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Wolf–Rayet stars, black holes and the first detected gravitational wave source

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HIGHLIGHTS

- The "Scenario Machine" that predicted that first LIGO event should be a BH+BH merge is used.
- Four evolutionary channels that could lead to GW150914 burst are studied.
- The work contains constraints on crucial evolutionary parameter of close binary stars.
- A possible explanation of low BH spin of merging black holes is proposed.

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ABSTRACT

The recently discovered burst of gravitational waves GW150914 provides a good new chance to verify the current view on the evolution of close binary stars. Modern population synthesis codes help to study this evolution from two main sequence stars up to the formation of two final remnant degenerate dwarfs, neutron stars or black holes (Masevich and Tutukov, 1988). To study the evolution of the GW150914 predecessor we use the "Scenario Machine" code presented by Lipunov et al. (1996). The scenario modeling conducted in this study allowed to describe the evolution of systems for which the final stage is a massive BH+BH merger. We find that the initial mass of the primary component can be $100 \div 140 M_{\odot}$ and the initial separation of the components can be $50 \div 350 R_{\odot}$. Our calculations show the plausibility of modern evolutionary scenarios for binary stars and the population synthesis modeling based on it.

1. Introduction

The LIGO discovery of the first gravitational wave burst GW150914 (Abbott, 2016b) starts a new era in physical and astrophysical studies (Abbott, 2016c, 2016d). The detector observed a merger of two black holes with masses $36^{+5}_{-4} M_{\odot}$ and $(29 \pm 4) M_{\odot}$, the amount of energy release in this merger in the form of gravitational waves was $(3 \pm 0.5) M_{\odot} c^2$, the mass of the remnant single black hole was $(62 \pm 4) M_{\odot}$, and its spin was $0.67^{+0.05}_{-0.07}$. This paper aims at a study of the possible evolution of a close massive binary star that leads to a merger of two black holes with parameters similar to those of GW150914. For our calculations we use the "Scenario Machine", see the latest version of its detailed description by Lipunov et al. (2009). A huge number of papers were dedicated to investigations of the evolution of close binary stars and its implications to parameters of mergers and merging rates of relativistic stars, e. g. Tutukov and Yungelson (2002), Belczynski (2016a), de Mink and Mandel (2016).

Lipunov et al. (1997) studied merging rates of neutron stars (NS) with neutron stars, neutron stars with black holes (BH), and black holes with black holes (i.e. NS+NS, NS+BH, BH+BH) under different assumptions of the BH formation. The BH+BH and NS+NS merger rates in a galaxy like the Milky Way were found to be, respectively, $(2-5) \cdot 10^{-5}$ and $\sim 10^{-4}$ per year. A typical BH is formed with a mass 3–10 times the NS mass (which was assumed to be $1.4 M_{\odot}$), so the expected detection rate of BH+BH merging by LIGO was found to be 10–100 times higher than the NS+NS merger detection rate for a wide range of evolutionary parameters. Therefore Lipunov et al. (1997) concluded that the first LIGO event should be the BH+BH merger. Belczynski (2016a) came to the same conclusion.

The discovery of gravitational waves by LIGO allows to trace an evolutionary scenario for massive binaries up to its final point and to estimate the possible range of evolutionary parameters. Here, we study some of them for the most massive merging BHs in connection with GW150914. One of the crucial parameters of the

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evolution of binaries is the stellar wind mass loss. In the Section 2 we describe the mass loss rate by massive stars that can be progenitors of compact stars. In the Section 3 we describe existing binary systems that consist of BHs and Wolf–Rayet (WR) stars that can be progenitors of massive merging binary BHs, also we mention the most massive close binaries with non-degenerate companions. In the Section 4 we briefly describe the "Scenario Machine" program. In the Section 5 the results of our study are presented. In the Section 7 we make final conclusions and some discussions of the results of this paper.

2. Stellar wind

Before 1990s the influence of mass loss in a form of stellar wind on the evolution of WR stars was highly overestimated. For example, Langer, 1989a), Langer (1989b) published the following formula to connect mass loss of WR stars $\dot{M}_{WR}$ and their masses M_{WR}:

$$\dot{M}_{WR} = -(0.6 - 1.0) \cdot 10^{-7} \left(\frac{M_{WR}}{M_{\odot}} \right)^{2.5}, \qquad (1)$$

where the coefficient 0.6 corresponds to WNE stars, and the value 1.0 corresponds to WC and WO stars. Eq. (1) leads to the so-called convergence effect: the mass of a WR star in the end of the evolution and the mass of its carbon–oxygen (CO) core does not exceed a few solar masses ($M_{CO} = 2 \div 4 M_{\odot}$) practically independently of its initial mass.

But how in this case are we able to understand the existence of black holes with masses in the range $10 - 15 M_{\odot}$, that is a reliable observational fact (Cherepashchuk, 2013)? Moreover, non-LTE models of WR stellar winds by Hillier (1991) lead to unrealistically high mass loss rates: $\dot{M} > 10^{-5} M_{\odot}$ yr^{-1}, up to $10^{-4} M_{\odot}$ yr^{-1}. The effects of light scattering on electrons at so high $\dot{M}$ should produce observable wings in emission line profiles. A high $\dot{M} \sim 10^{-4} M_{\odot}$ yr^{-1} also should lead to very deep blue shifted absorption components (like P Cyg) in the emission lines of WR stars. Such features are not observed in WR spectra. All these problems can possibly be resolved by the model of clumpy stellar winds of Wolf–Rayet stars. Most of existing data on mass loss rates of some tens of WR stars (and for O-B stars of I-II luminosity classes) are obtained on the basis of the analysis of their radio and infra-red (IR) thermal emission. Cherepashchuk (1990, 1991) noted that the presence of clumps in a stellar wind lead to overestimated values $\dot{M}$ for such stars, if the presence of clumps is ignored, because the thermal emission quadratically depends on the electron density. If the matter of the wind of the WR star is contained in numerous dense clumps, the intensity of the IR and radio emission grows in comparison with that for a uniform wind, so the real $\dot{M}$ value is overestimated.

