ON THE ONSET OF CONTACT IN EARLY-TYPE BINARIES

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ABSTRACT

A previously published model of a detached binary evolving into deep contact, under the assumption that both components fill the same equipotential surface, is tested for self-consistency. Hydrodynamic equations describing the flow between components at their interface indicate an enormous discrepancy in the magnitude and direction of the flow in the evolutionary calculation. This behavior strongly supports the view that binaries reaching contact in this way undergo a cyclic thermal instability as in many models of W Ursae Majoris systems, rather than overflowing an outer Lagrangian point.

1. INTRODUCTION

It was first shown by Benson (1970) and Yungel'son (1973) that an accreting secondary with a radiative envelope grows rapidly out of thermal equilibrium during the initial, rapid (thermal) time scale mass transfer in intermediate- and high-mass binaries. This rapid expansion typically brings the binary into contact when the secondary mass has increased only a few percent. This phenomenon has since been confirmed by many investigators (Mullen 1974; Ulrich and Burger 1976; Webbink 1976b; Kippenhahn and Meyer-Hofmeister 1977; Flannery and Ulrich 1977; Neo, et al. 1977; Packet and De Greve 1979), and is easily understood in terms of the marked increase with radius of the specific entropy within the envelope of a radiative star. When such a star accretes matter, high entropy material at the surface is buried, and must rid itself of its energy excess for the star to reach thermal equilibrium; if accretion is rapid compared with thermal relaxation in the envelope, the star cannot radiate this energy excess away, and becomes bloated and superluminous.

Several of these studies of accreting stars have attempted to follow evolution through the contact phase, imposing only the condition that the binary now fill a common equipotential surface, but neglecting

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the possibility of energy exchange independent of net mass transfer, although such energy transfer is clearly of profound importance to the structure of zero-age contact binaries, the W Ursae Majoris systems. In this contribution, one such calculation of accretion by a star with a predominantly radiative envelope is examined in detail, and the need for a non-equilibrium model for the structure of common envelopes exposed.

2. THE MODEL

A feature common to models of W Ursae Majoris systems which appeal to a large-scale circulation for energy transfer (Hazelhurst and Meyer-Hofmeister 1973; Nariai 1976; Webbink 1977b) is the existence of a potential surface within the common envelope on which pressure forces between components are balanced. A slight difference in density (or entropy) between components then leads to a slight pressure imbalance of opposite signs above and below this surface, creating conditions for a closed circulation. Whether or not this sort of circulation accounts for energy exchange in W Ursae Majoris systems, it is certainly true that the absence of pressure balance on equipotential surfaces will lead to a hydrodynamic mass flow between components.

As a test of whether the failure to insist on at least approximate local pressure balance is a serious oversight, an evolutionary sequence by the author (Webbink 1976b, first model with stream effects included) was adopted in which deep contact phases had been computed imposing only equality of surface potentials. Insistence on that condition is sufficient to determine the mass flow rate as an eigenvalue of the evolutionary problem, and it is this net mass transfer rate which we wish to compare to that obtained by an approximate solution to the hydrodynamic flow, given the common envelope structure at each state as determined by the evolutionary calculations. The model of the flow adopted is a modification of one previously employed by Webbink (1977a; Appendix), itself a variant of one by Jedrzejec (Paczynski and Sienkiewicz 1972). In the present modification, the mass flux on any equipotential surface was computed by identifying the component whose envelope pressure was higher on that surface, and allowing that material to expand freely and adiabatically to the sonic pressure, or to the pressure at the same equipotential in the companion's envelope, whichever was greater. The net mass flow is then obtained by integrating this flux, with the appropriate sign, over a surface normal to a line connecting the component centers.

The results of the hydrodynamic approximations to the mass transfer rate are compared in Figure 1 with those obtained in the simplified evolutionary treatment, Note the difference in scales. If the evolutionary calculations were self-consistent, the two estimates should agree tolerably well; in fact, there is an enormous discrepancy not only in the magnitude of the flow, but in its direction as well. Apparently,

