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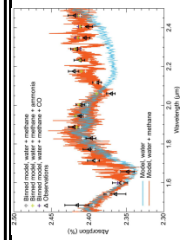
JPL



Exoplanet Spectroscopy

Exoplanetary Atmospheres: Observational Techniques

characterizing exoplanet atmospheres via molecular spectroscopy

Mark Swain

(Jet Propulsion Laboratory, California Institute of Technology)

Acknowledgements: Jeroen Bouwman, Ian Crossfield, Gautam Vasisht, Pieter Deroo, Daniel Angerhausen, Drake Deming, & Carl Grillmair

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Characterizing Exoplanet Atmospheres

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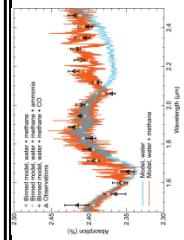
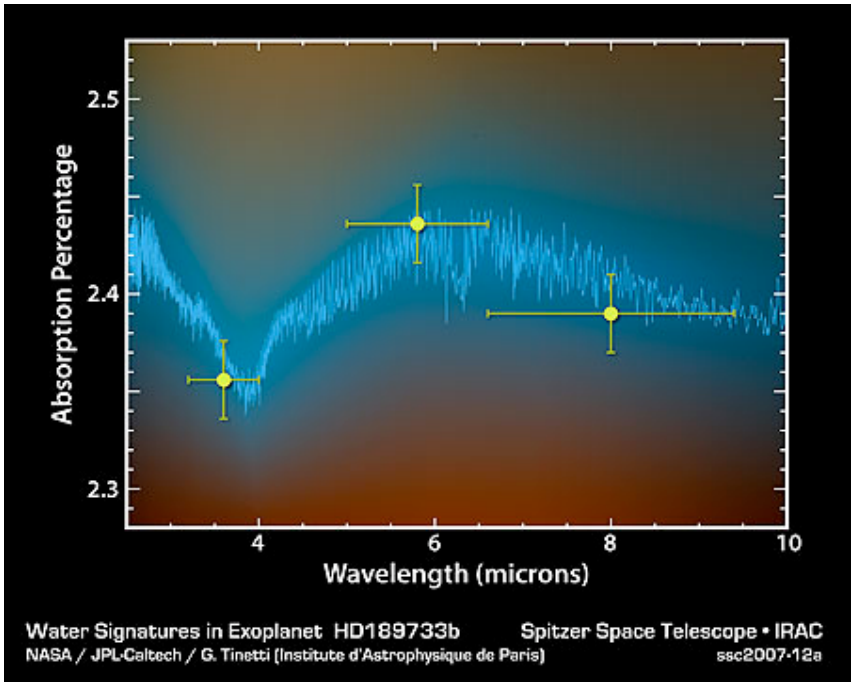


Exoplanet Spectroscopy

- What can be measured?
  - Transit
  - Secondary eclipse
  - Non-transiting light curve
- Photometry and Spectroscopy.
- What dynamic range is needed?
  - ~1000:1 mid-IR
  - ~10,000:1 near-IR
- Why study molecules?
  - They are probes of conditions, composition, and chemistry.



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State of the art - Molecules

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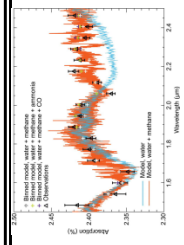
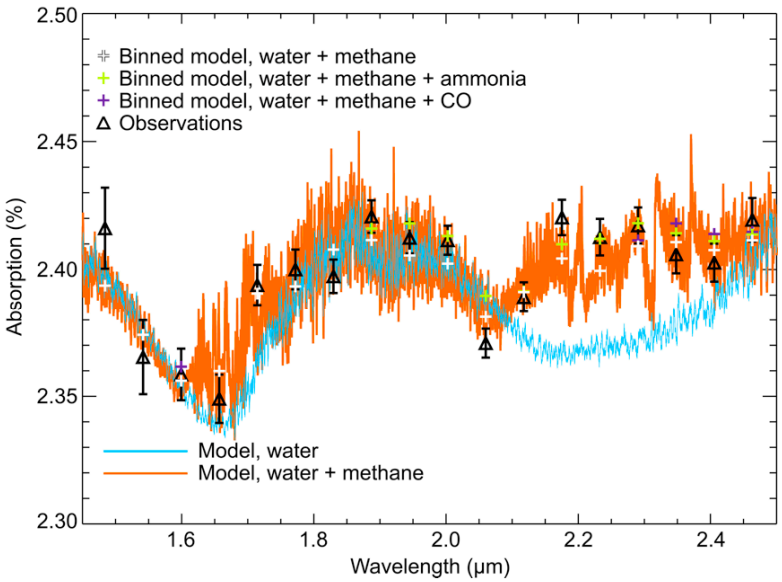
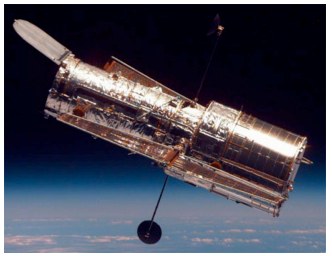
Exoplanet Spectroscopy

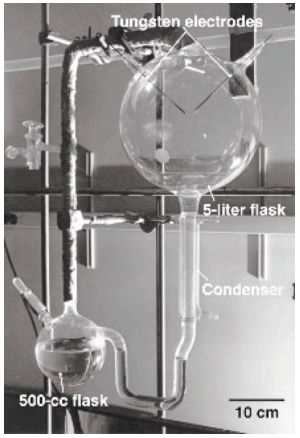


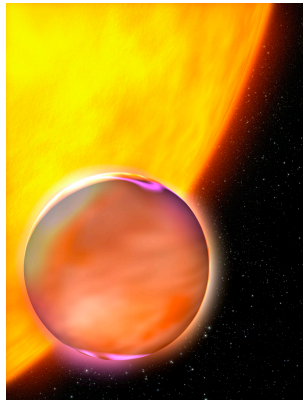


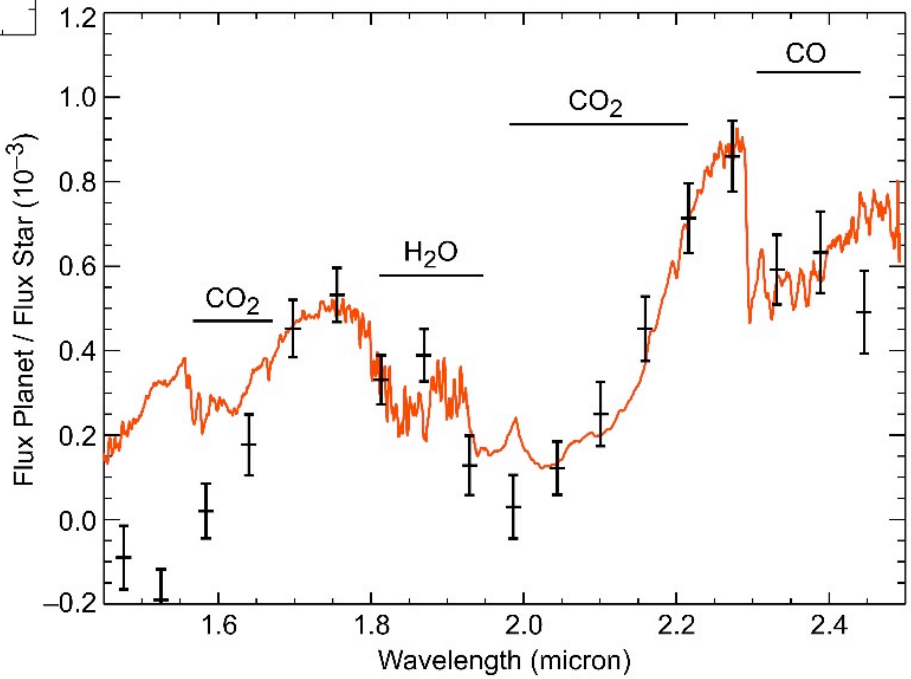
Swain, Vasisht & Tinetti 2008 Nature, 452, 329

- H_2O, CH_4, CO_2, & CO detected in the "hot-Jupiter" HD 189733b via infrared spectroscopy.









