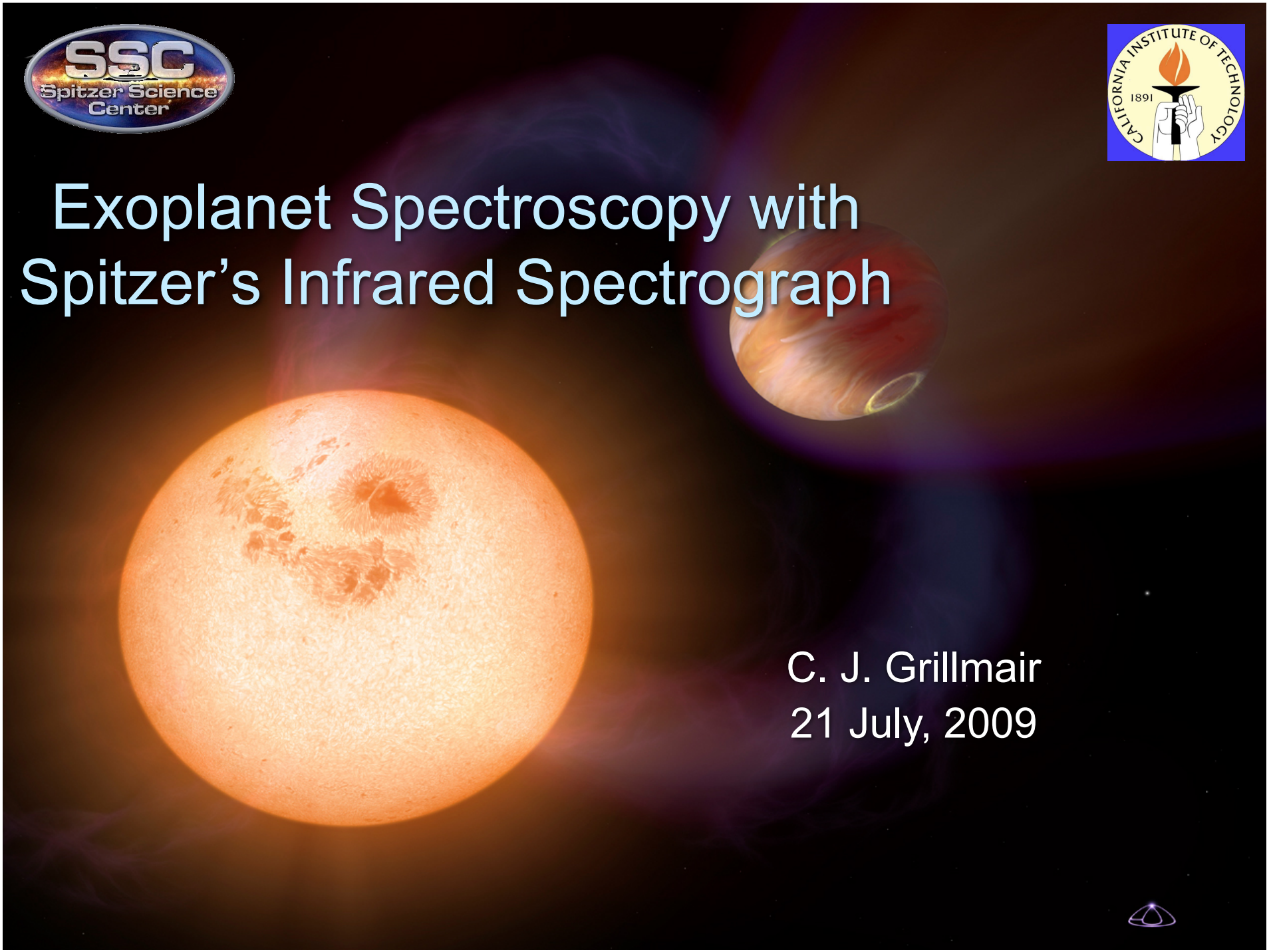
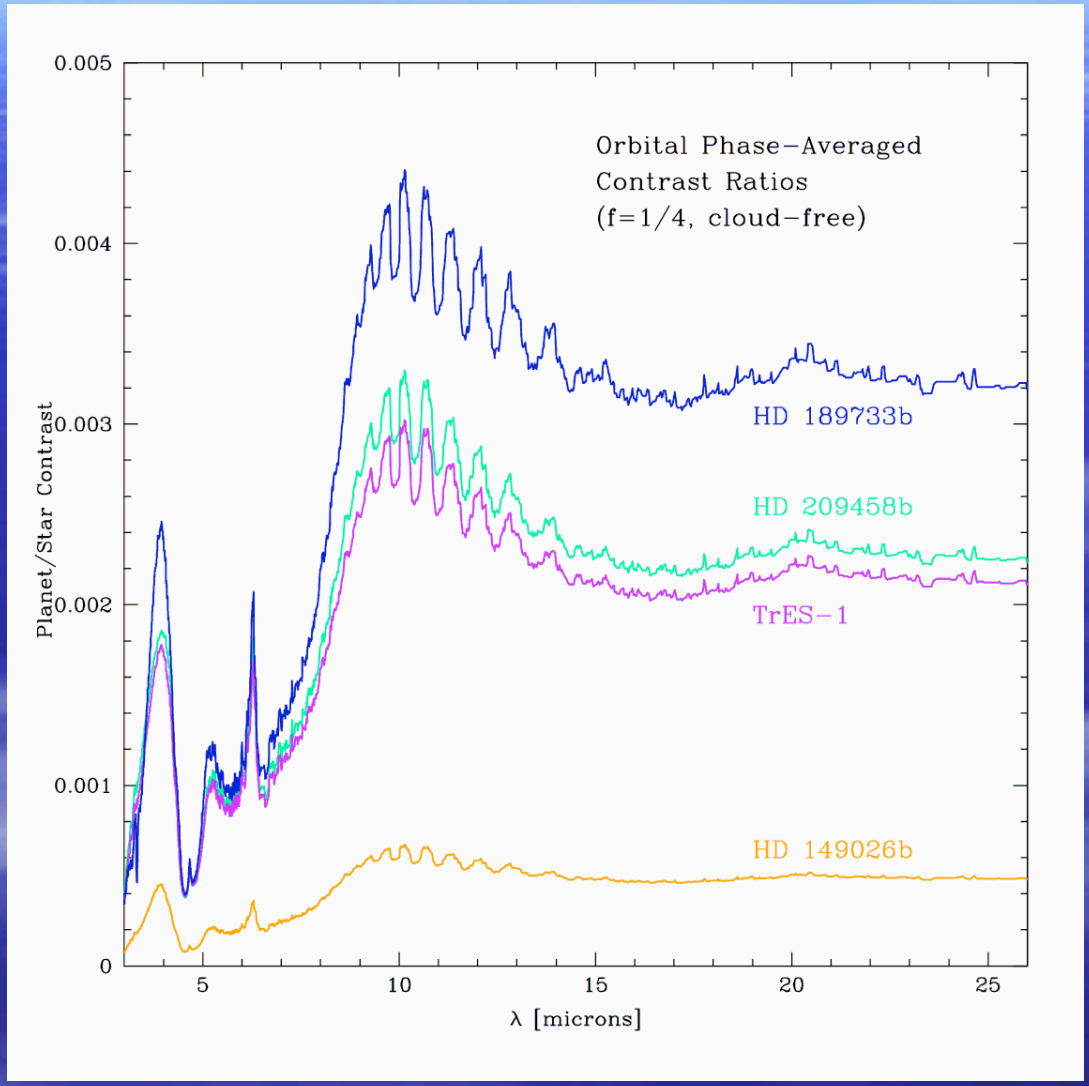