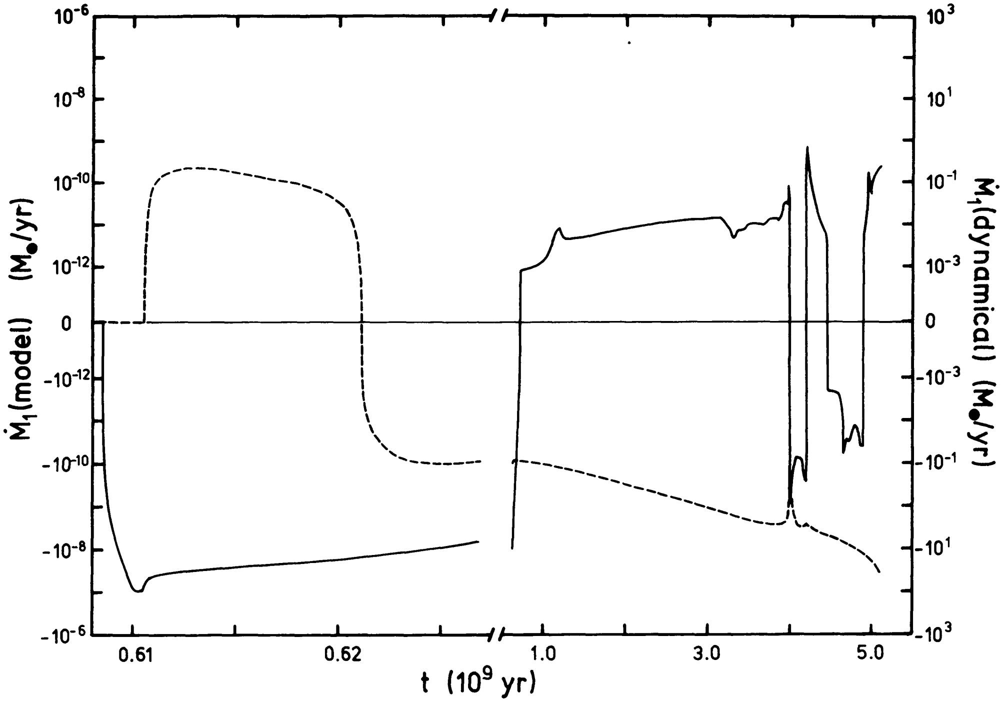

Figure 1. Comparison between mass transfer rates deduced for a binary (Webbink 1976b) evolving under the condition that both components fill the same equipotential surface (Solid line, scale at left) with rates computed for these models with a hydrodynamic model of the flow between components (broken line, scale at right).

the cooler, denser envelope of the secondary almost immediately reverses the mass flow once it expands beyond the inner critical potential. Even in the absence of any closed circulation or energy exchange, it is obviously unphysical to insist that the two components in these non-equilibrium contact systems have equal surface potentials. Even a slight difference in envelope structure between components is then adequate to produce an enormous mass flux in deep contact: in the evolutionary sequence used here, for instance, the two components never differed by more than 15 percent in effective temperature. Strong support is thus given to the stability arguments of Hazlehurst (1974). Under these circumstances, the entire subject of contact evolution in massive systems bears reconsideration.

3. CONCLUSIONS

The calculations presented here were a prime motivation for the original caution (Webbink 1976b) that the published models beyond establishment of contact were unphysical. As noted then, the structures of the two components as contact is attained bear a substantial resemblance to the corresponding phase in cyclically unstable contact binaries (Lucy 1976; Flannery 1976), and we should therefore anticipate a similar cyclic instability in these systems. With the possible exception of very massive contact binaries (Webbink 1979), their ultimate fate is probably the same (Webbink 1976a). Certainly, we should expect contact to be prevalent among evolved Case A systems, but remnants of these binaries do not appear to be present among Algol-type systems in the numbers to be expected if they did not coalesce (Plavec 1973; Ziolkowski 1976). On the other hand, if binaries evolving in Case B were initially near enough unit mass ratio that contact ensured after mass reversal, there is some possibility that these systems could yet emerge as Algol-type binaries, even if they were forced to evolve in marginal contact. This could result if the primary were actually the cooler component when contact was established, in which case energy exchange would proceed from secondary to primary, suppressing the expansion of the former while stimulating mass loss from the latter.

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REFERENCES

Benson, R.S. 1970, Ph.D. Thesis, University of California, Berkeley.
Flannery, B.P. 1976, Astrophys. J., 205, 217.
Flannery, B.P., and Ulrich, R.K. 1977, Astrophys. J., 212, 533.
Hazlehurst, J. 1974, Astr. Astrophys., 36, 49.
Hazlehurst, J., and Meyer-Hofmeister, E. 1973, Astr. Astrophys., 24, 379.
Kippenhahn, R., and Meyer-Hofmeister, E. 1977, Astr. Astrophys., 54, 539.
Lucy, L.B. 1976, Astrophys. J., 205, 208.
Mullen, E.F.F. 1974, Ph.D. Thesis, University of Florida.
Naraia, K. 1976, Publ. Astr. Soc. Japan, 28, 587.
Neo, S., Miyaji, S., Nomoto, K., and Sugimoto, D. 1977, Publ. Astr. Soc. Japan, 29, 249.
Packet, W., and De Greve, J.P. 1979, Astr. Astrophys., 75, 255.
Paczynski, B., and Sienkiewicz, R. 1972, Acta Astr., 22, 73.
Plavec, M. 1973, in "Extended Atmospheres and Circumstellar Matter in Spectroscopic Binary Systems", IAU Symposium No. 51, ed. A.H. Batten (Dordrecht: D. Reidel), p. 216.
Ulrich, R.K., and Burger, H.L. 1976, Astrophys. J., 206, 590.
Webbink, R.F. 1976a, Astrophys. J., 209, 829.
Webbink, R.F. 1976b, Astrophys. J. Suppl., 32, 583.
Webbink, R.F. 1977a, Astrophys. J., 211, 486.
Webbink, R.F. 1977b, Astrophys. J., 215, 851.
Webbink, R.F. 1979, review presented at IAU Colloquium No. 53.

