CONTACT BINARIES

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Abstract. Observational statements about close and contact binaries are compared with the theoretical consequences of assuming that contact binaries have a common convective envelope. It is concluded that such contact systems cannot be in thermal equilibrium, and that the inefficiency of convective heat transport in the common envelope must be allowed for. Even so, current theory seems to predict about equal numbers of contact and semidetached systems of short period, in conflict with the observations.

I shall begin by outlining the scheme of photometric classification of eclipsing variables. Starting from a general inspection of the light curves, one can apply successive criteria as follows:

(a) Is the light curve convex upwards, without flat portions, between minima?
If no, we have an Algol (EA) system.
If yes, then:

(b) We have an 'elliptical' system. In this case, are the successive minima nearly equal in depth?
If no, we have a β Lyr (EB) system.
If yes, then:

(c) We have a W UMa (EW) system. In this case, is the deeper minimum a transit? (Spectroscopy needed here.)
If no, we have a W-type system.
If yes, we have an A-type system.

Table I shows some general properties of the three photometric classes. The numbers in the fifth row also give a good idea of the relative space densities of the EB's and EW's, but not between these and the EA's (observational selection). A particularly important point to note is the complete dominance of the period range $0.2 < P < 0.4$ days by the EW's.

Quantitative analysis of the light curves indicates in the case of the EW's an extreme

TABLE I
General properties of the three photometric classes

	EA	EB	EW
Prototype	Algol	β Lyrae	W UMa
Periods	$P > 0.4$ days	$P > 0.4$ days	$0.2 < P < 1$ day
Spectra	B8–M1	B8–G3	F0–K0
Number >12 mag	~1000	~200	~100

	EW A-type	EW W-type
Hotter component	Primary (very slightly)	Secondary (very slightly)
Mean period	0.5 days	0.3 days
Period changes	Not detectable	Yes
Contact	Fairly deep	Shallow

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closeness or actual physical contact of the components. The degree of contact (or non-contact) found for a given system depends on the assumed light distribution over each of the stellar surfaces. Spectroscopic evidence, not contradicted by the photometry, indicates mass ratios for the EW's different from unity in all cases investigated so far.

This last observation makes the nearly-equal light curve minima a noteworthy property. For it indicates roughly equal mean surface brightnesses for the two unequal mass components, implying an 'apparent' violation of the main-sequence mass-luminosity relation.

Although such a violation could be of evolutionary origin, there is evidence that at least a proportion of the EW systems are of age zero:

(a) the presence of at least two systems (TX Cnc and M67-33) in galactic clusters several magnitudes below the turn-off points;

(b) the existence of field systems with spectral types as late as K0.

Noting that the spectral range of the EW systems corresponds to the range of stars with outer convective zones, Lucy (1968) introduced the model of a contact binary surrounded by a common convective envelope to represent these stars. Due to the high efficiency of convective mixing, such an envelope was assumed to have a single value for the entropy throughout, thus leading to similar atmospheres for the components, and, in particular, to equal mean surface brightnesses. The 'apparent' departure from the mass-luminosity relation was on this picture merely due to the flow of convected energy between the components, necessary for entropy equalisation, leading to a cooling of the primary and a heating of the secondary.

The two constraints defining the Lucy model were taken to be

(1) $\Delta S = 0$ (no entropy difference between envelopes of components);

(2) both components of age zero.

Now, prior to the investigations of Rucinski (1973, 1974), which will be described below, it seemed quite natural that to the above conditions a third be added, namely

(3) thermal and mechanical equilibrium;

and we shall take these three conditions as prescribing the original or 'Lucy A' model.

Under the above assumptions solutions were found for unequal component masses provided the sum of the masses satisfied

$$M_1 + M_2 = 2.5 M_\odot$$

a restriction too severe to enable this model to represent the large range in spectral types of the observed EW systems. This model met however with initial success due to the relatively good agreement with the observed light curves, essentially a consequence of condition (1) above.

Investigations by Rucinski (1973, 1974) of the period changes of EW systems suggested however that the W sub-class might not in fact be in a state of thermal equilibrium, and this development led Lucy (1975) to discard the equilibrium condition (3) as being essential to his models. This relaxation of the model specifications made it possible to construct systems with a range of total masses and therefore of spectral types.

