What Have We Learned About Exoplanet Atmospheres from Data?

Sagan Workshop 2009

Sara Seager

MIT

Overview

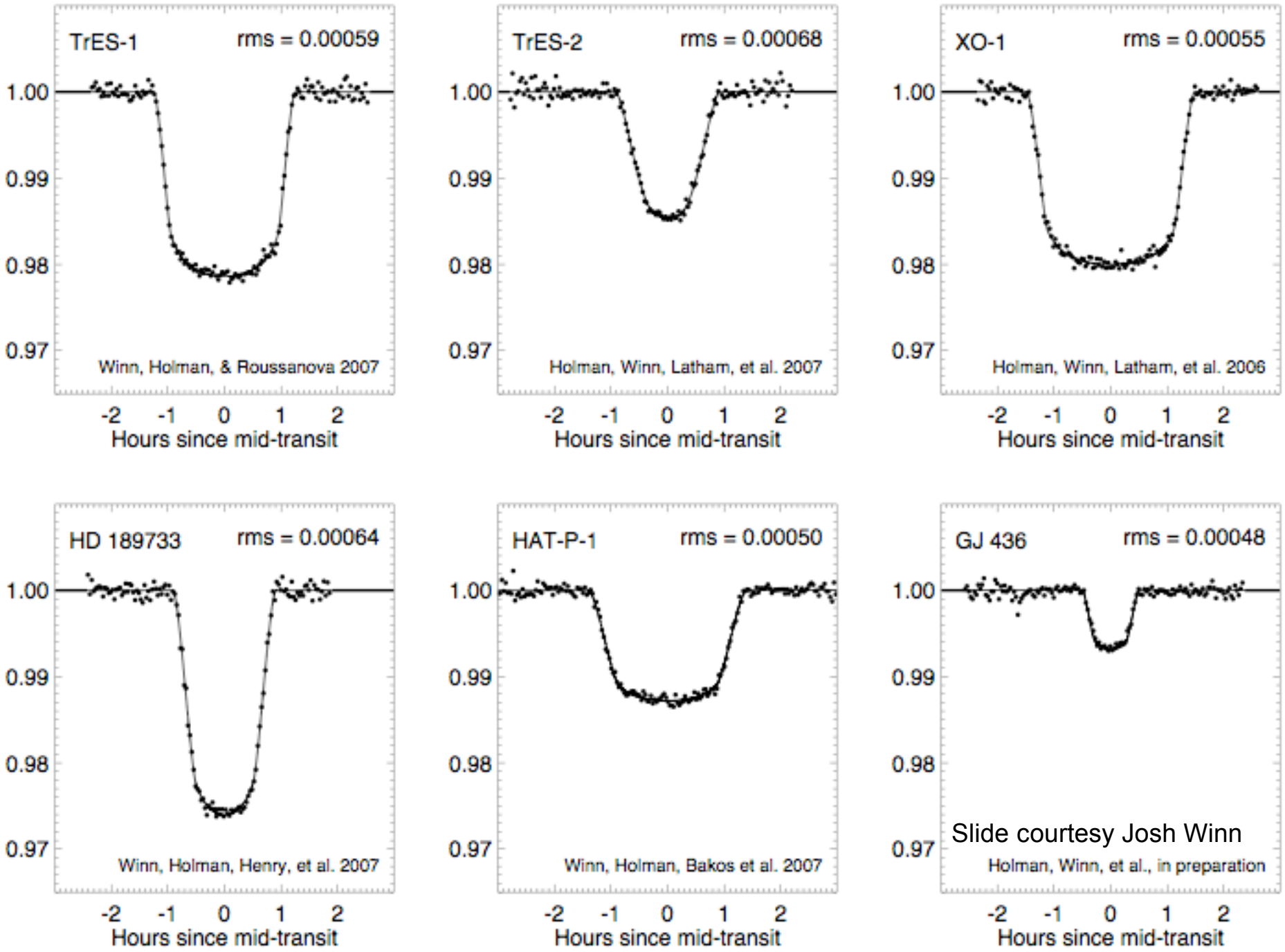
Introduction

Learned Without Models

Data

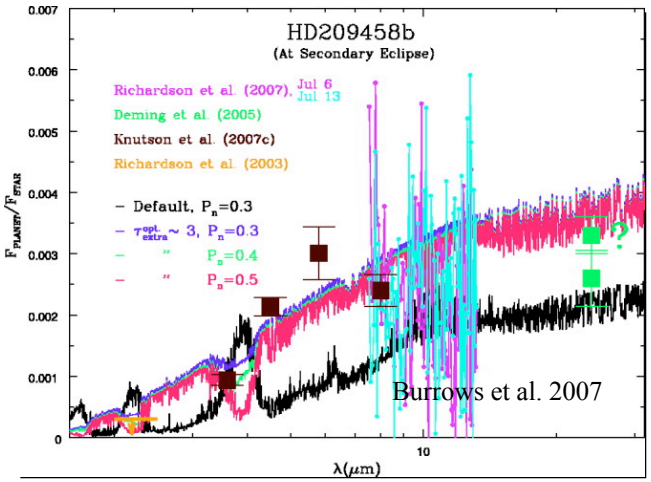
Learned With Models + Data

Prospects



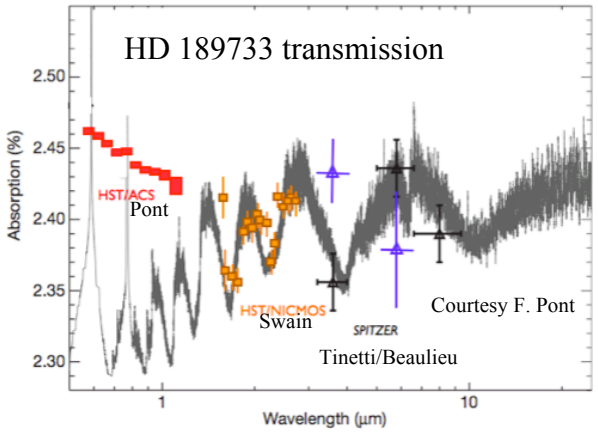
Slide courtesy Josh Winn

Exoplanet Atmospheres



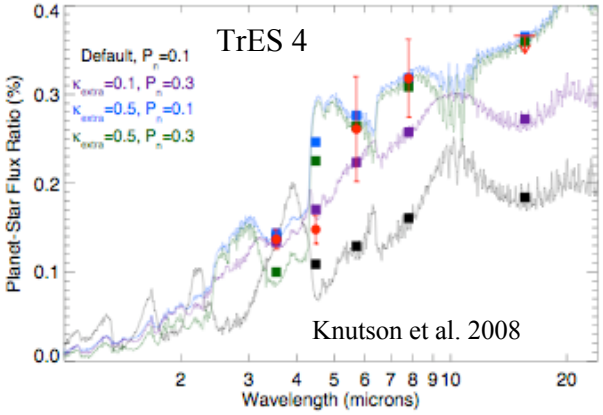
Burrows et al. 2007

TBD



Courtesy F. Pont

TBD



Knutson et al. 2008

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

Overview

Introduction

Learned Without Models

