Optical Imaging of Extrasolar Giant Planets From Space

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Abstract. We describe initial plans for detecting extrasolar giant planets with Eclipse, a 1.8-m space telescope + coronagraph that we will propose to NASA in the coming year. Our plans take both theoretical and observational constraints into account.

1. Introduction

One of NASA’s highest scientific priorities is to find planetary systems around nearby stars and to compare their properties and histories with our own solar system. Space missions to accomplish this goal include an imaging survey of nearby extrasolar systems capable of detecting giant planets followed by an even more challenging mission called Terrestrial Planet Finder (TPF). At this stage, it is unclear whether these surveys will be conducted by an optical coronagraph or infrared interferometer, or both. In this paper, we focus on the so-called TPF-precursor missions to image extragiant planets (EGP’s) with an optical telescope + coronagraph. Section 2 describes the predicted optical properties of EGP’s, which are seen in reflected light from the host star. Section 3 shows how these predictions can be used to begin planning for Eclipse, a proposed mission to image giant planets around other stars.

2. The Diversity of Extrasolar Giant Planets (EGP’s)

The hundred-plus EGP’s that have been discovered by Doppler techniques show an unexpected diversity of properties. Unlike our solar system where the term “giant planets” is synonymous with “outer planets,” EGP’s have been found as close as 0.022 AU from their host stars. Although the close-in planets have near-circular orbits, those farther out tend to have eccentric orbits, sometimes highly so. It is inferred from these observations that the atmospheric temperatures of
EGP’s must also show a very wide range. Planets of a given age and mass at greater distances from their host stars intercept a lower fraction of the warming stellar radiation and consequently are cooler. Planets having high albedos will also be cooler than those with low albedos. Also, planets revolving around late-type main-sequence stars at a given orbital distance are cooler than those hosted by earlier-type stars because of the lower stellar luminosities.

Table 1. Classes of Extra-Solar Giant Planets

<table>
<thead>
<tr>
<th>EGP Class</th>
<th>(a) (AU)</th>
<th>(T_{\text{eq}}) (K)</th>
<th>Features</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (Jovian)</td>
<td>5</td>
<td>130</td>
<td>(\text{NH}_3) clouds; (\text{CH}_4) abs.</td>
<td>Jupiter</td>
</tr>
<tr>
<td>II (Water)</td>
<td>1-2</td>
<td>200</td>
<td>(\text{H}_2\text{O}) clouds</td>
<td>55 (\rho^1)Cnc d</td>
</tr>
<tr>
<td>III (Clear)</td>
<td>0.5</td>
<td>500</td>
<td></td>
<td>51 Peg b</td>
</tr>
<tr>
<td>IV (Hot Jup.)</td>
<td>0.1</td>
<td>1000</td>
<td></td>
<td>55 (\rho^1)Cnc b</td>
</tr>
<tr>
<td>V (Roasters)</td>
<td>0.05</td>
<td>1500</td>
<td>Silicate or Fe clouds</td>
<td>HD 209458 b</td>
</tr>
</tbody>
</table>

Figure 1. Model Atmospheres and Spectra of Class-I EGP’s by SBH.

Sudarsky, Burrows, & Pinto (2000; hereafter SBP) and Sudarsky, Burrows, & Hubeny (2003; SBH) find that EGPs fall naturally into five classes defined by their compositions. Atmospheric compositions are roughly connected to atmospheric temperatures, which for low-mass, old EGPs are determined mostly by the equilibrium temperatures established by stellar irradiation. Table 1 gives a rough summary of their classification scheme. Successive columns of the table give the EGP class, typical orbital distance from a Sun-like star, equilibrium temperature, expected spectral features, and some examples. At present, the only examples of Class-I planets are the Jovian planets of the solar system. This
situation is bound to change as Doppler monitors at Keck and the AAT have a longer baseline to track outer planets over a full orbital period.

