“Spectra and Photometry: Windows into Exoplanet Atmospheres”

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Our Solar System
Radial Velocity
From the ground
Transits from space
Microlensing
Space Astrometry?

Mass $[M_{Jup}] \times \sin i$

semi-major axis $a$ [AU]
Transit
See thermal radiation and reflected light from planet disappear and reappear

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

Orbital Phase Variations
See cyclical variations in brightness of planet

Transiting Planets

figure taken from H. Knutson
With upper-atmosphere optical absorber

Transit chord

Graphics by D. Spiegel

P = 0.02 mbar, 5.7 mbar, 0.14 bar, 3.6 bar
Central Longitude: -90
Beyond Hot Jupiters: The Age of Kepler

Kepler found many Earths, super-Earths and sub-Neptunes, as well as Giants
Transit Spectra

- At terminator - couples aspects of day and night
- Chemistry at transition?
- Day/night temperatures
- Ingress/Egress asymmetry
Fractional Atmosphere vs. Wavelength

Burrows, Rauscher, Spiegel, & Menou 2010
GJ 1214b: Transit Radius vs. Wavelength

Howe & Burrows 2012, in press
Haze on HD 189733b

Figure from Pont, Knutson et al. (2007) showing atmospheric transmission function derived from HST ACS measurements between 600-1000 nm
HD 209458b: Transit Radius vs. Wavelength - Measuring Orbit and Wind Speeds?

Ingress vs. Egress

Using Burrows, Rauscher, Spiegel, & Menou 2010

Also, re tau Boo B
Atmospheric Clouds/Hazes

- Opacities
- Physical extent
- More important for transit spectra than secondary eclipse or light curve spectra, but ...
- HD 189733b (e.g., Pont et al.)
Secondary Eclipse - Emission Spectra, Hot Upper Atmospheres, and Inversions
Transit
See stellar flux decrease (function of wavelength)

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

Orbital Phase Variations
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Spitzer ST:
NICMOS

TrES-1

$P_n = 0.1$
$P_n = 0.3$
$P_n = 0.5$

IRAC

MIPS 24$\mu$m

$\lambda F_{\lambda}$ (10$^8$ ergs s$^{-1}$ cm$^{-2}$)

$\lambda$ (μm)

< 35%

< 10%
HD189733b
(At Secondary Eclipse)

Grillmair et al. (this paper)
Charbonneau et al. (2008)
P_n = 0.1, Burrows, Budaj, & Hubeny (2008)
P_n = 0.3, "

Water

CH_4?

CO

Water

?
Heated upper atmosphere!

IRAC 1 < IRAC 2!
Water in Emission!

Burrows et al. 2007

IRAC 1 < IRAC 2!

H$_2$O

Richardson et al. (2007), Jul 6
Deming et al. (2005)
Knutson et al. (2007c)
Richardson et al. (2003)

$F_{\text{PLANET}}/F_{\text{STAR}}$

$\lambda(\mu\text{m})$

Default, $P_n=0.3$
$\tau_{\text{opt.}} \sim 3$, $P_n=0.3$
$\tau_{\text{opt.}}$, $P_n=0.4$
$\tau_{\text{opt.}}$, $P_n=0.5$
Machalek et al. 2008

But stellar irradiation low; same as HD 189733b!

XO-1b
Indices of Upper-Atmosphere Heating and Inversion:

- **Inversion:** IRAC 2/IRAC1 - High “Bump” at IRAC3 (water in emission?) - “other” emission features

- **Hot Upper Atmosphere:** “High” planet-star flux ratios in IRAC 2, IRAC 3, and IRAC 4 bands (and at 24 microns?)

