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A relation between the brightness maxima separation and mass ratio in contact binaries

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Abstract. A new effect concerning the light curves of contact binaries is presented. The separation between the brightness maxima tends to be larger than half of the orbital phase, if the primary minimum is defined as during which the more massive star is being eclipsed.

Key words: stars – contact binaries – starspots

1. Introduction

The W UMa-type contact binaries are one of the most most peculiar examples of the interacting binary stars. According to their canonical model (Lucy, 1968), they consist of two (near) main sequence stars, both of which overfill their inner critical Lagrangian surface. It leads to sharing a common convective envelope, as well as to the interchange of both energy and mass (Flannery, 1976). Such configuration should result in an equal surface temperature for a whole binary with a brightness distribution dictated by the gravitational and limb darkenings.

The light curves of contact binaries are known to have minima of similar depths due to eclipses and prominent maxima between them due to the tidal distortion of the components. These light curves are known also for their intrinsic variability, which is commonly explained with the photospheric phenomena (starspots). The occurence of such a starspot introduces many interesting asymmetries to the light curve. One of them is the O'Connell effect, i.e. the difference between the height of the maxima. Other effect is tied to the brightness minima and the evolution of the starspot. As the starspot changes its location, the minima change their depths. It might be even the case that the minimum which once was the deeper one for some time is the shallower one (see Fig. 1, the KIC 9283826 have been phased using elements from the Kepler Eclipsing Binary Catalogue, KEBC, Prša et al., 2011). That in turn opens up a debate on the naming convention of the minima. Namely, which is the 'primary' one?

There are two definitions of the 'primary' minimum. First, purely phenomenological, identify the primary minimum as the deeper one. In the second definition the primary minimum is the one during which the more massive component of a binary is being eclipsed. Here, the more massive component is also called the 'primary component'. In case of contact binaries, the more massive

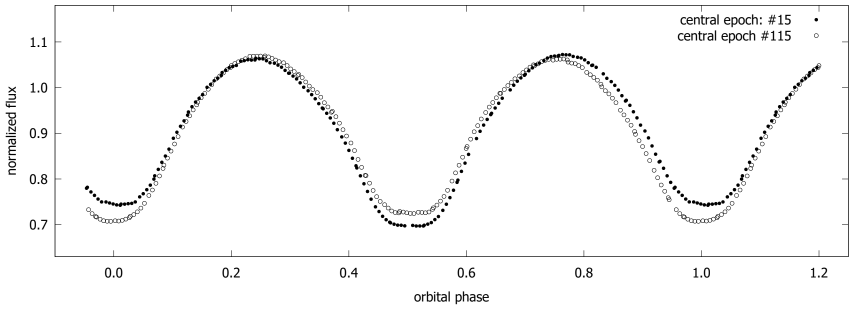


Figure 1. A comparison of the phase curves of KIC 9283826 taken with the Kepler Spacecraft in the Long Cadence mode. The first curve (solid circles) comes from a range of orbital epochs 10-21, while the second curve covers a range of epochs 110-121.

component is also the larger one. Together with the second definition it implies that, with a proper inclination, the total eclipse, which corresponds to the flat-bottom minimum in the light curve, is always during the secondary minimum. In this work the primary star is the more massive one and we employ the second definition of the primary minimum.

During our preliminary studies on Kepler light curves (Debski et al., 2015) we found that the positions of brightness maxima hardly ever lie exactly on the orbital phases $\phi = 0.25$ and $\phi = 0.75$. One could argue that such a feature is also caused by a starspot-related light curve distortion, but the effect exists even in light curves with no noticeable O'Connell effect. Since this new effect was initially found in the high-precision Kepler light curves, the measurement error also cannot be the cause.

We define the separation as $S = \phi_{max_{II}} - \phi_{max_{I}}$, where $\phi_{max_{I}}$ and $\phi_{max_{II}}$ are the positions in phase of the primary and secondary maximum, respectively. While conducting the aforementioned preliminary studies, we found presumptive evidence for a possible connection between the mass ratio and the maxima separation. Namely, the light curves of contact binaries with a mass ratio $q = \frac{M_2}{M_1} < 1$ had the separation between the brightness maxima always larger than half of the orbital phase, $S > 0.5\,\phi$ (here M_1 and M_2 are masses of the primary and secondary components, respectively).

