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Reflected eclipses on circumbinary planets

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Abstract. A photometric method to detect planets orbiting around short-periodic binary stars is presented. It is based on the detection of eclipse-signatures in the reflected light of circumbinary planets. Amplitudes of such 'reflected eclipses' will depend on the orbital configurations of binary and planet relative to the observer. Reflected eclipses will occur with a period that is distinct from the binary eclipses, and their timing will also be modified by variations in the light-travel time of the eclipse signal. For the sample of eclipsing binaries found by the Kepler mission, reflected eclipses from close circumbinary planets may be detectable around at least several dozen binaries. A thorough detection effort of such reflected eclipses may then detect the inner planets present, or give solid limits to their abundance.

1. Introduction

To date, no unambiguous planets orbiting around a main-sequence binary star have been detected. Such "circumbinary" or "P-type" (Dvorak et al. 1989) planets would constitute a new class of planets, whose potential existence is supported by the existence of several cases of circumbinary dust discs (e.g. Pichardo et al., 2008). The discovery of short-periodic circumbinary planets would also have some impact on the viability of migration scenarios: The closest stable coplanar (in the binary plane) planet orbits around equal-mass binaries have critical radii of about $a_c = 2.4a_b$, where a_b is the distance between binary components[1]. This distance ratio corresponds to a ratio in planet/binary period of about 3.7. However, for the planet orbits there exist regions of instability at small integer mean-motion resonances such as 4:1, and possibly for ratios up to 9:1 (Chambers et al. 2002). The existence of planets in orbits between zones of instability would therefore require compatible formation scenarios, with strict limits on potential migration routes. In the following, we give an outline of a method that might lead to the detection of such short-period binary planets, based on the detection of reflected light from the central binary off the planet.

[1] For binaries with other mass-distributions or non-coplanar planets, this ratio will be somewhat larger, for details see Dvorak et al. 1989, Chambers et al. 2002

2. Characteristics of the reflected eclipses

The basic idea is the detection of the binary eclipses in the reflected light signal from the planet (referred to hereafter as 'reflected eclipses' or RE, see Fig. 1). That is, the light that is reflected from the planet will vary with the brightness of the central binary stars as they are 'seen' by the planet, and will have the signatures of the binary-eclipses imprinted on it. A further modulation of the observed reflected light is given through a planetary phase-function, determined by the binary-planet-observer angle (Fig. 2). Such phase functions are indicative of a planet's atmospheric or surface composition (Seager et al. 2000; Sudarsky et al. 2005). Most commonly, Lambert phase functions are assumed, which are a reasonable approximation for cloud-free giant exoplanets. For atmospheres with clouds or aerosols, as well as for solid cloudless bodies, peaks in reflection for small phase angles are expected. The observed brightness variation for a given angle α due to RE is then identical to the amount of an exoplanet's reflected light (e.g. Seager, et al. 2000) multiplied by the relative depth of the binary eclipses *as seen by the planet.*

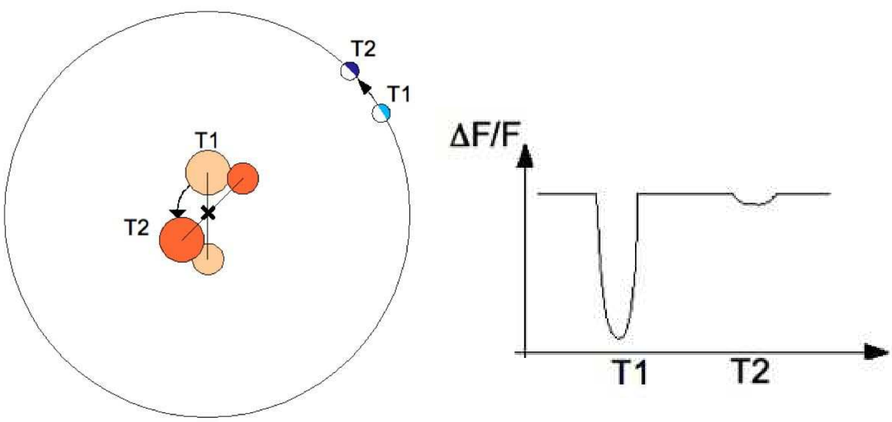

Figure 1.: *Schematic of a binary star with a coplanar (binary and planet in the same plane) orbiting planet. The observer is at a semi-infinite distance towards the bottom. At time T1, the observer perceives a primary eclipse from the binary component. At a later time T2, the binary is not eclipsing to the observer, but the planet perceives an eclipse from the binary, which will be imprinted in the light that is reflected from the planet. This appears to the observer as a much shallower eclipse at T2.*

