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# Binary Evolution

# COMMON-ENVELOPE EVOLUTION, THE FORMATION OF CVS, LMXBS, AND THE FATE OF HMXBS

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**Abstract.** Recent three-dimensional studies of the common-envelope phase of binary evolution have provided important insights into its theoretical description. The role of non-axisymmetric effects associated with gravitational torques is essential for understanding all aspects of the evolution. For successful ejection of the common envelope and survival of the remnant compact binary it is required that the orbital period of the progenitor system is long, so that one of the components of the system is in the red giant or red supergiant stage of evolution. Not only must there be sufficient energy released from the orbit to unbind the common envelope, but it is also necessary that a sufficiently steep density gradient exist above the evolved core of the giant. If these conditions are satisfied, the time scale for orbital decay in the region above the core exceeds the time scale for mass loss from the common envelope and merger is avoided. The implications of these results for the formation of cataclysmic variables (CVs), low-mass X-ray binaries (LMXBs), and the descendants of high-mass X-ray binaries (HMXBs) are discussed.

## 1. Introduction

The common-envelope phase of binary evolution has long been recognized as important for understanding the formation of many classes of binaries containing compact objects in short-period systems. Originally suggested nearly two decades ago by Ostriker (1975) and Paczynski (1976) as an evolutionary path for the origin of cataclysmic variables, the paradigm has

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been extended to include the formation of neutron star systems (such as LMXBs and binary radio pulsars) and black-hole candidate X-ray transient systems. In this phase of evolution, the two stars of the progenitor system gravitationally interact within a differentially rotating common envelope. This interaction leads to a significant shrinkage of the orbit, and the energy released in the process facilitates the ejection of the envelope. A significant fraction of the initial orbital angular momentum of the system is converted into spin angular momentum of the common envelope which is lost as well. This mass ejection results either from the hydrodynamical expansion induced by the high energy deposition rate into the common envelope or by processes responsible for mass loss in red giant stars.

The binary systems which evolve into the common-envelope phase are, generally, systems in which the mass ratio of the two components significantly differs from unity. For systems consisting of a red giant and a dwarf, the dwarf-like component can plunge into the envelope of its giant companion as a result of a tidal instability (Counselman 1973; Kopal 1978). In this case, there is insufficient angular momentum in the orbit for the dwarf to spin up the red giant to a state of corotation. Alternatively, the system can evolve into a common-envelope phase as a result of a mass transfer instability in which the mass is transferred from the giant to its companion at such a rapid rate that the matter cannot be assimilated by the mass gainer in a state of corotation (Webbink 1979).

A quantitative description of the common-envelope phase is lacking since the computational resources required for the calculation of the hydrodynamical interaction of the two stars in three spatial dimensions over a 100–1000 fold shrinkage of the orbit is prohibitive. As a consequence, all investigations directed toward a population synthesis of these compact binaries are based on crude energy arguments with a parameterization introduced for the efficiency of the mass ejection process. Although sufficient energy may be lost from the orbit to unbind the common envelope, it is still possible that the two cores coalesce. Survival of a remnant binary also requires that the orbital decay time scale increases sufficiently rapidly that the common envelope is lost before the cores can merge. The major goal of theoretical studies of the common-envelope phase is to (1) identify the distinguishing characteristics of the binary system parameters which lead to the survival of a remnant binary and to (2) determine the relationship between the parameters of the progenitor and post-common-envelope system. In this paper, I will highlight recent results from multi-dimensional simulations of the common-envelope phase. Particular reference will be made to recent studies in three spatial dimensions. The implications of these results for the formation of CVs, LMXBs, and the fate of HMXBs as well as the key issues that remain to be resolved will be discussed.

