THE FORMATION AND EVOLUTION OF SYMBIOTIC STARS

R. F. Webbink
Department of Astronomy, University of Illinois
1011 W. Springfield Ave., Urbana, IL 61801, U.S.A.

ABSTRACT. The evolutionary origins of symbiotic stars containing (i) disk-accreting main sequence stars, (ii) wind-fed, shell-burning white dwarfs, and (iii) disk-accreting neutron stars are described. Of particular interest are those white dwarf systems which have orbital periods too short to have escaped tidal mass transfer prior to becoming symbiotics. We show here that, under suitable circumstances, low-mass, long period binaries may undergo quasi-conservative mass transfer, rather than evolving through common envelope evolution to the cataclysmic variable state, thus accounting for the existence of these systems. Approximate expressions are given for the lifetimes, and relative efficiencies (mass accreted/mass of donor) for different modes of interaction among symbiotic binary systems.

1. INTRODUCTION

It is now apparent that symbiotic stars constitute a very heterogeneous class of objects. At least three types of symbiotic stars may be identified according to the energy source for their hot components: (i) disk-accreting main sequence stars (e.g., CI Cyg: Kenyon, et al. 1982; Mikołajewska and Mikołajewski 1983; Mikołajewska 1985); (ii) wind-fed, shell-burning white dwarfs with extended envelopes (e.g., AG Peg: Gallagher, et al. 1979; Keyes and Plavec 1980); and (iii) disk-accreting neutron stars (V2116 Oph = GX 1+4: Cutler, Dennis, and Dolan 1986). Those of type (ii) can be further subdivided into (iia) systems of relatively short orbital period ($P \lesssim 4$ yr), in which the donor star is a normal late-type giant or bright giant (S-type symbiotics, as in the example, AG Peg, cited above); and (iib) systems of indeterminant, but undoubtedly long orbital period ($P \gtrsim 15$ yr), which generally show strong near-infrared flux excesses, and whose cool components are frequently long-period variables in their own right (D-type symbiotics: see Whitelock 1987). In turn, the existence of symbiotic stars of type (iia), which have orbital periods too short to escape tidal mass transfer in future, implies the existence of yet another class (iia′), in which the burning white dwarf is fed by disk accretion from a Roche-

J. Mikolajewska et al. (eds.), The Symbiotic Phenomenon, 311–321.

lobe-filling cool companion. There is as yet no well-established example of a type (iia') system (cf. Kenyon and Webbink 1984), but it should be noted that nuclear burning on a typical white dwarf produces ~30 times as much energy per gram as does accretion, making the presence of an accretion disk problematical in the presence of a burning white dwarf. The status of the yellow (D'-type) symbiotic stars (Glass and Webster 1973; Allen 1982) within this classification scheme is not yet clear.

2. ORIGINS OF SYMBIOTIC STARS

It is evident that binary systems may arrive at a symbiotic state by a number of evolutionary paths. Some of these are quite straightforward. For example, practically any binary with a low-mass secondary, and a sufficiently large initial orbital separation to permit the more massive primary to reach the giant branch, is a candidate for a type (i) system (disk-accreting main sequence star), in the preceding classification scheme. Given a larger orbital separation yet, the more massive primary of such a system might evolve to a white dwarf stage without ever undergoing tidal mass loss. Such a system could become a type (iib) symbiotic as the secondary ascends the giant or asymptotic giant branch (Tutukov and Yungel'son 1976).

Other symbiotic stars (types iia, iia', and iii) must be the products of earlier phases of binary interaction, however. They have orbital periods too short to have escaped such a fate as the progenitors of their hot components evolved to the degenerate state. This raises some interesting problems in understanding their evolutionary history, because systems of similar total mass and angular momentum have also been identified as the progenitors of cataclysmic variables (Paczyński 1976; Ritter 1976; Webbink 1976). Those progenitors must have passed through a phase of common envelope evolution (Paczyński 1976; Meyer and Meyer-Hofmeister 1979) which removed much of the mass, and most of the initial angular momentum of the initial binary, leaving remnant systems with orbital periods of the order of hours or days, rather than months or years. How is it possible that the symbiotic stars escaped this fate?