Exoplanet Spectroscopy with Spitzer's Infrared Spectrograph

C. J. Grillmair

21 July, 2009

Spectroscopy Candidates

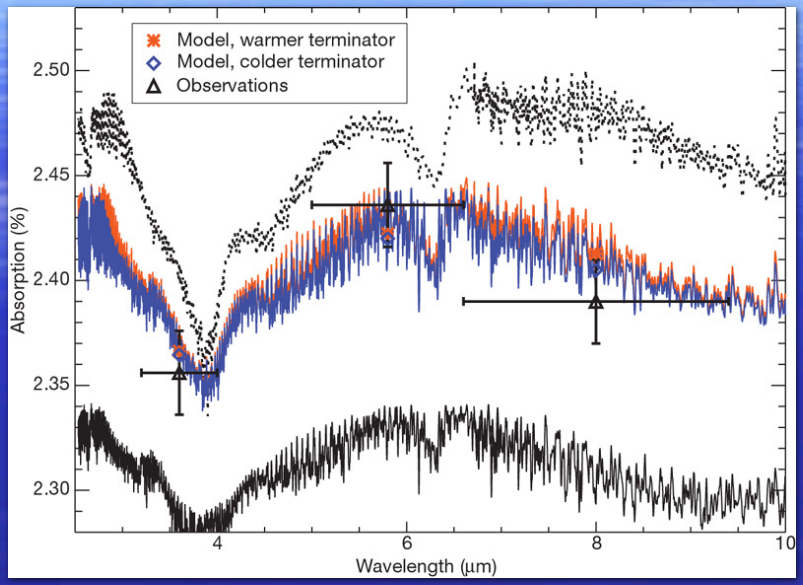


Burrows et al. 2005

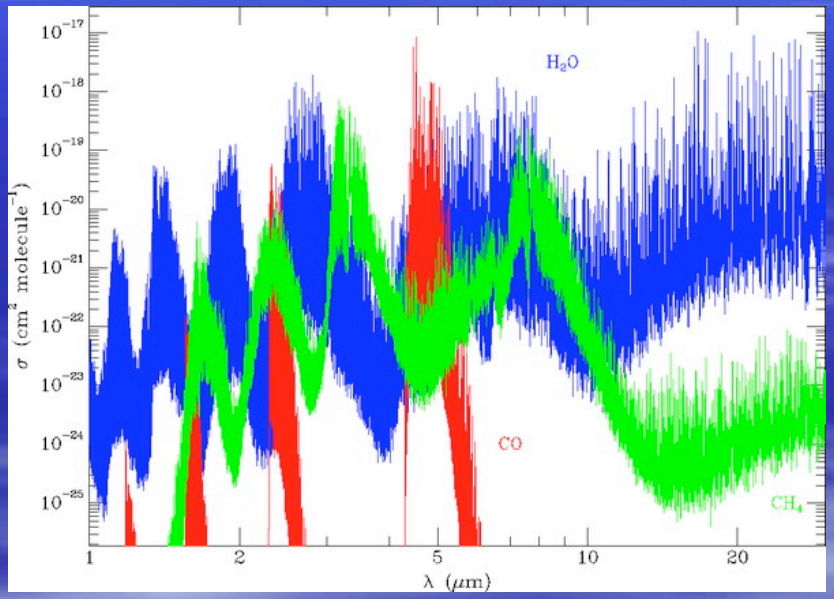
System Parameters

	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%

Why Spectra?



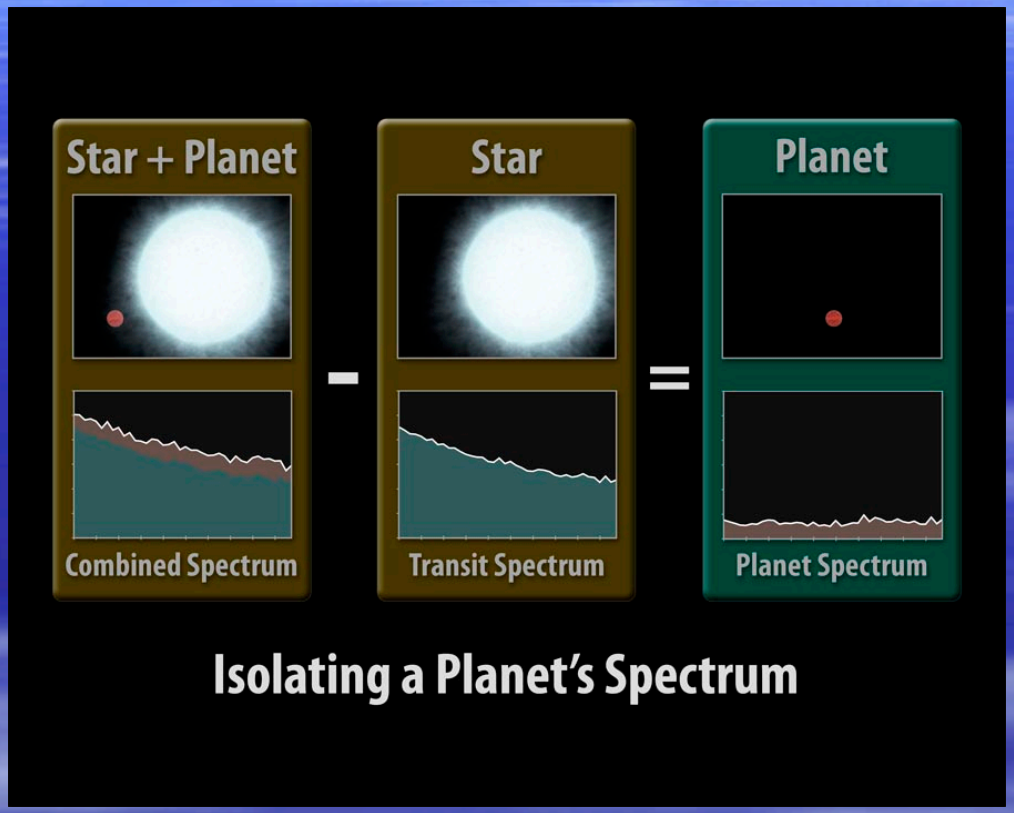
Tinetti et al. 2008, Nature 448, 169



Fortney et al. 2005, ApJ 652, 746

Need spectra to resolve the underlying molecular features.

Transit Spectroscopy



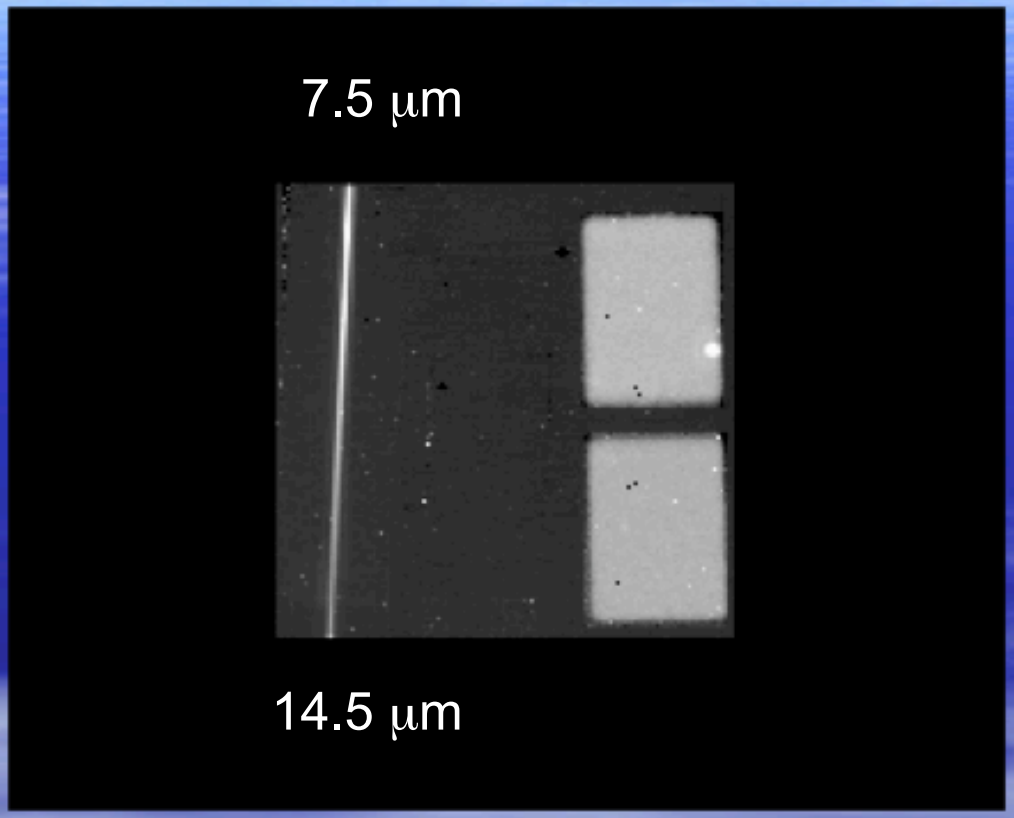
Observation Planning

- Use the IRS 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.

Observation Planning

- 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 provide sufficient out-of-eclipse measurements to establish star +planet flux without significantly compromising S/N.

