Abstract.

We review some of the characteristics of irradiated extrasolar giant planets (EGPs), in anticipation of their direct detection from the ground and from space. Spectral measurements are the key to unlocking their structural and atmospheric characteristics and to determining the true differences between giant planets and brown dwarfs. In this spirit, the theoretical spectral and atmospheric calculations we summarize here are in support of the many searches for EGPs to be conducted in the coming decade by astronomers from around the world.

1. Introduction

Since the discovery of 51 Pegasi b (Mayor and Queloz 1995) and the nearly one hundred extrasolar giant planets (EGPs) that have been detected subsequently by radial velocity techniques (see this proceedings and references in Burrows et al. 2001), an increasing fraction of the world’s astronomers has been engaged in determining the best means to detect such planets directly. While the orbital elements of substellar-mass objects with \( M_p \sin(i) \)s that range from \( \sim 0.2 \) to \( \sim 10 \) \( M_J \) can constrain formation mechanisms and dynamical evolution, they are no substitute for direct spectral measurements. It is by imaging the planet and obtaining optical, near-infrared, and mid-infrared spectra that an EGP’s atmospheric structure, composition, gravity, radius, and mass can be determined. Such physical characteristics are essential data if the study of EGPs is to mature in the next decade into a major astronomical field. They are also essential if the distinctions between brown dwarfs and giant planets of the same mass are to be determined. It may be that, for a given primary star, different origins and histories at birth translate into different compositions and rotation rates. Spectra will be essential in determining this.

From space, SIM will provide accurate astrometric masses (not merely \( M_p \sin(i) \)s) for the known EGPs. However, from the ground spectral deconvolution techniques, adaptive optics, interferometry (e.g., using the LBT, VLTI, KIA) and a host of promising and novel methods summarized during this conference encourage one to believe that light from an EGP will soon be detected.
From space, optical coronagraphs with ultrasmooth mirrors (e.g., Eclipse, ESPI, JPF), infrared interferometers, and precision transit missions (e.g., MOST, Eddington, Kepler, COROT) are in various stages of planning or preparation. The space-based transit missions will be preceded by a host of ground-based transit searches (e.g., STARE, BEST, WASP, STEPSS, TeMPEST). Transit data married with precise stellar and Doppler wobble measurements can provide mass-radius relations for the close-in EGPs (“roasters”) from which one can extract structural and evolutionary information (Guillot et al. 1996; Burrows et al. 2000). The first discovered transiting extrasolar planet, HD209458b, for which a large radius of $\sim 1.4 \, R_J$ and a mass of $0.69 \, M_J$ were obtained (Cody and Sasselov 2002; Brown et al. 2001; Charbonneau et al. 2000; Henry et al. 2000) has jump-started the scramble to understand EGPs under severe irradiation regimes. The demonstration that the depth of HD209458b’s transit is wavelength-dependent (Hubbard et al. 2001) and that neutral sodium resides in its atmosphere (Charbonneau et al. 2002) is an indication of the vast potential of transit studies. The discovery of a collection of transiting planets, not just one, will be a milestone in the study of EGPs.

This tempo of activity focused on obtaining direct measurements of EGP properties demands a corresponding effort by the theoretical community to calculate the spectra of EGPs around a variety of stars, at a variety of orbital distances, and with a variety of masses and ages. We have undertaken such a project and in this short contribution present some of our preliminary results. A more comprehensive treatment can be found in Sudarsky, Burrows, and Hubeny (2002, in preparation). We have calculated EGP spectra for 51 Peg b, τ Boo b, HD209458 b, ν And b,c,d, GJ 876 b,c, ε Eridani b, 55 Cnc b,c,d, HD114762 b, HD1237 b, and a host of other radial-velocity EGPs, as well as for theoretical objects at the full potential range of orbital distances, around a collection of stellar subtypes, and employing a variety of cloud models. The fluxes at the Earth, as well as the planet/star contrasts as a function of wavelength from 0.4 $\mu$m to 30 $\mu$m have been determined.

