Weighing in on black hole binaries with BPASS: LB-1 does not contain a 70M_☉ black hole

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ABSTRACT
The recent identification of a candidate very massive (70 M_☉) black hole is at odds with our current understanding of stellar winds and pair-instability supernovae. We investigate alternate explanations for this system by searching the BPASS v2.2 stellar and population synthesis models for those that match the observed properties of the system. We find binary evolution models that match the LB-1 system, at the reported Gaia distance, with more moderate black hole masses of 4 to 7 M_☉. We also examine the suggestion that the binary motion may have led to an incorrect distance determination by Gaia. We find that the Gaia distance is accurate and that the binary system is consistent with the observation at this distance. Consequently it is highly improbable that the black hole in this system has the extreme mass originally suggested. Instead, it is more likely to be representative of the typical black hole binary population expected in our Galaxy.

Key words: astrometry – binaries: close – stars: black holes – stars: individual LB-1 – Galaxy: stellar content

1 INTRODUCTION
The recent identification by Liu et al. (2019) of a candidate very massive black hole (BH) of 70 M_☉ with a solar metallicity stellar companion is a remarkable discovery. Our knowledge of BHs to date has come from interacting binaries and gravitational wave events. However, this new BH candidate binary and that of Thompson et al. (2019) are significant discoveries and represent a new window into this population through the observation of the motion of a still-living stellar companion.

The suggestion that a 70 M_☉ BH exists relatively nearby, within our Galaxy, is at extreme odds with the expected nature of such systems, which are predicted to occur only at very low metallicities. Consequently, based on current stellar evolution models, this discovery would imply that our entire understanding of stellar wind mass-loss rates and pair-instability supernovae is incorrect, as discussed by Belczynski et al. (2019). In fact, at Solar metallicity, stellar winds are strong enough to reduce all stellar progenitors of BHs to masses, at birth, below ~10 M_☉ (e.g Eldridge & Tout 2004; Özel et al. 2010; Farr et al. 2011; Eldridge & Stanway 2016; Eldridge et al. 2017).

Liu et al. (2019) propose three primary arguments in favour of the massive BH interpretation. First, that broad Hα line emission arises from a Keplarian disk close to the hidden compact object, giving a velocity half-amplitude of K_A = 6.4 ± 0.4 km s⁻¹ viewed at low inclination of ~15° to the line of sight. Second, that the most likely companion is a 8.5 M_☉ main-sequence star, which is identified as having a velocity half-amplitude of K_B = 52.8 ± 0.7 km s⁻¹. Third, that the source parallax reported by Gaia (Gaia Collaboration et al. 2018) is incorrect by a factor of two, placing the system at 4.23 ± 0.24 kpc instead of 2.14±0.31 kpc.

The first of these points is dependent on the correct interpretation of the Hα line profile, a subject which the authors recognise as problematic, due to the complications that can arise from hotspots, asymmetric structures and non-disk flows lying between the binary components. This is particularly true since there is no clear evidence that the compact object is actively accreting and so the presence of a relaxed, symmetric, accretion disk that reliably traces the BH is not
obvious. Even in well-established accreting BH systems during quiescent states, the Hz line distribution is usually complex (e.g., González Hernández & Casares 2010) and does not generally reliably track the BH (e.g., Neilsen et al. 2008). Liu et al. (2019) argue that some of these complications can be avoided by sampling the line wings, where the phasing appears to be correct. However, it is not clear whether the phase was a free parameter in the presented fits, how consistent this phase is, nor how well it is constrained. Here again we note that in cases where $K_A$ can be determined through other means, such semi-amplitudes are often not reliable measures of $K_A$ (e.g. Marsh et al. 1994).

The second point is the result of stellar evolution modelling. Liu et al. (2019) do consider the possibility of a lower mass BH, but argue that the thermal timescale is too short and that “No natural stellar models would be consistent with such a companion...”. This statement, however, is not substantiated by a search through the output models of binary evolution codes in Liu et al. (2019) nor in Belczynski et al. (2019).

The third point argues that the distance reported by Gaia (Lindegren et al. 2018; Gaia Collaboration et al. 2018) is incorrect by a factor of two due to a biased parallax measurement from the astrometric wobble induced by the BH, thus making the distance seem closer. This would require Gaia to have observed LB-1 at particular times of its orbit. To examine if this is the case requires non-trivial calculations.

