Reflected Light from Giant Exoplanets

Caroline Morley
UC Santa Cruz

Mark Marley
Nikole Lewis
Roxana Lupu
Jonathan Fortney
Michael Line
Kerri Cahoy

Image credit: NASA/JPL/University of Arizona
Albedo Spectra: Basics

pure Rayleigh atmosphere

geometric albedo

wavelength

0.75
Albedo Spectra: Basics

pure Rayleigh atmosphere

with gas absorbers

geometric albedo vs. wavelength

0.75

CH₄, NH₃, H₂O, Na, K, CO
Albedo Spectra: Basics

with clouds

geometric albedo

wavelength
Albedo Spectra: Basics

with clouds

Shoemaker–Levy 9 Impact on Jupiter seen with Hubble

Green

Methane

18 July 1994
Albedo Spectra: Basics

Marley et al. 1999

degeneracy between methane abundance and continuum opacity: need both weak and strong bands

lots of work done in ~1999-2005 developing models and making predictions for exoplanets

300 K, g=22 m/s²

water clouds
Albedo Spectra: Basics

300 K, g=22 m/s²
water clouds

clouds set the “continuum” opacity

Marley et al. 1999

degeneracy between methane abundance and continuum opacity: need both weak and strong bands

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Albedo Spectra: Basics

Marley et al. 1999

degeneracy between methane abundance and continuum opacity: need both weak and strong bands

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Exoplanet reflection spectra out of fashion for last ~5 years because **hot Jupiters are dark.**
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![Diagram showing exoplanet reflection spectra and class IV EGP.](image-url)
Exoplanet reflection spectra out of fashion for last ~5 years because hot Jupiters are dark.

Heng & Demory 2013

$A_g$ and $f_{\text{thermal}}$ as a function of $F_0$ (erg cm$^{-2}$ s$^{-1}$). The theoretical curves show $f_{\text{thermal}}$ for no redistribution and full redistribution. The data points represent observations of various exoplanets, with error bars indicating the uncertainty in the measurements. The figure illustrates the relationship between the geometric albedo and the thermal emission fraction, with the latter being a function of the incident stellar flux. The study of clouds or hazes is emerging as a major aspect of exoplanet research.
Kepler photometry allowed us to infer inhomogeneous clouds for the first time.
Theoretical Albedo Spectra: general approach

1D radiative-convective equilibrium model: temperature, composition
Theoretical Albedo Spectra: general approach

1D radiative-convective equilibrium model:
temperature, composition

coupled cloud model:
cloud tau, scattering, asymmetry
Theoretical Albedo Spectra: general approach

1D radiative-convective equilibrium model: temperature, composition
coupled cloud model: cloud tau, scattering, asymmetry

scattered radiation (Rayleigh, Raman, Mie)

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In Figure 15, we...
The temperature structure (set by stellar flux) controls the clouds.
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The temperature structure (set by stellar flux) controls the clouds.
A space coronagraph opens up a totally different class of planets for atmospheric characterization.
We’ll probe solar-system temperature planets AND warmer planets.
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RV targets span temperature range from alkali, to water, to ammonia, to methane clouds.

Figure from Nikole Lewis
RV targets span temperature range from alkali, to water, to ammonia, to methane clouds.

**HD 62509b**
(warm, alkali clouds)

**HD 99492c**
(cold, ammonia clouds)

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RV targets span temperature range from alkali, to water, to ammonia, to methane clouds.

HD 62509b (warm, alkali clouds)

HD 99492c (cold, ammonia clouds)

Figure from Nikole Lewis
Huge range of spectra possible (not just scaled Jupiters!)
Higher metallicity widens and deepens molecular features: can constrain metallicity!
Need a minimum resolution to resolve both strong and weak features
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`R~70`
Need a minimum resolution to resolve both strong and weak features
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Need a minimum resolution to resolve both strong and weak features
R~70 adequately samples several methane features.
We can apply powerful retrieval techniques to low SNR data to constrain CH$_4$, clouds, etc.

Figure from Roxana Lupu

Observed Jupiter spectrum with added noise to make SNR=5

See Roxana’s poster here!!!

Karkoschka 1994 spectrum
Figures from Roxana Lupu
See Roxana’s poster here!!!
CH₄ abundance (right within one sigma)

Figures from Roxana Lupu

See Roxana’s poster here!!!
Figures from Roxana Lupu
See Roxana’s poster here!!!
single scattering albedo of both cloud and haze

Figures from Roxana Lupu

See Roxana’s poster here!!!
Radial velocities give us critical information for understanding these planets.

*orbital information:*

- temperature
- $M \sin(i) \rightarrow M$

NASA, ESA, and R. Soummer (STScI)
Radial velocities give us critical information for understanding these planets.