Clumps in the stellar wind of a WR star were discovered by Cherepashchuk et al. (1984) by analysis of atmospheric eclipses in the V444 Cyg binary system (WN5+O6) in IR. They found that characteristic dimensions of the WN5 star's extended atmosphere are much greater in IR than in the optics, and they concluded that this wind was clumpy. Some years later Moffat et al. (1988) obtained spectra of WR stars with very high signal to noise ratio ($\sim$300) and found that the peaks of profiles of emission lines are variable: there are a lot of sharp emission components with the amplitude $\sim$1% from the total line height that move along the lines. This fact directly proves the existence of clumps in WR stellar winds, and the clumps move out of these stars with an acceleration.

Photometric and polarization observations of WR stars in close binary systems gave more information about clumpy WR stellar winds. The realistic mass loss rate of a WR star estimated using the increase of the orbital period of the V444 Cyg eclipsing binary is $0.6 \cdot 10^{-5} M_{\odot}$ yr^{-1} (Cherepashchuk, 2013). At the same time the value of $\dot{M}$ estimated using the analysis of IR and radio fluxes of this system is $\dot{M}_{WR} \approx 2.4 \cdot 10^{-5} M_{\odot}$ yr^{-1} (Prinja et al., 1990, 1991; Howarth and Schmutz, 1992). Observations of the linear polarization variability of some tens WR stars in close binaries (St.-Louis et al., 1988) also lead to values of $\dot{M}$ for WR stars several times less in comparison with values found from their IR and radio fluxes.

Cherepashchuk (2001) calculated the final masses of WR stars and their carbon–oxygen (CO) cores under the assumption of clumpy WR winds (Cherepashchuk, 1990; 1991). This allows to decrease the values of $\dot{M}_{WR}$ by a factor of $3 \div 5$. Cherepashchuk (2001) used the following empirical formula (obtained from polarimetry observations of close binary WR+OB stars) to connect $\dot{M}_{WR}$ and M_{WR}:

$$\dot{M}_{WR} = K M_{WR}^{\alpha}, \qquad (2)$$

here α is in the range 1÷2, and $\alpha = 1$ is the more preferable value (St.-Louis et al., 1988). The decrease of the mass loss rate of WR stars by a factor of three and the low power in Eq. (2) in comparison to Eq. (1) allow to escape the convergence effect (Cherepashchuk, 2001): the masses of CO cores of WR stars in the end of their evolution (they are the direct progenitors of relativistic objects) are in the wide range: $M_{CO}^{fin} = (1-2)M_{\odot} \div (20-40)M_{\odot}$. This interval of final masses of CO cores of WR stars includes the current observable interval of masses of neutron stars and black holes in X-ray binary systems: $M_{BH,NS} = 1 M_{\odot} \div 16 M_{\odot}$.

In summary we can conclude that the standard $\dot{M}_{WR}$ derived from their IR and radio fluxes should be reduced by a factor of $3 \div 5$ see e. g. Hillier (2003). In calculations of modern extended atmospheres of WR stars in the non-LTE approximation the clumpy wind is defined arbitrarily: one defines a porosity parameter of clumps and an average density jump in them. Values of these parameters are obtained in analysis of line profiles in spectra of WR stars, see, e. g. Hillier (2003). Stellar winds of massive hot OB and WR stars accelerated by radiation pressure in lines can be unstable to small perturbations of the wind density according to theoretical investigations, see, e. g. Puls (2003). Also we have to mention that the WR wind can be non-symmetrical (which introduces an uncertainty in the mass-loss rates of a factor 2–3).

3. Massive optical and degenerate binaries

Tutukov and Yungelson (1973a, 1973b) theoretically studied the possibility of the formation of WR stars in massive close binaries and suggested arguments in favor of the mass and angular momentum loss during the mass transfer before the formation of WR stars. The evolution of such binaries can include a stage with the close binary that consists of the WR star and the compact star. van den Heuvel and Heise (1972) considered Cen X-3 as an observational example of the binary system in the second mass exchange process that can preceed the formation of "WR+compact star" system, as was calculated by van den Heuvel and De Loore (1973).

At the present time there are three known black holes in close binaries with Wolf–Rayet stars: Cyg X-3, IC 10 X-1, NGC 300 X-1, and probable fourth system CXOU J123030.3+413853 (Esposito et al., 2013). In addition there are some systems that also are important to note for the aim of this paper: SS 433 (the only known super-Eddington accretor in the Milky Way at present time, this system can be a precursor of BH+WR binary), M33 X-7 (one of the most massive known black holes with a slightly evolved massive non-degenerate star), WR 20a, WR 22 (HD 92740), WR 21a, NGC 3603-A1, HDE 311884, and R 145 (LMC) that are close binaries with the most massive WR and O stars. Let us to discuss these binaries in some detail.

WR 20a was suggested to be a possible WR star by Shara et al. (1991), and found as a possible binary system by van der Heuvel (2001), because it has relatively weak emission