In this paper, we investigate plausible explanations for this system by searching through the extensive BPASS v2.2 1 grid of detailed binary stellar evolution models for systems matching the observed properties of both the early-type B-star and its unseen BH companion. We also explore whether the reported parallax could be significantly biased to impact Gaia’s distance constraint.

The outline of this article is as follows: We first describe our fitting mechanism and present the results of our model search in Section 2. We investigate the impact of the astrometric wobble due to binary motion on Gaia’s parallax measurement in Section 3. We then discuss in Section 4 the expected binary population of BH binaries from BPASS and suggest that future Gaia discoveries of these systems will allow us to rigidly constrain the formation of BH at the point of core collapse within stellar interiors.

2 METHOD AND RESULTS

We search the BPASS v2.2 grid of binary evolution models (for full details see Eldridge et al. 2017; Stanway & Eldridge 2018) at a metallicity of $Z = 0.020$, which is appropriate for Solar metallicity, as derived from spectroscopy of the B-star companion in LB-1 (Liu et al. 2019). We use our fiducial BPASS initial parameter distribution (see Stanway & Eldridge 2018) adopting the broken power-law initial mass function denoted “imf35-300”, which has low mass slope from Kroupa et al. (1993) and a Salpeter (1955) slope for massive stars, and extends to a zero age main sequence upper mass limit of $300 M_\odot$. The initial distributions for binary fraction, orbital period and mass ratio are drawn from the analysis of Moe & Di Stefano (2017).

We consider all binary stellar models that have already formed a BH, and record those that match the following parameters for the companion star (as derived by Liu et al. 2019):

(i) $(P_0/\text{days}) = 2.84 \pm 0.15$,
(ii) $(T_{\text{eff}}/K) = 4258 \pm 15$,
(iii) $(M_\text{BH}/M_\text{com}) = 5.25 \pm 0.14$,
(iv) $(P/\text{days}) = 78.9 \pm 20$,
(v) $(L/L_\odot) \geq 3.0$,
(vi) $K_{\text{surf}} \geq 0.1$,
(vii) $M_{\text{BH}} \geq 2.5 M_\odot$.

We note that BPASS models start with a range of initial orbital periods separated by 0.2 dex intervals. As a result, the final orbital period parameter space is not fully sampled, and some periods fall into gaps between adjacent models. To accommodate this, we permit a larger range for the orbital period than that determined from observations.

Three stellar models are found to lie within the $1 \sigma$ uncertainty range of all observed constraints on the binary parameters. These have initial parameters $(M_\text{com}/M_\odot, M_\text{BH}/M_\odot, (P_0/\text{days})) = (5, 3.2, 0.6)$, $(5, 3.2, 0.8)$ and $(6, 5.0, 0.6)$. A further five models match all observationally-derived constraints to within their $3 \sigma$ uncertainty range. These models all have a substantially lower mass for the B-star companion than the mass reported by Liu et al. (2019), but are still consistent with the observed surface gravity, due to an interaction between the B-star and BH which also circularizes the orbit. Liu et al. (2019) ruled out such a system due to not finding an evolutionary track that could produce it, as well as an estimated short evolutionary timescale.

We also consider a looser subset of constraints, requiring only points (i), (ii), (iv), (v) and (vii) above: this removes constraints – namely the binary mass ratio and surface hydrogen abundance – derived from model-dependant interpretation of the Hz line dynamics, the assumed system inclination and assumed distance. We find 42 (203) model that match these relaxed constraints within their $1 \sigma$ ($3 \sigma$) uncertainty ranges. These have similar parameters to the three systems identified above, but extend over a broader range which suggests that LB-1 is likely a subset of a larger class of BH binaries.

