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THE FORMATION OF ALGOLS WITHOUT CATASTROPHES

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ABSTRACT

A number of semi-detached Algol-like binaries must have initiated mass transfer at a late case B stage when the loser possessed a deep convective envelope. If the loser was still the more massive when mass transfer began (as expected in a conservative scenario) then the ensuing mass transfer would take place on a rapid hydrodynamic time scale probably leading to common envelope evolution and possibly to coalescence rather than to an Algol. However, if the initially more massive star loses enough mass by means of an enhanced stellar wind before filling its Roche lobe, overflow can begin on a nuclear time scale. In a more extreme situation the star may never fill its Roche lobe. Certain RS CVn systems indicate that the necessary enhanced mass loss is possible. We present detailed models of binary systems where ordinary stellar wind mass loss is enhanced by a binary companion according to a simple formula and we use these to interpret the evolution of Algol-like and related binaries.

Subject headings: stars: eclipsing binaries — stars: evolution — stars: mass loss

I. INTRODUCTION

Among semi-detached, Algol-like binaries, there are a number that may have begun their Roche lobe overflow in a late case B stage (Kippenhahn and Weigert 1967). This means that the primary (by which we mean the initially more massive star) filled its Roche lobe after, rather than before, it developed a deep convective envelope at the base of the red giant branch. Examples, ranging from probable to almost certain, are TW Dra, TT Hya, RY Gem, RZ Cnc, RT Lac, and AR Mon (Popper 1980). TW Dra (K0 + A3; 0.8 + 1.7 $M_\odot$; 3.4 + 2.4 $R_\odot$; 2.8 days) has a rather less extreme mass ratio, and hence more angular momentum, than most Algols with similar periods. Thus, if mass and angular momentum have been conserved, its orbital period was never less than ~ 1.8 days. This is large enough for a primary of up to 1.5 $M_\odot$ to have developed a deep convective envelope before filling its Roche lobe. If the system has suffered angular momentum loss, perhaps by magnetic braking, then the separation would have been even greater; whereas mass loss with the corresponding minimal angular momentum loss would have had the opposite effect. AR Mon (K3 + K0; 0.8 + 2.7 $M_\odot$; 14 + 11 $R_\odot$; 21.2 days) is a much clearer example since the period was probably never less than 7 days so that the primary can hardly have avoided developing a deep convective envelope well before overflow began.

This late case B origin for some Algols poses a problem: for if the more massive, more evolved, component of a pre-Algol binary had a deep convective envelope when mass transfer began, the mass transfer should have been very rapid, taking place on a hydrodynamic ($\sim$10–1000 yr) time scale (Paczyński 1965; Paczyński and Sienkiewicz 1972) rather than a thermal ($\sim 10^5$–10^7 yr) or a nuclear ($\sim 10^8$–10^{10} yr) time scale. Paczyński (1976) suggested that such rapid overflow would lead to common envelope evolution of which the final product could be a close binary ($P \approx \frac{1}{2}$ days) in a planetary nebula, like UU Sge in Abell 63 (Miller, Krzeminski, and Priedhorsky 1976; Bond, Liller, and Mannery 1978) or V477 Lyr in Abell 46 (Grauer and Bond 1981). Livio and Soker (1984), and Eggleton (1986) have suggested that unless the orbital period is so long (greater than $\sim$200 days) that the primary can become a red supergiant, rather than just a red giant or subgiant, the outcome of the common envelope process is likely to be coalescence—the final product being a single rapidly rotating red giant like FK Com (Bopp and Stencel 1981). In any event it seems unlikely that the product of a hydrodynamic mass transfer will be a rather tame Algol-like system.