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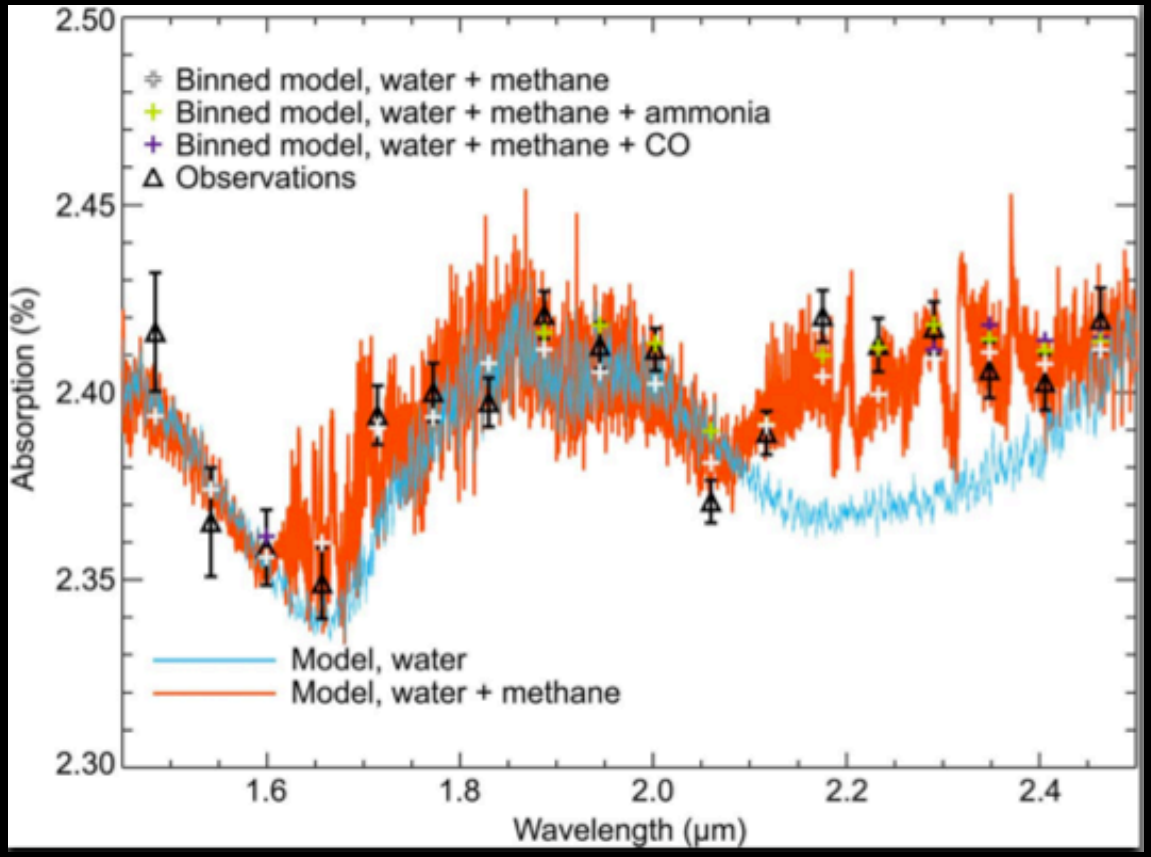
Learned With Models

Prospects

Identification of Atoms and Molecules



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

HD 189733b
Na, H_2O, CH_4 , CO_2, Hazes

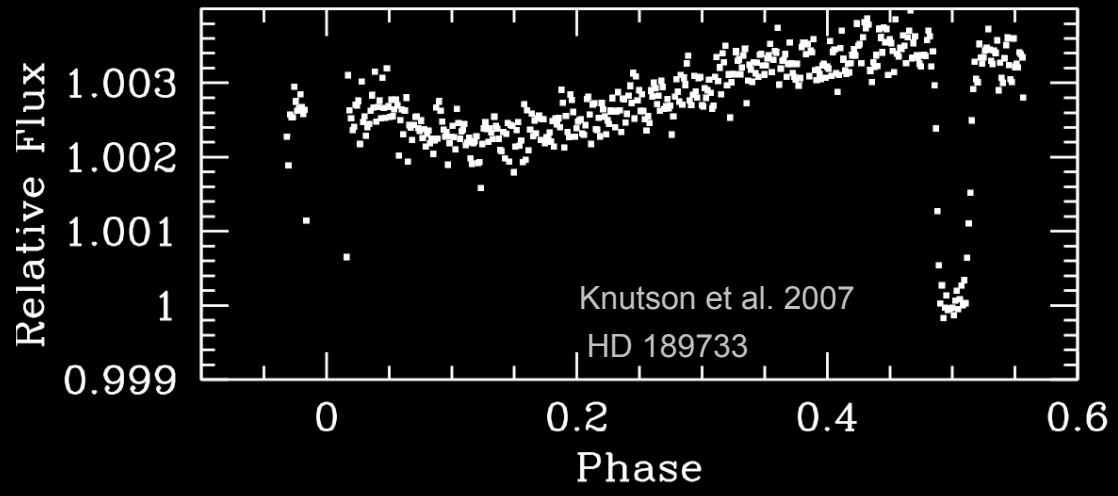
HD 209458b
Na, H_2O
H Ly α

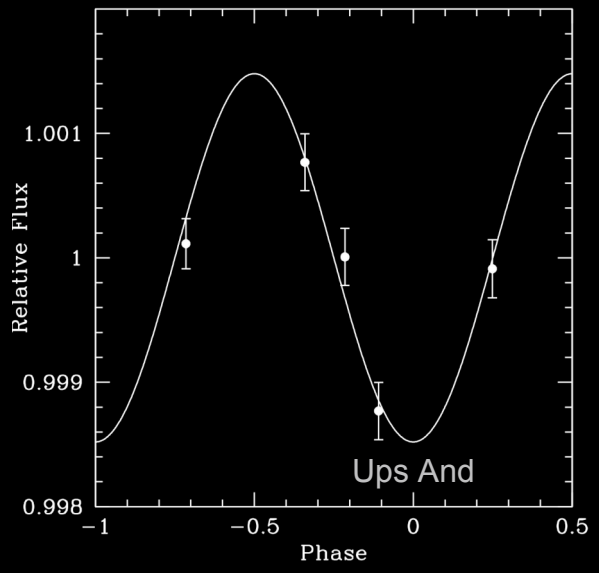
Thermal Phase Curves

See talks by
J. Fortney on Thermal Phase Curves
A. Showman on Atmospheric Circulation

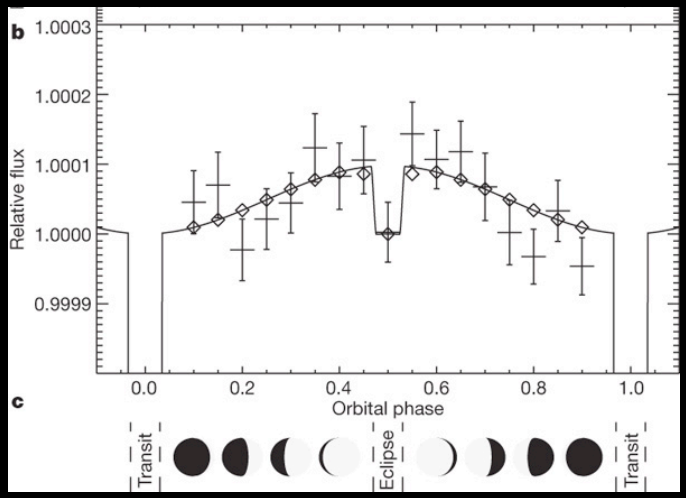
NASA/ESA/G. Bacon
Spitzer Space Telescope

