Research Note

On the properties of contact binary stars[★]

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Abstract. We have compiled a catalogue of light curve solutions of contact binary stars. It contains the results of 159 light curve solutions. The properties of contact binary stars were studied using the catalogue data.

As is well known since Lucy's (1968a,b) and Mochnacki's (1981) studies, primary components transfer their own energy to the secondary star via the common envelope around the two stars. This transfer was parameterized by a transfer parameter (ratio of the observed and intrinsic luminosities of the primary star). We prove that this transfer parameter is a simple function of the mass and luminosity ratios.

We introduced a new type of contact binary stars: H subtype systems which have a large mass ratio ($q > 0.72$). These systems show behaviour in the luminosity ratio- transfer parameter diagram that is very different from that of other systems and according to our results the energy transfer rate is less efficient in them than in other types of contact binary stars. We also show that different types of contact binaries have well defined locations on the mass ratio – luminosity ratio diagram. Several contact binary systems do not follow Lucy's relation ($L_2/L_1 = (M_2/M_1)^{0.92}$). No strict mass ratio – luminosity ratio relation of contact binary stars exists.

Key words. stars: binaries: close – stars: evolution – stars: binaries: eclipsing – catalogs

1. Introduction

Contact binary stars (or W UMa-type stars) consist of two dwarf stars whose spectral types are F, G or K (only a few examples are known of earlier spectral types, and no M spectral type contact binary star is known). Binnendijk (1965) pointed out that the components in a contact binary system have nearly equal surface temperatures and luminosities in spite of their often greatly different masses. If they are really dwarf stars as suggested from their spectra, what is the mechanism that equalizes their temperatures and luminosities? The answer can be found in Lucy's papers. The light curve characteristics of these binaries were successfully interpreted by the contact model (Lucy 1968a,b), which simultaneously explains the shape of the light curve and the equal temperatures and luminosities of the components, hence this model is accepted as a theoretical description of W UMa-type stars. The model assumes that both stars fill their Roche-lobe therefore they touch each other. Mass and luminosity are transferred from the primary star to the secondary star through the narrow neck between the components. In the model two main sequence stars are embedded

in a common photosphere which is convective. Although it explains the light curve shape and the temperature equalization, however, contact binary star evolution and the internal structure of the common photosphere remained open issues. Internal structure models were discussed by Kähler (1986) and a recent review on them can be found in Webbink (2003). Kähler (1989) summarized other possible theories of contact binary stars but he found that they were not confirmed by the observations. Recently, detailed computations on energy transfer and internal structure were published by Kähler (2002a,b, 2004).

In order to develop our empirical knowledge about these stars, a catalogue of the results of the light curve (LC) solutions for contact binary stars – based on LC-solutions published formerly in the literature – was compiled; it contains the solutions of light curve of 159 systems. This catalogue is presented in Sect. 2.

Based on the catalogue data, we investigated the efficiency of the energy transfer from the primary to the secondary star and the mass ratio – luminosity ratio relation. These are outlined in Sect. 3.

According to the contact model, the energy generated in the cores of the components is redistributed in the common convective envelope and therefore the observable luminosities have

[★] Tables 2 and 3 are available in electronic form at <http://www.edpsciences.org>

Fig. 1. Mass ratio – luminosity ratio diagram of contact binary stars. Open squares: A, filled squares: B, filled circles: H/A (A subtype systems with $q > 0.72$), open circles: H/W (W subtype systems with $q > 0.72$), filled triangles: W subtype systems. The solid line gives the $\lambda = q^{4.6}$, the main sequence mass-luminosity relation. The dashed line is Lucy's relation $\lambda = q^{0.92}$.

another dependence on the mass ratio than would be the case if one looks at two main sequence stars in detached configuration (where $L_2/L_1 = (M_2/M_1)^{4.6}$). Lucy (1968a) found that the observable luminosity ratio is proportional to the ratio of the stellar surfaces ($L_2/L_1 = (M_2/M_1)^{0.92}$). We will show that the situation is more complex.

