Planet influence on the shape of the hosting star - ellipsoidal variations of tau Bootis

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Abstract

This paper presents estimations on the possibility of detection of ellipsoidal variations, by means of measuring brightness of the star distorted by a close massive planet, **based on Wilson-Devinney method. The analytical formulation of the problem is given by Phafl 2008.** The effect is well known in the case of binary stars where the effect can produce light curves with amplitutudes of ellipsoidal variations of about 0.1 mag for distorted stars. For planets the effect is very small and usually less than 0.0001 mag. The detection of an exoplanet, by searching for small amplitude ellipsoidal variations, will be very difficult and affected by other photometric effects; however, it maybe possible for some extreme cases. Observations of ellipsoidal variations can provide additional constraints on the model of the system. Light curves for few star/planet systems have been calculated using PHOEBE eclipsing binary software based on Wilson-Devinney method. As an example of ellipsoidal variations the synthetic light curve for τBootis is presented. The amplitude of ellipsoidal variation is 0.01 mmag. The companion is massive (7.3 M_{Jup}) and short-period hot Jupiter.

1 Introduction

During the last decade we have observed a very fast development of extrasolar planet research. The new methods of detection have been successfully used. The observational techniques give us the possibility to detect more and more shallow effects like transits of a planet in front of the hosting star, a direct imaging of planets and measuring the chemical abundance in the planet atmosphere. In this paper I will **discuss** the question whether we can observe light curve variations of the hosting star distorted by the gravity field of a massive planet **for some already known systems. The detailed analytical formulation of ellipsoidicity effect caused by substellar companion is given by Pfahl et al. 2008.** A close massive companion of the star can produce tides analogue to the ones present in close binary stars. The effect is of course much weaker and difficult for detection. Actually, the presence of ellipsoidal variations among the transit candidates is treated as an evidence of a non planetary behaviour of the eclipses. Patzold et. al (2004) describe orbital period changes in planetary systems caused by gravity tides induced by exoplanets. Some short-period exoplanets, for example τBootis, are probably in tidal lock that demonstrates the significance of the tidal interaction. We can model ellipsoidal variations using a code based on Wilson-Devinney (WD) method developed for eclipsing binary stars. This method has already been used for modeling eclipses and radial velocity curves of transiting planets - one of them being OGLE-TR-56 (Voccaro and Van Hamme 2005).

2 Roche lobe and the massive planet

I will use a standard Wilson-Devinney method (PHOEBE software, Prša and Zwitter 2005) to describe the distortion of the hosting star by its planetary companion. In the case of eclipsing binaries we have a typical mass ratio of about $q = m_2/m_1 \sim 1$. For planetary systems, where $m_1 >> m_2$ we usually have a mass ratio less than 0.01. The ellipsoidal light curve variations in binary systems are dependent on the level of asymmetry of the distorted component. We have higher amplitude of light variations for stars that significantly fill their Roche lobes. For mass ratio of about 1 we observe distorted Roche lobes with high asymmetry near Lagrangean point L_1. For $q < 0.01$ the lobe of the star is almost spherical (for slow rotation) with a small asymmetry near L_1. The shape of the Roche lobe also depends on a rotational rate of the components. In WD method we use the synchronicity parameter f, **defined as**

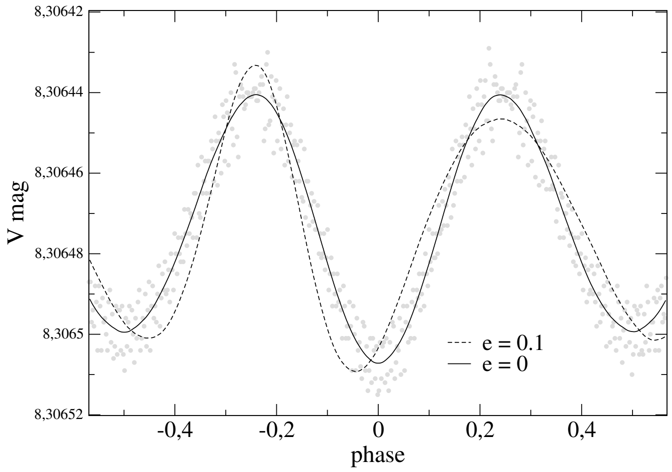

Figure 1: Synthetic light curve of the hypothetical system for two eccentricities, inclination of 79° and synchronous rotation. **The gray dots present the numerical noise for the circular orbit.**

the ratio between the axial and orbital revolution period. For high values of this parameter, $f \sim 1$ (synchronous rotation), we have a flattened star - this implies higher asymmetry because of smaller distance between the stellar surface to L_1. In table 1 we have listed values of amplitudes of ellipsoidal variations for two synchronicity parameters f of both the hosting star that fills its Roche lobe and for the MS star. The amplitude also depends on the gravity and limb darkening coefficients. The main contribution in ellipsoidal variation amplitude is connected with the stellar shape ($> 90\%$) and gravity brightening ($< 10\%$). We can expect notable ellipsoidal variations in two cases, considerable mass ratio or high filling of the Roche lobe. **The distortion computed by the Roche model is slightly overestimated for evolved stars because the mass is not concentrated in the barycenter but spread in a distorted star.**