For circular and coplanar orbits, reflected primary eclipses occur whenever the binary's and the planet's orbital phases are identical. This leads to a periodicity P_{re} of the RE given by $1/P_{re} = 1/P_b \pm 1/P_p$, where P_b and P_p are the binary and planetary periods, respectively, and the minus or plus signs corresponds to prograde respectively retrograde planetary orbits. Considering the above-mentioned minimum in the planet/binary period ratio of about 3.7, we may constrain P_{re} to values fairly close to P_p, namely: $0.78P_p \lesssim P_{re} \lesssim 1.37P_p$; out of which, for the prograde case only, $P_{re} > P_p$ need be considered. This restricted range of possible periods should facilitate any RE detection attempts.

The effects of orbital inclination in coplanar systems are illustrated in Fig. 3. The observed binary eclipse depths will be attenuated as the inclination of the system

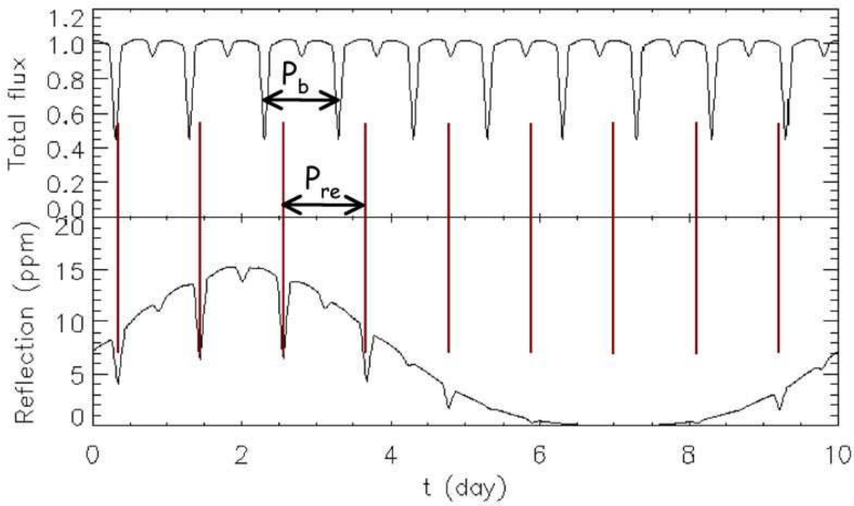

Figure 2.: *Simulated lightcurve from a system with a P_b=1d binary orbited by a prograde P_p=10d planet, with an inclination of $i_b = i_p = 90°$. The upper panel shows the total observed flux, which is dominated by the eclipses observed directly from the binary. The lower panel shows the reflected light from the planet. Note that its amplitude is on the order of* ppm. *The general shape of this sinusoidal light curve is due largely to the planetary phase function, upon which the reflected eclipses (positions indicated by vertical red lines) are imprinted, with a periodicity of P_{re}=1.11d.*

decreases away from 90°. However, the depth of the eclipses as seen by a coplanar planet does *not* change, although the total amount of reflected light from the planet to the observer changes with inclination, given by the phase function. Of interest is that circumbinary planets in strongly inclined systems may generate RE even when the central binary is *not* eclipsing from the observer's point of view (For an example, see the curve for $i = 30°$ in Fig. 3). Thus, planets around a non-eclipsing binary system may also be detected by their RE. Lastly, in systems of arbitrary mutual inclinations ($i_b \neq i_p$) , the reflected light curves depend not only on the respective inclinations but also on the angle between the nodal line (formed by planet and binary orbit) and the plane of the sky; the variety of possible models is therefore very large and beyond this discussion. It is important to note that *all* circumbinary planets will cross the binary plane at least twice during each orbit, and therefore will be subject to RE at least during part of their orbits (though, depending on respective orbital periods and phases, RE may not occur at each planet crossing of the binary plane). In principle, all circumbinary planets should therefore be detectable by RE irrespective of their orbital configurations. The one exception will be coplanar or near-coplanar systems with inclinations near 0°, where the direct binary eclipses are not observable, and the amount of reflected light will not show any dependence on the planet's orbital phase. The resulting RE signals can then not be disentangled from the signal of an eclipsing binary with a very low amplitude. Fortunately there are only two ways to obtain a pole-on planetary orbit, but many ways for a planetary orbit to be edge-on, so the former should be rare.