The critical question for the occurrence of common envelope evolution, as it is now understood, is the stability of the binary against dynamical time scale mass transfer. If the mass ratio, M_1/M_2 (donor/accretor), at the onset of mass transfer exceeds some critical value, q_{crit}, dynamical instability of the donor star develops (Paczyński, Ziołkowski, and Żytkow 1969), leading to common envelope evolution; otherwise, mass transfer proceeds quasi-conservatively, i.e., in a manner which is at least approximately conservative of the total mass and angular momentum of the binary. In turn, q_{crit} depends on the structure of the donor star. Values of q_{crit} are not yet known for detailed models of giant star donors, but the results for condensed polytropes (Hjellming and Webbink 1987) are well-approximated (for $m_c \gtrsim 0.2$) by

$$q_{crit} = 0.362 + \frac{1}{3(1 - m_c)} , \qquad (1)$$

where m_c is the fraction of the mass of the donor star contained within its degenerate core. This finding opens the possibility that binary systems of sufficiently long period and low mass to develop relatively large core masses before mass transfer may survive with their masses and angular momenta more or less intact (see Figure 1).

Can common envelope evolution itself give rise to symbiotic-like binaries? Adopting a very idealized model for this type of evolution (as described by Webbink 1984), we obtain the distribution of remnant systems illustrated in Figure 2. Among remnant systems with nondegenerate components still massive enough to evolve to the giant branch within the age of the Galaxy, none has an orbital period much exceeding one year, regardless of initial mass ratio. Since the distributions portrayed here optimistically assume perfect efficiency in converting orbital energy of the original binary to unbinding the envelope of the donor star, this remnant orbital period limit is itself undoubtedly an upper limit. Common envelope evolution thus fails to account for the long orbital periods of known symbiotic stars with hot white dwarf components.

Quasi-conservative evolution, on the other hand, succeeds in this regard, as illustrated in Figure 3. Two potential populations of symbiotic stars arise from this type of mass transfer. At larger mass and long orbital period, we find the remnants of intermediate mass binaries (initial primary masses of ~3-12 $M_\odot$) which encountered mass transfer while the initial primary was crossing the Hertzsprung gap (see Webbink 1979). At lower mass, a second population resulting from low mass systems of nearly equal initial masses and relatively long orbital period (as described above) appears. Because of the rapid increase in the initial mass function toward lower masses, it is undoubtedly this second population which should dominate among types (iia) and (iia') symbiotics. The orbital periods predicted for these systems on the assumption of conservation of total mass and angular momentum are somewhat longer than established orbital periods for symbiotics of this type, but this discrepancy disappears altogether if these systems lose one-third to one-half of their initial angular momenta during the course of mass transfer, as Algol binaries (which undergo this same mode of mass transfer) appear to do (Giuricin and Mardirossian 1981). Because the radii of the white dwarf progenitors in these systems are strongly dependent on their core masses, the white dwarf masses in these low-mass symbiotics should be strongly correlated with their binary periods.

The existence of V2116 Oph, a type (iii) system with a disk-accreting neutron star, strongly suggests that at least a few low-mass white dwarf symbiotics are able to avoid common envelope evolution

