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Investigating stellar-mass black hole kicks

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ABSTRACT

We investigate whether stellar-mass black holes have to receive natal kicks in order to explain the observed distribution of low-mass X-ray binaries containing black holes within our Galaxy. Such binaries are the product of binary evolution, where the massive primary has exploded forming a stellar-mass black hole, probably after a common envelope phase where the system contracted down to separations of the order of 10–30 $R_{\odot}$. We perform population synthesis calculations of these binaries, applying both kicks due to supernova mass-loss and natal kicks due to the newly formed black hole. We then integrate the trajectories of the binary systems within the Galactic potential. We find that natal kicks are in fact necessary to reach the large distances above the Galactic plane achieved by some binaries. Further, we find that the distribution of natal kicks would seem to be similar to that of neutron stars, rather than one where the kick velocities are reduced by the ratio of black hole to neutron star mass (i.e. where the kicks have the same momentum). This result is somewhat surprising; in many pictures of stellar-mass black hole formation, one might have expected black holes to receive kicks having the same momentum (rather than the same speed) as those given to neutron stars.

Key words: black hole physics – binaries: general – stars: neutron – supernovae: general – Galaxy: kinematics and dynamics – X-rays: binaries.

1 INTRODUCTION

It has long been known that neutron stars (NSs) receive kicks at birth in the range ∼200–400 km s^{-1} (so called *natal kicks* – NKs), when they are formed in core-collapse supernovae (SNe), for example via proper motion studies of pulsars (Cordes, Romani & Lundgren 1993; Lyne & Lorimer 1994). Whether stellar-mass black holes (for brevity, BHs hereafter) receive these kicks too is still a matter of debate. BHs can be studied via interacting X-ray binaries which contain them. There are several known X-ray binaries which are known to contain BHs or contain BH candidates (Jonker & Nelemans 2004; Özel et al. 2010). In these systems, the massive primary has evolved to form a BH via a core-collapse SN and material is currently flowing from the lower mass secondary (typically via Roche lobe overflow – RLO) on to the BH via an accretion disc (for a detailed review on the evolution of compact binaries see Tauris & van den Heuvel 2006). When the primary explodes as an SN, the mass-loss from the system can unbind the binary or at least give it a kick (as the mass lost has a net momentum in the rest frame of the binary). In addition, any NK received by the BH will affect the orbital properties of the binary and its orbit within the Galaxy. By studying the orbit of a binary, or even its location within the Galaxy, one might obtain a limit on the range of allowed NKs. A number of studies have considered the motion of individual binaries within the Galaxy.

Brandt, Podsiadlowski & Sigurdsson (1995) considered GRO J1655−40 (Nova Sco) and concluded that an NK more easily accounted for the high space velocity of the binary.

Nelemans, Tauris & van den Heuvel (1999) studied Cygnus X−1 and concluding that an NK was not necessary to explain its space velocity.

Willems et al. (2005) considered GRO J1655−40 and suggested that although an NK is not formally required to produce the system as observed today, the inclusion of a (modest) NK more readily explains the system. They also placed an upper limit on the NK of ≃ 210 km s^{-1}.

Dhawan et al. (2007) considered GRS 1915+105. They concluded that any peculiar motion of the binary was more likely due to later scattering within the Galactic disc than an NK when the BH formed.

The binary XTE J1118+480 is located at a very high latitude (1.5 kpc above the Galactic disc; see Remillard et al. 2000) and it has a high space velocity (Mirabel et al. 2001). Gualandris et al. (2005) concluded that for this system a BH NK was *required*. More recently, Fragos et al. (2009) placed the value of the NK in the range 80–310 km s^{-1}.

Wong, Willems & Kalogera (2010) considered Cygnus X−1. They found that in this case the BH progenitor could have received a relatively small NK (few tens of km s^{-1} with an upper limit of

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77 km s^{-1}). If the system originated in the Cyg OB3 association (Mirabel & Rodrigues 2003), then the upper limit on a kick would be reduced to 24 km s^{-1}.

In this paper, we consider the population of BH X-ray binaries as a whole (following the approach of Brandt & Podsiadlowski 1995; White & van Paradijs 1996; Jonker & Nelemans 2004; Zuo, Li & Liu 2008) rather than considering the kinematics of an individual system. We synthesize a population of BH low-mass X-ray binaries (BH-LMXBs), using various NK distributions, and integrating the systems within the Galactic potential. We then compare their locations within the Galaxy to a catalogue of known BH X-ray binaries having measured distances (Özel et al. 2010).

The paper is arranged as follows. We review the current state of observations of X-ray binaries containing either NSs or BHs in Section 2. Our treatment of the motion of stars in the Galactic potential is given in Section 3. In Section 4 we review the effects of both natal and SNe mass-loss kicks on binaries. In Section 5 we present the results of the binary population synthesis (BPS) which we discuss in Section 6. The paper is concluded in Section 7.

2 THE OBSERVED BINARIES

In our Galaxy there are 16 dynamically confirmed BHs in LMXBs and 33 NS-LMXBs, whose distance and Galactic position is known; see, respectively, Özel et al. (2010) and Jonker & Nelemans (2004), and references therein [in particular, Jonker & Nelemans consider only NSs not found in globular clusters (GCs)]. We present the binaries in Tables 1 and 2, along with their angular distribution, their distance from the Sun and their position, both in Galactic coordinates and in cylindrical ones (R refers to the radial distance from the Galactic Centre and z refers to the distance from the Galactic plane). Concerning the BH binaries, uncertainty on the distance is taken from Özel et al.; for the NS binaries, Jonker & Nelemans calculated the distance assuming two different Eddington peak fluxes, getting a maximum and a minimum value for the distance, of which we take the median value.

Table 1. Observed properties of BH-LMXBs.

Name	l (deg)	b (deg)	d (kpc)	Δd (kpc)	R (kpc)	z (kpc)	Ref. (distance)
4U 1543−47	330.0	+5.4	7.5	0.5	3.92	0.70	[1]
XTE J1550−564	325.9	−1.8	4.4	0.5	5.0	−0.14	[2]
GRO J1655−40	345.0	+2.5	3.2	0.5	4.98	0.13	[3]
1659−487	338.9	−4.3	9.0	3.0	3.25	−0.67	[4]
1819.3−2525	6.8	−4.8	9.9	2.4	2.14	−0.82	[5]
GRS 1915+105	45.4	−0.2	9.0	3.0	6.62	−0.03	[6]
GS 2023+338	73.1	−2.1	2.39	0.14	7.65	−0.09	[7]
GRO J0422+32	166.0	−12.0	2.0	1.0	9.91	−0.41	[8] [10]
A0620−003	210.0	−6.5	1.06	0.12	8.92	−0.12	[9]
GRS 1009−45	275.9	+9.4	3.82	0.27	8.48	0.62	[10]
XTE J1118+480	157.6	+62.3	1.7	0.1	8.73	1.50	[11]
1124−683	295.3	−7.1	5.89	0.26	7.63	−0.73	[10]
XTE J1650−500	336.7	−3.4	2.6	0.7	5.71	−0.15	[12]
1705−250	358.2	+9.1	8.6	2.1	0.55	1.36	[13]
XTE J1859+226	54.1	+8.6	8.0	3.0	7.23	1.20	[10]
GS 2000+251	63.4	−3.0	2.7	0.7	7.21	−0.14	[13]

References (from Özel et al. 2010): [1] Orosz et al. (2002), [2] Orosz et al. (2010), [3] Hjellming & Rupen (1995), [4] Hynes et al. (2004), [5] Orosz et al. (2001), [6] Fender, Hanson & Pooley (1999), [7] Miller-Jones et al. (2009), [8] Webb et al. (2000), [9] Cantrell et al. (2010), [10] Hynes (2005), [11] Gelino et al. (2006), [12] Homan et al. (2006) and [13] Barret, McClintock & Grindlay (1996).

Table 2. Observed properties of NS-LMXBs.