2. Observational data

In this study we used two different observational samples. The first one (a.k.a the *Kepler sample*) consists of 49 objects from the KEBC. All objects in the Kepler sample have light curves resembling contact binaries, almost equal minima depths and a prominent tidal distortion effect. The most important trait

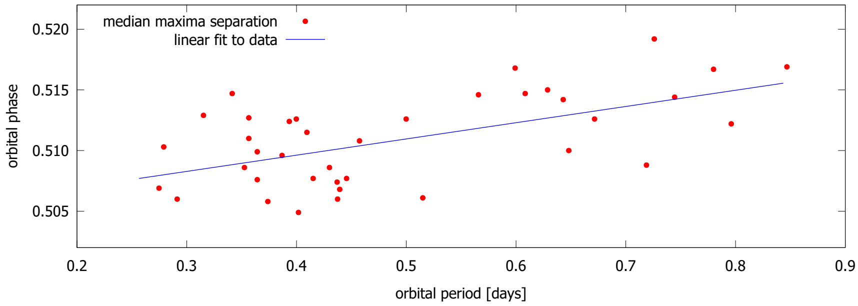


Figure 2. Median Maxima Separation in the Kepler sample as a function of the orbital period. The correlation coefficient is $r = 0.51$, while the slope of the fitted linear function is $b = 0.0134 \pm 0.0040$.

is that all the objects in the Kepler sample have very similar inclinations, close to $i = 90°$. This fact reduces the possible influence of the inclination on the observables. The second sample (hereafter the *Suhora sample*, Kreiner et al., 2003) is build with 42 objects observed in *UBVRI* Bessel filters and all have spectroscopically determined mass ratios (Lu et al., 2001).

2.1. Kepler light curves

Because most of the objects in *KEBC* don't have a measured mass ratio q, we settled on ensuring a proper light curve phasing to satisfy $q = M_2/M_1 < 1$. In order to do so, we focused our attention on light curves with a flat-bottom minimum. As mentioned before, having the secondary eclipse a flat-bottom one, it is to be expected to have a binary with a mass ratio $q < 1$.

The criteria of choosing objects into our sample from the *KEBC* were as follows: 1) the light curve must be flagged as an FB (flat-bottom minimum), 2) the light curve must have the shape typical for a contact binary, i.e. a great ellipsoidal effect present and not obvious beginning and end of the minimum profile, 3) minima must have similar depths, since both components should have similar surface temperatures. The rule of thumb was to throw away light curves with a minima depth difference larger than 0.1 of the normalized flux. We searched the database for objects with the orbital period less than $P = 1\,day$ and the morphology parameter $morph > 0.6$.

We measured the separations of the maxima in every subsequent orbital period for every object, while the measured phase curves were binned dynamically. The size of the bin varied, so that the phase curve would consist of at least 120 datapoints. Since the maxima separations were varying in time, for every object we calculated its Median Maxima Separation (MMS). We found that for

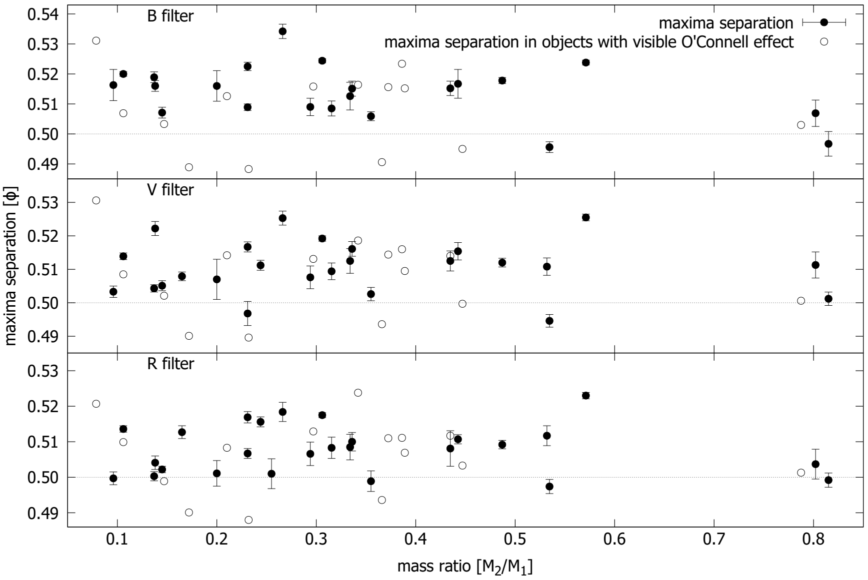


Figure 3. Measured maxima separations in the Suhora sample in the selected filters.

