IX. CONTACT BINARIES

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THEORIES OF CONTACT BINARY STARS

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ABSTRACT

We review and contrast two current theories for the structure of contact binary stars: discontinuity theory and thermal relaxation oscillation theory. We find that the two theories are complementary with the crucial theoretical issue to be resolved being the secular stability of the temperature inversion layer. Critical observational tests remain to be performed.

1. INTRODUCTION

Today I wish to review a fairly controversial subject, namely, current theories of contact binaries. There are two main contending schools of thought, which Lucy and Wilson (1979) have conveniently labelled the DSC and TRO theories. DSC, or discontinuity theory, was advanced principally by Shu, Lubow, and Anderson (1976, 1979), but some elements of it had already appeared in the earlier work of Biermann and Thomas (1972) and Vilhu (1973). TRO, or thermal relaxation oscillation theory, was advanced by Lucy (1976) and was also worked upon by Flannery (1976) and Robertson and Eggleton (1977).

Two conceptually distinct and yet ultimately related issues underlie the discussions. I shall refer to them as:

(a) Kuiper's paradox, which is the lowest order issue, concerns the structure of contact binaries. How can the structure of two stars in physical contact be made compatible with the requirements of the Roche geometry?

(b) Lucy's paradox, which is the next order issue, concerns the luminosity redistribution in contact binaries. How do the luminosities emerging from the interiors get transformed to become the surface brightness distribution characteristic of contact binaries?

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The ordering parameter is the actual energy flux F which is required to carry the heat out of the interior divided by the hypothetical enthalpy flux $\rho h a_s$ which would result if matter were to flow at the speed of sound a_s:

$$\delta = F/\rho h a_s \ . \tag{1}$$

The value of the parameter δ at the base of the common envelope (just above the inner critical surface) must be much less than the ratio of the depth of the common envelope, H, to the orbital separation, D, if the system is to achieve the good thermal contact required by the light curves of W UMa stars. Indeed, the light curve theory of Anderson and Shu (1977) derived from this assumption is virtually identical, except for minor details, to the theory of Lucy (1968b) which is well known to give a good fit to the observations. Models of ZAMS contact binaries with filled fractions $f \sim 0.5$ show δ to be $\sim 10^{-8}$ in models of low total mass and to be $\sim 10^{-5}$ in models of high total mass (Lubow and Shu 1977, 1979). There is some observational evidence that the filled fraction f is systematically less than 0.5 in the former contact binaries (Lucy 1973, Rucinski 1973), and this fact may be related to the issue of the maintenance of the temperature inversion layer (§ 5).

2. KUIPER'S PARADOX

Kuiper (1941) argued that the sizes of (what we now know to be) isolated main sequence stars are generally incompatible with the mechanical requirements of the Roche geometry for contact binaries unless the two stars are identical. A paradox arises because W UMa stars are main sequence stars which have mass ratios typically about 0.5 (Lucy 1968a).

Shu, Lubow, and Anderson (1976, 1979) have extended Kuiper's paradox to nonspherical stars of arbitrary amounts of core evolution. Given the masses of the two stars, M_I and M_{II}, and the orbital separation, D, plus the zero-order equations of stellar structure, we find that, except for special eigenvalue solutions of little physical interest, there are too many boundary conditions to satisfy if all thermodynamic variables are continuous across the inner critical surface. This extension brings us to the two proposed escapes from Kuiper's paradox: DSC theory and TRO theory.

3. THE CENTRAL FEATURES OF DSC THEORY

To lowest order in δ, horizontal and vertical hydrostatic equilibrium in the corotating frame requires the stellar fluid to be barotropic, i.e., the pressure P and the density ρ to be functions only of the effective potential Φ. In DSC theory, P is continuous across the inner critical surface but ρ (and the temperature T) need not be. In particular, Shu, Lubow, and Anderson (1976) argued that Kuiper's paradox can be resolved by allowing the specific entropy s (and the temperature T) below the Roche lobe of one of the stars be less (for mechanical stability) than the corresponding value at the base of the common envelope (contact discontinuity). To satisfy energy conservation, the thermodynamic variables are continuous across the Roche lobe of the other star, but their derivatives are not (weak discontinuity).

