

## Present and Near-Future Reflected Light Searches for Close-In Planets

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**Abstract.** Close-in extrasolar giant planets may be directly detectable by their reflected light, due to the proximity of the planet to the illuminating star. The spectrum of the system will contain a reflected light component that varies in amplitude and Doppler shift as the planet orbits the star. Intensive searches for this effect have been carried out for only one extrasolar planet system,  $\tau$  Boö. There exist several other attractive targets, including the transiting planet system HD 209458.

### 1. Introduction and Motivation

Radial velocity surveys of nearby Sun-like stars have uncovered a population of close-in orbiting companions of roughly Jupiter mass. The ten such objects with semi-major axes  $a \lesssim 0.1$  AU are listed in Table 1, along with the values for the semi-major axes, (minimum) masses, spectral types of the stars, and equilibrium temperatures (calculated from the estimated values for the semi-major axes, stellar radii and effective temperatures, and assuming a Bond albedo of  $A$ ).

Table 1. Close-In Planets Ordered by Increasing Semi-Major Axis

Star	Spectral Type	$a$ (AU)	$M_p$ ( $M_{\text{Jup}}$ )	$T_{\text{eq}}(1 - A)^{-\frac{1}{4}}$ (K)
HD 187123	G3 V	0.042	$0.52/\sin i$	1400
HD 75289	G0 V	0.046	$0.42/\sin i$	1600
$\tau$ Boö	F7 V	0.046	$3.87/\sin i$	1600
HD 209458	G0 V	0.047	0.69	1500
51 Peg	G2 V	0.051	$0.45/\sin i$	1300
$\nu$ And	F8 V	0.059	$0.71/\sin i$	1500
HD 217107	G7 V	0.072	$1.28/\sin i$	1000
HD 130322	K0 V	0.088	$1.08/\sin i$	800
55 Cnc	G8 V	0.11	$0.84/\sin i$	700
Gl 86	K0 V	0.11	$3.6/\sin i$	700

A successful spectroscopic detection of an extrasolar planet in reflected light would yield the inclination, and hence the planetary mass, and would also measure a combination of the planetary radius and albedo. Furthermore, it would

open the way to direct investigation of the spectrum of the planet itself. Conversely, a low enough upper limit would provide useful constraints on the radius and albedo of the companion.

The predicted albedo of a close-in extrasolar giant planet has been the focus of recent theoretical work (Marley et al. 1999; Seager, Whitney, & Sasselov 2000), and the possible values range by several orders of magnitude based on the atmospheric temperature, chemical composition (see, e.g., Burrows & Sharp 1999), and the presence (or absence) of atmospheric condensates, and their respective size distributions.

## 2. The Method of Reflected Light

The amplitude, relative to the star, of the observed flux reflected from a close-in planet viewed at a phase angle  $\alpha$  (where  $\alpha$  is the angle between the star and the observer as viewed from the planet) is given by

$$f_\lambda(\alpha) = \epsilon \phi_\lambda(\alpha) = p_\lambda \left( \frac{R_p}{a} \right)^2 \phi_\lambda(\alpha), \quad (1)$$

where  $R_p$  is the planetary radius,  $a$  is the semi-major axis, and  $p_\lambda$  is the wavelength-dependent geometric albedo. The quantity  $\epsilon$  is the contrast ratio at opposition. The phase function  $\phi_\lambda(\alpha)$  is the brightness of the planet viewed at an angle  $\alpha$  relative to its value at opposition (where by definition  $\phi_\lambda(0) = 1$ ), and is a monotonically decreasing function of  $\alpha$  for all physically reasonable atmospheres. For planets detected by the radial velocity technique alone,  $a$  is determined, and  $\alpha$  at a given time is prescribed by the known orbital phase  $\Phi$  and the unknown orbital inclination  $i$ , but  $R_p$ ,  $p_\lambda$  and  $\phi_\lambda(\alpha)$  remain unknown.