Name	l (deg)	b (deg)	d (kpc)	Δd (kpc)	R (kpc)	z (kpc)	Ref. (distance)
EXO 0748−676	279.98	−19.81	7.95	2.3	9.96	−2.70	[1]
2S 0918−54	275.85	−3.84	5.05	1.5	9.0	−0.34	[2] [29]
Cir X−1	322.12	0.04	9.15	2.7	5.67	0.00	[3] [30]
4U 1608−522	330.93	−0.85	3.3	1.0	5.36	−0.04	[4]
Sco X−1	350.09	23.78	2.8	0.3	5.49	1.13	[5]
4U 1636−53	332.91	−4.82	4.3	1.2	4.62	−0.36	[6]
4U 1658−298	353.83	7.27	9.85	2.9	2.01	1.25	[7]
4U 1702−429	343.89	−1.32	6.2	1.8	2.67	−0.14	[8]
4U 1705−44	343.32	−2.34	8.4	2.4	2.40	−0.34	[8]
XTE J1710−281	356.36	6.92	17.3	5.0	9.20	2.08	[8]
SAX J1712.6−3739	348.93	0.93	6.9	2.0	1.81	0.11	[9]
1H 1715−321	354.13	3.06	6.0	1.8	2.13	0.32	[10]
RX J1718.4−4029	347.28	−1.65	7.5	2.2	1.79	−0.21	[11]
4U 1728−34	354.30	−0.15	5.3	1.6	2.78	−0.01	[12] [31]
KS 1731−260	1.07	3.65	6.2	1.8	1.81	0.39	[13]
4U 1735−44	346.05	−6.99	9.4	2.8	2.48	−1.14	[8]
GRS 1741.9−2853	359.96	0.13	7.75	2.3	0.25	0.01	[14]
2E 1742.9−2929	359.56	−0.39	8.05	2.3	0.08	−0.05	[8]
SAX J1747.0−2853	0.21	−0.24	8.75	2.5	0.75	−0.04	[15]
GX 3+1	2.29	0.79	5.05	1.5	2.96	0.07	[16]
SAX J1750.8−2900	0.45	−0.95	6.1	1.8	1.90	−0.10	[17]
SAX J1752.3−3138	358.44	−2.64	9.25	2.7	1.26	−0.43	[18]
SAX J1808.4−3658	355.38	−8.15	3.15	0.9	4.90	−0.45	[19]
SAX J1810.8−2609	5.20	−3.43	5.95	1.7	2.15	−0.36	[20]
4U 1812−12	18.06	2.38	4.0	1.2	4.38	0.17	[21]
XTE J1814−338	358.75	−7.59	9.6	2.8	1.53	−1.27	[22]
GX 17+2	16.43	1.28	13.95	4.1	6.67	0.31	[23]
Ser X−1	36.12	4.84	11.1	3.2	6.59	0.94	[8]
Aq1 X−1	35.72	−4.14	5.15	1.5	4.86	−0.37	[24]
4U 1857+01	35.02	−3.71	8.75	2.5	5.08	−0.57	[25]
4U 1916−053	31.36	−8.46	8.8	2.6	4.56	−1.29	[26]
XTE J2123−058	46.48	−36.20	18.35	5.3	10.96	−10.83	[27] [32]
Cyg X−2	87.33	−11.32	13.35	3.9	15.02	−2.62	[28]

References (from Jonker & Nelemans 2004): [1] Gottwald et al. (1986), [2] Jonker et al. (2001), [3] Tennant, Fabian & Shafer (1986), [4] Murakami et al. (1987), [5] Bradshaw, Fomalont & Geldzahler (1999), [6] Fujimoto et al. (1988), [7] Wijnands et al. (2002), [8] Galloway et al. (2001), [9] Cocchi et al. (2001a), [10] Tawara et al. (1984), [11] Kaptein et al. (2000), [12] Basinska et al. (1984), [13] Muno et al. (2001), [14] Cocchi et al. (1999), [15] Natalucci et al. (2000), [16] Kuulkers & van der Klis (2000), [17] Kaaret et al. (2002), [18] Cocchi et al. (2001b), [19] in't Zand J. et al. (2001), [20] Natalucci et al. (2000), [21] Cocchi et al. (2000), [22] Strohmayer et al. (2003), [23] Kuulkers et al. (2002), [24] Jonker & Nelemans (2004), [25] Chevalier & Ilovaisky (1990), [26] Galloway et al. (2001), [27] Homan et al. (1999), [28] Smale (1998), [29] Cornelisse et al. (2002), [30] Brandt et al. (1996), [31] Hoffman et al. (1980) and [32] Tomsick et al. (1999).

Using the values in Tables 1 and 2, we plot the Galactic distribution of the binaries in Fig. 1. In representing the observed system on the (R, z) plane we propagate the uncertainty on the distance into an uncertainty on R and z, the corresponding range of values for R and z being represented as a solid line. The z-distribution of BH-LMXBs appears similar to the NS-LMXBs one (as already pointed out by Jonker & Nelemans 2004, who calculated the rms z for the two samples); the *Kolmogorov–Smirnov* (KS) probability P for the two distributions to be the same is indeed convincing: $P \sim 0.81$ (that increases to 0.85 if binaries located at $z > 2.0$ kpc are excluded from the test). Concerning the R distribution, we may observe that NS-LMXBs seem to be more concentrated towards the Galactic Centre with respect to the BH-LMXBs. This is very likely an observational bias, as already suggested by Jonker & Nelemans

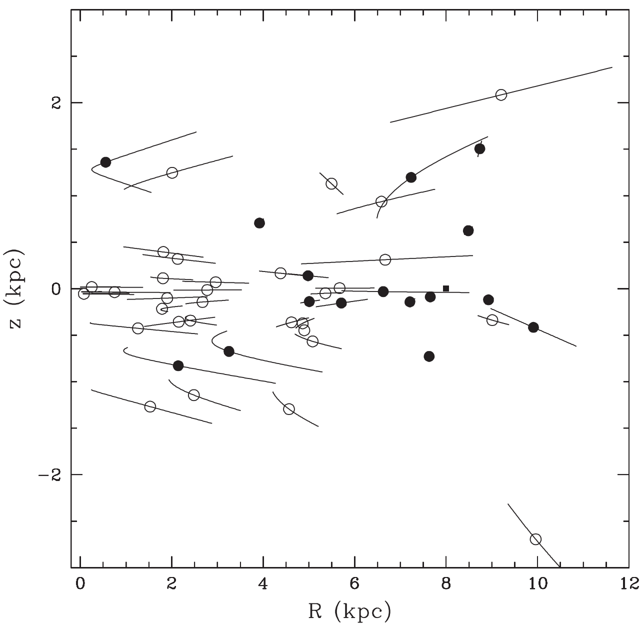

Figure 1. Galactic distribution of NS-LMXBs (open circles) and BH-LMXBs (filled circles). The radial distance from the Galactic Centre is $R = \sqrt{x^2 + y^2}$, where x and y are the Cartesian coordinates in the Galactic plane, whereas the distance from the plane of the Galaxy is $z = d \sin b$. Two NS binaries fall off the figure: XTE J2123−058 and Cyg X−2. The solid lines account for the uncertainty of the distance from the Sun for each binary. The Sun is indicated as a square.

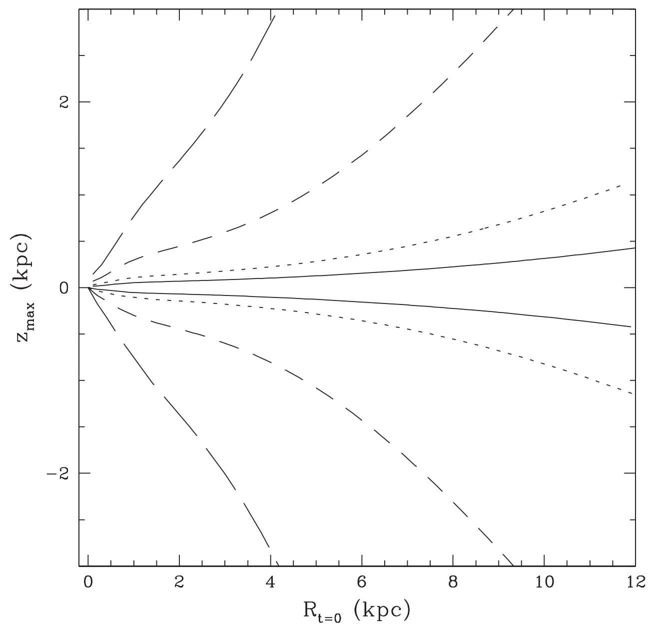

Figure 2. Maximum z reached by a binary over its trajectory. The object has been kicked perpendicularly to the Galactic plane, for four different magnitudes of the kick ($V_\perp = 20$, 40, 100 and 200 km s^{-1}).

(2004), since the BH binaries that we consider are those for which a dynamical measurement of the BH mass exists, and this biases the binaries towards those closer to us.

3 INTEGRATING ORBITS WITHIN THE GALAXY

In this section, we will give a short overview of how the orbital trajectories within the Galaxy are calculated. For the Galactic potential, we make use of the model proposed by Paczynski (1990). The potential is modelled as the superposition of three components due to the disc (Φ_d), the spheroid (Φ_s) and the halo (Φ_h), as given below:

$$\Phi_d(R, z) = -\frac{GM_d}{\sqrt{R^2 + \left(a_d + \sqrt{z^2 + b_d^2}\right)^2}}, \quad (1)$$

where $a_d = 3.7$ kpc, $b_d = 0.20$ kpc and $M_d = 8.07 \times 10^{10}\,M_\odot$;

$$\Phi_s(R, z) = -\frac{GM_s}{\sqrt{R^2 + \left(a_s + \sqrt{z^2 + b_s^2}\right)^2}}, \quad (2)$$

where $a_s = 0.0$ kpc, $b_s = 0.277$ kpc and $M_s = 1.12 \times 10^{10}\,M_\odot$;

$$\Phi_h(r) = \frac{GM_c}{r_c}\left[\frac{1}{2}\ln\left(1 + \frac{r^2}{r_c^2}\right) + \frac{r_c}{r}\arctan\left(\frac{r}{r_c}\right)\right], \quad (3)$$

where $r_c = 6.0$ kpc and $M_c = 5.0 \times 10^{10}\,M_\odot$.

