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What can we learn about giant planets from low resolution spectra?

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Abstract. Here we examine the visible spectra of giant planets in anticipation of the science return of missions like the Terrestrial Planet Finder-Coronagraph and proposed Discovery class space coronagraph missions EPIC and ECLIPSE. Our understanding of extrasolar giant planets is already greatly improving because of our studies of old brown dwarfs (which have effective temperatures similar to young giant planets), transiting hot Jupiters, and the planet Jupiter itself. The first data collected on Jupiter-like extrasolar giant planets will likely consist of magnitudes in a few filters or very low resolution spectra. We investigate diagnostics for determining planetary effective temperature, atmospheric chemical abundances, cloud cover, and mass using such limited data. In general, giant planet science is improved significantly if missions in the visible domain extend to wavelengths as long as possible, within engineering constraints.

Keywords. planets and satellites: Jupiter, planetary systems, radiative transfer

1. Introduction

The imaging and spectroscopy of extrasolar giant planets (EGPs) will be a main focus of astronomy in the in the next decade. Optical coronagraphs in space are attractive platforms for detecting stellar flux reflected from EGP atmospheres. It is nearly assured that the first data gathered on old, Jupiter-like EGPs will be in the form of magnitudes in a few well-placed filters, or perhaps very low resolution spectra. It is interesting to address what one could learn about giant planets from this kind of data. Other authors have published fairly hi-resolution spectra of EGPs Sudarsky *et al.* (2003)Sudarsky, Burrows, & Hubeny, Burrows *et al.* (2004)Burrows, Sudarsky, & Hubeny at a variety of orbital separations. Here, we use some of these published models, as well as our own independent spectral calculations, to determine what may be learned about EGPs with only a minimum amount of information. We focus on optical spectra of giant planets older than 1 Gyr and less massive than 10 M_J, and thus already limits our discussion to effective temperatures below ∼450 K Burrows *et al.* (2001)Burrows, Hubbard, Lunine, & Liebert.

2. EGP phase space to date

It is usually assumed that Jupiter-like EGPs are a form of *terra incognita*, and while this is for the most part true, there is already available data to help to constrain what these cool, Jupiter-like planets may look like. Our understanding of EGPs is currently progressing on three fronts, as there are three kinds of objects that are currently available for detailed study. These objects help to show us what EGPs are like when they are:

• **Young.** Old brown dwarfs below $T_{\rm eff}$ = 1000 K have spectral properties very similar young giant planets. Jupiter's $T_{\rm eff}$ after formation was probably ∼700-100 K, and there are already a handful of brown dwarfs that have been found in this temperature range. For example, we now have excellent data and models for Glies 570D, at ∼800 K Geballe *et al.* (2001)Geballe, Saumon, Leggett, Knapp, Marley, & Lodders. In addition, in the very near future even cooler brown dwarfs will be found. Isolated brown dwarfs below ∼500 K are expected to have water clouds in their visible atmospheres. So, in some sense, we understand what the spectra of young giant planets should be.

• **Hot.** Currently, thermal emission had been detected from two Pegasi planets (or "hot Jupiters") with the *Spitzer Space Telescope*. These are HD 209458b, which was seen in the MIPS 24 μm band by Deming *et al.* (2005) Deming, Seager, Richardson, & Harrington and TrES-1, which was seen in the IRAC 4.5 and 8.0 μm bands by Charbonneau *et al.* (2005)Charbonneau, Allen, Megeath, Torres, Alonso, Brown, Gilliland, Latham, Mandushev, O'Donovan, & Sozzetti. For both planets, soon data will be obtained in all 4 IRAC bands and the MIPS band. These planets will be an interesting test-bed for understanding giant planet atmospheres with only a few filters. It is probabilistically likely that cooler transiting planets, reaching perhaps down to 900 K, could be seen with *Spitzer* in the coming few years.

• **Jupiter itself.** While much attention is paid to refining atmosphere models for substellar objects through comparison with brown dwarf data, almost no attention is paid to Jupiter itself. However, it is the substellar-mass object that we understand best. If we aim to to understand EGP atmospheres in the 100-500 $T_{\rm eff}$ range, it makes sense to test our models against Jupiter data that has been in hand for decades.