In a previous paper we (Tout and Eggleton 1988) have suggested that mass loss by a stellar wind, enhanced by tidal or other interaction with the companion, would alter this picture of late case B substantially. Evidence for such enhanced mass loss is provided by some RS CVn systems that have well-determined masses. Popper (1980, his Table 6) lists 15 systems with the properties that (a) the primary is a red subgiant, (b) the secondary is still on the main sequence (although only just in some cases), and (c) the primary does not fill its Roche lobe, typically by a factor of 2 in radius. All these systems are potential pre-Algols. As one would expect on evolutionary grounds, most have a mass ratio $q > 1$ (q = primary mass/secondary mass), but three have $q < 1$ by a narrow margin. These are probably systems where a stellar wind has carried off a significant amount of mass. The best determined of these is Z Her (K0 + F5; 1.10 + 1.22 $M_\odot$; 2.6 + 1.6 $R_\odot$; 3.99 days). We estimated that the stellar wind must be enhanced by a factor ~ 100 over what might be expected from an extrapolation of red giant winds (Reimers 1975). Most of Popper's 15 potential late case B pre-Algol systems are well known as RS CVn binaries for which there is direct observational evidence of enhanced surface activity in X-rays (Walter *et al.* 1980) and radio emission (Spangler, Owen, and Hulse 1977). The subgiant components also tend to show a rotational distortion attributed to huge starspots, or clusters of spots, slowly migrating around the surface in the orbitally rotating frame (Hall 1975).

In § II we discuss the modeling of an enhanced mass loss process based on a model of Z Her; in § III we present some evolutionary models; and in § IV we discuss the relevance of this process to various evolutionary situations.

II. DETAILED MODELING

In our previous paper (Tout and Eggleton 1988) we discussed the implications of enhanced mass loss from red giants in binary systems and obtained some idea of the effect on evolution by using a simple red giant evolution algorithm capable of evolving several giants in a very short time. In this paper we present detailed models evolved using the stellar evolution program written and developed by Eggleton (1972). Because of the non-Lagrangian mesh used in this program it is a simple matter to remove mass from the surface of the star. The surface boundary condition is changed and the mesh is automatically redistributed.

To describe the mass loss before the star fills its Roche lobe and the mass transfer once it has done so we use the following simple formulae:

$$\dot{M}_1 = \begin{cases} -A\dfrac{R_1 L}{M_1}\left\{1 + B.\min\left[\left(\dfrac{R_1}{R_{L1}}\right)^6, \dfrac{1}{2^6}\right]\right\}, & \text{if } R_1 < R_{L1}\ ; \\ -C\left(\ln\dfrac{R_1}{R_{L1}}\right)^3, & \text{if } R_1 \geq R_{L1}\ ; \end{cases} \quad (1)$$

and

$$\dot{M}_2 = \begin{cases} 0, & \text{if } R_1 < R_{L1}\ ; \\ -\dot{M}_1, & \text{if } R_1 \geq R_{L1}\ ; \end{cases} \quad (2)$$

where M_1 is the mass of the losing star, R_1 its radius, L its luminosity and R_{L1} the radius of its Roche lobe (i.e., the radius of a sphere that has the same volume as the Roche lobe), while M_2 is the mass of the companion. When $B = 0$ (or when $R \ll R_L$) the formula reduces to that of Reimers (1975) which he obtained empirically using observations of the circumstellar lines in the spectra of single giants. The value of A is uncertain by $\sim 50\%$ and we have used $A = 4 \times 10^{-13}$ solar masses per year. The factor $(R/R_L)^6$ is included to concentrate enhancement strongly toward the Roche filling limit since we believe that this is the most important indicator of binary interaction. We have used the sixth power since the enhancement quite likely has tidal causes and tidal effects are often found to be proportional to $(R/R_L)^6$ (Zahn 1975; Campbell and Papaloizou 1983). We have included the cutoff in the growth of $\dot{M}$ at $R = \frac{1}{2}R_L$ to avoid very high mass loss rates when the star is almost filling its Roche lobe and since tidal effects will saturate when complete corotation is established. For the mass transfer rate during Roche lobe overflow we have used $C = 10^4$ but note that the actual value should not have much of an effect on the evolution considered here.

Before the star has filled its Roche lobe we assume that all the stellar wind is lost completely from the system. This simple assumption is most probably incorrect but it avoids the introduction of another parameter at this stage. In addition we assume that the escaping matter carries away its intrinsic angular momentum and that the spin angular momentum of the stars is negligible. During mass transfer through Roche lobe overflow we assume that total angular momentum is conserved so that, if J is the orbital angular momentum of the system then

$$\dot{J} = \begin{cases} \dot{M}_1 a_1^2 \Omega, & \text{if } R_1 < R_{L1}\ ; \\ 0, & \text{if } R_1 \geq R_{L1}\ ; \end{cases} \quad (3)$$

where a_1 is the orbital radius of the losing star and Ω the orbital angular velocity. This results in the formula $(M_1 + M_2)^2 P =$ constant during the mass loss phase and $P(M_1 M_2)^3 =$ constant during mass transfer. By computing detailed models of Z Her we have found that to obtain the required observable parameters we need $B \approx 10{,}000$ (see Tout and Eggleton 1988).