- **Hot Spot advection??**

- **What is absorbing in the optical at altitude?**
Light Curves
Transit
See stellar flux decrease (function of wavelength)

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

Orbital Phase Variations
See cyclical variations in brightness of planet
Planet/Star Flux Ratio vs. Wavelength and Phase

HD 209458b

$F_p/F_*$ vs. $\lambda$
Every 30° in Phase

Burrows, Rauscher, Spiegel, & Menou 2010
Methane Map: w/o Upper Atmos. heating
J-band HD 209458b Map (model a03)

Burrows et al. 2010
HD 209458b: Integrated Phase Light Curves:
With inversion/hot upper atmosphere

λ-dependent Trough/peak shifts

Burrows, Rauscher, Spiegel, & Menou 2010
HD 209458b: Integrated Phase Light Curves: No upper atmosphere absorber

λ-dependent Trough/peak shifts

Burrows, Rauscher, Spiegel, & Menou 2010
New Ups And b Phase Curve at 24 µm

Future: Kepler, warm Spitzer, JWST

Harrington et al. 2010
First Longitudinal Temperature Profile for an Exoplanet: HD 189733b’s Warm Night Side

Spitzer 8 μm observations of HD 189733b (Knutson et al. 2007b, Nature 447, 183).
Evidence for a Diversity of Day-Night Circulation Patterns

Large day-night brightness gradient
HAT-P-7 / Kepler

Small day-night brightness gradient
HD 189733b / Spitzer

Large gradients:
- u And b* (Harrington et al. 2007)
- HD 179949* (Cowan et al. 2008)
- HAT-P-7 (Borucki et al. 2009)

Intermediate gradients:
- HD 149026 (Knutson et al. 2009)

Small gradients:
- HD 189733b (Knutson et al. 2007)
- HD 209458 (Knutson et al., in prep.)

* non-transiting planet, brightness/temperature gradient degenerate with unknown orbital inclination and planet radius
Radius-Mass Relationship for Irradiated EGPs ("Hot Jupiters")

(dependence on age, star, semi-major axis distance, planet mass, "core mass," atmospheric opacities)
Giant Planet Radius Depends Upon Atmosphere

- Radius depends upon core entropy and mass
- Atmosphere regulates core heat loss
- Extra heating in atmosphere (e.g., Joule heating?) affects T/P profile and internal flux
- Day and Night sides cool differently
- Night side is colder, but may allow more core heat loss ($T_{n\text{eff}}$ vs. $T_{d\text{eff}}$)
- $T_{n\text{eff}} (S,g)$ ; $T_{d\text{eff}} (S,g)$ ---> $T_{\text{eff}} (S,g)$
- Opacities
- Metallicities
- Magnetic Torques and Joule Heating?
- Clouds
- 3D Effects (irradiation, rotation …)
Hundred of Planets Are Known to be Transiting.

Some planets appear to be inflated

Massive planets on highly eccentric orbits

Ice/Rock Planets
Planet diversity

CoRoT, M-Dwarf surveys

- Transit $\rightarrow$ fractional radius (relative to host star) $\rightarrow$ inclination.
- RV $\rightarrow$ planetary mass

Solid planets:
- CoRoT-7b: Period $\sim$ 0.85 d
- MEarth-1b: Period $\sim$ 1.50 d

$\Rightarrow$ Diversity
Core Entropy vs. Radius for Transiting Giant Planets

Spiegel & Burrows 2012
Approximate “Core” Mass vs. Stellar Metallicity

Note measurement of HAT-P-1b

See also Guillot et al. 2006
Day- and night-side cooling done consistently

Evolution of WASP–12b–like Planet's Radius
Extra interior heating: $2.4 \times 10^{-6} L_{\text{sun}}$

Standard $f=1/4$ model

Consistent day/night evolution, $P_n = 0.3$

Consistent day/night evolution, $P_n = 0.1$

Spiegel & Burrows 2012
Spectroscopic and Photometric Discriminants of Giant Planet Formation Scenarios

D. Spiegel and A. Burrows
2011
Initial BD/EGP Models are Quite Uncertain

- Initial Radius, entropies determine flux evolution for quite some time

- Hot-start/cold-start/warm-start - Signatures of mode of formation
1.0 M$_j$

Tidal

Hayashi Forbidden Zone

Olivine

51 Peg b
High-Contrast Imaging
Very Dusty Atmospheres - low gravity?

Madhusudhan, Burrows, & Currie 2011

See also Barman et al.
WFIRST-2.4 Exoplanet Imaging Sensitivity

- Very sensitive to contrast limit (& IWA)