Mochnacki (1981) assumed that the energy transfer rate from the primary to the secondary star depends only on the mass ratio. Liu & Yang (2000) calculated the energy transfer rate and determined its dependence on the mass ratio and on the evolutionary factor (which is defined as the ratio of the present radius and the zero-age radius of the primary component). Recently Kähler (2002a,b) examined this question with detailed numerical computations and he found the rate of the transferred luminosity to be variable in time. The transferred luminosity can vary within wide limits (see Fig. 2 of Kähler 2002b) for a contact binary. (It should be emphasized that recent theoretical internal structure models of contact binary systems are inconsistent, as was described in Kähler 2002b.)

Kalimeris & Rovithis-Livaniou (2001) found that the observed rate of energy transfer is a function of the luminosity of the secondary. We examined empirically the energy transfer rate and found a simple relation between the luminosity and mass ratios and the amount of the transferred luminosity.

It was pointed out to us by the referee that the width of the neck is determined by the fill-out factor (which measures the degree of contact) and W type systems have thinner necks than A-type systems (see e.g. Mochnacki 1981; this is confirmed in our sample) and accordingly have higher transfer rates and luminosity ratios than A-type systems (Figs. 1 and 2). One might expect that the thickness of the neck determines the amount of transferred luminosity because more luminosity can be transported through a thicker neck, but this proves not to be the case.

The reason for this paradox is not known yet. Note that Kähler's (2002b) numerical simulation showed that in general the degree of contact varies in phase with the transferred

Fig. 2. Transfer parameter β vs. bolometric luminosity ratio λ . Symbols are the same as in Fig. 1. The solid line describes the minimum rate of transfer parameter. Note that most systems are on this line. Systems which have $q > 0.72$ (H subtype systems) are far from this envelope. Dashed lines correspond to different values of α (see text for further explanation) and the numbers show the corresponding values.

luminosity (compare Figs. 1 and 2 in Kähler 2002b). The solution of this discrepancy between theory and observations requires further studies.

2. The catalogue

There are two recent catalogues of contact binary stars (Maceroni & van't Veer 1996; Pribulla et al. 2003). The catalogue of Maceroni & van't Veer (1996) lists 78 systems, while the catalogue of Pribulla et al. (2003) contains 361 field contact binaries. The contents of these and our catalogues are shown in Table 1 for comparison.

If a recent ephemeris was not available we repeated the ephemeris given in GCVS (Kholopov et al. 1998). Note that dimensionless surface potentials are generally assumed to be equal for the two components – the exceptions are noted in the catalogue. Gravity darkening exponents, albedos and limb-darkening coefficients were generally fixed by the modellers, with some exceptions, and these exceptions are noted in the catalogue. The catalogue together with its references is given in Table 2.

For homogeneity, we primarily collected results of LC-solutions carried out by any version of the Wilson–Devinney code; however, in order to increase the sample, the results of modeling done with the BYNSIN Code (Vinkó et al. 1992) was also included, but these are listed in a different table (see Table 3¹).

¹ Tables 2 and 3 are available electronically only at the homepage of the Konkoly Observatory via the URL: <http://www.konkoly.hu> and at EDP Sciences.

Table 1. Comparison of contents of different catalogues of contact binaries. MV96: Maceroni & van't Veer (1996), PKT03: Pribulla et al. (2003).

Content	MV96	PKT03	This study
Photometric mass ratio	X	X	X
Spectroscopic mass ratio	X	X	X
Average fractional radii	X		X
Temperatures of the components	X	X	X
Semiamplitude of V_{rad} of the primary star	X		
Magnitude of the O'Connell effect	X	X	
Absolute dimensions ($R_{1,2}$, $M_{1,2}$, $L_{1,2}$ of the components)	X		
Angular momentum of the system	X		
Ephemeris (epoch and period)		X	X
Number of available minima observations		X	
Information about period change		X	
Code which was used for light curve solution		X	
Inclination		X	X
Fillout factor		X	X
Spectral type and distance		X	
Range of variability		X	
$(m_1 + m_2) \sin^3 i$		X	
Fractional luminosity of the primary			X
Fractional luminosity of the third body			X
Dimensionless surface potentials			X
Spot parameters			X
Gravity darkening exponents			X
Albedos and limb darkening coefficients			X