We expect binary systems undergoing mass loss to evolve in one of three ways. (1) The primary loses its entire envelope before it has managed to fill its Roche lobe. This will result in a system consisting of a white dwarf and a main-sequence star which will, if it is massive enough, evolve to become a giant and follow similar evolution again. (2) The primary may lose a substantial amount of mass, undergoing mass inversion and a reduction of mass ratio below a value $q_{\rm crit} \approx 0.7$ but still fill its Roche lobe. In this case as mass transfer proceeds the Roche lobe expands at a rate greater than the expansion of the giant owing to mass loss alone and overflow continues on a slow time scale as the giant grows owing to nuclear burning. Such systems resemble the classical Algols. (3) The primary fills its Roche lobe quickly, before $q = q_{\rm crit}$, so that its own expansion owing to mass loss and the contraction of the Roche lobe cause mass transfer to take place on a much faster hydrodynamic time scale through positive feedback. Although it is conceivable that after a limited amount of such rapid overflow the system will resemble those in case (2) it is more likely that this rapid mass transfer will lead to common envelope evolution and possibly to coalescence.

III. RESULTS OF THE DETAILED MODELS

We have modeled in detail the behavior of one system from each of the above cases using the program written and developed by Eggleton (1972) with boundary conditions satisfying equations (1) and (2). For each model we have chosen an initial primary of 2 $M_\odot$ and an initial mass ratio of $q = 1.1$ so that the secondary mass is 1.818 $M_\odot$ which is kept constant throughout the detached part of the evolution. The main sequence lifetime of the secondary is 1.00×10^9 yr. We evolve the 2 $M_\odot$ star across the main sequence with no mass loss since, by comparison with the Sun, any mass loss is expected to be negligible. This takes 7.9×10^8 yr so that we have another 2.1×10^8 yr before the secondary begins to evolve off the main sequence, and hence it is reasonable to assume that it does not evolve significantly during the period that we are modeling. As the primary evolves off the main sequence we turn on mass loss according to equation (1). The star takes $\sim 7.5 \times 10^7$ yr to evolve to the base of the giant branch. It then grows until either it fills its Roche lobe, it loses enough mass to begin shrinking to a white dwarf, or it ignites helium in its core. The last occurs in single stars (or very wide binaries).

We present H-R diagrams showing evolutionary tracks for three cases in Figure 1. Each diagram shows the track of a star undergoing enhanced mass loss (*solid line*) compared with that of an initially identical star undergoing no mass loss evolved to the helium flash (*dotted line*). Also shown is the main-sequence evolutionary track of the 1.818 $M_\odot$ secondary. Figure 1*a* shows a star that evolves to a white dwarf in an entirely detached state. The initial period is 22 days and the final period (that reached when the primary has become a white dwarf and before the secondary has evolved off the main sequence) is 71 days while the mass of the white dwarf formed is 0.30 $M_\odot$. Since the helium flash has not been reached this will be a helium white dwarf. The secondary of mass 1.8 $M_\odot$ will be a late A star and will soon evolve to become a red giant perhaps like AY Cet (WD + G5III; 57 days; Simon, Fekel, and Gibson 1985).