When integrating the trajectory of a binary within the Galaxy, we make use of the cylindrical symmetry of the potential. The equations of motion which are thus integrated are given below:

$$\frac{dR}{dt} = v_R, \qquad \frac{dv_R}{dt} = -\left(\frac{\partial \Phi}{\partial R}\right)_z + \frac{j_z^2}{R^3}, \quad (4)$$

$$\frac{dz}{dt} = v_z, \qquad \frac{dv_z}{dt} = -\left(\frac{\partial \Phi}{\partial z}\right)_R, \quad (5)$$

where R and z are the cylindrical coordinates of the binary, j_z is the z-component of the angular momentum of the binary, and $\Phi = \Phi_d + \Phi_s + \Phi_h$.

It will turn out that typical kick velocities that the binary receives when the primary explodes as an SN are comparable to the circular orbital speed in the Galaxy (∼200 km s^{-1}). This implies that kicks can significantly affect the trajectory of the binary within the Galaxy. We can get an idea of the maximum z reached by the binary as a function of the initial peculiar velocity. We integrate the equations of motion of the binary for ∼10 Gyr [which is the typical main-sequence (MS) time of a sun-like star], using a fourth-order Runge–Kutta integrator developed by SR, and assuming that the system was born right in the Galactic plane with a peculiar velocity perpendicular to the plane $V_\perp$. We perform the integration for different values of the velocity ($v_\perp = 20$, 40, 100 and 200 km s^{-1}) and of the initial position $R_{t=0}$ over the plane, writing down the maximum z reached over the trajectory (see Fig. 2). We see how z_{max} is a rather strong function of the initial position: for a fixed value of $V_\perp$, z_{max} gets smaller as the binary gets deeper in the potential well (i.e. smaller values of $R_{t=0}$). It is clear from this figure that binary kick speeds in excess of 200 km s^{-1} will be required in at least some of the observed systems shown in Fig. 1.

4 KICKS RECEIVED BY SURVIVING BINARIES

In this section we consider the effects of the SN explosion on the binary. We will see how the rapid mass-loss from the SN alone could impart a kick on some systems whilst breaking others up. In addition, any kick imparted to the NS or BH on its formation (i.e. an NK) will also play a role, both in adding to the overall kick received by the binary, and in some cases ensuring that the binary remains bound.

It is important to note that a *conspiracy of three velocities* will have an important role, namely the coincidence that the following three speeds are comparable: the speed of a circular orbit in the Galaxy, the typical orbital speed within a tight stellar binary when the primary explodes as an SN and the characteristic kick speed the binary receives. This coincidence implies that kicks will significantly affect the orbit of the binary within the Galaxy.

We begin by considering the case of zero NK. In other words, where any kick is due solely to the rapid mass-loss occurring during the SN explosion. We will refer to this as the mass-loss kick $V_{\rm mlk}$ (also called *Blaauw kick*; Blaauw 1961), which is given by the expression

$$V_{\rm mlk} = \frac{\Delta M}{M'}\frac{M_2}{M}\sqrt{\frac{GM}{a}}, \tag{6}$$

where M is the total mass of the binary at the point of the SN explosion, M' is the total mass of the binary after the SN explosion, ΔM is the mass lost during the SN explosion (i.e. $\Delta M = M - M'$), M_2 is the mass of the secondary and a is the binary semimajor axis at the moment of the SN explosion.

$V_{\rm mlk}$ cannot be too large, since the binary must remain bound after the SN: the mass-loss must be less than half of the initial mass. If we agree on a common envelope phase having shrunk the binary down to an orbital separation of $\sim 10\,{\rm R}_\odot$, the resulting typical mass-loss kicks for BH-LMXBs are of the order of 20–40 km s^{-1} (for NS-LMXBs they are typically higher). Looking at Fig. 2, we immediately realize how kicks of this size cannot make the highest z BH binaries: in the optimal case of $V_{\rm mlk} \simeq 40$ km s^{-1} perpendicular to the Galactic plane, the maximum z reached over the trajectory never exceeds 1 kpc (however, we do see binaries in the halo of our Galaxy at larger values of z, see Table 1).

We consider now the case where the NS or BH produced in the SN receives an NK. If we assume that the orientation of the NK is random with respect to the orbital plane, the NK $V_{\rm nk}$ combines with the mass-loss kick $V_{\rm mlk}$ as given below:

$$V_{\rm k} = \sqrt{\left(\frac{M_{\rm bh}}{M'}\right)^2 V_{\rm nk}^2 + V_{\rm mlk}^2 - 2\frac{M_{\rm bh}}{M'}V_{\rm nk,x}V_{\rm mlk}}, \tag{7}$$

where we have chosen the x-axis aligned with the orbital speed of the BH progenitor and the y-axis along the line connecting the two stars at the moment of the SN explosion.

Many distributions to model NS NKs have been proposed. For example, Hansen & Phinney (1997) modelled the NK as a Maxwellian distribution peaked at 300 km s^{-1}. To solve the retention problem in GCs as well as the low eccentricity of a subclass of Be X-ray binaries, two-peak distributions have also been proposed where one peak occurs at a somewhat lower velocity (Pfahl, Rappaport & Podsiadlowski 2002a; Pfahl et al. 2002b).

We consider two different NK distributions here: one is the Hansen & Phinney distribution, and the other is a bimodal distribution proposed by Arzoumanian, Chernoff & Cordes (2002) which has a lower peak at $\sim$100 km s^{-1} and the higher peak at $\sim$700 km s^{-1}. We also consider modified versions of the above two distributions, which we term momentum-conserving kicks (MCKs), where we assume that the momentum imparted on a BH is the same as the momentum given to an NS using the two distributions. Thus, the kick velocities will be reduced: $V_{\rm nk,bh} = (M_{\rm ns}/M_{\rm bh})V_{\rm nk,ns}$. For example, a 7 M$_\odot$ BH receives an NK reduced by a factor of 5: for a NS NK of 300 km s^{-1}, the BH would receive a smaller kick of only 60 km s^{-1}. We show in Fig. 3 the NK distributions which we use.

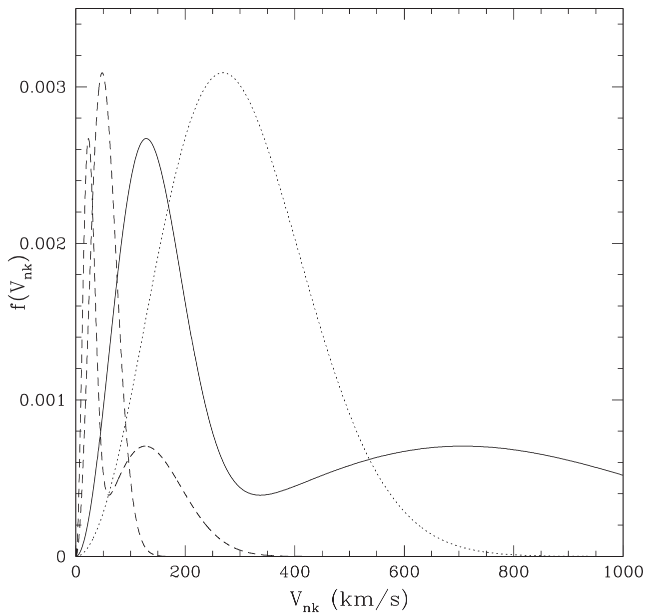

Figure 3. NK distributions used in our BPS calculations. The solid line corresponds to Arzoumanian distribution, the dotted line to Hansen & Phinney and the two dashed lines correspond to these two distributions but with kick speeds reduced, assuming that the momentum imparted to the BH is the same as the momentum imparted to the NS.

Table 3. Fraction of systems that stay bound after the SN.

	Fraction of bound systems	
	BH	NS
Hansen	58 per cent	30 per cent
	56 per cent[a]	35 per cent[a]
	64 per cent[b]	3 per cent[b]
Bimodal	54 per cent	29 per cent
	56 per cent[a]	30 per cent[a]
	52 per cent[b]	10 per cent[b]
Hansen MCK	99 per cent	–
Bimodal MCK	95 per cent	–

[a] For an NK lying in the orbital plane.
[b] For an NK perpendicular to the orbital plane.

It is important to recall that a large fraction of binaries are broken up when the primary explodes as an SN.

