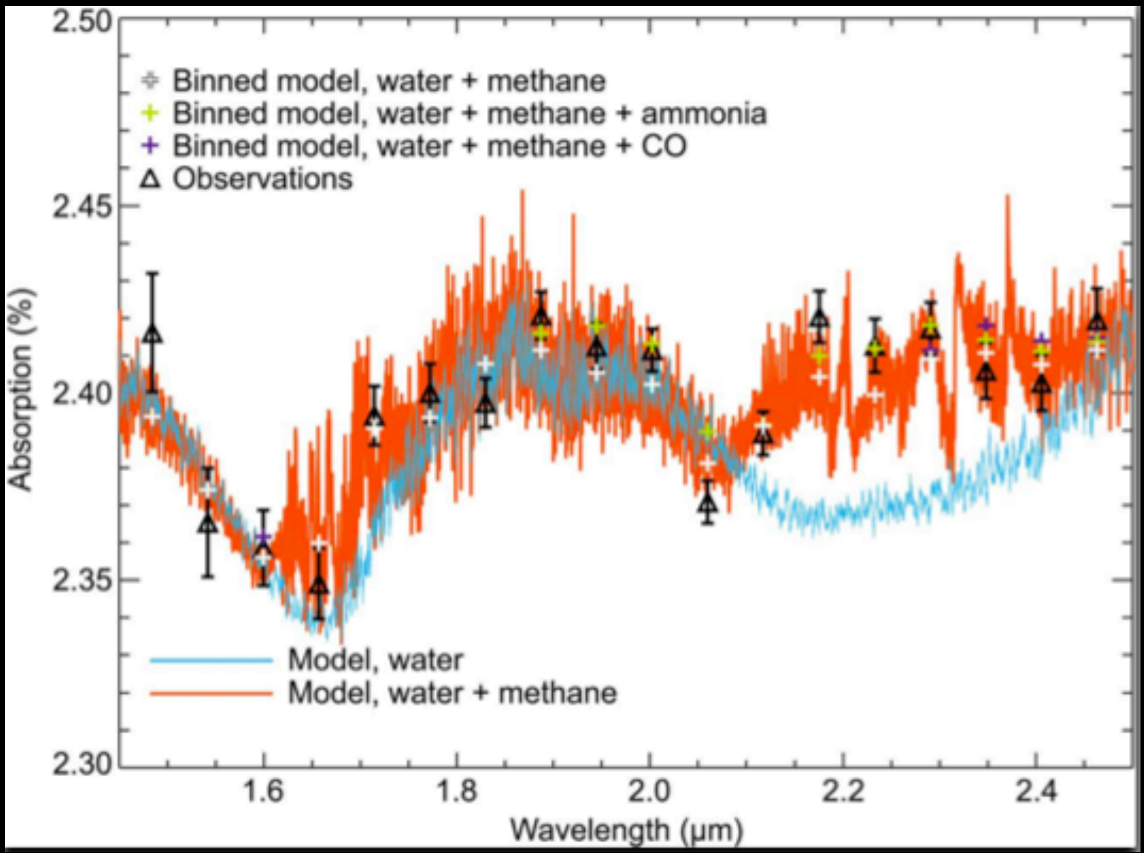
# Table of Spitzer Data

| *Planet* | *3.6* | *4.5* | *5.8* | *8.0* |
|---|---|---|---|---|
| CoRoT-2 | X | X | X | X |
| HD189733b | X | X | X | X |
| HD209458b | X | X | X | X |
| HD149026b | X | X | X | X |
| HD80606b | | | | X |
| GJ436b | X | X | X | X |
| HAT-P-1 | X | X | X | X |
| HAT-P-2 | | | X | X |
| HAT-P-7 | X | X | X | X |
| TrES-P-1 | X | X | X | X |
| TrES-2 | X | X | X | X |
| TrES-3 | X | X | X | X |
| TrES-4 | X | X | X | X |
| WASP-1b | X | X | X | X |
| WASP-2b | X | X | X | X |
| WASP-3b | | X | | X |
| WASP-8b | | X | | X |
| WASP-11b | | X | | X |
| WASP-12b | X | X | X | X |
| WASP-14b | X | X | X | X |
| WASP-17b | | X | | X |
| WASP-18b | X | X | X | X |
| WASP-19b | X | X | X | X |
| XO-1 | X | X | X | X |
| XO-2 | X | X | X | X |
| XO-3 | X | X | X | X |