Such systems, which we shall call 'Lucy B' systems, are unable, by virtue of their total masses being unequal to $2.5 M_\odot$, to find any equilibrium in contact; they undergo a form of 'secular evolution', alternately making and breaking contact in a vain attempt to achieve equilibrium. Lucy was only able to estimate the duration of these two phases, but more detailed calculations show that both the 'contact on' and 'contact off' phases last for

10^7 yr. The making and breaking of contact occurs as a result of mass transfer in alternating directions, and would thus be associated with period changes.

In Table II we summarise the principal characteristics, advantages and drawbacks of the Lucy A and Lucy B models.

I shall next explain what I mean by bad light curve behaviour. Due to the successive making and breaking of contact, a Lucy B system will alternately exhibit EW (during the on phase) and EB (during the off phase) light curves. Now since, as mentioned above, these phases would be of about equal duration, and since the total period changes due to this secular evolution are relatively small, it follows that, on the basis of this model, for every EW system of given period we should expect to see one EB system. Thus one could just possibly assign the very small number of definite age zero cluster systems to the EW phase of the Lucy B model; however one cannot apply this same explanation to the field systems since the chance of observing ~50 systems with $P < 0.4$ days during the on (EW) phase without seeing a single one in the off (EB) phase must be minute.

A possible clue to the reason for the inadequate photometric behaviour of the Lucy B model comes from the model's prediction of a correlation between the direction of period changes and the relative brightnesses of the two components, both being dependent on the mass transfer direction. An investigation of the W-systems reveals no such correlation however. The interpretation of this could be either that the period changes documented by Rucinski are not secularly significant (private communication, Herczeg) or else that the period changes are secularly real but that the actual EW systems never break contact. For it is the break in contact which cuts off the energy supply to the secondary through the common envelope, thus leading to the unwanted sharp change in the form of the light curve.

To retain contact, it is necessary to depart from the $\Delta S = 0$ condition (condition (1) above) or else to depart from the age zero condition (condition (2) above). We shall consider both alternatives.

The departure from the $\Delta S = 0$ condition is a physically reasonable step since in practice convection only has a finite efficiency. One then finds that, in contrast to the case $\Delta S = 0$ (which in this respect is singular) the case $\Delta S \neq 0$ does permit of a contact equilibrium; this equilibrium can be stable or unstable, depending on the assumed physics of convection and on the stellar structure parameters (Hazlehurst, 1974). Thus, explicit inclusion of a convective efficiency parameter offers the prospect of reducing the violence of the secular swings and of avoiding the photometrically undesirable break in contact.

TABLE II

The principal characteristics, advantages and drawbacks of the Lucy A and Lucy B models

Lucy A	Lucy B
Assumptions (1) and (2) plus thermal equilibrium	Assumptions (1) and (2) only
Solutions only for $M_1 + M_2 = 2.5\,M_\odot$	Solutions for $M_1 + M_2 \neq 2.5\,M_\odot$
No systems of types F5–K0 can be constructed	Solutions can be constructed for all relevant spectral types
Good light curve characteristics	Light curves behave badly

Calculations of such secular evolution by conventional stellar evolution methods would be extremely time-consuming due to the need to compute both stars simultaneously. We have therefore, using the Hamburg Henyey programme, adopted the alternative approach of investigating each star separately in response to arbitrarily prescribed variations of mass and energy transfer, so that the actual secular evolution can be subsequently synthesised from these individual responses. One interesting result is that these response functions are closely related to the secular modes of Aizenman and Perdang (1971, 1972).

It must however be admitted that there is to date no satisfactory age-zero model for the EW systems. We must therefore consider the alternative hypothesis, that most field systems are evolved. Apart from special systems such as ϵ CrA which could be in a relatively late stage of evolution (Tapia and Whelan, 1975) the EW's are main sequence objects; however even this modest degree of evolution is sufficient to permit the construction of 'permanently EW' systems i.e. the $\Delta S = 0$ condition does not now cause a break of contact.