## 2. Numerical Results

Three dimensional simulations of the common envelope phase of evolution have been carried out by De Kool (1987), Livio & Soker (1988), and Terman, Taam & Hernquist (1994). These studies demonstrated that non-axisymmetric effects are important in determining the evolution especially during the initial phases when the orbital period of the system is longer than the time scale for the orbital decay. Their results confirmed the earlier two dimensional studies of Bodenheimer & Taam (1984) and Taam & Bodenheimer (1989, 1991) in showing that the mass ejection occurs primarily in the orbital plane of the binary. These three dimensional studies, however, were limited in resolution and in the time over which the calculations were followed. In particular, it has not yet been demonstrated that the entire common envelope is ejected. For recent reviews of the observational and theoretical status see Iben & Livio (1993) and Taam (1994).

In this paper we present a brief summary of some recent results from the study by Terman, Taam & Hernquist (1995) in which it has been demonstrated that nearly the entire common envelope is ejected as a result of its hydrodynamical interaction with the two cores. Although we primarily concentrate on the evolution of a neutron star with a massive companion, the results are of a general nature and can be applied qualitatively to the evolution of a main-sequence star with its red giant companion.

As an example, we consider the common-envelope evolution of a binary system consisting of a $16\,M_\odot$ red supergiant and a $1.4\,M_\odot$ neutron star in orbit about their center of mass with a period of $\sim$1.3 yrs. In this illustration the supergiant is in its late core helium burning phase. Its luminosity and effective temperature are $7.12 \times 10^4\,L_\odot$ and 3,690 K, respectively. The evolution is numerically simulated using the smoothed particle hydrodynamics technique (Lucy 1977; Gingold & Monaghan 1977; Monaghan 1985, 1992) which is adaptive in both space and time (Hernquist & Katz 1989). The equation of state includes contributions from both gas and radiation, and the gravitational potential of the binary system is calculated with a hierarchical tree algorithm (Appel 1985; Barnes & Hut 1986; Greengard & Rokhlin 1987; Hernquist 1987). The $11\,M_\odot$ envelope of the $16\,M_\odot$ star is represented by 10,000 particles.

We assume that the supergiant is not rotating and, hence, the neutron star rapidly plunges into the envelope (see Fig. 1) on a time scale of 0.7 yrs. The action of the gravitational torques are effective in the outer layers of the star since a significant fraction of the mass of the star ($\sim$25%) is located in its outer half. As the binary orbit shrinks, the orbit tends to circularize. The time scale of the orbital decay is shown in Fig. 2, and it can be seen that after reaching a minimum of $\sim$95 days after the first $\sim$1000 days of

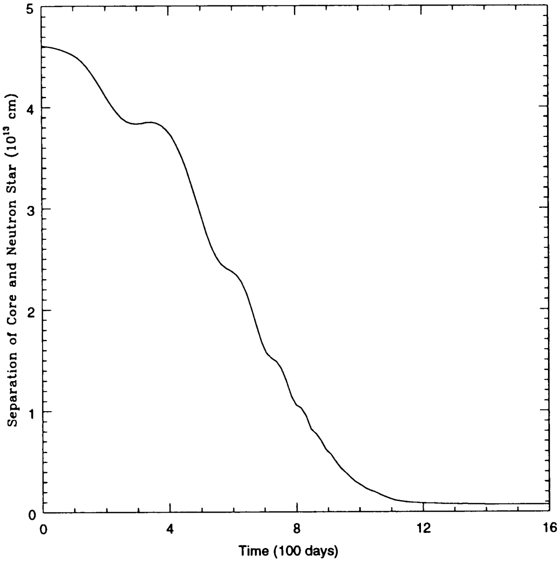

*Figure 1.* The variation of the orbital separation between the core of the red supergiant and the neutron star companion. The separation is in units of $10^{13}$ cm and the evolution time is in units of 100 days.

evolution it increased dramatically by more than a factor of 40, to ~11 yr by the end of the calculation.

The rate at which energy is deposited into the common envelope generally increased and was maintained at a level of ~1.3 $10^{40}$ ergs $s^{-1}$ for ~50 days before decreasing within ~200 days by nearly a factor of 3 (see Fig. 3). The latter trend reflects the spin up and ejection of matter in the vicinity of the core. In particular, the gas is spun up to within ~50% of corotation with nearly all of the initial orbital angular momentum from the binary converted into rotational angular momentum of the common envelope. We note that the use of a Bondi-Hoyle prescription for the energy deposition rate overestimates that calculated in the three dimensional simulations by several orders of magnitude. This is due to the subsonic nature of the flow associated with the reduction in relative velocity of the two cores with respect to the common envelope due to spin up, to the overestimate of the accretion radius when the density scale heights are much smaller, and to the higher sound speeds achieved when radiation pressure effects are included in the description of the accretion process (see also Shankar, Kley & Burkert 1994).