Considering a population of binaries where $M_1 = 11\,{\rm M}_\odot$, $M_2 = 1.5\,{\rm M}_\odot$, $M_{\rm bh} = 7.8\,{\rm M}_\odot$, $a = 10\,{\rm R}_\odot$ (M_1 is the mass of the progenitor of the BH, M_2 is the companion star and a is the pre-SN orbital separation), we impart the BH of each binary an NK drawn randomly from each of our four distributions. The fraction of systems remaining bound for each of the kick distributions is shown in Table 3. We also include the case where a 1.4 M$_\odot$ NS is produced instead of a BH (taking as the progenitor mass 3.5 M$_\odot$). A larger fraction of binaries remain bound for binaries containing BHs rather than NSs owing to the greater binding mass.

We show in Fig. 4 the distribution of kick velocities for BH-LMXBs that we obtain drawing from each of the four NK distributions. One should in particular note how the kick velocities for the MCKs are typically lower than $\sim$100 km s^{-1}.

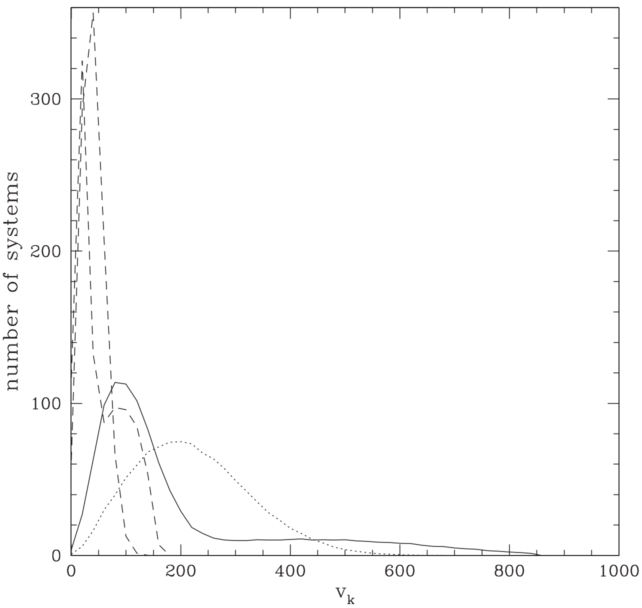

Figure 4. Peculiar velocity gained by the binary after an asymmetric SN. Natal kicks have been drawn from Arzoumanian distribution (solid line), Hansen & Phinney distribution (dotted line), whereas the dashed lines correspond to the MCKs. The total number of systems for each curve has been normalized to 1000 and only systems that stay bound after the SNe are represented.

5 BINARY POPULATION SYNTHESIS

In this section we discuss the calculation of the synthetic population of BH-LXMBs. We produce a population of BH-LMXBs considering their formation within the Galactic disc at a range of radii. For each binary, we randomly draw the BH NK, considering five different NK distributions (including a zero NK) and give this kick a random direction which we then add to the mass-loss kick due to the SN to produce the total kick speed of the binary $V_{\rm k}$. The gained velocity will be added randomly to the circular velocity of the binary within the Galaxy. Each system is then integrated forward in time within the Galactic potential for $\sim 3 \times 10^9$ yr (which is the MS time of the 1.5 $\mathrm{M_\odot}$ companion), and its position is noted at random times over the trajectory. We are thus able to produce an entire population of BH-LMXBs given the initial distribution of progenitor systems in the Galactic disc, their binary properties (separation and stellar masses) and the NK distributions for the BHs formed.

We populate the disc of the Galaxy assuming the disc distribution of binaries to be proportional to the surface density of stars $\Sigma(R) \sim \Sigma_0 \mathrm{e}^{-R/R_\mathrm{d}}$, with a maximum distance from the Galactic Centre of $R_{\max} = 10$ kpc. We chose R_d to be the length-scale of the thin disc of the Galaxy, where the progenitor systems are thought to be produced, $R_\mathrm{d} \sim 2.6$ kpc (McMillan 2011). Concerning the z-distribution of the binaries, we model it as an exponential with scale height $\sim$0.167 kpc (Binney, Tremaine & Freeman 1988).

The population is formed by 100 binaries with the following parameters: $M_1 = 11\,\mathrm{M_\odot}$, $M_2 = 1.5\,\mathrm{M_\odot}$, $M_\mathrm{bh} = 7.8\,\mathrm{M_\odot}$ and $a = 10\,\mathrm{R_\odot}$ (M_1 is the mass of the progenitor of the BH, M_2 is the companion star and a is the pre-SN orbital separation). For the BH mass, we choose the average mass of stellar BHs in the Galaxy (see Özel et al. 2010); for the initial orbital separation, our choice is guided by the typical results of common envelope evolution considered in detailed binary evolution calculations for progenitor systems. We choose a typical mass-loss in the SN explosion of $\sim 3\,\mathrm{M_\odot}$ (see Fryer & Kalogera 2001), which delivers an associated mass-loss kick of $\sim$20 km s^{-1}.

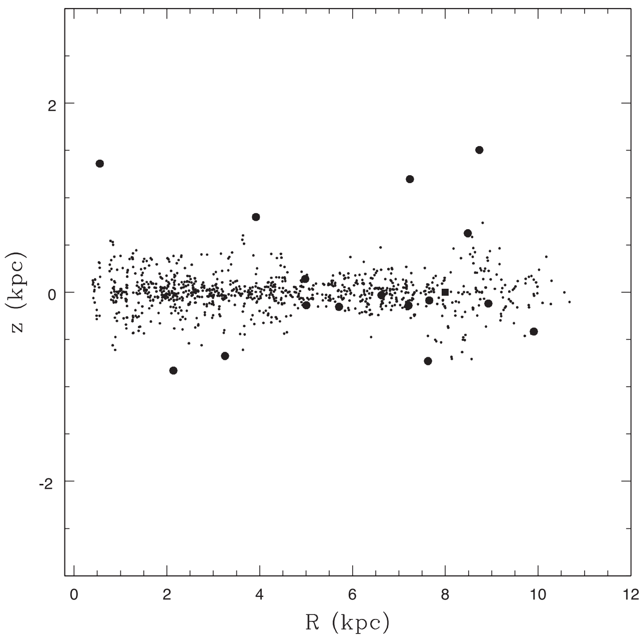

Figure 5. BPS for a sample of BH-LMXBs. No NK has been imparted to the BH. The smaller dots correspond to the synthetic population, the bigger ones to the observed binaries and the position of the Sun is denoted with a square.

In addition, the BH receives an NK drawn from one of the following five distributions: (1) an NK of zero km s^{-1}; (2) one drawn from the Hansen & Phinney distribution (Hansen & Phinney 1997); (3) one drawn from the bimodal distribution of Arzoumanian et al. (2002); (4) as (2) but with the kick speed multiplied by the factor $M_\mathrm{ns}/M_\mathrm{bh}$ and (5) as (3) but with the kick speed multiplied by the factor $M_\mathrm{ns}/M_\mathrm{bh}$.

We plot the positions of the 100 binaries – at random times of the trajectory – in Galactic cylindrical coordinates for zero BH NKs in Fig. 5 and for the other four NK distributions in Fig. 6. From Fig. 5 it is clear that it is impossible to place BH-LMXBs seen at larger values of z when the BHs receive zero NKs. Either the Hansen & Phinney or the Arzoumanian distributions appear to fit the observed distribution of BH-LMXBs, whereas those produced by NK distributions with velocities reduced by a factor of $M_\mathrm{bh}/M_\mathrm{ns}$ (bottom panels in Fig. 6) appear to produce distributions which are more concentrated on lower values of z.

5.1 Statistics of the results

In order to quantify the results of the BPS, we show in Fig. 7 the fraction of binaries that at some time over the trajectory are located at a distance z from the Galactic plane less than a certain value. We include in the plot the results of the BPS for which no NK has been imparted to the BH.