In summary, at the current time we have data to constrain EGP model atmospheres to temperatures down to $T_{\rm eff}$ = 700 K (from observations of the coolest brown dwarfs) and also at $T_{\rm eff}$ = 124.4 K, from Jupiter. Within several years even cooler brown dwarfs will be found that may reach down to 500 K, where water clouds will likely begin to form in these atmospheres Marley *et al.* (2002)Marley, Seager, Saumon, Lodders, Ackerman, Freedman, & Fan, Burrows *et al.* (2003)Burrows, Sudarsky, & Lunine.

3. Deriving Quantities of Interest from Spectra

Low resolution spectroscopy, while it will not provide the wealth of information that can be derived from high resolution spectra, can be used to determine valuable physical properties for EGPs. As noted earlier, if planetary systems to be studied by TPF-C (or Eclipse or EPIC) are older than 1 Gyr, this already greatly constrains planetary effective temperatures. For planets less massive than 10 $M_{\rm J}$ and greater than 1 AU from their parent star the planet's effective temperature is less than 450 K Burrows *et al.* (2001)Burrows, Hubbard, Lunine, & Liebert. For this range of planets, important physical quantities one could likely understand are detailed below.

• **Effective Temperature.** At visible wavelengths, determining $T_{\rm eff}$ is difficult, but potentially can be done two ways. The best method is to look for thermal emission for young or hot planets at the longest wavelengths one has available. As shown in Fig. 1, at some wavelengths longer than 0.85 μm thermal flux is greater than reflected flux. The ratios of the thermal flux peaks can be used as a temperature indicator down to ∼200 K, where thermal flux is finally swamped by reflected flux. If a mission bandpass can be extended to the near infrared, one could extend this method to even longer wavelengths. One also notices in Fig. 1 that the cooler the planet, the brighter it is in reflected light (at a given distance). This is due to the gradual formation of water and then ammonia clouds, which become optically thicker as a planet cools. To a point, the thicker clouds become more likely to scatter a given photon back into space. Thus, a more subtle indicator may an increasing brightness in the visible as the planet cools.

