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Population synthesis of Be/white dwarf binaries in the Galaxy

N. V. Raguzova[*]

Sternberg Astronomical Institute, Moscow University, Moscow 119899, Russia

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Abstract. Using the "Scenario Machine" (a numerical code that models the evolution of large ensembles of binary systems) we study the number and physical properties of binary Be stars with white dwarfs taking account of the compact object cooling and we discuss the ways of their formation. In our calculations we take into account the influence of tidal synchronization on the evolution of stars in a close binary. The synchronization time scale may be less than the life-time of a Be star on the main sequence after the first mass transfer. It has strong effects on the resulting number distribution of binary Be stars over orbital periods. In particular, it can explain the lack of short period Be binaries. According to our calculations the number of binary systems containing a Be star paired with a white dwarf in the Galaxy is very large – 70% of all Be stars formed as a result of binary evolution must have a white dwarf as a companion. Based on our calculations we conclude that the compact companion in these systems must have a high surface temperature. The number distribution over the surface temperature peaks at 2 10^4 K for all white dwarfs and at 4 10^4 K for white dwarfs paired with early-type Be stars (between B0 and B2). The registration of white dwarfs in such systems is hampered by the fact that the entire orbit of a white dwarf is embedded in the dense circumstellar envelope of the primary star (our calculations show that the majority of Be/WD systems have orbital periods less than one year) and all extreme-UV and soft X-ray photons of a compact companion are absorbed by the Be star envelope. The detection of a white dwarf is possible during the period when the Be star disc-like envelope is lacking by the detection of white dwarf extreme-UV and soft X-ray emission. This method of registration appears to be particularly promising for "single" early-type Be stars because in these systems the white dwarfs must have a very high surface temperature. However, the loss of the Be disc-like envelope does not often occur and it is a rather rare event for many Be stars. The best possibility of white dwarf detection is given by the study of helium spectral lines found in emission from several late-type Be stars. The ultraviolet continuum energy of these Be stars is found to be not enough to produce the observed helium emission. Besides, we also discuss the orbital properties of binary Be star systems with other evolved companions such as helium stars and neutron stars and give a possible explanation for the lack of Be/black hole binaries.

Key words. stars: binaries: close – stars: emission line, Be – stars: evolution – stars: white dwarfs – ultraviolet: stars – X-rays: stars

1. Introduction

The evolutionary state of Be stars is still a matter of debate. Mass transfer during primary's Roche lobe overflow in a close binary system can result in a rejuvenated and spun-up secondary star which may appear as a rapidly rotating Be star (Křiž & Harmanec 1975; Rappaport & van den Heuvel 1982; Waters et al. 1989; Pols et al. 1991; Portegies Zwart 1995; van Bever & Vanbeveren 1997). According to this model, the Be star should have an evolved companion, either a helium star, a white dwarf, or a neutron star. However, despite the large estimated number of Be binaries, only Be/neutron star systems have been found. Be stars in Be/X-ray binaries turn out to cover a very limited range in spectral type, namely between O9 and B2. This is due to the fact that only the more massive systems can produce a neutron star. Evolutionary calculations show that the less massive systems will produce a rapidly rotating Be star, which may be of later spectral type than B2, and a white dwarf or a helium star.

Systems with white dwarf companions have not yet been detected. The presence of helium companions has been advocated in the cases of HR 2142 (Waters et al. 1991) and ϕ Per (Poeckert 1981; Gies et al. 1998). The existence of a degenerate dwarf in γ Cas is doubted in present time (see Smith et al. 1998a, 1998b; Smith & Robinson 1999; Robinson & Smith 2000).

The formation of Be/white dwarf (Be/WD) binaries, the expected number of such systems and the possibility of finding these binaries were investigated by a series of researchers (Waters et al. 1989; Pols et al. 1991; Portegies Zwart 1995; van Bever & Vanbeveren 1997; Apparao 1991). Estimates for the fraction of Be stars (formed as a result of binary evolution) with white dwarf

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[*] e-mail: raguzova@sai.msu.ru

companions range from 70% (van Bever & Vanbeveren 1997) to 22% (Waters et al. 1989; Pols et al. 1991).

In this paper we perform the population computation of the abundance of Be/WD binaries, calculate their expected orbital and physical characteristics and discuss their influence on the observational appearances of white dwarfs in a binary system with Be star. For the first time in such calculations we take into account the compact object cooling and the influence of tidal synchronization on the evolution of a Be star in a close binary. Besides, we discuss the properties of binary Be star systems with other evolved companions such as helium stars and neutron stars and give a possible explanation for the lack of Be/black hole binaries.

All statistical computations have been made using the Scenario Machine (a numerical code that models the evolution of large ensembles of binary systems; Lipunov et al. 1996) developed at the Relativistic Astrophysics Department of the Sternberg Astronomical Institute. The demonstration version of the Scenario Machine is available at our WWW site `http://xray.sai.msu.ru/sciwork/scenario.html`

2. The problem of white dwarfs cooling

The problem of cooling is a central problem in studies of the evolution of white dwarfs. It is known that the dominant source of luminosity of a white dwarf is the consumption of the thermal energy of the ions stored in the stellar interior. At the stage of formation and early cooling of the white dwarf neutrino emission plays a large role in the evolution. The theory of cooling of single white dwarfs predicts the connection between the luminosity of white dwarf and its age, and is well-confirmed by observational data. The original theory has been developed by Kaplan (1950) and Mestel (1952).

The white dwarf consists of a radiative envelope of nondegenerate matter and a degenerate isothermal core. At the boundary between these regions the pressure of degenerate electrons is equal to the one of nondegenerate electrons. Without going into the details of the theory of white dwarf cooling we shall simply give the basic formula obtained for the dependence of the luminosity of a white dwarf on time, $L(t)$ (Shapiro & Teukolsky 1983):

$$L(t) = 1.82\ 10^{30}\ \mathrm{erg\ s^{-1}} \frac{\mu}{\mu_Z^2} \frac{M/M_\odot}{x_Z(1+x_H)} \times \left(\frac{\tau}{1.72\ 10^{10}\ \mathrm{yrs}} \frac{A}{x_Z(1+x_H)} \frac{\mu}{\mu_Z^2} + T_{7,0}^{-2.5} \right)^{-7/5} \quad (1)$$

where μ is the mean atomic weight, μ_Z is the number of nucleons per one electron, M is the white dwarf mass, x_Z is the fraction of heavy elements (all elements other than H and He), x_H is the fraction of H, τ is the cooling time of white dwarfs between the temperatures of core T_0 and T (in years), $T_7 = T/10^7$ K, A is the atomic weight (the ratio of the average mass per atom of the element to 1/12 of the mass of ^{12}C). It is commonly taken that in the envelope of white dwarfs $x_Z = 0.1$, $x_H = 0$, then, $\mu_Z = 2$, $\mu = 1.38$, $\mu/[\mu_Z^2 x_Z(1+x_H)] = 3.45$. Evidently if we know the initial temperature of the core then we can calculate the temperature at the surface of the white dwarf, T_{eff}, for any moment of time.

3. The population synthesis of binary Be stars paired with white dwarfs and their physical properties

3.1. The general principles of code operation

The calculations have been made using the Scenario Machine. The program Scenario Machine was described for the first time in a paper by Kornilov & Lipunov (1983). Recently a very detailed description of this program was given in a review by Lipunov et al. (1996). Here we will only describe some general principles of Scenario Machine operation and parameters which are needed for our calculations.

