MAIN CONCLUSIONS

1. The photometric pecularities of optical light curves of the x-ray binary HZ Her/Her X-1 (details on the light curves near the center of the primary minimum, emission peaks at certain phases of the orbital motion) and bursts of linearly polarized emission near the orbital phase 0.0 are connected with the emission of clumps of accreted material (blobs) formed as a result of the discrete flow of material from the visible star to the outer boundary of the accretion disk.

2. Estimates of the physical parameters of the blobs showed that they are semitransparent in the optical range and opaque in the near-infrared range. The calculated values of the intensity and polarization of their self-emission are in full agreement with the brightnesses of photometric details observed on the light curves, as well as with the magnitude of the burst of linear polarization of the emission of the HZ Her/Her X-1 system observed by Shakhovskoi and Efimov[8] at the optical phase 0.0.

3. A connection is established between the times of appearance of photometric details and bursts of linear polarization and the phases of the orbital motion and the 35-day cycle. This connection agrees well with the model of Ref. 5, describing a pattern of discrete flow of material from the surface of the visible star and its interaction with the oblique, precessing accretion disk.

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On the possibility of detecting close binary degenerate dwarfs

A. V. Tutukov and L. R. Yungel'son

Astronomical Council, USSR Academy of Sciences

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The parameters of binary degenerate dwarfs formed in the course of the evolution of close binary systems are analyzed. It is shown that the semiamplitudes of the radial velocities of a significant fraction of binary dwarfs lie in the range of 100–250 km/sec, accesible to observation. The length of the eclipses in such systems is 2–4 min with orbital periods of ~4 h. The closest of the binary degenerate dwarfs ($a \lesssim 2$–$3\ R_\odot$) merge owing to momentum loss to the emission of gravitational waves; the frequency of such events in the Galaxy is ~0.1/yr.

1. INTRODUCTION

An analysis of evolutionary scenarios for close binary stars of moderate masses ($0.8 \lesssim M_1/M_\odot \lesssim 10$) shows that the evolution of these systems, as a rule, leads to the formation of a pair of degenerate dwarfs.[1-7] It can be estimated that a merging of degenerate components occurs about once per 10 years in the Galaxy.[5] About 10% of the mergings may lead to explosions of type I supernovae (SN I), which is sufficient to explain the observed frequency of SN I. At least one wide system (∿ 175 AU) of two degenerate dwarfs is known.[8] It is appropriate to raise the question of the possibility of detecting close binary degenerate dwarfs. It is shown below that the parameters of such systems lie within limits accessible to observation.

2. WAYS OF FORMATION OF BINARY DEGENERATE DWARFS

The evolution of most close binary systems (CBS) is nonconservative in mass and angular momentum. The existence of cataclysmic variable stars and close binary nuclei of planetary nebulae can serve as the most convincing proof of the nonconservativity of the evolution. The main reason for nonconservativity is that the accretion rate $\dot{M}_a$ is limited to a value corresponding either to the thermal time of the envelope of the accretor star[9] or to the

Eddington luminosity. But the rate of loss of material by the donor star, filling the Roche lobe, may exceed M_a by several orders of magnitude. As a result, a common outflowing envelope is formed around the system, and the binary nucleus loses momentum by being retarded in it. The momentum loss and the corresponding approach of the components can sometimes be so pronounced that the components merge, remaining inside a common envelope. The majority of CBS pass through two stages of a common envelope after the Roche lobes of the primary and secondary components of the system are filled.

On the basis of the results of evolutionary calculations, the ways of formation of systems of degenerate dwarfs can be schematized as follows. (For simplicity, we assume that the initial masses of the components are close.)

a. The components of systems with $0.8 \le M_1/M_\odot \le 2.3$ and orbits with semimajor axes $10 \le a/R_\odot \le 500$ are converted into helium dwarfs with an average mass $M = 0.3\ M_\odot$.

b. The components of a system with $0.8 \le M_1/M_\odot \le 2.3$ and $500 \le a/R_\odot \le 1000$ are converted into carbon-oxygen dwarfs with $\bar{M}=0.6\ M_\odot$.

c. The components of systems with $2.3 \le M_1/M_\odot \le 10$ and $10 \le a/R_\odot \le 100$ are converted first into nondegenerate helium stars and then into carbon-oxygen dwarfs with $\bar{M}=0.6\ M_\odot$.

d. The components of systems with $2.3 \le M_1/M_\odot \le 10$ and $100 \le a/R_\odot \le 1000$ are converted first into nondegenerate helium stars and then into carbon-oxygen dwarfs with $\bar{M}=0.8\ M_\odot$.

e. In systems with $10^3 \le a/R_\odot \le 10^6$, carbon-oxygen dwarfs with $\bar{M} = 0.6\ M_\odot$ are formed. In these systems neither of the components fills the Roche lobe in the course of evolution, although the components lose material by means of stellar wind.