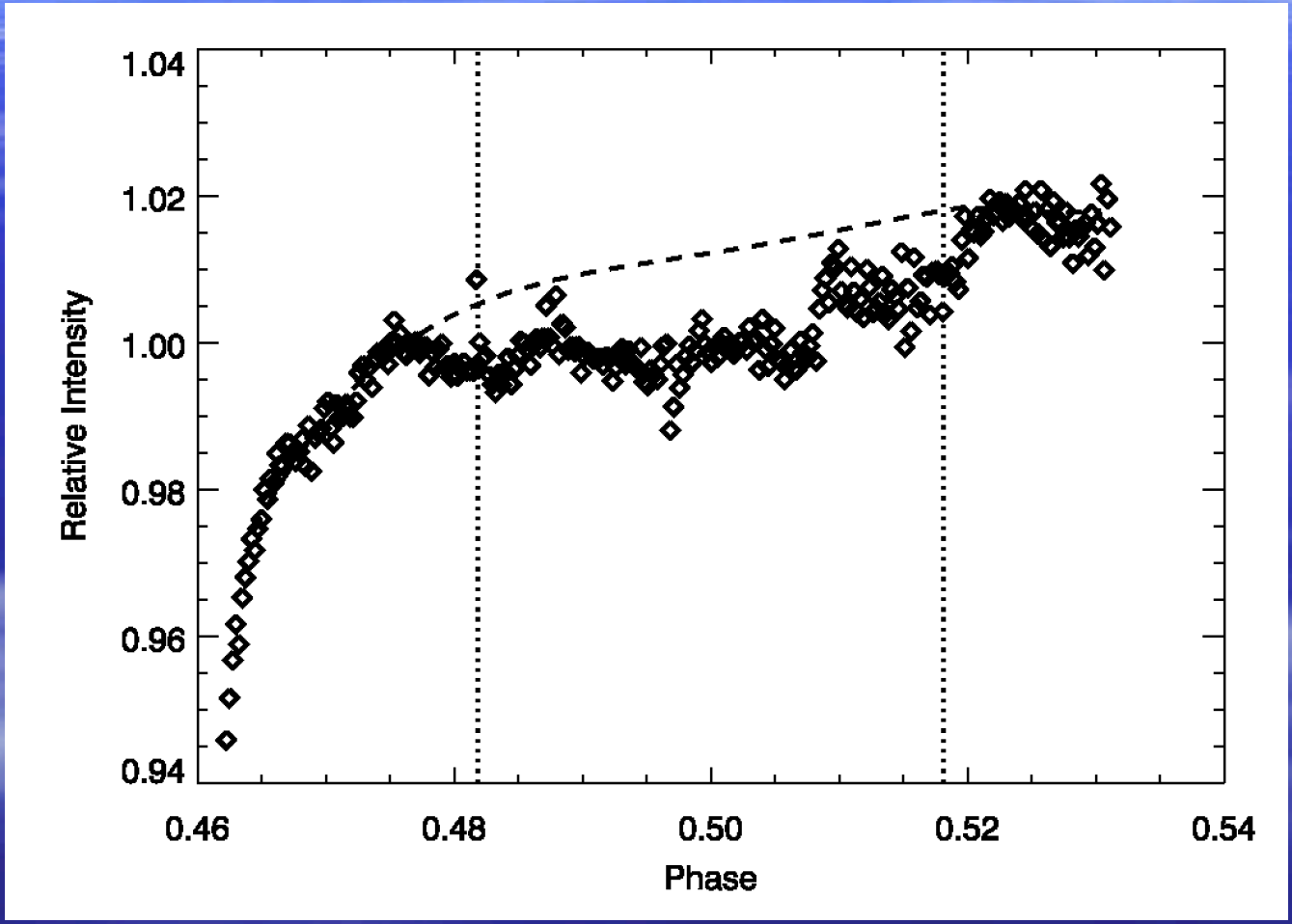
IRS Spectra



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

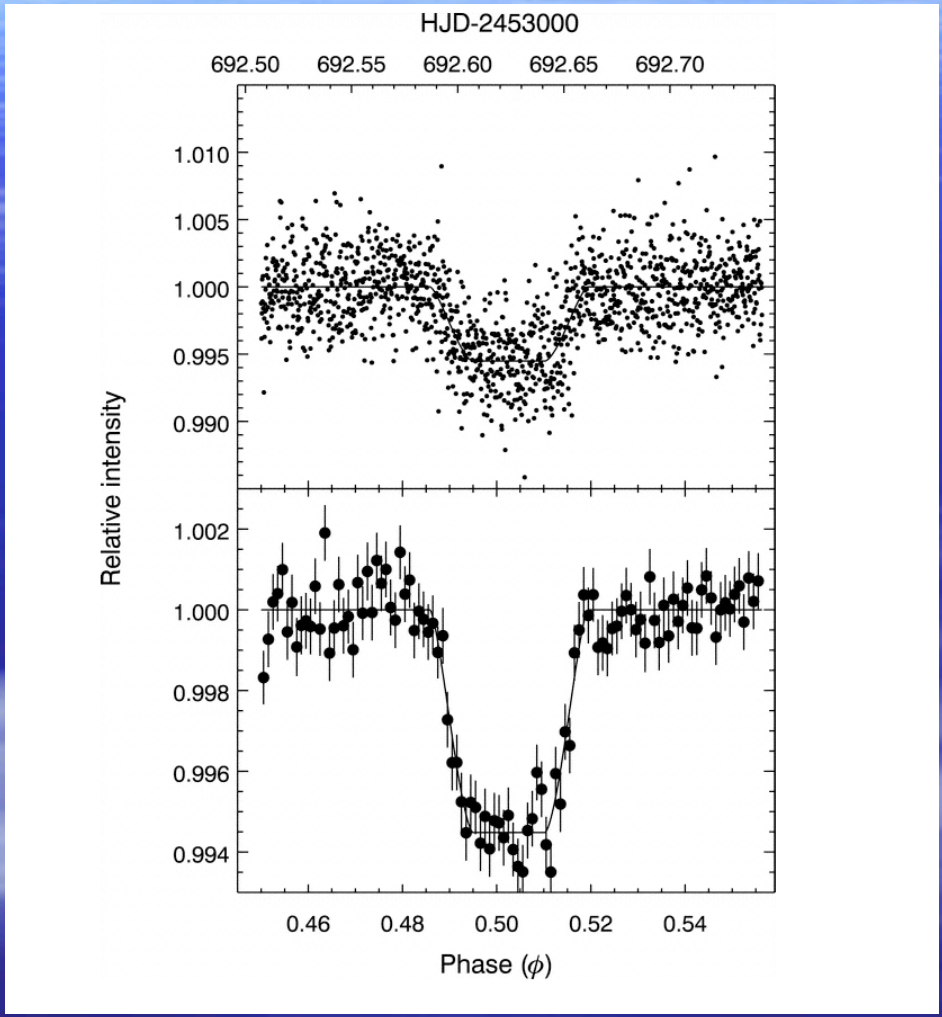
- For HD 189733, used standard SSC pipeline processing products, or Basic Calibrated Data (BCDs).
- 2D images were background-subtracted using off-order regions.
- 8045 individual spectra were extracted using SSC tool SPICE.
- Extraction carried out using fixed aperture windows and "non-optimal" extraction: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