The program computes the evolution of a large number of binary systems with randomly chosen parameters from the instant of the formation of the binary system to the present instant. The calculations are carried out by using the Monte Carlo method. The instant of binary formation is drawn at random, and so are its parameters which are distributed in accordance with currently established or accepted empirical laws. The binary system then begins to evolve in accordance with the current evolutionary scheme. We follow the basic ideas on stellar evolution to describe the evolution of binaries both with normal and compact companions based upon the original ideas that appeared in the papers by Paczynsky (1971), Tutukov & Yungelson (1973) and van den Heuvel & Heise (1972) (see recent review by van den Heuvel 1994). The continuous evolution of each binary component is treated as a sequence of a finite number of basic evolutionary states (for example, main sequence, red (super)giant, helium (Wolf-Rayet) star), in which stellar parameters significantly differ from each other. The evolutionary state of the entire binary can thus be determined as a combination of the states of each component, and alters once the faster evolving component goes into the next state. At each such stage it is assumed that the star does not change its physical parameters which affect the evolution of its companion. Every time the faster evolving component goes into the next stage its parameters are recalculated. Depending on the evolutionary stage, the state of the slower evolving star is changed accordingly or may remain the same. We follow Webbink (1979) in treating the first mass exchange modes for normal binary components, which account for the physical state of the star in more detail than the simple types of mass exchanged (A, B, C introduced by Kippenhann & Weigert 1967).

The evolution cannot be fully conservative as a rule, since during the first mass transfer episode the more massive star is usually characterized by a shorter thermal time-scale. At stages with Roche lobe overflow and both normal stars we assume a mildly non-conservative mass-transfer;

$$\dot{M}_{\rm c} = \dot{M}_{\rm o}\left[\frac{t_{\rm KH}(\rm donor)}{t_{\rm KH}(\rm accretor)}\right] \quad (2)$$

where $\dot{M}_{\rm c}$ is the accretion rate of the captured matter, $\dot{M}_{\rm o}$ is the mass loss rate of the donor star, $t_{\rm KH}$ is the thermal time of the star. The binary separation a changes differently depending on the mass exchange mode. We introduce a measure of non-conservativeness of the mass exchange in the form of the ratio between the accreting and the mass-loosing star mass changes:

$$\beta \equiv -(M_{\rm a}^{\rm i} - M_{\rm a}^{\rm f})/(M_{\rm d}^{\rm i} - M_{\rm d}^{\rm f}). \quad (3)$$

The notation "a" and "d" denotes the accreting star and the donor star, while "i" and "f" denote the initial and final values of parameters. If the mass transfer is conservative ($\beta = 1$, i.e. $M_{\rm a} + M_{\rm d} =$ const.) and one may neglect the redistribution of the intrinsic angular momenta of the components, the total orbital momentum conservation law implies:

$$\frac{a_{\rm f}}{a_{\rm i}} = \left(\frac{M_{\rm a}^{\rm i} M_{\rm d}^{\rm i}}{M_{\rm a}^{\rm f} M_{\rm d}^{\rm f}}\right)^2. \quad (4)$$

In a more general case of quasi-conservative mass transfer $0 \le \beta < 1$, the orbital separation changes depend on the specific angular momentum removed from the system by the escaping matter. To be specific, we use the "isotropic mass loss mode" by letting matter remove the specific orbital angular momentum of the accreting component ($j_{\rm a}$)

$$\dot{J}_{\rm out} = (1-\beta)\dot{M}_{\rm c} j_{\rm a}, \quad (5)$$

from which we straightforwardly find

$$\frac{a_{\rm f}}{a_{\rm i}} = \left(\frac{q_{\rm f}}{q_{\rm i}}\right)^3 \left(\frac{1+q_{\rm i}}{1+q_{\rm f}}\right) M \left(\frac{1+\beta/q_{\rm f}}{1+\beta/q_{\rm i}}\right)^{3+2/\beta}, \quad (6)$$

here $q = M_{\rm accr}/M_{\rm donor}$.

Each run of our calculations consisted of tracking the evolution of 1 000 000 ZAMS binaries with initial masses within a range from 2 to 120 $M_\odot$. The initial binary separations, a, were taken to be distributed as $f(\log a) =$ constant and chosen from the range 10 to 10^7 $R_\odot$. When calculating we made the zeroth order assumption that the mass ratio distribution has a flat shape, i.e. binaries with a high mass ratio occur as frequently as those with equal masses. Also we assume the primary mass to obey Salpeter's power law:

$$f(M_1) \propto M^\alpha \ (\alpha = 2.35),\ 2\ M_\odot < M_1 < 120\ M_\odot,$$

$$f(q) \propto q^{\alpha_q}\ (\alpha_q = 0),\ q = M_2/M_1 < 1.$$

The flat initial mass ratio spectrum was chosen because it is currently the most popular among researchers (e.g. Tutukov & Yungelson 1993; Pols & Marinus 1994). Salpeter's power law is currently universally accepted. As a rule, other possible initial mass functions fail to agree with observations.

We assume that Be stars are formed in binary systems where mass transfer spins up the accretor to high rotational velocity so that it starts showing the Be-effect. This scenario was proposed for the first time by Kriz & Harmanec (1975) and by Rappaport & Van den Heuvel (1982). Packet (1981) has shown that the accretor need gain only a few percent of its original mass in order to become a Be star. We also assume that Webbink's mass exchange modes IIa-IIf (Webbink 1979) produce Be star, mass of Be star falls in the range between 2.38 and 20 $M_\odot$ (see Harmanec 1988), and the common envelope stage must not occur during the first mass transfer. For B type systems in which Be stars can be produced we use the condition $q \le 0.3$ for the common envelope stage to occur.

A consideration of tidal synchronization in a binary system is made in accordance with Tassoul's theory (Tassoul 1987). He has presented a purely hydrodynamical mechanism which tends to synchronize the axial and orbital motions of the components of a binary. This process involves a large-scale meridional flow, superposed on the motion around the rotation axis of the tidally distorted component. These mechanically-driven currents cease to exist as soon as synchronization has been achieved in the star. This hydrodynamical mechanism was devised because, in the whole early spectral range, synchronous rotators and circular orbits are observed in main-sequence binaries with orbital periods substantially larger than previously thought possible.

In a recent paper, Rieutord & Zahn (1997) claim to have proven on theoretical grounds that Tassoul's mechanism cannot operate in real stars. In reply to their paper, Tassoul & Tassoul (1997) in their new paper explain why Rieutord & Zahn (1997) have *not* proven that tidally driven currents do not exist in a nonsynchronous rotator. They show that Rieutord & Zahn's mathematical analysis of the problem is incomplete, so that it cannot be used to prove or disprove the existence of these currents. They also explain why planetary systems, such as Io-Jupiter or 51 Peg and its planet cannot be used as counter-examples to Tassoul's hydrodynamical mechanism.

Detailed studies by Claret & Gimenez (1995) and Claret et al. (1995) give further support to Tassoul's hydrodynamical mechanism for binary systems containing early-type stars with radiative envelopes. According to Tassoul (1987) and Claret et al. (1995) for nearly circular orbits the synchronization time scale is

$$\tau_{\rm syn} = 5.35\ 10^{3-N/4}\frac{1+q}{q}L^{-1/4}M^{5/4}R^{-3}P^{11/4} \quad (7)$$

where M, L and R are in solar units, P is in days, $\tau_{\rm syn}$ is in years, q is mass ratio. The parameter N is connected with the different ways to transport energy into the outer layers of the stars. For stars with envelopes in radiative equilibrium, $N = N_{\rm r}$ assumed to be 0.

