Mass distributions of relativistic objects and Wolf-Rayet stars in close binary systems

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1. Introduction

Wolf-Rayet (WR) stars, which are the naked helium cores of previously massive stars, lose most of their hydrogen envelope due to intense mass loss (Conti 1976) or interactions in close binary systems (Paczyński 1973). After completing their evolution, such stars transform into neutron stars (NS) or black holes (BH) by the collapse of the CO cores formed before the explosion of a type Ib/c supernova (SN).

Observational data show that the mass of neutron stars and black holes formed as a result of the collapse of WR stars differs significantly from the expected theoretical distribution of their core masses. A dip in the mass region between about 2 and 5 $M_\odot$ is observed, which cannot be explained only by the effect of observational selection. The main goal of this study is to test new observational data to identify possible anomalies in the mass distributions of relativistic objects.

2. NS and BH mass distribution

As immediate precursors of binaries with NS and BH we consider binary close binary stars containing a Wolf-Rayet (WR) star. WR stars are not observed in pairs with low-mass stars, although it is believed that close binary stars with a large mass ratio form low-mass X-ray binaries (LMXBs) after the collapse of a massive companion. The WR+OB systems, a sample of which is considered in this paper, can be considered precursors of only one class of systems - high-mass X-ray binaries (HMXBs), but statistics on them remain scarce.

Observational data on the compact objects mass distribution we used include three groups of sources: HMXBs (Fortin et al. 2023; Neumann et al. 2023), LMXBs (Avakyan et al. 2023; Fortin et al. 2024), and some wide binaries recently discovered by Gaia (El-Badry et al. 2024a; El-Badry et al. 2024b; El-Badry et al. 2023a; El-Badry et al. 2023b; Gaia Collaboration 2024). Although the evolution paths of different classes of objects differ, the Kolmogorov-Smirnov (K-S) test showed good compatibility of the HMXB and LMXB mass distributions (87.5% for $p = 0.95$), allowing them to be combined. Adding Gaia objects to the total sample, despite some discrepancies, is considered justified due to the small size of the new sample and its insignificant effect on the overall picture. The combined distribution includes 99 objects with approximately equal shares of NS and BH. This distribution demonstrates a clearly pronounced bimodal character with one peak corresponding to neutron stars ($\sim 1.4\ M_\odot$) and the second one associated with black holes. The lack of reliable evidence for the existence of compact objects with masses in the range of $\sim 2.5 - 4.6\ M_\odot$ ("mass gap") deserves special attention, requiring further study.