To constrain each property of the components of LB-1 we must account not only for the range of models which fit the data and the quality of the fit, but also for how long they remain in that state. The mean for each parameter (for instance initial mass $M_i$ or initial binary period $P_i$) is

| Table 1. Summary of the best fitting values using the strongly constrained values. The values from our weaker constraints are identical within the uncertainties. |
|---------------------------------|---------------------------------|
| Initial Parameters              | Current Parameters              |
| $M_{\text{com}}/M_\odot$        | $M_{\text{com}}/M_\odot$        |
| $M_{\text{BH}}/M_\odot$         | $M_{\text{BH}}/M_\odot$         |
| $\log(P_0/\text{days})$         | $\log(P_0/\text{days})$         |
| $\log(L/L_\odot)$               | $\log(L/L_\odot)$               |
| $\log(\text{age}/\text{yrs})$   | $\log(\text{age}/\text{yrs})$   |

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1 Binary Population and Spectral Synthesis; https://bpass.auckland.ac.nz and https://warwick.ac.nz/bpass
calculated by,
\[
\langle A \rangle = \frac{\sum_{i,j} \Delta \tau y A_{i,j} \prod_{k=1}^{4} p_k}{\sum_{i,j} \Delta \tau y \prod_{k=1}^{4} p_k}
\]
where \( \langle A \rangle \) is the mean of the parameter we are determining, \( i \) is an index over matching stellar models, \( j \) is the timestep of the model, \( A_{i,j} \) is the \( i \)’th models \( j \)’th timestep value of the parameter, \( \Delta \tau \) is the corresponding model timestep length in years, and \( y \) is the model weighting from the initial population synthesis parameter distribution. The term \( p_k \) reflects how closely the model parameters \( g_{k,\text{mod}} \) fit the observed constraints \( g_{k,\text{obs}} \) and is calculated by,
\[
p_k = \exp\left(-\frac{(\log(g_{k,\text{obs}}) - \log(g_{k,\text{mod}}))^2}{2\sigma_{\log g_{k,\text{obs}}}^2}\right)
\]
We use four observational constraints in this calculation, specifically constraints (i), (ii), (iii) and (iv).

The best fitting initial parameters of the components of LB-1 and the uncertainty in their values, as derived from matching binary stellar evolution models, are listed in Table 1. We include weighted means as described above based on all models fitting the observational parameters within 3\( \sigma \). We show results based on the fully constrained model sample (N=8) while noting that those from the less constrained sample (N=208) are consistent given the uncertainty on each parameter. When the weaker constraints are adopted, the masses of the objects decrease and the age of the system increases.

In Figure 1 we consider the track of the 3 best-matching LB-1 models through the Hertzsprung-Russell diagram, and also the evolution of the mass of the system and the stellar and orbital radii for the best-matching model. At all times the masses are less than those suggested by Liu et al. (2019). The best-matching system has an initially \( \approx 3\,M_{\odot} \) BH with a with a 5\( \,M_{\odot} \) companion, and evolves through Roche-lobe overflow into the binary observed today, with an approximately 1\( \,M_{\odot} \) companion and a 7\( \,M_{\odot} \) BH at the current time. The other matching models show similar behaviour. Based on the middle panel of Figure 1, we can infer the binary has either just finished a phase of interaction, or is heading towards a second one. In the first scenario, the envelope is collapsing and the companion is transitioning to a sub-dwarf state, whereas in the second case the companion is once again expanding and becoming a giant. In both instances, the orbit is expected to be circular from the interactions, thus naturally reproducing the observed very low eccentricity for LB-1. Regardless of which scenario corresponds to the observed system, we can conclude that the B-star is evolving on a thermal timescale.

The total intervals during which the models could be observed within 1\( \sigma \) of their inferred locations in the Hertzsprung-Russell diagram are of the order of 2\( \times 10^4 \) to 8\( \times 10^4 \) years (1\( \times 10^3 \) to 4\( \times 10^3 \) years within 3\( \sigma \)) depending on the stellar evolution model considered. Some systems, including the one shown in Figure 1, agree with the observed system at multiple evolutionary phases. From the matching models we can estimate the number of systems we expect to observe that match the constraints on LB-1. In our standard BPASS population we find that there are 0.11 per 10\(^6\)\( \,M_{\odot} \) stars formed in the Galaxy that match all the observational constraints within their 1\( \sigma \) uncertainty ranges. There are 1.19 such stars per 10\(^6\)\( \,M_{\odot} \), if we relax the requirement to fit within 3\( \sigma \) of the observed values. When our weaker constraints are considered, we find substantially more matches to the observed parameters: 42 (203) models within 1\( \sigma \) (3\( \sigma \)) where we expect 2.61 (13.08) per 10\(^6\)\( \,M_{\odot} \) stars formed.