When calculating the evolution one should take into account that the synchronization time scale may be less than the main-sequence life-time of the Be star after the first mass transfer. It has strong effects on the resulting number distribution of Be binaries over orbital periods. The critical orbital period for Be binary can be obtained by equating the life time of the star on the main sequence and the synchronization time-scale. If the binary has an orbital period under the critical value then the Be star has time to synchronize its rotation with the orbital motion and loses its Be character before it leaves the main sequence. Thus the short-period binary Be stars will be removed from the population by the operation of the synchronization mechanism.

The life-time of a helium star is determined by the helium nuclear burning duration (Iben & Tutukov 1985) and for modes IIa-IIf (see Webbink 1979):

$$t_{\rm He} = \begin{cases} 1658M^{-2} & M < 1.1 \\ 1233M^{-3.8} & M > 1.1, M_{\rm max} < 10 \\ 0.1t_{\rm H} & M_{\rm max} > 10 \end{cases} \qquad (8)$$

where time is expressed in million years ($t = t/10^6$ yr), $M_{\rm max}$ is the maximum mass the star attained during its previous evolution, M is the mass of the helium star in solar masses, $t_{\rm H}$ is the hydrogen burning time.

The different chemical composition of white dwarfs (He-, CO- and O-Ne-Mg-white dwarfs) was also taken into account in the calculations. We also take into consideration that during the evolution of a binary system CO- and O-Ne-Mg-white dwarfs can increase their mass to the Chandrasekhar limit due to accretion of matter and evolve into a neutron star.

3.2. Physical properties of Be/WD systems

The existence of white dwarf companions to Be stars is of significant importance from an evolutionary standpoint since they must have evolved from massive progenitors, perhaps close to the maximum mass for white dwarf progenitor stars, and they are likely themselves to be much more massive than the mean for white dwarfs in general (0.57 $M_{\odot}$, Finley et al. 1997). The presence of a component of spectral class B implies that the white dwarf progenitor star was massive enough to evolve faster and to leave the main sequence and, then, to collapse into white dwarf. It is evident that the maximum of the number distribution of Be/WD binaries over masses of degenerate companion must shift to larger masses compared to similar distributions for single white dwarfs and their analogs in low mass binary systems. Our calculations support this conclusion. The expected number distribution of Be/WD binaries over mass of the compact object is shown in Fig. 1. It is seen that the masses of white dwarfs lie in the broad range between 0.3 and 1.4 $M_{\odot}$. The peak of the distribution falls between 0.8−1.0 $M_{\odot}$. This peak owes its origin to a large number of degenerate carbon-oxygen dwarfs. A second peak is in evidence at 0.3−0.4 $M_{\odot}$ due to the presence of long-lived late-type Be stars with helium degenerate dwarfs.

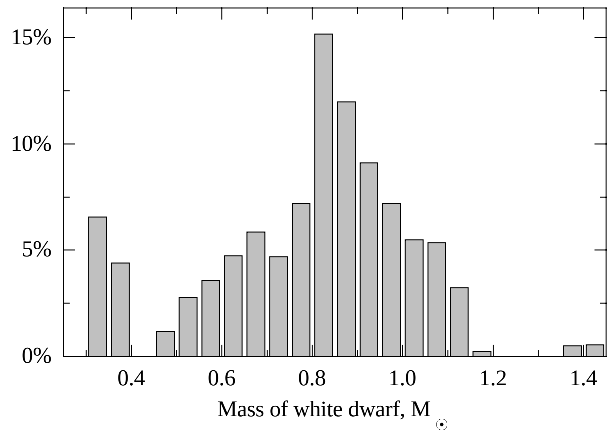


Fig. 1. The expected number distribution of Be/WD binaries over mass of the compact object

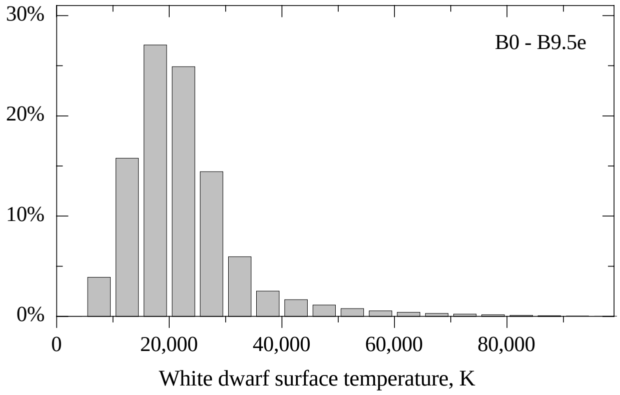


Fig. 2. The expected number distribution of Be/WD binaries over temperature at the white dwarf surface

The expected number distribution of Be/WD binaries over surface temperature of the white dwarf is shown in Fig. 2. The initial temperature of the core in the calculations is equal 1 10^8 K by recognizing that the maximum surface temperature of white dwarf obtained from observations is equal to 90 000−95 000 K. Our calculations show that in spite of the abundance of low-mass long-lived late-type Be stars, white dwarfs in Be/WD systems have insufficient time to cool down in the life-time of the Be star and have temperatures lying in the range from 5 10^3 to 8 10^4 K with a maximum at 2 10^4 K. It is evident that the hottest white dwarfs must be observed in binary systems containing early-type Be stars. Their distribution is shown in Fig. 4. Most white dwarfs in such systems have temperatures falling in the range from 3 10^4 to 5 10^4 K. Based upon the obtained results the detection of extreme-UV and soft X-ray emission from the hot surface of the compact object could be proposed as one way to identify these systems. However, as was shown in a paper by Apparao (1991), this registration method does not always work, especially in the case of very close binary systems.

Let us consider the orbital properties of Be/WD systems obtained from our calculations. The number distribution of Be stars paired with white dwarfs over orbital characteristics is shown in Fig. 3. Both orbital periods and

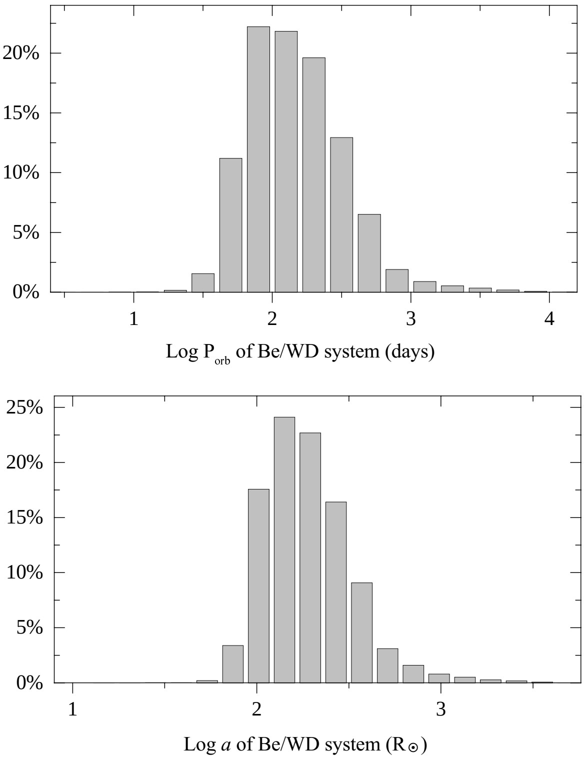


Fig. 3. The expected number distribution of Be/WD binaries over orbital parameters