Time Series Spectrophotometry: Latents and Drifts



Richardson et al. 2007, Nature 445, 892

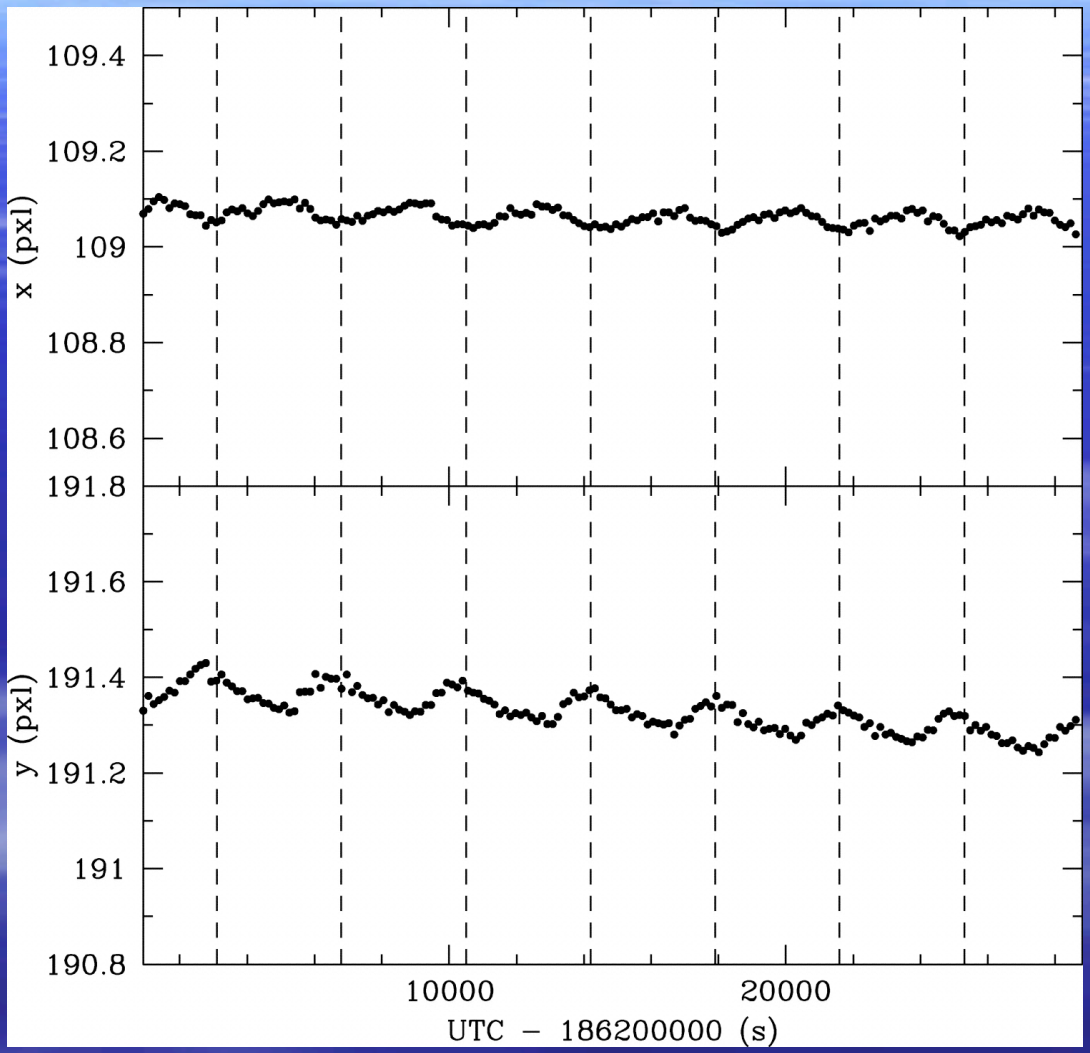
Constraint



16 μm Peak-Up Imaging
Deming et al. 2006, Nature 434, 740

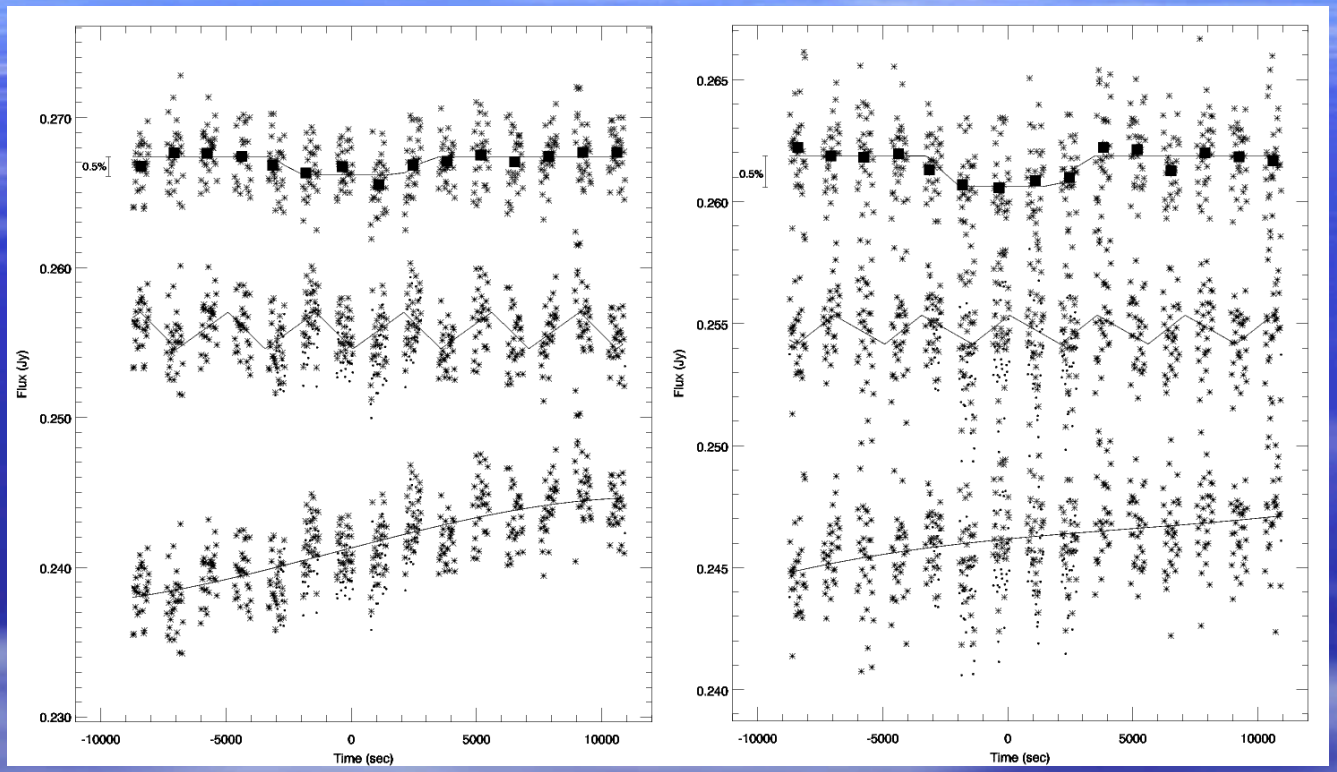
- For each wavelength bin, use a single, photometrically-determined model light curve.
- Fit only for a single parameter, namely the depth of eclipse.
- Light curve fitting (as opposed to in-eclipse – out-of-eclipse subtraction) has the advantage that it makes use of the ingress and egress portions of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

The Sawtooth



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

Effects of Pointing Oscillations

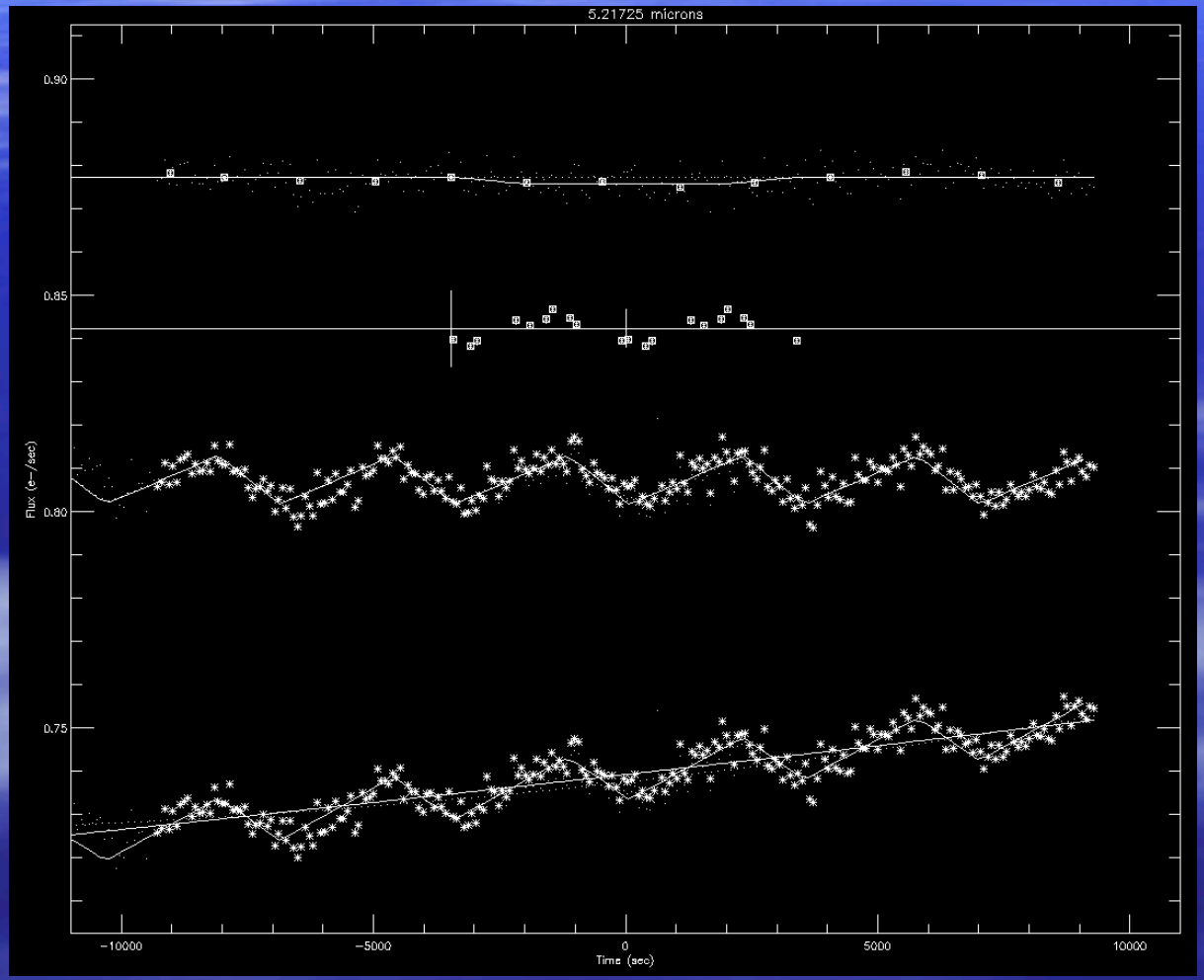


9.81 μm

9.87 μm

Pointing oscillations can push measured fluxes in either direction!

Signature Removal



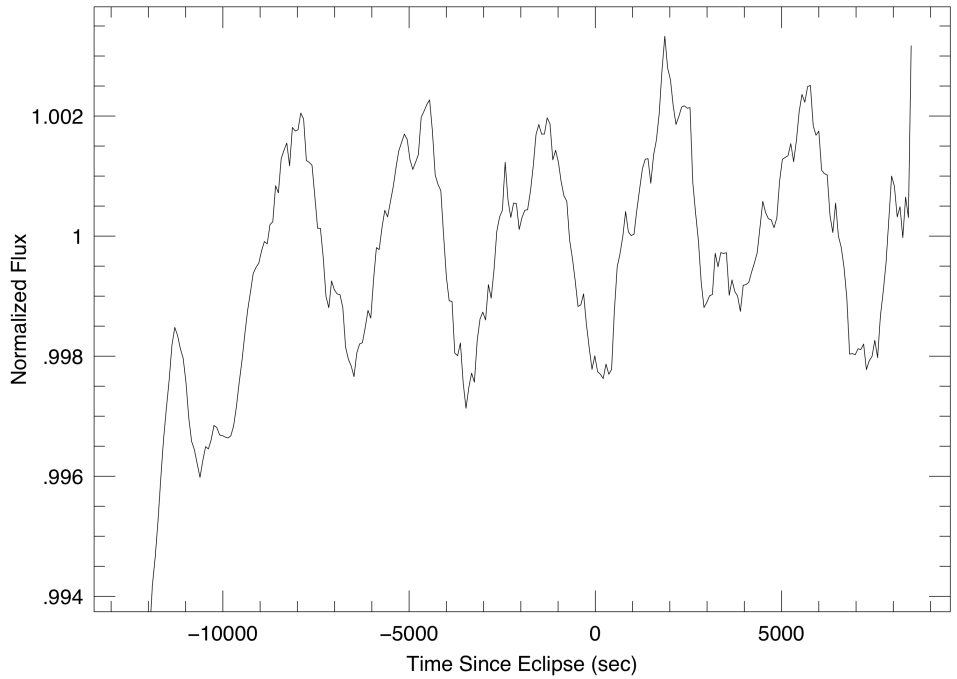
(4) Iterate to minimize χ^2

(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.