Hot Jupiter Thermal Phase Curves



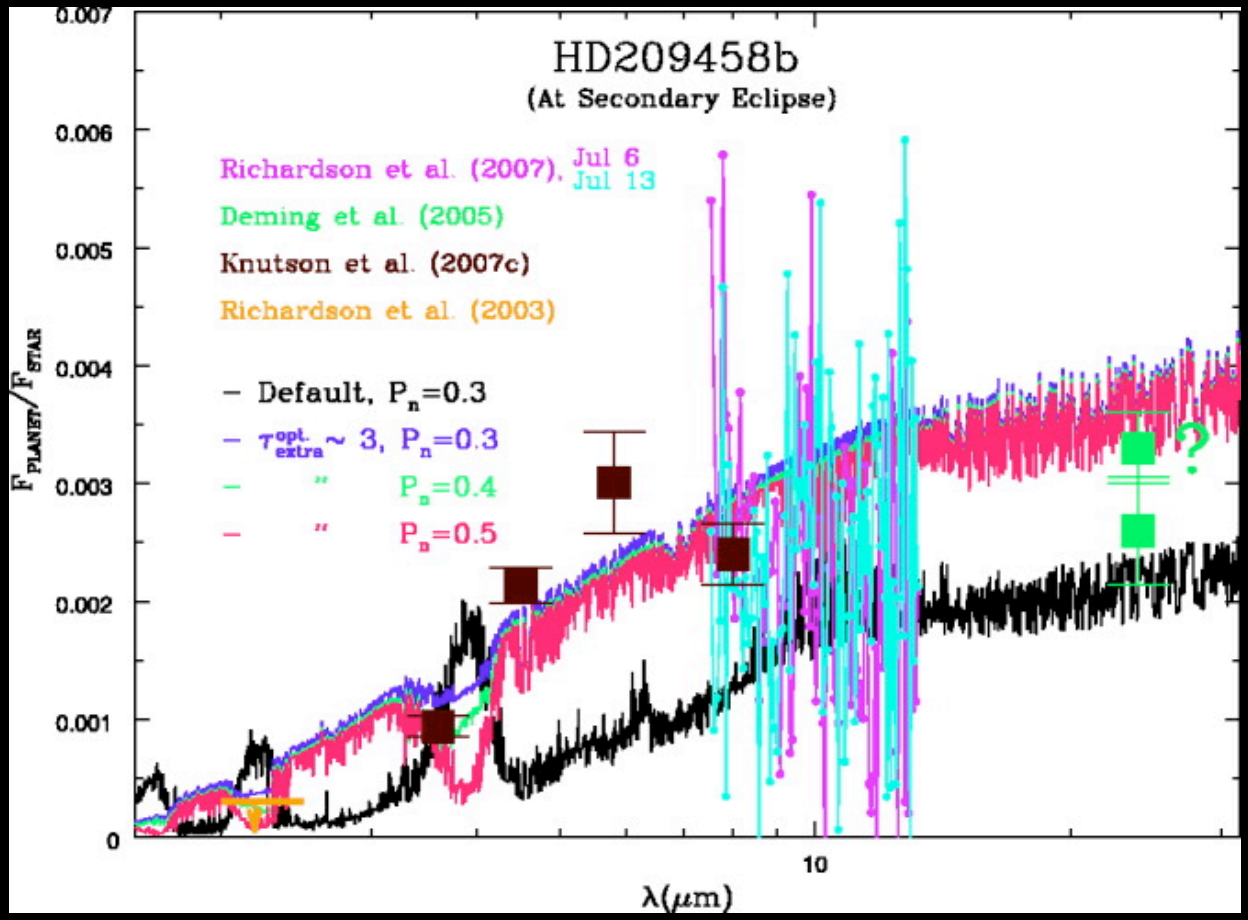


Harrington et al. 2006



CoRoT 1b
Snellen et al. 2009

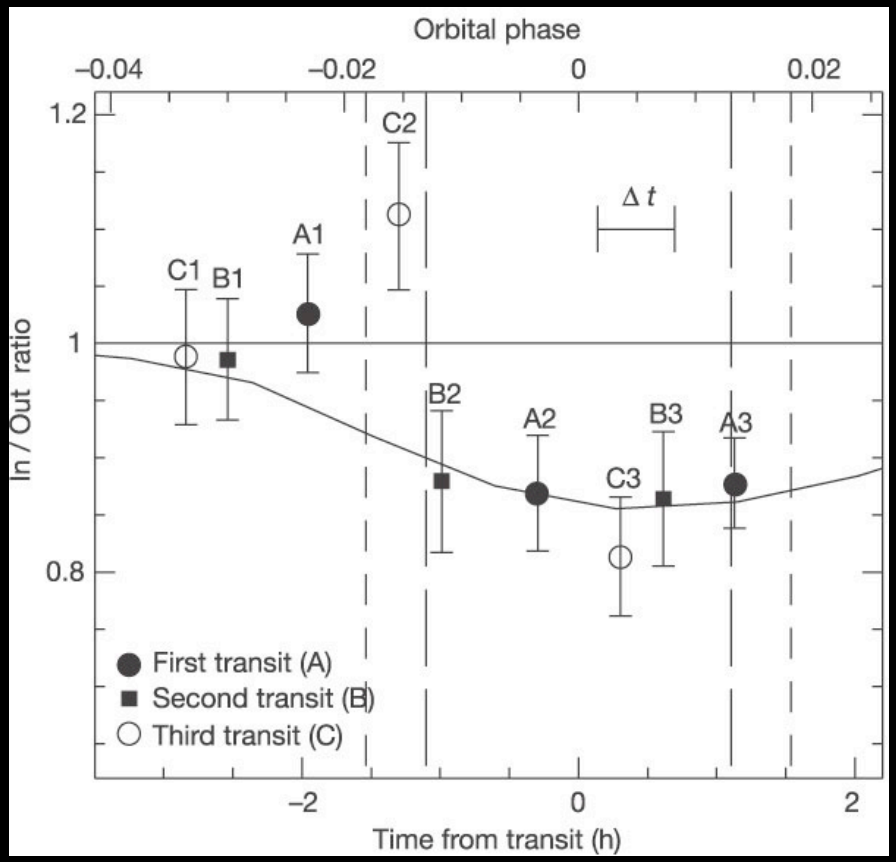
Thermal Inversion

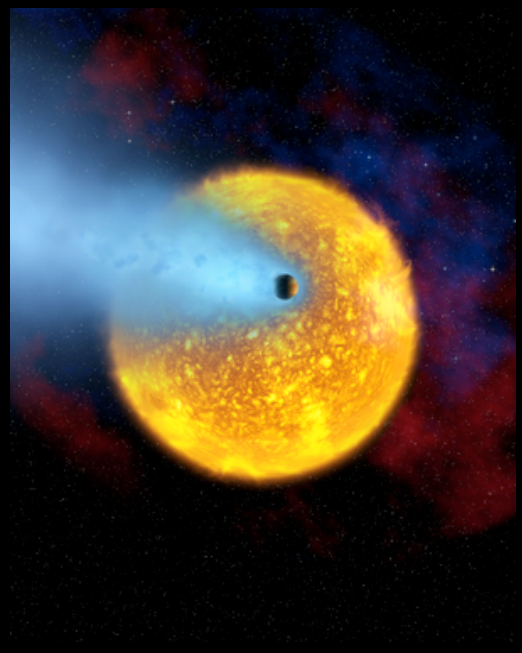


Evidence for thermal inversion assuming water vapor

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

Atmospheric Escape





See J.-M. Desert talk on Atmospheric Escape

Vidal-Madjar et al. 2003

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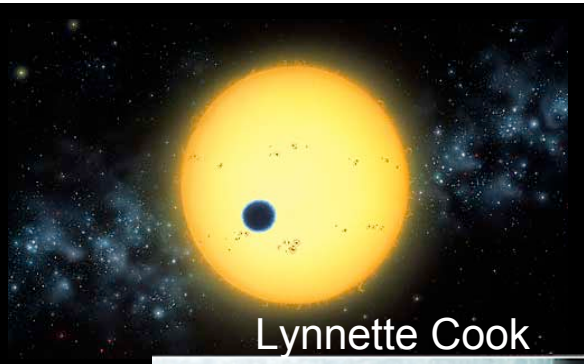
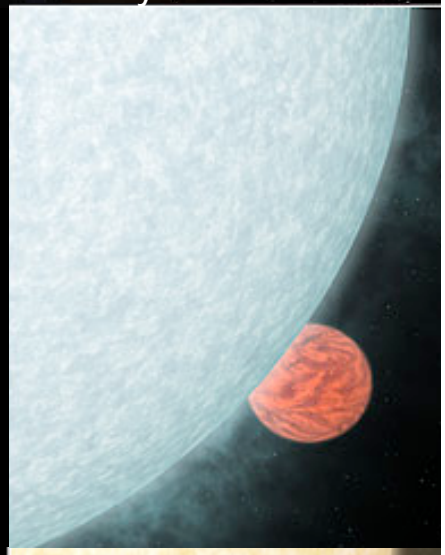
Hot Jupiter Planet-Star Flux Ratios

