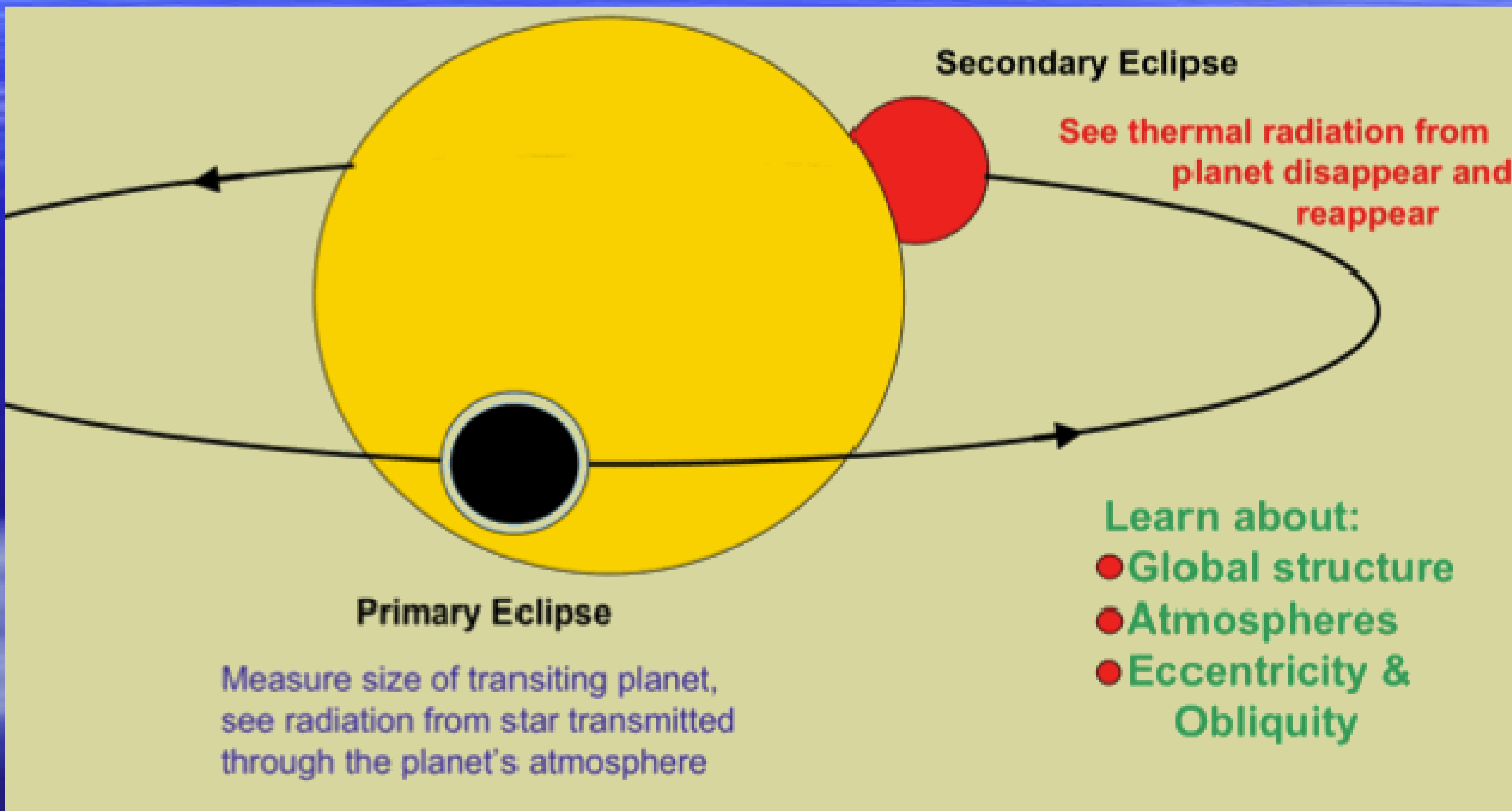
Transiting Exoplanets: Photometry and Spectroscopy

C. J. Grillmair

10 November, 2009

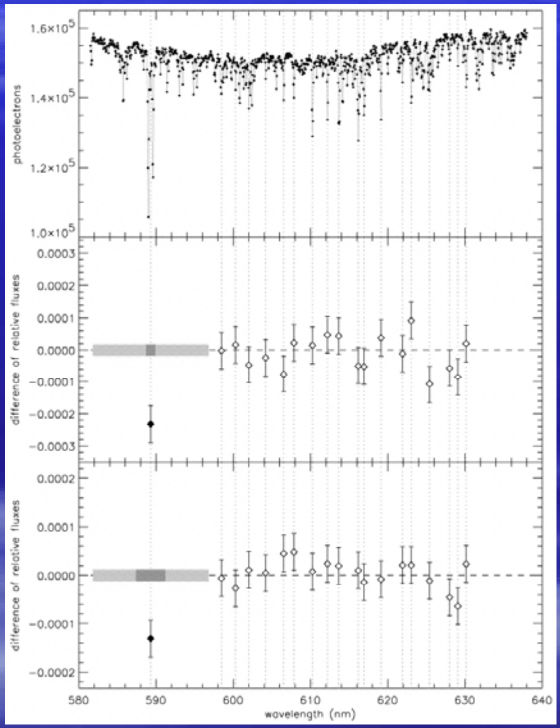
Why Transits?