# Table of Spitzer Data

| Planet Name | *Spitzer* Instrument and Wavelength (µm) | Type of Observation | Date Released to Archive (day/month/year) | Approx. duration of data set (h) | *Spitzer* Program ID |
|---|---|---|---|---|---|
| COROT-2b | IRAC 4.5, 8 | Sec. eclipse | 11-02-2009 | 5.2 | 486 |
| GJ 436b | IRAC 8 | Transit | 13-07-2007 | 4.03 | 30129 |
| GJ 436b | IRAC 3.6, 4.5, 5.8, 8 | Sec. eclipse | 13-07-2007 | 19.5 | 30129 |
| GJ 436b | IRAC 3.6, 4.5, 5.8, 8 | Sec. eclipse | 19-02-2008 | 19.5 | 40685 |
| GJ 436b | IRS PUI 16 | Sec. eclipse | 15-02-2008 | 6.8 | 40685 |
| GJ 436b | MIPS 24 | Sec. eclipse | 15-01-2008 | 6 | 40685 |
| HAT-P-1 | IRAC 3.6, 4.5, 5.8, 8 | Sec. eclipse | 08-01-2009 | 13 | 30129 |
| HAT-P-2 | IRAC 5.8 | Sec. eclipse | 6-04-2009 | 8.7 | 40685 |
| HAT-P-7 | IRAC 3.6, 4.5, 5.8, 8 | Sec. eclipse | 13-11-2008 | 9.23 | 40685 |
| HD 149026 | IRS PUI 16 | Sec. eclipse | 11-24-2008 | 7 | 40135 |
| HD 149026 | IRAC 3.6, 5.8, 8 | Sec. eclipse | 18-04-2009 | 29 | 40135 |
| HD 149026 | IRAC 5.8, 8 | Sec. eclipse | 6-04-2009 | 29 | 50517 |
| HD 189733 | MIPS 24 | Sec. eclipse | 10-01-2006 | 5.1 | 261 |
| HD 189733 | IRAC | Sec. eclipse | 10-01-2006 | 5 | 261 |
| HD 189733 | IRS PUI 16 | Sec. eclipse | 10-01-2006 | 6 | 260 |
| HD 189733 | IRAC 8 | Sec. eclipse and phase | 15-11-2007 | 33 | 30825 |
| HD 189733 | IRAC 3.6, 5.8 | Transit | 15-11-2007 | 4.5 | 30590 |
| HD 189733 | IRAC 8 | Sec. eclipse | 31-10-2008* | 26.5 | 40238 |
| HD 189733 | IRAC 8 | Transit | 2-12-2008* | 21 | 40238 |
| HD 189733 | IRAC 4.5, 8 | Transit | 2-12-2008 | 9 | 40732 |
| HD 209458b | MIPS 24 | Sec. eclipse | 16-12-05 | 6 | 3405 |
| HD 209458b | MIPS 24 | Transit | 22-07-06 | 6 | 3405 |
| HD 209458b | MIPS 24 | Transit | 22-07-06 | 6 | 20605 |
| HD 209458b | MIPS 24 | Sec. eclipse | 16-12-06 | 6 | 20605 |
| HD 209458b | IRAC 3.6, 8 | Phase curve | 14-12-2006 | 5.23 | 20482 |
| HD 209458b | IRS PUI 16 | Transit | 3-02-2007 | 6 | 20605 |
| HD 209458b | IRS PUI 16 | Sec. eclipse | 3-02-2007 | 6 | 20605 |
| HD 209458b | IRAC | Sec. eclipse | 14-12-2006 | 8.23 | 20523 |
| HD 209458b | IRAC 8 | Phase curve | 8-01-2009 | 23 | 40280 |
| HD 209458b | IRAC 3.5, 4.6, 5.8, 8 | Transit | 8-04-08 | 20 | 461 |
| HD 80606 | IRAC 8 | Sec. eclipse, partial phase curve | 2-12-2008 | 23.5 | 40386 |
| TrES-1 | IRS-PUI 16 | Transit | 20-06-2007 | 5.8 | 20605 |
| TrES-1 | IRS-PUI 16 | Sec. eclipse | 20-06-2007 | 17.5 | 20605 |
| TrES-1 | IRAC 4.5, 8 | Sec. eclipse |  | 6 | 227 |
| TrES-1 | IRAC 3.6, 5.8 | Sec. eclipse | 6-10-2006 | 6 | 20523 |
| TrES-2 | IRAC 3.6, 4.5, 5.8, 8 | Sec. eclipse | 23-08-2007 | 9 | 30129 |
| TrES-4 | IRS PUI 16 | Sec. eclipse | 1-11-2007 | 8 | 463 |
| TrES-4 | IRAC 3.6, 4.5, 5.8, 8 | Sec. eclipse | 1-11-2007 | 16 | 463 |
| WASP-1b | IRAC 3.6, 5.8 | Sec. eclipse | 26-09-2007 | 8.3 | 30129 |
| WASP-1b | IRAC 4.5, 8 | Sec. eclipse | 12-01-2007 | 8 | 282 |
| WASP-2b | IRAC 3.6, 5.8 | Sec. eclipse | 13-07-2007 | 3.9 | 30129 |
| WASP-2b | IRAC 4.5, 8 | Sec. eclipse | 21-12-2006 | 5 | 282 |
| WASP 8b | IRAC 3.6, 4.5, 5.8, 8 | Sec. eclipse | 13-01-2009 | 15 | 40685 |
| WASP-11b | IRAC 4.5, 8 | Sec. eclipse | 6-04-2009 | 5.7 | 50517 |
| WASP 12b | IRAC 3.6, 5.8 | Sec. eclipse | 13-11-2008 | 6.3 | 50517 |
| WASP-14b | IRAC 4.5, 8 | Sec. eclipse | 6-04-2009 | 5.7 | 50517 |
| WASP-18b | IRAC 3.6, 4.5, 5.8, 8 | Sec. eclipse | 13-01-2009 | 9 | 50517 |
| XO-1 | IRAC 3.6, 4.5, 5.8, 8 | Sec. eclipse | 22-08-2008 | 12 | 30879 |
| XO-2 | IRAC 3.6, 4.5, 5.8, 8 | Sec. eclipse | 2-12-2008 | 12 | 40780 |

