



LB-1 Is Inconsistent with the X-Ray Source Population and Pulsar–Black Hole Binary Searches in the Milky Way

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Received 2019 December 23; revised 2020 August 18; accepted 2020 August 18; published 2020 September 29

Abstract

If confirmed, a wide binary system consisting of a $70 M_{\odot}$ black hole (BH) and an $8 M_{\odot}$ main-sequence star (LB-1) is observed to reside in the Milky Way (MW). While we remain agnostic about the nature of LB-1, we show that long-term evolution of an $8 M_{\odot}$ star around a BH with mass between 5 and $70 M_{\odot}$ makes them visible as ultraluminous X-ray (ULX) sources in the sky. Given the expected ULX phase lifetime (≈ 0.1 Myr) and their lack of detection in the MW, we conclude that the frequency of an 8 – $20 M_{\odot}$ star to be in binary around a stellar mass BH should be less ($f < 4 \times 10^{-3}$). This is in tension with Liu et al., who claimed the detection frequency of an LB-1-like system to be around 8 – $20 M_{\odot}$ stars ($f \approx 3 \times 10^{-2}$). Moreover, the $8 M_{\odot}$ star is likely to end as a neutron star (NS) born with a very small kick from an electron-capture supernova (ECSN), leaving behind a wide NS–BH binary. So far, less than 1% of all the detectable pulsars in the MW have been mapped and there has been no detection of any pulsars in binary systems around BHs, which sets an upper bound of about 100 possible pulsar–BH systems in the MW. We show whether the NS is born from ECSN, a frequency upper limit of ($f \approx 10^{-3}$) for stars with masses ≈ 8 – $20 M_{\odot}$ in the MW to have a BH companion. The rate discrepancy will further increase as more pulsars are mapped in the MW, yet these searches would not be able to rule out the Liu et al. detection frequency if NSs are instead born in core collapse SNe with the commonly inferred high kick velocities.

Unified Astronomy Thesaurus concepts: Astrophysical black holes (98); Pulsars (1306); Binary stars (154); Common envelope binary stars (2156); Interstellar dust extinction (837)

1. Introduction

If confirmed, the formation of LB-1, the recently discovered $8 M_{\odot}$ blue star orbiting a $70 M_{\odot}$ black hole (BH) in a low eccentricity orbit ($e \approx 0.03$) and semimajor axis of about $300 R_{\odot}$ (Liu et al. 2019) lacks a convincing explanation. In short there are two issues with this system: (i) the mass of the BH is above pair-instability pulsation supernovae for metal-rich stars (Population I/II), although a $70 M_{\odot}$ BH is allowed (at the extreme) for metal-free stars (Population III; Woosley 2017) while the stellar companion for this BH in LB-1 is at solar metallicity. (ii) The $8 M_{\odot}$ star is orbiting this massive BH at a distance of about $300 R_{\odot}$, which is smaller than the expected radius of the progenitor star of the $70 M_{\odot}$ BH when it expanded into its giant phase. Some of the stellar evolution models with reduced mass loss rates appear to be consistent with the formation of BH up to $70 M_{\odot}$ at high metallicity, but unable to explain how a binary star system like LB-1 could have formed without invoking some exotic scenarios (Belczynski et al. 2020; Tanikawa et al. 2019).

Attempts to explain LB-1 by reducing the wind mass loss efficiency in metal-rich stars by a factor of about 5 have not been successful. Moreover, it has been shown that the $70 M_{\odot}$ BH cannot be a binary of two less massive BHs given the H- α line emission profile of this system (Shen et al. 2019). Also we note that follow-up analyses have challenged the results of Liu et al. (2019) indicating that LB-1 does not host a $70 M_{\odot}$ BH (Abdul-Masih et al. 2019; El-Badry & Quataert 2019; Eldridge et al. 2020).

In this article, we remain agnostic as to whether LB-1 hosts a $70 M_{\odot}$ BH or a smaller BH companion. However, we ask if a wide binary system as claimed in Liu et al. (2019) could exist in the Milky Way (MW) and slip detection. In Section 2 we

estimate the expected number of LB-1-like systems given the formation rate of 8 – $20 M_{\odot}$ main-sequence stars. In Section 3 we present forward modeling of LB-1 and show that such systems enter a short ultra-luminous X-ray (ULX) phase and discuss how the lack of such objects on the sky constrains the possible number of LB-1-like systems in the Galaxy. In Section 4 we estimate the expected number of pulsar–BH systems in the MW. In Section 5 we discuss the survival probability of LB-1-like systems as pulsar–BH binaries given the natal kicks of the newly born NSs, and how this puts an upper limit on the total number of LB-1-like systems in the MW. In Section 6 we discuss caveats related to our work.