Assuming a state lifetime of 8\( \times 10^4 \) years per system, and that the Milky Way has been forming stars at a steady rate of 3.5\( \,M_{\odot} \)yr\(^{-1} \) for the last 10\(^8 \) years, these population synthesis expectations correspond to extant current-day populations of 0.03 (0.3) or 0.73 (3.7) binary systems matching these observational constraints in the Milky Way (for tightly constrained and less constrained 1\( \sigma \) (3\( \sigma \)) matches respectively). While this is clearly a relatively rare system, it is not unreasonable to find several such objects in the Milky Way given our current understanding of stellar evolution.

Comparing the predicted photometry from these models to that observed for LB-1 (Reed 2003; Cutri et al. 2003) we find infer distances that range from 1.60 to 2.17 kpc, in good agreement with the distance of 2.14\( \pm 0.31 \) kpc derived from Gaia astrometry (Gaia Collaboration et al. 2018; Lindegren...
et al. 2018). We also fit the radial velocity data reported in Liu et al. (2019) using The Joker2 (Price-Whelan et al. 2017; Astropy Collaboration et al. 2013; Price-Whelan et al. 2018) to determine the minimum mass of the BH based on fits to the binary mass function and an assumed companion mass of 0.77 $M_\odot$. We find a minimum BH mass of $M_{BH, min} = 2.1 \pm 0.93 M_\odot$. If we assume that the BH mass is $5.37 M_\odot$, as in our best fit, we derive an inclination of $21^\circ$, which agrees with the low inclinations derived in Liu et al. (2019) to within $\sim 15 - 33\%$.

The extragalactic dust extinction along the line of sight towards LB-1 is $A_V = 2.1$ or $E(B-V) = 0.66$ (Schlafly & Finkbeiner 2011). The extinction derived from our SED fit, to get an SED that is consistent with the spectrum inferred effective temperature and gravity, is $M_V = 1.90$ or an $E(B-V) = 0.61$, which is similar to that found by Liu et al. (2019) of $E(B-V) = -0.5 \pm 0.03$. Liu et al. (2019) found this extinction was consistent with the value derived from the Pan-STARRS 3D Galactic dust map (Green et al. 2018) at the greater distance. At the location of LB-1, a map suggests that reddening values between $E(B-V) = 0.22$ and $E(B-V) = 0.40$ are expected at the distances best-fitting our models. This suggests there may also be local extinction associated with the stellar source. We note that fixing the dust extinction at a lower level consistent with the map estimates does not change our conclusions, but would suggest a slightly lower mass for both the BH and its companion.

When we relax the derived constraints on our fit – i.e. suppressing constraints (iii) and (vi) – we find brighter systems than those preferred by our more conservative model selection. These would require more significant deviation from the expected, Gaia-derived distance and line of sight extinction but permit systems that are at greater distances than those given here. They do not require a main sequence B-star and thus allow a very massive BH (similar to the one expected, at a lower level consistent with the map estimates does not change our conclusions, but would suggest a slightly lower mass for both the BH and its companion)

Our preferred (zero age main sequence) initial parameters for the system which generates this BH binary are an initial period $P_i = 100$ days, a mass ratio $M_1/M_2 = 1$ and an initial period $P_i/\text{days}$ in the range of $1.2$ to $2$. Such a binary is quite typical given the current best constraints on initial binary parameters (Moe & Di Stefano 2017).

3 THE DISTANCE TO LB-1

The scenario for a $70 M_\odot$ BH demands that the source parallax reported by Gaia is incorrect by a factor of two. Liu et al. (2019) argue that the astrometric wobble induced by the BH is sufficient to bias the parallax by this amount. This is only plausible if Gaia preferentially observed the system at particular times during the system’s orbit. Otherwise the wobble will induce variance to the astrometric fit, not bias. Taking the Gaia scanning law and a period of 78.9 days (Liu et al. 2019), we find that Gaia observed LB-1 at uniformly random times during the orbit. This makes the parallax unlikely to be systematically biased by the orbital motion.