# Identification of Atoms and Molecules

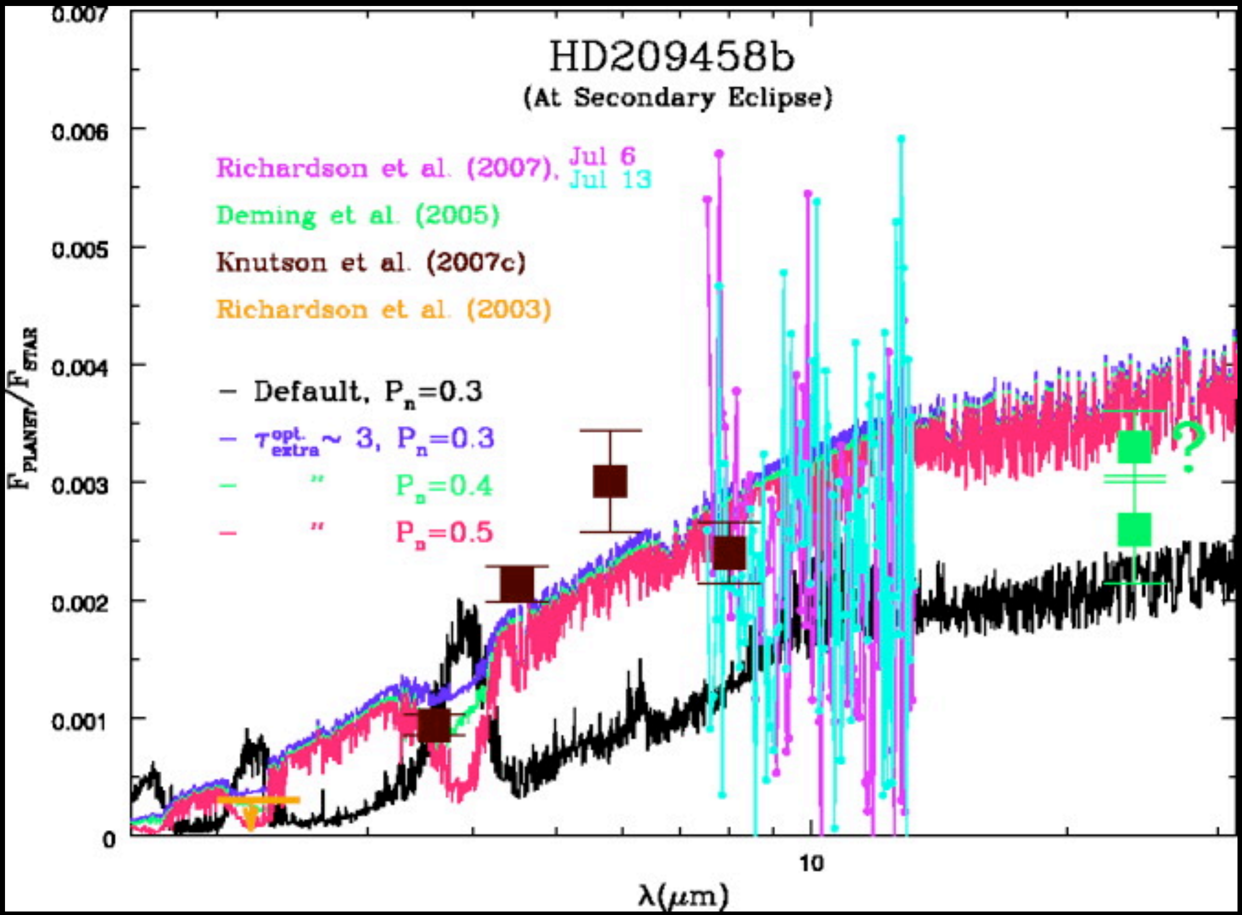



<u>HD 189733b</u>
Na, $H_2O$, $CH_4$ , $CO_2$, Hazes

<u>HD 209458b</u>
Na, $H_2O$
H Ly $\alpha$

$H_2O$ and $CH_4$ in transmission from HST
Swain et al. (2008)