3. Relation between astrophysical quantities

3.1. Subtypes of contact binaries

In 1965, contact binary stars were divided into two sub-types: A-type systems (the larger star is the hotter one) and W-type systems (the smaller star is the hotter one) (Binnendijk 1965). Later Lucy & Wilson (1979) introduced the class of B-type systems which are systems in geometrical contact, but not in thermal contact and therefore there are large surface temperature differences between the components. In this study we call B-type systems those systems that have a surface temperature difference between the components of 1000 K or larger. Note that B-type systems are sometimes referred to as PTC (Poor Thermal Contact) systems (e.g., in Rucinski & Duerbeck 1997).

We do not use the term “E(arly)-type systems” which would mean contact binaries of O, B and A spectral types. In Figs. 1–4 they do not have any special position unlike H-type systems. This conclusion is in agreement with Kähler's (1989) remark: from an observational viewpoint there is no difference between early and late spectral type systems.

In our sample we have 45 A, 13 B, 24 H and 77 W subtype systems.

Fig. 3. Transfer parameter β corrected for the mass ratio vs. bolometric luminosity ratio λ . Symbols are the same as in Fig. 1. **Fig. 4.** Transfer parameter excess $(\beta - (1 + \lambda)^{-1})$ vs. mass ratio. Symbols are the same as in Fig. 1. The solid line is the excess = $0.52q^{4.1}$ fit.

3.2. Mass ratio – luminosity ratio relation

Several systems were excluded from the subsequent analysis because some authors did not publish all parameters of the light curve fitting. If the fill-out factor was not given, we computed it with the BinMaker 2.0 software (Bradstreet 1992) from the mass ratio and surface potential, but other missing results could not be reproduced by us. For this reason these systems were omitted from the sample.

The temperatures of the components were known from the modelings, therefore we could calculate the bolometric luminosity ratios from the measured ratios in the V band via $\lambda = (L_2/L_1)_{\text{bol}} = (L_2/L_1)_V 10^{0.4(\text{BC}_1 - \text{BC}_2)}$. The bolometric luminosity ratio vs. mass ratio ($q = M_2/M_1$) is shown in Fig. 1. (The bolometric correction was calculated from Flower's (1996) tables.)

The subtypes of W UMa-stars are located in different regions in this diagram. W subtype systems have larger luminosity ratio than A subtype systems at a given mass ratio. This is natural because the radius ratio is proportional to $q^{0.46}$ at

a given mass ratio², the temperature ratio T_2/T_1 is larger in W systems and hence the luminosity ratio is higher in W than in A systems.

Both A and W subtype systems have larger luminosity ratios than any B subtype systems. A line represents the mass-luminosity relation if the components were main-sequence stars (in this case $\lambda = q^{4.6}$). Note that all systems are above this line (with three exceptions: W Crv and LP UMa, and the B-type system HW Per). B-subtype systems are located between A/W systems and the $\lambda = q^{4.6}$ line.

Another interesting fact is that A-type systems are relatively rare objects at high mass ratios, but W-type systems show the completely opposite behaviour: they populate the region of higher mass ratios, and there are only a few W-type systems below $q = 0.3$. This effect was discovered by Maceroni et al. (1985) while studying properties of W UMa stars based on a sample containing 42 systems. We confirm their result using a much larger sample.

3.3. Energy transfer

It is clear from Fig. 1 that different mass ratio – luminosity ratio relations exist for the case of different subtypes. The systems also show a remarkable diversity in the λ - q plane. This is not due to the scatter of data. The luminosity ratio can be determined with an accuracy of 1–2% or better, while the precision of the mass ratio measured photometrically is generally better than a few per cent. In general, spectroscopically and photometrically determined mass ratios show a good agreement (Maceroni & van't Veer 1996; Pribulla et al. 2003). The diversity can be due to the different rate of luminosity transferred from the primary to the secondary star. (Kähler 2002b suggested such an effect: in the same contact binary the transferred luminosity varies with time. At a given mass ratio this can cause a diversity in luminosity.)