The projected size of the orbit based on the derived values of LB-1 by Liu et al. (2019) is $\sim 0.322 \text{mas}$, while the parallax is $\sim 0.236 \text{mas}$. This suggests that the position of the B-star observed by Gaia should be significantly affected by the binary motion around the BH. However, based on the results in Table 1, at a distance of $2.17 \text{kpc}$ the projected orbit size is $\sim 0.266 \text{mas}$ while the parallax is $\sim 0.461 \text{mas}$. The parallax derived by Gaia is $0.44 \pm 0.086 \text{mas}$ which suggests that the orbital motion should not have a significant effect on the observed parallax. This is inconsistent with the derived results of Liu et al. (2019), but is not in strong tension with the results in Table 1. Figure 2 illustrates the parallax from the inferred distance to LB-1 for our best fit model and that derived by Liu et al. (2019) as well as the parallax observed by Gaia. An example of the combined parallax and binary motion, where a random orbital phase is chosen, is also shown. A different phase choice will change the exact position of the companion star, but will not have a broad effect on the overall motion that the companion traces over long periods of time since LB-1’s orbital period is significantly less than the observing span of the second Gaia data release. The added binary motion of the companion star using our best fit model is consistent with the reported Gaia parallax error. Conversely, the observed parallax is not well described by the combined orbital and parallactic motion of the companion star from Liu et al. (2019) because the combined motion is dominated by the orbit around the BH. We therefore find, that a lower mass BH and companion star with a closer distance is favored by Gaia’s observed parallax over a higher mass BH and companion at a larger distance. We also note that while LB-1 was only visited 12 times during Gaia’s 2nd data release, it is scheduled to be observed $\sim 100$ times by the end of the Gaia mission.

Liu et al. (2019) also argue that the parallax reported by Gaia is unreliable because of strong correlations between position and parallax. However, these correlations depend primarily on Gaia’s scanning pattern and not the source orbital properties. This is illustrated in Figures 3 and 4 where we show the mean ra_parallax_corr and dec_parallax_corr for all Gaia sources brighter than $G < 14$. The scanning pattern is clearly evident. The inset axes shows individual Gaia sources within $2^\circ$ in (l,b) of LB-1, the largest circle. While Liu et al. (2019) comment that the magnitudes of these correlation coefficients are large, they are fully consistent with what is expected from the scanning pattern.

In short, the orbit is evenly sampled in time, the expected astrometric wobble in our preferred scenario is consistent with Gaia observations, and the correlation coefficients between position and parallax is an expected consequence of the Gaia scanning law. For these reasons we argue that the Gaia parallax for LB-1 remains reliable, making the $70 M_\odot$ scenario untenable.

4 DISCUSSION & CONCLUSIONS

The binary systems containing black holes reported by Liu et al. (2019) and Thompson et al. (2019) represent significant discoveries that will be key to our future understanding of how stars evolve, particularly those that are massive enough.

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2 In the course of this work we learned that Adrian Price-Whelan (Flatiron Institute) also performed this analysis independently: https://gist.github.com/adria/4df5159f545926c1badf63e090080c

3 https://gaia.esac.esa.int/gost/
to form black holes in their death throes. These systems represent a previously unknown population of relatively quiet binary systems rather than the more easily-found class of interacting black hole binaries (e.g. Özal et al. 2010; Farr et al. 2011).

We have searched the outputs of a binary population synthesis code to find binary evolution models that match the LB-1 black-hole binary observed by Liu et al. (2019). The only models that were found to match the properties of the observed system contain a BH with significantly lower mass than reported in Liu et al. (2019)—a scenario they discounted due to a suggested lack of such models in the stellar model grids they used.

It is possible that they were not able to identify such models due to their use of a rapid population synthesis code (e.g. Belczynski et al. 2008, 2019). Although these methods are powerful, they lack the physics that is included in detailed binary evolution codes and the ability to follow the response of the stellar envelope to any interaction. Furthermore, many such codes also use the Fryer et al. (2012) rapid supernova mechanism prescription to estimate the remnant mass formed at core-collapse. By construction, this does not allow the formation of low mass black holes below ~5M⊙, and was suggested to agree with observed black hole binaries by Belczynski et al. (2012). However, the identification of new lower-mass black holes binaries suggests that the Fryer et al. (2012) rapid supernova mechanism may need to be revisited, and that fewer assumptions should be made regarding the final fate of compact objects formed in the ‘Mass Gap’.

Liu et al. (2019) also reject lower mass B-stars due to their short evolutionary timescale. However, as we have discussed above, the number of these systems in our Galaxy while low, is not insignificant, making this discovery less unlikely than suggested. To further illustrate this point we show in Figure 5 the full population of BHs with living companions expected from the BPASS population synthesis. As the figure illustrates, there are many systems with similar or longer periods to the LB-1 case.