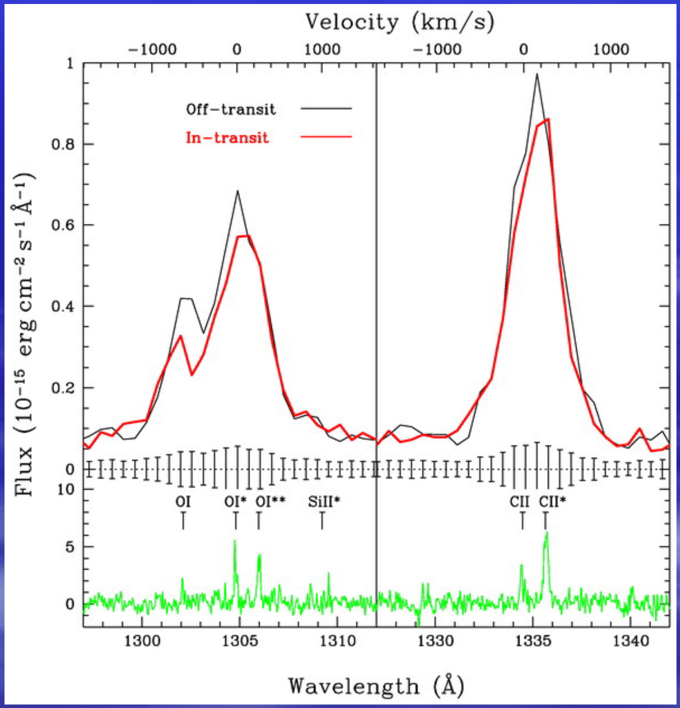


Courtesy Lori Allen

Transmission Spectra

Primary transit spectra of HD 209458b with STIS spectroscopy



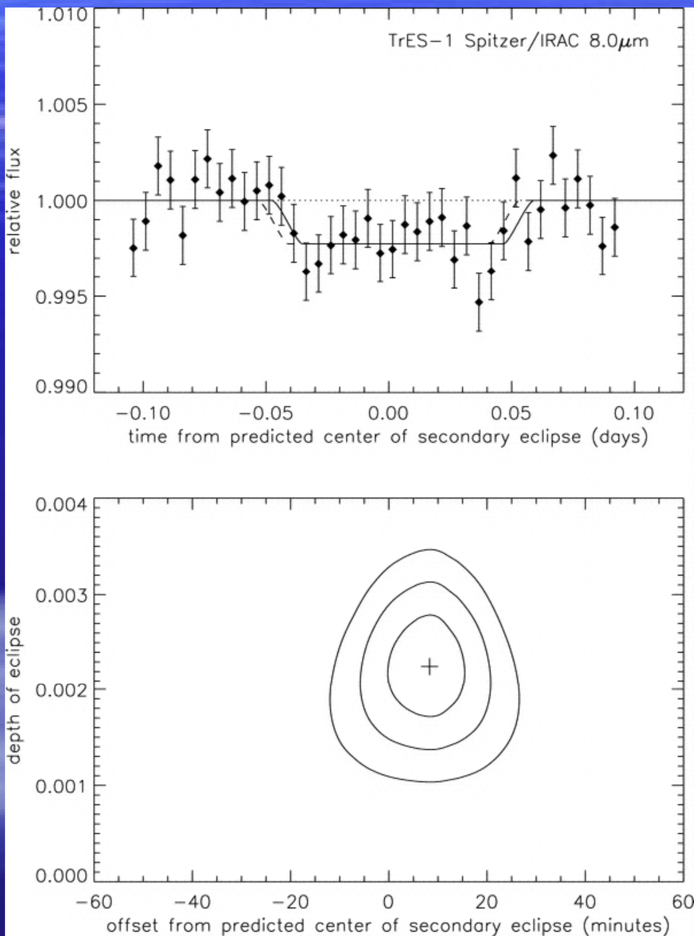


Charbonneau et al. 2002, ApJ, 568, 377

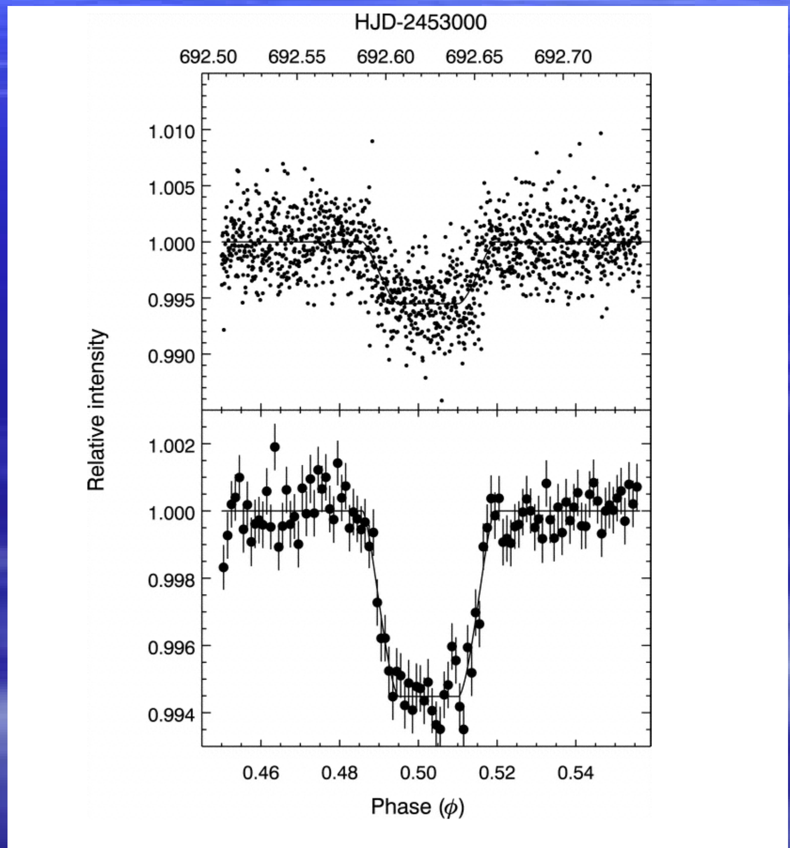
Vidal-Madjar et al. 2004, ApJ, 604, L69

First Detections of EP Photons

Broad-band photometry at secondary eclipse

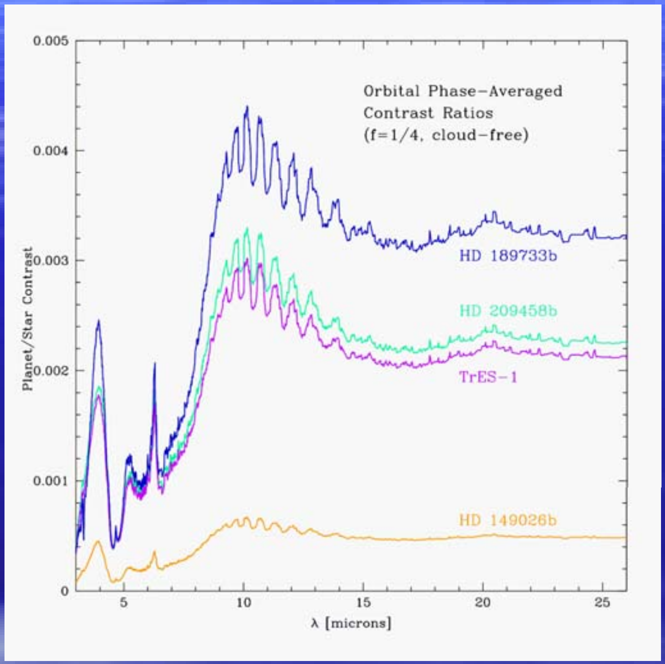


Charbonneau et al. 2005, ApJ, 626, 523



16 μm Peak-Up Imaging
Deming et al. 2006, ApJ, 644, 560

Spectroscopy Candidates to Date

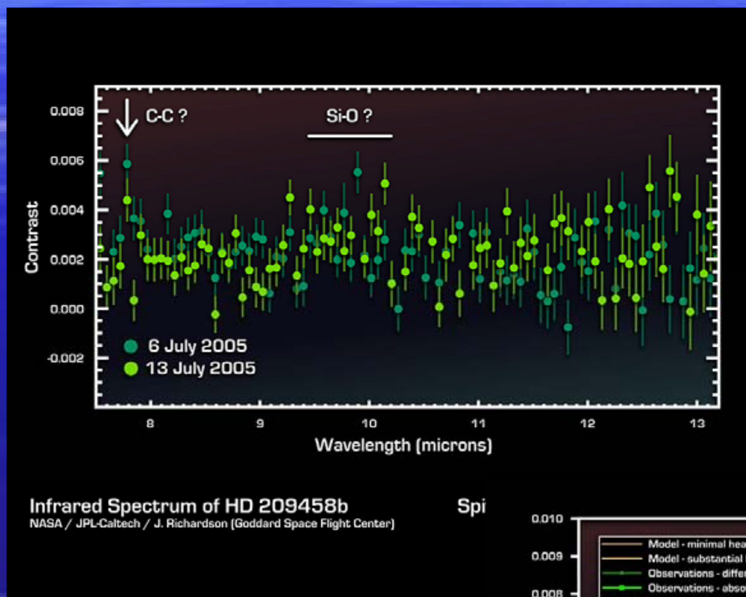


Burrows et al. 2005

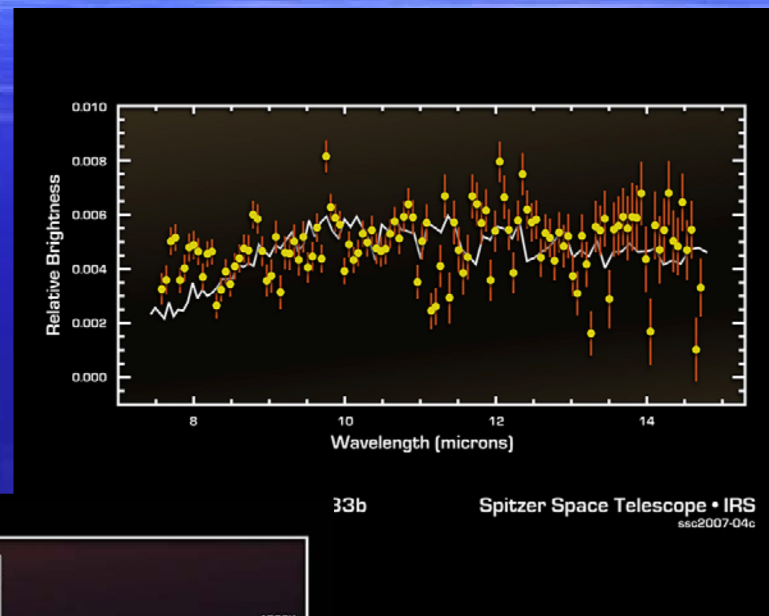
	HD 189733b	HD 209458b
Distance	19 pc	47 kpc
Spectral Type	K0 V	G0 V
Brightness	V = 7.8	V=7.7
Orbital Period	2.2 days	3.5 days
Orbital Radius	0.031 AU	0.047 AU
Orbital Inclination	85.79°	86.68°