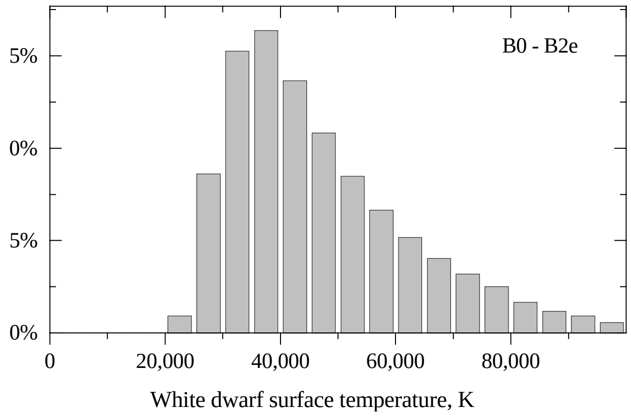


Fig. 4. The expected number distributions of Be/WD binaries over temperature at the white dwarf surface for early-type Be stars

semimajor axes are shown. It is seen that such systems do not have orbital periods more than one-two years, that is, all these binaries are close. There is a lack of systems with periods 10–30 days. As was shown in paper by Raguzova & Lipunov (1998) the lack of short-period Be/X-ray binaries can be explained by the effect of tidal synchronization in the binary system. The same mechanism operates in this case. The short-period Be/WD binaries are removed from the population by the operation of the synchronization mechanism.

Notice that all observed Be binaries have orbital periods longer than 17 days (see, for example, Negueruela 1998). This phenomenon was long unexplained although it was thought that some tidal mechanism operates in this case. The inclusion of the influence of tidal synchronization on the Be star evolution in a close binary according to Tassoul's theory is capable of solving this problem.

The semimajor axes of the majority of Be/WD systems are under 300 $R_\odot$. The orbit of the white dwarf in such systems is circular because the formation of white dwarf does not involve a supernova event kicking the newly formed compact object out of the original orbital plane. The equatorial plane of the Be star is coincident with the orbital plane of the white dwarf for the same reason. The sizes of Be discs are found to be from several tens to several hundreds of stellar radii (Tavani & Arons 1997). This means that the entire orbit of the white dwarf is embedded in the *dense* circumstellar envelope of the primary star. It poses great difficulties for the registration of a white dwarf in Be/WD binaries.

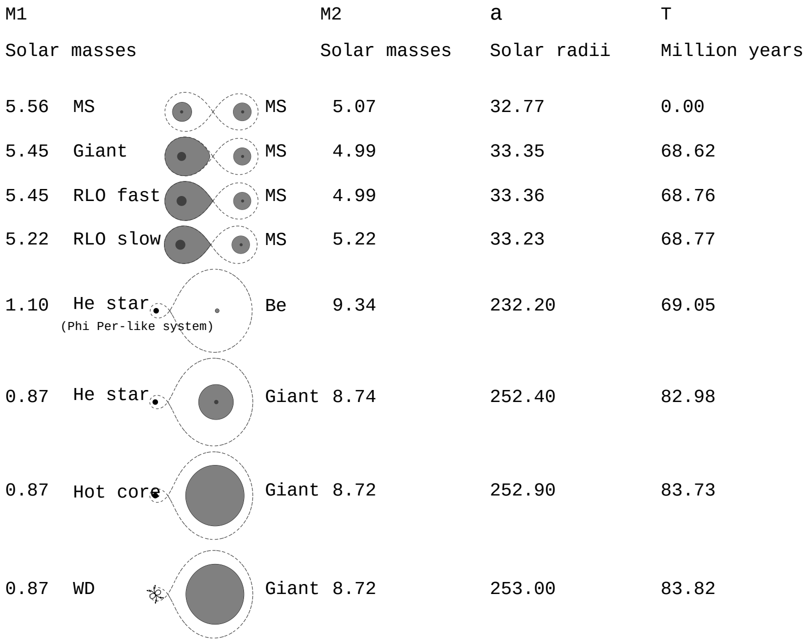
4. Be stars paired with other evolved companions

4.1. Be/helium star systems

In the process of mass exchange, the hydrogen envelope of the star can be almost completely lost, leaving behind as a remnant a hot naked core (it is almost entirely degenerate except for the outer layers and nuclear reactions do not occurs in it) for initial mass $M \leq 2.5\ M_\odot$, or a non-degenerate helium star for higher masses (a Wolf-Rayet star in the case of a star with initial mass $> 10\ M_\odot$). The life-time of a helium star is determined by the helium nuclear burning duration (Iben & Tutukov 1985).

The helium star may fill its Roche lobe and transfer almost pure helium to the main-sequence companion (case "BB" of mass transfer, Delgado & Thomas 1981). Case BB mass transfer can take place only after the exhaustion of helium in the core of the primary and start before or after the ignition of carbon. For helium stars with core mass below the Chandrasekhar limit, the end result of BB mass exchange, is a carbon-oxygen white dwarf with a companion still close to the main sequence. In the relatively rare cases for initial masses somewhat larger than 10.3 $M_\odot$, carbon burning will continue until a degenerate ONe core is formed.

The term "helium star" in the present context refers to a stripped-down, bare He-burning stellar core. The actual surface abundance depends on how much of the envelope was retained after mass transfer. One of the best candidates for Be/helium star system is the long-period (127 days) binary ϕ Per. Poekert (1981) presented the first evidence of a helium star companion in this bright Be binary. Based on the antiphase velocity curve of the He II 4686 Å emission line, Poeckert argued that the emission originates in hot gas surrounding the companion. The high temperature required to ionize helium led Poeckert to suggest that the companion must be a very hot star, possibly the stripped-down remnant from prior mass transfer. Gies et al. (1998) derived a double-lined solution for the radial velocity curve that yields masses of $9.3 \pm 0.3\ M_\odot$



M1 Solar masses		M2 Solar masses	a Solar radii	T Million years
5.56	MS / MS	5.07	32.77	0.00
5.45	Giant / MS	4.99	33.35	68.62
5.45	RLO fast / MS	4.99	33.36	68.76
5.22	RLO slow / MS	5.22	33.23	68.77
1.10	He star / Be (Phi Per-like system)	9.34	232.20	69.05
0.87	He star / Giant	8.74	252.40	82.98
0.87	Hot core / Giant	8.72	252.90	83.73
0.87	WD / Giant	8.72	253.00	83.82

Fig. 5. The evolutionary track for a Phi Persei-like binary. Note that a Be star paired with a white dwarf cannot be formed in this system

and $1.14 \pm 0.04\ M_\odot$ for the Be star and its companion, respectively.

The identification of this system is of significant importance from an evolutionary standpoint since it can provide support for the binary origin of Be stars. It is of interest to consider a possible evolutionary track leading to the formation of a ϕ Per-like binary system. This track is presented in Fig. 5 and includes the possible future fate of ϕ Per-like system. In order to obtain the evolutionary track for this system we assumed fully conservative mass transfer. It is of interest that this ϕ Per-like binary system can *never* evolve into a Be/WD binary, since the primary component has had time to leave the main sequence and to go towards the red giant region in the Hertzsprung-Russell diagram during the Be/helium star phase. Notice, that the evolutionary track for a ϕ Per-like binary system cannot be obtained in a case of non-conservative mass transfer in accordance with the current evolutionary scheme used in the Scenario Machine model.

In Figs. 5 and 8 we use the following notation for particular evolutionary stages of the components: MS = a main sequence star inside its Roche lobe (RL); RLO = a MS or post-MS star filling its Roche lobe and transferring matter onto the companion; RLO(fast) = Roche lobe overflow on a thermal timescale; RLO(slow) = slow (evolutionary driven) phase of mass transfer; He star = a helium star; He RLO = a He star filling its Roche lobe (case "BB" mass transfer); Hot core = a naked stellar core left after mass exchange, it is almost entirely degenerate except for the outer layers, after its cooling a white dwarf is formed; WD = a white dwarf. All numerical data are given at the onset of each stage.