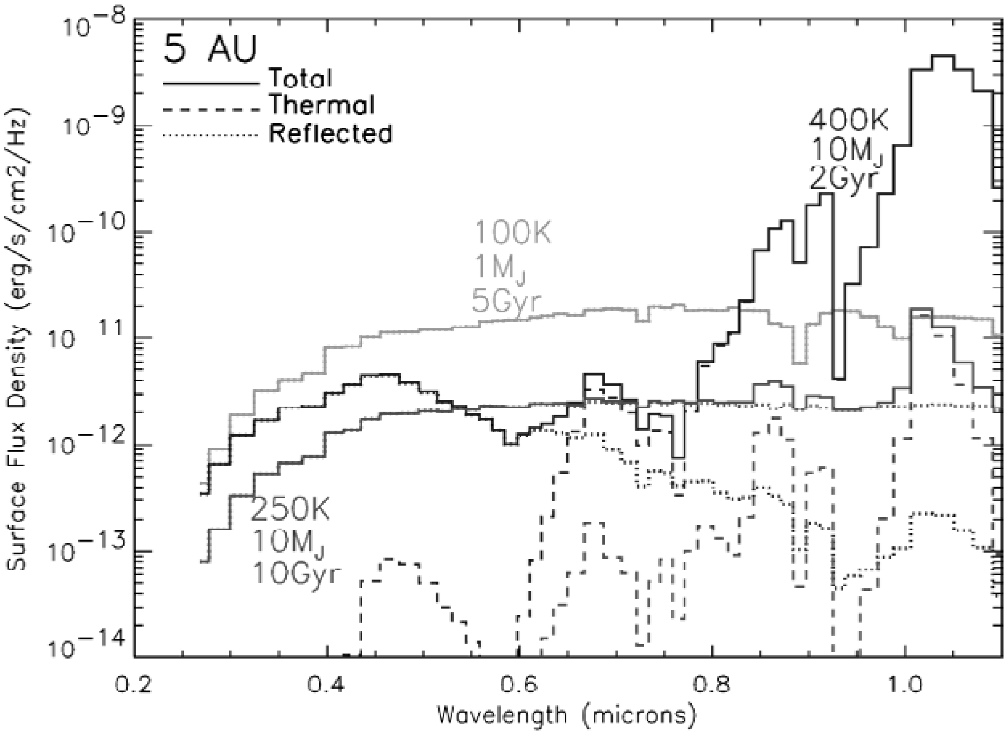

Figure 1. Emergent surface fluxes for 3 planets at 5 AU from the Sun. Thermal (dashed line), reflected (dotted line), and total (solid line) are shown for each planet. Labels indicate the intrinsic effective temperature, mass, and and approximate planet age. A description of our atmosphere code can be found in Marley *et al.* (1996)Marley, Saumon, Guillot, Freedman, Hubbard, Burrows, & Lunine, Burrows *et al.* (1997)Burrows, Marley, Hubbard, Lunine, Guillot, Saumon, Freedman, Sudarsky, & Sharp, and Fortney *et al.* (2005a)Fortney, Marley, Lodders, Saumon, & Freedman.

• **Cloud Properties.** Fig. 1 shows that the slope of the reflected spectrum is a sensitive indicator of cloud optical depths. As ammonia and water clouds are expected to be essentially gray scatterers, a planet with optically thick clouds should show a reflection of the stellar spectrum at wavelengths where the planet's atmosphere has no absorption features. A slope that deviates to the blue from ∼0.45 to 0.6 μm indicates holes in clouds or a cloud that is less optically thick. This spectral slope could be determined from a simple wide-band color-color diagram. (See also Metallicity.)

• **Metallicity.** Methane dominates the visible spectra of these objects. However, if one is only able to gauge the depth of one methane band, then it is not possible to determine if an absorption band depth is due to a methane abundance effect to a cloud height effect. However, bands of different strengths are formed at different pressures in a planet's atmosphere. Stellar photons that are absorbed in weak methane bands penetrate deeper into the planet's atmosphere before they are absorbed. In this way, observing the strength of 2 (or hopefully 3 or 4) methane bands, either through medium-bandwidth methane filters or low resolution spectra, can be used to simultaneously determine the methane abundance and cloud top height. The methane abundances in the atmospheres of Jupiter and Saturn are ∼3 and 7 times what would be expected for a solar composition atmosphere. This tells of something (that we are still trying to decipher) about the planet formation process in our solar system. Spectral models of Jupiter-like planets with varying

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methane abundances look nearly identical in wide-band color-color diagrams, so it is quite important to place filters directly on methane features. However, the flux from these bands is necessarily lower, so significantly more integration time may be needed.

• **Mass.** Determining a planet's mass with the help of radial velocity or astrometry is much preferred over any spectral methods. However, a combination of a system's age, a determined effective temperature (as described above) and theoretical cooling models, which are likely accurate for Jovian planets at Gyr ages Fortney & Hubbard(2003), can be used to estimate a planet's mass.

4. Data and Models to Date

4.1. *Jupiter*

Jupiter will long remain our best studied giant planet. The spectrum of Jupiter can be used to test chemical abundance calculations, cloud models, and radiative transfer methods. In Fig. 2(left) we plot flux vs. wavelength for full-disk observations of Jupiter, as seen at opposition, based on data obtained by Karkoschka (1994). This spectrum is computed by multiplying the solar spectrum at 5.2 AU by the Karkoschka (1994) geometric albedo data of Jupiter. We overplot our model atmosphere, with a metallicity of [M/H]=0.5 (3.2 $\times$ solar) which is roughly consistent with Jupiter's atmospheric abundances Atreya *et al.* (2003)Atreya, Mahaffy, Niemann, Wong, & Owen. We use the cloud model of Ackerman & Marley(2001) (with a sedimentation efficiency parameter, $f_{\rm sed}$, of 3) to describe the ammonia cloud particle distribution and optical properties. These spectra are normalized at 0.7 μm. As one can see, at wavelengths longer than 0.5 μm, our model is an excellent match to the overall spectral slope. At wavelengths shorter than 0.5 μm, Jupiter's photochemically derived stratospheric haze layer darkens the planet Rages *et al.* (1999) Rages, Beebe, & Senske. We do not include this haze in our models. One should also notice that our band depths, which are essentially all due to CH_4, are not as deep as observed. This may be because our cloud of condensed NH_3 is too high in the planet's atmosphere. But overall the spectrum is a good match given the lack of any fine tuning.