To evaluate the optical properties of giant planets, we turn to the models of Sudarsky, Burrows, and Hubeny (2003; SBH). Figure 1 shows their models for two Class-I (Jovian) planets orbiting a sun-like star: one at 6 AU, the other at 15 AU. The left panel shows the run of temperature and pressure through the planetary atmosphere. The thick segment of a model atmosphere outlines the approximate region where the observed spectrum is formed (actually, where the Rosseland mean optical depth is between 0.1 and 1.0). The dashed curves show the condensation curves for water and ammonia. Clouds form where the model atmosphere intersects a condensation curve and extend upwards by a pressure scale-height or so. Class-I atmospheres have two cloud decks, a low one composed of water-ice, and an ammonia cloud layer at somewhat higher altitudes. It is the high albedo of the ammonia clouds that makes Jovian EGP’s highly reflective.

The right panel shows the spectra of the two EGP models. The flux of the EGP model at $a = 15$ AU has been multiplied by $(15/6)^2$ to compensate for the different orbital radii. As expected, the model spectra are similar to the observed spectrum of Jupiter, which is shown in Figure 2. Jupiter’s high albedo is due to ammonia ice crystals in its atmosphere. Methane absorption dominates the optical spectrum as can be seen from a comparison with the absorption spectrum of CH$_4$.

[Image: Figure 2. Observed Spectrum of Jupiter (Karkoschka 1994). The CH$_4$ absorption spectrum at top is plotted on an arbitrary flux scale.

Class-II planets are too hot for ammonia clouds to form (Figure 3), but they are still bright (i.e. highly reflective) due to the high reflectance of water clouds. The same cannot be said of Class-III planets, which are too hot for any clouds to form. These “Clear EGP’s” are consequently quite dull. The only reflective process is Rayleigh scattering, which helps give the planet its pronounced blue color. Also, without a reflecting layer of clouds, starlight penetrates deeply in
the atmosphere, where it is absorbed mainly by gaseous methane and water, thereby suppressing the flux at the long-wavelength end of the spectrum.

The “Hot Jupiters” and “Roasters” (Classes IV and V) were discovered by Doppler surveys and have been studied extensively. Such giant planets spell doom for terrestrial planets that might have formed in these systems. In any case, such EGP’s are too close to the star to be imaged by Eclipse, so we omit them from future discussion.

The correspondence between temperature and orbital distance in Table I assumes that the planet has no internal heat left over from the formation of the planet. However, this is incorrect for very young EGP’s such as ɛ Eri b, which should be much warmer than older planets orbiting similar stars at the same distance. This implies that we need to predict EGP spectra on a case-by-case basis. Such individualized studies have already been started as a follow-on to SBH for well-known planets found by the Doppler technique.

3. Application to the TPF-Precursor Mission, ECLIPSE

The model spectra by SBH provide a useful guide to planning missions to detect EGP’s orbiting nearby stars. Here, we discuss the application of these models to ECLIPSE, a 1.8-m visible and near-IR coronagraphic space telescope (Trauger et al. 2003) that will be proposed to NASA in the coming year. With its precise wavefront control, which corrects for even the slightest errors in the telescope optics, ECLIPSE is expected to be able to detect EGP’s one billion times fainter than the star, even those that are only 0\".25 away from the star.
To start planning for the Eclipse mission, we adopted the target list compiled for Terrestrial Planet Finder (Ebbets 2003). This list contains 259 nearby, main-sequence stars of spectral types early-A to mid-M. Only main-sequence stars (luminosity classes V and IV) are included in the list. Known close binaries, flare stars, and variable stars are excluded. All the targets are less than 30 pc away, and the median distance is about 15 pc. In the near future, the target list will be updated with estimates of stellar age so we can account for internal heating of the atmosphere in very young planets, and estimates of the stellar metallicity so we can account for deviations from a solar-system molecular chemistry.

Figure 4. The TPF target list (Ebbets 2003). Left: HR diagram of the target stars. Right: apparent visual magnitudes of Jovian planets orbiting the target stars at 5 AU.