The spatial distribution of the ejecta is similar to that found by Terman *et al.* (1994) in their calculation of a common-envelope configuration

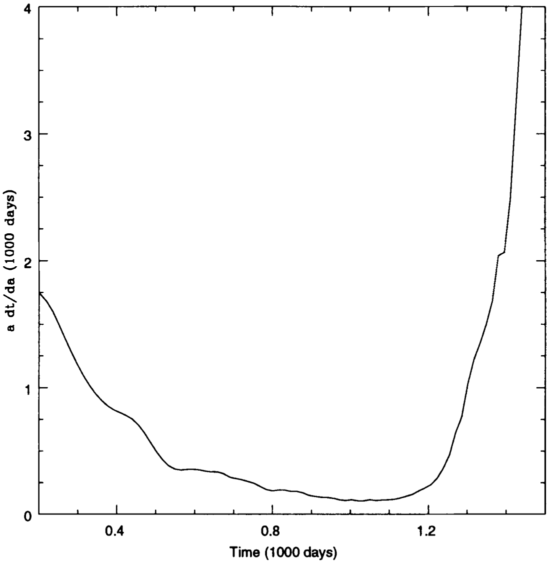

*Figure 2.* **The time scale of the orbital decay $(a/\dot{a})$ as a function of time. Both times are in units of 1000 days.**

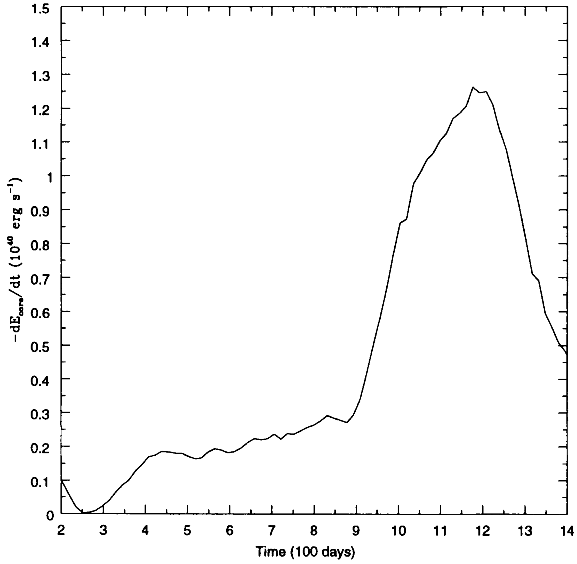

*Figure 3.* **The energy deposition rate into the common envelope resulting from the interaction of the two cores as a function of time. The deposition rate is in units of $10^{40}$ ergs $s^{-1}$ and the time is in units of 100 days.**

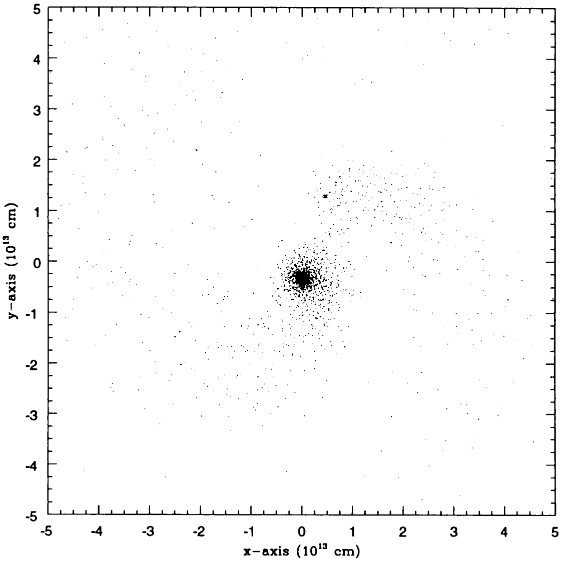

***Figure 4.*** **The distribution of the unbound matter projected onto the orbital plane of the binary system at an evolution time of 1.89 yrs. The spatial dimensions are in units of $10^{13}$ cm.**