Planetary Radius	1.154 R_J	1.32 R_J
Planetary Mass	1.15 M_J	0.69 M_J
Eclipse Duration	1.9 hrs	3.9 hrs
Flux Ratio @ 10μm	0.5%	0.4%

First Emission Spectra

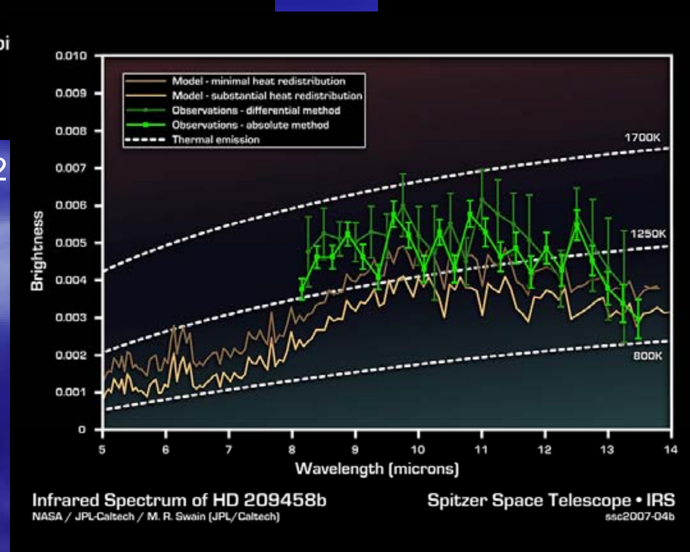
Spitzer spectroscopy at secondary eclipse



Richardson et al. 2007, Nature 445, 892



Grillmair et al. 2007, ApJ, 658, L115



Swain et al. 2008, ApJ, 674, 482

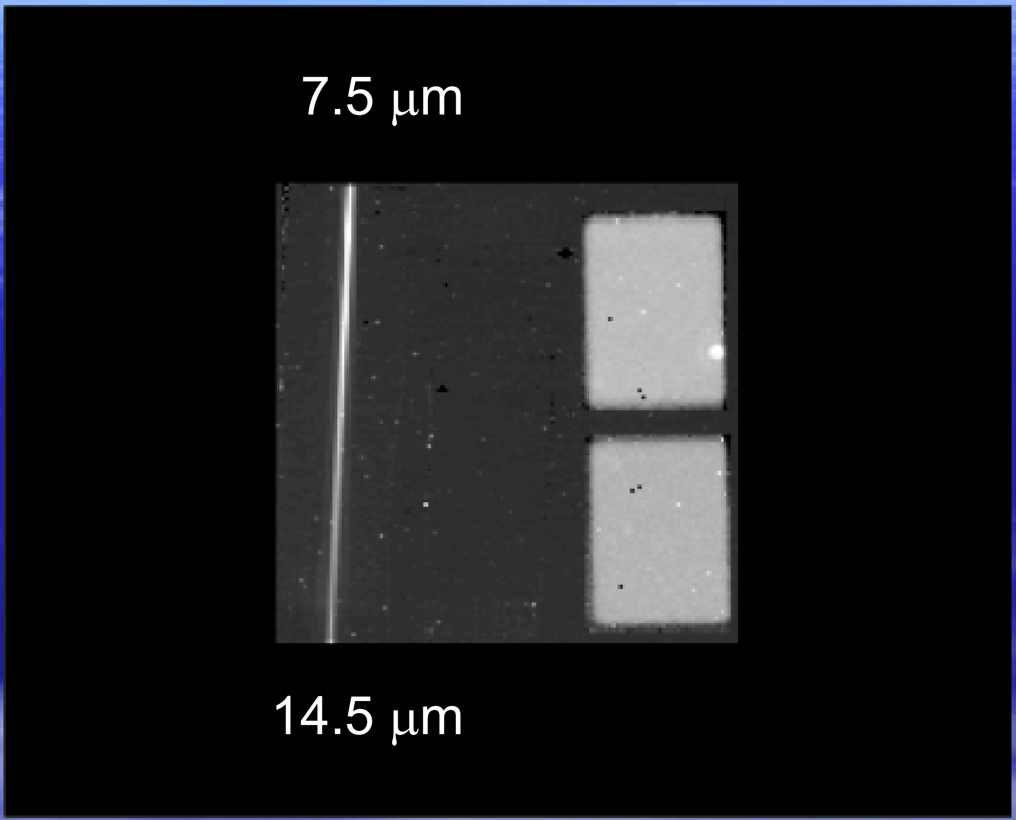
Spectroscopy

- Used the Infrared Spectrograph as 128 independent single-channel photometers.
- Since absolute calibration of IRS only good to ~2%, all measurements need to be differential.
- Several observing techniques have been tried, including:
  - Observe at one nod position, then at the other, and making sure eclipse profiles are mirror image of each other.
  - Nod back and forth slowly to prevent latent charge build-up.
  - Keep target at fixed position on the detector.