Since systems such as LB-1 occur naturally within the BPASS fiducial population, we do not find its discovery surprising and do not need to invoke the existence of a 70M⊙ BH that is in tension with our understanding of stellar evolution at the near-Solar metallicities expected within the Galaxy. We note that despite our reservations about the H line tracing the BH dynamics, our favoured models would still imply a low value for K_A, consistent with the semi-amplitudes presented.

There are of course uncertainties that affect these predictions, primarily in how remnant masses are calculated from stellar models and the strength of any BH kicks. In addressing the former we note that the BPASS models are able to also reproduce the observed masses of BHs in X-ray binaries and also the masses and rates of GW transients (Eldridge & Stanway 2016; Eldridge et al. 2017, 2019b). Additionally, BPASS already predicts large BH masses at higher metallicities than other codes, as exemplified by the fact that it was possible in Eldridge & Stanway (2016) to reproduce the GW 150914 system at a metallicity mass fraction of Z = 0.010 (albeit at low probability). The maximum mass of a Solar metallicity BH at its formation in BPASS is 8M⊙ but as we see in Figure 5 this can grow up to ~40M⊙ as a result of accretion. Therefore achieving the proposed BH mass of 70M⊙ would require doubling the assumed efficiency of mass accretion by the BH prior to its observation. This may not be entirely unreasonable, but would significantly affect the
predicted mass distribution of BHs and gravitational wave transient rates from this model.

As we discuss above, LB-1 has a predicted orbital separation in our models of ≈ 200 AU (of the order of 1 AU). At a distance of 2.14 kpc (Liu et al. 2019) this would equate to an angular diameter of 0.266 milliarcseconds. This is certainly resolvable by Gaia and future data releases will be able to firmly settle the nature of LB-1, including the BH mass (Lindegren et al. 2018; Andrews et al. 2019). More such binaries will also be detectable in the future via Gaia astrometry (e.g. Mashian & Loeb 2017; Breivik et al. 2017, 2019) and radial velocity surveys (e.g. Yi et al. 2019). While BH candidates discovered through radial velocity surveys will be subject to viewing angle uncertainties, astrometric discoveries by Gaia will allow dynamical mass measurements down to the 5–10% level (Andrews et al. 2019).

We emphasise that we have not varied any of our fiducial model parameters to find these binaries; they are naturally occurring in our population. This same population has also been verified and tested against many other observations of
individual stars, galaxies, galaxy populations and the thermal history of the Universe (e.g Eldridge et al. 2017, 2018, 2019b, a; Ma et al. 2016; Rosdahl et al. 2018; Shenar et al. 2016; Stanway et al. 2014, 2016; Stanway & Eldridge 2018; Steidel et al. 2016; Wilkins et al. 2017, 2019; Wofford et al. 2016; Xiao et al. 2018, 2019).

In summary, our search of the currently available library of BPASS binary stellar evolution models has revealed a number of good matches to the observed LB-1 system. We were able to identify at least one model whose stellar parameters place it at a distance in agreement with the Gaia distance of $2.14_{-0.35}^{+0.51}$ kpc. We find that the Gaia distance should not be ignored due to the high values of the correlation coefficients. We estimate that several such systems are to be expected given the star formation history of the Milky Way. We conclude that the LB-1 system of (Liu et al. 2019) is likely to be explained by a naturally occurring binary containing a BH of moderate mass ($\approx 8M_\odot$), rather than one reaching $70M_\odot$. If the higher mass is proven to be correct by further observations, we suggest that a revaluation of the accretion model with BPASS may be able to provide a more massive BH.

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Figure 5. Prediction of compact remnant binaries at solar metallicity after 10 Gyr of star formation. Each contour represents an order of magnitude in number of systems expected in that bin. The shaded contours represent all BH binary systems and the orange contours indicate those that match the observed companion in LB-1 and the orbital period. The dark blue line is the period of LB-1, the dotted red lines are the values for LB-1 determined by Liu et al. (2019), the solid red lines are the values for LB-1 determined in this work and the light blue line are the values for the system observed by Thompson et al. (2019). The red triangles are values for the black-hole binaries listed by https://stellarcollapse.org.

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