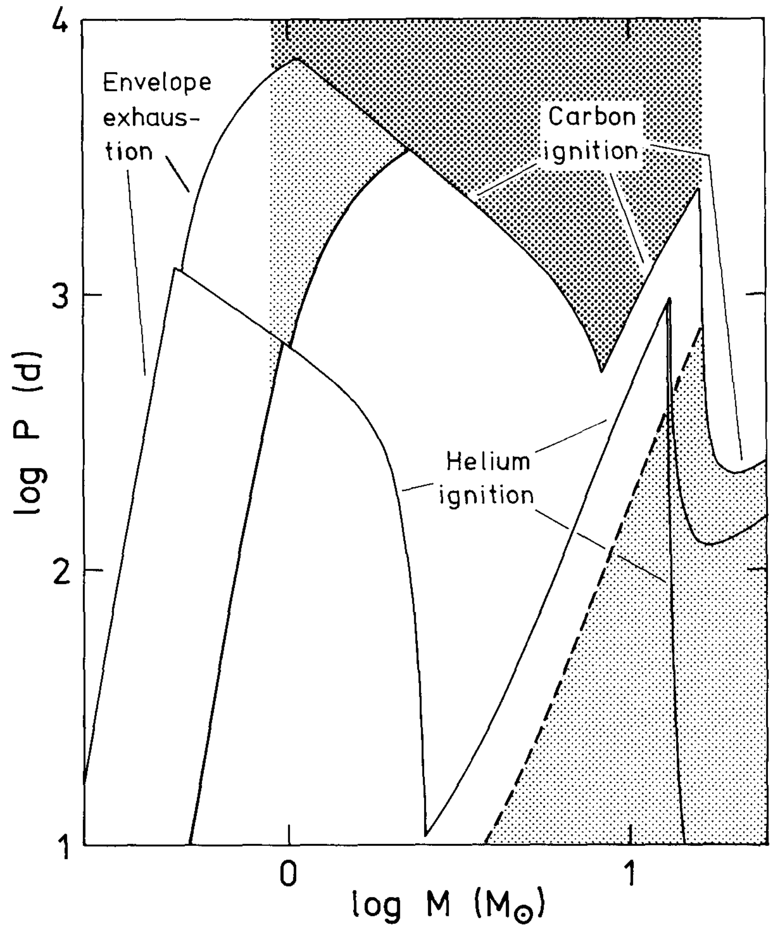

Figure 1. The orbital period-primary mass diagram for the progenitors of symbiotic stars containing hot white dwarfs. The orbital periods of binary systems with lobe-filling components at various critical phases of their evolution are labeled in the diagram. The heavy dashed line at lower right denotes the base of the giant branch; the heavy solid line paralleling that labeled "envelope exhaustion" marks the limiting period above which binaries of unit mass ratio are stable against dynamical mass transfer. Lightly shaded regions denote systems of unit mass ratio which undergo quasi-conservative evolution within 1.3 x 10^{10} yr. Systems in the unshaded region between them undergo common envelope evolution. The heavily shaded region at long period denotes long-period systems which may contain late-type giants, but interact only via stellar winds.

