Exoplanet Characterization 101:

What is the planet’s bulk composition?
What is its temperature?
Its atmospheric composition?
What about atmospheric circulation?

Hot Jupiters are good test cases for exoplanet characterization (big, hot, lots available). Current challenge is to explain diversity in observed properties.

Kepler, CoRoT, and Mearth are enabling the first studies of smaller and/or cooler transiting planets.
Bright Stars Make the Best Targets for Atmosphere Studies

Field is dominated by a few benchmark systems.

Gas Giant Planets

Ice/Rock Planets

Super-Earths (<10 Mearth)
What Do Different Types of Events Tell Us About the Planet’s Atmosphere?

**Transit**
See radiation from star transmitted through the planet’s atmosphere

**Secondary Eclipse**
See thermal radiation and reflected light from planet disappear and reappear

Why eclipsing systems?
Can characterize planets without the need to spatially resolve the planet’s light separate from that of the star.
Scaling Laws for Transiting Planets

Absorption During Transit (%):

\[
\frac{10R_p}{R_*^2} \left( \frac{kT_p}{\mu g} \right)
\]

Secondary Eclipse Depth (IR):

\[
\left( \frac{R_p}{R_*} \right)^2 \left( \frac{T_p}{T_*} \right)
\]

Orbital Phase Variations:

Always less than secondary eclipse depth.

Three ways to decrease signal: smaller planet, lower temperature, heavier atmosphere.

M stars preferred!
A good understanding of limb-darkening is crucial for determining the planet’s wavelength-dependent radius.

HST STIS transits of HD 209458b from 290-1030 nm (Knutson et al. 2007a)
Sources of Stellar Limb-Darkening Models


1. Empirical
   - Quadratic coefficients

2. 1D Stellar Atmosphere Models
   - Four-parameter nonlinear coefficients
   - Kurucz/ATLAS models; good for FGK stars. Available at:
     http://kurucz.harvard.edu
   - PHOENIX models; better for M stars (include TiO), higher resolution in mid-IR. Available at:
     ftp://ftp.hs.uni-hamburg.de/pub/outgoing/phoenix/NextGen

3. 3D Models (Hayek et al. 2012)
   - HD 189733, HD 209458

Calculating LD Coefficients from a Model:

1. Calculate photon-weighted average $I(\mu)$ over desired bandpass (e.g., Sing 2012)
2. Fit $I(\mu)$ with desired limb-darkening model to obtain coefficients.
Caveats and Cautions

- Generally, the broader the band, the more reliable the prediction
- Limb-brightening in line cores
- Uncertainties are greater at shorter wavelengths
- Late M stars also more problematic (models not as reliable, well-tested)

David Sing’s website is a great resource for limb-darkening coefficients:
http://www.astro.ex.ac.uk/people/sing/David_Sing/Limb_Darkening.html

The Sun in EUV (image credit NASA/Goddard/SDO AIA team)
Stellar Activity is Bad for Transits

Scenario 1: Occulted Spot

Carter et al. (2011)

Scenario 2: Non-Occulted Spot
Will Stellar Activity Affect All Transiting Planets Orbiting M Stars?

*R’ band transits of GJ 1214b, 6.5 m Magellan Clay telescope* (Carter et al. 2011)

Effect of spots + LD is minimized at longer wavelengths.

*Spitzer 4.5 μm transit of GJ 1214b* (Desert et al. 2011)
What to do when spots are unavoidable.

Spot contrast is wavelength-dependent. Can model as difference between two stellar spectra with different effective temperatures. For HD 189733, spot is \(~500\) K cooler than photosphere.
Correcting for Unocculted Spots With Ground-Based Monitoring Data

Three-Step Spot Correction (Sing et al. 2011)

1. Determine spot temperature from occulted spots.
2. Determine decrease in flux $dF$ due to spots at time of observations.
3. Use model spot spectra to convert $dF$ to band of transit observations, add $dF$ to transit light curve and fit for transit depth.
Result: A High-Altitude Haze

Spot occultations were trimmed for this measurement.

Rayleigh Scattering Model

Cloud-Free Model (Fortney et al. 2010)

Data

Sing et al. (2011) HST STIS Obs. In Transit

Larger radius

Smaller radius

Wavelength (Å)
What Do We Learn From Transmission Spectroscopy?

What do we measure?
- Lyman alpha, ionized metals
- Sodium, potassium, TiO(?)
- Water, methane, CO, CO₂

What do we learn?
- Atmospheric mass loss
- Clouds/hazes or transparent?
- Other absorbers?
- Is the chemistry in equilibrium?
A Less Conventional Transit Observation: Doppler Shifts with High Resolution IR Spectroscopy

HD 209458b; Snellen et al. (2010)
GJ 1214b; Crossfield et al. (2011)
Detection of RV-Shifted Absorption from HD 209458b During Transit

Barycentric RV + 14.8 km/s

RV Shifted CO absorption band

R = 100,000 K band spectrum

CO absorption detected at 5.6σ

Marginally significant (2σ) blueshift -> winds?

Strength of CO Cross-Correlation

VLT/CRIRES, Snellen et al. (2010)
Transmission Spectroscopy of Super-Earth Atmospheres

Compositions:
- solar
- 30x solar
- 50x solar
- H₂O (steam)
- 50/50 H₂O, CO₂
- CO₂ (Venus)

Scale Height

$$H = \frac{kT}{g \mu}$$

Miller-Ricci & Fortney (2010)
Planet must have water-dominated or cloudy atmosphere.
What Do Different Types of Events Tell Us About the Planet’s Atmosphere?