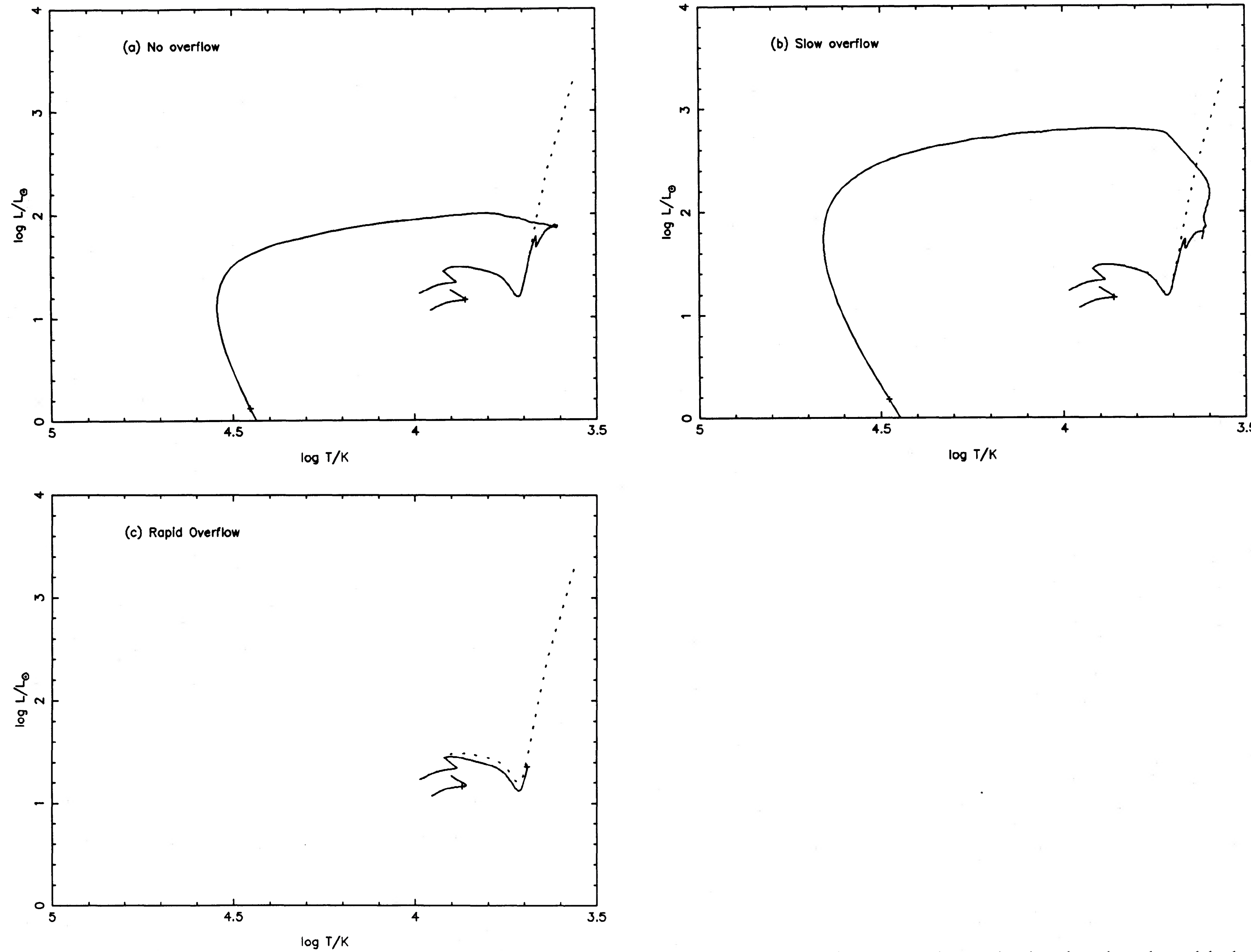

FIG. 1.—Hertzsprung-Russell diagrams showing evolutionary tracks of stars in close binary systems. In each case the longer solid line is a 2 $M_\odot$ primary undergoing enhanced mass loss and the shorter solid line is the main-sequence evolution of a 1.818 $M_\odot$ secondary. The dotted line shows the track that would be followed by the primary up to the core helium flash if there were no mass loss. The plus symbol (+) marks equal age points for the two stars. Three cases are shown: (*a*) initial period 22 days—the primary evolves to a white dwarf entirely in a detached state; (*b*) initial period 10 days—the primary evolves to a white dwarf via slow Roche lobe overflow; and (*c*) initial period 4 days—drastic Roche lobe overflow occurs and prevents further following of the evolution.