For an additional comparison, we plot a Burrows *et al.* (2004)Burrows, Sudarsky, & Hubeny spectrum for a Jupiter-like planet a 6 AU from a G2V parent star. Again this spectrum is normalized at 0.7 μm. A main difference between their spectrum and that of Jupiter is the overall visible spectral slope, which in their models is bluer than Jupiter. In addition, their band depths for a solar composition atmosphere are considerably deeper than Jupiter in most bands, but is actually too shallow near 1 μm. These differences could be partially accounted for if in their models, their cloud optical depths at visible wavelengths are not as large as in the real planet. This could be due to a particle size effect. In potential support of this hypothesis, we show our cloud-free "Jupiter" model spectrum, which has a similar slope to the Burrows *et al.* (2004)Burrows, Sudarsky, & Hubeny model from 0.5 to 0.8 μm. A consequence of the bluer Burrows *et al.* (2004)Burrows, Sudarsky, & Hubeny spectral slope in that in wide-band color-color diagrams, while our models plot very close to the actual planet, those of Burrows *et al.* (2004)Burrows, Sudarsky, & Hubeny do not. We not that this comparison has only been performed over the visible spectral range and the agreement between each of the models and Jupiter may be better or worse in the infrared. The main point is that cloud optical properties, rather than gaseous optical properties, dominate the visible spectrum.

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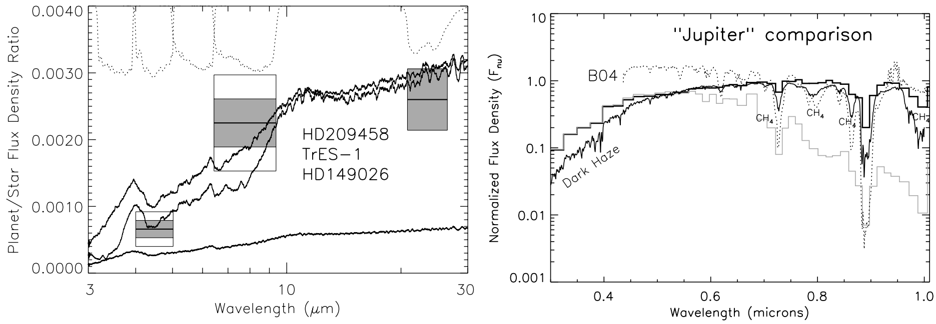

Figure 2. Left: Normalized flux density vs. wavelength for model planets and the observed Jupiter. The actual Jupiter spectrum is the solid high resolution spectrum. A Burrows *et al.* (2004)Burrows, Sudarsky, & Hubeny model of a solar-composition planet at 6 AU from a G2V star is the dotten high resolution line. Our newly computed low resolution models are the solid, histogram-type lines. The dark line is for a 3 times solar model at 5.2 AU including predicted cloud opacity. The gray line is for a solar composition atmosphere, but neglects cloud opacity. **Right**: Planet-to-star flux density ratios for, from top to bottom, HD 209458b, TrES-1, and HD 149026b. Spitzer data are shown—shaded areas are 1 σ error bars, and open boxes are 2 σ error bars. The 4.5 and 8.0 μm data are for TrES-1and the 24 μm datum is for HD 209458b. The four Spitzer IRAC bands and MIPS band are shown as dotted lines at the top. Data will eventually be taken in all of these available bands. There is no data yet published for HD 149026b.