Signal-to-Noise

- Within each eclipse observation, signal-to-noise ratio is dominated by the 2-4 hour duration of the eclipse.
- Increasing signal-to-noise ratio simply requires observing more eclipses.
- For a fixed time allocation, 6-hour observations provided sufficient out-of-eclipse measurements to establish star+planet flux without significantly compromising S/N.
- Future missions will need to have appropriate scheduling flexibility.

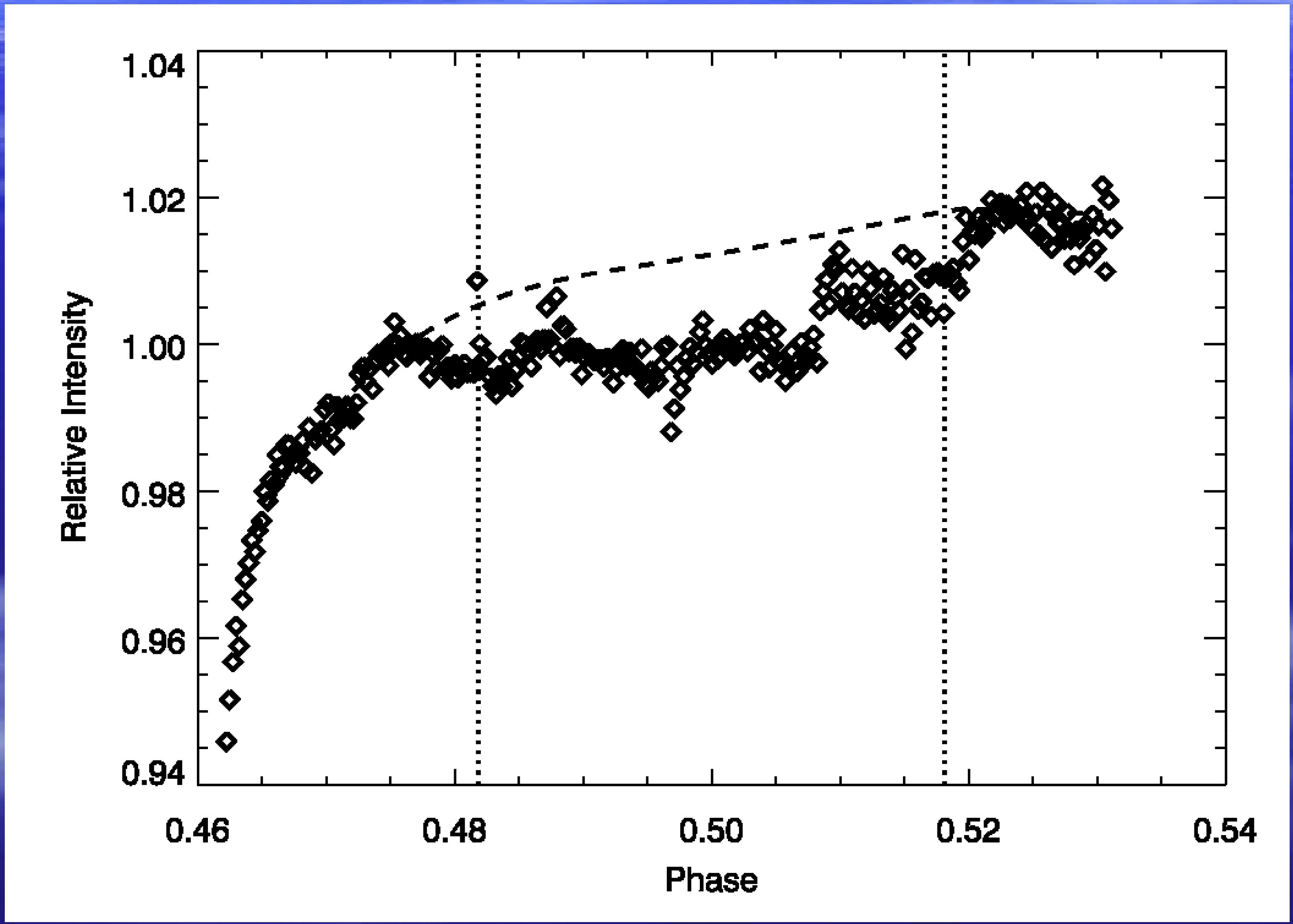
IRS Spectra



Short-Lo, 1st order, R ~ 60
Short-Lo, 2nd order, R ~ 120

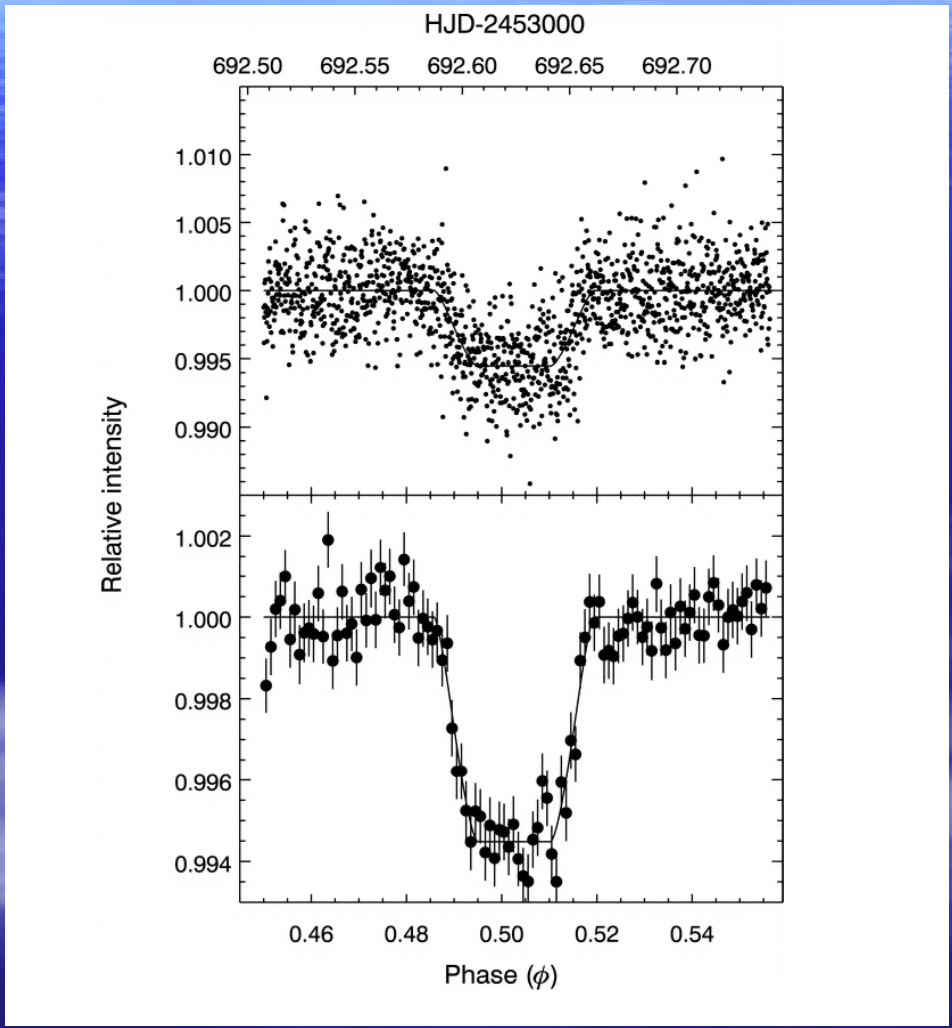
- For HD 189733, used standard SSC pipeline processing products, or Basic Calibrated Data (BCDs).
- 2D images were background-subtracted using off-order regions.
- 8045 individual spectra were extracted using SSC tool SPICE.
- Extraction carried out using fixed aperture windows and “non-optimal” extraction:
  - Reduce noise, preserve pointing oscillations and detector drifts, and avoid undersampling effects.