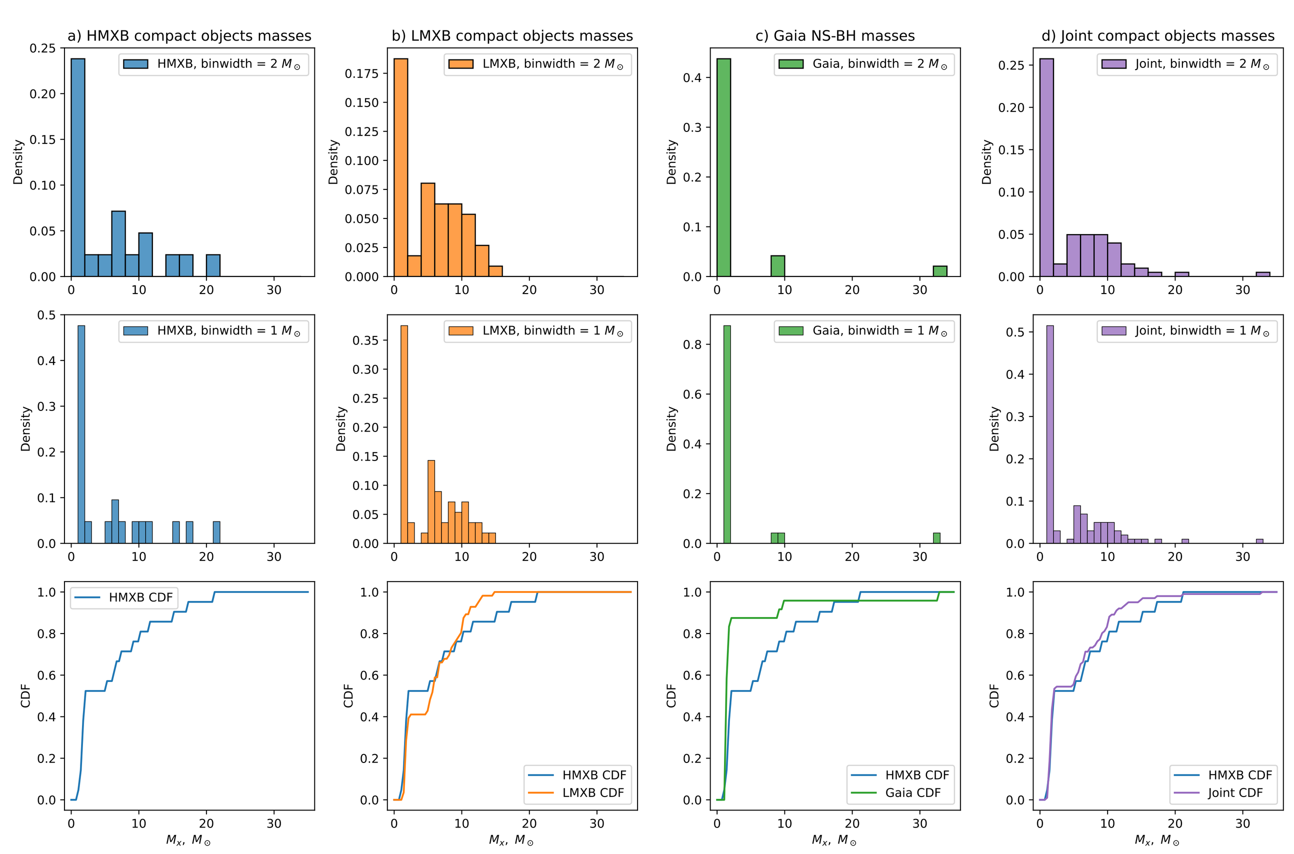

Fig. 1: Distribution of NS and BH in binary of different types. Vertically - histograms with 2 and $1\ M_\odot$ resolution, as well as cumulative distributions. Horizontally: a) HMXBs, b) LMXBs, c) Gaia NSs & BHs, d) combined distribution. In the lower panels b)-d) the distribution for HMXBs resulting from the evolution of WR+OB binaries is given for comparison.

3. WR and their CO cores mass distribution

To construct the WR mass distribution in the WR+OB close binaries type, observational data from our Galaxy and the Magellanic Clouds were used (Cherepashchuk and Shaposhnikov 2025). Only systems with signs of the presence of both components in the spectra (SB2) and an estimated orbital inclination were analyzed. The final sample included 35 such systems, each with reliably measured masses of WR stars. The most accurate estimates were selected as the base for the subsequent analysis. The resulting distribution shows a peak near the mass of $15\ M_\odot$, characterized by a sharp increase in the number of stars starting from values of about $4 - 5\ M_\odot$ and a subsequent smooth decrease in the number of stars with a further increase in mass.

The observed WR mass distribution allows us to estimate the mass range of their carbon-oxygen (CO) cores at the end of their evolution, i.e. at the moment immediately before the collapse. In the calculation, it is assumed that the observed mass distribution of WR stars corresponds to the zero age at this stage, and the evolution time and the mass of the CO core are calculated iteratively taking into account the WR mass loss in the stellar wind (Cherepashchuk 2001). As an approximation of the dependence of the WR mass loss rate on its mass at a given moment in time, a power-law (Langer 1989) dependence of the form $\dot{M}_{WR} = k(M_{WR})^{1.61\pm0.29}$ is adopted, determined from a number of our dynamic estimates of the WR mass loss rates in close binary systems based on observations of secular changes in the orbital period of a number of systems (Shaposhnikov et al. 2023a; Shaposhnikov et al. 2023b; Shaposhnikov et al. 2024; Shaposhnikov 2024b; Shaposhnikov 2024a). The coefficient k for each value of α is calculated from M_{WR} and $\dot{M}_{WR}$ values for well-studied system V444 Cyg.