It is evident how the mass-loss kicks alone cannot account for the z-distribution of the observed binaries. A reduced Hansen & Phinney NK cannot make the binaries that are located at $z \gtrsim 1$ kpc; in particular, the percentage of binaries that get to z higher than 1 kpc is only 0.5 per cent. With a reduced Arzoumanian NK the percentage gets higher ($\sim$6 per cent), though the fit remains unsatisfactory (see Table 4). It then turns out to be very difficult, with a MCK, to reproduce the binaries XTE J118+480, 1705−250,

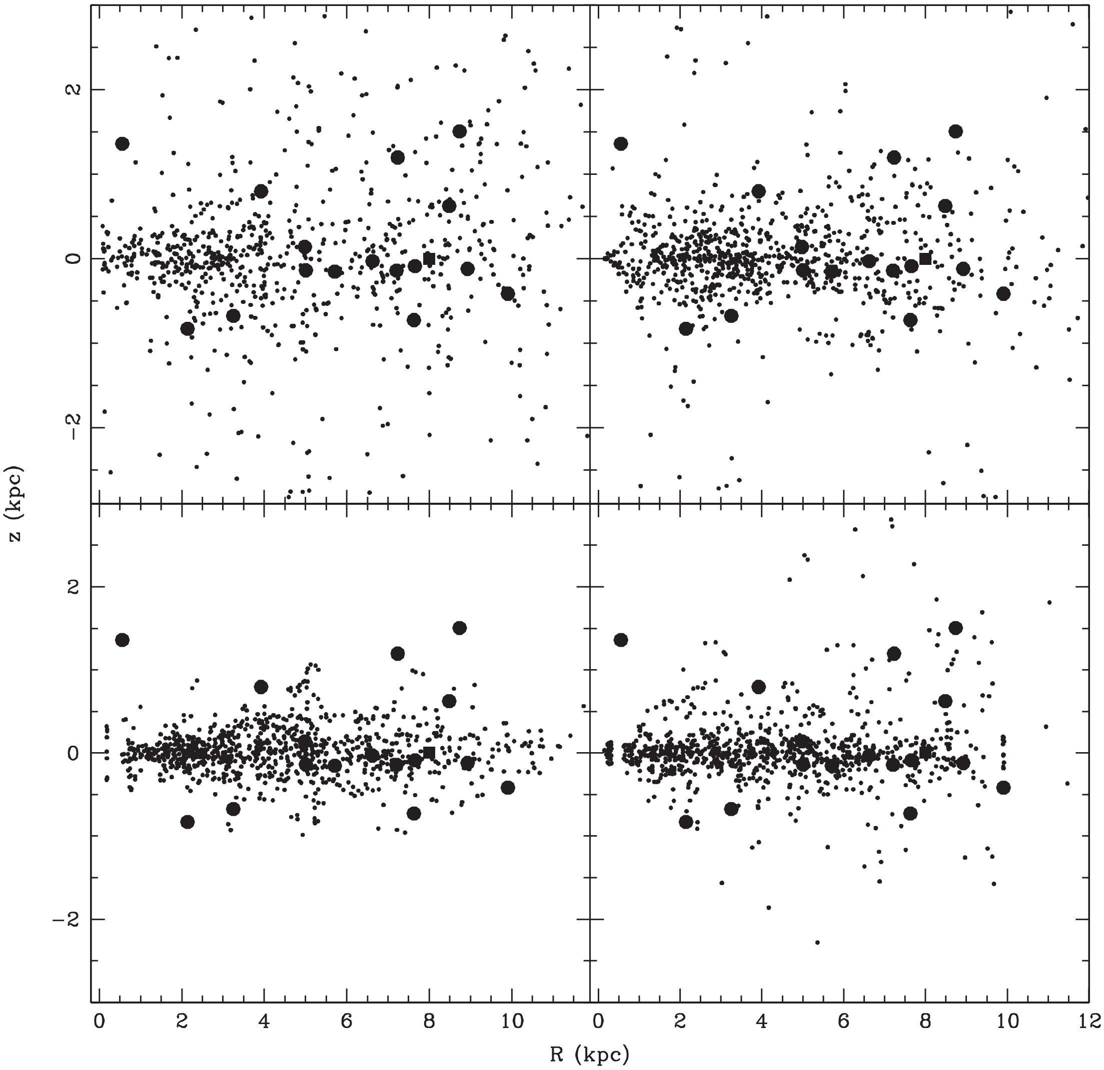

Figure 6. BPS for a sample of BH-LMXBs. NKs have been drawn from the Hansen & Phinney (top-left) distribution, a bimodal distribution (top-right), whereas the bottom figures correspond to the reduced NKs. The smaller dots correspond to the synthetic population, the bigger ones to the observed binaries and the position of the Sun is denoted with a square.

XTE J1859+226, which are located respectively at $z = 1.5$, 1.36 and 1.20 kpc. Section 6 is dedicated to the detailed study of these sources.

We are aware that the integration time we chose ($\sim 3 \times 10^9$ yr) might be higher than the actual age of some of the observed binaries, particularly those whose mass transfer is driven by angular momentum losses, or those with a relatively massive companion star ($M_2 \sim 3\,\mathrm{M}_\odot$, see the updated catalogue Ritter & Kolb 2003). We then carry out other two syntheses for the BH-LMXBs, integrating their trajectories for $\sim 10^8$ yr and for $\sim 5 \times 10^8$ yr. In the first integration, the percentage of binaries that reach z higher than 1 kpc is 0 per cent for a reduced Hansen & Phinney NK and 1 per cent for an Arzoumanian reduced NK. In the second integration, the percentages are, respectively, 0.2 and 2.2 per cent. Concerning the KS test, the resulting probabilities get one or two orders of magnitude lower when choosing a reduced integration time; this is easily explained, since the binary does not live long enough to be seen at high z.

We wonder whether a larger mass-loss kick would affect our conclusions. Referring to equation (6), we see that the mass-loss kick increases either in the case of a larger mass-loss, or a more compact initial binary, or a larger companion mass. It is believed that in the SN event the helium star loses no more than 3–4 $\mathrm{M}_\odot$ (before exploding as an SN, the helium star suffers from strong Wolf-Rayet winds after the common envelope phase, see e.g. Fryer & Kalogera 2001). Concerning the initial orbital separation, there is a limiting minimum value for which either one or both of the two stars fill their Roche lobe. The parameters $M_1 = 11\,\mathrm{M}_\odot$, $M_2 = 3.0\,\mathrm{M}_\odot$, $M_{\mathrm{bh}} = 7.8\,\mathrm{M}_\odot$ and $a = 6\,\mathrm{R}_\odot$ give a recoil velocity V_{mlk} of $\sim$40 km s^{-1}. We then perform two syntheses in which we fix the mass-loss kick to $\sim$40 km s^{-1}, testing the two types of reduced NKs. The corresponding KS probabilities remain unsatisfactory: 2×10^{-3} for a reduced Hansen NK and 2×10^{-2} for a reduced bimodal NK. We shall also stress that the integration time for these two syntheses has been set to $\sim 3 \times 10^9$ yr; decreasing the integration time would make the KS probabilities even lower.

We perform a BPS for NS-LMXBs as well (binary parameters chosen: $M_1 = 3.5\,\mathrm{M}_\odot$, $M_2 = 1.0\,\mathrm{M}_\odot$, $M_{\mathrm{ns}} = 1.4\,\mathrm{M}_\odot$ and $a = 7.0\,\mathrm{R}_\odot$): in Fig. 8 results are shown. It is pretty clear that a bimodal distribution better fits the observed sample. This is a strong case

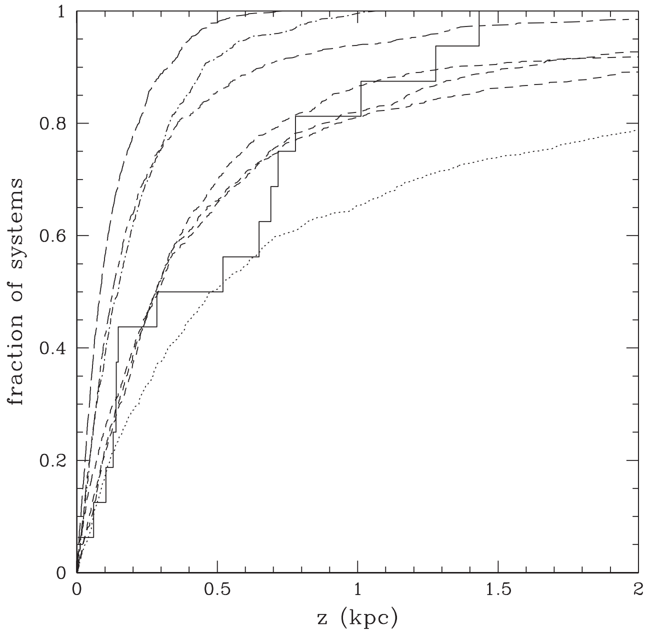

Figure 7. Cumulatives which show the fraction of BH-LMXBs versus the distance from the Galactic plane, for the four different NKs (dotted line is for a Hansen & Phinney NK, dot–dashed line is for a reduced Hansen & Phinney NK, short-long-dashed is for a reduced Arzoumanian NK, whereas a zero NK scenario corresponds to the long-dashed line). For the Arzoumanian NK, we tested two additional scenarios, an NK lying in the orbital plane and an NK perpendicular to it (see the three short-dashed lines). Cumulatives are to be compared with the observed one (solid line).

