Blue Stragglers
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HYDRODYNAMIC INSTABILITIES IN CLOSE BINARY SYSTEMS AND THE FORMATION OF BLUE STRAGGLERS

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ABSTRACT Hydrostatic equilibrium configurations for close binary systems can become unstable. Both secular and dynamical instabilities can occur. Here I discuss the implications of these instabilities for the terminal evolution of coalescing main-sequence-star binaries and the formation of blue stragglers. In particular, I point out that many systems could merge on a dynamical timescale and form blue stragglers without ever passing through a stable contact or semi-detached phase.

INTRODUCTION

Close binary systems are traditionally studied in the Roche approximation, where they are modelled as massless gas in hydrostatic equilibrium in the effective potential of a point-mass system (Kopal 1959). This model applies well to very centrally condensed objects (with effective polytropic indices $n \geq 3$) such as red giants and main-sequence stars with radiative envelopes. In the opposite limit of *incompressible*, fully self-gravitating configurations, the tensor virial method has been used very successfully to calculate hydrostatic equilibrium solutions (Chandrasekhar 1969). The important new effect arising in the self-gravitating case is that the equilibrium solutions can become *unstable*. For instance it is known that the solutions of the classical Darwin problem for two identical, incompressible stars in a close binary system become dynamically unstable before the surfaces of the two stars can come into contact (Tassoul 1975). Instabilities cannot occur in systems containing very compressible, centrally condensed objects, since the dynamics is essentially that of two point masses

Until very recently, little was known about the stability properties of the intermediate category of systems containing stars that are neither very centrally condensed nor quasi-homogeneous (effective polytropic index $0 < n < 3$). All binaries containing low-mass white dwarfs or main-sequence stars belong precisely to this category since they have $n \approx 1.5$. They include the likely progenitors of blue stragglers in (at least some) globular clusters, which are low-mass main-sequence stars in contact binaries or very short-period semi-detached systems (Mateo et al. 1990, and these Proceedings; Kallrath et al. 1992).

Some results about the stability properties of these systems have been obtained recently using both analytic methods (Lai, Rasio, & Shapiro 1993a, here-

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after LRS) and numerical hydrodynamic simulations (Rasio & Shapiro 1992, 1993, hereafter RS). The results of these recent studies are summarized, and their implications for the formation of blue stragglers are briefly discussed in succeeding sections.

INSTABILITIES IN CLOSE BINARY SYSTEMS

Dynamical Instabilities

The results of LRS for dynamical stability can be summarized as follows. For Roche-type binaries (systems where one of the two components is much more compact than the other and can therefore be represented by a *point mass* in the analysis), when the polytropic index $n \lesssim 2.5$, there exists a range of mass ratios such that dynamical instability sets in before the system can reach the Roche limit. The values defining this range are strong functions of both the polytropic index and the degree of synchronization. For Darwin-type binaries (containing two *identical* polytropes), the dynamical stability limit is reached before contact when $n \lesssim 1.5$. This result has been confirmed by the three-dimensional numerical simulations of RS using smooth-particle hydrodynamics (SPH). The analytic work is now being extended to systems with mass ratios not equal to unity (Lai, Rasio, & Shapiro 1993b).

The physical reason behind the existence of dynamical instabilities in close binary systems is easy to understand. Circular orbits in a central potential steeper than $1/r^2$ can become unstable to small radial perturbations. A familiar example is provided by the case of test particles orbiting around a Schwarzschild black hole (see, e.g., Shapiro & Teukolsky 1983, Chap. 12). Even in Newtonian binary systems, the effective gravitational interaction between the two stars can be stronger than $1/r^2$ because of tidal effects. Not surprisingly then, instabilities can develop when tidal effects are large, i.e., for configurations near contact or close to the Roche limit. More compressible configurations are less susceptible to instabilities since tidal effects are smaller for stars with more centrally concentrated density profiles.

What is the ultimate fate of a dynamically unstable system? The numerical simulations of RS for binaries containing two identical polytropes show that the nonlinear growth of the instability leads to the rapid merging of the two stars into a single ellipsoidal object (like in a "time-reversed fission"). A brief episode of violent equatorial mass-shedding follows, resulting in the formation of an outer massive disk of gas. The final equilibrium configuration consists of a maximally rotating, axisymmetric central object embedded in this disk. Clearly, the final coalescence in this case is a purely hydrodynamic process, and the properties of the final merged object are completely independent of any dissipation or angular momentum loss mechanism.