Swain et al. 2009 ApJ, 690, 114

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State of the art - instruments

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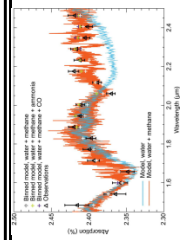
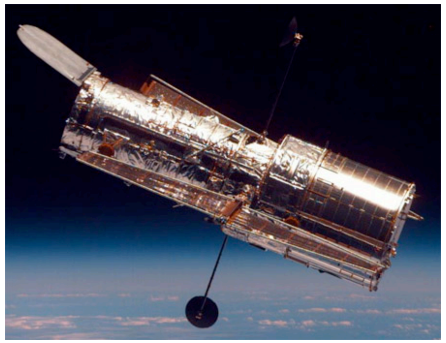
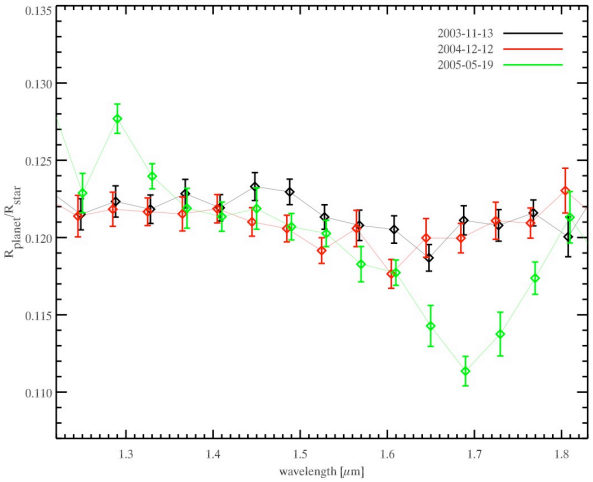
Exoplanet Spectroscopy

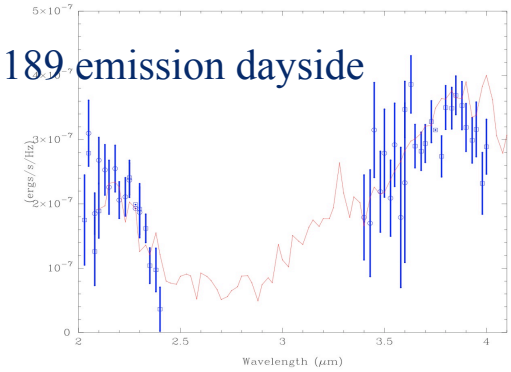


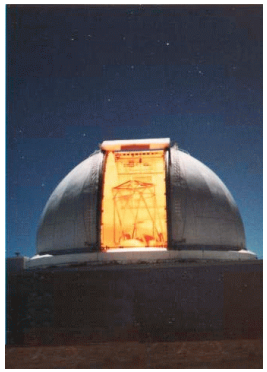
- Hubble NICMOS
- Spitzer IRS
- Ground soon?

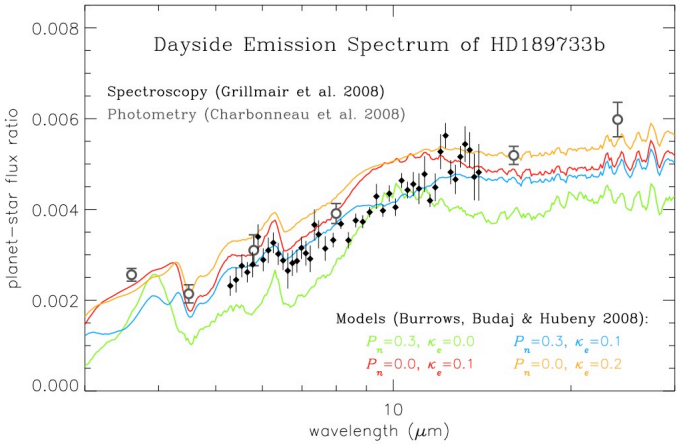




Deroo et al. in preparation







Grillmair et al. Nature 2008

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State of the art – atmospheric profiling

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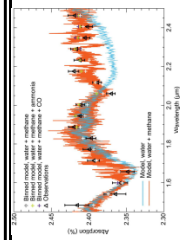
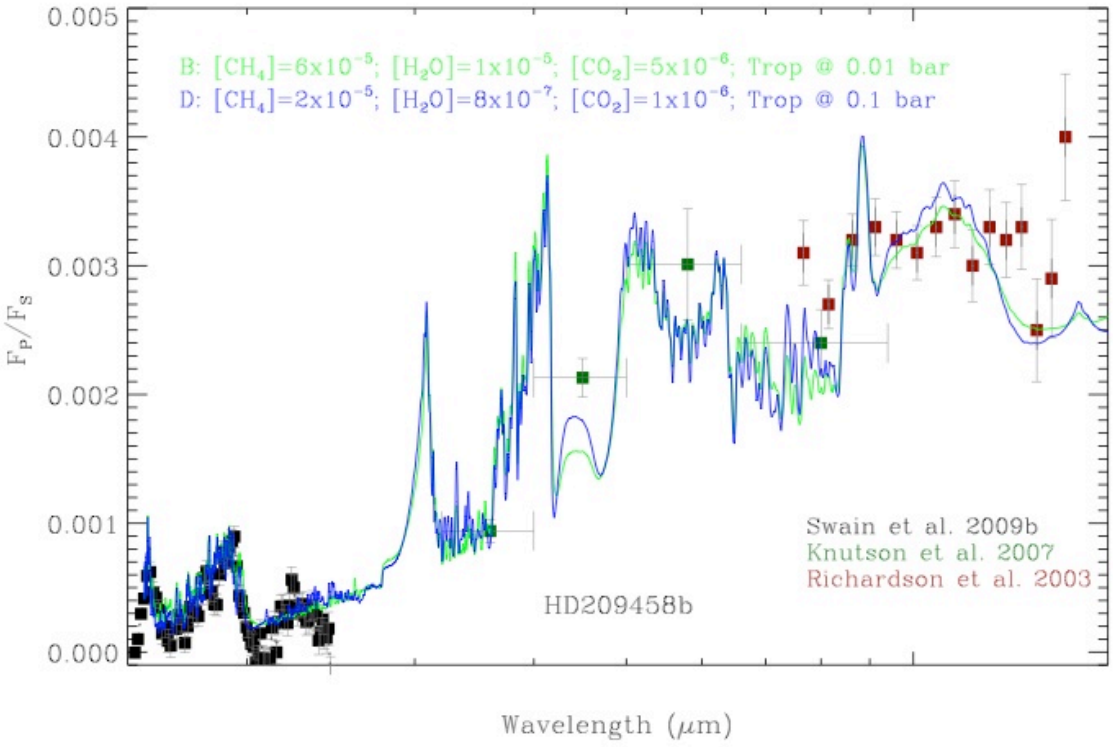
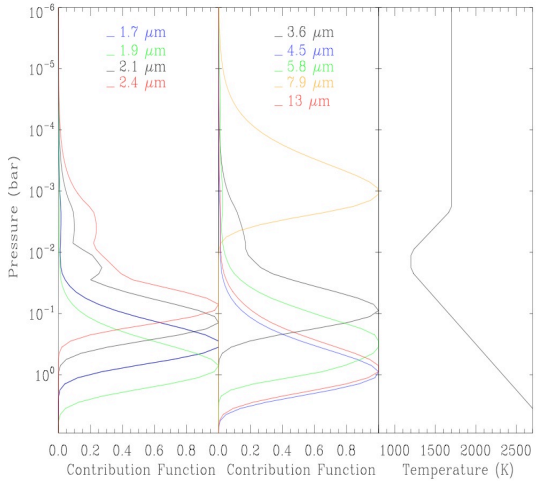
Broad wavelength coverage needed

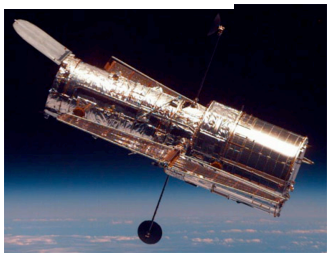


Exoplanet Spectroscopy



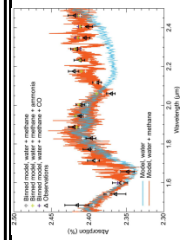


Swain et al. 2009 submitted to Ap. J.