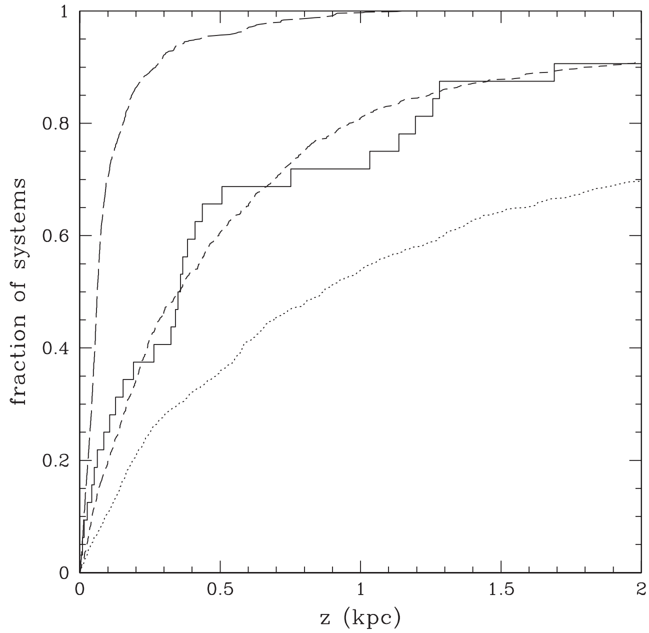

Figure 8. Cumulatives which show the fraction of NS-LMXBs versus the distance from the Galactic plane, for the four different NKs (dotted line is for a Hansen & Phinney NK, short-dashed line is for an Arzoumanian NK, whereas a zero NK scenario corresponds to the long-dashed line). Cumulatives are to be compared with the observed one (solid line).

Table 4. KS probabilities for the BPS.

KS probabilities		
	BH-BPS	NS-BPS
	Integration time 3×10^9 yr	
Hansen NK	0.20	2.6×10^{-3}
Bimodal NK	0.18	0.78
Hansen MCK	2×10^{-3}	–
Bimodal MCK	1×10^{-2}	–
zero NK	2×10^{-4}	5×10^9
	Integration time 5×10^8 yr	
Hansen MCK	7×10^{-4}	–
Bimodal MCK	5×10^{-3}	–
	Integration time 10^8 yr	
Hansen MCK	4×10^{-4}	–
Bimodal MCK	6×10^{-4}	–

for NSs receiving a bimodal NK at birth. Previous studies, focused on NSs in Be X-ray binaries and double NS binaries (see works by Pfahl et al. 2002b and Wong et al. 2012), showed that at least some of the NSs should have received a lower kick at birth. We highlight our work as the first test of a bimodal distribution being a better fit to the Galactic position of NS-LXMBs. When excluding from the test the observed NS binaries that are located at $z > 2$ kpc, the KS probability rises to 0.19; this is easily explained, since the change in normalization shifts the simulated curve towards the observed one.

In Table 4, KS probabilities for the different types of scenario are shown (the probabilities are reasonably accurate for our number of data points, see Press et al. 1993).

6 DISCUSSION

We now aim at deriving the minimum NK required to place the observed BH-LMXBs in their current locations. Rather than considering the properties of a general progenitor binary system (i.e. stellar masses, BH mass and binary separation), we use the observed properties for each known system, where possible, to more accurately calculate the mass-loss kick and the effect of any NK on the particular system (see Ritter & Kolb 2003 for an updated catalogue of LMXBs in the Galaxy).

For simplicity here, we consider a kick in the (optimal) direction perpendicular to the Galactic disc. We first compute, via conservation of energy, the minimum kick $V_\perp$ for the binary to reach the current position (R_0, z) after travelling in the Galactic potential, assuming that the binary is born right over the Galactic plane at some radius R_0. Thus

$$\frac{1}{2} {V_\perp}^2 + \Phi(R_0, 0) = \Phi(R_0, z), \quad (8)$$

where Φ is the gravitational potential of the Galaxy.

We show in Table 5 the minimum perpendicular kick $V_\perp$ and minimum NK $V_{\rm nk}$ required for those BH-LMXB systems which have relatively well-constrained binary properties. One should understand that the NK value quoted in Table 5 is the absolute lower limit, assuming that the NK occurred in the perfectly optimal direction. In practice, the NK required will be much larger in many realizations (i.e. different kick directions for the natal and mass-loss kicks). For example, for many directions, the necessary NK to reproduce the current location of XTE J1118+480 is up to 300 km s^{-1} (as was also seen in Fragos et al. 2009).

The minimum peculiar velocity is normally greater than 80 km s^{-1} for binaries that are located at $z > 1$ kpc, or for binaries that are closer in towards the Galactic centre and at $z > 0.6$ kpc. Particularly, for systems that are located at $R \lesssim 3$ kpc from the Galactic centre, typical required velocities are greater than 100 km s^{-1} for

Table 5. $V_\perp$ necessary to get to the observed position, and corresponding minimum NK V_{nk}[a].

Name	$V_\perp$ (km s^{-1})	V_{nk} (km s^{-1})	R (kpc)	z (kpc)
4U 1543−47	95	80	3.92	0.70
XTE J1550−564	22	10	5.0	−0.14
GRO J1655−40	36	0	4.98	0.13
1659−487	113	–	3.25	−0.67
1819.3−2525	160	190	2.14	−0.82
GRS 1915+105	5	0	6.62	−0.03
GS 2023+338	10	0	7.65	−0.09
GRO J0422+32	25	10	9.91	−0.41
A0620−003	10	0	8.92	−0.12
GRS 1009−45	40	15	8.48	0.62
XTE J1118+480	80	70	8.73	1.50
1124−683	50	40	7.63	−0.73
XTE J1650−500	20	–	5.71	−0.15
1705−250	420	450	0.55	1.36
XTE J1859+226	80	–	7.23	1.20
GS 2000+251	15	0	7.21	−0.14

[a]For BH-LMXBs that lack strong observational constraints, we are unable to calculate accurately V_{nk} so leave it blank here.

the highest z systems. These high velocities cannot evidently be accounted for by a mass-loss kick alone. In other words, the current location of at least some systems clearly requires the presence of a BH NK broadly in the range 100−500 km s^{-1}. For other systems, the current location could be reached with the BH having received no NK. We note that our results are consistent with those found earlier (Nelemans et al. 1999; Jonker & Nelemans 2004; Willems et al. 2005; Dhawan et al. 2007; Fragos et al. 2009).

The system 1705−250 requires the largest minimum NK. This is because the system is located close to the Galactic Centre and therefore has climbed out of a deeper potential well, assuming it was born at a comparable radius in the Galactic disc. As there is a strong radial dependence of the Galactic potential this close in, we compute the minimum peculiar velocity launching the binary out of the disc both at $R = 0.5$ kpc (the current location is at $R = 0.55$ kpc, $z = 1.36$ kpc) and $R = 2$ kpc. In the first case, we get $V_\perp \sim 400$ km s^{-1}, while in the second case a velocity $V_\perp \sim 250$ km s^{-1} is needed. These velocities require a minimum NK of 440 km s^{-1} and 260 km s^{-1}, respectively. Our results might have been affected by the choice of a spherically symmetric bulge (i.e. $a_{\mathrm{s}} = 0.0$ kpc, see equation 2 for the potential of the spheroid); we then take a *pseudo-bulge* with $a_{\mathrm{s}} = 1.0$ kpc. The resulting $V_\perp$ is ∼320 km s^{-1} for $R = 0.5$ kpc and $V_\perp \sim 220$ km s^{-1} for $R = 2.0$ kpc. The associated minimum NKs are 340 and 230 km s^{-1}, respectively. For the two models for the Galactic potential, the required velocities are larger than the largest velocities drawn from a reduced-velocity kick, from either the Hansen & Phinney or Arzoumanian kick distributions.

We may wonder whether our conclusions on the required minimum NK would be affected by a new estimation of the distance. For all of the previously mentioned four binaries, the distance has been derived from the estimation of the absolute magnitude of the companion (see, respectively, Barret et al. 1996; Orosz et al. 2001; Orosz et al. 2002; Gelino et al. 2006). Jonker & Nelemans (2004) observed that this method typically underestimates the distance. Also, we point out that any underestimation of the contribution of the disc to the observed magnitude of the companion star would lead to an underestimation of the distance. To quantify the effect of a new estimation of BH binary distance, we computed the minimum required NK, the distance being 10, 25, 50 and 100 per cent larger than the nominal value. We perform the computation for our four candidates of BHs receiving the same NKs as NSs. The required minimum NK decreases in all the cases except for XTE J1118+480. This is easily explained since a larger distance would move the binary further out of the Galactic potential well. The binaries 4U 1543−47, 1819.3−2525 and 1705−250 require a minimum NK of 45, 22 and 92 km s^{-1}, respectively, when the distance is increased by 100 per cent. XTE J1118+480 shows instead an increase of the minimum NK up to ∼100 km s^{-1} when the distance is multiplied by a factor of 2.