We studied the energy transfer rate by the introduction of the transfer parameter. It was defined as

$$\beta = \frac{L_{1,\text{observed}}}{L_{1,\text{ZAMS}}}. \quad (1)$$

It is easy to show that β can be computed as

$$\beta = \frac{1 + q^{4.6}}{1 + q^{0.92}(\frac{T_2}{T_1})^4} \quad (2)$$

or

$$\beta = \frac{1 + \alpha \lambda^{5.01}}{1 + \lambda} \quad (3)$$

where $\alpha = (T_1/T_2)^{20.01}$. The transfer parameter was plotted against the luminosity ratio (Fig. 2), and a good correlation was found for all systems except those which have $q > 0.72$ (they are marked by a different symbol in the figures). The envelope

is due to the minimum rate of the transfer parameter at a given luminosity ratio, so it is

$$\beta_{\text{envelope}} = \frac{1}{1 + \lambda}. \quad (4)$$

It is interesting that systems with $q > 0.72$ are far from this envelope (hereafter we will call these systems H-systems, meaning high mass ratio systems) but other subtypes are close to it.

To quantify the deviation from Eq. (4) we calculated the transfer parameter excess, which was defined as the difference between β and the envelope given by Eq. (4). The excess was found to be a function of the mass ratio (Fig. 4) and a fit showed that the excess is proportional to $0.52(\pm 0.02)q^{4.1(\pm 0.1)}$.

The systems should increase the luminosity transfer from the primary to the secondary to equalize the surface temperatures if the mass ratio is lower, but the situation is more complex than this. Note that Kalimeris & Rovithis-Livaniou (2001) found that the transferred luminosity is a function of the luminosity of the secondary. Our results showed that the rate of the transferred luminosity is not related only to the luminosity ratio but is a function of the mass ratio, too.

In Fig. 2 the β – λ curves for different α values ($\alpha = 0.25, 0.5, 1.0, 2.0, 4.0$ and 8.0) are also shown. (Note that α depends strongly on the surface temperature ratio: $T_1/T_2 = 1.11$ corresponds to $\alpha \approx 8$.) The α values of A, B and W subtype systems generally are close to 1 while H subtype systems have a larger temperature ratio. If the mass ratio is close to 1, we would expect that the two components have very similar features and hence that their surface temperature ratio (and α) is close to 1. In reality we found the opposite case: at large mass ratios the surface temperatures can be very different.

From the definition of the transfer parameter it is clear that the amount of transferred luminosity is $\Delta L = (1 - \beta)L_1$. Substituting $\beta = (1 + \lambda)^{-1} - 0.52q^{4.1}$ we found that $\Delta L = (\frac{\lambda}{1+\lambda} - 0.52q^{4.1})L_1$.

Figure 3 shows the corrected β ($\beta_{\text{corr}} = \beta - 0.52q^{4.1}$) against bolometric luminosity ratio. The correlation between them is very good, confirming our conclusion that the transferred luminosity is a function of the mass and luminosity ratios.

4. Summary

The results of this research note can be summarized as follows.

- 1 We compiled a catalogue of light curve solutions of contact binary stars. The catalogue contains LC-solutions of 159 systems.
- 2 We found that there is no strict mass ratio – luminosity ratio relation for contact binary stars. Such a relation was suggested by Lucy (1968a), but Kähler's (2002b) results indicated large luminosity ratio variations with small mass ratio variations, which are practically unobservable by light curve modeling. Kähler's model does not contradict our results.
- 3 The energy transfer from the primary star to the secondary star was found to depend on the mass ratio and the luminosity ratio. In H systems the energy transfer rate is less efficient than in other type ones at a given luminosity ratio.

² This relation was found by Kuiper (1941), and it is a natural consequence of the Roche-geometry assumption in light curve models. We also checked this relation applying the catalogue data, and $(R_2/R_1) = q^{0.459 \pm 0.003}$ was found.

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