4.2. *Pegasi planets*

The *Spitzer* observations of HD 209458b by Deming *et al.* (2005) Deming, Seager, Richardson, & Harrington and TrES-1 by Charbonneau *et al.* (2005)Charbonneau, Allen, Megeath, Torres, Alonso, Brown, Gilliland, Latham, Mandushev, O'Donovan, & Sozzetti are the best data available for use in understanding the atmospheres of this interesting class of EGPs. Fig. 2 (right) shows how our models of the atmospheres of these Pegasi planets match the available observations. The modeling procedures and a more detailed discussion can be found in Fortney *et al.* (2005a)Fortney, Marley, Lodders, Saumon, & Freedman, Fortney *et al.* (2005b)Fortney, Saumon, Marley, Lodders, & Freedman. The planet-to-star flux density ratios we obtain from our models are in general a good fit. We are within the 1 σ error bar for HD 209458b. For TrES-1, we are at the 1 σ error bar a 4.5 μm, but our models are too dim by 2-3 σ at 8.0 μm. Our model is bluer than a blackbody, but apparently the planet is redder than a blackbody in this spectral region Charbonneau *et al.* (2005)Charbonneau, Allen, Megeath, Torres, Alonso, Brown, Gilliland, Latham, Mandushev, O'Donovan, & Sozzetti. We find the agreement is better for an atmosphere enhanced in metals by 3-5$\times$, or one that has a hot stratosphere, but more data will be needed for a definitive conclusion. Also plotted are the predicted flux density ratios for HD 149026b, a recently discovered transiting planet with a very small radius Sato *et al.* (2005)Sato, Fischer, Henry, Laughlin, Butler, Marcy, Vogt, Bodenheimer, Ida, Toyota, Wolf, Valenti, Boyd, Johnson, Wright, Ammons, Robinson, Strader, McCarthy, Tah, & Minniti. In the coming years, *Spitzer* data on these and other transiting planets will be our best testing ground for trying to understand EGP atmospheres with data in only a few wide filters.

5. Conclusions

Our understanding of EGPs is progressing as we learn more about old brown dwarfs (which have spectra similar to young giant planets), Pegasi planets (which can be ob-

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served with *Spitzer*, and Jupiter (which is itself an important data point). Low resolution spectra, or colors from several visible filters, can potentially be used to gauge an object's $T_{\rm eff}$, metallicity, some aspects of cloudiness, and perhaps to constrain its mass. An instrument spectral range out to at least 1 μm helps these derivations considerably, especially for determining $T_{\rm eff}$. By the time that old Jupiter-like planets are directly imaged from space in visible light, perhaps with TPF-C or a smaller platform, model atmospheres will be even better constrained by additional brown dwarf and transiting planet data.

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Discussion

W. Traub: What Jupiter data are you using? The planet's belts and zones vary considerably.

J. Fortney: This is the full-dusk full-phase data from Karkoschka (1994).

M. Liu: Would you care to comment on non-equilibrium chemistry? This has been seen with CH_4 and CO in T dwarf spectra.

J. Fortney: The main reactions will be CH_4/CO, and NH_3/N_2. CO is dredged up from deeper layers, where it is stable, and only slowly is converted to CH_4, relative to the mixing timescale, so the CH_4/CO ratio is smaller than one would expect. Similarly, in the other reaction NH_3 is found in a lower abundance, since N_2 is only slowly converted to NH_3. In reality this issue should not have that great of an effect on cool giant planets.

E. Guidos: Please explain again what kind of cooler transiting planets you expect?

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J. Fortney: I meant that it is statistically likely that cooler transiting planets will soon be found. However, these cooler planets will be more difficult to detect with *Spitzer*.

W. Benz: You mentioned our "ground truth" measurements of abundances for Jupiter's atmosphere from the Galileo Entry Probe, and how they mostly agreed with ground-based determinations. Can you comment on the apparent disagreement between Cassini derived abundances and those from the ground?

J. Fortney: Well, I would consider Cassini just another remotely sensed observation, and less reliable than an entry probe.

someone: For the *Spitzer* observations what is actually measured are the brightness temperatures, not the effective temperatures, correct?

J. Fortney: Yes, that is true. We compute brightness temperatures for our models and that is what we actually compare to the data. I was quoting effective temperatures for models that match the observed brightness temperatures.




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