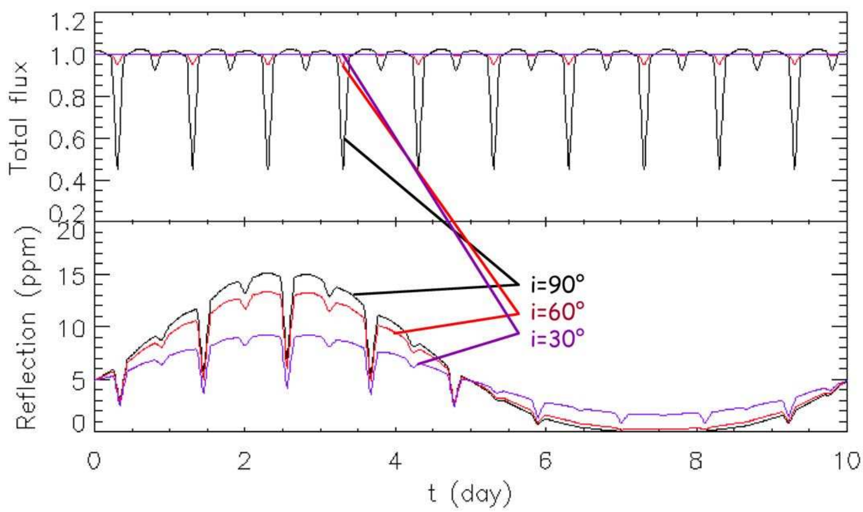

Figure 3.: *Similar to Fig. 2, showing the total light and the reflected light from coplanar systems at several inclination values. Note the absence of directly observable eclipses at* $i = 30°$ *in the upper panel while still allowing the detection of reflected light from the binary-coplanar planet.*

3. Light time effects (LTE)

Up to this point, we have used purely geometrical arguments about the positions of binary and planet while ignoring any light time effects (LTE) from the varying distances between binary, planet and observer. Without the LTE, and considering only coplanar circular orbits, the RE will be strictly periodic with P_{re}, as given previously. However, the light with the imprinted eclipse needs to travel from the binary to the planet, and then from the planet to the observer. This leads to advances or delays over strict periodicities with amplitudes principally determined by the light-travel time for the binary - planet distance.

For the binary and planetary orbit being both circular and coplanar, this corresponds to a sinusoidal 'O-C' (observed-minus-calculated) timing variation of the REs respective to strict periodicity. More complex behavior will occur if eccentricity and/or significant non-coplanarity are present. We expect however that the timing of the RE – with the binary's total mass being given – should in principle allow the derivation of a full orbital solution of a circumbinary planet's orbit.

4. Detectability of RE signals

Following the previous discussion, amplitudes of RE signals may be expected to be of the same order of magnitude as the reflected light itself. To date, the amount of such reflected light has been measured during occultations in three hot giant planets (CoRot-1b, CoRoT-2b and Hat-P-7b, all with periods of 1.5 to 2.2 days) to be about 100-130 parts per million (ppm) of the total photometric signal. For circumbinary planets, a maximum RE signal will of course arise from those that are at the inner