DSC theory applies to contact binaries of all masses and stages of stellar evolution as long as synchronism is maintained and $\delta << 1$ at the base of the common envelope. The results of Lubow and Shu (1977, 1979) for ZAMS contact binaries show:

(a) ZAMS contact binaries of low total mass have common convective envelopes, with the contact discontinuity residing on the secondary (star II). Thus, the specific entropy of the convection zone beneath star II's Roche lobe is less than the specific entropy of the common convective envelope.

(b) ZAMS contact binaries of intermediate total mass have common radiative envelopes, with the contact discontinuity residing on the secondary. Thus, the specific entropy of the convection zone beneath star II's Roche lobe is less than the specific entropy at the base of the common envelope.

(c) ZAMS contact binaries of high total mass have common radiative envelopes, with the contact discontinuity residing on the primary. Thus, the specific entropy of the <u>induced</u> convection zone beneath star I's Roche lobe is less than the specific entropy at the base of the common envelope.

Our studies showed a contact discontinuity to be <u>sufficient</u> to

(a) resolve Kuiper's (1941) paradox,

(b) explain Eggen's (1967) period-color relation for W UMa stars,

(c) account for the existence of contact binaries with common radiative envelopes (Rucinski 1973, Leung 1980).

Shu, Lubow, and Anderson (1979) also claimed that a contact discontinuity is generally also <u>necessary</u> for all viable theories of contact binaries (with synchronous spins), with or without evolved cores, and with or without thermal equilibrium.

4. THE CENTRAL FEATURES OF TRO THEORY

To see that a contact discontinuity would also naturally arise even in TRO theory, let us review Lucy's (1976) model. I shall confine my remarks to Lucy's version of TRO theory because only Lucy's version uses commonly accepted zeroth-order equations of stellar structure (cf. Flannery 1976 and Robertson and Eggleton 1977).

Lucy's theory applies only to contact binaries of low enough total masses to have common convective envelopes. To motivate his model in the context of what we have discussed so far, let us imagine what would happen if we initially force the specific entropy in the outer convection zones of the equilibrium model of low total mass in Lubow and Shu (1977, Fig. 2) to have a single value above and below the inner critical surface. The imposition of a higher value of s beneath the Roche lobe of star II would lead to an expansion of those layers. To compensate so that star II can still fit inside its Roche lobe, we would need to decrease the volume occupied by the deep radiative interior. Lucy (1976) performs this task elegantly by artificially lowering the nuclear energy generation rate in the secondary's core for time $t < 0$. For $t > 0$, the energy generation rate is allowed to have its natural value. The overcompressed secondary responds by expanding and transferring mass to the primary. With a uniform value imposed for s in the outer layers, the mass ratio is then determined as an eigenvalue of each subsequent instant of time t. Mass transfer from the less massive star to the more massive with the conservation of total angular momentum increases the orbital separation, which leads eventually to the loss of contact (see Fig. 3 of Lucy 1976).

When contact is lost, the secondary detaches from its Roche lobe and shrinks toward its naturally smaller ZAMS state for isolated stars. In the meantime, the primary tries to expand toward its naturally larger ZAMS state for isolated stars. Because the primary is then constrained to fill its Roche lobe, this expansional tendency leads to mass transfer from the lobe-filling primary to the detached secondary. This decreases the orbital separation and eventually causes the two stars to come once again into contact. Lucy (1976) ends his formal calculations just before contact is reestablished with the comment that hydrodynamic events would accompany the formation of the contact configuration. Thus Lucy's calculations end with the <u>hope</u> that an oscillatory cycle would ensue.