### 2. A Potpourri of Irradiated EGP Spectra

Figure 1 depicts the run with orbital distance from 0.05 to 1.0 A.U. of self-consistent EGP reflection spectra (including heating by stellar irradiation) around a G0 V star. What is actually shown in Fig. 1 is the planet/star flux ratio, a quantity that in some ways is more useful to potential observers. Rayleigh scattering at short wavelengths, methane features for the more distant (hence, cooler) objects, Na-D and K I features at 0.589 $\mu$m and 0.77 $\mu$m, respectively, and water (steam) features are in evidence. Without Rayleigh scattering, the flux shortward of 0.6 $\mu$m would be 3-6 orders of magnitude lower. This set of models does not include clouds (Sudarsky, Burrows, and Hubeny 2002), but the characteristic increase in the trough/peak contrasts with increasing distance, the relative strength of the planet at 3-5 $\mu$m, and the wide range of flux ratios from $\sim 10^{-3}$ to $\sim 10^{-10}$ serve to emphasize that the choice of spectral range is crucial if the direct light of the planet is to be measured. In addition, though for roasters the planet flux at 10 parsecs in the near infrared can reach $\sim$10 milli-Janskys (a rather large number), the glare of the star is still a challenge to direct
Figure 1. Theoretical planet/star flux ratios from 0.4 µm to 5.0 µm for EGPs placed at orbital distances from 0.05 A.U. to 1.0 A.U. These models do not include the possible effects of clouds.
detection. Figure 2 portrays the corresponding temperature/pressure profiles. A signature of irradiation, the bump near one bar pressure, is in evidence.

Figure 3 shows a representative theoretical spectrum at an average phase for a planet that may be orbiting \( \epsilon \) Eridani at 3.3 A.U. (Hatzes et al. 2000). This model spectrum incorporates water clouds with 5-micron ice particles. As can be seen in Fig. 3, the presence of clouds elevates the flux in the optical to a significant degree. The result is the classic “two–hump” spectrum (crudely, reflection at short wavelengths and emission at long wavelengths) (Saumon et al. 1996), but with important differences. In particular, there is a pronounced excess near \( 4–6 \mu \text{m} \) and the spectrum is peppered with \( \text{CH}_4 \) and water absorption features.

For the close-in EGPs such as 51 Peg b, HD209458b, and \( \tau \) Boo b, the planet/star flux ratios shortward of one micron are \( \sim 10^{-5} \), but they climb to \( 3 \times 10^{-4} \) around \( 1.65 \mu \text{m} \) and \( 2.2 \mu \text{m} \). At \( \sim 4.0 \mu \text{m} \), they can be near \( 10^{-3} \), with a slight dependence on the presence of clouds. The \( \upsilon \) And system, boasting three EGPs with orbital distances from 0.059 A.U. to 2.5 A.U., shows the entire range of potential behaviors for irradiated giant planets. The corresponding flux ratios can vary from three to twelve orders of magnitude, depending upon wavelength and cloud model. The planets around GJ 876 (M4 V) provide an example of irradiation by a dim star. A transit by an EGP of such a late star (with a small radius) would be spectacular in a way that the few nanoJansky fluxes in the near infrared from the wider of the pair of GJ 876’s planets is not.

3. On the Wavelength Dependence of EGP Transits

HD209458b, while not a Rosetta Stone for the subject of EGPs, does nevertheless show the presence of atmospheric sodium and has provided a mass-radius point. More such points are anticipated. The HST/STIS data for HD209458b (Brown et al. 2001; Charbonneau et al. 2002) cover the wavelength range from 0.58 \( \mu \text{m} \) to 0.64 \( \mu \text{m} \), which includes the Na-D line at 0.589 \( \mu \text{m} \). To \( \sim 4\sigma \), a difference between the transit depth at Na-D and the average depth was detected. However, Na-D is not the only feature predicted in the transit depth spectrum. Figure 4 from Hubbard et al. (2001) shows that measurements of the transit depth as a function of wavelength can be used to reveal other atmospheric constituents such as potassium and, importantly, water. “Absorption” features appear upside-down on Fig. 4, where a large radius reflects a larger opacity. Therefore, a transit spectrum can be used as an erzatz for a direct reflection spectrum (that may be more difficult to obtain) to determine atmospheric abundances.