2. Expected Number of LB-1-like Systems in the MW

The end life of LB-1 is a wide binary BH–NS system if the system survives the natal kick at the formation of the NS. We denote the formation rate of 8 – $20 M_{\odot}$ stars by R_8 . LB-1 is found after a spectroscopic follow up on 3000 targets in the K2-0 field of Kepler for stars brighter than 14 mag, which we will later use for comparison. We assume that a fraction (f) of all the stars with mass between 8 and $20 M_{\odot}$ are in an LB-1-like configuration. Therefore, the formation rate of 8 – $20 M_{\odot}$ stars having a massive BH companion is

$$R_{8,bh} = f \times R_8. \quad (1)$$

Given that the lifetime of $8 M_{\odot}$ stars is approximately 50 Myr (Cummings et al. 2018), the mean age of stars with mass between 8 – $20 M_{\odot}$ is about 20 Myr. Therefore, the expected number of such binary systems in the MW is

$$N_{LB-1} \approx R_{8,bh} \times 20 \text{ Myr} \approx 4 \times 10^5 f. \quad (2)$$

As the end life of stars with this mass is likely an NS, we have assumed $R_8 \approx 0.02 \text{ yr}^{-1}$ following Licquia & Newman (2015), who assume a Kroupa initial mass function, which gives 2×10^8 NSs formed in the MW over 10 Gyr.

The limiting magnitude of the Liu et al. (2019) target is $m = 14$. Assuming the disk extends to $\approx 14 \text{ kpc}$ (Minniti et al. 2011), and the Sun is at about 8 kpc from the center (Eisenhauer et al. 2003), by looking in the direction of Galactic anticenter, the distance range in the Liu et al. (2019) sample is from 0 to 6 kpc. The limiting magnitude corresponds to an absolute magnitude at each distance according to $M_{\text{abs}} = 14 - 5 \log(d) + 5$, where d is distance to the source in parsecs. We can read off the corresponding luminosity of the source in solar units from M_{abs} at each distance by $L = 10^{0.4(M_{\text{abs},\odot} - M_{\text{abs}})}$, where we take $M_{\text{abs},\odot} = 4.83$. The luminosity is then converted to mass based on the mass–luminosity relation of zero-age main-sequence stars (Tout et al. 1996). This allows a minimum mass m_{min} observable in a 14 mag limited survey as a function of distance to be derived. The m_{min} we compute is about 1, 2, and $3 M_{\odot}$ at 1, 3, and 6 kpc from the Sun, respectively. At each distance, we compute the fraction of stars with masses between $8\text{--}20 M_{\odot}$ over the stars with mass between $m_{\text{min}} - 150 M_{\odot}$ assuming a Kroupa-type initial mass function $\zeta(m) \propto m^{-2.35}$. We weight the resulting fraction by the lifetime of a star with mass m_{min} relative to the lifetime of an $8 M_{\odot}$ star on the main sequence ($t_{\text{ms}} \propto m^{-2.92}$; Demircan & Kahraman 1991). We finally derive the total fraction weighted by the volume at each distance shell ($\propto d^2$) and conclude that the expected total number of $8\text{--}20 M_{\odot}$ stars in Liu et al. (2019) is about 1% of their sample. Therefore, the detection rate of LB-1-like systems around $8\text{--}20 M_{\odot}$ stars in Liu et al. (2019) is about 1 in 30 ($f \approx 3 \times 10^{-2}$). We note that this is a lower limit in that we have not yet taken into account the overall drop in stellar density with Galactic radii, which could increase the detection frequency above 1 in 30. This means that according to Liu et al. (2019) the total number of LB-1-like systems in the Galaxy is more than about 1.4×10^4 (see Equation (2)).

To account for the dust extinction we perform the following analysis. The limiting magnitude of the Liu et al. (2019) target is $m_{\text{Kepler}} = 14 \text{ mag}$ in the Kepler bandpass and all stars were observed in a narrow ($\approx 15 \times 15 \text{ deg}^2$) centered at Galactic coordinates $l = 191.64$, $b = 5.85$. We estimate the corresponding initial mass limit by assuming that the MW is represented by a disk with an exponential density profile in radius and height (Kalberla & Dedes 2008) with atomic hydrogen density:

$$n_{\text{H}} = n_{\text{H},0} e^{-\frac{r-R_0}{R_n} - \frac{z}{H}}, \quad (3)$$

where $n_{\text{H},0} = 0.9 \text{ cm}^{-3}$, $R_0 = 8 \text{ kpc}$, $R_n = 3.5 \text{ kpc}$, $H = 300 \text{ pc}$, and $r = \sqrt{x^2 + y^2}$ is the Galactocentric radius, and z is the disk height. We inject stars with a known initial mass into the MW disk with their locations (x, y, z) in kiloparsecs toward the Galactic coordinates for K2-0 above and where the Sun is located at $(x, y, z) = (8, 0, 0)$, that is with $(x, y, z) = (-d \cos(b) \cos(l) + R_0, -d \cos(b) \sin(l), d \sin(b))$ and with $d \in [0, 6] \text{ kpc}$, $l \in [184.1, 199.2] \text{ deg}$, $b \in [-1.7, 13.4] \text{ deg}$. As star formation traces hydrogen density, we assume that the number density of stars as a function of Galactocentric radius and disk height is $n^* \propto n_{\text{H}}$ and inject 10^6 stars following a