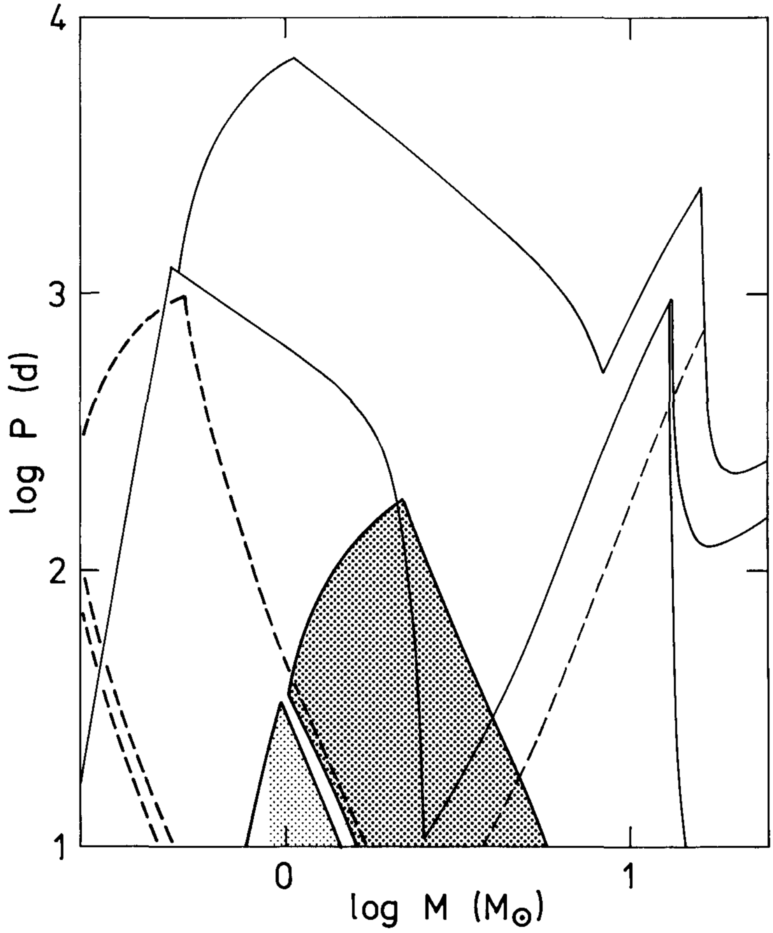

Figure 2. The period-mass diagram for remnants of common envelope evolution. Various critical periods are indicated as in Figure 1. The mass in this case is that of the non-degenerate component. Enclosed within the heavy solid lines are remnants of systems with unit initial mass ratios. The shaded regions mark systems which reach the second phase of mass transfer within 1.3 x 10^{10} yr: heavy shading, those with CO white dwarfs; light shading, those with He white dwarfs. The heavy dashed lines enclose the corresponding regions for binaries with initial mass ratios $M_1/M_2 = 2.5$.

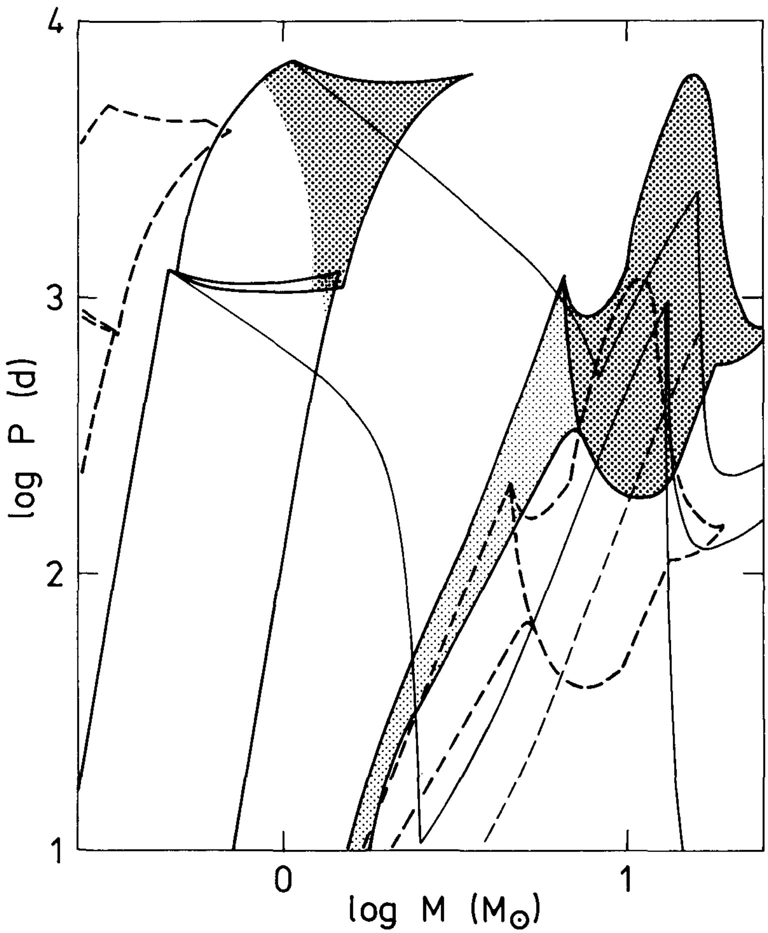

Figure 3. The period-mass diagram for remnants of conservative mass transfer. As in Figure 2, the mass is that of the non-degenerate component, the heavy solid lines enclose remnants of systems with unit initial mass ratios, the heavy dashed lines those of systems with initial mass ratios of 2.5. Once again, the shaded regions mark systems which reach the second phase of mass transfer within 1.3 x 10^{10} yr: heavy shading, those with CO white dwarfs; light shading, those with He white dwarfs.

https://doi.org/10.1017/S025292110010377X Published online by Cambridge University Press

during their second phases of mass transfer as well. Taam and van den Heuvel (1986) argue that the high magnetic moment deduced for the X-ray pulsing neutron star in this system indicates that it is a very young neutron star, and therefore probably a product of accretion-induced collapse of a white dwarf. The progenitor of V2116 Oph is therefore itself likely to have been a type (iia′), disk-accreting white dwarf symbiotic.