This evolutionary picture does however encounter several difficulties. Firstly, the systems of spectral type as late as K0 cannot have evolved to any significant extent within the lifetime of the galaxy. Secondly the precursors of the EW's with periods $0.2 < P < 0.4$ days cannot be close non-contact pairs because these would show up as EB's with similar periods, and such EB's are not observed; on the other hand if the predecessors were rather wider pairs their lifetimes would be nuclear before contact and thus appreciably greater (see Hazlehurst and Meyer-Hofmeister, 1973) than the lifetimes of the contact descendents. This again appears difficult to reconcile with the relative numbers of EW's, EB's and EA's.

In conclusion, it is noteworthy that the two alternative hypotheses (age-zero and evolved) imply, indeed beg, the copious presence of EB systems with periods $0.2 < P < 0.4$ days; and, as far as I know, not a single example of such a system has ever been found.

References

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DISCUSSION

Eggleton: Isn't there also another assumption that might be relaxed, namely constancy of angular momentum? If there were steady angular momentum loss on about the same time scale as the thermal time of the secondary, might you not reduce the off state relative to the on state?

Hazlehurst: You certainly would – but you would reduce the whole lifetime of the system. By taking away angular momentum in a time scale of 10^7 yr, the system would show a good light curve during its whole (brief) life; by taking away in 10^8 yr, I would guess you would not substantially improve the on/off ratio. Basically, you must destroy the system before it has time to go from on to off.

Rucinski: Have you deliberately skipped the four systems in NGC 188? They seem to be about 3 mag below the turn-off point of this cluster.

Hazlehurst: No – I just thought TX Cnc was a more obvious zero-age case, being 4 mag below the turn-off point of Praesepe. The NGC 188 systems are dispersed in their magnitudes, but some could be age-zero.

Lynden-Bell: Suppose you have two beakers of water, one containing heavy water and one light water, but in contact near the top. Heavy water flows over the contact and displaces light water that flows back. Thus a high entropy star will show a double exchange of mass in steady flow. The diffusion of entropy at the contact of the two fluids will regulate the rate of flow after the initial exchange. I do not understand why the basic models discussed are not of this type. There could be models of steady flow with no net mass exchange.

Hazlehurst: I think diffusion would occur at the entropy interface in the secondary so that you would gradually get a light-heavy (i.e. hot-cool) gradient across the top. Such a gradient would be necessary to maintain the circulation and would give the stars an 'unwanted' colour difference.

Paczynski: In Lucy's model (1975) accretion energy is not taken into account. Can it help to rise the temperature of the secondary during the off phase?

Hazlehurst: Not really – it might lift the temperature by 100 deg or 200 deg – well below what is required.

Van't Veer: It is impossible to construct zero age models and you are looking for models of evolved stars. Why cannot the W UMa stars be unevolved to the extent that they have not yet arrived at the main sequence?

Hazlehurst: Consider TX Cnc in Praesepe. If this system is as old as the cluster (3×10^8 yr) the secondary of $0.6\,M_\odot$ must already have completed its pre-main-sequence evolution.

Shu: I have developed exactly the same idea as Lynden-Bell and believe that the answer to this problem is to introduce a contact discontinuity on the star with the 'heavy water'. The 'light water' sits above both cups. At Berkeley, we are in the process of constructing ZAMS models of this type. The problem may not be having enough models, but having too many.

Wilson: It seems that the contact cannot be broken for very long because, at the instant that contact is broken, one has a configuration which is morphologically identical to that of the semi-detached configuration of a binary in the rapid phase of mass transfer. Therefore as soon as the secondary ceases to provide a net flow of mass to the primary, at the breaking of contact, immediately a large flow in the reverse direction will begin, and it seems that this must re-establish contact. Therefore it is very difficult to see how the intervals of broken contact can be very long in duration, and this would account for the lack of observed semi-detached systems in the appropriate period range. In fact, probably this argument can be extended to prohibit breaking contact at all.

Hazlehurst: I would like to emphasise that irrespective of convection theory, certain basic problems remain. If convection is efficient, the stars break contact and have a bad light curve. If it is inefficient, the stars remain in contact and have a bad light curve, since there is a difference in the surface temperatures of the components.