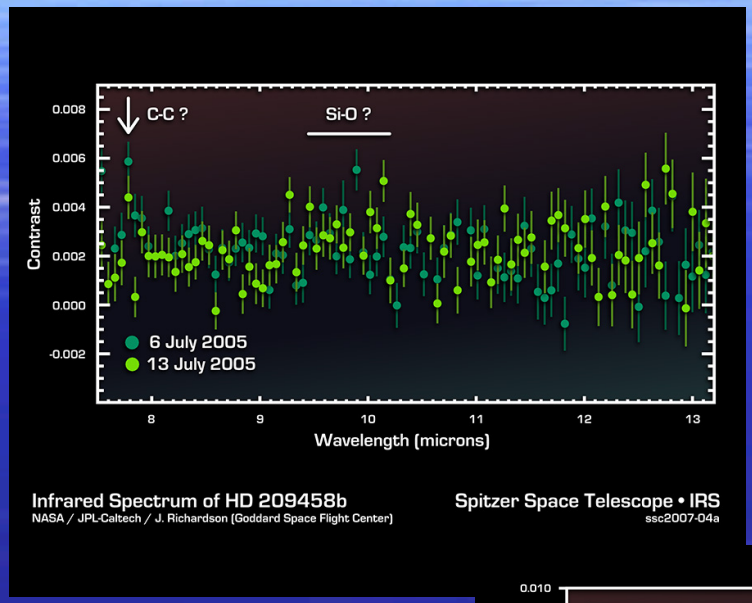
Signature Removal

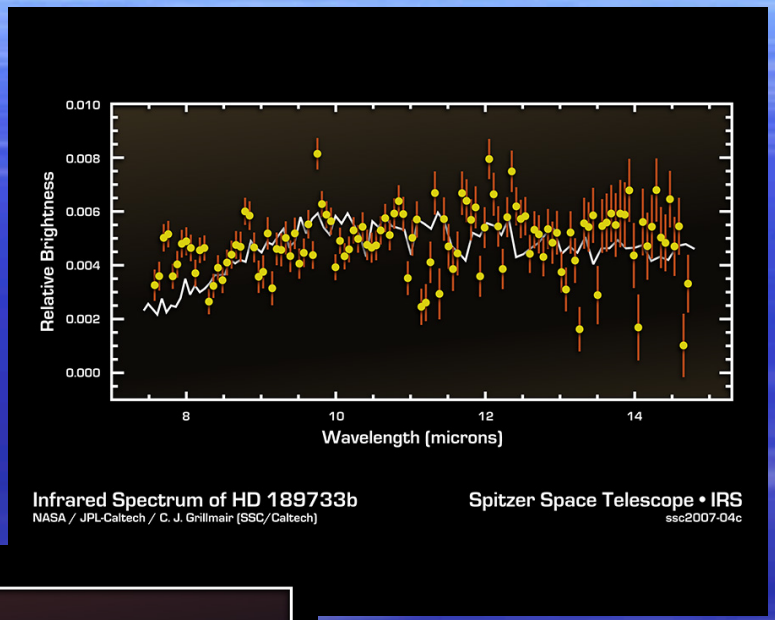


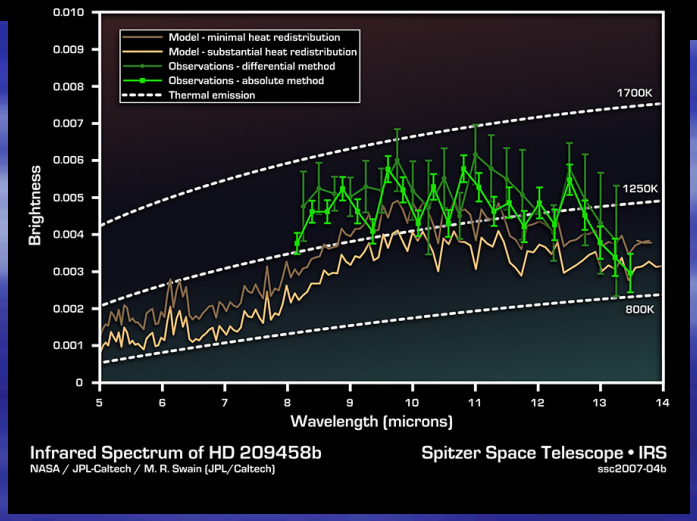
Refined sawtooth/pointing model

9.87 μm

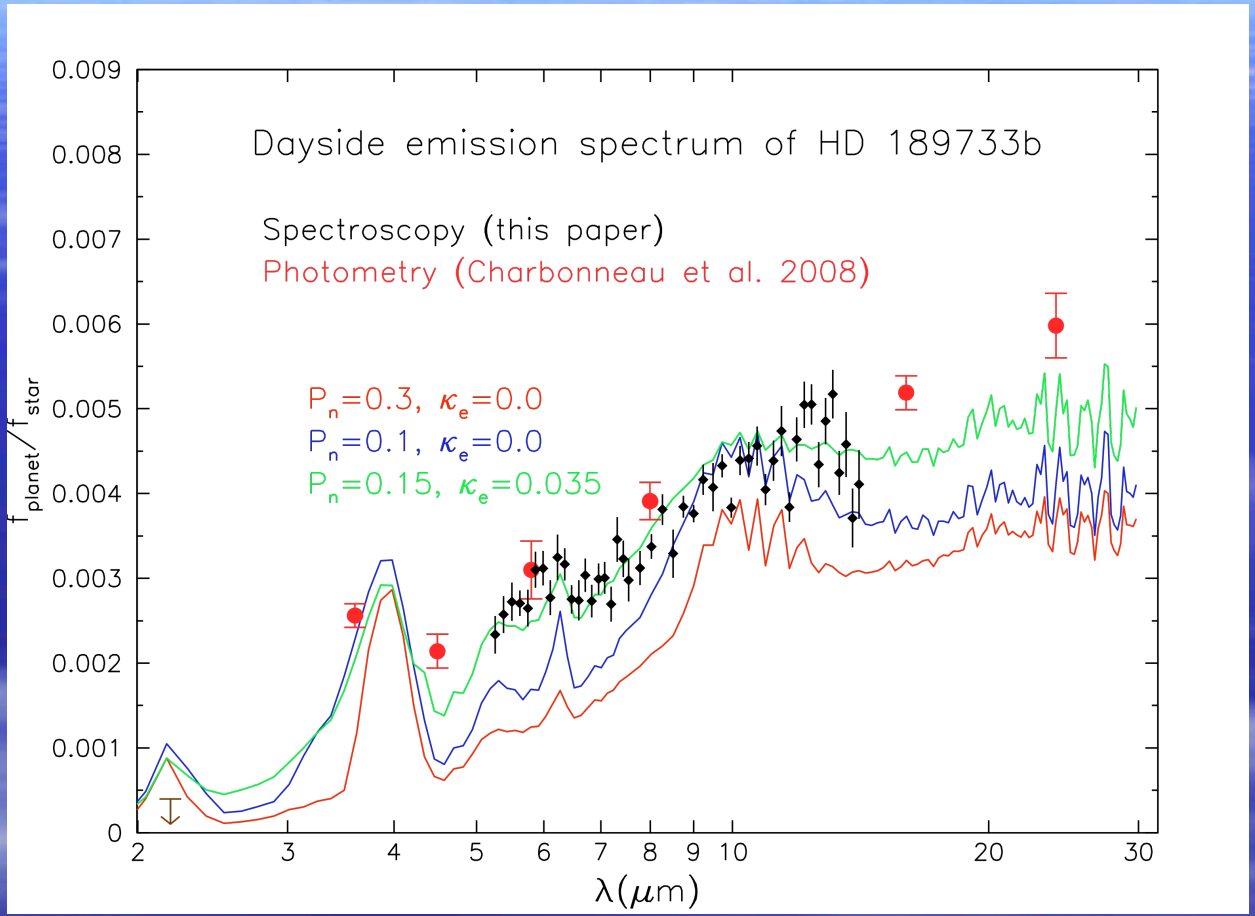
First Emission Spectra