An alternative scenario for the formation of BH binaries would be via dynamical interactions in GCs. However, it is still uncertain whether BHs are retained in GCs or whether they follow a different dynamical evolution than NS binaries. So far, no BH X-ray binary has been found in Galactic GCs (Verbunt & Lewin 2006); the strongest BH candidate in a GC is the one found by Maccarone et al. (2007), in the Galaxy NGC 4472. The question whether BHs might be retained in a GC has been largely discussed in the literature (e.g. Kulkarni, Hut & McMillan 1993; Sigurdsson & Hernquist 1993; Portegies Zwart & McMillan 2000; Miller & Hamilton 2002). It is generally thought that BHs would tend to decouple dynamically from the rest of the cluster and to segregate into the core, where they would form BH–BH binaries. Sequential dynamical interactions between these binaries and single BHs would lead to the ejection of the BHs from the cluster in a time-scale shorter than $\sim 10^9$ yr. In case one BH survives in the cluster, it could potentially capture a stellar companion via two main mechanisms: tidal capture of a star by the BH or exchange interactions of the BH with a primordial binary (see Kalogera, King & Rasio 2004, and reference therein). Stars the BH is interacting with have a typical mass $\lesssim 1\,\mathrm{M_\odot}$ at this stage of the life of the GC. It has been shown that the two-body tidal capture scenario between an NS and a low-mass star is likely to result in a merger (McMillan, Taam & McDermott 1990; Rasio & Shapiro 1991; Davies, Benz & Hills 1992; Kumar & Goodman 1996). Specifically, Davies et al. (1992) showed that an encounter between an NS and a red giant would result in a merger in some 70 per cent of the cases, and some 50 per cent for an encounter between an NS and an MS star. For a BH, tidal forces are expected to be much larger, so that the merger becomes even more likely. Regarding the exchange interaction scenario, we find it unlikely that the resulting BH–MS star binary will get a large kick in subsequent dynamical encounters for the binary to be expelled from the cluster. Nevertheless, in the optimistic case that the binary managed to be ejected from the cluster with a velocity comparable to the escape speed of the cluster, we may compute the resulting overall distribution of Galactic BH binaries. We assume the binaries to be born in a spheroid of 20 kpc radius around the Galactic Centre, taking the halo distribution of Dehnen & Binney 1998. We then kick the binaries with a velocity of 45 km s^{-1} and we follow their motion in the Galactic potential for $\sim 3 \times 10^9$. The resulting KS test gives probabilities lower than 8×10^{-7}, even when we double the BH binaries distance. This result is not surprising since we rarely get any binaries in the disc when assuming that all binaries are born in GCs. It could be that this mechanism would work for the BH binaries found at the highest z. However, at least in the case of XTE J1118+480 there are strong arguments for rejecting a GC origin. Gualandris et al. (2005) estimated the age of the system, using stellar evolution calculations, to be between 2 and 5 Gyr, rendering a GC origin unlikely. Hernandez et al. (2008) performed a detailed chemical analysis of the optical star. Starting from different initial metallicities of the companion, they calculated the expected abundances after contamination from SN nucleosynthesis products and were able to rule out a halo origin for this BH binary. Additionally, Fragos et al. (2009) claimed that the surface metallicity of the donor star right before the onset of RLO might have been even higher than the observed one, which would make the argument for a disc origin stronger. An NK seems to be required for this system and one which exceeds the range of kicks obtained from either the Hansen & Phinney or Arzoumanian distributions with a reduction by the ratio of BH to NS masses.

From Table 5 we see that NKs exceeding 70 km s^{-1} are required for several systems: 4U 1543−47, 1819.3−2525, XTE J1118+480 and 1705−250. These binaries provide us with evidence that BHs receive NKs of the same size as those received by NSs. One might have expected the BH NKs to carry the same momentum as those for NSs if, for example, an NS formed first (and having received a kick) and then a BH formed later as a result of fall-back material within the SN. In particular, the magnitude of the NK imparted to the BH depends on the competition between two time-scales: the fall-back time-scale $\tau_{\rm fb}$ and the time-scale of the mechanism leading to the NK $\tau_{\rm nk}$. If $\tau_{\rm fb} > \tau_{\rm nk}$, we expect the fall-back material not to receive the same NK as the proto-NS; the BH NK will then be reduced by the ratio $M_{\rm ns}/M_{\rm bh}$. In case $\tau_{\rm fb} \lesssim \tau_{\rm nk}$, we expect the BH to receive a full NK. From our simulations it seems that at least in some of the cases the fall-back material received the same NK as the proto-NS. Our result, already strongly suggested in the overall distribution of z seen in the BPS, is surprising. However, one should note the large NK speeds obtained by the BH in some of the SN simulations performed by Fragos et al. (2009).

We would also like to point out the recent measurement of the distance of the BH candidate MAXI J1659−152 (Jonker et al. 2012). Taking the medium value for the distance in the allowed range $d = 6 \pm 2$ kpc, we derive a distance from the Galactic plane of $z \sim 1.7$ kpc. This candidate would add to the number of BH binaries found at a large distance from the plane of the Galaxy (see also Kuulkers et al. 2012), thus likely enlarging the sample of strong candidates for BHs receiving large kicks.

A number of mechanisms have been suggested for NKs received by NSs, some of which will also apply to BHs, especially those forming through the subsequent fall-back of material on to a proto-NS. Suggested kick mechanisms include two main scenarios: hydrodynamically driven kicks and neutrino-driven kicks. The former can either be caused by asymmetries in the convective motions under the stalled shock (see Herant et al. 1994; Burrows, Hayes & Fryxell 1995; Janka & Mueller 1996, and the recent work by Nordhaus et al. 2012) or by overstable oscillation modes of the progenitor core (Goldreich, Lai & Sahrling 1996). The latter are produced by asymmetries in the neutrino flux in a strong magnetic field (Arras & Lai 1999; Lai & Qian 1998). Electromagnetically driven kicks, instead, act once the NS has formed: the off-centre rotating dipole impart the NS a kick (Harrison & Tademaru 1975; Lai, Chernoff & Cordes 2001). For a review of NS NKs, see Lai (2004). Alternatively, if the core is rotating extremely rapidly it may form a central object surrounded by a massive disc on collapse, which may in turn fragment possibly producing a second compact object orbiting close to the central BH or NS. This secondary will rapidly spiral-in towards the primary. If the secondary is an NS, then it may transfer mass to the primary until it reaches the minimum mass for an NS at which point it will explode potentially giving the primary a kick (Colpi & Wasserman 2002; Davies et al. 2002). In case both objects are BHs, then a merger kick may result from the asymmetric emission of gravitational waves (see Rasio & Shapiro 1994; Zhuge, Centrella & McMillan 1994; Rosswog et al. 2000; Ruffert & Janka 2001). In both cases, the kick received can be several hundred km s^{-1}. Or else, when the disc on collapse forms directly around a BH, it might release its energy as a powerful jet: if this jet happens to be one-sided, it might impart a kick to the central BH, as suggested by Barkov & Komissarov (2010). The BH–BH merger scenario might be tested via BH spin measurement. Evidence of highly rotating BHs comes from the properties of X-ray spectra of Galactic BH binaries (see for example Laor 1991; Zhang, Cui & Chen 1997, and also Fender, Gallo & Russell 2010). Ruling out the accretion of matter from a low-mass companion as the origin of the BH spin (see McClintock et al. 2006), a BH–BH merger might fit well in this scenario. Herrmann et al. (2007) estimated the recoil velocity for two coalescing BHs of equal mass and opposite and equal spin. The recoil velocity reaches ∼470 km s^{-1} in the extreme case. Merritt et al. (2004) considered the case of two BHs of unequal mass; they calculated a maximum recoil velocity of 450 km s^{-1} for a mass ratio q in the range 0.2−0.4.

7 CONCLUSIONS

In this paper, we have considered the distribution of LXMBs containing BHs within the Galaxy as a function of the distribution of NKs given to the BHs. We have synthesized a BH-LMXB population by forming systems randomly throughout the Galactic disc, weighted by stellar surface density of the disc. We have given each binary a mass-loss kick due to the SN explosion of the primary and added to this kick a BH NK drawn from one of five kick distributions: (1) an NK of zero km s^{-1}; (2) one drawn from the Hansen & Phinney distribution (Hansen & Phinney 1997); (3) one drawn from the bimodal distribution of Arzoumanian et al. (2002); (4) as (2) but with the kick speed multiplied by the factor $M_{\rm ns}/M_{\rm bh}$ and (5) as (3) but with the kick speed multiplied by the factor $M_{\rm ns}/M_{\rm bh}$. We have added the two kicks together with random directions and combined (randomly) with the original orbital velocity within the Galaxy. The trajectory of each binary has then been integrated within the Galaxy.

A number of observed BH-LMXBs are found in excess of 1 kpc from the Galactic disc. By comparing our synthesized population to the observed systems, we show that the hypothesis that BHs only rarely receive an NK is ruled out at very high significance. The computed distribution is most similar to the observed distribution when the BH NKs are drawn from the same velocity distribution as for NSs. Although we are unable to rule out that BHs receive smaller kicks than NSs, in a number of cases the required NK is very likely to exceed the maximum possible kicks in the reduced-velocity distributions (i.e. distributions 4 and 5 above).