Let us take a hypothetical system with a relatively distorted star characterized by a mass ratio of 0.001, a short orbital period of 1d and a semi-major axis of 5 $R_\odot$. The main parameters of the system are close to those of OGLE-TR-56. The mass of the planet is 0.0013 $M_\odot$ (1.3 M_{Jup}). The host star is slightly evolved with a mass of 1 $M_\odot$ and a radii of 1.3 $R_\odot$. The obtained light curve has peak to peak amplitude of about 0.00006 mag. The distorted star has the following dimensions: $R_{\rm side} = 1.32179$, $R_{\rm point} = 1.32184$, $R_{\rm back} = 1.32183$, $R_{\rm pole} = 1.30846$ **in solar units. Two curves are presented, one for circular and one for eccentric orbit (fig. 1). For a more evolved star with radii 2.5 $R_\odot$ we have peak to peak amplitude of 0.0005mag.**

We have two minima of different depths, which is the result of different surface temperature of the star near Lagrangean points L_1 (lower) and L_2 (higher). Two maxima are different because of the eccentric orbit that gives a variable separation of components for different phases. This implies changes of radii/temperature of the star. We can also see another effect of the orbital eccentricity - shifted minima and maxima. The reflection effect was switched off, just as in the other modeled objects. **The numerical noise in LC is on the level of** 10^{-5} **for stellar surface grid raster** $n_{star} = 60$ **(maximal for PHOEBE). For the future aplications the exoplanet mode with denser grid can be of use for modeling shallow effects.**

3 Ellipsoidal variations of known systems

Among the discovered systems listed in *exoplanet.eu* data-base some stars have been checked for ellipsoidal variations using WD simulations. The star with higher amplitude is HD 41004B. For the generation of its light curve the results of Zucker et al. 2004 were used. Around the host star there is a massive

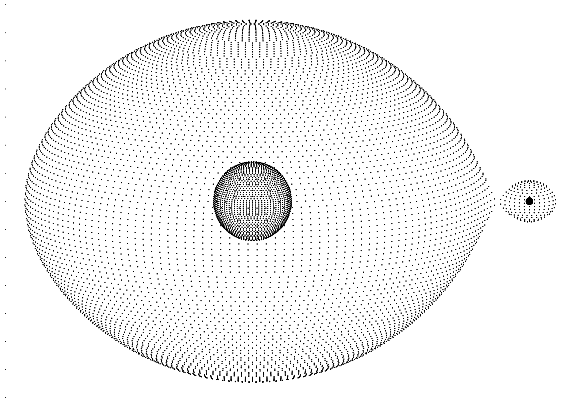

Figure 2: Both components of the τBootis system inside their Roche lobes for inclination 80°, which presents better the flatness of the lobes.

Table 1: Maximal V amplitude of ellipsoidal variations vs. mass ratio for the star that fill its Roche lobe and for the main sequence star. Inclination is 90°, component 2 is small and spherical - does not involve the curve shape. The host star has one solar mass, the semi-major axis is 5 $R_\odot$ and the period $\sim 1.3d$.

mass ratio	evolved		main sequence	
q	f=0.1	f=1	f=0.1	f=1
1	0.27	0.28	0.022	0.022
0.1	0.12	0.13	0.0025	0.0025
0.01	0.025	0.044	0.00025	0.00025
0.001	0.0045	0.013	10^{-5}	10^{-5}
0.0001	0.0004	0.0032	-	-

companion (18.5 M_{Jup}) orbiting, the mass of which is above the limit of 13 M_{Jup} usually applied for planets; therefore, we can classify this object as a brown dwarf. The semi major axis of the orbit is very small 0.018 AU and the orbital period is 1.3d. Obtained LC presents variations with peak to peak amplitude of 0.0002 mag (V). The theoretical amplitudes for other examined stars are: τBootis - 0.00001, OGLE-TR-56 - 0.00006 mag.

The former - τBootis - is a well studied system discovered in 1997 (Butler et al. 1997). For the WD simulations system parameters (table 2) listed in Leigh et al. (2003) were adopted. This work presents spectroscopic search for reflected light. The projected orbital velocity amplitude was found to be $K_p = 97 \pm 8kms^{-1}$ ($K_s = 469 \pm 5ms^{-1}$) The most probable orbital inclination is $i = 37 \pm 5°$, which implies planetary mass $M_p = 7.28 \pm 0.83$ M_{Jup}. The synthetic light curve for two inclinations is presented in figure 3. The higher possible peak to peak amplitude of ellipsoidal variations without eclipses ($i = 80°$) is $3 \cdot 10^{-5}$mag and for inclination 37° we obtain $1 \cdot 10^{-5}$mag variability. The eccentricity is small and unnoticeable on the light curve. The shape of the star depends on the filling of the Roche lobe (fig. 2). During the evolution τBootis will expand and fill equipotential surfaces with higher asymmetry, which will increase the ellipsoidal variations (table 3).