# Thermal Inversion

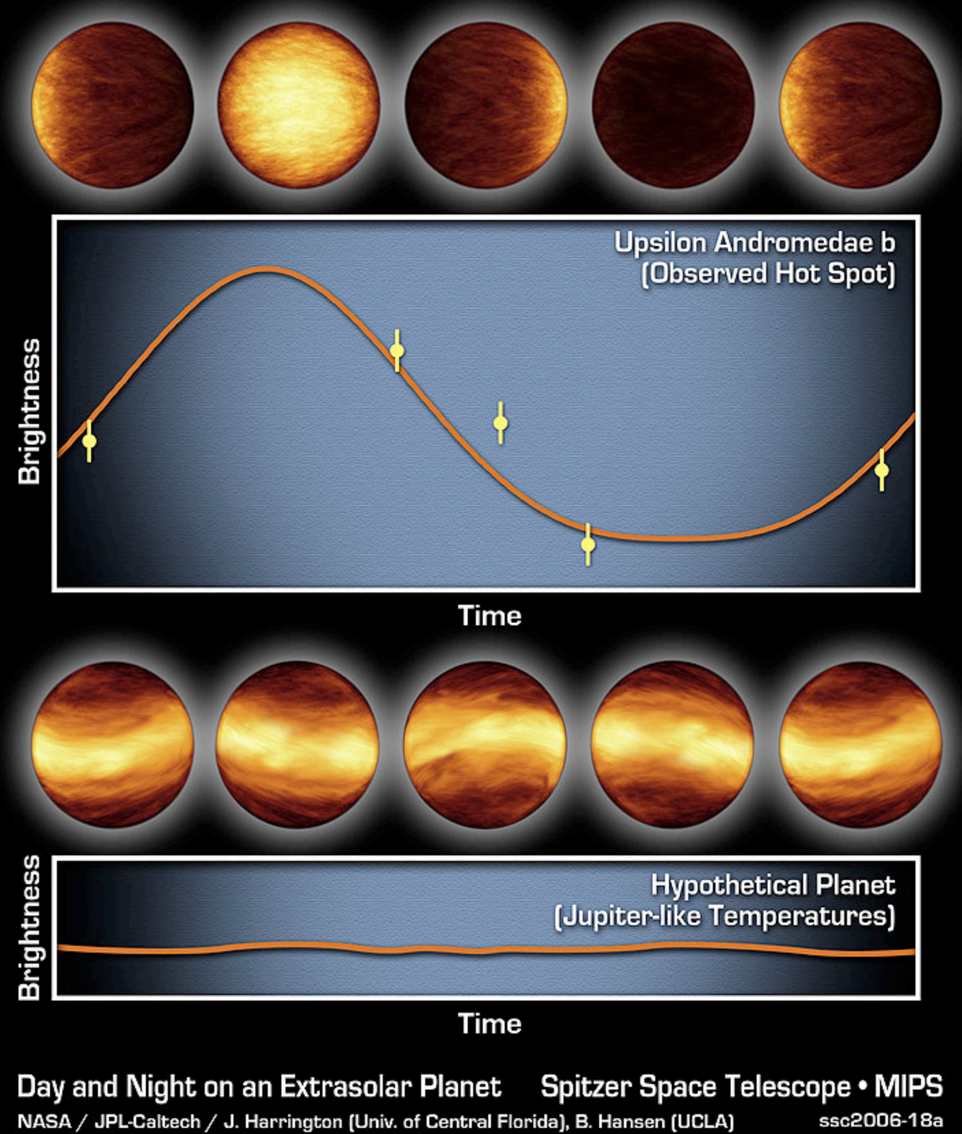


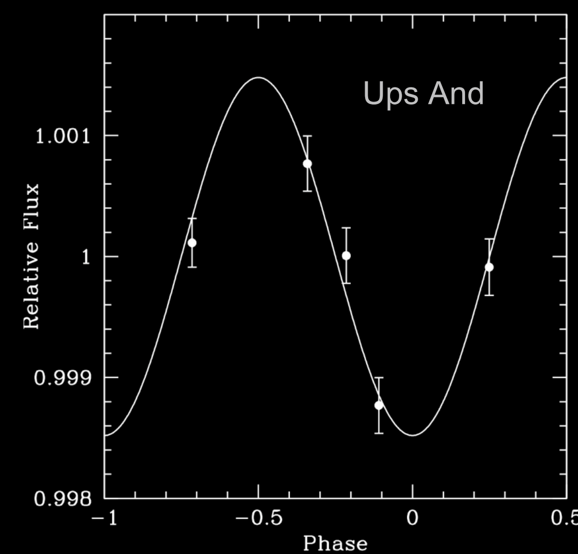

Data from Knutson et al. 2008
Burrows et al. 2007

# Tidally-Locked Hot Jupiter

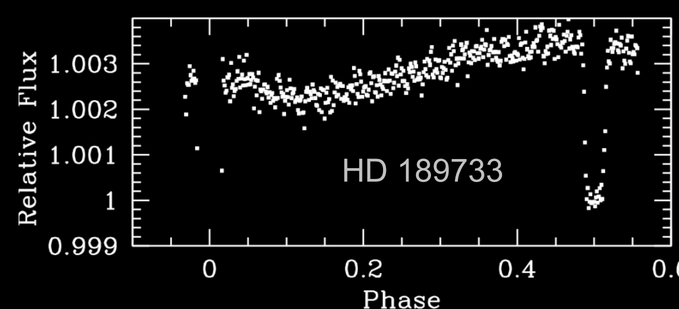
NASA/ESA/G. Bacon
*Spitzer Space Telescope*