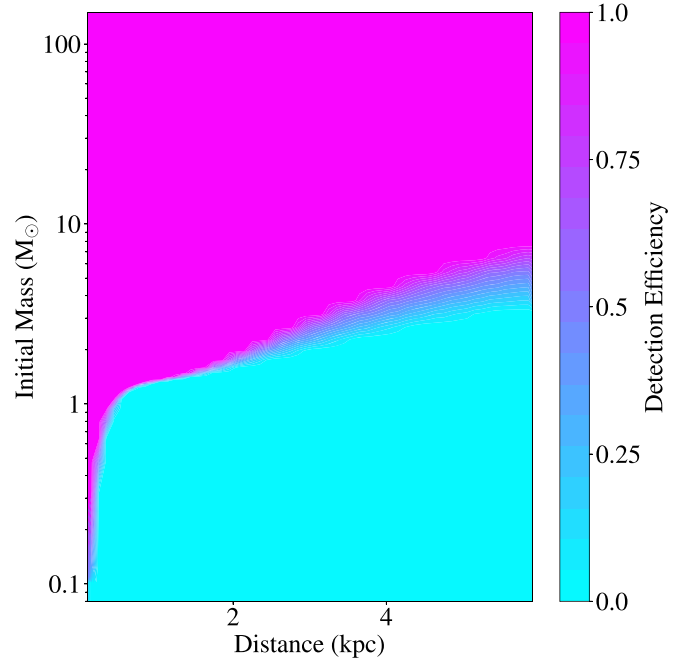


Figure 1. Detection efficiency of stars with a given initial mass and distance from the Sun assuming that all stars are detected in the Kepler bandpass with $m_{\text{Kepler}} < 14 \text{ mag}$. We inject stars into the MW disk and account for dust extinction following the procedure described in Section 2.

probability density function equal to the normalized atomic hydrogen density at their location. We then calculate the column of atomic hydrogen along the line of sight to the Sun and convert that quantity to a V-band extinction following Güver & Özel (2009) and then to extinction in the Kepler bandpass using `pysynphot` and the Kepler filter transmission function ($A_{\text{Kepler}} \approx 0.83 A_V$). The average line-of-sight extinction in the K2 bandpass is $A_{\text{Kepler}} = 1.29 \text{ mag}$.

We determine the absolute magnitude of stars with a given initial mass close to the terminal age main sequence by analyzing Mesa Isochrone & Stellar Tracks (MIST) single-star evolutionary tracks (Choi et al. 2016, 2017) where the star has reached 10% hydrogen mass fraction in its core. Assuming that stars in the field are well represented by these tracks, we look up the Kepler in-band absolute magnitude at this stage in the star’s evolution, which is calculated directly by MIST. Finally, we calculate the recovery fraction of stars with a given initial mass and in different mass bins by determining the fraction of stars detected with $m_{\text{Kepler}} < 14 \text{ mag}$ along all lines of sight. The fraction of stars we recover averaged along all lines of sight as a function of initial mass and distance ($E(m, d)$) is shown in Figure 1.

For reference, the initial mass at which 50% of stars are recovered is about 1.3, 2.3, and $4.5 M_{\odot}$ at 1, 3, and 6 kpc from the Sun, respectively. At large separations from the Sun, these mass estimates are strongly affected by dust extinction as represented by the atomic hydrogen column density along different lines of sight.

Using these detection efficiencies, we then ask what the intrinsic fraction of stars with initial masses from 8 to $20 M_{\odot}$ is relative to stars detectable in the magnitude-limited simulation above? Assuming a Kroupa-type initial mass

function with $\zeta(m) \propto m^{-2.35}$ for $0.5 M_{\odot} < m$ and $m^{-1.3}$ for $0.08 M_{\odot} < m < 0.5 M_{\odot}$, we weight the resulting mass bins by the lifetime of a star with a particular mass relative to the lifetime of a $8 M_{\odot}$ star on the main sequence ($t_{\text{ms}} \propto m^{-2.92}$; Demircan & Kahraman 1991). Integrating for heliocentric distances < 6 kpc and initial masses $0.08 M_{\odot} < m < 150 M_{\odot}$, we calculate the following fraction,

$$\eta = \frac{\int_V \int_8^{20} \zeta(m) t_{\text{ms}} n^*(d, \Omega) E(m, d, \Omega) dm dV}{\int_V \int_{0.08}^{150} \zeta(m) t_{\text{ms}} n^*(d, \Omega) E(m, d, \Omega) dm dV}, \quad (4)$$