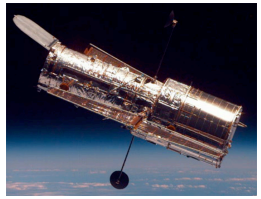
Noncontemporaneous spectra – caution

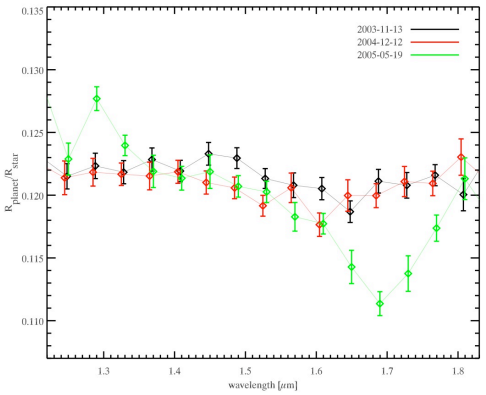
JPL



- We need broad spectral coverage to resolve the temperature/composition in an emission spectrum.
- But variability has been detected in two planets (Grillmair et al. 2008, Deroo in preparation).
- So how valid is a noncontemporaneous composite spectrum?

Exoplanet Spectroscopy





Deroo et al. in preparation

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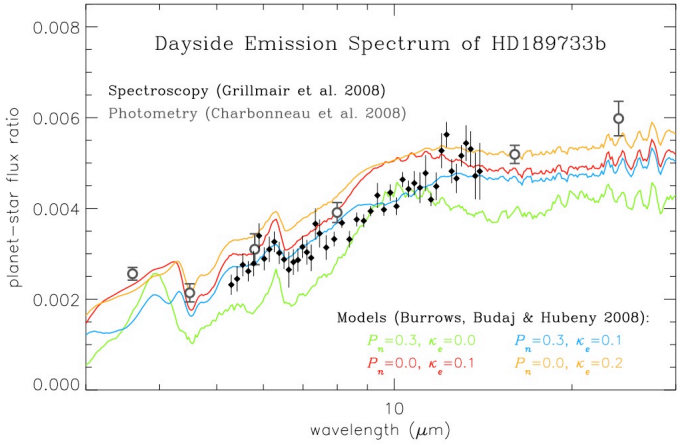

Grillmair et al. Nature 2008

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Comparative Exoplanetology

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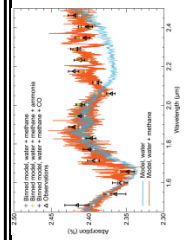
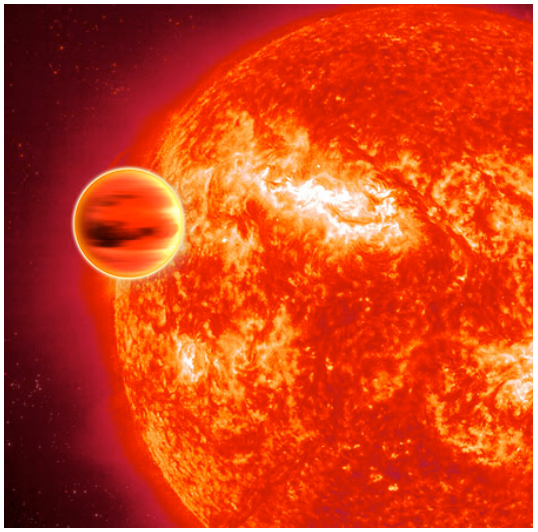


Exoplanet Spectroscopy

- Things you might want to determine…
  - Temperature profile
  - Atmospheric composition
  - Temporal variability
  - Spatial variability



- How much of the following do you need?
  - Spectral coverage
  - Spectral resolution
  - Dynamic range
  - Duration of measurement
  - Duration of calibration

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What we can learn from Grote Reber

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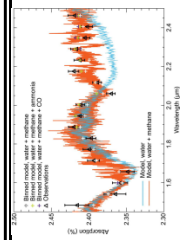
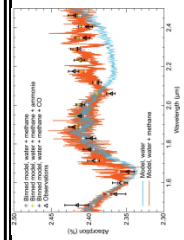


Exoplanet Spectroscopy

- Understand your instrument
- Question conventional wisdom
- Validate the measurement

Photo credit: NRAO

The Instrument



- What limits instruments?
  - Bright object limit
  - Something changes
- What limits YOUR instrument?
- How much dynamic range do you need?
  - How much will your “requirement” push the demonstrated dynamic range with your intended instrument?
- What is the dynamic range duration requirement?
  - Single visit – easier
  - Multiple visits – discontinuous parameters, long-term drifts

Exoplanet Spectroscopy

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Picking an instrument – due diligence

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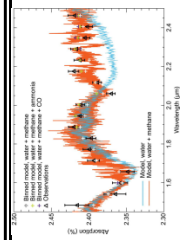

Exoplanet Spectroscopy

- You have already determined requirements for:
  - Dynamic range, wavelength, spectral resolution, measurement duration, etc…
- Audit the possible instruments
  - Count the photons (instrument throughput)
  - Other noise sources – read noise, dark current, etc.
- Identify known systematics
  - Read all papers
  - Discuss observations with builders of instrument
  - Be aware that a complicated instrument will likely behave differently in different modes
  - Determine method for wavelength calibration
  - Determine stability

What is a "Systematic" Error?

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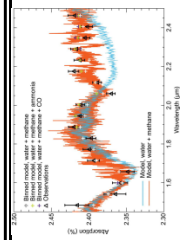
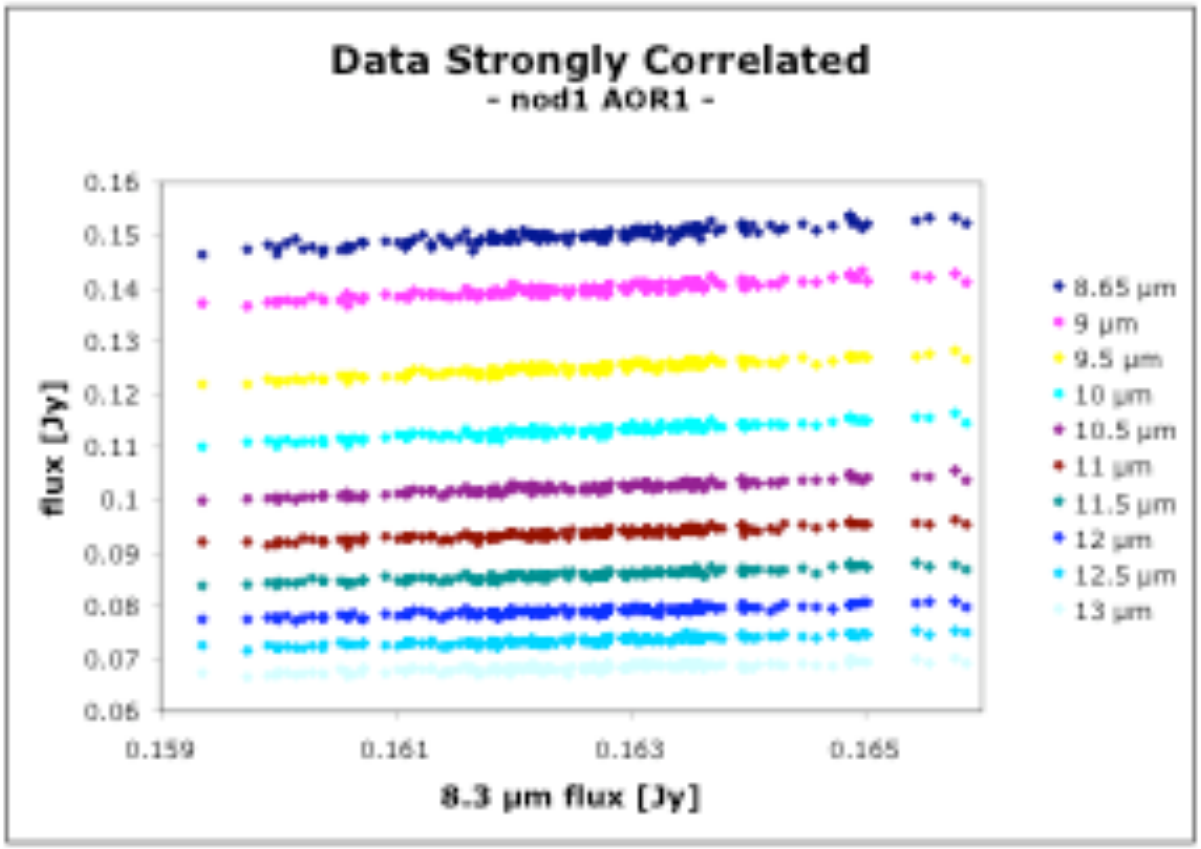
Exoplanet Spectroscopy



- A measurement error that is not random.