Let us pursue in our imagination what the subsequent events might be. At the instant of contact, the primary has a higher outer value of the specific entropy (proportional to -log K in Table 1 of Lucy 1976) than the secondary. The outer layers of the primary, being therefore buoyant, would flow to cover the secondary and to form a common convective envelope. The entropy of this outer convective envelope would continue to maintain a relatively high value because it is determined by photospheric boundary conditions. The entropy of the convection zone beneath the Roche lobe of the secondary would maintain a lower value (i.e., the secondary would maintain a <u>contact discontinuity</u>) for at least the thermal timescale required to heat up this layer. The crucial difference in <u>opinion</u> of DSC theorists and TRO theorists centers precisely on this issue. DSC proponents <u>speculate</u> that after initial transients have died away, the contact discontinuity so established could continue to be maintained by fluid flow for <u>nuclear</u> timescales. TRO proponents <u>speculate</u> that the contact discontinuity so established cannot be maintained and would heat up the interior of the secondary -- presumably to establish an <u>oscillatory cycle</u>. Let us merely note here that even if TRO theory is correct, the original model must be modified so that the oscillations take place about a state with a contact discontinuity. In other words, the zero-order models of DSC theory constitute the equilibrium states about which TRO models oscillate.

5. LUCY'S PARADOX

From the above discussion, we see that the crucial issue boils down to whether the equilibrium models of DSC theory are secularly stable. We believe that this issue is intimately related to the next order issue: Lucy's paradox. A generalization of Lucy's (1968a) arguments which lead to this paradox is given below (see also Fig. 2 of Shu, Lubow, and Anderson 1979). To lowest order in δ, the stellar fluid is barotropic with all thermodynamic variables functions only of the effective potential Φ. For such a barotorpic state, the luminosities perpendicular to equipotentials can be shown to satisfy:

$$L_{rad} \propto -dT/d\Phi, \; L_{conv} \propto (-ds/d\Phi)^{3/2}, \; L_{fluid} = 0, \tag{2}$$

with known proportionality constants. Applied to an equipotential surface B which lies just above the inner critical surface, equation (2) yields a definite ratio of the luminosities L_I' and L_{II}' which enter the common envelope on the sides of stars I and II. In general, the luminosities L_I and L_{II} which cross the equipotential surfaces W and C just below the Roche lobes of stars I and II will not equal L_I' and L_{II}'. (For example, in thermal equilibrium L_I and L_{II} equal the nuclear energy generation rates in the cores, which are unrelated to the distribution laws [2] required by the barotropic state above the inner critical surface.) If the surfaces W, C, and B can be chosen to lie arbitrarily closely (as in non-DSC theories), then the conversions $L_I \to L_I'$ and $L_{II} \to L_{II}'$ would require infinite horizontal fluid fluxes (a finite luminosity redistribution through a vanishingly small cross-sectional area). It is precisely the realization that the energy carrying capacity of fluid flow is finite (although very large) that led Shu, Lubow, and Anderson (1976, 1979) to propose the following resolution of Lucy's paradox:

The uneven heating of the base of the common envelope by the emergent interior luminosities leads to a spatially thin baroclinic layer which straddles the inner critical surface. To lowest order in δ, the thin layers which sandwich the inner critical surface are modelled by a contact discontinuity and by a weak discontinuity. To next order, the fractional thickness of these layers can crudely be estimated to be of order $\delta^{2/5}$, with fluid flow hypothesized to maintain the "discontinuity" structures in a quasi-stationary state.