- 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 ∇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

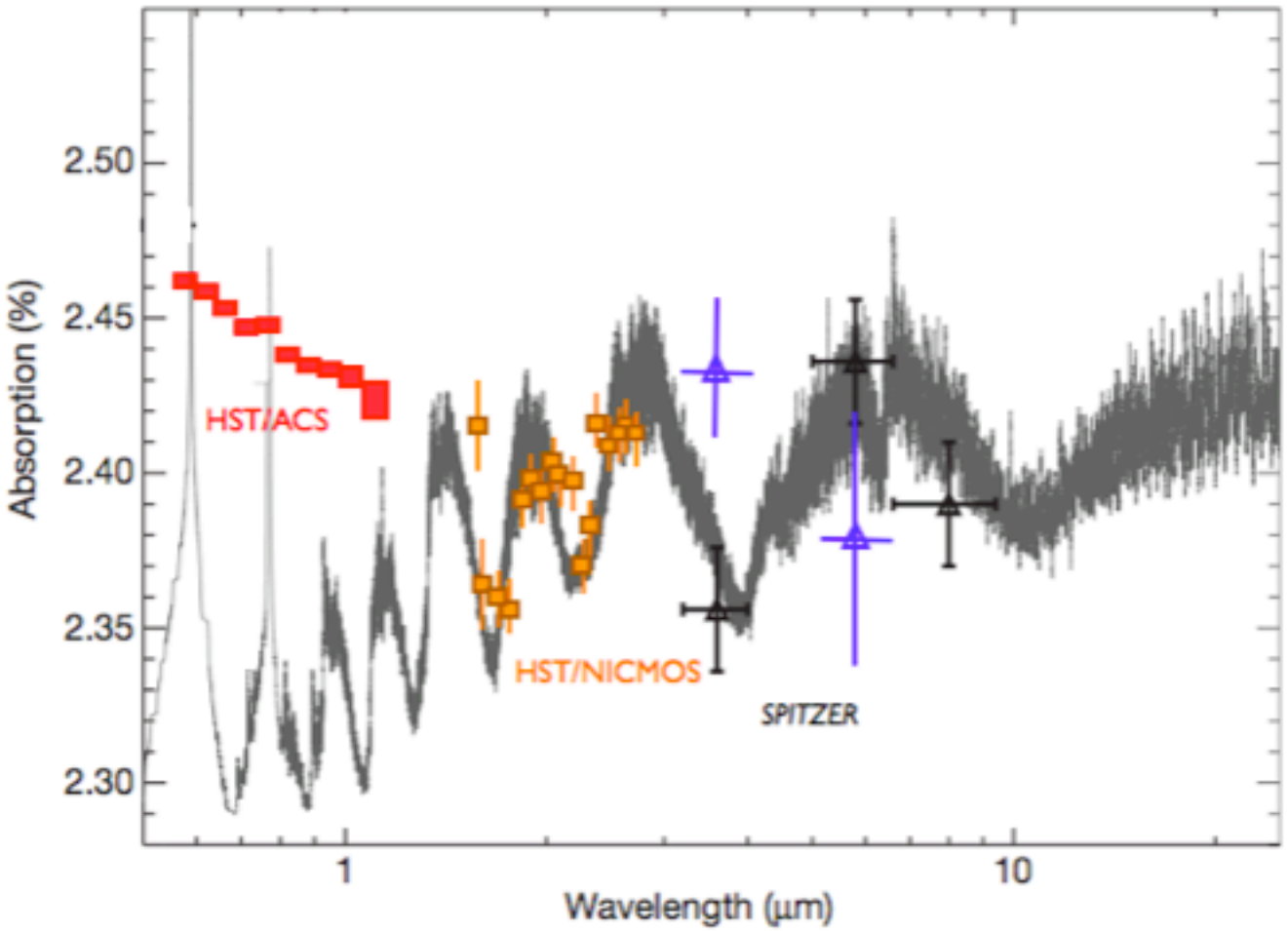
Enabled by a differential measurement but observations are still challenging!


Lynnette Cook




NASA/JPL-Caltech
R. Hurt (SSC)