Time Series Spectrophotometry: Latents and Drifts

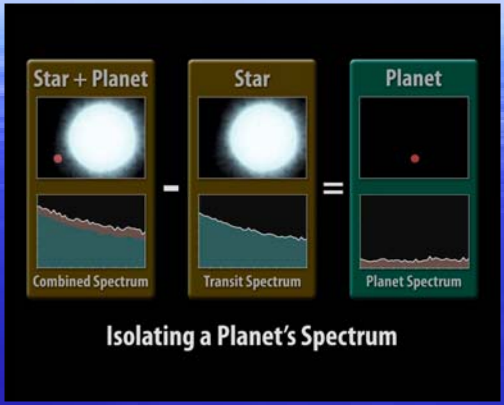


Richardson et al. 2007, Nature 445, 892

A Useful Constraint

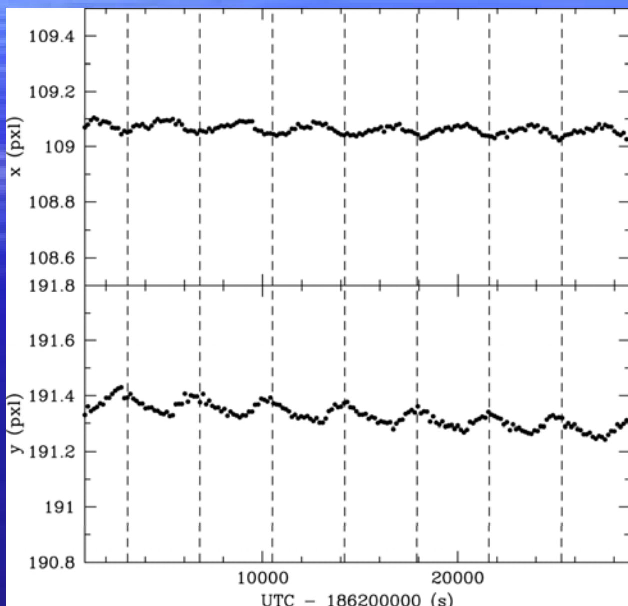


16 μm Peak-Up Imaging
Deming et al. 2006, ApJ, 664, 560

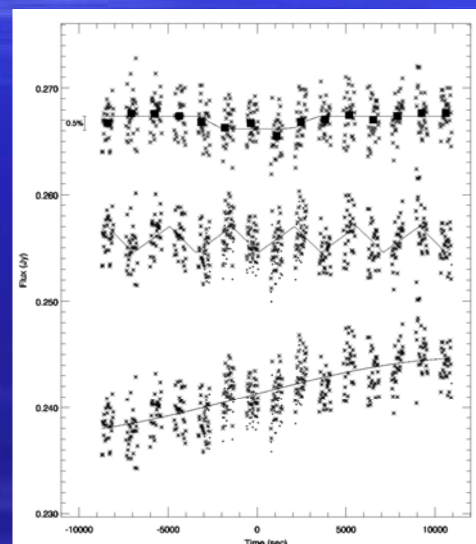


- For each wavelength bin, use a single, photometrically-determined model light curve.
- Fit only for a single parameter, namely the depth of eclipse.
- Light curve fitting (as opposed to in-eclipse – out-of-eclipse subtraction) has the advantage that it makes use of the ingress and egress portions of the data.