# Hot Jupiter Thermal Phase Curves

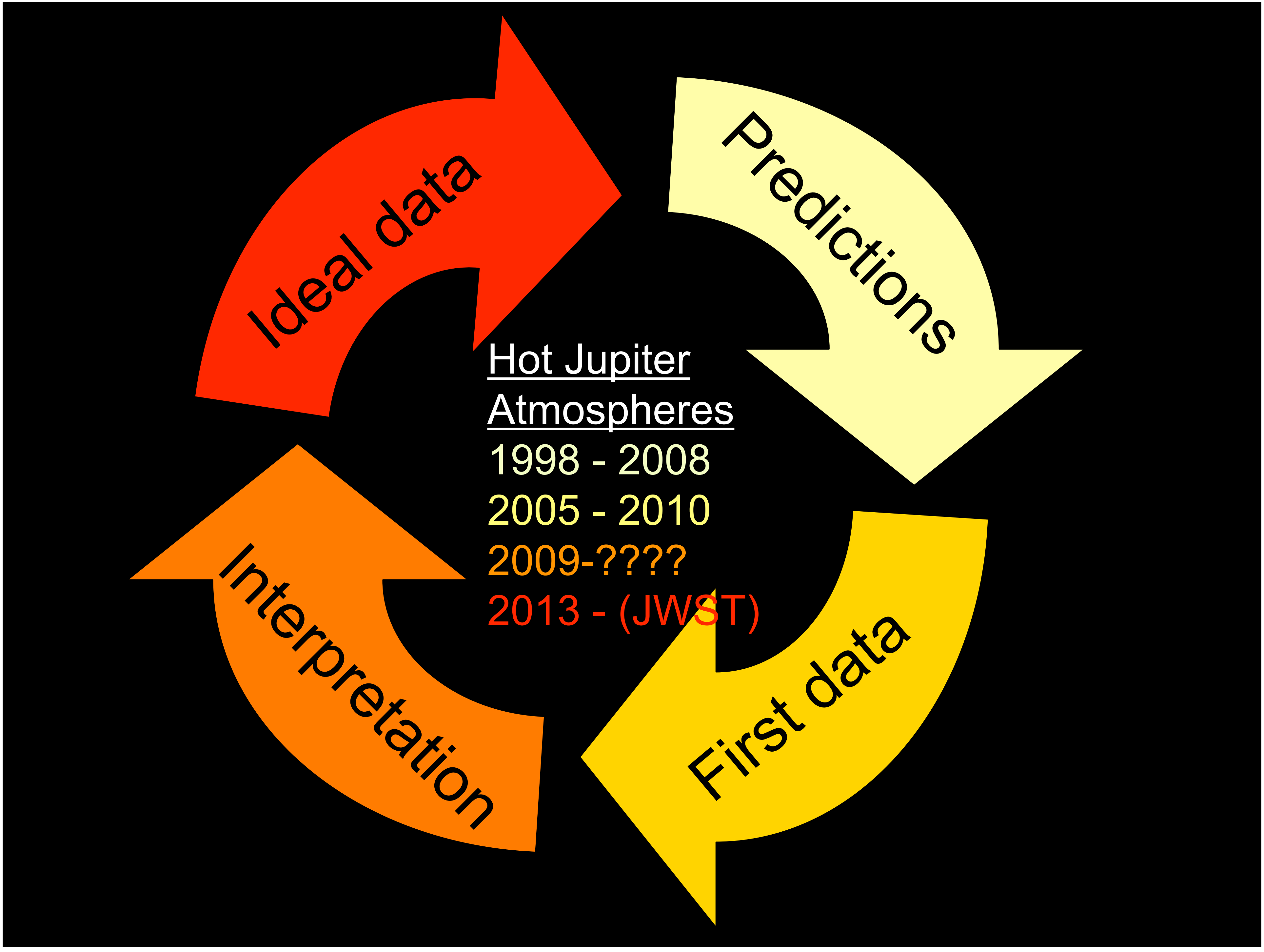


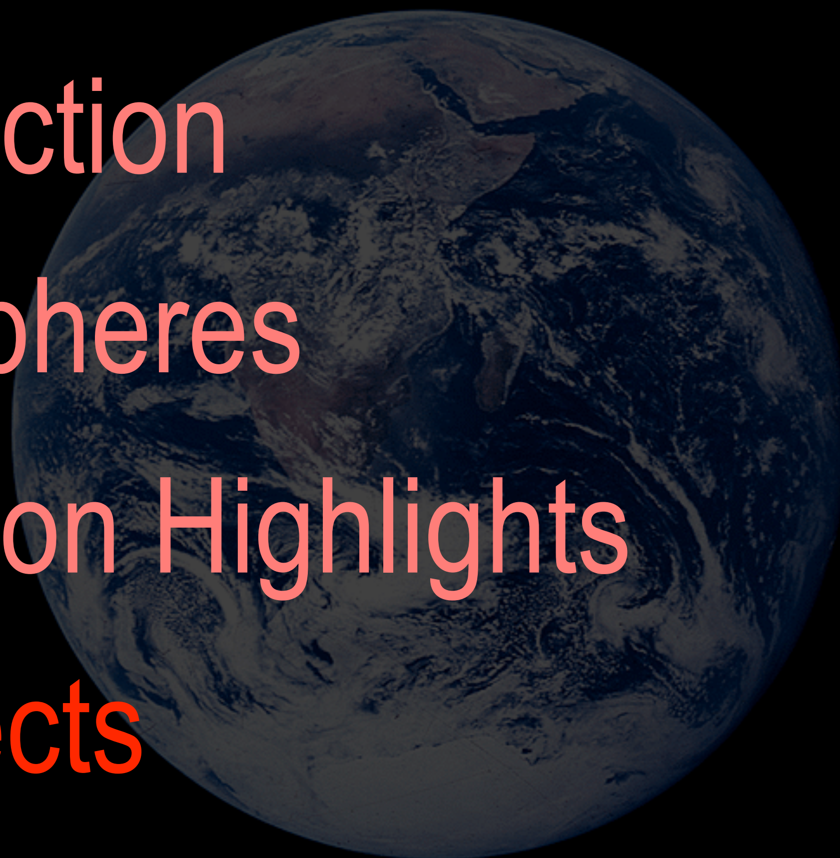

Harrington et al. 2006




Knutson et al. 2007


Ideal data
Predictions
First data
Interpretation
Hot Jupiter
Atmospheres
1998 - 2008
2005 - 2010
2009-????
2013 - (JWST)