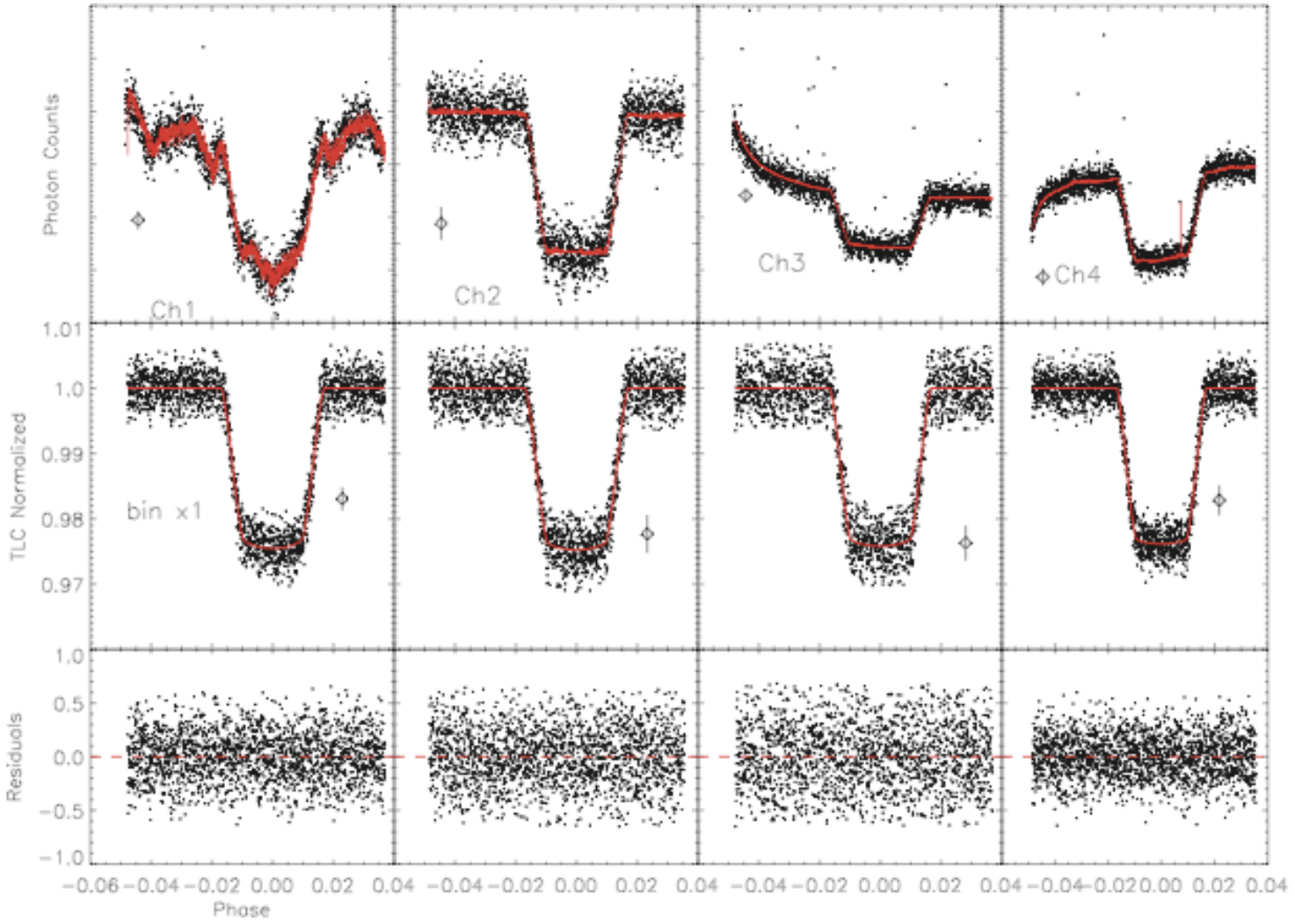
HD 189733 Transmission



Courtesy F. Pont

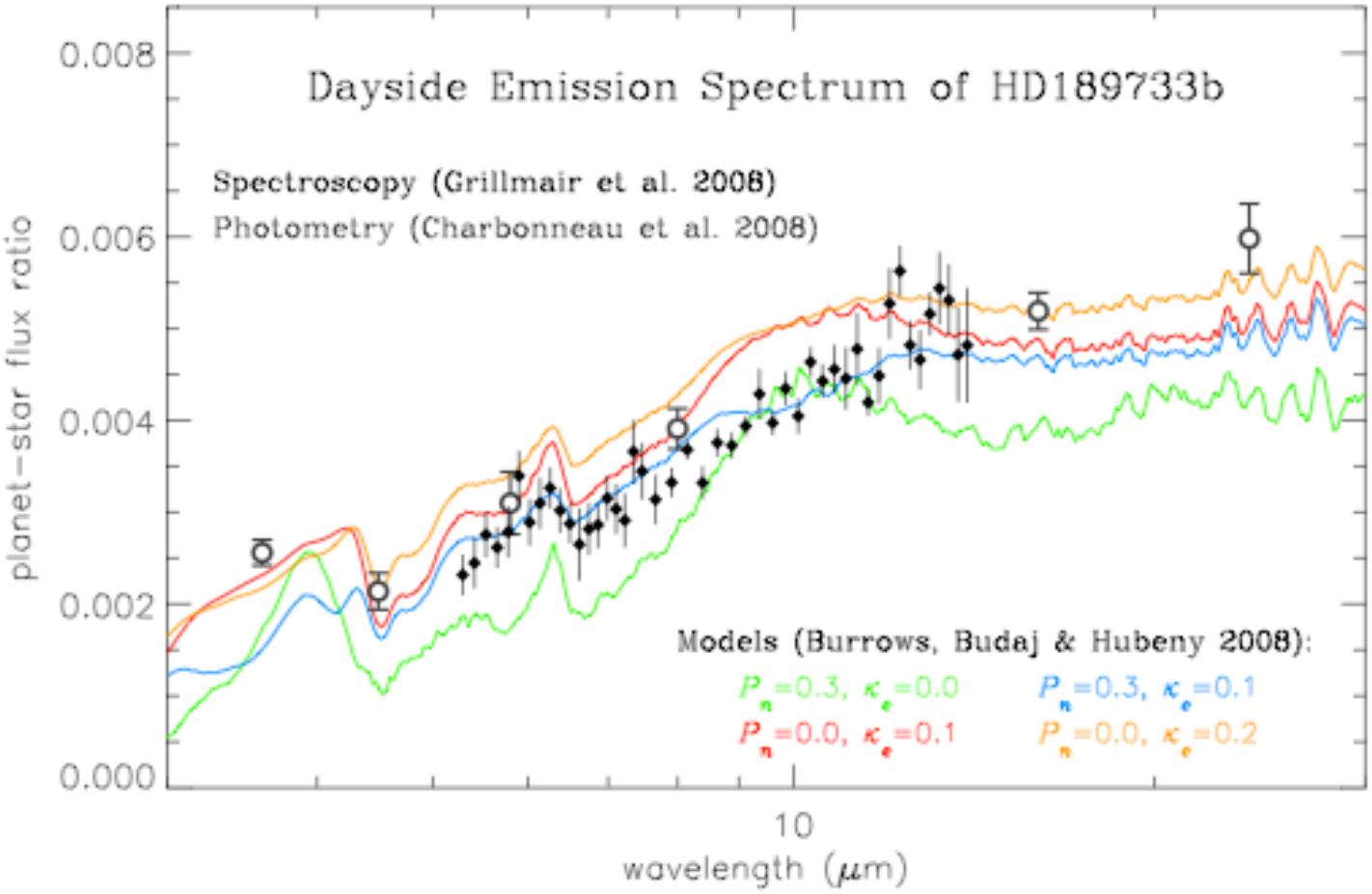
See also Desert et al. 2009

Spitzer HD 189733



Desert et al. 2009

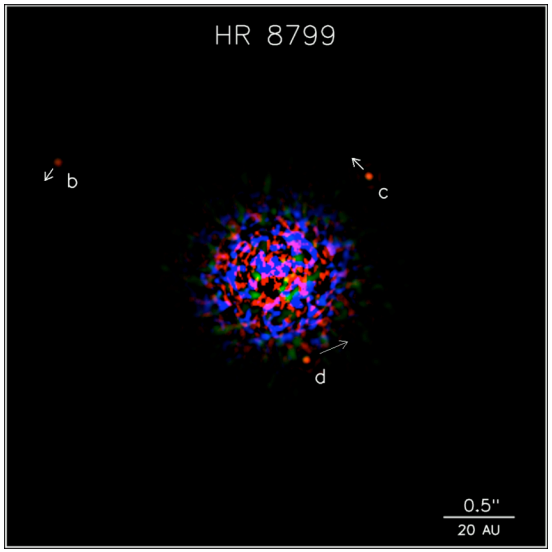
HD 189733 Thermal Emission



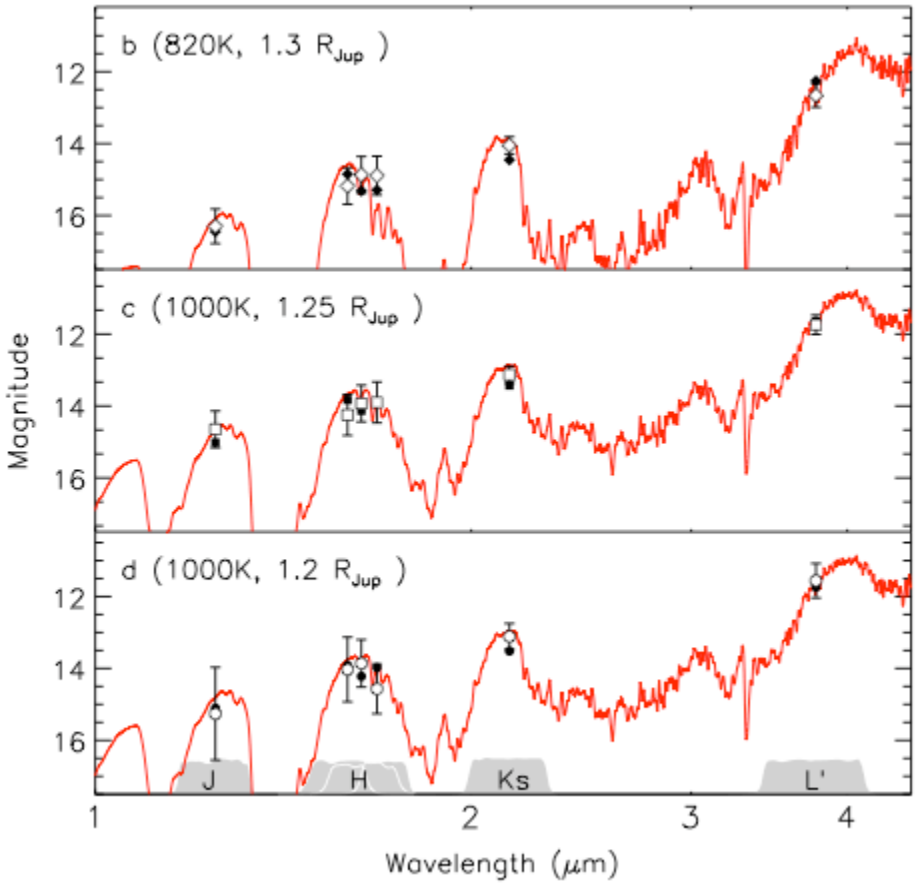
120 hours of *Spitzer* IRS time!