Systematic Error Removal

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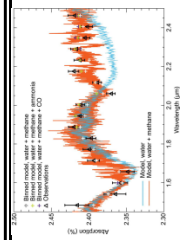

Exoplanet Spectroscopy

- Many possible approaches
  - Detailed modeling – fit for parameters (Spitzer)
  - Generalized modeling – Gauss-Markov method (Hubble)
  - Signal recovery methods – PCA (IRTF)
- Fundamentally, one is detrending the data.
- Data should become uncorrelated when the scene is constant (when time stationarity of the source can be assumed).

Measuring progress & validation

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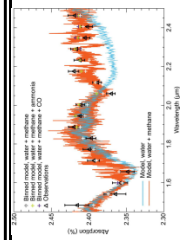
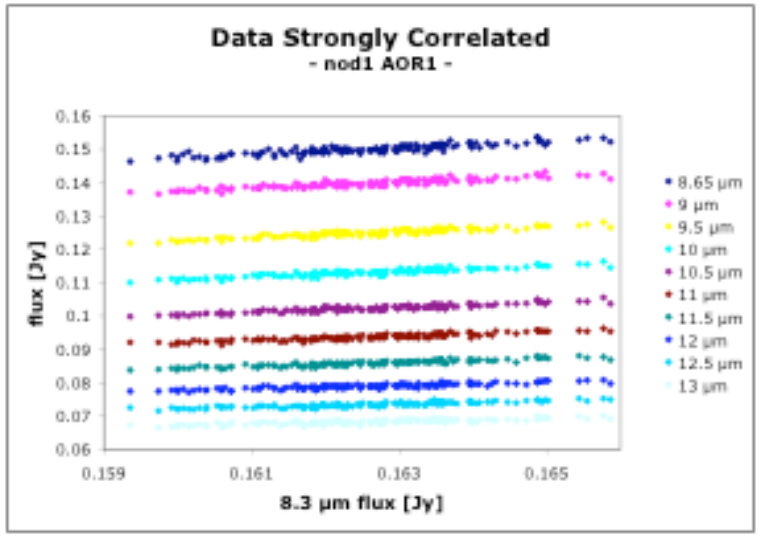
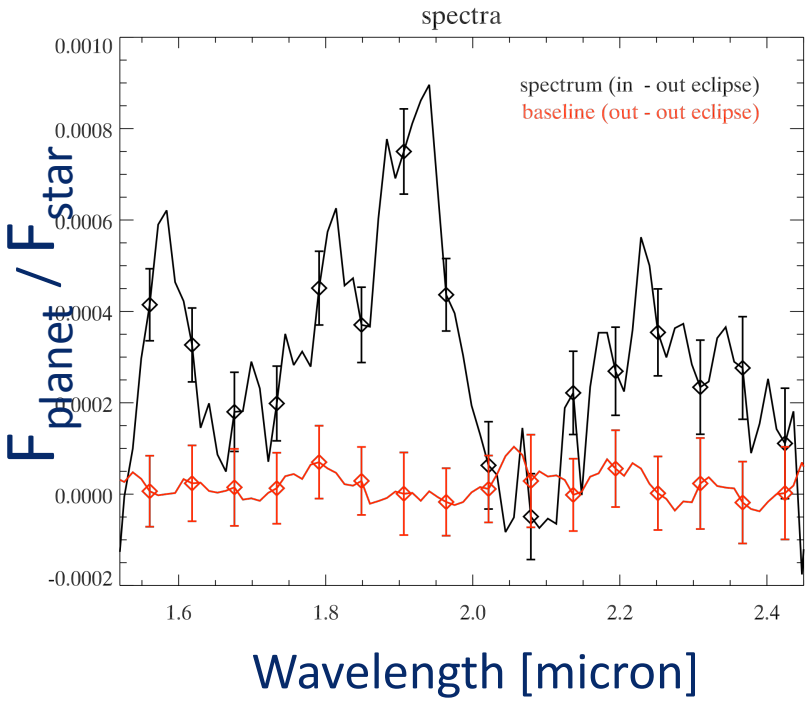
Exoplanet Spectroscopy



- Define metrics and track at each step
  - S' vs S pairs, rms time series, correlation coef.
- Validation of result
  - Compare two methods
  - "out – out"





System light curve detection

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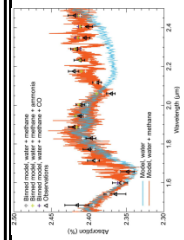
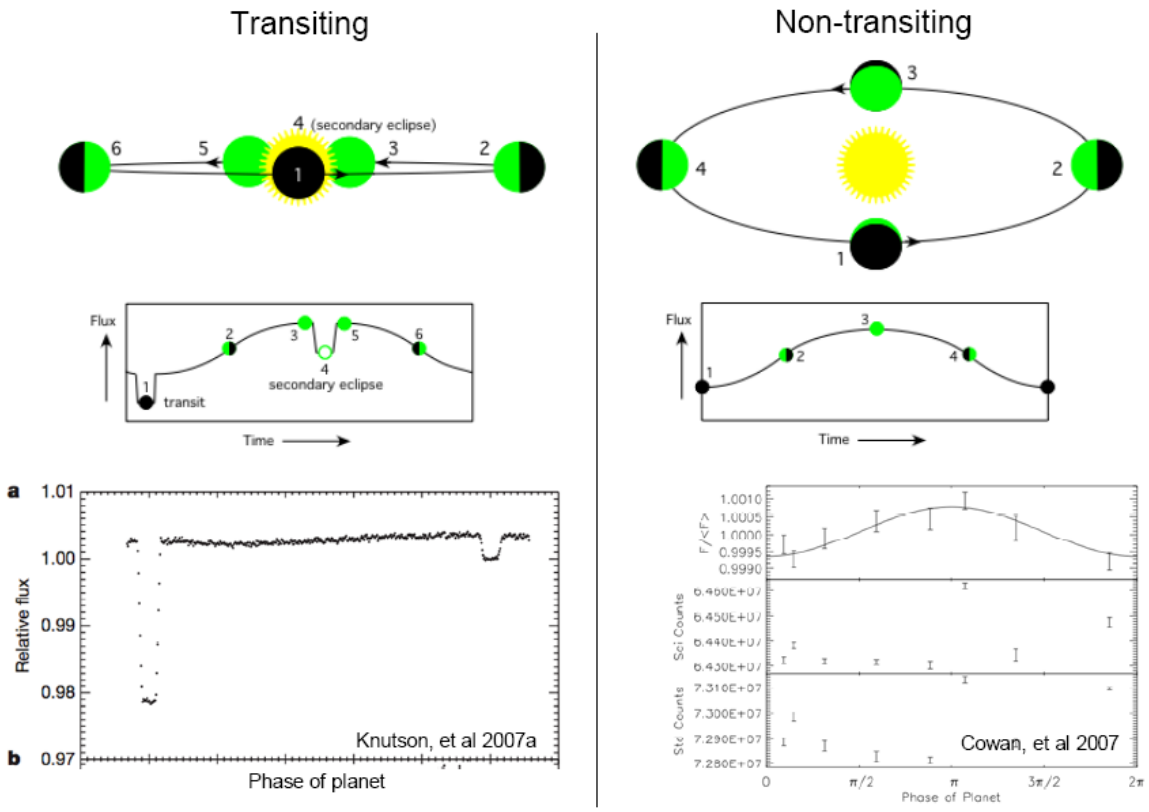


- Enables non-transiting planet atmospheric characterization.
- Long-term calibrated stability needed
- Non-transiting light curve photometry demonstrated with Spitzer (Harrington et al. 2006, Cowan et al. 2007)

