Galactic population of black holes in detached binaries with low-mass stripped helium stars: the case of LB-1 (LS V+22 25)

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ABSTRACT
We model the Galactic population of detached binaries that harbour black holes with (0.5-1.7) $M_\odot$ companions – remnants of case B mass exchange that rapidly cross Hertzsprung gap after the termination of the Roche-lobe overflow or as He-shell burning stars. Several such binaries can be currently present in the Galaxy. The range of $M_{\text{BH}}$ in them is about 4 to 10 $M_\odot$, the orbital periods are tens to hundreds day. The unique BH-binary LB-1 fits well into this extremely rare class of double stars.

Key words: stars: evolution – stars: binaries – stars: black holes.

1 INTRODUCTION
Liu et al. (2019) reported the discovery of a unique Galactic long-period ($P_{\text{orb}}$=78.9 ± 0.3 day) spectroscopic binary LB-1 (LS V+22 25) harbouring a B-type star with an invisible massive compact companion. They associated broad Hα emission line observed in the spectrum with the invisible component and, based on this, estimated the masses of components as 8.2$^{+0.4}_{-0.3} M_\odot$ and 68$^{+11}_{-10} M_\odot$, respectively. A $\gtrsim 70 M_\odot$ compact object should be a black hole (BH). However, currently it is expected that there exists a gap in the masses of Galactic BHs between about 40 and 120 $M_\odot$ due to the pair-instability phenomenon (see, e.g., Parmer et al. 2019; Renzo et al. 2020, and references therein).

Abdul-Masih et al. (2019) and El-Badry & Quataert (2020) questioned the association of the periodic variability of the Hα emission with the compact object and suggested that it can be related to the visible star or circumbinary matter. Also, atmospheric parameters of the B-component inferred from spectroscopic measurements were reanalysed using new and archival data (e.g., Irrgang et al. 2020; El-Badry & Quataert 2020; Simón-Díaz et al. 2020). These revisions resulted in the reduced implied mass of the compact object to about (4 - 20) $M_\odot$. Besides, Shen et al. (2019) have shown that implied $M_{\text{BH}}$=70$M_\odot$ cannot result from the merger of two less massive BH components in a triple system, while according to Tanikawa et al. (2019) LB-1 cannot be formed by dynamic processes in a cluster.

Irrgang et al. (2020), based on a quantitative spectroscopic analysis, photometric measurements of the angular diameter of the system and its Gaia parallax, argued that the visible star mass is 1.1 ± 0.5 $M_\odot$ and it may be a “stripped helium star of sdB-type, masquerading as a normal B-star; the mass of the compact object in LB-1 exceeds 2.6^{+0.4}_{-0.5} M_\odot”. If the orbital inclination is not too extreme ($i > 20$°), the mass of the compact object can be $\gtrsim 20 M_\odot$. Importantly, spectroscopic analysis (Irrgang et al. 2020; Simón-Díaz et al. 2020) revealed that the matter in the surface layers of the visible component is CN-processed.

The mass 1.1 ± 0.5 $M_\odot$ exceeds ascribed to subdwarfs “canonical” mass 0.47 $M_\odot$ (see Heber 2009, for a review). “Stripped helium stars” are considered as the remnants of donors in “case B” Roche lobe overflow (RLOF), which occurs after hydrogen exhaustion, but prior to helium ignition in the stellar core (Kippenhahn & Weigert 1967). Hence, the remnant masses should range from the minimum mass for core helium ignition, $\simeq 0.33 M_\odot$, to several dozens $M_\odot$. However, to the best of our knowledge, there are only five helium subdwarfs with measured or estimated masses between 0.6 and 1.7 $M_\odot$, comparable to the estimate for visual component of LB-1. Between the most massive known subdwarf, 60 Cyg. (1.7 $M_\odot$, Peters et al. 2013) and the least massive Galactic WR stars ($\sim 7 M_\odot$, e.g., Shenar et al. 2020) no He-stars have been observed for as yet unknown reason.