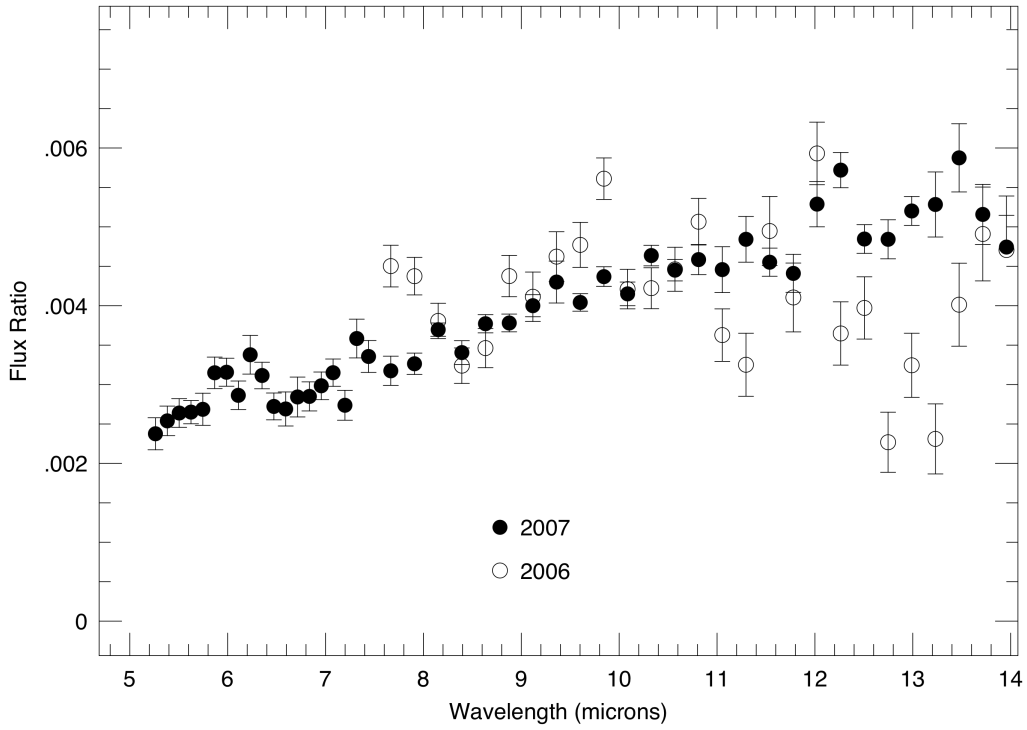


Composite Cycle 4 Spectrum

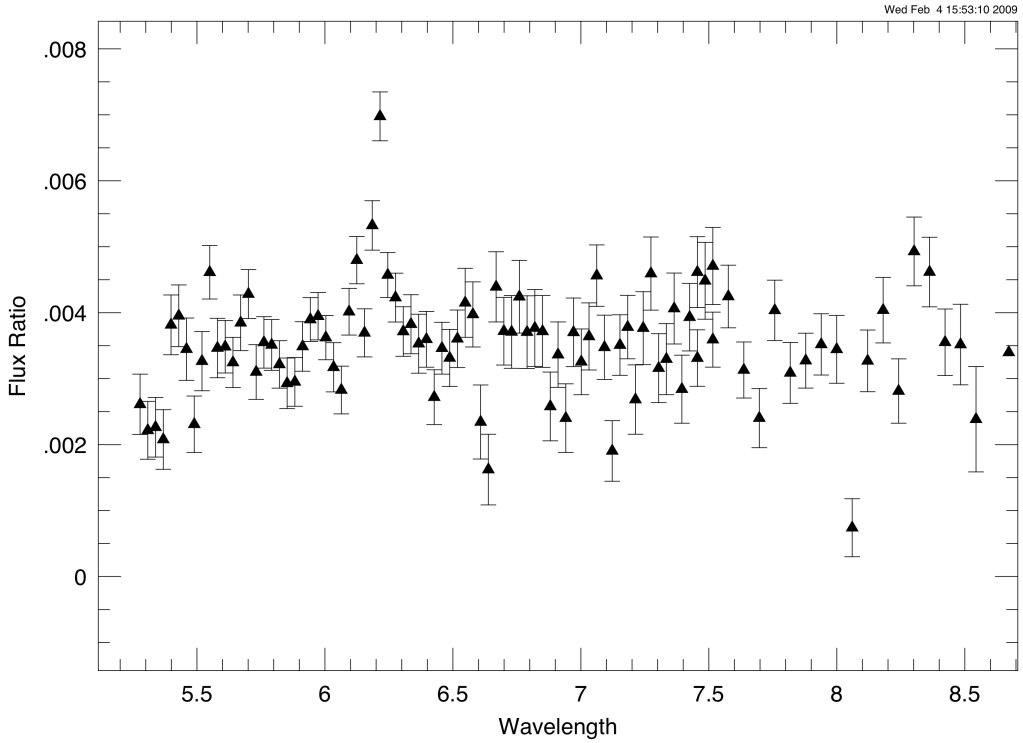


Grillmair et al. 2008, Nature 456, 767
Charbonneau et al. 2008, ApJ 686, 1341
Barnes et al. 2007, MNRAS 382, 473

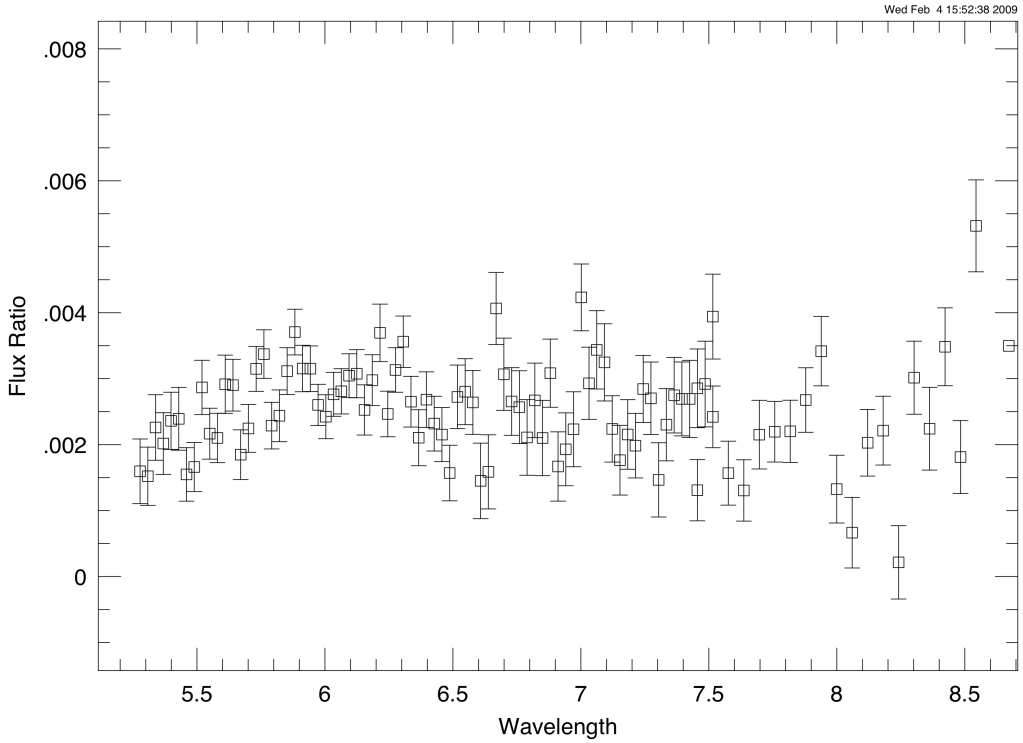
What Happened?