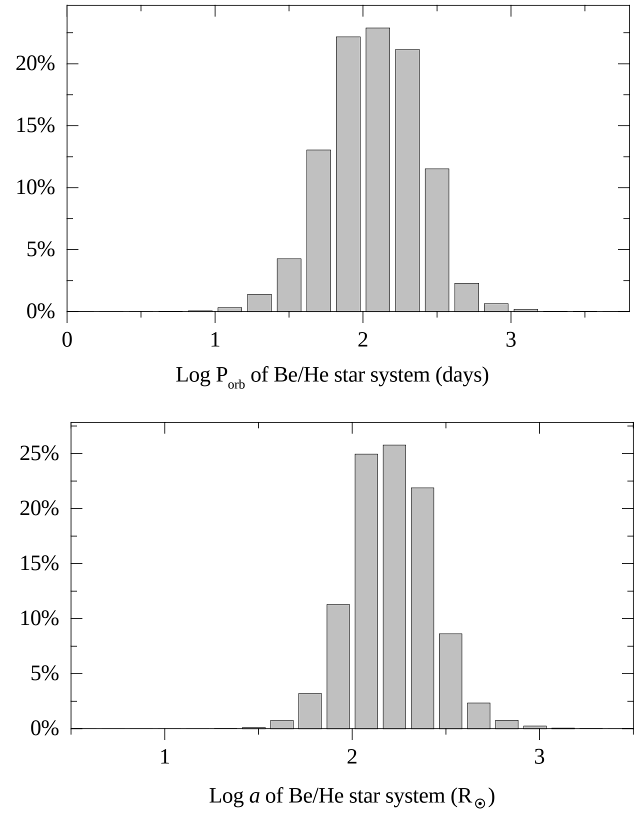


Fig. 6. The expected number distributions of Be/He star binaries over orbital parameters

The number distribution of Be stars paired with helium stars over orbital characteristics are shown in Fig. 6. The lack of short-period system is evident, which is caused by the influence of synchronization. Very long-period

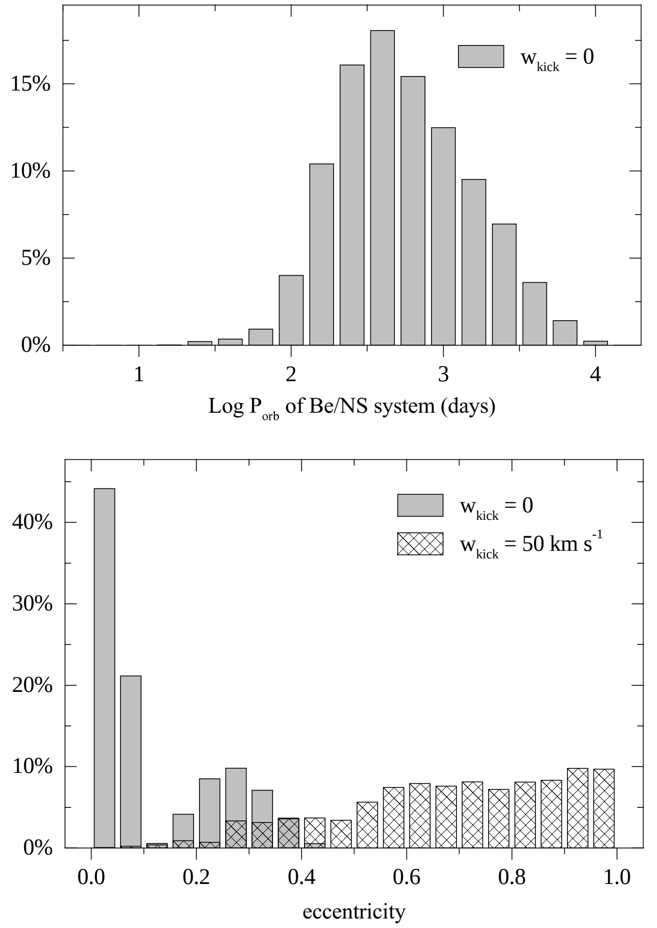


Fig. 7. The expected number distributions of Be/NS binaries over orbital period and eccentricity

binaries with orbital periods more than 2–3 years are also absent. Thus it can be concluded that in these binary systems the secondary component is always embedded in the *dense* circumstellar envelope of the Be star. The distributions of Be/He star binaries over orbital properties are similar in shape to the related distributions for Be/WD systems. This is no surprise since from the beginning of the stage with a helium star to the white dwarf formation nothing has happened that could have led to significant changes of the orbital parameters (the exception is the rare stage when the helium star fills its Roche lobe that results in an increase of the orbital period, see Fig. 8).

4.2. Be/NS systems (Be/X-ray binaries)

The properties of these systems have been studied extensively in a previous paper (Raguzova & Lipunov 1998), in which the evolutionary tracks were calculated which can lead to the formation of Be + X-ray-pulsar binaries with parameters similar to those of some observed Be/X-ray systems. It is known that even in the spherically symmetrical case, the supernova explosion changes both the semimajor axis of the system and its eccentricity. In the presence of weak asymmetry, the explosion can turn the orbital plane of the binary system relative to the rotation axis of the secondary, and the compact object (neutron star) that is formed will experience a substantial additional impulse. As a result, the eccentricity of the orbit will in most cases increase sharply. It seems that to get good agreement with the observed parameters of Be/X-ray binaries, a kick velocity less than 50 km s^{-1} is enough (see Raguzova & Lipunov 1998). However, the possible anisotropy of the collapse cannot be neglected, as the peak of the observed number distribution of Be/NS systems over eccentricities falls in the range 0.3–0.4, and Be/X-ray binaries are observed with $e > 0.8$ (see Raguzova & Lipunov 1998). As is evident from Fig. 7, a kick velocity $w = 50$ km s^{-1} is enough to get eccentricities 0.8–0.9. For $w = 0$ km s^{-1} we obtain apparent disagreement with the observations. The lack of short-period systems is also evident. Notice, that due to the necessity to explain the observed lack of short-period Be/X-ray binaries, the authors of the previous paper (Raguzova & Lipunov 1998) considered different factors having influence on the parameters of a binary system, and concluded that Tassoul's tidal mechanism can be the main cause of the lack of Be stars in short-period systems.

4.3. Be/black hole binaries

So far no Be/black hole binaries have been identified. The Be stars in such systems should be more massive than in the Be/NS systems, since the progenitor of a black hole is a massive star and the large initial mass ratio can lead to the common envelope stage during the first mass transfer (this stage inhibits the Be star formation). In a paper by Raguzova & Lipunov (1999) the possible evolutionary track leading to the formation of a black hole in a Be binary was presented with a Be star mass $\sim 20\ M_\odot$, corresponding to spectral type O8–O9.

The lack of such systems may be associated with the presence of some evolution phase, that prevents, for example, the Be star formation. As the "preventing" evolution stage the luminous blue variable (LBV) phase may be proposed, which is identified with the hydrogen shell burning phase of a star with an initial mass larger than $\sim 50\ M_\odot$ (Humphreys 1991). In luminous blue variables the observed stellar wind mass loss rates are large enough ($\gtrsim 10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$) to prohibit a further expansion of the star (Maeder 1983; Vanbeveren 1987). Recently Vanbeveren et al. (1998) suggested a new scheme for the evolution of the most massive close binaries. When a binary component with initial mass larger than $40-50\ M_\odot$ reaches the LBV phase prior to its Roche lobe overflow, a stellar wind mass loss phase sets in at rates which are large enough to prohibit the occurrence of Roche lobe overflow.