# Overview



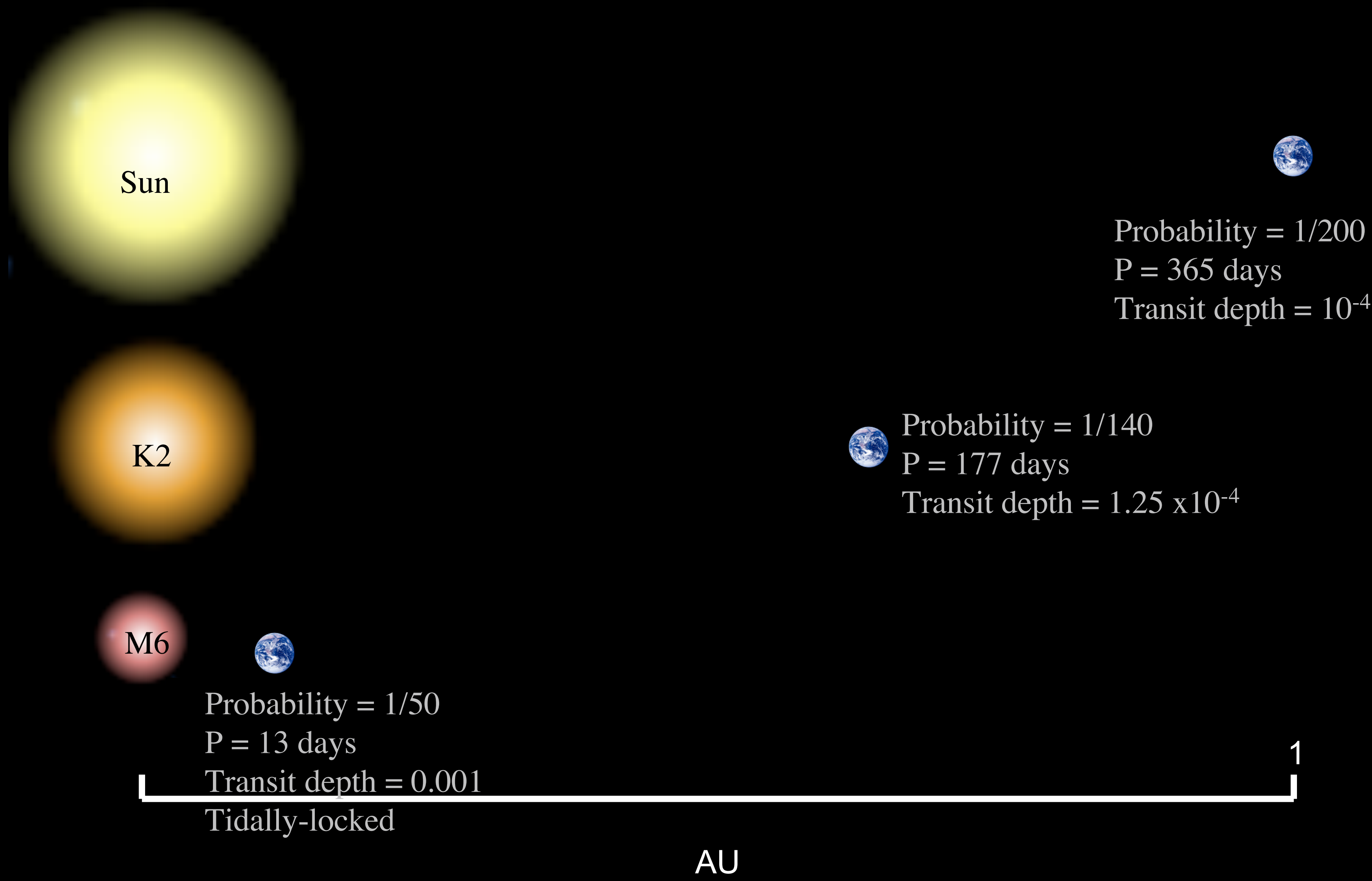
Introduction

Atmospheres

Detection Highlights

Prospects

# The M Star Opportunity



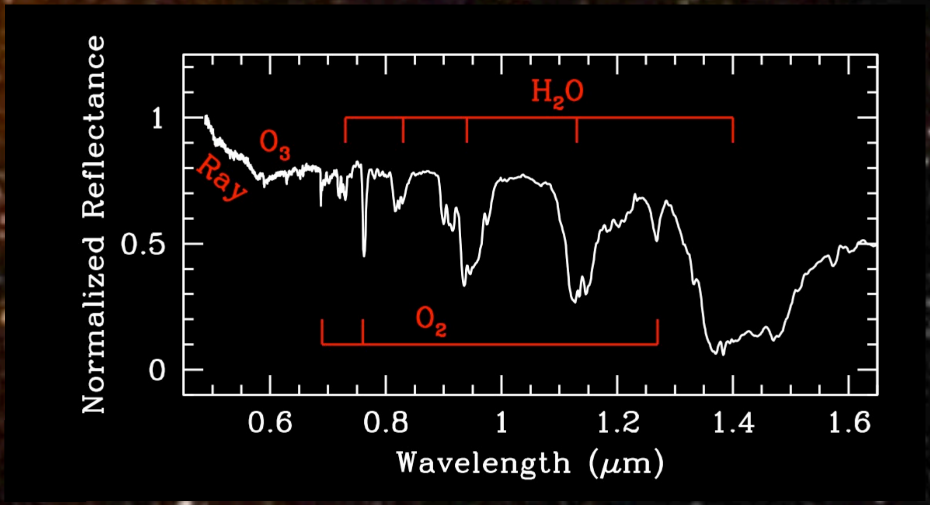

John E. Kauffman used with permission http://jek2004.com/