3. LIFETIME OF THE SYMBIOTIC STATE

All of the varieties of symbiotic stars enumerated above involve interaction between the two components of a binary system, with the accretion of mass by the hot component via either stellar winds (iia, iib) or tidal mass transfer (i, iia′, iii). The duration of the symbiotic phase should therefore reflect, at least crudely, the duration of this accretion phase. Moreover, the fraction of this time during which the hot component is sufficiently luminous to produce a recognizably symbiotic spectrum must depend as well on the amount of matter accreted by that component during the interaction lifetime. Both of these factors depend primarily on the properties of the donor star and the orbital parameters of the binary, and only very weakly on the nature of the accreting hot component.

Order of magnitude expressions are given in Table 1 for the durations (Δt) and relative efficiencies ($\Delta M_2/M_1$ = fraction of the initial mass of the donor, star 1, accreted by the hot component, star 2) of each of these modes of interaction. In these expressions, P is the orbital period, τ_R the *e*-folding time scale for the growth of the donor star in radius due to nuclear evolution, τ_W the *e*-folding time scale for the growth in wind mass loss rate, m_c the fraction of the mass of the donor star contained within its degenerate core, $R_{1,max}$ the maximum radius achieved by the donor star, and A the orbital separation. In the case of wind accretion, the Bondi-Hoyle approximation has been adopted, with the wind velocity from the giant assumed equal to its escape velocity, and the contribution of orbital motion to the relative velocity of the accretor neglected (see Tutukov and Yungel'son 1976). In the case of tidal mass transfer, analytic solutions for the time-development of the mass transfer rate are given by Webbink and Iben (1987) for the early phases of both dynamical time

TABLE 1. MASS TRANSFER MODES

Type	Δt	$\Delta M_2/M_1$
Pre-dynamical	$(\tau_R^2\ P)^{1/3}$	$(P/\tau_R)^{1/3}$
Quasi-conservative	τ_R	$1 - m_c$
Wind	$(\tau_W^{-1} + \tau_R^{-1})^{-1}$	$\frac{1}{4}\ (M_2/M_1)^2(R_{1,max}/A)^2$

scale and quasi-conservative mass transfer. Long term evolution in the quasi-conservative case is described by Webbink, Rappaport, and Savonije (1983).

If we adopt a simple parametric model of giant or asymptotic giant branch evolution, the expressions given in Table 1 can be rewritten in terms of the initial mass of the donor star, M_1, and the ratio, Π, of the orbital period, P, to the limiting period for tidal interaction, P_{RG} or P_{AG}. The resultant expressions, for donors of relatively low initial mass ($M_1 \lesssim 2.5\ M_\odot$), are listed in Table 2. Stellar winds have here been treated in Reimers' (1975) approximation, insofar as the wind accretion models and evaluation of P_{AG} are concerned; they have been neglected in evaluating the expressions for tidal mass transfer and P_{RG}.

TABLE 2. SYMBIOTIC STAR LIFETIMES

	Δt (yr)	$\Delta M_2/M_1$
(a) Red Giant Branch Donor (critical period $P_{RG} = 640^d\ M_1^{-0.89}$)		
Pre-dynamical	$6 \times 10^4\ M_1^{-0.33}\ \Pi_{RG}^{-0.12}$	$0.005\ M_1^{-0.28}\ \Pi_{RG}^{0.56}$
Quasi-conservative	$1.1 \times 10^7\ M_1^{-0.05}\ \Pi_{RG}^{-0.68}$	$1.- 0.46\ M_1^{-1.08}\ \Pi_{RG}^{0.14}$
Wind ($P/P_{RG} \equiv \Pi_{RG}<1$)	$1.9 \times 10^6\ M_1^{-0.05}\ \Pi_{RG}^{-0.68}$	$0.010\ M_1^{-2.25}\ \Pi_{RG}^{0.99}$
Wind ($\Pi_{RG}>1$)	$1.9 \times 10^6\ M_1^{-0.05}$	$0.010\ M_1^{-2.25}\ \Pi_{RG}^{-1.33}$
(b) Asymptotic Giant Branch Donor (critical period $P_{AG} = 2200^d\ M_1^{0.74}$)		
Pre-dynamical	$3 \times 10^4\ \Pi_{AG}^{0.33}$	$0.015\ \Pi_{AG}^{0.33}$
Quasi-conservative	2×10^6	$1.- 0.62\ M_1^{-0.59}\ \Pi_{AG}^{0.24}$
Wind ($P/P_{AG} \equiv \Pi_{AG}<1$)	4×10^5	$0.04\ (1.- 0.58\ M_1^{-0.69})\ \Pi_{AG}^{1.66}$
Wind ($\Pi_{AG}>1$)	4×10^5	$0.04\ (1.- 0.58\ M_1^{-0.69})\ \Pi_{AG}^{-1.33}$