The observed lower limit to the initial black hole progenitor (main sequence star) mass was proposed by Kaper et al. (1995) to be $\geq 50\ M_\odot$, based on the new measurement of a lower limit to the mass of the supergiant Wray 977 in the binary X-ray pulsar GX 301–2. Since the initial mass of the progenitor of a black hole falls in the range of masses, for which the LBV phase inevitably occurs, the formation of a Be star by means of mass transfer in such a binary system is impossible. Making a Be star in the binary requires the primary to fill its Roche lobe which in the course of the mass exchange transfers enough angular momentum towards the secondary star to spin it up to its critical rotation velocity. In the "LBV stage" the donor loses the mass in a spherically symmetric way, therefore the secondary component does not obtain the amount of angular momentum required to spin up to its break-up rotational velocity and a Be star cannot be formed.

In previous calculations (Pols et al. 1991; van Bever & Vanbeveren 1997) the total number of Be stars formed by mass transfer in the calculations is insufficient to explain the entire observed Be star population. Hence, Be stars can also form in isolation or wide binaries, as stars that are born rotating rapidly. Then it is entirely possible that the companion to a black hole will be born spinning rapidly and therefore can be a Be star of its own accord, just like single Be stars. In this case Be/black hole binaries can exist without the need for mass transfer.

5. The evolutionary scenarios for the formation of Be stars paired with white dwarfs of different chemical composition

Possible evolutionary tracks leading to Be/WD binary formation are shown in Fig. 8. Our calculations show that degenerate dwarfs of different chemical composition can be in a pair with a Be star. For the most part, they are massive CO- and O-Ne-white dwarfs. Helium white dwarfs are formed in systems with the latest spectral type Be stars. On average 35% of Be/WD binaries should have a O-Ne-white dwarf, 58% a CO-white dwarf and only 7% a He-white dwarf.

As is evident from the tracks leading to He-degenerate dwarf formation (see Fig. 8) the primary star is stripped below the threshold for helium ignition. A hot naked core is formed as a result. It is almost entirely degenerate except for the outer layers. Nuclear reactions do not occur in this remnant, the naked core cools down and contracts (in a time $\sim 10^5$ years), and a He-white dwarf is formed as a result.

In the more massive systems the first mass transfer finishes when the 3α-reaction ignites in the mass-losing star. These binaries pass through a detached helium star phase on their way to becoming carbon-oxygen (CO) white dwarfs paired with Be stars. The upper limit on initial mass for stars which can produce a CO degenerate dwarf is about 10.3 $M_\odot$ (Iben & Tutukov 1985). Potential progenitors of O-Ne-white dwarfs have initial masses in the range 8.8−10.6 $M_\odot$. Whether or not a binary component of mass somewhat larger than 8.8 $M_\odot$ will produce an O-Ne-degenerate dwarf is a sensitive function of initial binary masses and of initial orbital parameters.

As is evident from Fig. 8, the evolutionary track leading to He-white dwarf formation differs from the tracks leading to CO- and O-Ne-white dwarfs formation in that it does not contain a nondegenerate helium star phase. The hot naked core remaining after the first mass transfer in the less massive system cannot be called a "helium star" due to the absence of nuclear reactions.

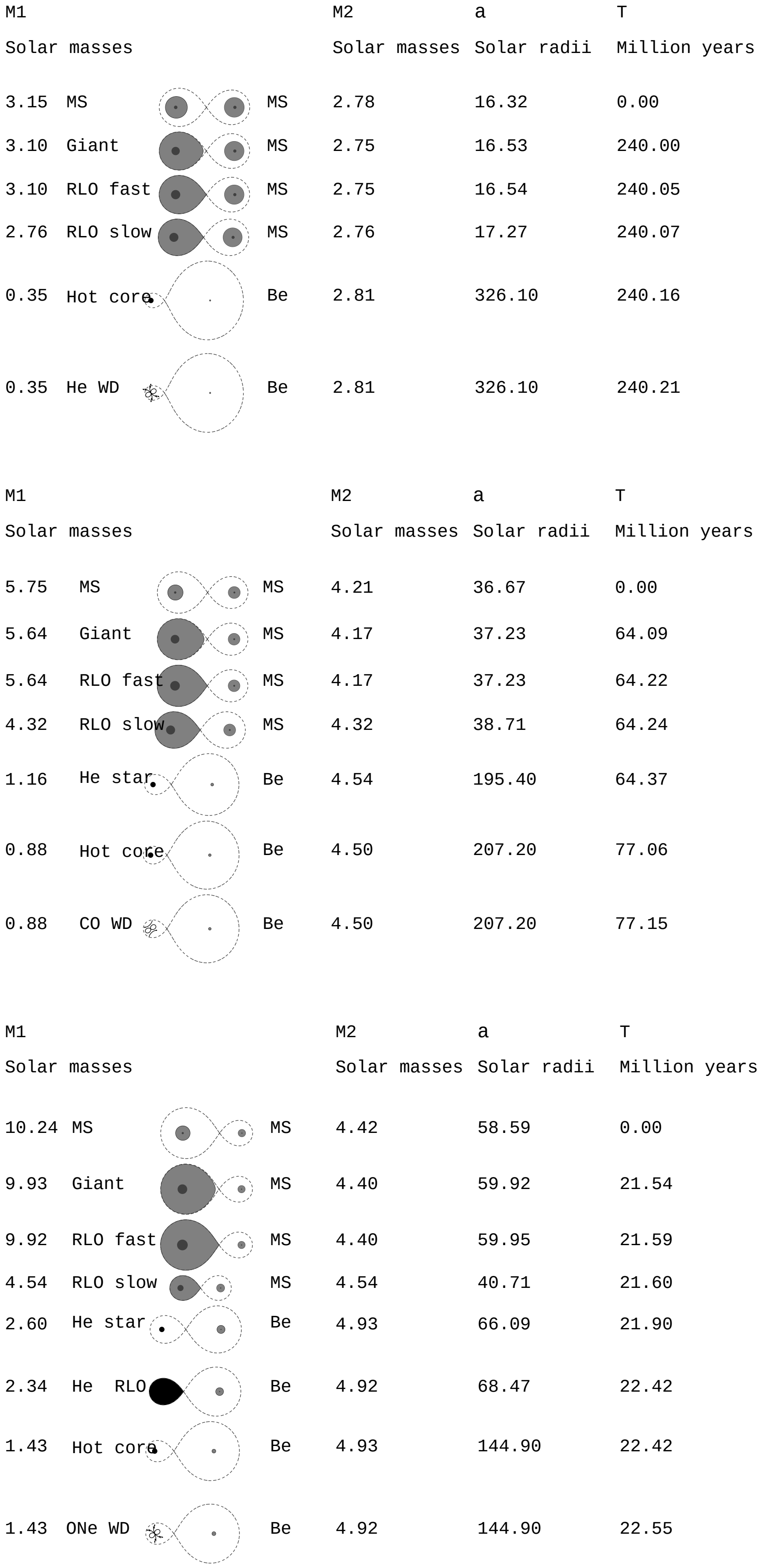
If the primary component has an initial mass in the range 5.6−14 $M_\odot$ the helium star can fill its Roche lobe after the exhaustion of helium in the core. The relatively rare case "BB" of evolution starts (Delgado & Thomas 1981). Both CO- and O-Ne-white dwarf can be formed as a result of such a mass exchange (see, for instance, bottom of Fig. 8).