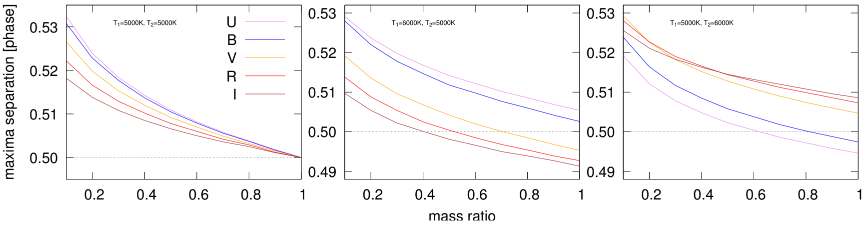
all objects in the sample the MMS was larger than half of the orbital phase, $MMS > 0.5\,\phi$, if their mass ratio was set as $q < 1$ (see Fig. 2).

2.2. Multicolor & spectroscopic observations

Objects in the next sample were all rephased so that their mass ratio would be $q < 1$ and their maxima positions were found by fitting the Gaussian functions to the narrow, selected parts of their phase curves. We measured maxima separations in every filter and found that, in general, the maxima separations were again $S > 0.5\,\phi$. Only the light curves with a noticeable O'Connell effect were not following this rule. We presented the results in selected filters in Fig. 3. There is no visible correlation between the separation of the maxima and the mass ratio, possibly due to the high diversity of the sample in inclination. There is a visible trend in the color: in general, the redder the filter, the smaller the maxima separation.

3. Numerical simulations

We designed a grid of synthetic light curves with the Wilson-Devinney code (Wilson & Devinney, 1971). We found that the main factor shaping the distribution of maxima separations was the limb darkening. The influence of gravitational brightening was smaller, but also non-negligible. Because of that, we



decided to extend the simulations from binaries with a components of equal surface temperatures, to extreme cases of temperature inequality. In the simulations the temperatures are taken with a $1000\,K$ step, but we do not simulate binaries with a temperature difference between the components larger than $1000\,K$. Our grid covers contact binaries with a range of mass ratios ($q \in (0.1, 1)$, step 0.1), fill-out factors ($ff \in (0, 100\%)$, step 10%) and inclinations ($i \in (20^\circ, 90^\circ)$, step 2° for $i \geq 70^\circ$ and 10° for $i < 70^\circ$). The fill-out factor ff here is defined as follows: $ff = (\Omega_s - \Omega_{L_1})/(\Omega_{L_2} - \Omega_{L_1}) \cdot 100\%$, where Ω_s is the pseudopotential of the binary surface, while Ω_{L_1} and Ω_{L_2} are the pseudopotentials of the equipotential surfaces crossing Lagrangian points L_1 and L_2 respectively. An excerpt from the simulated maxima separations is presented in Fig. 3.

The most interesting insight from the simulations is that the maxima separation for contact binaries with components of equal temperatures indeed are larger than half of the orbital phase, if $q < 1$. The same holds even for highly unequal temperatures of the components, but only in case of $ff = 0\%$. Moreover, the lower the mass ratio, the maxima separation should be larger. Interestingly, the separation of the maxima also grows significantly larger for lower inclinations. When compared in different filters, maxima separation differs, as it should, if it is caused predominantly by the limb darkening.

4. Summary

The main conclusion of this study is that the maxima separation in the light curves of contact binaries hardly ever equal to the half of the orbital phase of the system. If one defines a primary minimum as the one during which the more massive star is being eclipsed, then it is possible to point at it by phasing the light curve so that the maxima separation would be $S > 0.5\,\phi$. The primary minimum will then sit at phase $\phi = 0.0$. According to our simulations, this criterion works for all cases of $T_1 \leq T_2$. In case of $T_1 = T_2 + 1000\,K$, the criterion works always for $ff = 0\%$.

The simulations show that for very low mass ratios maxima separation should grow rather large, up to $S > 0.52\,\phi$ and larger. This is not the case in the Suhora sample. The lack of trend there may lead to at least two scenarios: 1) low-mass contact binaries have some hidden traces of photospheric phenomena, not visible straight in the light curves yet influencing the maxima separation or 2) models of contact binaries and/or limb darkening coefficients in these are faulty. The second scenario is particularly worrisome, as many studies of contact binaries rely on the accuracy of the Wilson-Devinney code.

Another opportunity rises with the multicolor observations of the maxima separation effect. The simulations showed that the maxima separation is greater in bluer filters in case of components of equal surface temperatures or the primary being the hotter one. The separation S becomes larger for redder filters only if the secondary is hotter than the primary. Interestingly, almost all objects from the Suhora sample (from those which show no O'Connell effect) have *color separation*, that is $S_B - S_R$ (maxima separation in the B filter minus the separation in the R filter) larger than zero, which means that in their case the primary is most likely the hotter one. That holds even if the secondary minimum is the deeper one, which makes *color separation* a promising tool for studying a temperature ratio in the binary.

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