A distant observer viewing the solar system in the  $V$  band would measure a tiny reflected light ratio of  $f \simeq 4 \times 10^{-9}$  from Jupiter viewed at opposition. This ratio increases dramatically for close-in, giant planets, due to the small orbital separation. Scaling equation (1), we find

$$f_\lambda(\alpha) \simeq 9.1 \times 10^{-5} p_\lambda \left( \frac{R_p}{R_{\text{Jup}}} \right)^2 \left( \frac{0.05 \text{AU}}{a} \right)^2 \phi_\lambda(\alpha). \quad (2)$$

This photometric modulation is most likely beyond the reach of ground-based observations, but will be accessible to upcoming photometric satellite missions, such as COROT (see, e.g., Rouan et al. (1999)), provided such missions can achieve a precision of  $\sim 20 \mu\text{mag}$  with stability over timescales of a few days.

Photometry alone will not yield the orbital inclination, and hence the planetary mass will remain constrained only by the lower limit imposed by the radial velocity observations. However, a spectrum of a close-in planet system will contain a secondary component that varies in brightness according to equation (1) and in Doppler shift (relative to the star) according to

$$v_p(\Phi) = - K_s \frac{M_s + M_p}{M_p} \cos 2\pi\Phi, \quad (3)$$

where  $M_s$  and  $M_p$  are the stellar and planetary masses. The stellar radial velocity amplitude  $K_s$  and orbital phase  $\Phi$  are determined from the observed radial

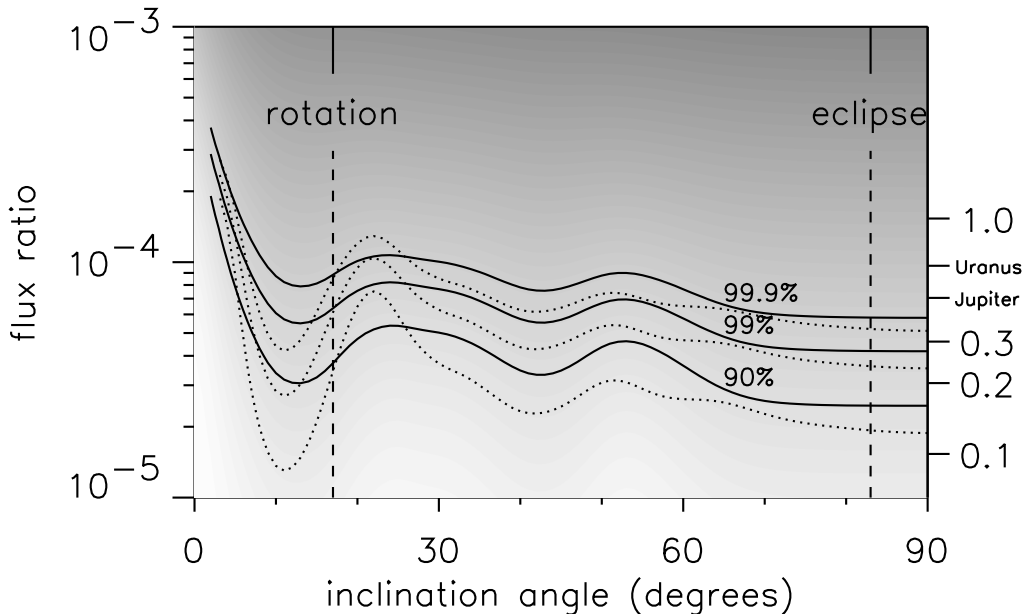


Figure 1. The solid curves are the confidence levels on the upper limit for the relative reflected flux  $\epsilon$  in the  $\tau$  Boö system as a function of orbital inclination  $i$ , if the reflected light is a copy of the stellar spectrum. The dashed curves are the same confidence levels under the assumption that the system is tidally locked and thus the planet reflects a non-rotationally-broadened copy of the stellar spectrum. Upper limits on the geometric albedo  $p$  under the assumption that  $R_p = 1.2 R_{\text{Jup}}$  are shown on the right-hand axis, and the values for Jupiter and Uranus are included for comparison. The lack of transits (Baliunas et al. 1997) excludes  $i \gtrsim 83^\circ$ , and  $i \lesssim 17^\circ$  can be excluded under the assumption that the stellar rotation axis is co-aligned with that of orbital motion, as it would imply an abnormally large rotational velocity (Gray 1982).

velocity orbit of the star. For the close-in planets,  $|v_p| \simeq 100 \text{ km s}^{-1}$ , which is two orders of magnitude larger than the resolution of current spectrographs. If the reflected light spectrum of the planet is detected, then the planetary mass is determined by equation (3).