N.B.: All masses are in solar units.

It is evident from Table 2 that the existence of even a small minority of symbiotic stars undergoing quasi-conservative Roche lobe overflow could dominate symbiotic star statistics. Such systems have not only significantly longer lifetimes than other modes of interaction, but also much higher efficiencies in accreting the envelopes of their companion stars. The absence of examples of type (iia') symbiotics suggests that conditions for this type of mass transfer rarely arise among those symbiotic stars containing hot white dwarfs which have previously undergone mass transfer. We should therefore expect that white dwarf (type ii) systems are primarily wind-fed, as observed, but with an appreciable minority of short-period systems in pre-dynamical Roche lobe overflow, and with a distinct preference for nearly-lobe-filling configurations even among wind-fed systems. Among main sequence star accretors (type i systems) on the other hand, quasi-conservative mass transfer may well occur in long-period, low-mass binaries of nearly equal initial masses (see Figure 1). *If* such systems transfer mass in bursts (and they achieve peak accretion rates in excess of $\sim 10^{-6}\ M_{\odot} yr^{-1}$ – see Kenyon and Webbink 1984), they may constitute the majority of type (i) systems.

The remaining factor governing the detectability of symbiotic systems is of course the nature of the hot component. Hydrogen-burning white dwarfs typically liberate ~3000 times as much energy per gram of accreted material as do non-burning, accreting main sequence stars. They are thus able to produce detectable nebular emission at much lower accretion rates (such as those occurring via stellar winds) than main sequence accretors, which require Roche lobe overflow (cf. Kenyon and Webbink 1984). Neutron stars release ~30 times as much energy per gram of accreted material as hydrogen-burning white dwarfs, but their characteristic spectral energy distribution is so hard that they are no more efficient at producing hydrogen-ionizing photons than disk-accreting cold white dwarfs. Thus, they probably also require Roche lobe overflow to produce symbiotic spectra.

4. CONCLUSIONS

The above considerations regarding the origin and stability of symbiotic binaries lead to the following broad conclusions:

1. Long-period symbiotics ($P \geq 15$ yr) are powered by wind-accreting white dwarfs (Tutukov and Yungel'son 1976), having evolved to their present state without tidal interaction.

2. Symbiotics powered by accretion onto main sequence stars are necessarily shorter in orbital period, as they require Roche lobe overflow, and may occur over a wide range of initial conditions. However, those systems with orbital periods of ~2-10 yr with initial mass ratios near unity may be very long-lived in the symbiotic state.

3. Short-period ($P \lesssim 15$ yr) symbiotics containing hot white dwarf components are products of quasi-conservative mass transfer. Two populations may occur: (a) relatively massive systems ($M_{cool} \sim 4$-$10\ M_{\odot}$, $P \sim 100$-1000 days); and (b) low-mass systems ($M_{cool} \sim 1$-$2\ M_{\odot}$, $P \sim 200$-5000 days). Some low-mass systems containing massive white dwarfs may avoid common envelope evolution, surviving as symbiotic stars for a very long time ($\sim 2 \times 10^{6}$ yr) in a Roche lobe-filling state;

https://doi.org/10.1017/S025292110010377X Published online by Cambridge University Press

but such systems are evidently relatively rare. Except for these systems, those in which interaction occurs via stellar winds should dominate statistically, but it remains problematical why observed systems of this type so often underfill their Roche lobes by a large margin (see Kenyon and Gallagher 1983; Kenyon and Fernandez-Castro 1987; and discussions therein). The white dwarf masses among low-mass systems should be correlated with their orbital periods.