Figure 1*b* shows a system with a lower initial period of 10 days. In this case the primary does manage to fill its Roche lobe but only after it has lost so much mass that the mass ratio $q = 0.52$. Its period has increased to 19 days. Thus the ensuing mass transfer causes R_L to increase faster than R and consequently proceeds on a slow nuclear time scale. In this case it is possible to follow the evolution through the semidetached phase where it resembles a long period Algol like RY Gem (K2 + A2; 0.6 + 2.6 $M_\odot$; 6 + 3 $R_\odot$; 9.3 days; Popper 1980). Mass transfer ceases when the primary becomes a white dwarf of mass 0.36 $M_\odot$ and the orbital period is 148 days. The mass of the secondary has increased to 2.41 $M_\odot$ but otherwise the system resembles the main sequence, white dwarf pair of Figure 1*a*.

Figure 1*c* shows a system with a much shorter initial period of 4 days. In this case the primary loses 10% of its mass even before it reaches the giant branch but fills its Roche lobe when its mass has fallen only to 1.79 $M_\odot$ so that $q = 0.98$ causing the overflow rate to increase with overflow to such an extent that the evolution cannot be followed by our code even with very short time steps. As mentioned earlier, it is likely that the primary envelope will expand to form a common envelope leading either to a cataclysmic variable or to coalescence.

IV. DISCUSSION

This process of enhanced mass loss in binary systems (specifically those undergoing late case B overflow) has considerable effect on the evolution and it is, therefore, important to study it in more detail. The evidence already presented, although mainly qualitative, has led to the possible quantitative approach of §§ II and III. Clearly more quantitative evidence will be very useful in improving equation (1). In particular we might expect the mass-loss rate to depend strongly on the magnetic fields in the losing star which will probably be enhanced by a winding up process connected with the approach to corotation. Indeed, as pointed out earlier, the RS CVn systems show enhanced surface magnetic activity. With enhanced magnetic fields we must also consider the probability that the matter in the wind will continue to corotate out to some Alfvén radius and consequently carry off more angular momentum than suggested in this paper thus driving the stars into a closer orbit.

In the search for further evidence it is interesting to consider the elusive system RZ Oph (M III + F5 Ib; 261.9 days; Hiltner 1946) which photometry (Olson 1987) reveals to have a steady state accretion disk around the hot star (the secondary in our nomenclature). Although it has not been ruled out that the system is semidetached it seems more likely that it is in a detached state (Knee *et al.* 1986) in which case the combined spectroscopy and photometry yield parameters (0.70 ± 0.06, 5.65 ± 0.23 $M_\odot$; 41 ± 6, 5.4 ± 0.6 $R_\odot$) and hence $q = 0.12$. It is conceivable that RZ Oph might be a product of Roche lobe overflow in which the primary has retreated inside its Roche lobe temporarily as a result of helium ignition. If conservative mass transfer is assumed, it would have had to start with a period of ~15 days if the masses were initially nearly equal. For the moderately high masses (~3 $M_\odot$) that this scenario requires it is marginally possible that the primary originally filled its Roche lobe before developing a deep convective envelope and thus avoided rapid hydrodynamic overflow. However, we find it unlikely that so much mass (three-quarters of the initial primary mass) could have been transferred given that helium ignition should have taken place soon after the primary filled its Roche lobe. We therefore prefer a nonconservative picture in which the binary would have started with somewhat larger masses (~4.5 + 3.5 $M_\odot$) and a longer period (~150 days). The primary would then have ignited helium before filling its Roche lobe and settled down to nuclear–time-scale evolution with a radius gradually increasing from ~0.3 to 0.6 of its lobe radius. During this phase it could suffer extensively from enhanced mass loss. Olson (1987) has deduced from the disk luminosity that there must be an accretion rate of 6×10^{-7} $M_\odot$ per year. If we take the assumption of $i = 90°$ and the data of Knee *et al.* (1986) we may estimate the luminosity of the primary using $L = 4\pi R^2 T_{\rm eff}^4$. We take $T_{\rm eff} \approx 4000$ K from the table of di Benedetto and Rabbia (1988), giving $L \approx 380$ $L_\odot$. Then Reimers' formula (equation 1 with $B = 0$) gives $\dot{M} = -9 \times 10^{-9}$ $M_\odot$ yr^{-1} which is almost two orders of magnitude less than the accretion rate. Now $R/R_L = 0.6$ so that our formula predicts enhancement by a factor of ~160 leading to a rate of 1.4×10^{-6} $M_\odot$ year^{-1}. If ~40% of this is accreted by the secondary then we obtain the required rate. Furthermore, the primary would have ~4×10^7 yr in its core helium burning state which is enough time to lose ~4 $M_\odot$ with a mass-loss rate that has been increasing to what it is now.