where $n^*(d, \Omega)$ is analogous to the normalized atomic hydrogen density used as a proxy for stellar density above, but we account for different likelihoods of finding a star along different lines of sight Ω (covering all solid angles viewed with respect to the Sun, rather than averaged as in Figure 1) and at different heliocentric distances d . Similarly, we account for different efficiencies with respect to the line of sight in $E(m, d, \Omega)$. We then integrate over all mass bins dm and volume V within a heliocentric distance $d = 6$ kpc, with volume elements dV subdivided into heliocentric distance elements dd and solid angle elements $d\Omega$. Under these assumptions, we estimate that the expected total number of $8\text{--}20 M_{\odot}$ stars in Liu et al. (2019) is about $\eta = 0.95\%$ of their sample. Therefore, the detection rate of LB-1-like systems around $8\text{--}20 M_{\odot}$ stars in Liu et al. (2019) is approximately 1 in 29 (i.e., 1 in 0.95% of 3000, $f = 3 \times 10^{-2}$). This means that according to Liu et al. (2019) the total number of LB-1-like systems in the Galaxy is more than about 14,000 (see Equation (2)).

3. Forward Evolution Modeling of LB-1-like Systems

We study the forward evolution of LB-1 based on models discussed in Mondal et al. (2020), where they are based on StarTrack population synthesis analysis (Belczynski et al. 2008).

We begin the evolution of our binary system at time $t = 37.446$ Myr when the initially $8.0 M_{\odot}$ star finishes its main-sequence evolution. At this moment, the binary consists of a $M_2 = 7.9 M_{\odot}$ optical component orbiting a BH with mass $M_1 = 68.0 M_{\odot}$; orbital semimajor axis is $a = 327.6 R_{\odot}$ and eccentricity is $e = 0.0$ (orbital period $P = 78.9$ days). The optical component at this point ($R_2 = 8.1 R_{\odot}$) is well within its Roche lobe radius ($R_{l,2} = 70.8 R_{\odot}$).

The optical star is subject to rapid radial expansion on the Hertzsprung gap and at time $t = 37.54$ it overflows its Roche lobe ($R_2 = 71.0 R_{\odot}$), initiating a stable mass transfer phase onto the BH. At this point, the optical star $M_2 = 7.8 M_{\odot}$ has a He core mass of $M_{2,\text{He}} = 1.6 M_{\odot}$.

The Roche lobe overflow (RLOF) mass transfer rate is very high $dM/dt_{\text{rlof}} = 1.6 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$, and in particular it significantly exceeds the Eddington limit for a $68 M_{\odot}$ BH: $dM/dt_{\text{Edd}}: 1.8 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$. Note that we only allow a small fraction of this mass to be accreted onto the BH: $dM/dt_{\text{acc}}: 7.5 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$, while the rest of the mass is assumed to be ejected from the system with angular momentum characteristic of the BH component (as in the model presented by Mondal et al. 2020). Note that this marks the onset of a very bright ULX phase, as the isotropic X-ray luminosity of the system is $L_{x,\text{iso}} = 5.5 \times 10^{40} \text{ erg s}^{-1}$, and if it is beamed it may reach $L_{x,\text{beamed}} = 5.8 \times 10^{42} \text{ erg s}^{-1}$ (Mondal et al. 2020).