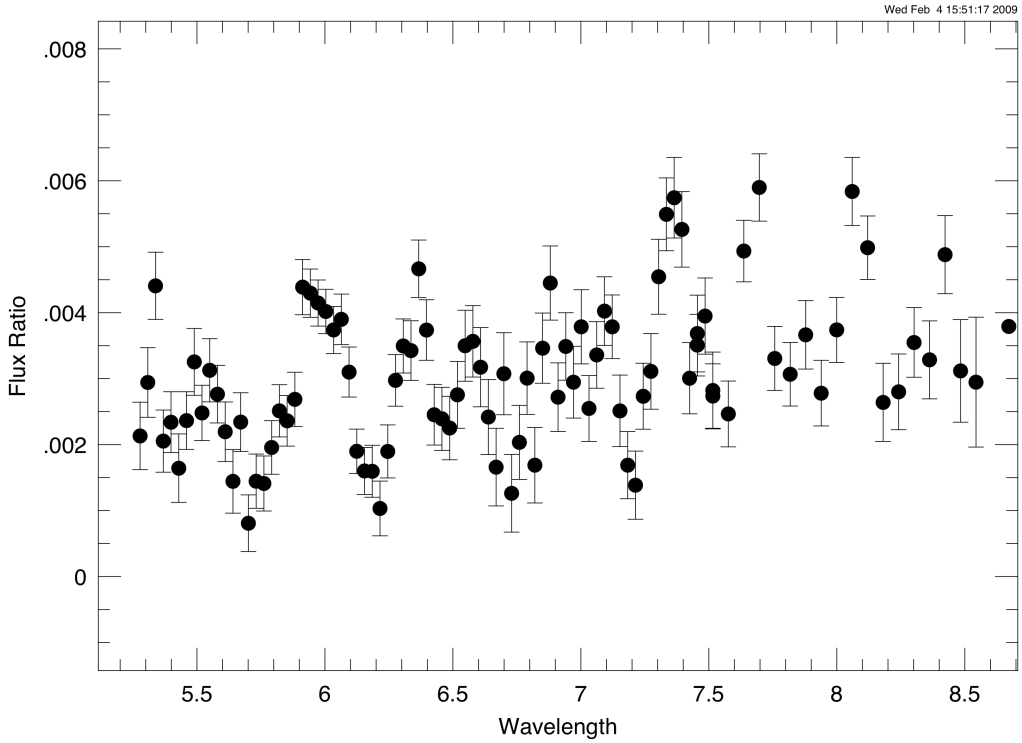
Time Series Spectroscopy



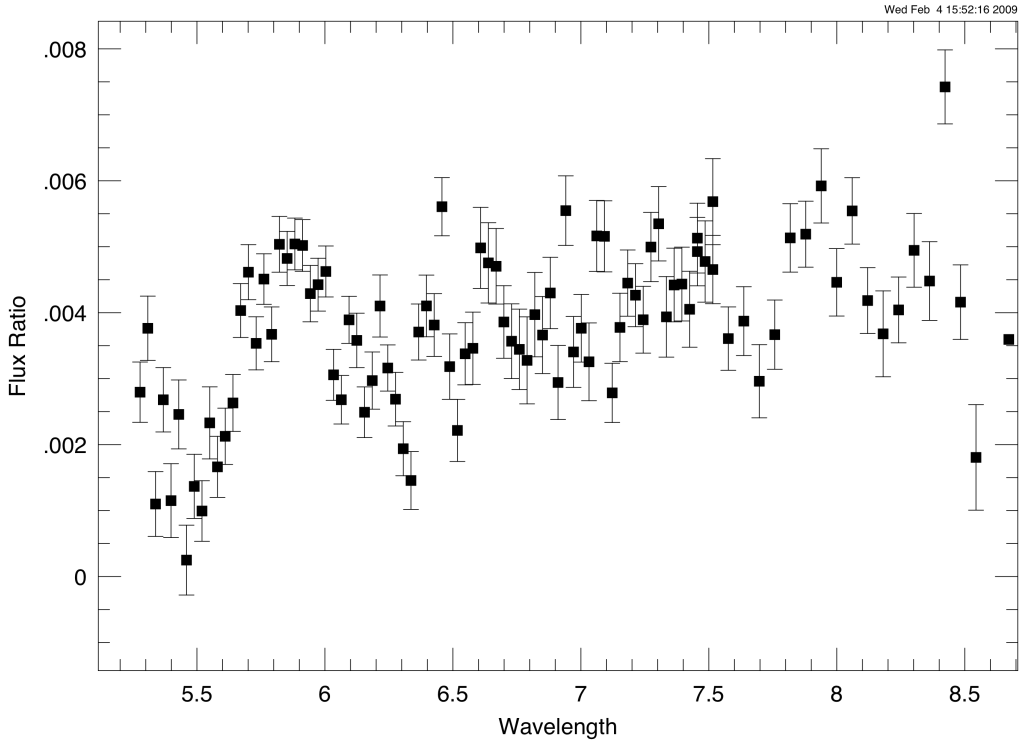
Time Series Spectroscopy



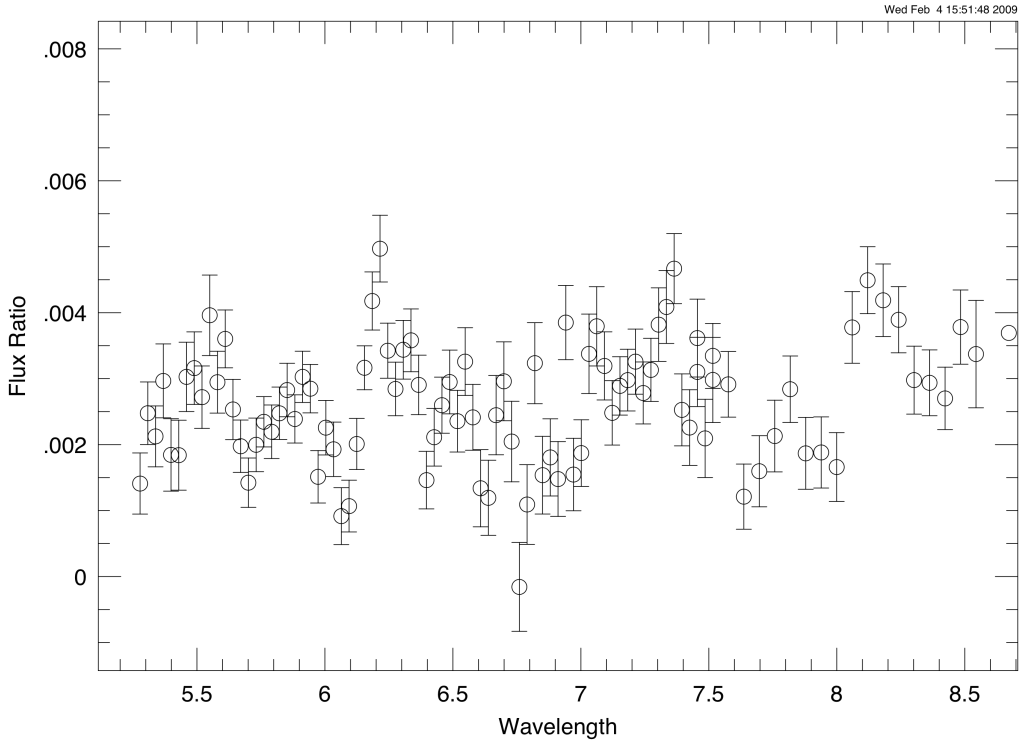
Time Series Spectroscopy



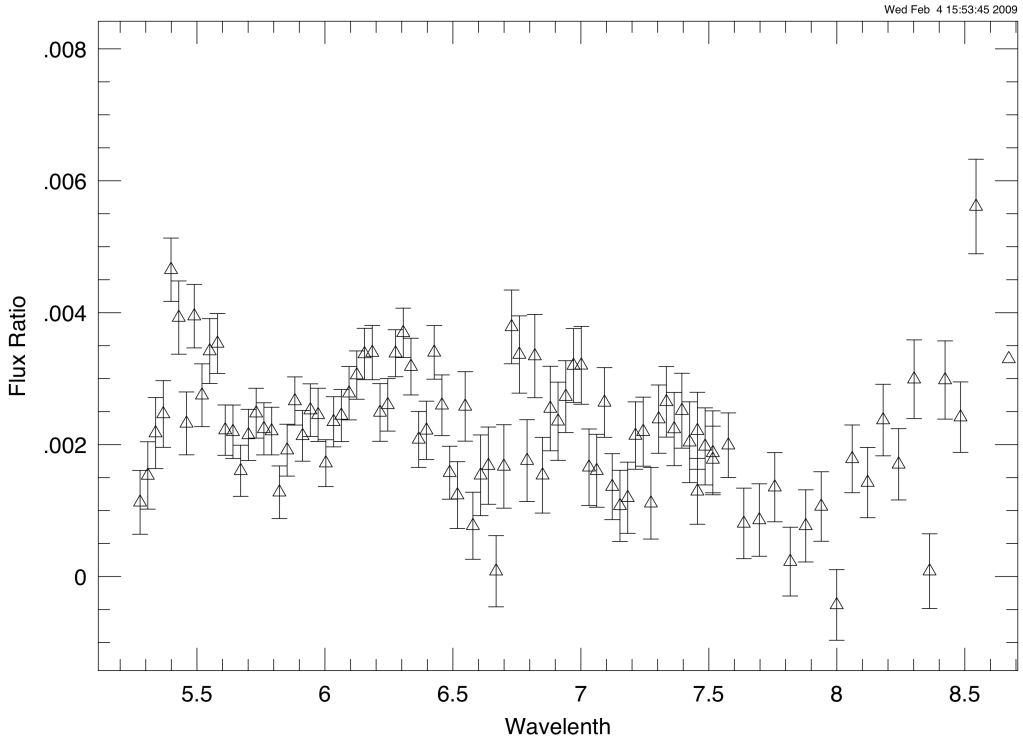
Time Series Spectroscopy



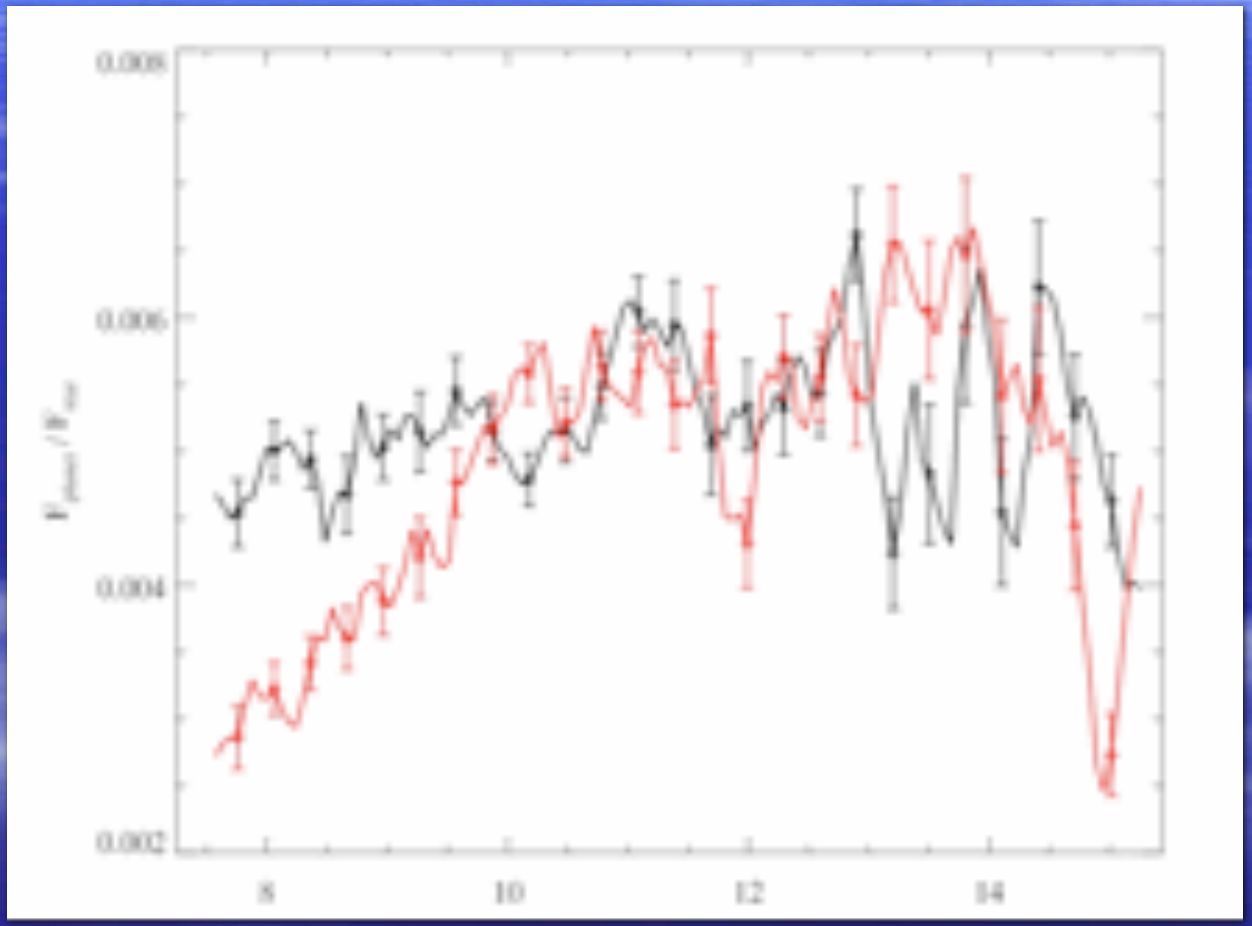
Time Series Spectroscopy



Time Series Spectroscopy

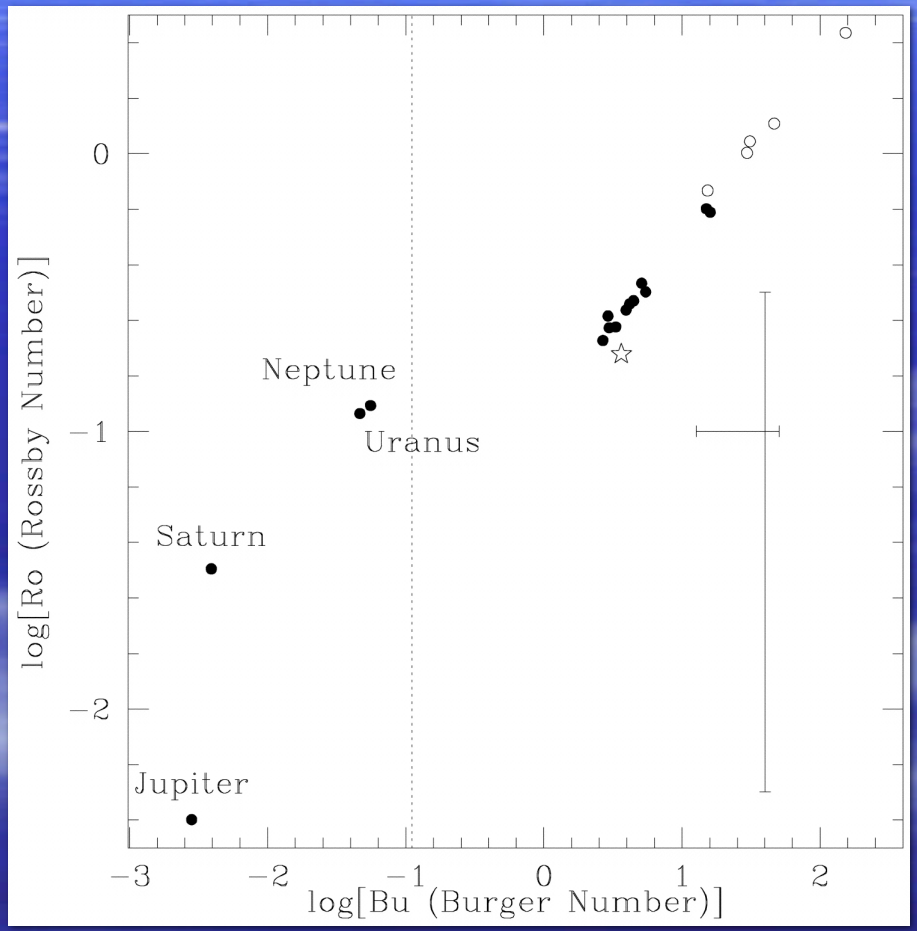


An Independent Analysis…



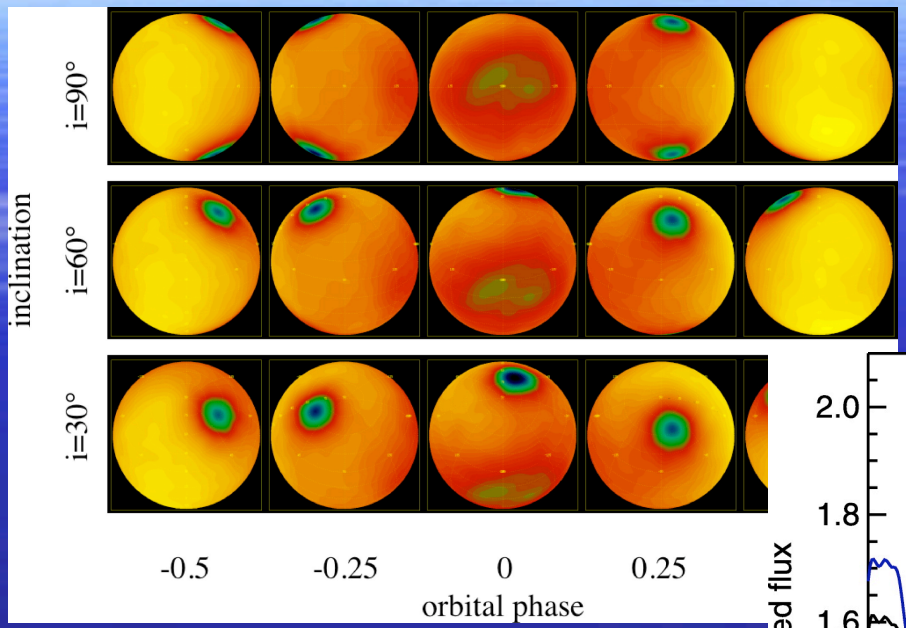
Swain, Bouwman, et al., in prep.

Planet-wide weather?

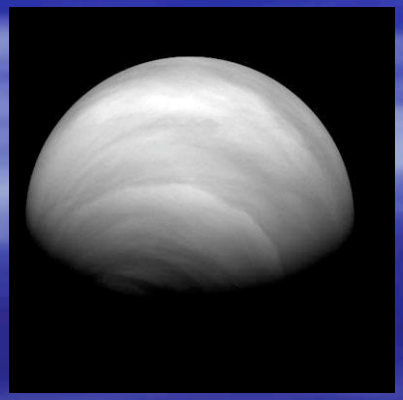


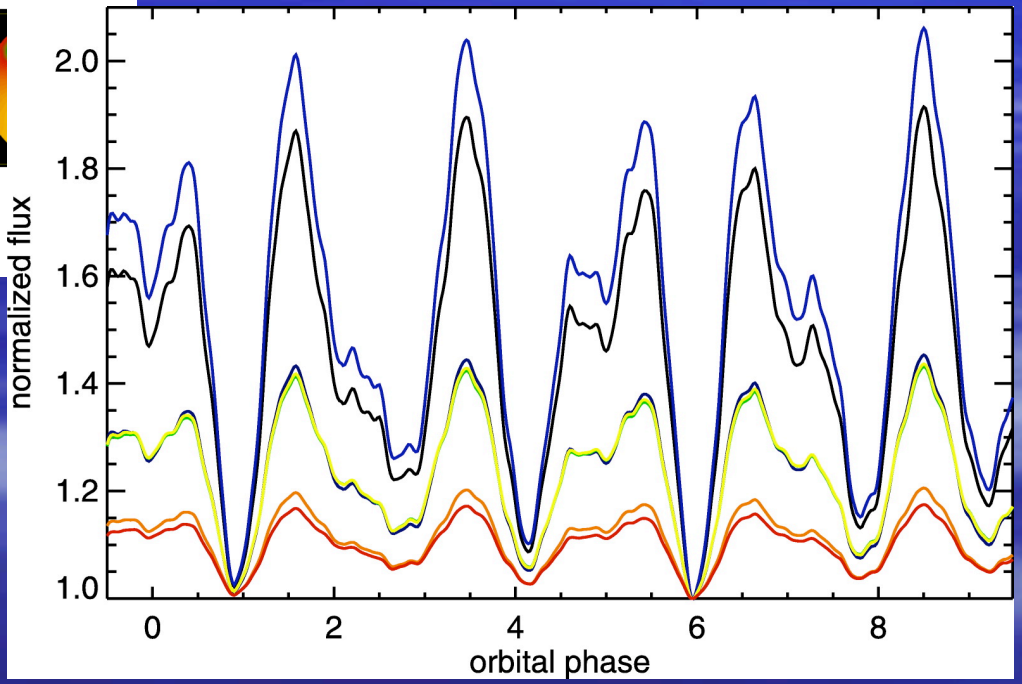
Menou et al. 2003, ApJ 587, L113

Planet-wide weather cont'd?



- Turbulence can generate phase shifts and deviations from periodicity in phase curves.





- Rauscher et al. 2008, ApJ 681, 1646

What's Next

- Transit spectroscopy of extrasolar planets has been demonstrated.
- With cryogen depletion, IRS observations are now at an end.
- NICMOS will continue to be useful for the newly-discovered, nearby transiting giant planets.
- Ground-based near-IR spectroscopy – NIRSPEC, MICHELLE?
- JWST
- We now need to hone our techniques and instrumentation for application to smaller, cooler, habitable-zone planets.
- We need to ask the right questions.
- THESIS?