A similar system in some respects is SX Cas (K3 III + B7; 1.5 + 2.8 $M_\odot$; 36.6 days; Koch 1972; Plavec, Weiland, and Koch 1982). Although the data are not as compelling we again appear to have a detached system in which the hot star is surrounded by an accretion disk. Indeed, Plavec *et al.* suggested that this system is possibly an example of enhanced stellar wind accretion.

An important observational consequence of the theory presented here is that the mass of the white dwarf resulting from the primary is rather low (~0.3 $M_\odot$ for a 2 $M_\odot$ progenitor) and is not very dependent on the initial period whereas white dwarfs produced by common envelope ejection or by ordinary (Reimers) mass-loss rates are much larger (>0.6 $M_\odot$ for a 2 $M_\odot$ progenitor). Of the systems that are observed to contain white dwarf components some have fairly short periods and low-mass functions consistent with such low-mass white dwarfs: AY Cet has P = 56.8 days and $f(m) = 0.0029$ $M_\odot$ (Simon *et al.* 1985); HD 185510 has $P = 20.659$ days and $f(m) = 0.0019$ $M_\odot$ (Balona 1987); FF Aqr has $P = 9.21$ days and $f(m) = 0.0188$ $M_\odot$ (Dworetsky *et al.* 1977); and V651 Mon, the central star of the planetary nebula NGC 2346 has $P = 15.995$ days and $f(m) = 0.0073$ (Méndez and Niemela 1981). Thus the confirmed existence of low-mass white dwarfs would be important evidence for enhanced mass loss and the accurate determination of white dwarf masses in such systems would be useful in improving equation (1).

Further consequences of our picture of enhanced mass loss may be relevant to such other problems as symbiotic binaries and barium stars which are possible remnants of late case C Roche lobe overflow. Symbiotic systems can be expected to fall into two major classes (Plavec 1982; Kenyon and Webbink 1983): those with main-sequence gainers, and those with white dwarf or hot subdwarf gainers. We expect that in neither case is the red giant or supergiant likely to be a lobe-filling star, although it may be quite close to it. It seems more likely that the hot companion is accreting from a wind, and probably a considerably enhanced wind if $R/R_L > 0.3$ for the cool component. This wind may easily exhaust the entire envelope of the loser before it can expand to $R = R_L$. In fact, if stellar wind mass loss prior to Roche lobe overflow were sufficiently modest that the mass ratio was not significantly altered we should be surprised to find any of the nova-like symbiotics (Plavec 1982), since they would have suffered rapid overflow at an early stage in their evolution. Similar considerations apply to barium stars if the binary hypothesis of their origin (McClure 1983) is accepted.

In the literature one can find about two dozen binaries with (*a*) at least one component a probable white dwarf or hot subdwarf, and (*b*) a period in the range 1–10^4 days (which excludes almost all cataclysmic and precataclysmic variables). These objects range from a pair of white dwarfs (EG 52: DC9 + DC9; 20.5 yr; 0.46 + 0.46 $M_\odot$; Harrington, Christy, and Strand 1981; Greenstein 1986) through ~10 symbiotics, and some presymbiotics like HD 128220 (SDO + F4 IV; 870 days; Wallerstein and Wolff 1966; Goy 1977), to HD 49798 (SDO 6 + ?; 1.55 days; Thackeray 1970) with a fairly uniform spread in log *P*. Such objects must be quite common given the intrinsic difficulty in recognizing a white dwarf in an moderately close binary except (arguably) for symbiotics where there is a fairly copious wind from a companion for the dwarf to interact with. Thus many late case B/C systems avoid a spiral-in type of evolution following rapid overflow. Indeed, EG 52 must have survived two potential episodes of rapid overflow. We believe that probably the best evidence for the evolutionary effects of wind loss or Roche lobe overflow, or both, in late case B/C systems is likely to come from improved observational knowledge of such systems as these.

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