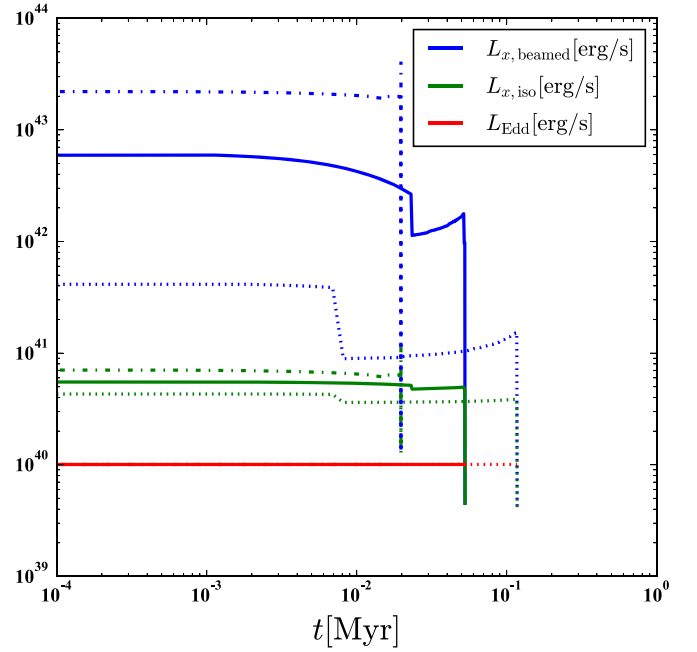


Figure 2. X-ray luminosity evolution of a wide binary consists of a massive BH of mass about $70 M_{\odot}$ and a companion star with mass $8 M_{\odot}$ (solid lines), $6 M_{\odot}$ (dotted lines), and $12 M_{\odot}$ (dotted-dashed lines) from the onset of RLOF considered to be $t = 0$. For the $6 M_{\odot}$ case, the system enters the RLOF phase twice but only the first phase is shown in this figure. The isotropic, beamed, and Eddington luminosities for each case is shown in blue, green, and red, respectively. Both the isotropic and beamed X-ray luminosities of all three systems exceed the Eddington luminosity of the accreting BH by a large factor. Therefore, irrespective of the precise mass of the companion, such wide binaries are observable as ULXs on the sky.

RLOF ends at $t = 37.60$ Myr, when the H-rich envelope of the optical component is significantly depleted ($M_2 = 2.7 M_{\odot}$ with $M_{2,\text{He}} = 1.6 M_{\odot}$). At this stage, the star has evolved to core helium burning and starts contracting instead of expanding. At this point the mass transfer slows down to $dM/dt_{\text{rlof}} = 6.9 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$, but it is still high enough that the system continues to be a very bright ULX: $L_{x,\text{iso}} = 4.7 \times 10^{40} \text{ erg s}^{-1}$ and $L_{x,\text{beamed}} = 9.7 \times 10^{41} \text{ erg s}^{-1}$. At the end of this evolutionary phase, the BH has not gained significant mass: $M_1 = 68.04 M_{\odot}$ as most of the transferred mass ($5.1 M_{\odot}$) was ejected from the system. The mass loss from the binary leads to a significant increase in the binary separation: $a = 2575 R_{\odot}$ ($P = 1801$ days).

At $t = 41.8$ Myr, the optical star has lost the remainder of its H-rich envelope via stellar winds and it has become a naked helium star with mass $M_2 = 2.12 M_{\odot}$. At $t = 42.48$ Myr, the evolved helium star with mass $M_2 = 2.04 M_{\odot}$ and CO core of mass $M_{2,\text{He}} = 1.38 M_{\odot}$ is assumed to undergo an electron-capture supernova (ECSN), forming a low mass NS ($M_2 = 1.26 M_{\odot}$). An explosion happens on the circular and very wide orbit: $a = 2663 R_{\odot}$ (orbit has expanded due to wind mass loss from the optical star). Depending on the adopted natal kick (if any in case of an ECSN; Gessner & Janka 2018) and mass loss ($\approx 0.7 M_{\odot}$; Blaauw kick) the system either survives as a BH-NS binary or is disrupted forming two single compact objects. We investigate the impact of natal kicks in detail in the next section. The evolution described above is shown with solid lines in Figure 2.

We have carried out two more simulations. In the first, we evolve a $6 M_{\odot} + 68 M_{\odot}$ BH. This system enters a stable RLOF

and becomes ULX between which lasts 0.117 Myr (from 68.819 to 68.936 Myr). Then the star detaches (contraction during core helium burning). The star re-expands during AGB evolution entering a second phase of RLOF that lasts 0.197 Myr (from 78.216 to 78.413 Myr). At $t = 78.58$ Myr the system ends as a $1.39 M_{\odot}$ carbon–oxygen white dwarf (WD) and a $68.51 M_{\odot}$ BH at $2873 R_{\odot}$. The first RLOF evolution of this system is shown with dotted lines in Figure 2. In the second simulation, we evolve a $12 M_{\odot} + 68 M_{\odot}$ BH starting with $a = 333 R_{\odot}$. This system enters a stable RLOF and becomes ULX between 17.928 and 17.941 Myr. This is much shorter than the timescale in which the $6 + 68$ system lasts as ULX. After RLOF the system is $68.01 M_{\odot}$ BH + $2.99 M_{\odot}$ star with a He core mass of $2.7 M_{\odot}$ at a separation of $4374 R_{\odot}$. At $t = 20.85$ Myr a supernovae explosion takes place in a system composed of a $2.5 M_{\odot}$ ($M_{\text{CO}} = 1.63 M_{\odot}$) at $4459 R_{\odot}$. This leaves a $1.11 M_{\odot}$ NS in a core collapse supernova (CCSN). This above evolution is shown with dotted–dashed lines in Figure 2.