Yungel'son, L.R. 1973, Nauchn. Inf. Akad. Nauk S.S.S.R., 27, 93.
Ziolkowski, J. 1976, in "Structure and Evolution of Close Binary Systems", IAU Symposium No. 73, ed. P. Eggleton, S. Mitton, and J. Whelan (Dordrecht: D. Reidel), 321.

DISCUSSION FOLLOWING WEBBINK

Budding: Can W UMa systems live as long as 10^{10} years?

Webbink: This is a question I attempted to address in a paper this January in the Astrophysical Journal. Certainly we do see W UMa systems in the very old open clusters, for example, AH Cnc in M 67, which is roughly half the age of the globular clusters. One cannot exclude that some contact binaries may arise out of the evolution of initially detached systems, but apart from that possibility, my inclination is that, though primordial contact binaries may survive 10^{10} years, the mass ratio will necessarily have become so extreme in that time (to accommodate growth of the primary), that their low amplitudes and short periods will make them very difficult to detect.

Sugimoto: Consider the case when gas is being transferred almost dynamically from the secondary star to the primary. When the gas contained in the common envelope has been transferred, new gas has to be pumped up from the secondary in order to continue the mass transfer. It requires much energy and makes the radius of the star smaller. Therefore, the mass transfer in this direction seems to stop. How far did you follow this mass transfer in your numerical computations, or in other words, how long the mass transfer continued at the rate as high as $10^{-3} \sim 10^{-1}$ $M_\odot$ yr^{-1} and how much mass was transferred in your computations? Did not you solve the initial-boundary value problem, or did you solve only the boundary value problem?

Webbink: Your points are well-taken. I should make perfectly clear that the hydrodynamic estimates of mass flow rates are indeed made by treating the so-called evolutionary sequence of models as a sequence of initial-value problems; these estimates do not themselves form a self-consistent time sequence. Clearly, it is absurd to suppose that mass transfer rates as large as the estimates you cite can be sustained for 10^7 years, as portrayed in Figure 1; personally, I find it difficult to envision net mass transfer rates in either direction much exceeding the thermal rate, $\sim 10^{-7}$ $M_\odot$/yr. Rather, when contact is first reached, the primary is very undersized and underluminous for its mass, while the secondary is oversized and overluminous for its mass; this is precisely the same condition of thermal disequilibrium as in the TRO models of W UMa systems at the beginning of their good thermal contact phase. In those models, the energy supply needed to keep the secondary in contact, to which you refer, is provided by energy transfer from the primary, rather than from the core of the secondary. This dams up the energy outflow from its interior, permitting it to remain oversized and lobe-filling, even though it is losing mass. My feeling is that the same circumstances are appropriate here, but as you imply, this should be demonstrated by calculating a self-consistent evolutionary sequence using a detailed model of mass flow such as the modified Jedrzejec model I have used here. This remains to be done.

Linnell: Perhaps I can ask Ron whether there is a problem concerning the total mass flux rate through L_1. In his paper on mass circulation, the total mass flow is 2 or 3 orders of magnitude larger than the net mass transfer between components. If the solutions indicating extremely marginal contact are correct, is there any problem with the rate of mass flow near L_1 which would be required on the mass circulation model?

Webbink: In that paper, I tried to estimate the minimum depth of contact at which mass flow at sonic velocities could carry the required net energy flux. It is roughly this state about which systems should oscillate in the TRO models, and the data I had at hand at that time seemed to indicate the depths of contact are indeed more or less evenly apportioned to either side of this marginal state. Systems in extremely marginal contact, i.e., having smaller depths of minima than this threshold, cannot then be presently in good thermal contact: although possibly still in physical contact, they correspond more nearly to the semi-detached phase of the TRO model.

Shu: If this scenario is right, what are Algols?

Webbink: That is precisely the reason why this problem needs so desperately to be resolved. I think the tendency of theoretical studies to show formation of contact systems is to a large extent an artifact of choosing initial systems with rather extreme mass ratios, which tends to aggravate the problem. It is embarrassing that none of the theoretical calculations including evolution of the secondary has succeeded in producing an Algol system. I have offered some speculations on how this dilemma might be resolved, but though I would like to think these are educated guesses, they should be recognized as nothing more.