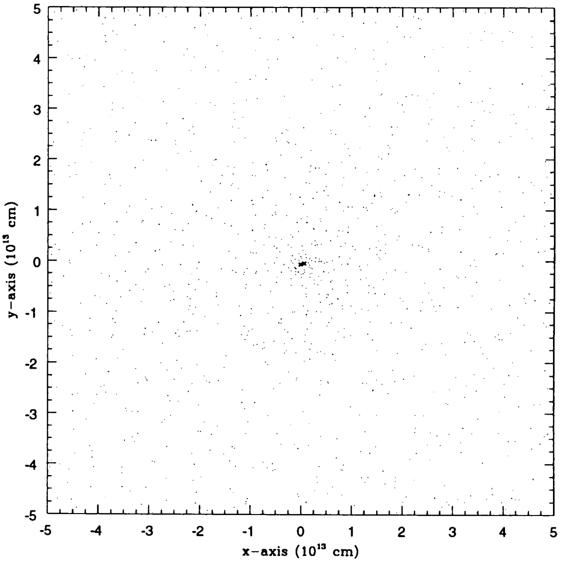

***Figure 5.*** **The distribution of the unbound matter projected onto the orbital plane of the binary system at an evolution time of 3.82 yrs. The spatial dimensions are in units of $10^{13}$ cm.**

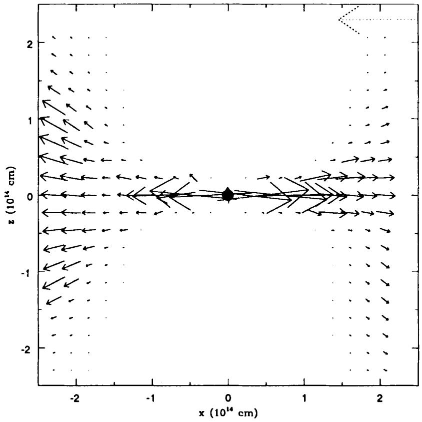

*Figure 6.* **The velocity field in the plane perpendicular to the orbital plane of the binary system containing the two cores during the last stage of evolution after a time of 3.8 yrs. The dotted arrow in the upper right hand corner of the figure corresponds to a velocity of 68 km s$^{-1}$. The spatial dimensions are in units of 10$^{14}$ cm.**

consisting of a 4.67 $M_\odot$ red giant with a 0.94 $M_\odot$ dwarf. During the initial stage the matter is ejected in the form of spirals (see Fig. 4) whereas, at later stages, it is ejected more uniformly in a circular distribution (see Fig. 5) for matter projected onto the orbital plane. Additional insight into the morphology of the mass ejection process is obtained upon inspection of the velocity field in the plane perpendicular to the equatorial plane $(x, z)$ described by the two cores illustrated in Fig. 6. It can be seen that most of the matter that is ejected from the red giant is the result of the action of an equatorial wind.

The fraction of unbound mass with respect to the common envelope rapidly rises within ~100 days to ~85% of the envelope at a time (~1050 days) when the neutron star enters the dense gas surrounding the core of the red supergiant. The entire common envelope is likely to be ejected as a result of tidal spin up (Taam & Bodenheimer 1991; Taam, Bodenheimer & Rozyczka 1994) since the density distribution of the red supergiant is sufficiently steep, and the mass contained above the helium core is small. The efficiency of the mass ejection process, defined to be given by the ratio of the actual binding energy of the ejected mass (which is the sum of the internal and gravitational potential energies) to the amount of energy lost from the orbit of the binary, is found to be ~42%. Since the ratio of the time scale for orbital decay to the time scale for ejection of the remaining matter in the common envelope rapidly increases (~5 at the end of the calculation), the orbital decay will eventually cease with the mass inside the orbit contracting away from the neutron star to the helium core (see Taam & Bodenheimer 1991). The end product of this initial long period binary system will be a neutron star orbiting about the helium core at a distance $\lesssim 6\,R_\odot$ in a period $\lesssim 12$ hrs.