1 Liu et al. (2019) claim that the visible companion is best-fit by a B-subgiant located on the HRD close to the main-sequence turn-off. However, its spectrum is definitely neither that of an sdB star nor of a normal main-sequence B-type star because of the signal of the CNO-processed material (U. Heber, private communication).
Irrgang et al. (2020) found that the optical component of LB-1 has \( T_{\text{eff}} = 12720 \pm 260 \) K and \( \log(g) = 3.00 \pm 0.08 \), which is consistent with Abdul-Masih et al. (2019) data, but differ from Lin et al. (2019): \( T_{\text{eff}} = 18104 \pm 825 \) K, \( \log(g) = 3.43 \pm 0.15 \). However, the estimated \( T_{\text{eff}} \) and \( \log(g) \) are significantly lower than the typical ones for sdB stars.

Liu et al. (2019) and Irrgang et al. (2020) noted that the visual star in LB-1 may be in the state after completion of the RLOF episode in the red giant (RG) region on the Hertzsprung-Russel diagram (HRD), when it crosses HRD in the Kelvin-Helmholtz time scale toward high \( T_{\text{eff}} \). Independently, Eldridge et al. (2019), ran a grid of evolutionary tracks by a binary population synthesis (BPS) code and found several systems with stripped helium components that fit within certain accuracy the parameters of LH-1; the best matching systems they found have \( M_{\text{bin}} \approx 7 M_\odot \), and \( M_{\text{bin}} \approx 1 M_\odot \); the optical components are in the H-shell burning stage.

We aim at verifying whether the standard stellar binary evolution is able to reproduce the mass, effective temperature, luminosity of the optical star in LB-1, and the “typical” stellar mass of BH-component. We model the population of similar binaries and evaluate the Galactic number of LB-1 type systems. To this end, we use the population synthesis and supplementary evolutionary calculations.

2 THE MODEL

Motivated by the relatively low values of \( T_{\text{eff}} \) and \( \log(g) \) of the optical component in LB-1, we try to find detached binaries in which (i) the initially more massive component has evolved into a BH, (ii) the binary system has survived the SN explosion, and (iii) the companion to the BH has completed case B mass exchange and either crosses HRD toward high \( T_{\text{eff}} \) having a He-core and a H-burning shell or has a CO-core and a He-burning shell and evolves toward lower \( T_{\text{eff}} \) (or makes loops in HRD). We select the binaries with \( M_{\text{bin}} \approx (0.5 - 1.7) M_\odot \). We do not consider stripped He-core burning stars as viable components of LB-1 stars, because of their high \( \log(g) \). We model the population of binaries with components similar to those of LB-1, irrespective of their orbital periods and luminosity and provide an example of a binary which reasonably fits all parameters of LB-1.

As the first step, we apply an updated version of the open BPS code BSE (Hurley et al. 2002) to model a population of binaries in which the primary component has collapsed into BH and the secondary companion is a moderate-mass (4 - 9 \( M_\odot \)) star which has evolved into a He-star after case B RLOF. Such binaries are expected to have passed through an evolutionary stage where they could resemble LB-1, or to become similar to LB-1 later.

Our typical BPS run traces the evolution of 1.5 \( \times \) 10^5 binaries. The initial masses of the primary components in the binaries are distributed according to the Salpeter’s law. The binary mass ratios \( q = M_2/M_1 \leq 1 \) and orbital eccentricities \( e \) are distributed as \( dN/de = const. \), \( e \in [0.1;1] \) and \( dN/de = const. \ e \in [0;1] \). Galactic stellar binarity rate \( B \) is set to 50\%, i.e., 2/3 of all stars reside in binaries with assumed metallicity \( Z = 0.02 \). The initial distribution of the binary orbital periods is taken as \( f(\log P_{\text{bin}}) \propto \log P_{\text{bin}}^{-0.55} \) (Sana et al. 2012). Stellar winds of massive stars and stripped He-stars are treated as in Vink et al. (2001) and Vink (2017).

BHs are assumed to form by direct collapse of the progenitor’s CO-core, i.e., the mass of a nascent BH is set equal to the mass of the CO-core of the collapsing star with the 10% gravitational mass defect. The nascent BHs are assigned an isotropic kick velocity \( v_k = 30 \) km s\(^{-1} \). (See for comparison with delayed collapse model § 4).