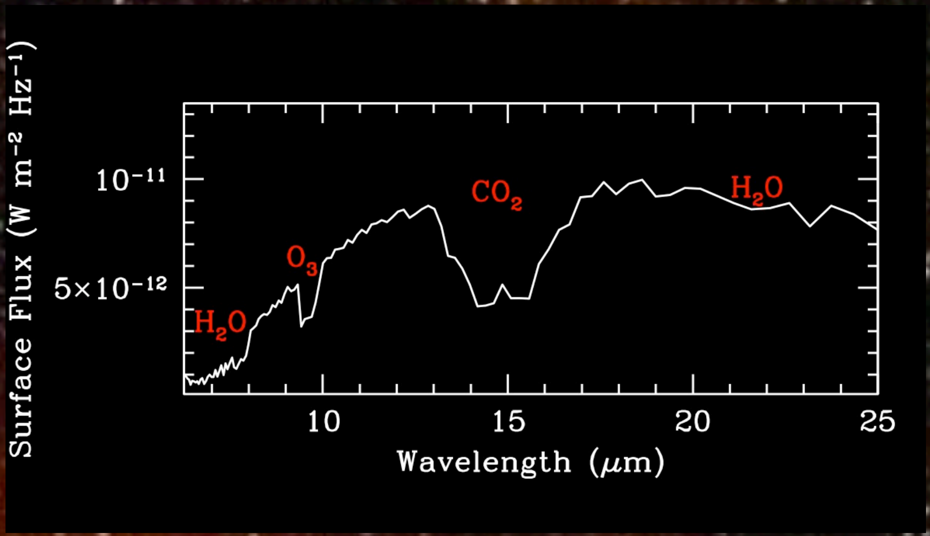
# JWST: 2013 Transit Planet Follow-up

- 26 $m^2$ collecting area
- 0.7 - 25 microns
- Secondary eclipse spectra
- Transit transmission spectra