## 3. Discussion

The numerical results of SPH simulations for a range of masses and orbital periods (Terman *et al.* 1995) indicate that survival of a remnant binary is likely for progenitor systems containing a red giant or supergiant component. For binary systems containing an unevolved star or slightly evolved star, the engulfed companion will merge with the core. In all cases the majority of the mass is ejected when the two cores evolve in a tight orbit. The cores strongly torque up gas in its vicinity and produce a strong equatorial wind that ejects mass primarily in the orbital plane of the binary. The initial orbital angular momentum is distributed throughout the common envelope and, for the cases in which successful envelope ejection occurs, the gas surrounding the red giant core is spun up to within ~50%–60% of the corotational value. Since most of the energy and angular momentum is imparted to matter in the equatorial plane of the common envelope the efficiency for the mass ejection process is less than 100%, ranging from ~30%–50%. The final stage of the common envelope phase ends with a slow material outflow and with the time scale for the decay of the orbit rapidly increasing as the gravitational torques become ineffectual in response to the formation of a low density region about the two cores. Thus, the qualitative aspects gleaned from numerical simulations in two spatial dimensions in the equatorial plane (Taam, Bodenheimer & Rozyczka 1994) and in the meridional plane (Taam & Bodenheimer 1991) are confirmed. Taken together the results of the multi-dimensional simulations indicate that the presence of a steep density gradient above the core in the progenitor star is essential for the successful ejection of the common envelope and the production of a short-period compact binary system.

Based on these results, the progenitor systems of cataclysmic variables with white dwarfs more massive than about $0.6\,M_\odot$ must have had orbital periods $\gtrsim 1$ yr. Although Terman *et al.* (1994) found very low efficiencies for the mass ejection process (~15%), more recent unpublished calculations in which the evolution was followed for a greater orbital shrinkage and in which an equation of state including radiation pressure was included indicate that an efficiency factor ~50% is more representative. The evolutionary calculations for the progenitors of CVs ($M \sim 2$–$8\,M_\odot$) indicate that the steep density gradients necessary for survival of the remnant binary depend on the mass of the star on the asymptotic red-giant branch (see Taam &

Bodenheimer 1992). For example, the gradients are sufficiently steep and extend to orbital separations of several solar radii for carbon-oxygen degenerate cores more massive than 0.65, 0.9, and $1.06\,M_\odot$ for stars of 3, 5, and $7\,M_\odot$ respectively. On the other hand, for stars less massive than $2.25\,M_\odot$, the steep density gradients that exist in stars on the red-giant branch with helium degenerate cores more massive than $0.35\,M_\odot$ (corresponding to orbital periods greater than several months) make these stars more favorable for successful ejection of the common envelope with regard to the formation of cataclysmic variables containing low-mass white-dwarf components ($\lesssim 0.5\,M_\odot$) with orbital separations of several solar radii.

For systems which contain white dwarfs outside these mass ranges successful ejection of the common envelope is difficult to understand within the common-envelope framework since the above conditions cannot be simultaneously satisfied. A possible solution for the formation of systems of this type is to tap the additional energy source associated with nuclear fusion (Taam & Bodenheimer 1989). If the material circulations induced in the inner region of the common envelope lead to significant compositional mixing in the hydrogen and helium rich regions, then the ejection of the remainder of the common envelope could be facilitated. The absence of steep density and pressure gradients in less evolved giant stars may facilitate this mixing to enhance the energy generation rates in the nuclear burning shells. Such mixing may render the hydrogen and helium burning shells unstable and lead to the ejection of the common envelope (see Taam 1994). If the masses of the two cores are comparable, such a process might be effective since significant differential rotation is induced in the inner regions surrounding the red-giant core, in this case, as a result of its motion about the center of mass. The degree of differential rotation and presumably the turbulence induced by hydrodynamical instabilities (see Fujimoto 1987) may be sufficient to produce the required mixing.