Furthermore, as first discussed in Charbonneau, Jha & Noyes (1998), if the star has been tidally spun-up so that its rotation period is equal to the planetary orbital period, then the planet would reflect a non-rotationally-broadened spectrum, further distinguishing these features from the stellar lines.

In summary, the observational challenge is similar to that of transforming a single-lined binary system into a double-lined system, in the case of an exceptionally large contrast ratio between the two components. See Charbonneau et al. (1999), hereafter C99, for more details.

### 3. Results for $\tau$ Boö

Figure 1 summarizes our search for the reflected light spectrum from the planet orbiting the star  $\tau$  Boö, as described in C99. At the 99% confidence level, we find no evidence for a reflected flux ratio in excess of  $1 \times 10^{-4}$ . For edge-on values of the inclination ( $i \gtrsim 70^\circ$ ), this ratio is further restricted to be less than  $5 \times 10^{-5}$ . Assuming a planetary radius of  $1.2 R_{\text{Jup}}$  (Guillot et al. 1996), this limits the geometric albedo to  $p_\lambda \leq 0.3$  for  $466 \text{ nm} \leq \lambda \leq 498 \text{ nm}$ .

These conclusions are marginally in conflict with the recent claim of a possible detection of reflected light for the same system by Cameron et al. (1999). They find a reflected light ratio of  $(1.9 \pm 0.4) \times 10^{-4}$  in the wavelength range from 456 nm to 524 nm, and do not detect the planet in wavelength bands on either side of this region (385 nm to 456 nm, and 524 nm to 611 nm). Figure 2 demonstrates the confidence intervals that we would have obtained on the two unknowns  $\{\epsilon, i\}$  for inclinations near the one claimed by Cameron et al. (1999) and for a selection of contrast ratios.

Taking into account the different descriptions of the assumed phase function  $\phi_\lambda(\alpha)$ , and the respective errors stated in the two papers, it is possible that the two results are consistent, i.e. the inclination claimed by Cameron et al. (1999) is correct, but the amplitude of the signal is less than their most probable value by 1.5 times their quoted error. However, Cameron et al. (1999) caution that there is a 5% possibility that their detection is spurious. This controversy should be resolved by observations in the near future that can now be tailored (in selection of wavelength region and orbital phase) to verify the claimed detection.

### 4. Additional Targets

There are two principal considerations that enter into the choice of which planets may be most easily detected by reflected light: An ideal system is one with a small semi-major axis and a large stellar apparent brightness, and thus a large reflected light signal relative to the photon noise of the star. There are two other systems that satisfy these criteria, and we compare below the prospects for detecting each of these with those for  $\tau$  Boö ( $a = 0.046 \text{ AU}$ ,  $V = 4.5$ ).

The planet orbiting  $v$  And is further from its star ( $a = 0.059 \text{ AU}$ ), but the star has a greater apparent brightness ( $V = 4.1$ ). Combining these two effects, the detection threshold that could be established (given an equivalent amount of observing time) would be 1.36 times higher relative to the primary star than that for  $\tau$  Boö. For the planet orbiting 51 Peg, the larger semi-major axis ( $a = 0.051 \text{ AU}$ ) and fainter star ( $V = 5.5$ ) result in a detection threshold that is 1.93 times higher than that for  $\tau$  Boö.

Near edge-on inclinations ( $i \simeq 90^\circ$ ) are desirable for reflected light observations since they allow the planet to be viewed at the full range of phase angles. There are additional considerations that may constrain the inclination for these two systems. Assuming that the orbital planes of the three planets orbiting  $v$  And (Butler et al. 1999) are co-aligned, stability arguments (Laughlin & Adams 1999) favor  $\sin i \gtrsim 0.75$ . However, *Hipparcos* astrometry favors (Mazeh et al. 1999)  $\sin i \simeq 0.4$ . The rotation periods of  $v$  And and 51 Peg indicate that the stellar rotation has not become tidally locked to the orbital period, and this