To estimate the frequency ν of formation of binary degenerate dwarfs, we assume that the masses of their components are distributed by a Salpeter law with an exponent -1.5 and that the range of semimajor axes of the binary systems is $10\text{-}10^6\ R_\odot$ within this range the stars are distributed as $dN = 0.2d \log a$ (Ref. 10). Then

$$d^2\nu = \frac{1}{2}\,(0.2d\lg a)\,\frac{dM}{M^{2.5}}\ \ \text{yr}^{-1} \tag{1}$$

The frequency of formation of binary degenerate dwarfs corresponding to (1) is $\sim 0.5\ \text{yr}^{-1}$.

3. RADIAL VELOCITIES OF BINARY SYSTEMS OF DEGENERATE DWARFS

To estimate the variation in the semimajor axis of the orbit in the stage of a common envelope, we assume that the destruction of the envelope occurs at the expense of the orbital energy of the components,[11]

$$\alpha\frac{MM_R}{a_f} = \frac{M^2}{a}, \tag{2}$$

where α is the efficiency parameter, which we take as equal to one, M_R is the mass of the remnant of the donor star, and a and af are the initial and final values of the semimajor axis. Applying Eq. (2) twice, we find that the maximum semiamplitude of the radial velocity of a system of two degenerate dwarfs is

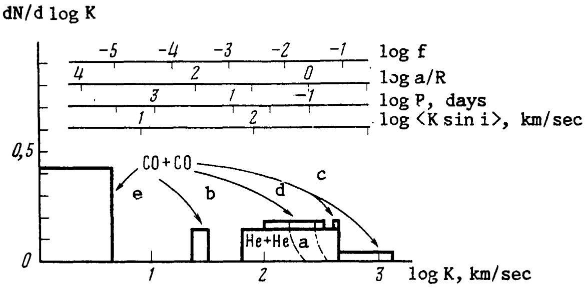

FIG. 1. Distribution of binary white dwarfs with respect to the semiamplitudes of the radial velocities K_1. Components a-e correspond to variants "a-e" enumerated in Sec. 2. The scales of averaged radial velocities $\overline{K_1 \sin i}$, semimajor axes a of the orbits, geometrical probabilities f of eclipses, and orbital periods P are plotted. The fractions of binary dwarfs that merge in times of 10^{10} and $3\cdot10^8$ years are marked by dashed lines.

$$K_1 = \frac{310}{\alpha}\left(\frac{M_R}{M_\odot}\Big/\frac{a_{ff}}{R_\odot}\right)^{0.5} = \frac{310}{\alpha}\left(\frac{M}{M_\odot}\right)^{1.5}\left(\frac{M_R}{M_\odot}\right)^{-1}\left(\frac{a}{R_\odot}\right)^{-0.5}\ \text{km/sec}.$$

Here aff is the distance between the dwarfs.

In wide systems ($a > 10^3\ R_\odot$) the angular momentum carried off by the wind material is equal to the specific moment of the components. Therefore, $a_{ff} = aM/M_R$ and

$$K_1 = 310\left(\frac{M}{M_\odot}\right)^{-0.5}\left(\frac{M_R}{M_\odot}\right)\left(\frac{a}{R_\odot}\right)^{-0.5}\ \text{km/sec}. \tag{4}$$

If the orbital planes of the dwarfs are distributed randomly relative to the line of sight, the observed velocities are $\overline{K_1 \sin i} = (\pi/4)K_1$.

Using Eqs. (1), (3), and (4), we constructed a distribution of systems of degenerate dwarfs with respect to the semiamplitudes of the radial velocities (see Fig. 1). It was assumed that each of the five groups of stars enumerated in Sec. 2 consists of objects with masses equal to the weighted-mean value over the Salpeter spectrum for the mass range corresponding to the given group. The contribution of each group is isolated in Fig. 1. (For simplicity, all the wide systems (variant e) are shown in the interval $K_1 = 1\text{-}4.5$ km/sec, although their K_1 may actually be only ~ 0.1 km/sec). A rigorous allowance for the distributions of the stars by masses and by the mass ratios of the components and allowance for the dependence on M of the limits of the different variants of evolution with respect to a may somewhat "blur" the boundaries of the isolated groups.