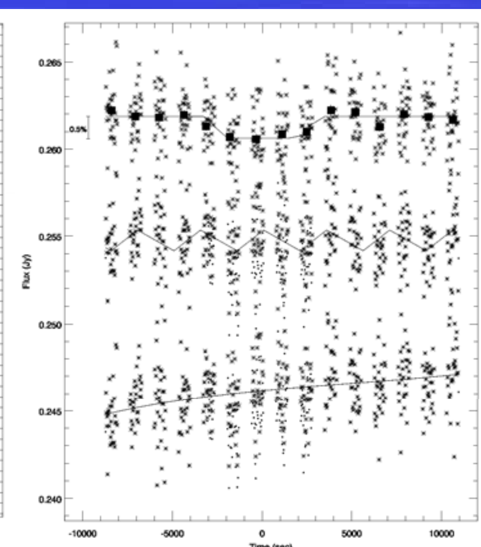
Effects of Pointing Oscillations



Morales-Calderon et al. 2006, ApJ 653, 1454



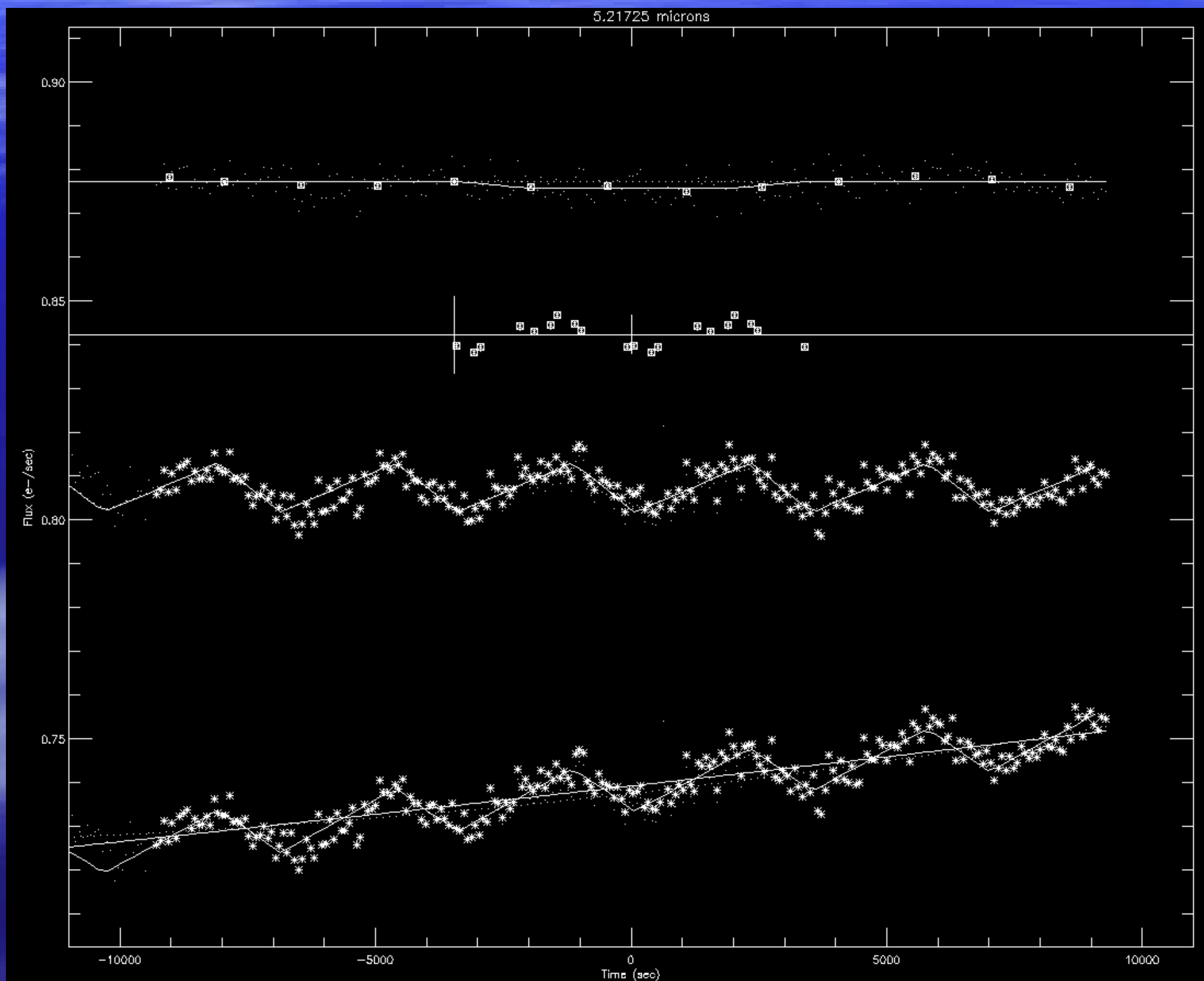
9.81 μm



9.87 μm

Limited flat fielding accuracy and intrapixel sensitivity variations ➔ pointing oscillations can push measured fluxes in either direction.

Telescope/Detector Signature Removal



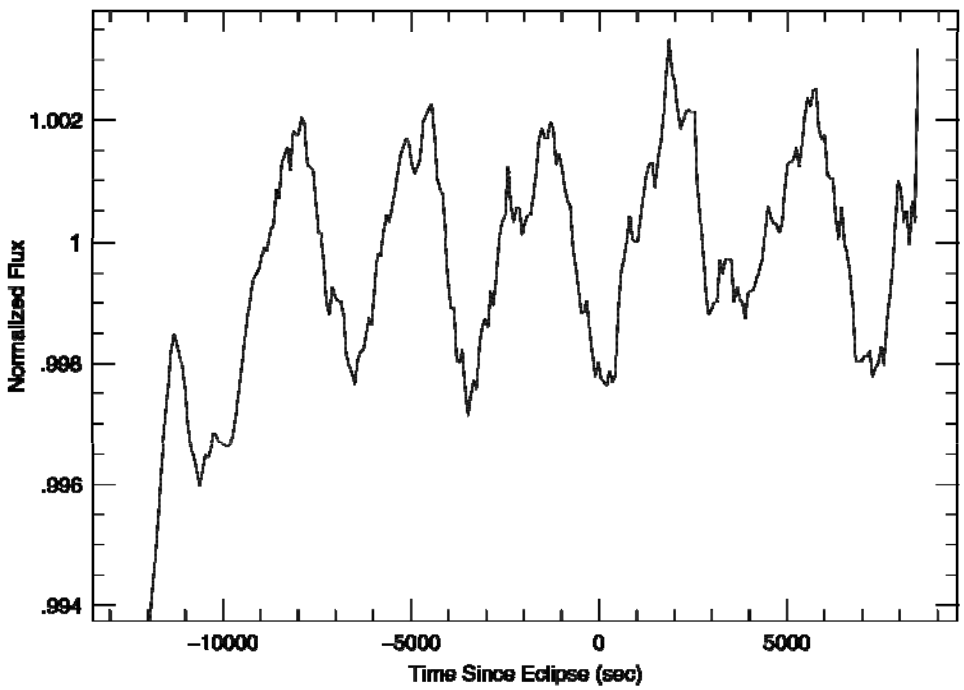
(4) Iterate to minimize χ^2

(3) Fit light curve – depth is the spectral contrast ratio at this wavelength.

(2) Fit for amplitude (+ or -) of sawtooth and divide out. Phase and shape of sawtooth are unique for each eclipse observation.

(1) Guess at the eclipse depth, divide by the scaled light curve, fit for and divide by a polynomial ramp.