Grillmair et al. 2008

HR 8799 Thermal Emission



Marois et al. 2008



See D. Saumon talk on brown dwarf atmospheres and hot young planets.

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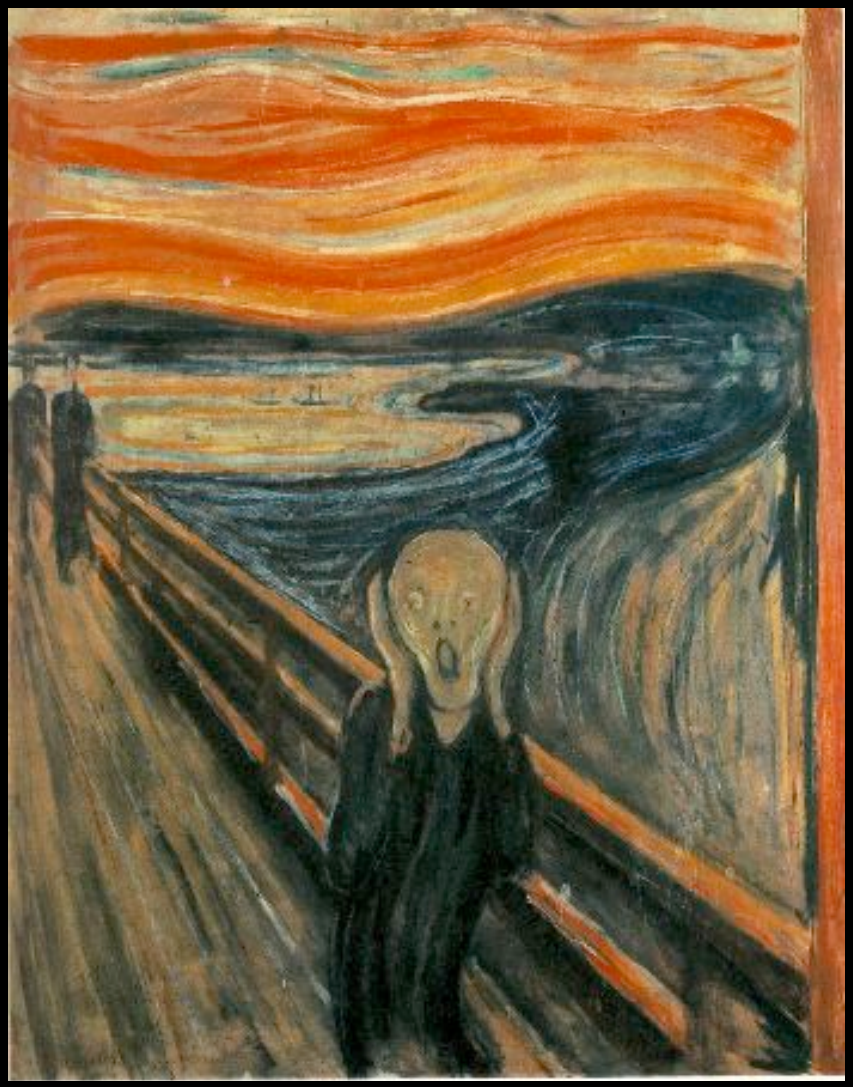
Learned With Models + Data

Prospects

What Have We Learned from Models + Data?



Planet Atmosphere Equations

$$\frac{dI(s,\nu,\mu,t)}{ds} = \varepsilon(s,\nu,\mu,t) - \kappa(s,\nu,t)I(s,\nu,\mu,t)$$

Energy transport

$$E_{out} = E_{in,*} + E_{in,planet}$$

Consv. of Energy
(in each layer)

$$\frac{dP(r)}{dr} = -\frac{Gm(r)\rho(r)}{r^2}$$

Hydrostatic Eq.