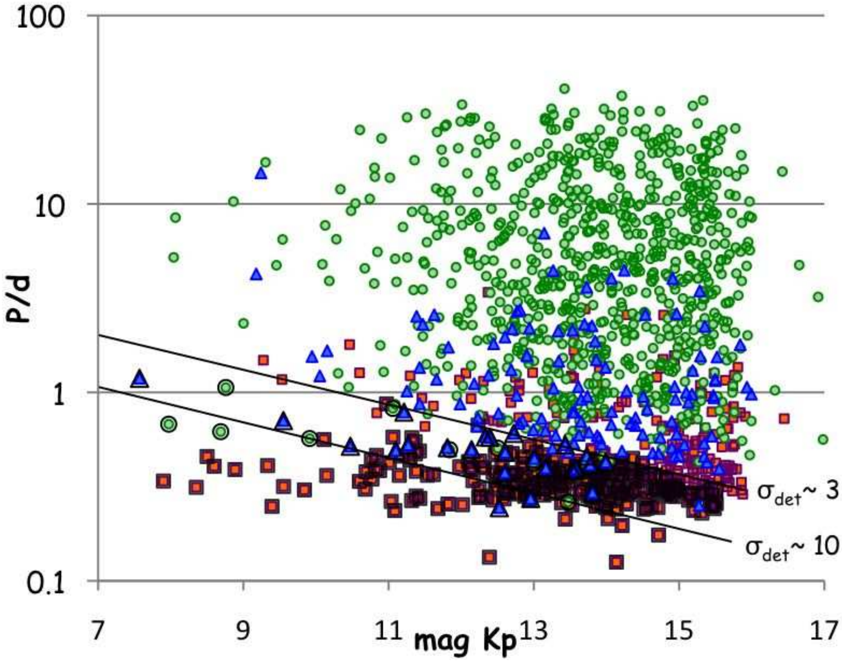

Figure 4.: *Detectability of RE from planets at minimum stable orbital distances for eclipsing binaries in the Kepler data. Shown are 1601 eclipsing binaries from Prsa et al. 2010, plotted against Kepler-magnitude and period. Green circles are detached systems, blue triangles are semi-detached, and orange squares are over-contact systems. Systems with an RE detectability of* $\sigma_{det} > 3$ *are indicated by larger symbols. The two black lines give the approximate slope below which 3 or 10 sigma detections are possible.*

orbital stability limit. For planets around deeply eclipsing ($\Delta I = 0.4 - 0.5$) short periodic binaries with $P_b \lesssim 1d$, and corresponding minimal stable orbits with $P_p \lesssim 4d$, we may therefore expect RE amplitudes in the range of 10 -100ppm. Using the Kepler mission as a reference, we may then perform a rough estimate on the number of systems in which RE may be detected. To this end, we compare noise-determinations from Kepler long-cadence data (Jenkins et al. 2010) with estimations of RE amplitudes from planets at the inner stability limit, using 1601 eclipsing binaries (EB) catalogued by Prsa et al. (2010) in the Kepler field. A very preliminary analysis assuming a 1-year long light-curve and Jupiter-sized planets (Fig. 4) implies that significant numbers of binaries may warrant a search for RE signals. There are about 240 binaries in which planets may be detected at the 3 sigma (or greater) level, and about 60 for which detections with 10 sigma (or more) may be possible. Although these numbers may still vary significantly when performing a more detailed analysis, they indicate that a search for RE signals in the most suitable EBs in the Kepler sample may be a fruitful undertaking. Since nearly all configurations of binaries with close-periodic planets will generate RE signals of similar amplitudes, such searches will then not only be sensitive to positive detections (like transit searches), but absences of RE signals will also allow the setting of hard limits onto abundances of close circumbinary planets. Regarding the observability of the LTE for these systems, the sinusoidal 'O-C' amplitude for planets at the inner stability limit is simply $\Delta\tau = -a_c/c$. For all EBs with an RE detection sigma ≥ 3, this amplitude is typically around 10 seconds, and never above 20 seconds. For the most suitable candidates (in the lower left corner in Fig. 4) Kepler should be able to detect RE of planets at orbital distances up to 4 times the stability limit, with corresponding LTE amplitudes approaching about 1 minute. Considering, however, that RE detections themselves will not be an easy task, we expect that LTE detections of the RE may only be marginally possible with Kepler. LTE detections of circumbinaries' RE may however be feasible with future missions focussed on brighter stars (e.g. ESA's PLATO mission), for which the RE of longer-periodic planets may be detectable, which consequently will have larger timing effects.

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