Exoplanet Spectroscopy



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Example – the problem

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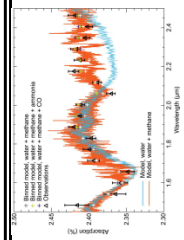
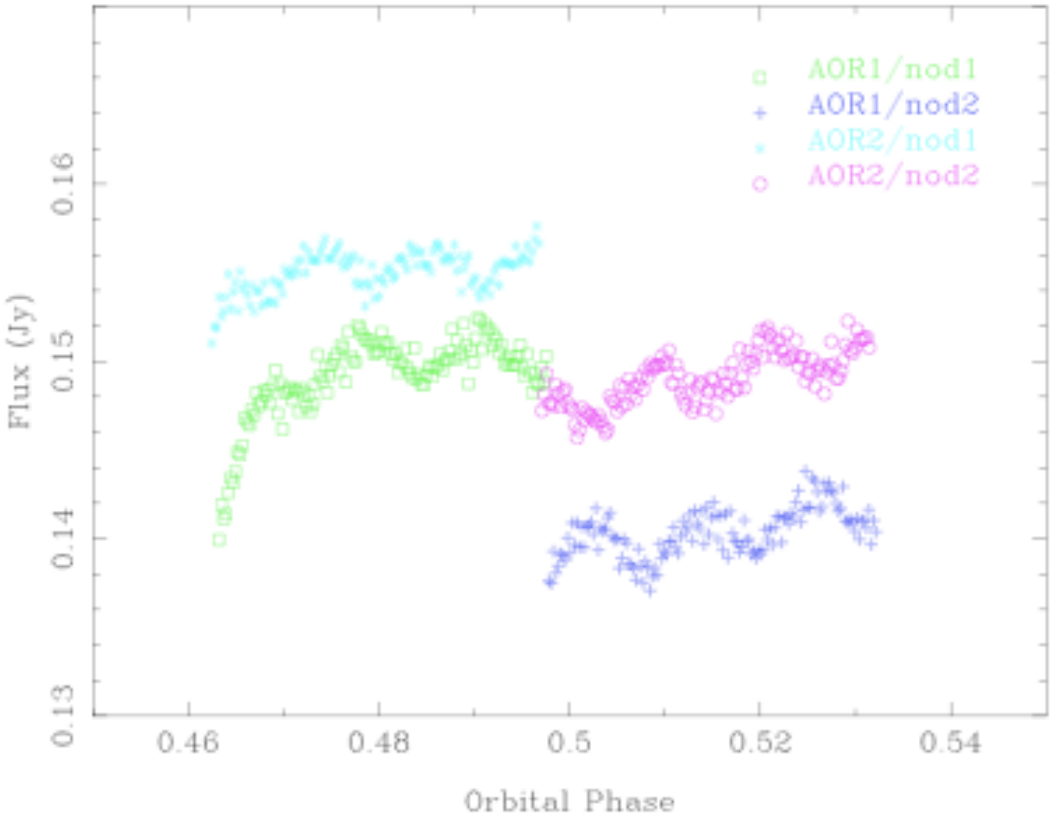


- Spitzer IRS SL1 (7.5 – 15 μm) spectroscopy
- Two secondary eclipse observations of HD 209458b
- Where is the eclipse?

Exoplanet Spectroscopy



Swain et al. 2008 Ap. J 674, 482

Example – approach with 2 methods

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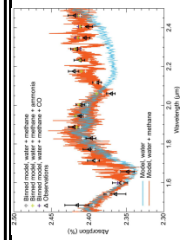
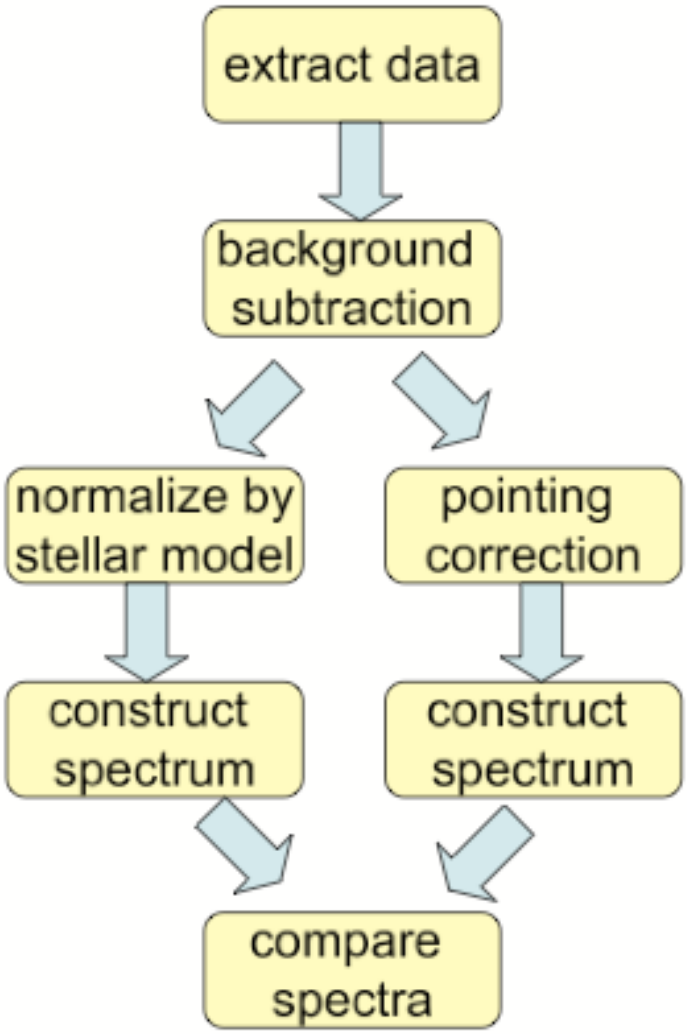
Exoplanet Spectroscopy



- 2 methods
  - "differential"
  - "absolute"



Swain et al. Ap. J 2008

Pointing correction

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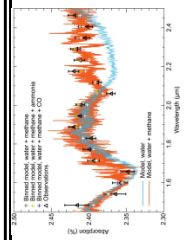
Exoplanet Spectroscopy



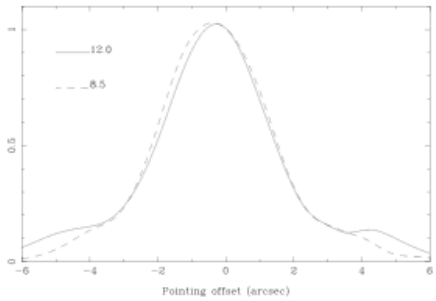
- Known pointing error for Spitzer
- Coupled flux moduation
- Determine the pointing error

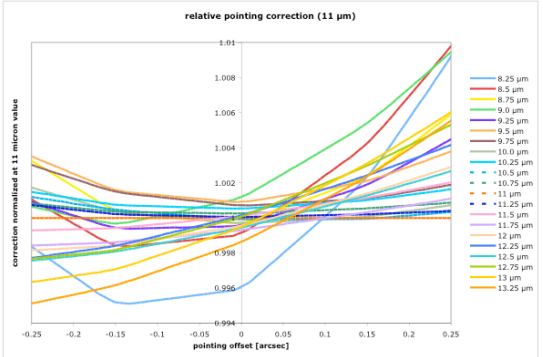
$$\dot{\theta} = \dot{\theta}_0 + A_\theta sin(\omega t - \phi_\theta),$$
$$x = x_o + m_x t + A_x cos[\omega\theta(t) - \phi_x],$$
$$y = y_o + m_y t + A_y cos[\omega\theta(t) - \phi_y],$$