Future mass photometry space missions, for example Kepler (Christensen-Dalsgaard et al. 2006), will be able to detect such level of variability. **The prospects of detection to be performed by Kepler mission have been discussed by Pfahl et. al. 2008**. The differential photometry will reach precision of 20ppm for 12mag G2V star. The detection of ellipsoidal variations will be affected by the

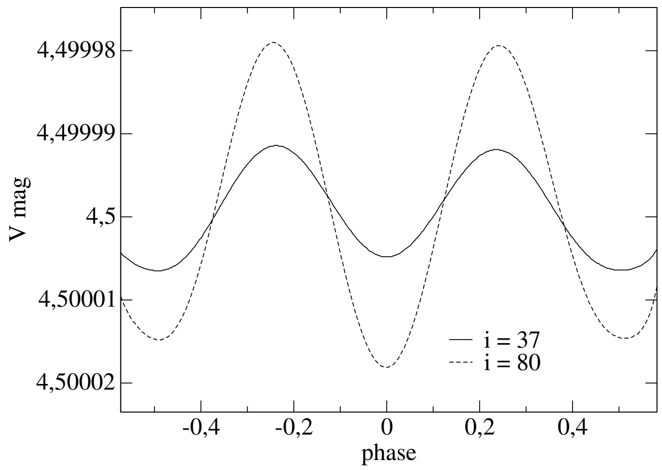

Figure 3: Synthetic light curve of τBootis A for two orbital inclinations. The curves have been shifted for better comparison and smoothed to remove the "numerical noise".

other photometric effects induced by planets - chromospheric activity, scattered light and, not connected with the companion, for example spots and convection (the intrinsic stellar noise). The MOST satellite has detected a variability on τ Bootis A probably induced by the planet (Walker et al. 2008). The active region close to the sub-planetary point has been found. This variable spot produces brightness variations with peak to peak amplitude of 1 mmag. This effect is higher than ellipsoidal variations so their detection will probably be impossible if the active region is stable and present in the future. A similar effect was found on HD 179949 by Shkolnik et al. (2005). If such spots are typical for 51 Peg systems, searching for ellipsoidal variations of hosting stars will be more difficult. The predicted level of scattered light for τBootis by Green et al. (2003) is two orders lower $1 \cdot 10^{-5}$mag and comparable with the ellipsoidal variations effect.

4 Conclusions

The future mass photometry missions can be used for detection of exoplanet candidates by searching for effects weaker than transits like induced spots, ellipsoidal variations or sca-ttered light. The WD code is already used for modeling transits of exoplanets. This method can be usful for calculating weaker effects like ellipsoidal variations or spots on the host star induced by the planetary companion, and maybe applied for the scattered light after some modification of the code. The method can also be useful for modeling the Rossiter-McLaughlin effect in radial velocity curves.

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Table 2: Parameters of τBootis system used for the synthetic curve and obtained dimensions of the components for double tidal lock.

Parameter	star	planet
i	37°	
q	0.005	
$A(\mathrm{R}_\odot)$	10.51 (0.0489 AU)	
Period (d)	3.31245	
e	0.018	
ω	65°	
Ω	7.12	1.93
x_V	0.54	-
Mass($\mathrm{M}_\odot$)	1.42	0.007 (7.28 M_Jup)
Radii($\mathrm{R}_\odot$)	1.48	0.12 (1.2 R_Jup)
T_eff (K)	6360	1576 (estimated)
$R_\mathrm{side}(\mathrm{R}_\odot)$	1.480000	0.122414
$R_\mathrm{point}(\mathrm{R}_\odot)$	1.480034	0.122472
$R_\mathrm{back}(\mathrm{R}_\odot)$	1.480028	0.122472
$R_\mathrm{pole}(\mathrm{R}_\odot)$	1.477926	0.122393

Table 3: Relation between the filling of the Roche lobe by the host star (Ω) and the ellipsoidal variations (Δm) for τ Bootis. The dimensions of the star (point & side) are given in units of semi-major axis.

Ω	radii $\mathrm{R}_\odot$	Δm	R_point	R_side
7	1.5	$1 \cdot 10^{-5}$	0.143	0.143
3	3.6	$2.5 \cdot 10^{-4}$	0.341	0.340
2	5.7	$1.2 \cdot 10^{-3}$	0.542	0.541
1.6	8.0	0.005	0.789	0.771

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