However, care must be exercised in the interpretation of such “spectra”; they are not the same as reflection spectra. In particular, the transit depth spectrum is a probe of the slant column near the terminator of the planet, the cord optical depth. The actual spectrum of the planet is related more to the normal column depth and to the radial temperature/pressure profile; it is an integral measure of whole-planet emissions. Fortney et al (2002, in preparation and presented at this conference) interpret the discrepancy between the STIS Na-D results and the Hubbard et al. (2002) predictions at 0.589 \( \mu \text{m} \) as being due to the neglect by the latter of photoionization and charge exchange in HD209458b’s
Figure 2. Profiles of the temperature (in Kelvin) versus pressure (in bars) for the models depicted in Fig. 1. The inner boundary condition for this model set is an effective temperature of 500 K. A gravity of $3 \times 10^3$ cm s$^{-2}$ was assumed. Deep in the interior the models are convective. The bump in the middle of the profiles near one bar pressure reflects the effect of irradiation (heating) from outside.
Figure 3. A theoretical spectrum at average phase of the putative planet orbiting $\epsilon$ Eridani at 3.3 A.U. The star-planet angular separation for this system is $\sim 1''$. A water cloud model with 5-micron ice particles is incorporated into this calculation. Note the presence of the pronounced feature around a wavelength of 5.0 microns, at which the planet’s spectrum may be near 10 microJanskys (as seen at Earth). As suggested by the figure, the fluxes at longer wavelengths in the mid-IR are expected to be even higher.
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Figure 4. Predicted variation of transit radius $R$ with wavelength (heavy curve, nominal $P-T$ profile; light curve, cold $P-T$ profile; open dots, hot $P-T$ profile). The right-hand scales show, in percent, the variation of $R$ with respect to $R_1$ and with respect to $R_T$, an ∼“average” transit radius in the visual wavelength band, adopted as $R_T = 96500$ km = 1.35$R_J$. At wavelengths where slant optical depth is high, $R$ is larger. “Absorption” features thus appear upside-down on this plot. Prominent features are labeled with the responsible molecule (Figure taken from Hubbard et al. 2001).
upper atmosphere (down to $\sim 1$–$5$ millibars). When Fortney et al. (2002) include the ionization of sodium in their transit spectrum calculation (which involves 2D Monte Carlo transport), they can reproduce the transit observations. But when we calculate the reflection spectra for the same object with and without ionization down to the level necessary to reproduce the HST/STIS results, we see very little difference. In short, a transiting planet’s reflection spectrum does not reveal much about its transit-depth spectrum and care must be taken not to confuse the two.

4. Summary Thoughts

NASA and ESA are poised to spend 100’s of millions of dollars in the next decade to detect and characterize extrasolar planets. The best data in the short term will be for EGPs, not terrestrial planets. Hence, for those most interested in discovering Earths, the natural and inevitable path is by way of the giant planets now being discovered in profusion in the solar neighborhood. For those for whom EGPs are not mere stepping stones, the next decade promises a rich harvest of new worlds and stimulating finds. Our calculations are designed to provide the necessary theoretical underpinnings for this quest at one of astronomy’s newest frontiers.

Acknowledgments. The authors thank Bill Hubbard, Jonathan Lunine, Jim Liebert, Ivan Hubeny, Christopher Sharp, Drew Milsom, Maxim Volobuyev, Curtis Cooper, and Jonathan Fortney for fruitful conversations and help during the course of the work summarized here, as well as NASA for its financial support via grants NAG5-10760 and NAG5-10629. They would also like to congratulate the organizers, Drake Deming and Sara Seager, for pulling off without a perceptible hitch such a useful and important meeting.

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