Secular Instabilities

Binary configurations can also become secularly unstable, i.e., unstable in the presence of some internal dissipation mechanism such as viscosity. For *synchronized* systems, the secular stability limit (if it exists) corresponds to the orbital separation r_s where the total equilibrium energy $E(r)$ and angular momemtum

$J(r)$ attain a *minimum*. Equilibrium configurations with $r < r_s$ are secularly unstable – dissipation can drive them out of synchronization, towards a new equilibrium state of lower total energy. The existence of such secularly unstable synchronized configurations is well-known in the context of tidal evolution of satellites in the solar system (Counselman 1973; Hut 1980). Although the existence of a minimum of $J(r)$ for close binaries has been noted previously (van't Veer 1979; Hachisu & Eriguchi 1984), its implications for coalescing binary systems have never been explored.

LRS find that *all* Roche-type binaries become secularly unstable before reaching the Roche limit, independent of the mass ratio and polytropic index. For Darwin binaries with identical components, they find that the secular instability occurs before contact when the polytropic index $n \lesssim 2$. If both dynamical and secular instabilities occur, the secular instability is always encountered first along an equilibrium sequence with decreasing binary separation. These results are also confirmed by numerical simulations (RS). Thus it appears that secular instabilities are even more common than dynamical instabilities in close binary systems.

The existence of secular instabilities for synchronized configurations can have important consequences for the orbital evolution of coalescing binaries. Merely from the existence of a minimum of $E(r)$, one can infer that the orbital decay of the system cannot proceed quasi-statically along the synchronized equilibrium sequence. Indeed, one would find that the secular rate of change of the binary separation $\dot{r} = \dot{E}/(dE/dr) \rightarrow \infty$ at the minimum of E, even for infinitesimally small dissipation. Instead, upon reaching the secular stability limit, the system will be driven rapidly out of synchronization. The subsequent orbital evolution may then be driven by internal viscous dissipation (which determines the growth rate of the secular instability) rather than angular momentum losses (cf. Hut 1981 and references therein). Independent of which mechanism dominates, the system will evolve further and further out of synchronization. The final merging must then be dynamical, since nonsynchronized contact configurations do not exist in equilibrium.

IMPLICATIONS FOR BLUE STRAGGLER FORMATION

The most immediate implication of the above results is that main-sequence stars in close binaries may coalesce on a dynamical timescale, either directly through a dynamical instability, or indirectly after the growth of a secular instability. If the instability is reached before the Roche limit or contact, a blue straggler can form immediately, although the progenitor could never be observed as a contact or semi-detached binary.

Even if a stable contact or semi-detached binary does form, the duration of the contact phase may be much shorter than predicted from simple considerations of angular momentum losses, since it can be interrupted abruptly by the onset of dynamical instability. If a secular instability occurs, the orbital decay may be accelerated as it becomes driven by internal viscous dissipation rather than angular momentum losses. Detailed comparisons of the theoretical results with the observed distributions of mass ratios and orbital periods in various types of close binaries will require a more complete analysis including the treatment of configurations where both components have finite size but the mass ratio is not unity. This analysis is now being carried out (Lai, Rasio, & Shapiro 1993b).

CONCLUSIONS

It appears that three qualitatively different mechanisms can lead to the formation of blue stragglers at the end-point of binary coalescence: dynamical instability, secular instability driven by internal viscous dissipation, or quasi-static merging driven by the loss of angular momentum. Which formation mechanism is followed may affect the observable properties of blue stragglers. The degree to which hydrodynamics plays a role is likely to determine how much mixing takes place during the final merging. As pointed out recently by Bailyn (1992), different amounts of mixing will result in blue stragglers with different observed locations in the color-magnitude diagram. It appears likely that at least the most massive blue stragglers in a given cluster, which must come from binaries with mass ratios close to unity, have formed through a violent hydrodynamic process rather than quasi-static merging.

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