# A Pale Blue Dot

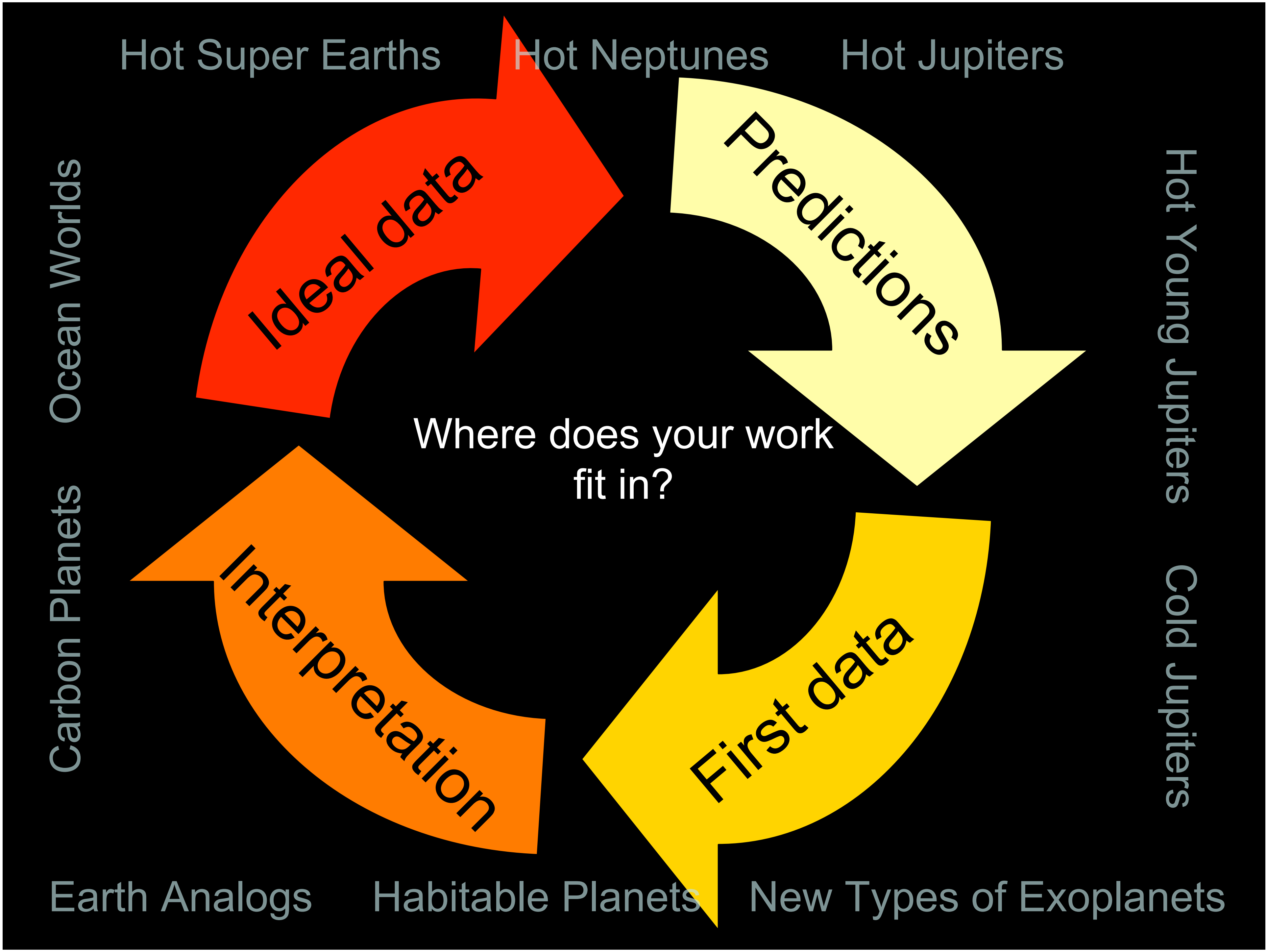
# Earth’s Spectrum

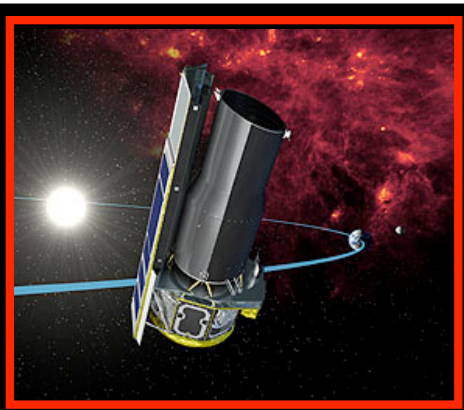



Turnbull et al. 2007

Pearl and Christensen 1997


Hot Super Earths
Hot Neptunes
Hot Jupiters
Ocean Worlds
Ideal data
Predictions
Hot Young Jupiters
Where does your work fit in?
Carbon Planets
Interpretation
First data
Cold Jupiters
Earth Analogs
Habitable Planets
New Types of Exoplanets



# Summary

- Introduction
  - This is prime time for hot Jupiter atmosphere detections
- Atmospheres 101
  - Mass and composition of super Earth atmospheres are not known in advance
  - Planet star flux ratios
- Detection Highlights
  - Identification of atoms and molecules
  - Thermal inversions
  - Day/night thermal gradients