For the common envelope stages, we adopted the \( \alpha \)-formalism (Webbink 1984) with account for the binding energy of the envelope factor \( \lambda \) (de Kool 1990), for which we use the values from Loveridge et al. (2011). In the present study we assume the common envelope efficiency \( \alpha_{ce} = 1 \).

A critical issue in the formation of LB-1 systems is the stability of mass transfer from the companion to BH and the avoidance of merging of the components in the common envelope which depends, mainly, on the mass and angular momentum loss from the system. van den Heuvel et al. (2017), using the fits to the evolutionary tracks, have estimated that, if the mass ratio of the donor and BH is \( \approx 3.5 \) and the former has a radiative envelope, mass transfer through \( L_1 \) can be stabilized by “isotropic reemission” – the loss of the excess of matter from the system with the specific angular momentum of the accretor, e.g., Soberman et al. (1997); Postnov & Yungelson (2006). In addition, we have assumed that in semi-detached systems with compact components \( \delta = 10\% \) of the mass lost by the donor leaves the system via the outer Lagrange point \( L_2 \) carrying specific angular momentum of \( L_2 \). Binary separation change in this case is described, e.g., by Eq.(6) in Cherepashchuk et al. (2018). This assumption almost does not influence \( M_{\text{bin}} - M_{\text{bin}} \) relation, but affects the \( P_{\text{bin}} \)-distribution of LB-1 systems (see Figs. 3 and 6).

Instead of using formal criteria for the mass transfer stability and analytic lifetime estimates of the stars of interest in the specific evolutionary stages, as the second step of modelling we have applied stellar evolution code MESA (Paxton et al. 2019, and references therein) to compute a sufficiently dense grid of evolutionary tracks encompassing the LB-1 stage for the systems with BHs taken from the BSE output. If a particular binary did not merge in the common envelope, we used the computed lifetimes in the LB-1 part of the track to evaluate the Galactic number of such systems. Otherwise, we rejected the binary from the statistics.

To calculate the current number of the Galactic LB-1 systems, we took into account the star formation rate (SFR) in the Galactic thin disc after Yu & Jeffery (2010): \( \text{SFR}(t) = 11 e^{(t-t_0)/4} + 0.12 (t - t_0) \), with the time \( t \) in Gyr, \( t_0 = 4 \) Gyr, \( \tau = 9 \) Gyr, and the Galactic age of 14 Gyr. This model gives the total mass of the Galactic thin disc \( M_\odot = 7.2 \times 10^8 M_\odot \), which we use for normalisation of calculations.

3 RESULTS

Figure 3 presents the probability (in colour scale, per \( M_\odot \)) of finding BHs with (0.5 - 1.7) \( M_\odot \) H- or He-shell burning companions, stripped during case B of RLOF. We account the stars with luminosity of the H-burning shell \( L_\odot \), \( L_\odot \geq L_{\odot} \), where \( L_{\odot} \) is the luminosity of the He-burning stellar core,
and stars with CO-cores and He-burning shells. If they refill Roche lobes, we do not count the duration of the RLOF phase in the statistics. We assume that the LB-1 stage ends when $T_{\text{eff}}$ of the star evolving in the HRD diagram toward high $T_{\text{eff}}$ reaches that corresponding to the CO WD formation. In fact, this location almost coincides with the ZAMS for He-stars. Note that the probability of finding an LB-1 system varies in the diagram within three orders of magnitude and increases for high $T_{\text{eff}}$ because of slow-down of stellar evolution with approach of He-core formation.

Overplotted in Fig. 3 is an evolutionary track for a star evolving in the HRD diagram toward high $T_{\text{eff}}$ before formation of a He-star. Note, the range of estimated $T_{\text{eff}}$ for LB-1 is reached already in $\approx 5$ kyr after the end of RLOF. The presence of a gas disc around the compact object in LB-1 can be related to the brevity of this time. In the lower panel of Fig. 2, we plot the mass-loss rate by the donor, accretion rate onto the BH, and mass-loss rate from the system during non-conservative RLOF. Remarkably, the system avoids a common envelope despite (dM/$dt$) exceeds the Eddington limit by more than two orders of magnitude. This means that the effect of the mass and momentum loss by the isotropic re-emission leading to the widening of the system is much more efficient than the opposite effect of the mass loss from $L_2$ (see also Fig. 3).