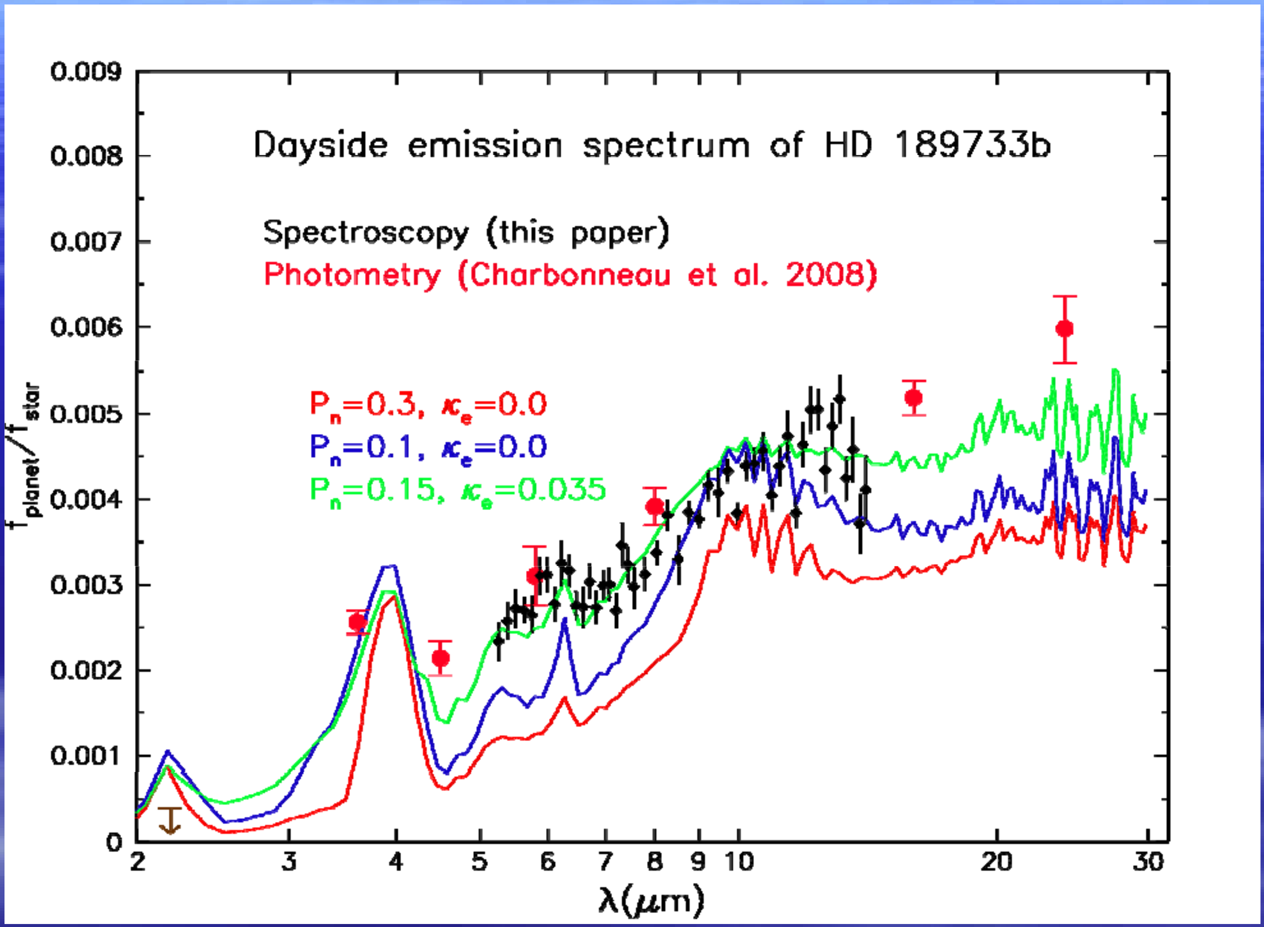
Non-periodic Pointing Oscillations



Refined sawtooth/pointing model

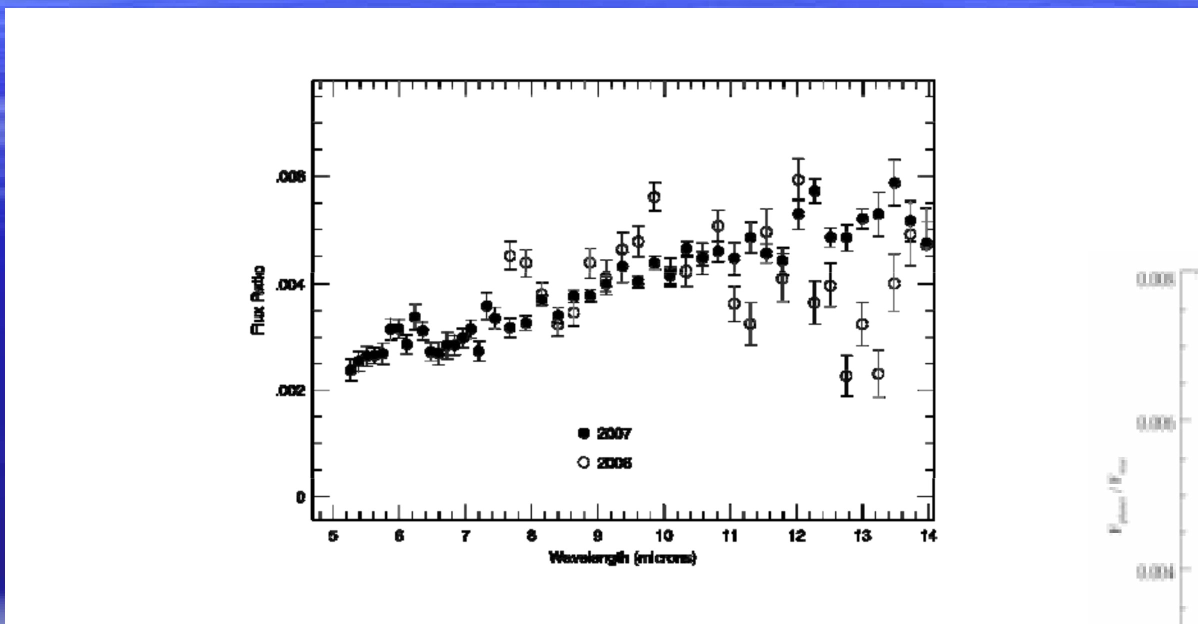
9.87 μm

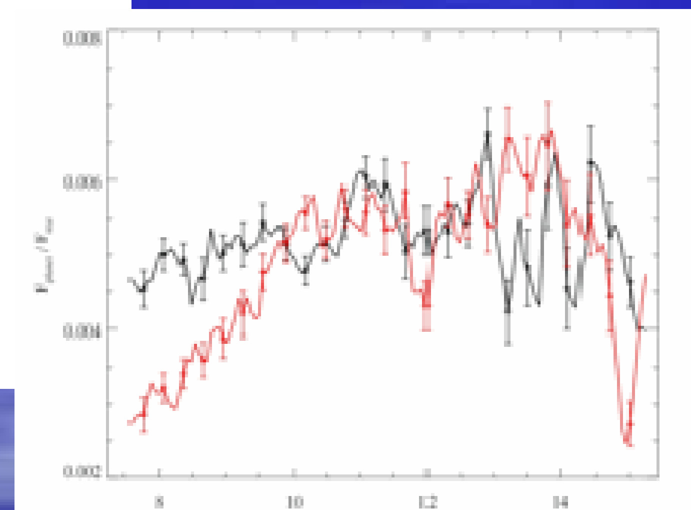
Composite HD 189733b Spectrum



Grillmair et al. 2008, Nature 456, 767
Charbonneau et al. 2008, ApJ 686, 1341
Barnes et al. 2007, MNRAS 382, 473

Variations with Time?