$$P = nkT$$

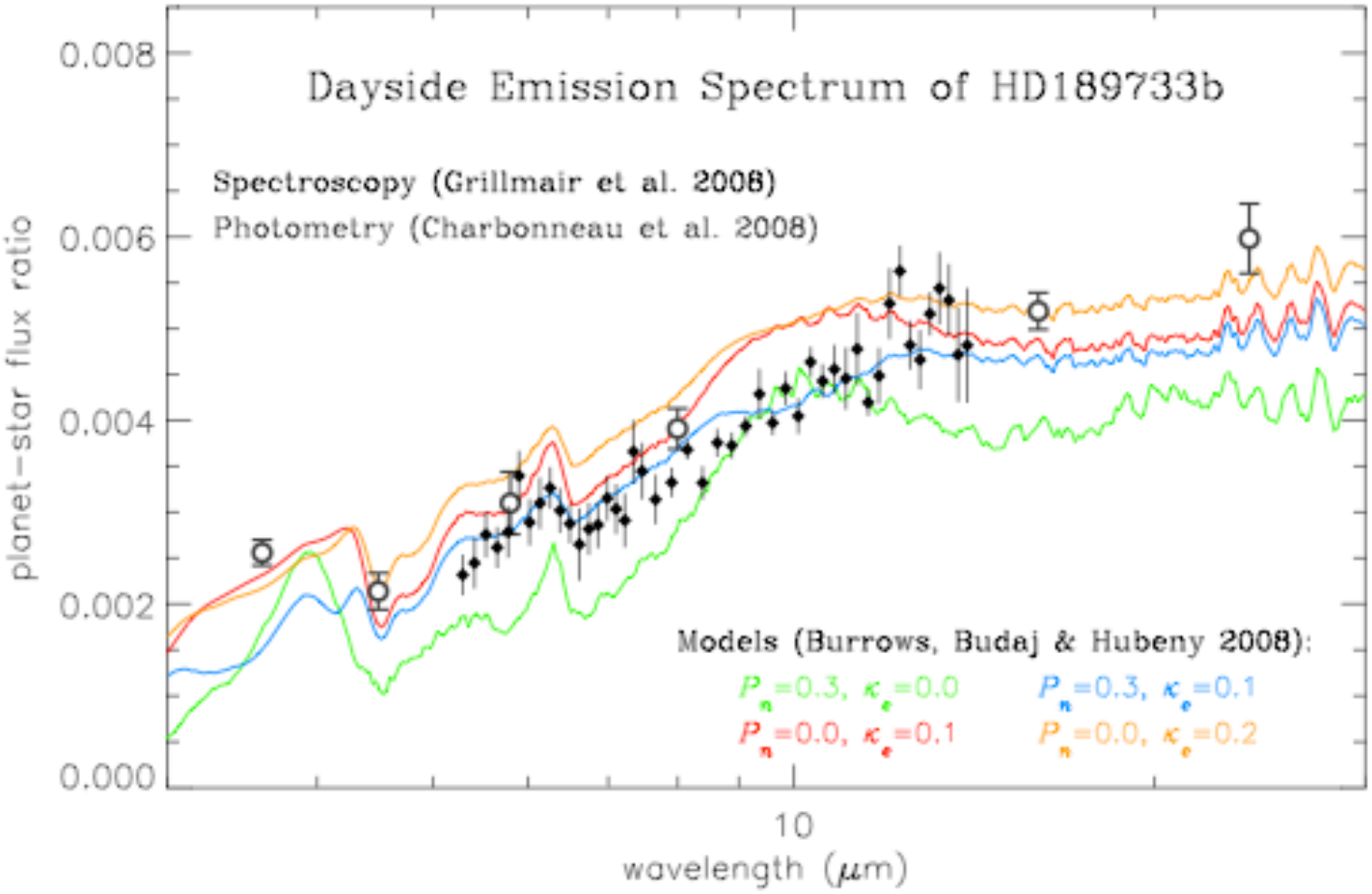
Ideal Gas Law

No simple equation

Chemical Equilibrium

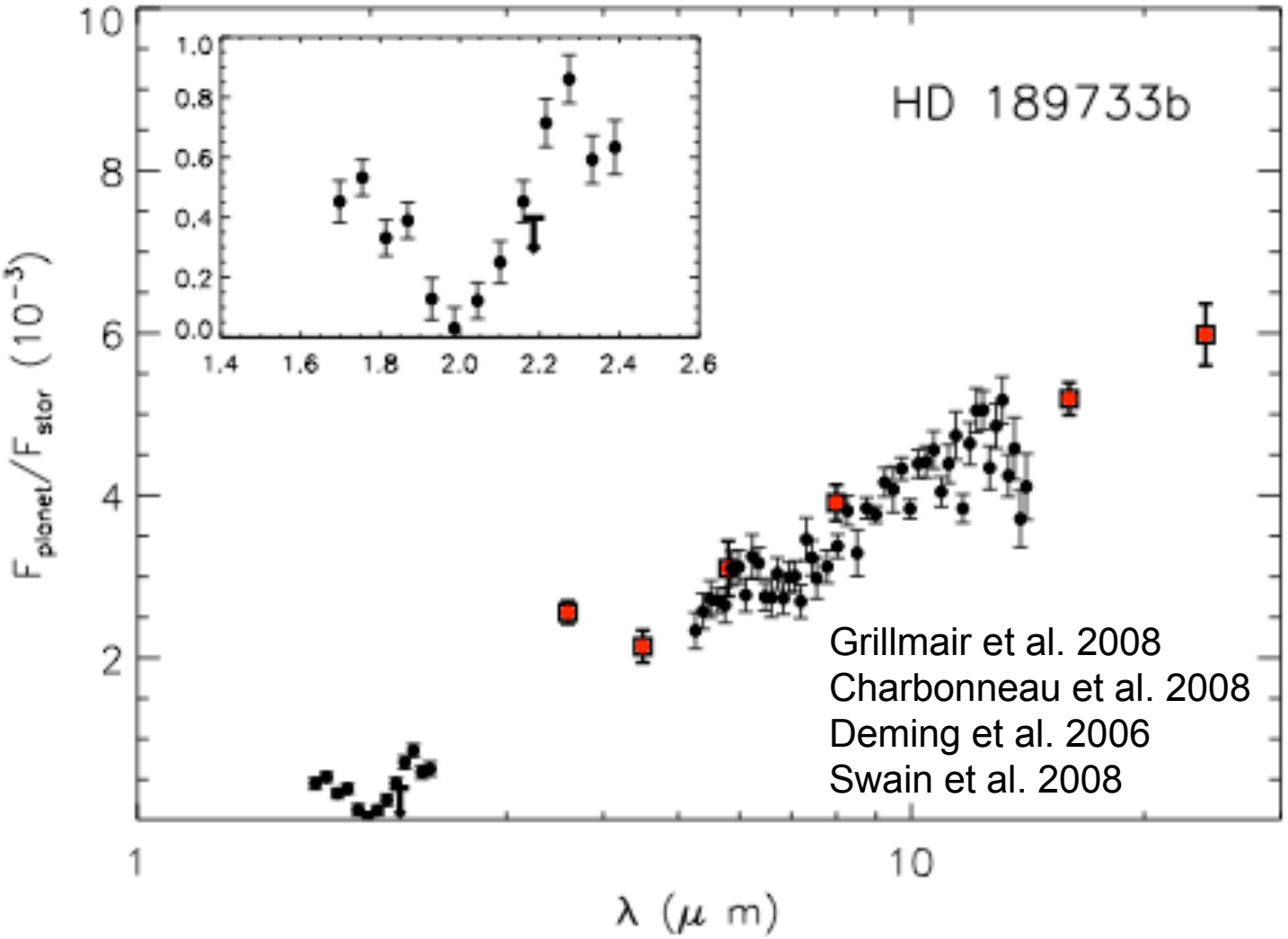
Want to derive: Flux, T, P, ρ, chemical composition

HD 189733 Thermal Emission



120 hours of *Spitzer* IRS time! Grillmair et al. 2008

HD 189733

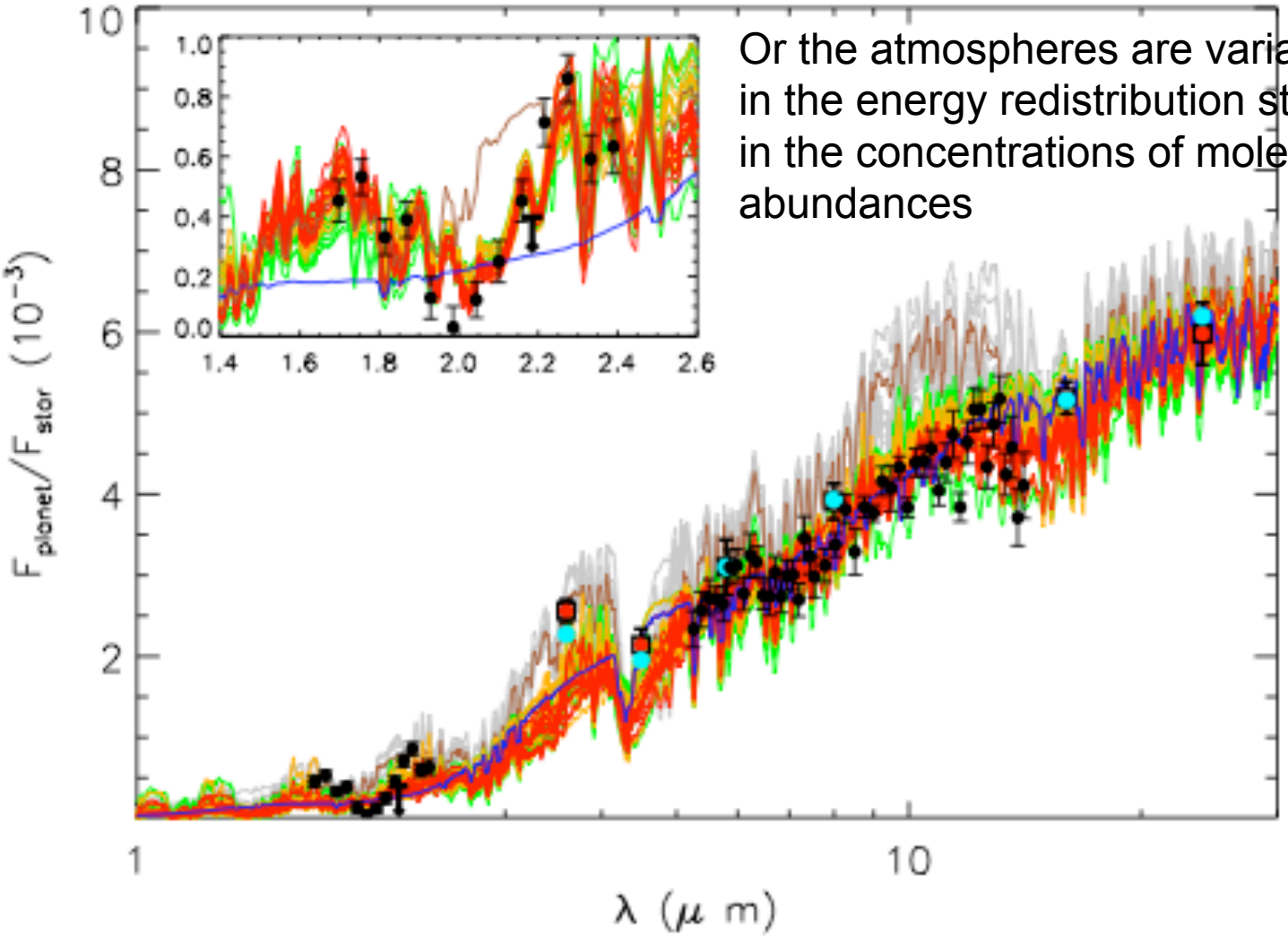


Madhusudhan and Seager, submitted to ApJ

Variability:

True scatter in the data? Then no useful limits on molecular abundances

Or the atmospheres are variable both in the energy redistribution state and in the concentrations of molecular abundances