Therefore, regardless of the exact mass of the secondary, such a wide binary system is expected to enter a ULX phase, with similar lifetimes, that cannot be missed in the X-ray sky (Grimm et al. 2002). As before, the expected number of such ULXs is given by:

$$N_{\text{ulx}} \approx f_{\text{b,ulx}} R_{8,\text{bh}} \times t_{\text{ulx}} \approx 2 \times 10^3 f, \quad (5)$$

where t_{ulx} denotes the lifetime of the ULX phase (assumed to be 0.1 Myr). The accretion disks in these systems are Eddington limited in all directions and not beamed, and therefore we use a beaming factor of $f_{\text{b,ulx}} = 1$. The rejection confidence level (CL) in the absence of any active ULX in the sky is given by $\text{CL} = N_{\text{ulx}} / \sqrt{N_{\text{ulx}}}$, from which values of $f \gtrsim 4 \times 10^{-3}$ are thus ruled out at 99% CL given the nondetection of such systems (Grimm et al. 2002). This is in tension with the detection rate of Liu et al. (2019), which we estimate to be $f \approx 3 \times 10^{-2}$. We note that if the optical star has a mass less than $8 M_{\odot}$, our calculations above need to be revised accordingly.

4. Could LB-1 Host a Less Massive BH?

Recent reanalyses of the LB-1 system suggest that the BH could have a mass between 5 and $20 M_{\odot}$ (El-Badry & Quataert 2019). We performed our simulations of a wide binary consisting of an $8 M_{\odot}$ star with 5 and $10 M_{\odot}$ BHs and found that in both these cases the system becomes a ULX source for a similar lifetime of about 0.1 Myr. Therefore, our results in Section 3 hold if the companion of the $8 M_{\odot}$ star is a BH less massive than $70 M_{\odot}$. We conclude that for LB-1 to have a BH companion of any mass is in tension with the lack of detection of ULXs in the sky as long as the optical component is a massive B star ($> 6 M_{\odot}$).

5. Expected Number of Wide Pulsar–BH Systems in the MW

We assume that the formation rate of neutron stars (NSs) in the MW is the same as the formation rate of $8\text{--}20 M_{\odot}$ stars

$$R_{\text{ns}} \approx R_8. \quad (6)$$

Of these NSs, a fraction (f_{bh}) will be born in binary systems with BH companions, and of those, a fraction (f_{wide}) will be in

wide binary systems. Therefore, the formation rate of NSs in wide BH–NS binaries is:

$$R_{\text{ns}}^{\text{bh,wide}} \approx f_{\text{bh}} f_{\text{wide}} R_{\text{ns}}. \quad (7)$$

The total expected number of such NSs detectable as normal pulsars is:

$$N_{\text{plsr}}^{\text{bh,wide}} \approx R_{\text{ns}}^{\text{bh,wide}} t_{\text{plsr}} f_{\text{b,plsr}} \approx 4 \times 10^5 f_{\text{bh}} f_{\text{wide}}, \quad (8)$$

where we have taken $t_{\text{plsr}} = 100$ Myr as a typical age of a normal pulsar in the MW (Halpern & Gotthelf 2010), and $f_{\text{b,plsr}} = 0.2$ as a typical beaming factor for the normal pulsars (O’Shaughnessy & Kim 2010). The total number of pulsars agrees with the expected number of them after correcting for their beaming factor (Kaspi 2010; Keane et al. 2015).

We take $f_{\text{bh}} \approx 10^{-4}$, and $f_{\text{wide}} \approx 0.5$ for NSs to be in wide binaries around BHs (Olejak et al. 2020). Therefore, we expect about $N_{\text{plsr}}^{\text{bh,wide}} \approx 20$ systems in the MW, while $N_{\text{plsr}}^{\text{bh,wide}} = 0$ is certainly possible given the current nondetection of NS–BH systems in the Galaxy. We note that this statistic does not further divide the sample based on BH mass.

6. Survival Chance of LB-1-like Systems As Wide NS–BH Binaries

In this section, by “LB-1-like system” we mean a system with characteristics similar to the current state of LB-1. A wide binary system of a $8 M_{\odot}$ star around a massive BH evolves first to a stable mass transfer through RLOF. At this stage the donor loses mass (about $\approx 5 M_{\odot}$), which leads to the expansion of the orbit by (Toonen et al. 2016):

$$\frac{a_f}{a_i} = \left(\frac{m_{\delta,i} m_{\alpha,i}}{m_{\delta,f} m_{\alpha,f}} \right)^2, \quad (9)$$

where the subscripts i and f denote the pre- and post-mass transfer values for the donor and accretor (denoted by δ and α , respectively).