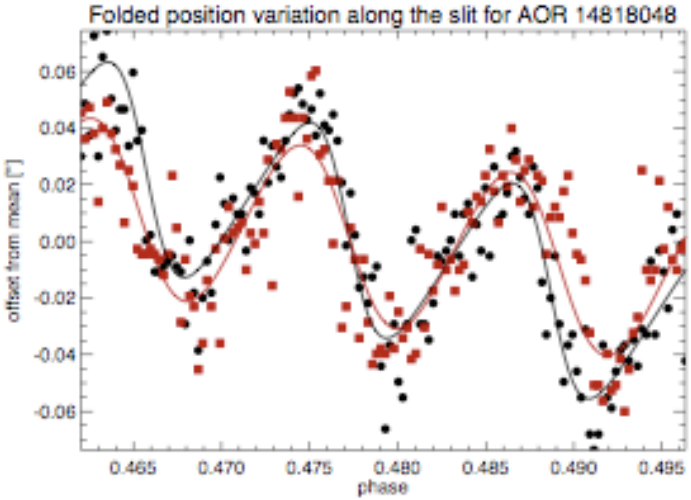
$$(y_0, m_y, A_y, \phi_y)$$

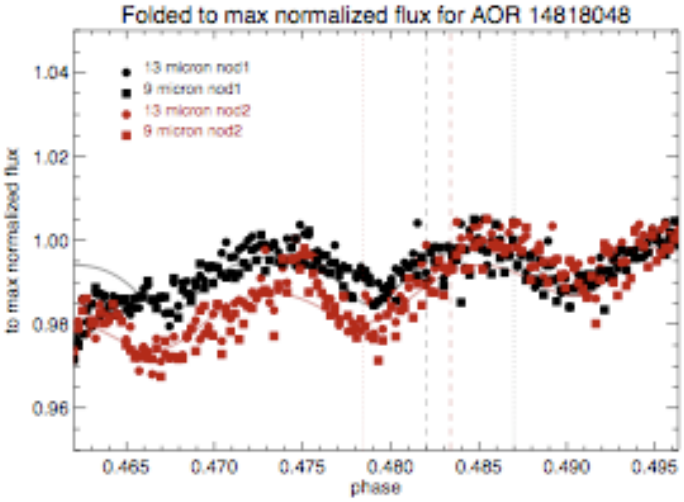
- Correct the pointing error

$$F = S/\zeta(y).$$









Swain et al. Ap. J 2008

Example – correction applied

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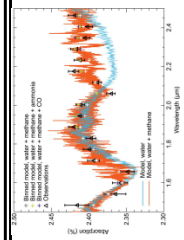
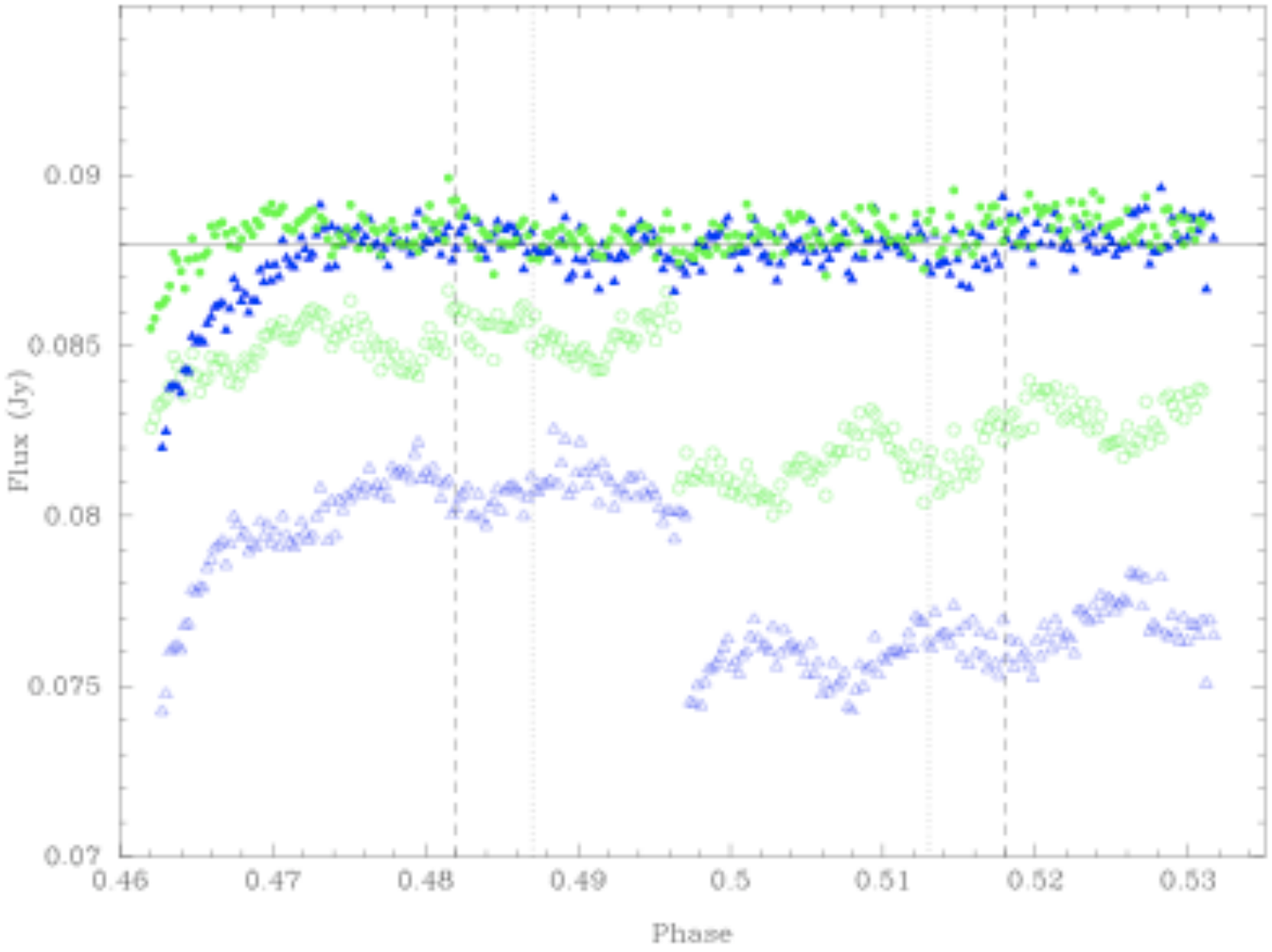
Exoplanet Spectroscopy



- Before and after the pointing error correction



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Example - validation

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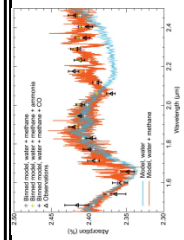
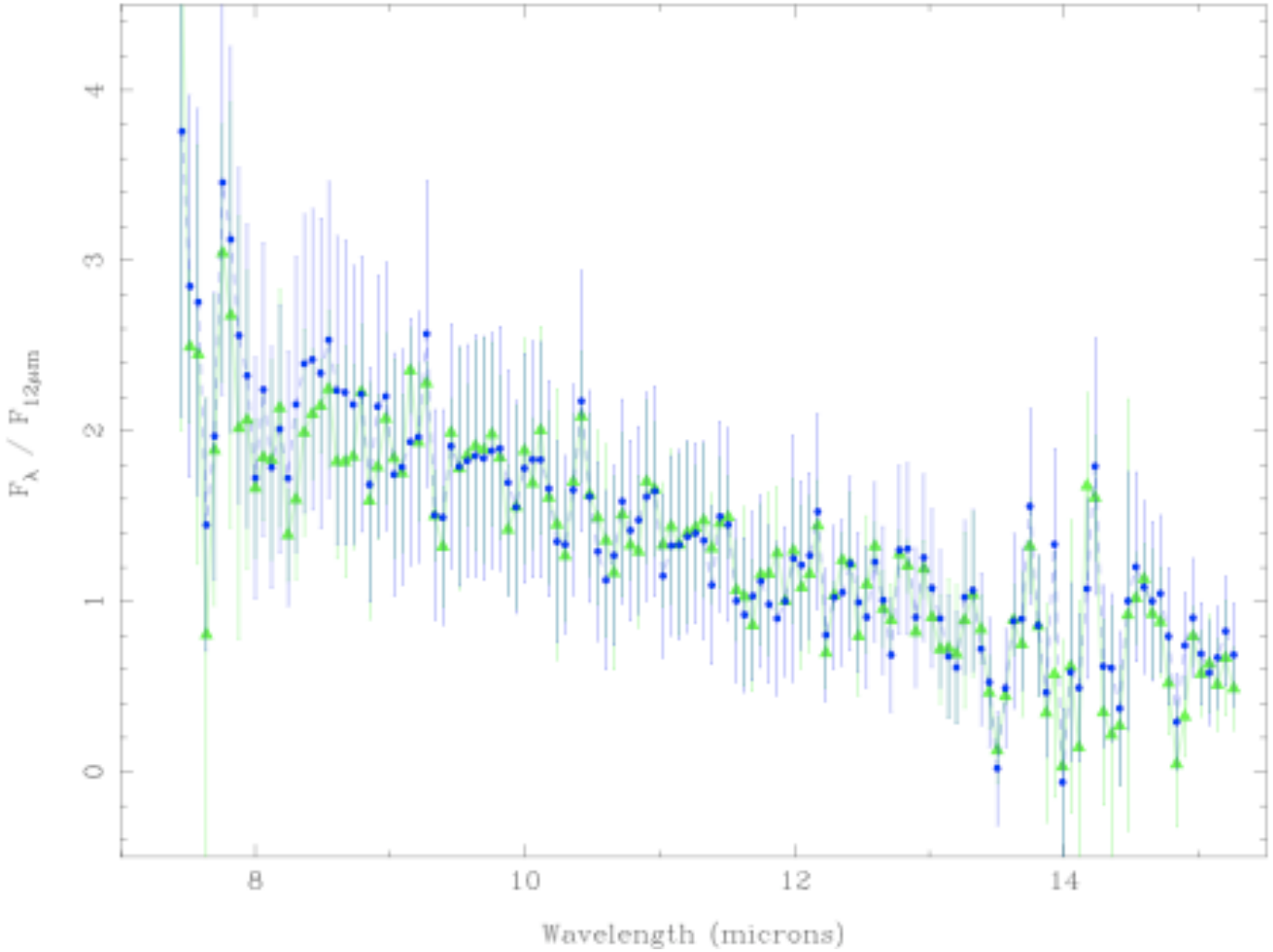
Exoplanet Spectroscopy



- Comparing the "absolute" and the "differential" methods.