The numerical results of the common envelope phase of systems containing a massive star, as described in the previous section, are directly relevant to the formation of LMXBs and to the fate of HMXBs. In particular, the critical orbital periods of progenitor binary systems, $P_{\rm crit}$, which favor the survival of the binary through the common-envelope phase can be estimated on energetic grounds if an efficiency for the mass ejection process is assumed. Provided that no other energy sources can be tapped besides that derived from the orbit, and that an efficiency for the mass ejection process corresponding to the average found from the numerical calculations ($\sim$38%) is assumed, we find that $P_{\rm crit}$ increases with increasing mass ranging from $\sim$80 days to 2 yrs for systems consisting of a $1.4\,M_\odot$ neutron star and massive companions ranging in mass from $12\,M_\odot$ to $24\,M_\odot$. The estimate for the critical period at the lower end of the mass range is likely to

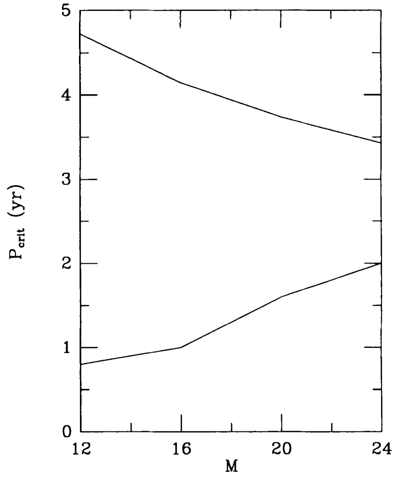

***Figure 7.*** **The critical orbital periods as a function of the mass of the massive star (in units of $M_\odot$). For periods below the lower curve a $1.4\,M_\odot$ neutron star is expected to merge with the companion. Above the upper curve the binary system does not enter into the common-envelope phase. Within the boundaries described by the two curves the formation of a short period system consisting of a neutron star and a helium core is possible.**

be an underestimate since the density gradients above the nuclear burning shells for these stars are not as steep as those found for the more massive stars at longer orbital periods. A critical period of about 0.8 yr is a better estimate for a star of $12\,M_\odot$. We display this critical period relation as well as the period relation above which the system would not evolve into the common-envelope stage (for an assumed maximum stellar radius of $10^{14}$ cm) in Fig. 7. Although these curves have been derived for progenitor systems with characteristics similar to HMXBs, they are also relevant for systems consisting of a low-mass main-sequence star and a massive companion (for application to the formation of LMXBs) provided that the engulfed star's mass is not significantly different from $1.4\,M_\odot$. In order for the system to survive the common-envelope phase, the orbital period of the system must be enclosed within the boundaries defined by these two curves. For such long orbital period systems the companion to the neutron star must be in its red-supergiant phase. For $P < P_{\rm crit}$, the system will merge to form a single star. In the case of a neutron star companion, a recycled pulsar of low space velocity could form (see Bhattacharya & Van den Heuvel 1991) following its intermediate phase as a Thorne-Zytkow object (Thorne & Zytkow 1977; Biehle 1991; Cannon *et al.* 1992; Cannon 1993). We point out that stars with $M \gtrsim 30\,M_\odot$ do not expand to the red-supergiant phase due to the action of strong stellar winds. Hence, these stars would not contribute to the population of compact systems formed via the common-envelope phase (see Van den Heuvel 1994).

The progenitor systems which survive the common-envelope phase as a compact binary are a class of systems known as Be/X-ray binaries (see Rappaport & Van den Heuvel 1982; Van den Heuvel & Rappaport 1987; Van den Heuvel 1992). The remnant binary will consist of the helium core of the red supergiant and its neutron star companion. Systems with low-mass main-sequence companions are also expected to survive, however their progenitor systems may not be Be binaries. The future evolution of these products can either lead to the merger of the two components or to the production of close compact binary systems such as PSR 1913+16 and PSR 1534+12 (see Flannery & Van den Heuvel 1975; De Loore *et al.* 1975) for a neutron star companion, and to LMXBs for a main-sequence like companion.