Figure 2-21: This figure is a snapshot in time of contrast and separation for model planets, ranging in size from Mars-like to several times the radius of Jupiter, for about 200 of the nearest stars within 30 pc. Color indicates planet mass while size indicates planet radius. Crosses represent known radial velocity planets. Solid black lines mark the baseline technical goal of $1 \text{ ppb}$ contrast and $0.2 \text{ arcsec IWA}$, while the dotted lines show the more aggressive goals of $0.1 \text{ ppb}$ and $0.1 \text{ arcsec IWA}$.
Exoplanet Science: Current Measurement and Interpretative Limitations
Systematic Uncertainties/Ambiguities in Spectral Models

- Planets are not Stars - They have “character,” added complexity
- Opacities (line profiles …?)
- Abundances
- NLTE
- NCE
- Clouds
- Photochemistry
- 3D Effects (irradiation, rotation …)
- $\chi^2$ is of dubious real use when models systematics-dominated (models not merely a matter of physical parameters - but can have errors of unknown magnitude and kind)
- Retrieval (forward and inverse) techniques have been primitive - multiple degeneracies, systematic limitations
- Stellar Atmospheres took ~100 years to evolve as a discipline - molecular/exoplanetary atmospheres are more complicated
Systematic Uncertainties in Data

- Limited SNR, bandwidths, resolution
- Star spots
- Absolute Calibration
- Earth’s atmosphere (H₂O, OH, …)
- Spitzer “Ramps”
- Spitzer not designed for better than 10⁻² - pushed to ~10⁻³
- Planet/Star flux ratios have varied by factors of ~2 from epoch to epoch
- Measured Transit depths at the same wavelengths vary by factors of ~2
Parameters > Number of Data Points

- Model fits are often under-constrained
- Frequently, just two points fit (e.g., $F_p / F_\star$)!
- In the context of systematic data uncertainties, ....
- $CO_2$, abundances, thermal inversions, C/O ratios?
One-D models for 3D objects?

- Many adjustable parameters (f, $\varepsilon$, $\alpha$, $\kappa_a$, $P_n$, ”A,” abundances, $T_{\text{eff}}$, T/P profiles, “TiO”…)
- Advection of composition and heat?
- Latitudinal and longitudinal dependence of emissions/spectra - antenna gain?
- Solar ratios of elements?
- Metallicity dependence (weak for emission (secondary eclipse); strong for transit (primary eclipse)?)
- Mixing-length convection?
- Eddy mixing?
- Transit spectra are for terminator region - transition region, ingress/egress asymmetry
Limitations of 3D GC Modeling

- 3D models have Mach ~ 1, but use “primitive” equations that assume M << 1
- Filter sound waves (one exception)
- Can’t handle shock waves
- Based on Earth GCMs and parametrizations
- Use Rayleigh drag, even for close-in EGPs (“hot Jupiters”)
- Super-rotational speeds depend on ad hoc parameters
- Non-ideal MHD?
- Don’t match to core convective regions consistently
- Don’t incorporate 3D multi-frequency radiative transfer

- Importantly, GCMs were configured to look at winds/pressure, not spectral emissions - there is a mismatch between the traditional goals of Planetary and Earth scientists and Exoplanet Astronomers
Need high-quality, uniform, calibrated data over a large spectral bandwidth

Need much more physical models, with realistic (multi-D) radiative transfer
Training Set

- Many (most?) conclusions will be overturned

- The past 15 years has been but a training exercise - educating a community

- Community has been practicing for the future - winnowing of ideas, techniques ....

- With 2\textsuperscript{nd} and 3\textsuperscript{rd}-generation data and much better and more comprehensive models, we may start truly to learn about exoplanet atmospheres and spectra

- Need mature ground-based and space-based initiatives and a credible, reliable international plan/Roadmap for exoplanet exploration in the next ~20 years

- Are we ready?
Spitzer ST:
Theoretical Questions

- What limits super-rotational atmospheric flows?
- Day/Night Contrasts?
- What is the “extra absorber” in many hot-EGP atmospheres?
- Why are some “Hot Jupiters” so large ($R_p$ vs. $M_p$)?
- Is there a dynamical, structural, and/or thermal role for B-fields?
- What condensates reside in planetary atmospheres?
- Winds and Evaporation?
- Tidal Effects?
- Atmospheric, Envelope, and Core compositions?
- Mode(s) of Formation (and Signatures!)?