Swain et al. Ap. J 2008

Example – calibrated data

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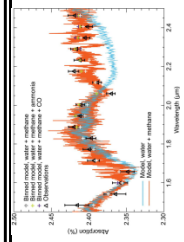
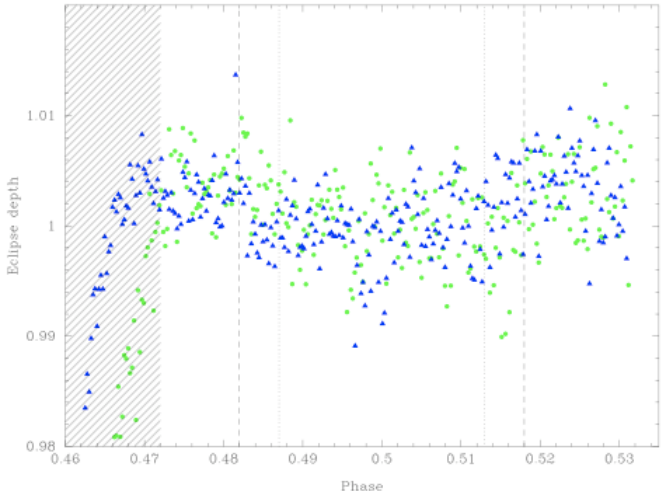
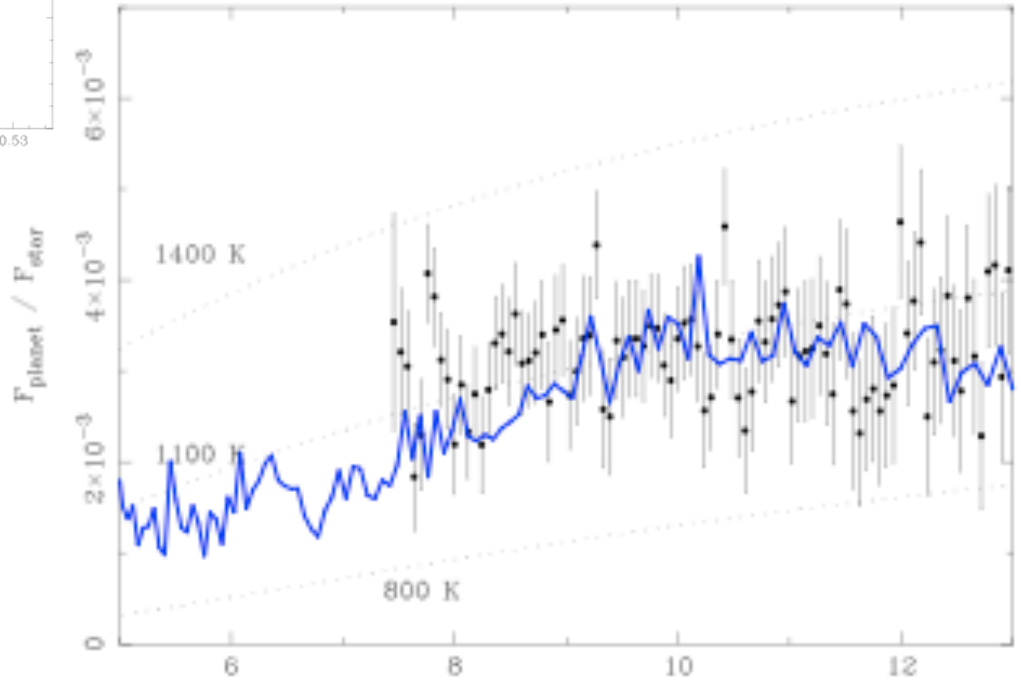
Exoplanet Spectroscopy

- Calibrated light curve and secondary eclipse spectrum.





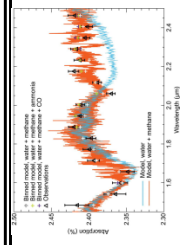


Swain et al. Ap. J 2008

National Aeronautics and Space Administration

Useful tips – not ironclad rules

JPL

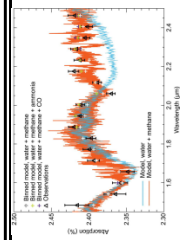


Exoplanet Spectroscopy

- Change nothing
  - Configure the instrument and “lock it down”
  - Do not repoint
- Use other data sets for additional calibration constraints
  - Spitzer IRS – custom spectral response function, slit scan
- 2 method validation
- Do not waist time on mediocre data
- All instruments are different
  - Method from instrument A may or may not be appropriate to instrument B.
- Coupled flux modulation (slit based instruments)
  - A plan will be needed
- Inter and intra-pixel gain differences

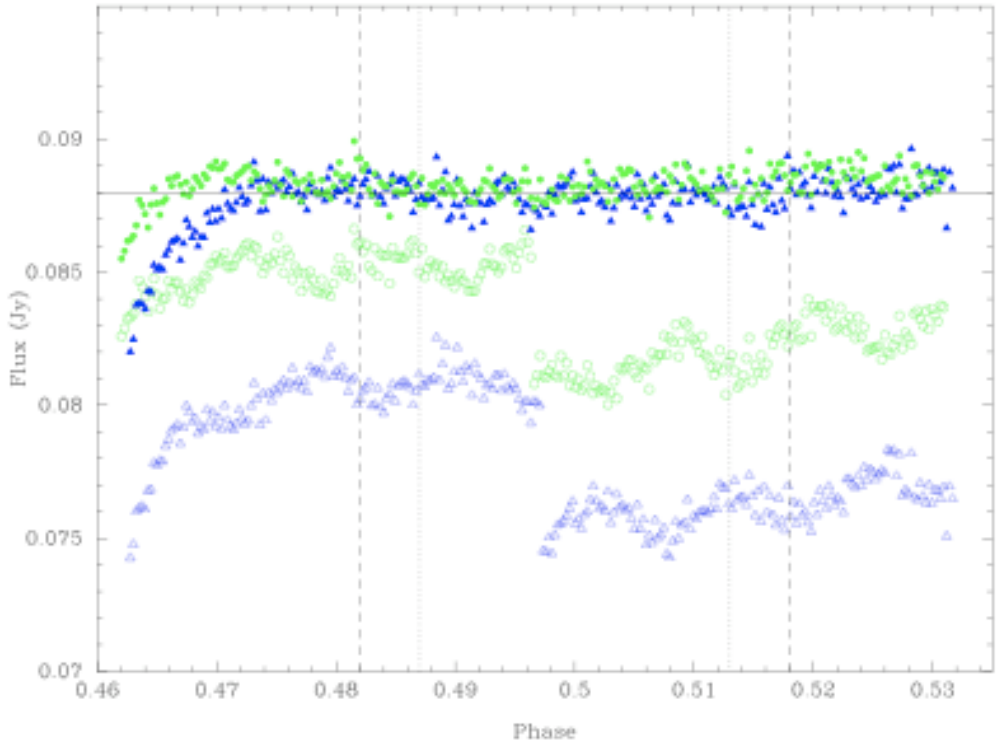
Your job

JPL

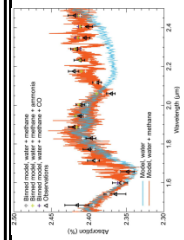


Exoplanet Spectroscopy

- Consider all possibilities
- Leave no stone unturned
- Look at calibration methods in other fields
- Listen to your instrument