The further approach of the dwarfs takes place due to the emission of gravitational waves. The relative lifetime of a system before the merging of the components can be estimated as

$$\tau \approx \frac{T}{10^{10}} = \left(\frac{168\ \text{km/sec}}{K_1}\right)^8 \frac{M_R}{M_\odot}. \tag{5}$$

The estimate (5) shows that the components of $\sim 20\%$ of all the systems of two degenerate dwarfs may merge over cosmological time, i.e., the frequency of such events is ~ 0.1/yr. In Fig. 1 we show the limits on the fraction of merging dwarfs, $(0.3 + 0.3)M_\odot$ corresponding to cosmological time (10^{10} years) and a time $T \approx 3\cdot10^8$ years, after which the probability of the detection of cooling white dwarfs decreases rapidly.[12]

4. POSSIBILITIES OF DETECTING BINARY DWARFS

An analysis of curves of cooling of white dwarfs shows that the probability of discovery is highest for young nuclei of planetary nebulae with an absolute stellar magnitude $M_V \approx 3\text{-}6^m$ (because of their high brightness and the presence of shells) and for dwarfs with $M_V \approx 10\text{-}14^m$ and an age of $\sim 3 \cdot 10^8$ years. Figure 1 demonstrates that binary nuclei of planetary nebulae may be discovered predominantly as spectral binaries. The discovery of binary degenerate objects among the most numerous observed dwarfs with $T \approx 3 \cdot 10^8$ years is complicated by the large width of lines in their spectra, although it is possible in principle using modern apparatus. It can be expected that these will be predominantly dwarfs of type DA, the periods should be several hours, the semiamplitudes of the radial velocities should be 100-250 km/sec, and the shifts of spectral lines should be ~ 1 Å.

Using the mass–radius relation for degenerate CO dwarfs,[13] $R/R_\odot \approx 0.0195\text{-}0.0116\, M_{CO}/M_\odot$, we can estimate that the geometrical probability of an eclipse in a system of two dwarfs with masses $0.6\ M_\odot$ is

$$f \approx 2R/a \approx 0.025\, R_\odot/a. \quad (6)$$

The probability of the eclipse of helium dwarfs is somewhat higher. The values of f for CO dwarfs are also given in Fig. 1. An estimate shows that for typical unmerged systems with $K_1 \approx 100$ km/sec, which comprise $\sim 10\%$ of all binary dwarfs, the duration of observations required to detect eclipses is $\sim 4000^h$ (for periods of $\sim 30^h$ and an eclipse of length ~ 4 min). Since the expected probability of eclipses is ~ 0.1, the observing program should include ~ 100 dwarfs. Actually, if the photometric probability of eclipses is taken into account, the duration of the necessary observations may be still greater.

The detection of binary degenerate dwarfs is also possible, in principle, from the results of spectrophotometric observations, since the superposition of two Planckian spectra with different temperatures can be observed in this case.

5. MERGING OF WHITE DWARFS AND ITS CONSEQUENCES

The variant of the formation of a binary CO dwarf in the course of evolution of stars with $M = 2.3\text{-}10\ M_\odot$ and $a = 10\text{-}100\ R_\odot$ was analyzed formally in Sec. 2. Here the formation of the dwarf precedes the formation of the helium star. The radii of the helium stars are[14] $R/R_\odot \approx 0.2(M/M_\odot)^{0.92}$. If the initial masses of the components are close, then estimates on the basis of Eq. (2) show that the merging of two helium stars in the second stage of a common envelope is possible for several percent of all binary systems. Thus, helium stars with masses of up to $\sim 1.5\ M_\odot$ can be formed, which may evolve further into stars of the R Coronae Borealis type.

The merging of helium white dwarfs leads to the formation of helium stars with masses of up to $\sim 1\ M_\odot$, which may appear as sdB stars, i.e., compact objects of low luminosity having signs of hydrogen in the spectrum; after losing the hydrogen envelope through the stellar wind and the burnup of helium, they can be converted into white dwarfs of types different from DA.

We note that the merging itself is connected with the liberation of an energy of $\sim 10^{50}$ erg, i.e., this is a phenomenon of supernova scale. The study of processes of merging of dwarfs and the evolution of the products of merging is essentially a new and not yet fully investigated field in the theory of stellar evolution.

6. CONCLUSION

The factor α [see (2)] introduces the greatest uncertainty in the distribution of binary degenerate dwarfs; its numerical value cannot yet be estimated. Variation of α leads to a shift proportional to α^{-1} in the distribution with respect to K_1. Therefore, as Fig. 1 shows, a threefold decrease in α, for example, leads to a considerable decrease in the number of systems with $K_1 \lesssim 100$ km/sec.

The discovery of close binary degenerate dwarfs and an observational estimate of their numbers would serve as an important test of modern concepts about the evolution of close binary stars of moderate masses.

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