Figure 3 presents relations $M_{\text{opt}}$-$M_{\text{BH}}$ and $M_{\text{opt}}$-$P_{\text{orb}}$. The plot reveals an evident trend of $M_{\text{opt}}$ to the low values. The masses of their progenitors are $(3 \sim 7) M_\odot$. The masses of BH progenitors range from 18 to $40 M_\odot$. Note, the maximum of the $P_{\text{orb}}$-distribution in the entire model population is close to 100 day, not far from that of LB-1. However, we should cautionary note that the stars that fit the range $\log(T_{\text{eff}}) = 4.0-4.2$ and have the luminosity appropriate for LB-1 can be related to the brevity of this time. In the lower panel of Fig. 2, we plot the mass-loss rate by the donor, accretion rate onto the BH, and mass-loss rate from the system during non-conservative RLOF. Remarkably, the system avoids a common envelope despite (dM/$dt$) exceeds the Eddington limit by more than two orders of magnitude. This means that the effect of the mass and momentum loss by the isotropic re-emission leading to the widening of the system is much more efficient than the opposite effect of the mass loss from $L_2$ (see also Fig. 3).

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The plot clearly shows that the mass loss via $L_2$ plays a substantial role for orbital periods of LB-1 systems.

During the RLOF stage of the evolution of LB-1’s precursors, the interiors of their donors, where hydrogen burned, should be exposed. The histogram of surface abundances of He, C, N, O in the models of donors after the end of RLOF is shown in Fig. 4. Later, the abundances hardly change, as the stellar winds from the stripped stars are expected to be very weak. These distributions should be compared to the initial abundances of the same species assumed in MESA: log\(X(\text{He})=-0.55\), log\(X(\text{C})=-2.46\), log\(X(\text{N})=-3.0\), log\(X(\text{O})=-2.03\) and the abundances derived for LB-1 (Irrgang et al. 2020): log\(X(\text{He})=-0.19\), log\(X(\text{C})=-4.08\), log\(X(\text{N})=-2.53\), log\(X(\text{O})=-3.15\) (we omit the errors). Simón-Díaz et al. (2020) found depletion of C by a factor $\gtrsim 7$ and enhancement of N by $\sim 2.5$. Examination of Fig. 4 and data of Simón-Díaz et al. (2020) show that the surface abundances of the model LB-1’s optical components have the trend expected for the layers of stars exposed after experiencing H-burning in the CNO bi-cycle and loss of the envelopes in case B RLOF.

Convolution of the formation rate of LB-1’s and related systems per $M_\odot$ with SFR in the Galactic disk enables an estimate of their current Galactic number: $\approx 200$ core He-burning stars of (0.5–1.7) $M_\odot$ with BH companions, $\approx 50$ LB-1 binaries burning H or He in the shells, and only a few such stars with log\(T_{\text{eff}}\)=4.0–4.2 and log\(L/L_\odot\) $\geq 2.8$.

We also found some binaries (typically, with pre-RLOF $M \lesssim 4 M_\odot$). He-core mass $\lesssim 0.5 M_\odot$), which, upon completion of the RLOF, retain H-rich envelopes of $\approx 0.2 M_\odot$. They do not evolve to high $T_{\text{eff}}$, but continue to move along RG-branch in HRD, single RGSs with failed blue loops (Figs. 5 and 6). They may be called “stripped red giants”\(^4\). The end products of their evolution should be “hybrid” CO/He WD. As post-AGB stars, they rapidly cross HRD, where, in principle, they also may be discovered. We estimate their current Galactic number as $\approx 200$. There is also a small admixture of stars experiencing case C RLOF (after core-H exhaustion) and later evolving up and leftward in the HRD. The binary like 2MASS J05215658+4359220, harbouring an RG and a massive unseen component ($P_{\text{orb}}=82$ day, $M_{\text{RG}} = 3.2\pm1.0 M_\odot$, $M_{\text{comp}} = 3.3\pm0.8 M_\odot$, Thompson et al. (2019)), may be a progenitor of this type stars.