After the expansion, the He core of the stripped star experiences a supernova explosion resulting in a kick imparted to the newly born NS. The magnitude of this kick can be very small (order of a few km s^{-1}) for an ECSN explosion, or larger for a Fe core collapse explosion of a more massive He core (e.g., Holland–Ashford et al. 2017). After this SN explosion, the system can remain bounded depending on the mass loss experienced during the explosion (ΔM), the total mass of the binary before the explosion (M_{tot}), the magnitude of the kick (v), and the relative velocity of the NS with respect to the central mass of the system (v_{rel}). Averaged over random kick directions, the probability that the binary remains bounded is given by (Hills 1983; Tauris et al. 2017):

$$P_{\text{bound}} = \frac{1}{2} \left\{ 1 + \left[\frac{1 - 2\Delta M/M_{\text{tot}} - (v/v_{\text{rel}})^2}{2(v/v_{\text{rel}})} \right] \right\}. \quad (10)$$

This functional form is bounded between zero and one. We assume about $5 M_{\odot}$ is lost from a binary in the RLOF phase from the $8 M_{\odot}$ star, which leads to an orbital expansion factor of about 9, after which we consider an SN kick.

We assume that the natal kick of the NSs follows a Maxwell–Boltzmann (MB) distribution. Analyzing the proper motion of 233 pulsars, Hobbs et al. (2005) arrive at an MB distribution with rms 1d velocity dispersion of 265 km s^{-1} .

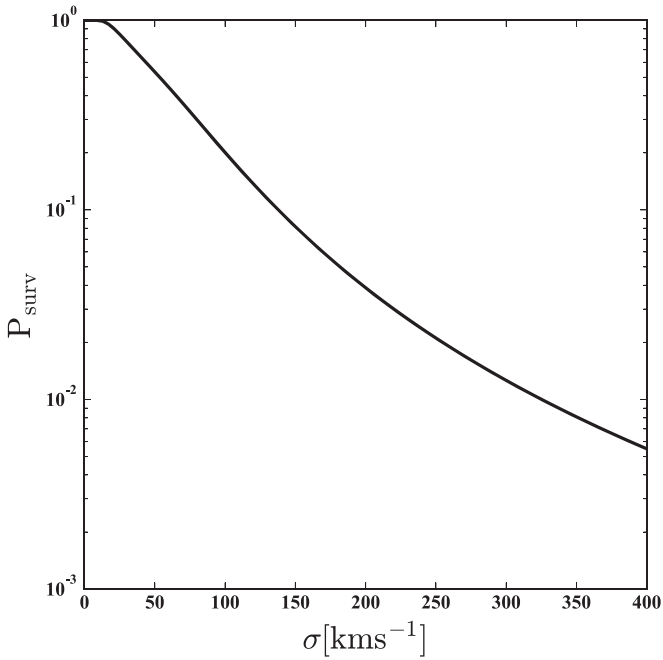


Figure 3. Overall survival chance of an $8 M_{\odot}$ star orbiting a $70 M_{\odot}$ BH as a function of the 1d velocity dispersion of the MB distribution describing the kick magnitude the NS receives at birth. We have assumed the binary period prior RLOF expansion is 80 days in this calculation.

However, if the end product of the $8 M_{\odot}$ star is an NS, it is likely not coming from a massive Fe core collapse with large kicks, but rather from ECSN (Nomoto 1984) with small kicks (Suwa et al. 2015; Janka 2017).

The overall survival probability of such systems can be computed as

$$P_{\text{surv}} = \int P_{\text{bound}}(v) P(v) dv. \quad (11)$$

Here we assume $P(v)$ follows an MB distribution. Figure 3 shows the effect of σ on the survival chance if we assume that binary period prior RLOF expansion was 80 days. For example with $\sigma \approx 130 \text{ km s}^{-1}$ we expect 10% of such systems to survive.

The maximum number of detectable radio pulsars in wide binaries around BHs as end life of LB-1-like systems is given by:

$$N_{\text{plsr}}^{\text{bh, wide}} \gtrsim P_{\text{surv}} N_{\text{LB-1}} f_{\text{b, plsr}}, \quad (12)$$

where P_{surv} is the survival chance of LB-1-like systems to end as wide NS–BH binaries and not get disrupted by the natal kick. This is an upper limit for the product of $P_{\text{surv}} N_{\text{LB-1}}$ since there might exist alternative pathways to make wide pulsar–binary BHs in nature than as the endpoint of LB-1-like systems.

Figure 4 shows the upper limit on $N_{\text{LB-1}}$ as a function of P_{surv} assuming $N_{\text{plsr}}^{\text{bh, wide}} = 10(100)$ shown with the solid (dashed) line. Since such wide binaries make NSs with very small kicks, the P_{surv} is effectively unity for such systems.