In the meantime, we can use the target list to estimate some of the photometric properties of EGP’s that will be discovered by Eclipse. The left panel of Figure 4 displays the HR diagram of the candidate targets. The targets range over 9 magnitudes in luminosity. The right-hand panel of Figure 4 shows the approximate apparent magnitudes of Jovian EGP’s (i.e. Jupiter-size planets in a 5-AU orbit) seen a quadrature. These calculations assume a planet-star contrast, Δm ∼ 22.2 magnitudes. Only 19 targets have Jovian planets brighter than V=26, but the numbers increase quickly at fainter magnitudes: 73 targets are brighter than V=27, and 183 targets are brighter than V=28.0.

Of course, not all planets discovered will be Jovian planets. For the closer targets, Eclipse will be able to probe closer in, to an orbital distance corresponding to an inner working angle, IWA=0′.25. Figure 5 shows the orbital radii and temperatures of planets whose maximum elongation is 0′.30 (left) or 0′.60 (right). (We are most likely to detect planets when they are furthest from the star.) Planets whose maximum elongation is 0′.60 will be mostly Jovian or “Water” planets; those at r = 0′.30, will be mostly “Water” (Class-II) EGP’s. Eclipse might even detect a few Class-III EGP’s orbiting the closest stars like α Cen. Because of their different optical properties, we take EGP class into account in predicting the apparent brightnesses of potential planets.
Figure 5. Estimated temperatures and orbital radii of EGP's detected at separations of $0'30$ (left) and $0'60$ (right) from the star. It is assumed that the planets are detected at maximum elongation. The EGP class is shown, although there are no distinct boundaries between classes. As in Figure 4, the star symbols are shaded according to the effective temperature of the star (dark=cool; light=hot).

We can use these photometric results to simulate detection schemes for ECLIPSE. Figure 6 shows an example for a Jovian planet orbiting $\beta$ Com (G0 v) at 5 AU. The top three panels show simulated images of the planet in three optical passbands. The stellar background from an early version of the model ECLIPSE coronagraph is included (c.f. Trauger 2003). This simulation assumes that a deformable mirror compensates for both phase and amplitude errors in the bottom half, thereby producing a “dark hole” in the scattered background light. The bottom-left panel shows a coaddition of the three passbands. The planet is clearly distinguishable from the background not only by its brightness but also by its shape – the planet appears as a point source, whereas the speckle background is stretched out into radial streaks. The planet is also visible in the difference image shown in the bottom-right panel. Since a speckle moves outward from the star by a distance proportional to its wavelength, we can magnify a short-wavelength image so that the speckle streaks coincide with those on a long-wavelength image and take the difference. Much of the background is canceled out in the residual image (c.f. Sparks & Ford 2002).

We still have a long way to go. ECLIPSE is still in the proposal phase, and the models described in Section 2 are preliminary. But there is time. If ECLIPSE is selected by NASA, it won’t be launched until 2009 or 2010. By that time, Doppler surveys should have found Jovian planets in Jupiter-like orbits around other stars. By then, we will have refined our models to make them internally consistent and more physically realistic. We can then start to do real astrophysical analyses of planets around other stars.
Figure 6. Simulated ECLIPSE observations of a Jovian planet orbiting β Com at $a = 5$ AU. The top three panels show images taken in the ‘V’, ‘R’, and ‘I’ bands. A 72-ksec exposure time is assumed for each band. The occulted star is at the center. The bottom-left panel shows a coaddition of the three passbands. The bottom-right panel shows a difference image formed by the addition of two residual images. One residual image is the result of subtracting from the R-band image the V-band image magnified by 1.22X. The other is the I-band image minus the R-band image magnified by 1.27X. Detection algorithms would take advantage of the fact that the difference image actually shows both a positive of the EGP and a negative of the EGP slightly further out from the star.
References

Ebbets, D. 2002, SPIE, 4860, 120