\(^4\) An interesting problem, which is beyond the scope of our study, is whether they may appear as symbiotic stars with BHs powered by wind accretion from the RG/AGB companions.

\section{Discussion and Conclusion}

We have shown that the origin of binaries similar to LB-1 and their parameters, as derived by Irrgang et al. (2020), can be explained by the standard evolution theory of close binaries and current BHs formation scenarios. LB-1 is a star that has a very rapidly crossing HRD visual component that lost most of H-rich mantle in the early case B RLOF and is in the H-shell burning stage. If the mass of the visual component of the model star would exceed $\approx 0.8 M_\odot$, He in

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Distribution of surface abundances of He, C, N, O of the model optical stars in LB-1 systems. Horizontal lines connect abundances in homogeneous stars set in MESA (circles) and values for LB-1 (crosses) derived by Irrgang et al. (2020).}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Model probability (per $M_\odot$) of finding an RGB/AGB/post-AGB+BH system in HRD. Blue lines correspond to the detached stages of post-RLOF donor evolution.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{Same as in Fig. 3 for RG/AGB + BH systems.}
\end{figure}
its core could be already exhausted and it could be in the He-shell burning stage. Such stars may make several loops between ZAMS of He stars and the RGB (see, e.g., Iben & Tutukov 1985) and have at that $T_{\text{eff}}$ and $L$ comparable to those of LB-1. LB-1 systems may have $P_{\text{orb}}$ in the range from several dozen to hundred day; this range is strongly sensitive to the amount of mass and angular momentum lost via $L_2$ during RLOF.

Belczynski et al. (2020), using code MESA, have shown that at $Z = 0.07 M_\odot$, BH, in principle, may form, if the stellar wind mass-loss rate is reduced by a factor $\sim 5$ compared to the “standard” values (de Jager et al. 1988; Vink et al. 2001). However, any theoretical or observational justifications for such a reduction of the mass loss are lacking.

Eldridge et al. (2019), as mentioned, computed a grid of models searching for systems with parameters reported in Liu et al. (2019), but aiming at the mass ratio $M_{\text{BH}}/M_{\ast}$ instead of the absolute value of $M_{\text{BH}}$. The ranges $P_{\text{orb}} = (60 - 100)$ day and $\log(L_{\text{vis}}/L_\odot) \gtrsim 3.0$ were attempted to fit. Like in our study, Eldridge et al. (2019) found that LB-1’s may be systems with stripped He-stars with H-burning shells and stellar mass (4 - 5) $M_\odot$ BH components. However, the tracks they found, did not fit all parameters of LB-1 simultaneously.

An important argument supporting the LB-1 formation scenario via case B RLOF in a binary, with an intermediate-mass secondary, as argued by Irrgang et al. (2020), is the consistency with the young age of LB-1, inferred from its location in the Perseus arm. The short timescale of the “transition” of the putative progenitor of LB-1 to its position in HRD after RLOF (Fig. 2) allows one to consider the gas disc in the system as a remnant of a structure formed during RLOF. This also explains the paucity of LB-1 systems.

We have used some assumptions that need special mentioning. There is a certain mismatch between the BSE and MESA calculations, since the former is based on the evolutionary tracks for single stars by Pols et al. (1998) and “educated guesses” for close binaries evolution, while the latter is a full-fledged evolutionary code with the modern input physics. Thus, the output of BSE modeling may differ from that of a BPS code would it be based on MESA calculations. This concerns mainly the masses of stellar remnants, stellar lifetimes and the outcome of mass exchange.