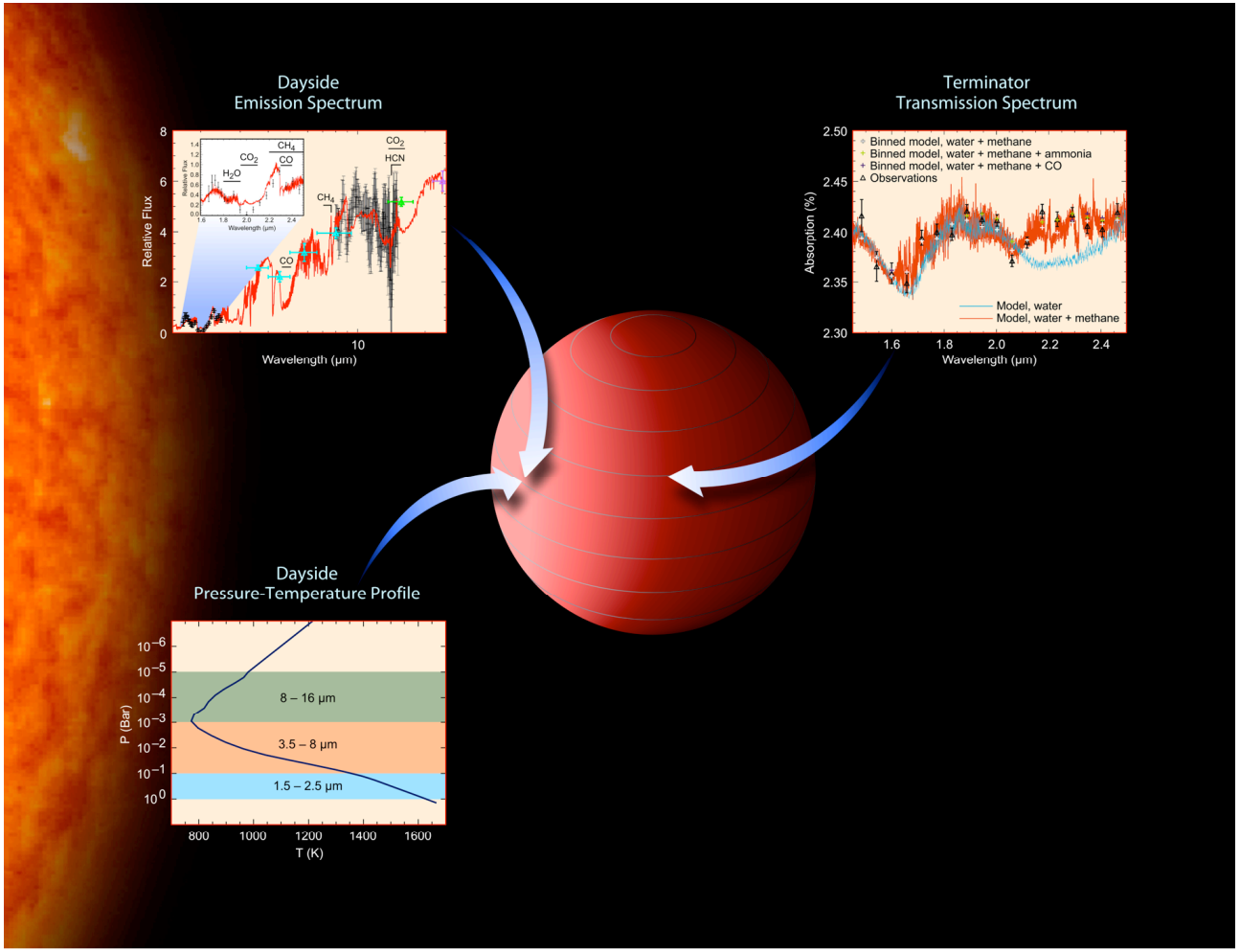


Your reward



Exoplanet Spectroscopy

- Measurements of an exoplanet atmosphere with the most powerful tool available

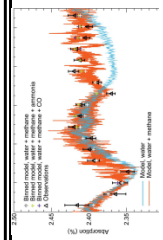


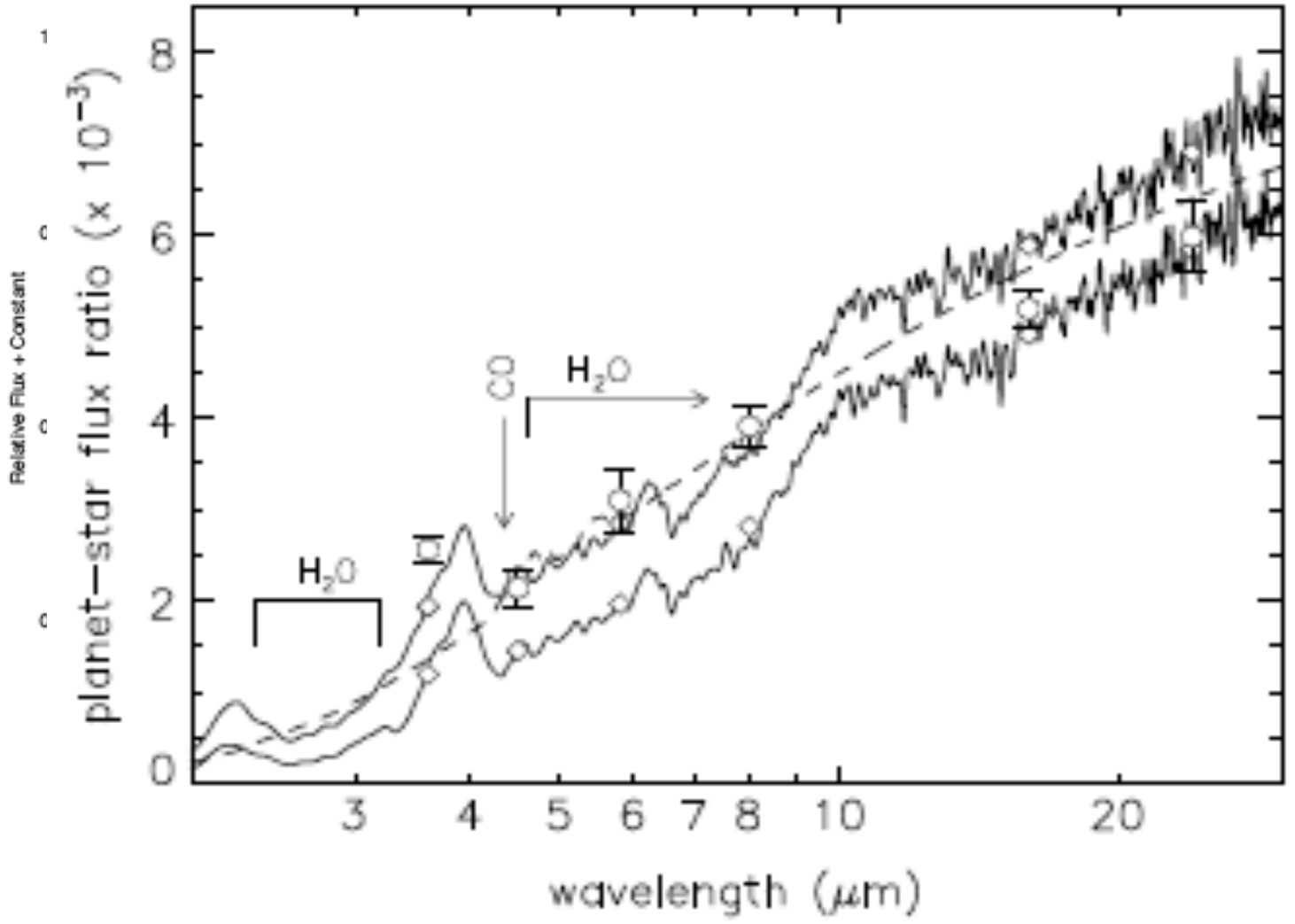
Deming, et al. 2006, Grillmair et al. 2007, Swain et al. 2008/2009, Charbonneau et al. 2008, Knutson et al. 2008

An Example

JPL

Exoplanet Spectroscopy





Charbonneau et al. 2008