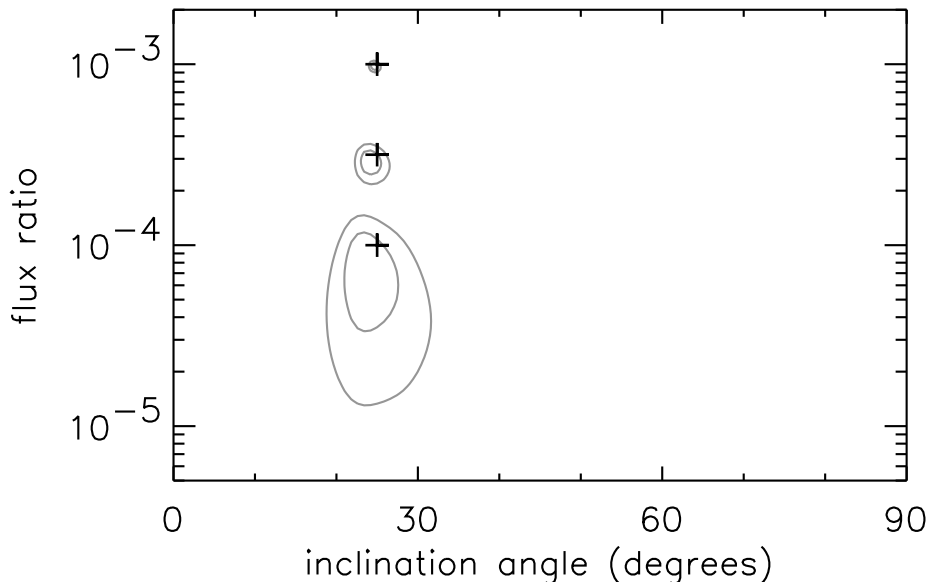


Figure 2. The detection thresholds shown in Figure 1 were tested by directly injecting a secondary into the data at a given amplitude and inclination. Three such tests are shown above, and the black crosses indicate the input parameters. The contours demarcate the 68% and 95% confidence regions on the derived parameters for the planet.

in turn might imply planetary masses which are near the minimum mass values (Drake et al. 1998).

We expect 51 Peg b and  $\nu$  And b to have larger radii than the more massive  $\tau$  Boö b (Guillot et al. 1996). If  $\tau$  Boö b has been detected, it has a very large surface area. If 51 Peg b and  $\nu$  And b have comparable albedos to  $\tau$  Boö b, they should have a comparable or larger reflected light ratio.

## 5. The Transiting System HD 209458

In the case of a planet that is observed to transit its star, the situation improves considerably. Since transit observations yield  $R_p$  and  $i$ , then only remaining unknowns in equation (1) are  $p_\lambda$  and  $\phi_\lambda(\alpha)$ .

The first transiting extrasolar planet, HD 209458 b, was detected by Charbonneau et al. (2000) and Henry et al. (2000). The dominant uncertainty in deriving the planetary radius and orbital inclination is the estimation of the stellar radius, and not the photometric precision. A detailed analysis of the stellar modeling, and the resulting derivation of the planetary parameters and the systematic uncertainties is presented in Mazeh et al. (2000). They derive  $R_p = 1.40 \pm 0.17 R_{\text{Jup}}$ ,  $a = 0.467$  AU, and  $i = 86^\circ.1 \pm 1^\circ.6$ . Substituting these values into equation (3), we find  $f_\lambda(\alpha) = 2.1 \times 10^{-4} p_\lambda \phi_\lambda(\alpha)$ .

Transiting systems such as HD 209458 are particularly desirable targets for reflected light measurements since by securing measurements near opposition (where  $\phi_\lambda(0) \simeq 1$ ), an observed reflected light amplitude is a direct measurement of the geometric albedo. Furthermore, one can use the spectra obtained while the planet is behind the star (rather than near inferior conjunction) to create the required stellar template spectrum. One difficulty is that HD 209458 is significantly fainter ( $V = 7.6$ ) than the systems described above.

We have simulated what could be achieved in a modest observing run using the Keck-1 telescope and HIRES spectrograph (Vogt et al. 1994), based on experience gained from our earlier observing run on  $\tau$  Boö (C99). In three nights when the planet is near opposition, we would obtain a detection threshold of  $4 \times 10^{-5}$  for the reflected flux ratio. Thus we would constrain the geometric albedo to be  $p_\lambda \leq 0.2$ , or directly detect the planet in reflected light.

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