Above, we assigned to all BHs a uniform isotropic natal kick $v_\text{k}=30$. The problem of BH formation and kicks is far from being solved. To test our assumptions on the BH kicks, in addition to the direct collapse model, we tested the BH formation model with fallback (Fryer et al. 2012), as parameterized by Giacobbo et al. (2018, Eq. (8) and Appendix A). In this model, $v_\text{k}$ is randomly drawn from a Maxwellian distribution with one dimensional rms $\sigma = 265$ km s$^{-1}$, scaled by a function of the pre-SN masses of the star and its CO and Fe cores. We found that the formation probability of BH+He-star binaries remained qualitatively similar to the simpler case of the direct collapse. The total number of LB-1 type systems reduces by about 50%.

LB-1’s descend predominantly from the binaries with ZAMS $q \approx 0.2 - 0.4$. Other possible initial parameter distributions of massive binaries or binarity rates, e.g., $f(q) \propto q^{-0.16} \times (1 - 0.6 B = (0.69 \pm 0.09) / q^{1.75})$ and $f(q) \propto q^{-0.3}$ $B = (1.0 \pm 0.2)$ (Moe & Di Stefano 2017, $B > 1$ means the presence of a close tertiary component), while being quite uncertain, can influence our estimates. Using the extreme components in Sana et al. and Moe and Di Stefano, $f(q)$ changes the LB-1 Galactic number by $\lesssim \pm 25\%$ Having in mind the uncertainty in the binarity $B$, we conclude that our results depend on the statistical data within a factor of two, which is less than other uncertainties plaguing BPS.

Assuming $Z=0.02$ for the entire lifetime of the Galactic disk, we estimate that there should be $\sim 2 \times 10^5$ wide non-merging BH+WD systems accumulated in the Galaxy. Stellar evolution is $Z$-dependent: in particular, stars with $Z < Z_0$ are more compact and have more massive end products, thus affecting the occurrence of case B mass exchange (see, e.g., Klencki et al. 2020), and references therein). Hence, the formation of LB-1 systems and their progeny is $Z$-dependent and should be traced along with the Galactic SFR and $Z$ evolution. We do not consider such a task currently feasible due to the lack of systematic investigations of low-Z close binaries and the absence of statistical data on the distribution over their masses, mass ratios and orbital separations. However, it is possible that the lower formation rate of low-Z LB-1’s may be compensated by a higher SFR, and the number of wide BH+WD could remain of the same order.

Despite the uncertainties of the evolutionary scenario we have used in our study, we confirm that the origin of LB-1 and the presence of a (4-10) $M_\odot$ BH in this binary and in inevitably existing similar systems can be explained by the standard stellar evolution which predicts the current presence of a few such systems in the Galaxy.

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REFERENCES

Abdul-Masih M., et al., 2019, arXiv e-prints, p. arXiv:1912.04092
Belczynski K., et al., 2020, ApJ, 890, 113
Cherepashchuk A. M., Postnov K. A., Belinski A. A., 2018, MNRAS, 479, 4844
El-Badry K., Quataert E., 2020, MNRAS, 493, L22
Eldridge J. J., Stanway E. R., Breivik K., Casey A. R., Steeghs D. T. H., Stevanage H. F., 2019, arXiv e-prints, p. arXiv:1912.03599
Farmer R., Renzo M., de Mink S. E., Marchant P., Justham S., 2019, ApJ, 887, 53
Fryer C. L., Belczynski K.,Wiktorowicz G., Dominik M., Kalogera V., Holz D. E., 2012, ApJ, 749, 91
Giacobbo N., Mapelli M., Spera M., 2018, MNRAS, 474, 2959
Heber U., 2009, ARAA, 47, 211
Hurley J. R., Tout C. A., Pols O. R., 2002, MNRAS, 329, 897
Iben I. J., Tutukov A. V., 1985, ApJ Suppl. Ser., 58, 661
Irrgang A., Geier S., Kreuzer S., Pelisoli I., Heber U., 2020, A&A, 635, L5
Kippenhahn R., Weigert A., 1967, ZA, 65, 251
Klencki J., Nelmanns G., István A., Pols O., 2020, arXiv e-prints, p. arXiv:2004.00628
Liu J., et al., 2019, Nature, 575, 618
Loveridge A. J., van der Sluys M. V., Kalogera V., 2011, ApJ, 743, 49