Transit
See radiation from star transmitted through the planet’s atmosphere

Secondary Eclipse
See thermal radiation and reflected light from planet disappear and reappear
Spitzer observations of HD 189733b
(Charbonneau, Knutson et al. 2008)

Observe the decrease in light as the planet disappears behind the star and then reappears.

Secondary Eclipse Spectroscopy
Comparison to Models

Stellar Atmosphere Model

PHOENIX, 5200 K

Wavelength (μm)

Flux (erg s\(^{-1}\) cm\(^{-2}\) cm)

10\(^{15}\)
10\(^{14}\)
10\(^{13}\)
10\(^{12}\)
10\(^{11}\)
10\(^{10}\)

1
10

1200 K planet
Barman et al. (2008)

Planet Atmosphere Model

Model assumes solar composition atmosphere, chemistry in local thermal equilibrium.

\[
\text{depth}(\%) = \frac{F_{\text{planet}}}{F_{\text{star}} + F_{\text{planet}}} \approx \frac{F_{\text{planet}}}{F_{\text{star}}}
\]

\(F_{\text{star}}\) + \(F_{\text{planet}}\)

\(F_{\text{star}}\)

depth(%) = \frac{F_{\text{planet}}}{F_{\text{star}} + F_{\text{planet}}} \approx \frac{F_{\text{planet}}}{F_{\text{star}}}

time from predicted center of eclipse (days)
A Broadband Emission Spectrum For HD 189733b

Data from Charbonneau, Knutson et al. (2008)
Model from Barman (2008)
The Atmospheric Composition of HD 189733b

Best-fit abundances:

- $\text{H}_2\text{O}$: $10^{-4}$-$10^{-3}$
- CO: $10^{-4}$-$10^{-2}$
- CH$_4$: $<6 \times 10^{-6}$
- CO$_2$: $\sim 7 \times 10^{-4}$

Data from Charbonneau, Knutson et al. (2008)
Data from Grillmair et al. (2008)
Data from Swain et al. (2009)

Model from Madhusudhan & Seager (2009)

Model fits allow us to test assumptions about chemistry, pressure-temperature profiles

Photochemistry

Figure courtesy N. Madhusudhan
What Happens When Your Planet is Not a Uniform Disk?

\[
\Psi_0(\theta, \phi) \leftrightarrow \lambda_0(t)
\]

\[
\Psi_1(\theta, \phi) \leftrightarrow \lambda_1(t)
\]

\[
\Psi_2(\theta, \phi) \leftrightarrow \lambda_2(t)
\]

\[
\Psi_3(\theta, \phi) \leftrightarrow \lambda_3(t)
\]

\[
\Psi_n(\theta, \phi) \leftrightarrow \lambda_n(t)
\]

Majeau, Agol, & Cowan (2012)

HD 189733b 8 \( \mu \)m secondary eclipse (Agol et al. 2010, de Wit et al. 2012).

Also see Williams et al. (2006).
Secondary Eclipse Mapping

\[ \Delta I_j = \frac{\Delta F_j'}{\Delta A_j'} \]

\[ \bar{I}_j' = \frac{\Delta F_j'}{\Delta A_j'} \]

\[ \Delta F_1' = \Delta F_1 \]

\[ \bar{I}_1 = \frac{\Delta F_1}{\Delta A_1} \]

Majeau, Agol, & Cowan (2012)
Secondary Eclipses + Transits
Constrain Orbital Eccentricity

HAT-P-2b
F_{periast} = 10 \times F_{apastron}

Pál et al. (2010):
\begin{align*}
M &= 9.09 \, M_J \\
\epsilon &= 0.5171 \\
P_{\text{orb}} &= 5.6 \, \text{days} \\
P_{\text{rot}}^\star &= 1.9 \, \text{days}
\end{align*}

\* Parameterization from Hut (1981)

\( \text{figure credit G. Laughlin (oklo.org)} \)
Secondary Eclipses + Transits
Constrain Orbital Eccentricity

HAT-P-2b at 3.6 μm
Lewis, Knutson et al. in prep

RV alone:
\( e = 0.567 \pm 0.013 \)
\( \varpi = 4.40^\circ \pm 0.50^\circ \)

RV + Spitzer photometry:
\( e = 0.50978 \pm 0.00031 \) (40x smaller!)
\( \varpi = 8.31^\circ \pm 0.28^\circ \)

Also see Pál et al. (2010)
Wrapping it Up: An Observation Planning Cookbook for Transits + Eclipses

Absorption During Transit (%):

$$\frac{10R_p}{R_*^2} \left( \frac{kT_p}{\mu g} \right)$$

Secondary Eclipse Depth (IR):

$$\left( \frac{R_p}{R_*} \right)^2 \left( \frac{T_p}{T_*} \right)$$

Good resources include:
Exoplanet Atmospheres by Sara Seager, and Exoplanets (ed. Sara Seager)
Ground vs. Space

**Pro:** Stable, ultra-precise photometry + spectroscopy, higher IR sensitivity

**Con:** Small apertures generally limit targets to bright (V<12) stars, limited wavelengths available. Hard to do large surveys.

**Pro:** Better for faint stars, many bands available. Conducive to large surveys.

**Con:** Requires wide field of view, multiple comparison stars. Can be systematics-limited for bright stars.
Conclusion: Think Outside the Box

One outstanding mystery is whether hot Jupiters have magnetic fields... could we detect auroral emission lines from a hot Jupiter, perhaps in secondary eclipse?