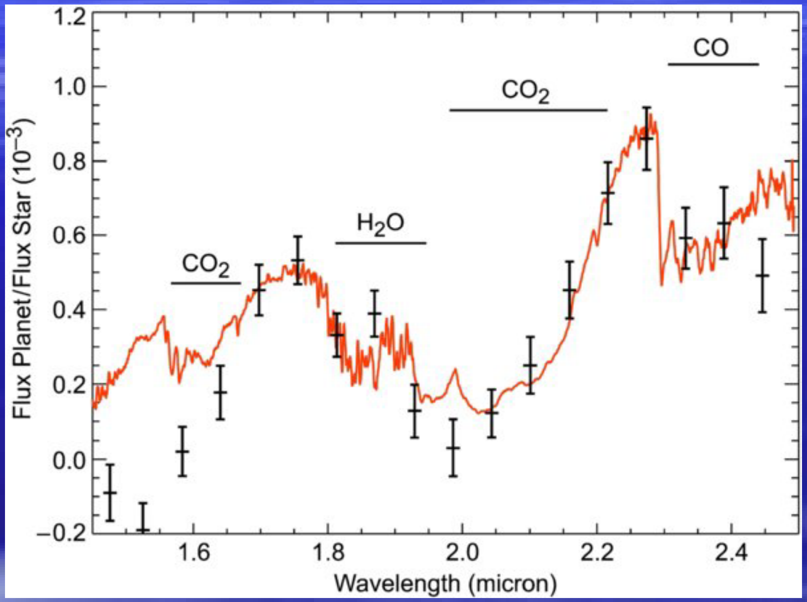




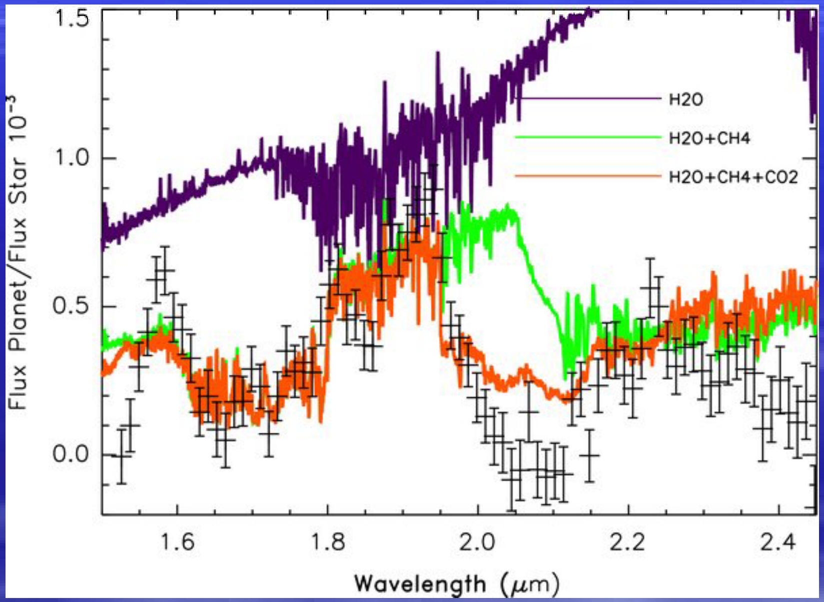
Exposure time non-linearities?Large-scale weather?

Swain, Bouwman, et al., in prep.

NICMOS – CO, CO_2, & Methane

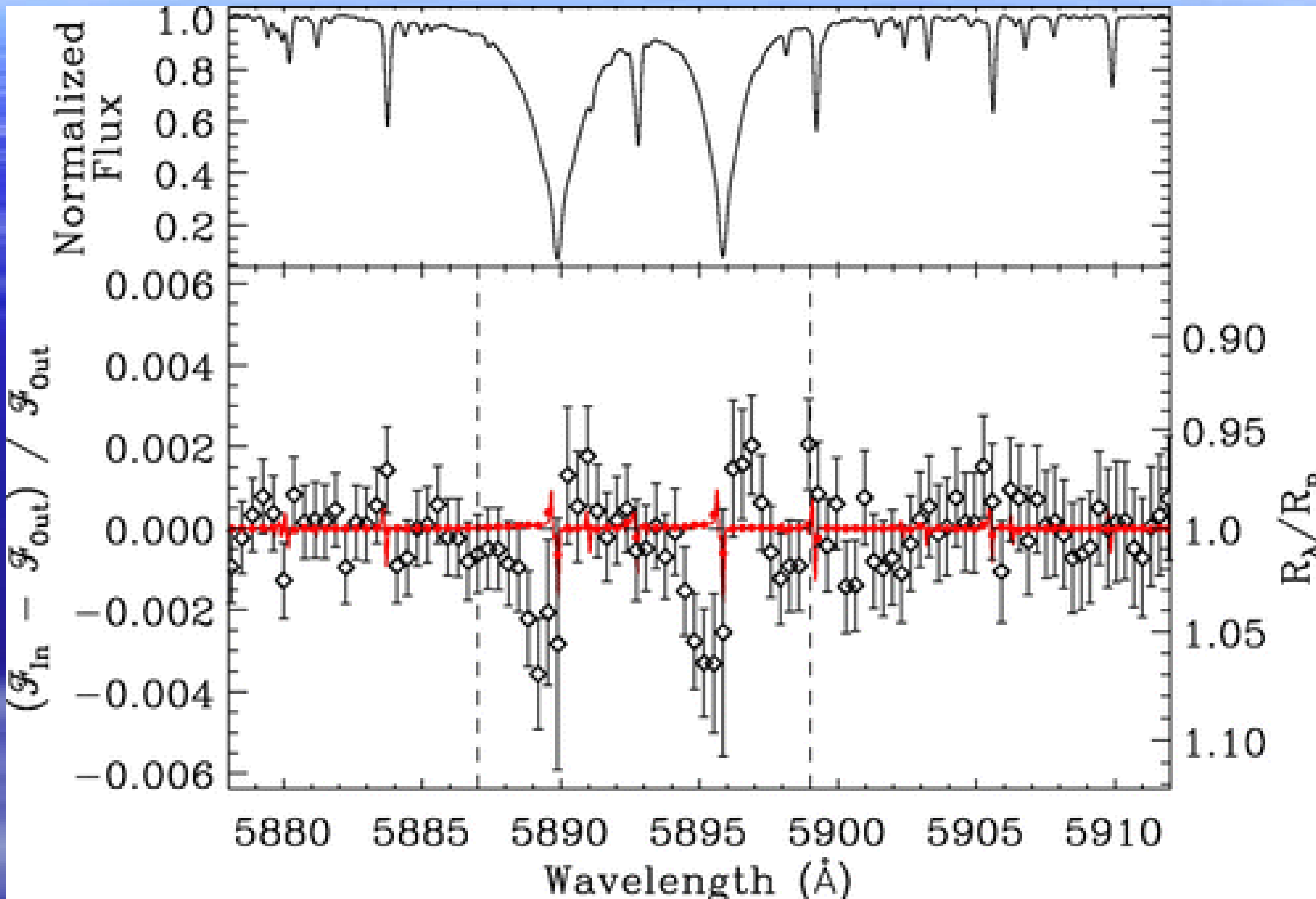


HD 189733b
Swain et al. 2009, ApJ, 690, L114



HD 209458b
Swain et al. 2009, ApJ, 704, 1616

Sodium in HD 189733b – from the Ground?



Redfield et al. 2008, ApJ, 673, L87

Lessons Learned

- Photometry and spectroscopy of transiting extrasolar planets are reasonably straightforward for bright stars and large, hot planets.
- Future transit observations of fainter stars and smaller, cooler planets would benefit from:
  - better pointing stability on all time scales
  - preflashing or other pre-exposure detector conditioning
  - simultaneous offset comparison star monitoring
  - improved inter- and intra-pixel flat-fielding
  - all-sky scheduling flexibility
  - broader wavelength coverage
  - bigger aperture