This research was supported by National Science Foundation grants AST 83-17916 and AST 86-16992. I also thank Dr. W. Dziembowski, Director, and the staff of the N. Copernicus Astronomical Center, Warsaw, where a portion of this work was completed, for their gracious hospitality.

REFERENCES

Allen, D.A. 1982, in *IAU Colloquium No. 70, The Nature of Symbiotic Stars*, ed. M. Friedjung and R. Viotti (Dordrecht: Reidel), p. 27.
Cutler, E.P., Dennis, B.R., and Dolan, J.F. 1986, *Astrophys. J.*, **300**, 551.
Gallagher, J.S., Holm, A.V., Anderson, C.M., and Webbink, R.F. 1979, *Astrophys. J.*, **229**, 994.
Giuricin, G., and Mardirossian, F. 1981, *Astrophys. J. Suppl.*, **46**, 1.
Glass, I.S., and Webster, B.L. 1973, *Monthly Notices R. Astr. Soc.*, **165**, 77.
Hjellming, M.S., and Webbink, R.F. 1987, *Astrophys. J.*, **318**, 794.
Kenyon, S.J., and Fernandez-Castro, T. 1987, *Astr. J.*, **93**, 938.
Kenyon, S.J., and Gallagher, J.S. 1983, *Astr. J.*, **88**, 666.
Kenyon, S.J., and Webbink, R.F. 1984, *Astrophys. J.*, **279**, 252.
Kenyon, S.J., Webbink, R.F., Gallagher, J.S., and Truran, J.W. 1982, *Astr. Astrophys.*, **106**, 109.
Keyes, C.D., and Plavec, M.J. 1980, in *IAU Symposium No. 88, Close Binary Stars: Observations and Interpretation*, ed. M. J. Plavec, D. M. Popper, and R. K. Ulrich (Dordrecht: Reidel), p. 365.
Meyer, F., and Meyer-Hofmeister, E. 1979, *Astr. Astrophys.*, **78**, 167.
Mikołajewska, J. 1985, *Acta Astr.*, **35**, 65.
Mikołajewska, J., and Mikołajewski, M. 1983, *Acta Astr.*, 33, 403.
Paczyński, B. 1976, in *IAU Symposium No. 73, Structure and Evolution of Close Binary Systems*, ed. P. Eggleton, S. Mitton, and J. Whelan (Dordrecht: Reidel), p. 75.
Paczyński, B., Ziołkowski, J., and Żytkow, A. 1969, in *Mass Loss from Stars*, ed. M. Hack (Dordrecht: Reidel), p. 237.
Reimers, D. 1975, *Mem. Soc. R. Sci. Liége*, 6e ser., **8**, 369.
Ritter, H. 1976, *Monthly Notices R. Astr. Soc.*, **175**, 279.
Taam, R.E., and van den Heuvel, E.P.J. 1986, *Astrophys. J.*, **305**, 235.
Tutukov, A.V., and Yungel'son, L.R. 1976, *Astrofiz.*, **12**, 521 (English transl.: 1977, *Astrophys.*, **12**, 342).
Webbink, R.F. 1976, *Astrophys. J.*, **209**, 829.

Webbink, R.F. 1979, in *IAU Colloquium No. 53, White Dwarfs and Variable Degenerate Stars*, ed. H. M. Van Horn and V. Weidemann (Rochester: U. Rochester Press), p. 426.

Webbink, R.F. 1984, *Astrophys. J.*, **277**, 355.

Webbink, R.F., and Iben, I., Jr. 1987, in *IAU Colloquium No. 95, The Second Conference on Faint Blue Stars*, ed. A.G.D. Philip, D.S. Hayes, and J. Liebert (Schenectady: L. Davis Press), in press.

Webbink, R.F., Rappaport, S., and Savonije, G.J. 1983, *Astrophys. J.*, **270**, 678.

Whitelock, P. 1987, *Publ. Astr. Soc. Pacific*, **99**, 573.