So far about 1% of all the detectable pulsars in the MW have been mapped (Lorimer 2008; Stovall et al. 2013) and there has been no detection of any pulsars in binary systems around BHs. This sets an upper bound of about 100 possible pulsar–BH systems in the Galaxy that are yet to be detected. Given Equation (12) an upper limit of 500 LB-1-like systems could

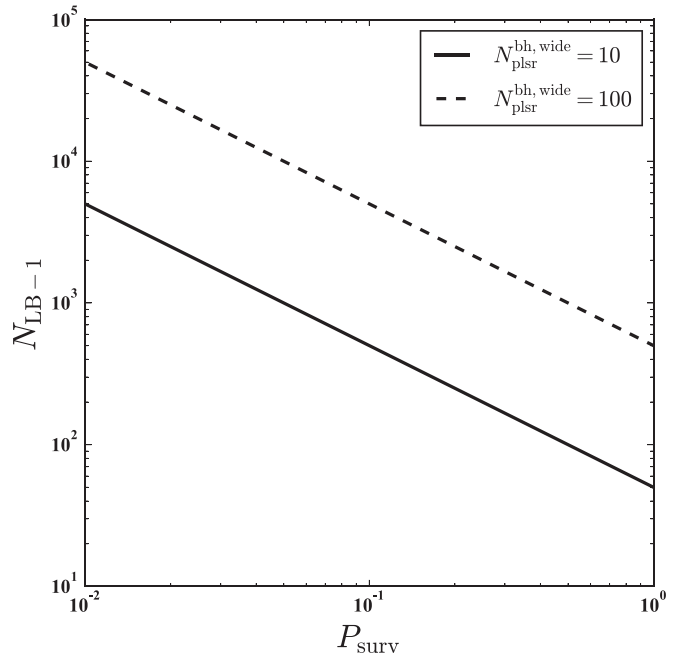


Figure 4. Upper limit on $N_{\text{LB-1}}$ as a function of P_{surv} assuming $N_{\text{plsr}}^{\text{bh, wide}} = 10(100)$ shown with the solid (dashed) line. If NS natal kick is less than a few km s^{-1} , which is expected in the case of EC SNa, LB-1-like systems would end as wide pulsar–BH binaries. In this case, if all of the pulsars in the MW are mapped and fewer than 100 pulsar–BH systems are found, no more than 500 LB-1-like systems could exist in the MW. This number scales linearly with the number of future pulsar–BH binary detections.

reside in the MW if less than 100 pulsar–BH system is found when the entire pulsars in the MW are mapped. Therefore, stars with mass $\approx 8 M_{\odot}$ in the MW could have a massive BH companion with a frequency less than $f = 1.25 \times 10^{-3}$ (Equation (2)). This is in strong tension with the detection rate of such systems based on Liu et al. (2019) results. We note that this is assuming that the NS is born in an ECSN with a very small kick. If, however, the NS is born from CCSN with high kicks such that $P_{\text{surv}} = 0.01$, the pulsar searches would not be able to rule out the detection frequency of Liu et al. (2019).

7. Summary and Conclusions

Recently Liu et al. (2019) claimed the discovery of LB-1, a wide binary system of a $70 M_{\odot}$ BH and an $8 M_{\odot}$ main-sequence star in the Galaxy. This detection has recently been challenged and no viable formation mechanism has been put forth for such a system.

In this article we remain agnostic about how such systems could have formed, and instead investigate the upper bound on the number of LB-1like systems in the Galaxy. We show that in their long-term evolution, such systems become ULX sources, independent of the BH mass, after which they end as wide NS–BH binaries if they survive the natal kick imparted to their newly born NS. Given the birth rate of NSs in the MW, and the lifetime of ULX sources based on our simulations, we show that the frequency of an $8\text{--}20 M_{\odot}$ star to be in binary around a stellar mass BH should be less ($f < 2 \times 10^{-3}$), which is in tension with Liu et al. (2019), who claimed that the detection frequency of the LB-1-like system was around $8\text{--}20 M_{\odot}$ stars ($\approx 3 \times 10^{-2}$).

Moreover, the $8 M_{\odot}$ star likely ends as an NS born with a very small kick from an ECSN, which leaves the final endpoint of the system as a wide NS–BH binary. So far less than 1% of all the detectable pulsars in the MW are mapped and there has been no detection of any pulsars in binary systems around BHs, which sets an upper bound of about 100 possible pulsar–BH systems in the Galaxy. If the NS is born from ECSN, we show that the current null detection of pulsar–BH systems implies a frequency upper limit of ($f = 5 \times 10^{-4}$) for stars with masses $\approx 8\text{--}20 M_{\odot}$ in the MW to have a BH companion. The discrepancy with the Liu et al. (2019) rate will increase even further as more pulsars are mapped in the MW and are found to have no BH companions.

We are thankful to the referee for constructive comments. We are thankful to Chris Belczynski and Aleksandra Olejak for providing us the data for the ULX part of this work, and Scott Ransom, Ryan Foley, Duncan Lorimer, and Josiah Schwab for helpful discussions. M.T.S. and E.R.R. thank the Heising-Simons Foundation, the Danish National Research Foundation (DNRF132), and NSF (AST-1911206 and AST-1852393) for support. K.B. acknowledges support from the Polish National Science Center (NCN) grant Maestro: 2018/30/A/ST9/00050.

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