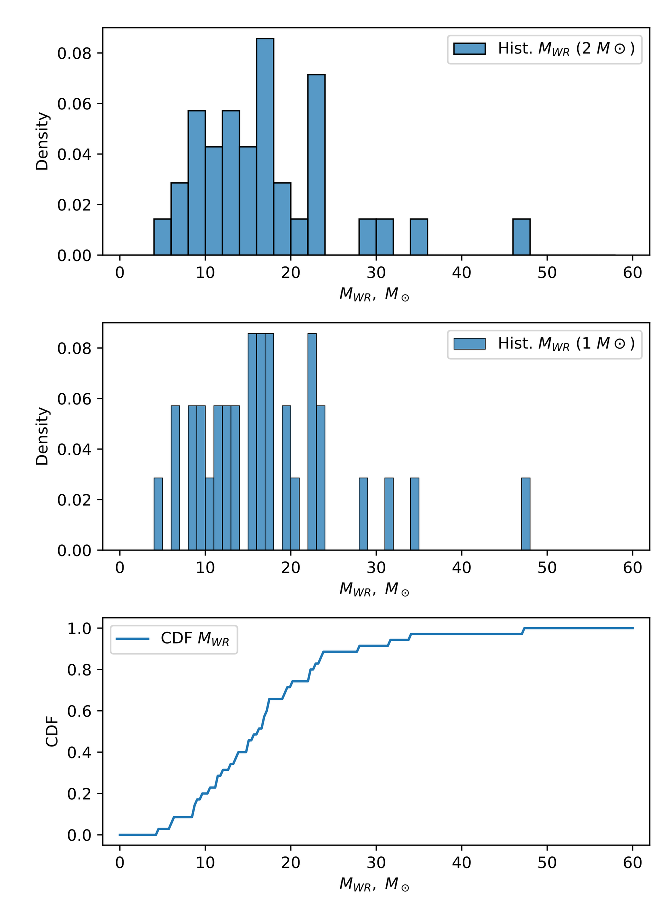

Fig. 2: Distribution of WR masses in WR+OB binaries. Vertically - histogram with a binwidth 2 and $1\ M_\odot$, cumulative distribution.

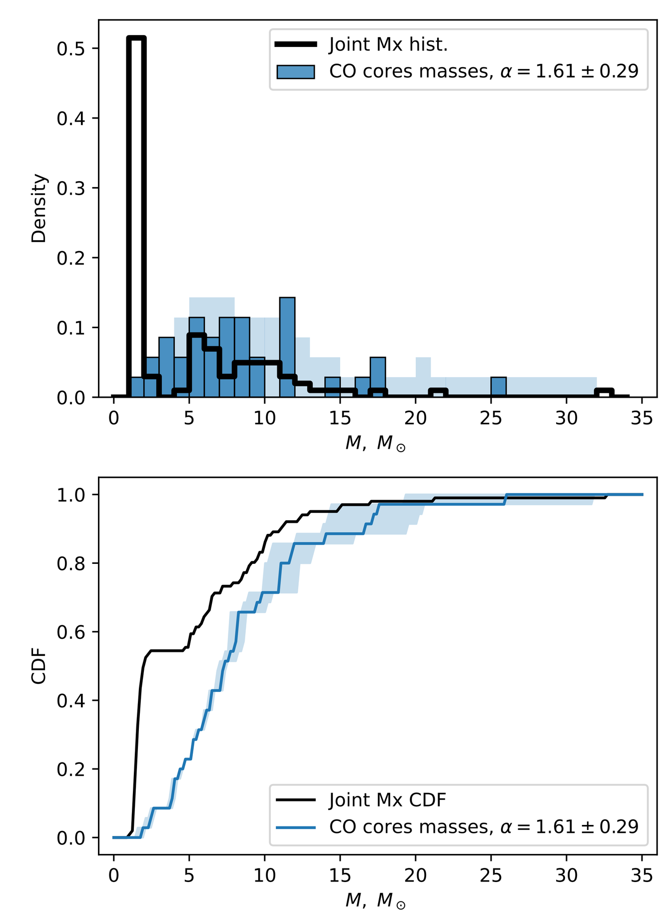

Fig. 3: Distribution of calculated CO cores masses for observed WR in WR+OB binaries. Vertically - histogram with a binwidth $1\ M_\odot$ cumulative distribution (blue for CO cores with $\alpha = 1.61$, light blue for α uncertainty, black for compact object).

The calculation with k and α we found for the $\dot{M}_{WR}(M_{WR})$ dependence leads to a wide spectrum of masses that does not contradict the masses of known BHs in binaries (there is no "convergence effect" that was noted in Langer 1989 for $\alpha = 2.5$).

4. Discussion

It is obvious that constructing a unique transformation from the distribution of the CO of the cores of WR stars before collapse to the distribution of the masses of compact objects is a difficult and unpromising task. Let us note here some possibilities discussed in the literature as an explanation for the anomalies of the mass distribution of compact objects (primarily BH).

One explanation for the deficit of observed BHs with masses less than $\sim 5\ M_\odot$ in binary systems may be the more probable destruction of such systems during a SN explosion, since more energy should be released during the collapse of a less massive core during a SN outburst. However, this explanation is contradicted by the large number of known systems with NSs, which are formed during the collapse of even less massive stars.

In the work (Belczynski et al. 2012), as a mechanism determining the result of the collapse in the form of NSs or BHs, a different scale of instability developing during the collapse is proposed - collapsing objects with "rapid" turbulence are more likely to produce NSs.

In the work (Postnov and Cherepashchuk 2003), as an explanation for the observed deficit of the "mass gap" BHs, a mechanism associated with enhanced quantum evaporation of low-mass BHs was proposed. To date, no significant confirmation of this hypothesis has been obtained, and experiments give a very small spatial scale of the additional spatial dimension required here (small fractions of a millimeter).

Thus, the observed anomalies in the mass distribution of compact objects do not follow from any features in the mass distribution of pre-SNe and require further study. Most likely, the observed features are due to the complex physics of stellar collapse and the behavior of matter at extreme densities (of the order of nuclear densities), and the distributions described above may contain some kind of clue to answer these complex questions.

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