The topic of the long-term maintenance of the temperature inversion layer excites all the present controversy. The detailed arguments are too complex to discuss here; let me merely state here the crucial issues and refer the reader to the original discussion in the literature. How does the long-term maintenance of the temperature inversion layer work in theory (cf. Hazlehurst and Refsdal 1978)? The basic requirements involve a "heat engine" and a "refrigerator" (Shu, Lubow, and Anderson 1979). Can it work in principle (cf. Papaloizou and Pringle 1979)? Yes, the principle involves a locally time-dependent form of "negative eddy conductivity" (Shu, Lubow, and Anderson 1979, 1980). Why should it work in detail (cf. Smith, Robertson, and Smith 1979)? Because the zero-order theory allows three independent parameters (taken for convenience to be M_I, M_{II}, and D), the thickness of the common envelope can be adjusted to yield the critical value of δ at the base of the common envelope required for the "heat engine" to drive the "refrigerator" by exactly the right amount to maintain the transition layer in a steady state for given total mass $M_I + M_{II}$ and total angular momentum J (Shu, Lubow, and Anderson 1980). The likelihood of solutions satisfying this requirement is large because the possible range of δ corresponding to the range of filled fractions from f = 0 to f = 1 is large. This last conjecture is important for answering the objection of Lucy and Wilson (1979) that DSC models do not provide unique evolutionary sequences. Would the proposed solution be secularly stable? Shu, Lubow, and Anderson (1980) have given a physical argument that the solution would be secularly stable, but more detailed calculations are needed.

6. SUMMARY

Although DSC and TRO theory seem superficially to be quite distinct, they are actually complementary. Without proving secular instability of the temperature inversion layer, TRO theory remains incomplete because the existence of a <u>complete</u> cycle has not yet been demonstrated with standard assumptions. On the other hand, without proving secular stability, the long-term maintenance of the contact discontinuity of DSC theory remains an unproven <u>assumption</u>. Lucy and Wilson (1979) argue that observations favor the TRO theory although the evidence at present is not yet decisive. More specific comparisons will become possible after the DSC theory is made complete by a (perhaps semi-empirical) evaluation of the critical value of δ at the base of the common envelope for a given total mass and angular momentum. We believe that critical observational tests will come in two different directions:

(a) Specific predictions by TRO and DSC theories concerning filled fractions, ratios of systems in the two phases of relaxation oscillation, and the properties of contact binaries with common radiative envelopes.

(b) Evolutionary sequences: Webbink (1977) has claimed that TRO theory requires contact binaries to evolve into single stars. We have hopes that the complete DSC theory would ultimately allow the evolution of W UMa stars into cataclysmic variables (Kraft 1965).

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DISCUSSION FOLLOWING SHU

Sugimoto: In the region of the temperature inversion near the contact discontinuity, there should be a great jump in entropies. Is convection transporting the correct amount of energy across it which is coming from the deep interior of the star?

Shu: The "correction" in the temperature inversion layer arises not from any internal instability but from being driven from above (by "dredging").

Sugimoto: When the contact is realized as a result of rapid mass transfer, the primary star below the common envelope is greatly out of thermal equilibrium and much mass outflow, say $10^{-4} M_\odot yr^{-1}$, is required in order to keep the radius of the star smaller than the critical Roche lobe, as was seen in the case of SV Cen. Are the theories discussed by you applicable even in such cases of mass transfer, or does such a case require a third theory?

Shu: I don't know. It depends on how badly out of thermal equilibrium is the deep interior, I would guess.

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van 't Veer: Your computations are based on the hypothesis of conservation of angular momentum. However it becomes more and more evident from the reports we heard this morning and yesterday that for solar-type binaries great angular momentum losses must occur. So I believe that your and Lucy's models are not valid for the majority of contact binarie

Shu: Our computations are for equilibrium configurations; we did not consider the effects of evolution.

Wilson: What does DSC presently say about the marginal contact of the W-type systems?

Shu: If there really is a "magic value" for delta, say 10^{-5} or so, low-mass contact binaries would have f considerably less than 0.5 while high-mass contact binaries would have f typically substantially more in contact. This is, however, a very speculative answer which requires more careful theoretical and observational considerations.

Lucy: I believe that Frank Shu has given us a fair-minded view of the current theoretical situation. In particular, I agree that the existence of the TRO cycles depends on an unproved assumption that the equal entropy condition will be re-established when the components come back into contact.

With regard to observational tests of the competing theories, Bob Wilson and I have a recent paper (Ap. J., 1979) discussing all the tests we could think of.