Madhusudhan and Seager, submitted to ApJ

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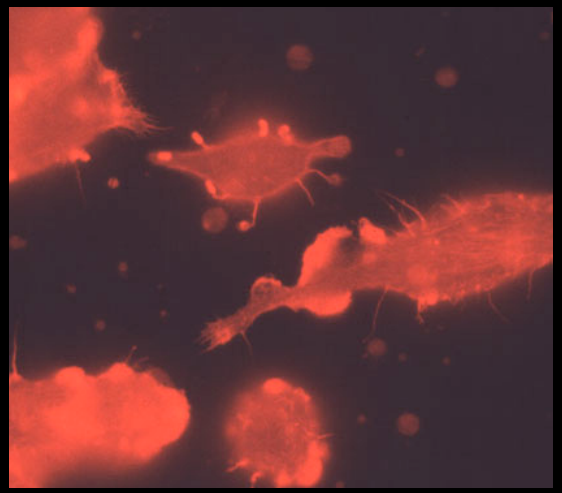
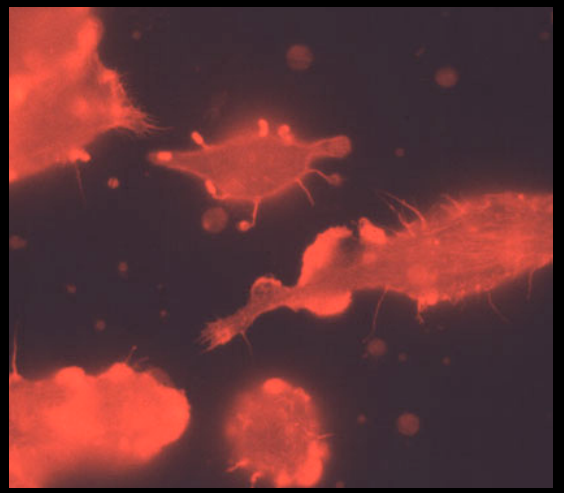
www.geocities.com/ artboook2001/alien-555.jpg



www.listeriablog.com/listeria2.jpg

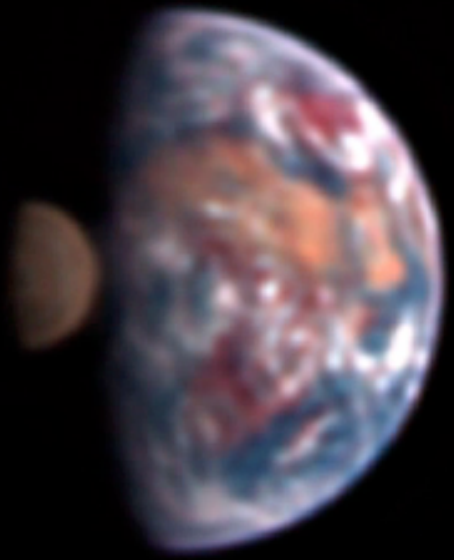
Prospects

www.geocities.com/ artboook2001/alien-555.jpg



www.listeriablog.com/listeria2.jpg

“Nothing would be more tragic in the American exploration of space than to encounter alien life and fail to recognize it…” COEL report 2007



NASA/EPOXI PI: M. A'Hearn Deputy PI: D. Deming

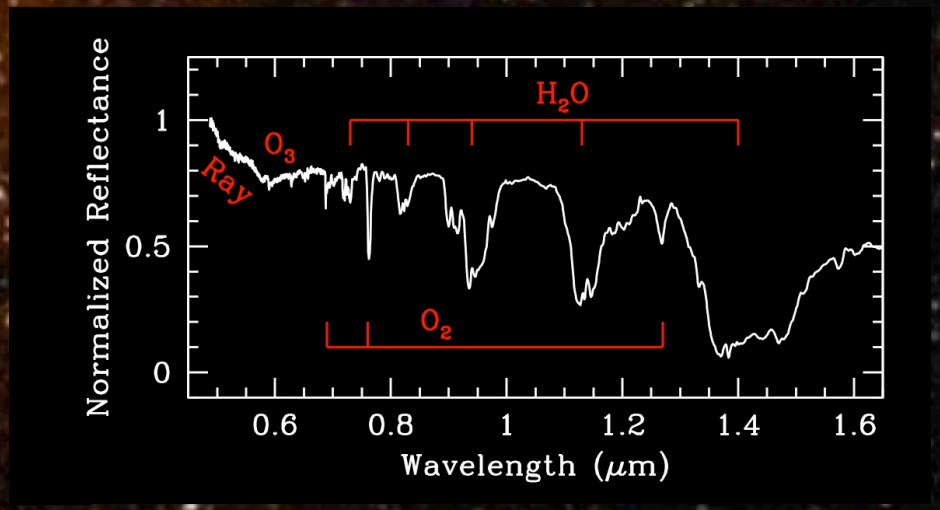
EPOCh + DIXI + = EPOXI

Don Lindler/GSFC

http://www.nasa.gov/topics/solarsystem/features/epoxi_transit.html

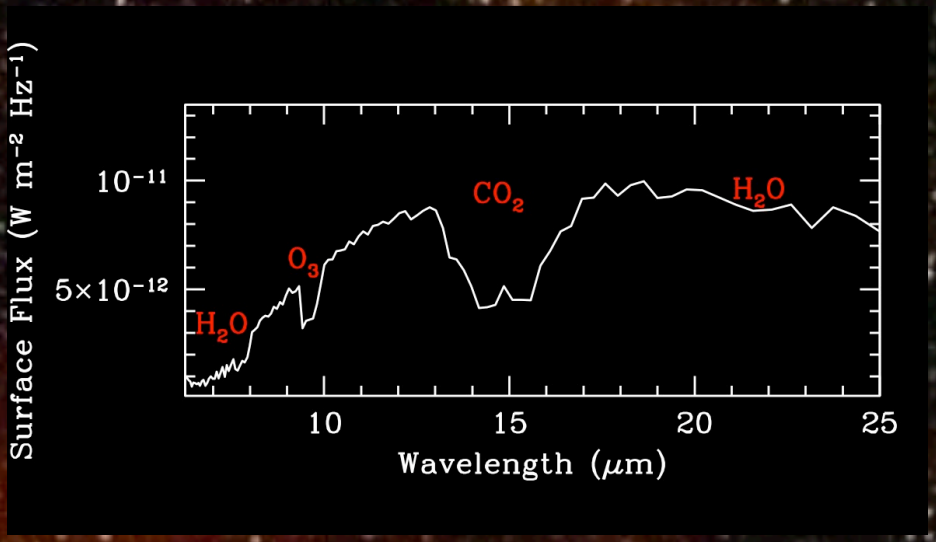
Earth as an Exoplanet

Earth's Spectrum



What we have learned

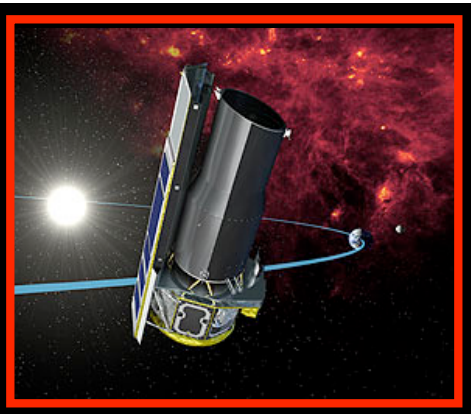
- H_2O, O_2, O_3, CO_2
- Rayleigh scattering
- Red edge?



Turnbull et al. 2007

Pearl and Christensen 1997

Lessons Learned



- Robust Findings
  - Always start with what you can learn from the data without models
  - Hot Jupiter highlights
    - Atom/Molecule identification
    - Day-night temperature gradients
    - Thermal inversions
    - Atmospheric Loss
- Understand the Data
  - How dependent is the data on the removal of systematics?
- Understand the Models
  - Computational applied physics models are needed for further data interpretation
  - Make a list of the free parameters in the models and understand their input range and effect on model output