6. Discussion

According to our calculations the number of binary systems containing a Be star paired with a white dwarf is very large – 70% of all Be stars formed as a result of the binary evolution must have a white dwarf as a companion. 20% of binary Be stars should have a subdwarf ("helium" star) companion and 10% are Be/NS (Be/X-ray) binaries. The results of our calculations are quantitatively similar to Van Bever & Vanbeveren's results (1997). Based on statistical calculations they obtained similar number fractions of different Be binaries. Our number of Be stars with a helium star companion is smaller than in the calculations of Pols et al. (1991). This is most likely due to the different timescales for helium stars used in our study and their paper. The account of the influence of tidal synchronization on the evolution of stars in a close binary can also effect on the resulting number of Be/He star binaries.

However, despite all favourable theoretical estimates for Be/WD binaries so far none of those systems has been discovered, whereas about 30 Be/X-ray binaries (a very rare type of systems according to our estimates) are known in the Galaxy. Based on the validity of the modern evolutionary scenario of Be star formation in binary systems, the explanation for the observational lack of Be/WD systems should be given. Also one should consider all selection effects which are responsible for the non-detection of these binaries.

To the present only three systems containing a white dwarf paired with a B star are known – y Pup, θ Hya and 16 Dra (Burleigh & Burstow 1998, 1999, 2000). These stars display no activity and do not belong to the Be star population, although they have spectral class B (B5 Vp, B9.5 V and B9.5 V, respectively). The white dwarfs in these systems were discovered in the extreme ultraviolet (EUV) range due to their high surface temperature. Our calculations show that white dwarfs in systems with Be stars should be hot (see Figs. 2 and 4). The question arises whether the presence of a white dwarf could be established by the detection of its EUV continuum shortward of the Be star's continuum turnover at 1000 Å? In such a manner the above-mentioned systems with B stars have been discovered. Unfortunately the answer to this question is rather negative. In order to reach this conclusion, one should consider in more detail the conditions which a white dwarf experiences in a Be binary.



M1			M2	a	T
Solar masses			Solar masses	Solar radii	Million years
3.15	MS	MS	2.78	16.32	0.00
3.10	Giant	MS	2.75	16.53	240.00
3.10	RLO fast	MS	2.75	16.54	240.05
2.76	RLO slow	MS	2.76	17.27	240.07
0.35	Hot core	Be	2.81	326.10	240.16
0.35	He WD	Be	2.81	326.10	240.21

M1			M2	a	T
Solar masses			Solar masses	Solar radii	Million years
5.75	MS	MS	4.21	36.67	0.00
5.64	Giant	MS	4.17	37.23	64.09
5.64	RLO fast	MS	4.17	37.23	64.22
4.32	RLO slow	MS	4.32	38.71	64.24
1.16	He star	Be	4.54	195.40	64.37
0.88	Hot core	Be	4.50	207.20	77.06
0.88	CO WD	Be	4.50	207.20	77.15

M1			M2	a	T
Solar masses			Solar masses	Solar radii	Million years
10.24	MS	MS	4.42	58.59	0.00
9.93	Giant	MS	4.40	59.92	21.54
9.92	RLO fast	MS	4.40	59.95	21.59
4.54	RLO slow	MS	4.54	40.71	21.60
2.60	He star	Be	4.93	66.09	21.90
2.34	He RLO	Be	4.92	68.47	22.42
1.43	Hot core	Be	4.93	144.90	22.42
1.43	ONe WD	Be	4.92	144.90	22.55

Fig. 8. The possible evolutionary tracks for formation of binary Be stars paired with white dwarfs of different chemical composition

Firstly, from our calculations it follows that the compact object is almost without exception embedded in the *dense* circumstellar disc of the primary star. Therefore apart from the fact that the white dwarf paired with a Be star should be hot, the white dwarf should accrete matter from the Be star disc (Waters et al. 1989). X-ray observations of cataclysmic variables which contain a white dwarf accreting matter from a companion, have shown that the emitted spectrum has a blackbody component with a temperature corresponding to about 40 eV and a higher energy component with kT about a few keV (Apparao 1991). The bulk of the emission energy is in the blackbody component. The presence of a massive optical star with an equatorial disc radically alters the appearance of a degenerate dwarf in a close binary system. The fact is that *all* blackbody extreme-ultraviolet and soft X-ray photons are absorbed by the gas in the envelope of the Be star in which the white dwarf is embedded. Apparao (1991) made the calculations for a Be disc of size $10^{12}-10^{13}$ cm and density of the gas $10^{10}-10^{12}$ atom cm^{-2} and concluded that the column density then is sufficient to absorb all extreme-UV and soft X-ray radiation. Our calculated orbital periods and semimajor axes fall into Apparao's calculation range. Therefore the suggestion about the registration of a white dwarf in a pair with a Be star by the detection of its extreme-UV continuum shortward of the Be star's continuum turnover at 1000 Å, where the primary star ceases to give the dominant contribution into emission, is of little use in practice.

Due to the absorption of the hard radiation of a compact companion an H II region is produced which emits optical continuum and lines. It is known that the Be star, as such, ionizes the material of its circumstellar disc which is composed essentially of hydrogen atoms. The Lyman continuum of the Be star ionizes hydrogen atoms and after recombinations cascade transitions occur causing the observed spectral line to form. The white dwarf in such a system is an additional source of ionization of the circumstellar disc of the Be star. Apparao (1991) has shown that for a luminosity of 4 10^{36} erg s^{-1} of the blackbody extreme-UV radiation, the H II region formed gives out H$_\alpha$ radiation with a luminosity of 1.6 10^{35} erg s^{-1} and an optical luminosity of 2.7 10^{34} erg s^{-1}. He has calculated a change in the visual magnitude due to the formation of the white dwarf H II region and concluded that the increase in the optical and H$_\alpha$ fluxes is larger than given out by the H II region produced by the Lyman continuum of the Be star for spectral types later than B1 (Apparao 1991; Apparao & Tarafdar 1987). The X-ray luminosities of the white dwarfs should be in the range $10^{32}-10^{36}$ erg s^{-1} according to the theory of accretion from the gas envelope around the Be star (Waters et al. 1988). Because of this, Apparao's calculations give only the maximal change in the stellar magnitude due to the presence of a compact companion, in practice this change must be smaller than the one calculated for a luminosity 4 10^{36} erg s^{-1} and such a change is difficult to detect (taking into account the variability of the Be envelope).

In support of the existence of hot compact companions (and nondegenerate helium stars) in Be binaries one can argue that He I lines λ5876 and λ10830 were found in emission from several Be stars (κ CMa B2 IV, *o* Pup B1 IV, HR 4830 B1 III (Dachs et al. 1992)). The UV continuum above the ionization potential for He I is found to be enough to produce the observed emission only for stars earlier than B1 (Apparao & Tarafdar 1987). To explain the observed emission for stars of later type, a source of helium ionizing photons is needed. Apparao & Tarafdar (1987) have shown that He I line emission can arise from the Strömgren sphere (H II region) formed by X-ray and extreme-UV emission from a compact binary companion to the Be star. It is known that Be stars sometimes lose their disc-like envelope transforming into the usual main sequence B stars. The newly formed envelope expands, but the He line emission, however, occurs when the expanding envelope reaches the compact star, so that there should be a period in which H$_\alpha$ emission from the ejected envelope is seen, and not the He line emission, before the envelope reaches the compact star. Also the increase in the optical and H$_\alpha$ emission line fluxes should be observed simultaneously.