Coalescence of the two components may take place if the remnant system undergoes a second common-envelope phase as a result of the expansion of the helium star beyond the orbit of its companion. This is a distinct possibility since helium stars less massive than about $4\,M_\odot$ (corresponding to hydrogen-rich stars less massive than $\sim 16\,M_\odot$) expand to $\gtrsim 3\,R_\odot$ with stars in the mass range of 2–$2.7\,M_\odot$ developing a red-giant structure after central helium burning (Habets 1985, 1986). In fact, for sufficiently large mass ratios, the mass transfer process will not be conservative and a second common-envelope phase will result. We remark that our calculations require that the progenitor star has a red-giant like structure for successful ejection of the common envelope. Assuming that this requirement is also necessary for the survival of the system through the second spiral-in phase as well, then the small orbital separation characteristic of the products of the first spiral-in phase ($\lesssim 6\,R_\odot$) is likely to lead to merger of the helium core and the neutron star and to the formation of a neutron star or a black hole (see below) with a surrounding remnant accretion disk in the second spiral-in stage unless sufficiently steep density gradients are produced as a result of the mass loss process itself. Hence, the survival probability of a binary system through two common-envelope phases in massive star systems may be expected to be low.

On the other hand, for remnant binary systems where the mass ratio is not large the system may avoid a common-envelope phase and quasi-conservative mass transfer can result. In this case, the helium star transfers mass to its neutron star companion at rates ($\sim 10^{-4}$ to $10^{-3}\,M_\odot\,yr^{-1}$) significantly in excess of the Eddington limit. For such high mass transfer rates and spherically symmetric accretion by the neutron star, photon trapping in the flow can be effective with the gravitational potential energy lost directly in the form of neutrinos (Chevalier 1993). As a result, the neutron star may accrete sufficient mass to exceed its mass limit and, thereby, produce a black hole. Further evolution of the helium star may lead to the formation of a neutron star, and to the existence of a short-period binary consisting of a black hole and a neutron star. Alternatively, if the mass transfer process leads to jet formation as in SS 433, the neutron star in the remnant binary may not accrete appreciably and the system likely evolves to the close double neutron star stage.

In contrast, systems containing helium stars more massive than $\sim 4\,M_\odot$ are not expected to merge with their companion provided that the orbital decay time scale is longer than the nuclear burning evolutionary time scale. In these systems, the helium star will evolve to the supernova stage either producing a high-velocity pulsar or a neutron star remnant in a bound orbit. It is likely that a kick velocity in the retrograde sense relative to the orbit will be necessary to bind the system because the system would be unbound for a helium core more massive than $4.2\,M_\odot$ for a $1.4\,M_\odot$ neutron star companion, or more massive than $3.8\,M_\odot$ for a $1\,M_\odot$ main sequence-like companion in the absence of a kick. This suggests that, for a given helium core remnant, the mass loss associated with the supernova event is more likely to disrupt a system composed of a low-mass main-sequence star than a neutron star. Additional effects related to the sizes of the stellar objects further restricts the survival probability of main-sequence stars with a neutron star companions since the orbit cannot be so highly eccentric that the newly born neutron star collides with its companion during periastron passage.

A number of key issues remain for detailed study. Among them I include the investigation of the dependence of the efficiency of the mass ejection process on the mass of each of the components of the system, the evolutionary state of the stars, and the degree to which the components are out of synchronous rotation at the onset of the common-envelope phase. A better understanding of the final stage of this phase of evolution with regard to the possibility of forming steep density gradients in the structure of the common envelope as a result of the mass ejection process itself will be necessary in order to place constraints on the fraction of binaries containing compact stars which form short-period systems, and at the same time, to establish the relationship between the orbital parameters of the post common-envelope binary to that of the pre common-envelope binary. Finally, studies of the nuclear assisted hypothesis are necessary to determine its viability for the formation of low-mass white dwarfs in close binary systems within the framework of the common-envelope paradigm.

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