**orbital information:**
- temperature
- \( M \sin(i) \rightarrow M \)

**limits on radius**
Radial velocities give us critical information for understanding these planets.

**orbital information:**
- temperature
- $M \sin(i)$ → $M$
- limits on gravity
- limits on radius

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**Image Description:**
- A diagram illustrating the orbital information from radial velocities, including temperature, $M \sin(i)$ to $M$, limits on gravity, and limits on radius.
- The diagram includes labeled paths and arrows connecting different aspects.

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**Figure:**
- A graph showing geometric albedo versus wavelength in microns, with data points for different models.
- The x-axis represents wavelength (μm), ranging from 0.4 to 1, and the y-axis represents geometric albedo, ranging from 0 to 0.8.
- The graph includes data for Model Jupiter at 5 AU, 3x, 0 deg, and Karkoschka 1994.

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**Caption:**
- Radii determined to what extent this occurs for the Jupiters as well as Neptunes. We also plan to investigate decreasing the metallicity that we can differentiate between at cooler, larger planet–star separations. For the Jupiter case, it appears that the difference that we can differentiate between at cooler, larger planet–star separations is easier to detect when probing deeper into the volumes of atmosphere at smaller phase angles than at larger phase angles. This implies that it will be more challenging to determine to what extent this occurs for the Jupiters as well as Neptunes. We also plan to further increase the metallicity of Jupiter analogs to with large abundances of heavy elements. In future work, we would be interested targets for direct imaging observations of...
Radial velocities give us critical information for understanding these planets.

*orbital information:* temperature

\[ M \sin(i) \rightarrow M \]

limits on gravity

\[ \log_{10}(\text{CH}_4) = -2.02^{+0.98}_{-0.75} \]

limits on radius

\[ \log_{10}(g) = 1.94^{+0.68}_{-0.63} \]
Radial velocities give us critical information for understanding these planets.

**orbital information:**
- temperature
- $M \sin(i) \rightarrow M$
- limits on gravity
  - $\log_{CH4} = -2.02^{+0.98}_{-0.75}$

**limits on radius**
- $\log_g = 1.94^{+0.68}_{-0.63}$

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**Figure 11.**

As expected, the albedo decreases with increasing phase angles. In Figure 15, we show the albedo spectra of the Jupiter and Neptune models as a function of phase. The spectra show two distinct features near 0.94 and 0.1 microns. These features are also shown in Figure 14, which shows the ratio of the albedo spectra to the spectrum of the Sun. The model features are well-matched to the features observed in the spectra of Jupiter and Neptune.

In Figure 12, we present the phase functions for our Jupiter and Neptune models, as well as data from other exoplanets. Although we can calculate a phase function for each wavelength individually, we instead present the phase functions for our model Jupiter at 5 AU and 3x resolution. We also generate phase functions for our model Neptune from data taken in 2009 September.

From the albedo spectra as a function of phase, we can infer the atmospheric properties of these exoplanets. The model phase function shown is an average of the phase function for each wavelength. The reference spectrum used in this work is the solar spectrum obtained from the Virtual Observatory. The limits on radius are calculated using the volume of the atmosphere at different phases.
Radial velocities give us critical information for understanding these planets. **orbital information:**

- temperature
- $M \sin(i) \rightarrow M$
- limits on gravity
- \[ \log_{CH4} = -2.02^{+0.98}_{-0.75} \]
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Radial velocities give us critical information for understanding these planets.

**orbital information:**
- temperature
- $M \sin(i)$ → $M$
- limits on gravity
- limits on radius

**Diagram:**
- Model Jupiter at 5 AU, 3x, 0 deg
- Karkoschka 1994

**Graph:**
- Geometric Albedo vs. Wavelength (µm)

**Notes:**
- Radial velocities give us critical information for understanding these planets.
- orbital information:
  - temperature
  - $M \sin(i)$ → $M$
  - limits on gravity
  - limits on radius
Radial velocities give us critical information for understanding these planets.

**orbital information:**
- temperature
- $M \sin(i) \rightarrow M$
- limits on gravity

**limits on radius**

**phase information:**
- makes interpreting spectra much easier
Radial velocities give us critical information for understanding these planets.

orbital information:
temperature

\[ \text{M sin}(i) \rightarrow \text{M} \]

limits on gravity

limits on radius

phase information:
makes interpreting spectra much easier

Information-rich set of objects
Space coronagraph gives us a catalog of RV planets that spans wide unexplored $T_{\text{eff}}$ space.
Conclusions

- Albedo spectra finally poised to provide **powerful constraints on planet properties**
- Can retrieve methane abundance, cloud locations, cloud albedos for Jupiter-like planets
- Critical “catalog” for years to come
- RV sample provides **context for new discoveries**