It is likely that spectroscopic investigations of helium emission lines are the most promising means of detection of nondegenerate helium companions and white dwarfs in Be binaries (recall the ϕ Persei system). The mass ratios of the post-mass transfer Be binaries are small ∼0.1–0.3, whereas the orbital periods >30 days. This implies very small radial velocity variations in the primary spectrum. For instance, a 5 $M_\odot$ Be star with a $0.5-1.0$ $M_\odot$ companion would have a velocity amplitude $K/\sin i <$ $10-20$ km s^{-1} for orbital periods $>$ 30 days. Such small variations are difficult to detect in the spectrum of a Be star as the primary atmosphere exhibits intrinsic variability and line broadening due to the presence of a circumstellar disc, limiting spectral velocity measurements to a resolution of order 10 km s^{-1}. However, it might be possible to detect the hot degenerate dwarf or the helium star due to the presence of helium lines, as is the case in ϕ Persei. The radial velocity variations derived from helium lines can be observed more easily. For instance, a 5 $M_\odot$ Be star with a 1.0 $M_\odot$ companion would have a helium velocity curve amplitude $K/\sin i > 70$ km s^{-1} for orbital periods $<$ 100 days.

7. Conclusion

Despite the conclusion that a large number of the Be/WD binaries should exist, the above-listed selection effects restrict the possibility of registration of these systems. The loss of the Be disc-like envelope does not often occur and it is a rather rare event for many Be stars. Therefore the registration of a white dwarf by the detection of its hard emission in the absence of the circumstellar disc of the primary is a very difficult task. The careful investigations of helium lines in emission from late spectral type Be stars give the best chance to detect secondary white dwarfs and helium stars. Notice that the companion in this case has to have a high enough surface temperature. It follows from our calculations that white dwarfs in Be binaries have insufficient time to cool down in the life-time of the Be star. Therefore it is reasonable to hope that these binaries will be discovered in the future.

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References

Apparao, K. M. V. 1991, A&A, 248, 139
Apparao, K. M. V., & Tarafdar, S. P. 1987, ApJ, 322, 976
Bisnovaty-Kogan, G. S. 1989, Physical problems in the theory of stellar evolution, Moscow, Izdatel'stvo Nauka
Burleigh, M. R., & Barstow, M. A. 1998, MNRAS, 295, 15
Burleigh, M. R., & Barstow, M. A. 1999, A&A, 341, 795
Burleigh, M. R., & Barstow, M. A. 2000, A&A, 359, 977
Claret, A., & Gimenez, A. 1995, A&A, 296, 180
Claret, A., Gimenez, A., & Cunha, N. C. S. 1995, A&A, 299, 724
Contini, T., Davoust, E., & Considere, S. 1995, A&A, 303, 440
Dachs, J., Hummel, W., & Hanuschic, R. W. 1992, A&AS, 95, 437
Delgado, A. J., & Thomas, H.-C. 1981, A&A, 96, 142
Finley, D. S., Koester, D., & Basri, G. 1997, ApJ, 488, 375
Gies, D. R., Bagnuolo, W. G., Jr., Ferrara, E. C., et al. 1998, ApJ, 493, 440
Harmanec, P. 1988, Bull. Astro. SocCzechoslovakia, 39, 329
Humphreys, R. 1991, in IAU Symp. 143, WR stars and interrelations with other massive stars in galaxies, ed. K. A. van der Hucht, & B. Hidayat (Kluwer, Dordrecht), 485
Iben, I. Jr., & Tutukov, A. V. 1985, ApJS, 58, 661
Kaper, L., Lamers, H. J. G. L. M., Ruymaekers, E., et al. 1995, A&A, 300, 446
Kaplan, S. A. 1950, AZh, 27, 31
Kippenhann, R., & Weigert, A. 1967, Zs.Ap., 65, 251
Kornilov, V. G., & Lipunov, V. M. 1983, AZh, 60, 284
Kříž, S., & Harmanec, P. 1975, Bull. Astro. SocCzechoslovakia, 26, 65
Lipunov, V. M., Postnov, K. A., & Prokhorov, M. E. 1996, Astrophys. Space Phys. Rev., 17, 1
Maeder, A. 1983, A&A, 120, 113
Mestel, L. 1952, MNRAS, 112, 583
Negueruela, I. 1998, A&A, 338, 505
Packet, W. 1981, A&A, 102, 17
Paczynski, B. 1971, ARA&A, 9, 183
Poeckert, R. 1981, PASP, 93, 297
Pols, O. R., Cote, J., Waters, L. B. F. M., & Heise, J. 1991, A&A, 241, 419
Pols, O. R., & Marinus, M. 1994, A&A, 288, 475
Portegies Zwart, S. F. 1995, A&A, 296, 691
Raguzova, N. V., & Lipunov, V. M. 1998, A&A, 340, 85
Raguzova, N. V., & Lipunov, V. M. 1999, A&A, 349, 505
Rappaport, S. A., & van den Heuvel, E. P. J. 1982, in IAU Symp. 98, Be stars, ed. M. Jaschek, & H. G. Groth (Reidel, Dordrecht), 327
Rieutord, M., & Zahn, J.-P., ApJ, 474, 760
Robinson, R. D., & Smith, M. A. 2000, ApJ, 540, 474
Schaerer, D. 1996, ApJ, 467, L17
Schwarzschild, M. 1958, Structure and Evolution of the Stars (Princeton Univ. Press, Princeton, New Jersey)
Shapiro, S. L., & Teukolsky, S. A. 1983, Black Holes, White Dwarfs, and Neutron Stars, Cornell University, Ithaca, New York
Smith, M. A., Robinson, R. D., & Corbet, R. H. D. 1998, ApJ, 503, 877
Smith, M. A., Robinson, R. D., & Hatzes, A. P. 1998, ApJ, 507, 945
Smith, M. A., & Robinson, R. D. 1999, ApJ, 517, 866
Tassoul, J.-L. 1987, ApJ, 322, 856
Tassoul, M., & Tassoul, J.-L. 1997, ApJ, 481, 363
Tavani, M., & Arons, J. 1997, ApJ, 477, 439
Tutukov, A. V., & Yungelson, L. R. 1973, NIAS, 27, 70
Tutukov, A. V., & Yungelson, L. R. 1993, AZh, 70, 812
Van Bever, J., & Vanbeveren, D. 1997, A&A, 322, 116
van den Heuvel, E. P. J., & Heise, J. 1972, Nat. Phys. Sci., 239, 67
van den Heuvel, E. P. J. 1994, in Interacting binaries, ed. S. N. Shore, M. Livio, & E. P. J. van den Heuvel (Springer Verlag: Berlin), Ch. 3
Vanbeveren, D. 1987, A&A, 182, 207
Vanbeveren, D., de Donder, E., van Bever, J., et al. 1998, NewA, 3, 443
Waters, L. B. F., Taylor, A. R., van den Heuvel, E. P. J., et al. 1988, A&A, 198, 200
Waters, L. B. F., Pols, O. R., Hogeveen, S. J., et al. 1989, A&A, 220, L1
Waters, L. B. F., Cote, J., & Pols, O. R. 1991, A&A, 250, 437
Webbink, R. F. 1979, in IAU Colloquium 53, White Dwarfs and Variable Degenerate Stars, ed. H. M. Van Horn, & V. Weidemann (Rochester University Press, Rochester), 426