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REFERENCES

Arras P., Lai D., 1999, ApJ, 519, 745
Arzoumanian Z., Chernoff D. F., Cordes J. M., 2002, ApJ, 568, 289
Barkov M. V., Komissarov S. S., 2010, MNRAS, 401, 1644
Barret D., McClintock J. E., Grindlay J. E., 1996, ApJ, 473, 963

Basinska E. M., Lewin W. H. G., Sztajno M., Cominsky L. R., Marshall F. J., 1984, ApJ, 281, 337
Binney J., Tremaine S., 1988, Galactic Dynamics. Princeton Univ. Press, Princeton, NJ
Blaauw A., 1961, Bull. Astron. Inst. Netherlands, 15, 265
Bradshaw C. F., Fomalont E. B., Geldzahler B. J., 1999, ApJ, 512, L121
Brandt N., Podsiadlowski P., 1995, MNRAS, 274, 461
Brandt W. N., Podsiadlowski Ph., Sigurdsson S., 1995, MNRAS, 277, L35
Brandt W. N., Fabian A. C., Dotani T., Nagase F., Inoue H., Kotani T., Segawa Y., 1996, MNRAS, 283, 1071
Burrows A., Hayes J., Fryxell B. A., 1995, ApJ, 450, 830
Cantrell A. G. et al., 2010, ApJ, 710, 1127
Chevalier C., Ilovaisky S. A., 1990, A&A, 228, 115
Cocchi M., Bazzano A., Natalucci L., Ubertini P., Heise J., Muller J. M., in't Zand J. J. M., 1999, A&A, 346, L45
Cocchi M., Bazzano A., Natalucci L., Ubertini P., Heise J., Kuulkers E., Muller J. M., in't Zand J. J. M., 2000, A&A, 357, 527
Cocchi M., Bazzano A., Natalucci L., Ubertini P., Heise J., in't Zand J. J. M., 2001a, Mem. Soc. Astron. Ital., 72, 757
Cocchi M., Bazzano A., Natalucci L., Ubertini P., Heise J., Kuulkers E., Cornelisse R., in't Zand J. J. M., 2001b, A&A, 378, L37
Colpi M., Wasserman I., 2002, ApJ, 581, 1271
Cordes J. M., Romani R. W., Lundgren S. C., 1993, Nat, 362, 6416
Cornelisse R. et al., 2002, A&A, 392, 885
Davies M. B., Benz W., Hills J. G., 1992, ApJ, 401, 246
Davies M. B., King A., Rosswog S., Wynn G., 2002, ApJ, 579, L63
Dehnen W., Binney J., 1998, MNRAS, 294, 429
Dhawan V., Mirabel I. F., Ribó M., Rodrigues I., 2007, ApJ, 668, 430
Fender R. P., Hanson M. M., Pooley G. G., 1999, MNRAS, 304, 865
Fender R. P., Gallo E., Russell D., 2010, MNRAS, 406, 1425
Fragos T., Willems B., Kalogera V., Ivanova N., Rockefeller G., Fryer C. L., Young P. A., 2009, ApJ, 697, 1057
Fryer C. L., Kalogera V., 2001, ApJ, 554, 548
Fujimoto M. Y., Sztajno M., Lewin W. H. G., van Paradijs J., 1988, A&A, 199, L9
Galloway D. K., Chakrabarty D., Muno M. P., Savov P., 2001, ApJ, 549, L85
Gelino D. M., Balman Ş., Kiziloğlu Ü., Yilmaz A., Kalemci E., Tomsick J. A., 2006, ApJ, 642, 438
Goldreich P., Lai D., Sahrling M., 1996, in Bahcall J. N., Ostriker J. P., eds, Unsolved Problems in Astrophysics. Princeton Univ. Press, Princeton, NJ
Gottwald M., Haberl F., Parmar A. N., White N. E., 1986, ApJ, 308, 213
Gualandris A., Colpi M., Zwart S. P., Possenti A., 2005, ApJ, 618, 845
Hansen B. M. S., Phinney E. S., 1997, MNRAS, 291, 569
Harrison E. R., Tademaru E., 1975, ApJ, 201, 447
Herant M., Benz W., Hix W. R., Fryer C. L., Colgate S. A., 1994, ApJ, 435, 339
Hernandez J. I. G., Rebolo R., Israelian G., Filippenko A. V., Chornok R., Tominaga N., Umeda H., Nomoto K., 2008, ApJ, 679, 732
Herrmann F., Hinder I., Shoemaker D., Laguna P., 2007, ApJ, 661, 430
Hjellming R. M., Rupen M. P., 1995, Nat, 375, 464
Hoffman J. A., Cominsky L., Lewin W. H. G., 1980, ApJ, 240, L27
Homan J., Méndez M., Wijnands R., van der Klis M., van Paradijs J., 1999, ApJ, 513, L119
Homan J., Wijnands R., Kong A., Miller J. M., Rossi S., Belloni T., Lewin W. H. G., 2006, MNRAS, 366, 235
Hynes R. I., 2005, ApJ, 623, 1026
Hynes R. I., Steeghs D., Casares J., Charles P. A., O'Brien K., 2004, ApJ, 609, 317
in't Zand J. J. M. et al., 2001, A&A, 372, 916
Janka H. T., Mueller E. I., 1996, A&A, 306, 167
Jonker P. G., Nelemans G., 2004, MNRAS, 354, 355
Jonker P. G. et al., 2001, ApJ, 553, 335
Jonker P. G., Miller-Jones J. C. A., Homan J., Tomsick J., Fender R. P., Kaaret P., Markoff S., Gallo E., 2012, MNRAS, 423, 3308
Kaaret P., in't Zand J. J. M., Heise J., Tomsick J. A., 2002, ApJ, 575, 1018
Kalogera V., King A. R., Rasio F. A., 2004, ApJ, 601, L171
Kaptein R. G., in't Zand J. J. M., Kuulkers E., Verbunt F., Heise J., Cornelisse R., 2000, A&A, 358, L71
Kulkarni S. R., Hut P., McMillan S., 1993, Nat, 364, 421
Kumar P., Goodman J., 1996, ApJ, 466, 946
Kuulkers E., van der Klis M., 2000, A&A, 356, L45
Kuulkers E., Homan J., van der Klis M., Lewin W. H. G., Méndez M., 2002, A&A, 382, 947
Kuulkers E. et al., 2012, preprint (arXiv:1204.5840)
Lai D., 2004, in Hoflich P., Kumar P., Wheeler J. C., eds, Cosmic Explosions in Three Dimensions: Asymmetries in Supernovae and Gamma-ray Bursts. Cambridge Univ. Press, Cambridge
Lai D., Qian Y. Z., 1998, ApJ, 505, 844
Lai D., Chernoff D. F., Cordes J. M., 2001, ApJ, 549, 1111
Laor A., 1991, ApJ, 376, 90
Lyne A. G., Lorimer D. R., 1994, Nat, 369, 127
Maccarone T. J., Kundu A., Zepf S. E., Rhode K. L., 2007, Nat, 445, 7124
McClintock J. E., Shafee R., Narayan R., Remillard R. A., Davis S. W., Li L.-X., 2006, ApJ, 652, 518
McMillan P. J., 2011, MNRAS, 414, 2446
McMillan S. L. W., Taam R. E., McDermott P. N., 1990, ApJ, 354, 190
Merritt D., Milosavljevic M., Favat M., Hughes S. A., Holz D. E., 2004, ApJ, 607, L9
Miller M. C., Hamilton D. P., 2002, MNRAS, 330, 232
Miller-Jones J. C. A., Jonker P. G., Dhawan V., Brisken W., Rupen M. P., Nelemans G., Gallo E., 2009, ApJ, 706, 230
Mirabel I. F., Rodrigues I., 2003, Sci, 300, 1119
Mirabel I. F., Dhawan V., Mignani R. P., Rodrigues I., Guglielmetti F., 2001, Nat, 413, 139
Muno M. P., Chakrabarty D., Galloway D. K., Savov P., 2001, ApJ, 553, L157
Murakami T., Inoue H., Makishima K., Hoshi R., 1987, PASJ, 39, 879
Natalucci L., Bazzano A., Cocchi M., Ubertini P., Heise J., Kuulkers E., in't Zand J. J. M., Smith M. J. S., 2000, ApJ, 536, 891
Nelemans G., Tauris T. M., van den Heuvel E. P. J., 1999, A&A, 352, L87
Nordhaus J., Brandt T., Burrows A., Almgren A., 2012, MNRAS, 423, 1805
Orosz J. A. et al., 2001, ApJ, 555, 489
Orosz J. A., Polisensky E. J., Bailyn C. D., Tourtellotte S. W., McClintock J. E., Remillard R. A., 2002, BAAS, 34, 1124
Orosz J. A., Steiner J. F., McClintock J. E., Torres M. A. P., Remillard R. A., Bailyn C. D., Miller J. M., 2010, ApJ, 730, 2
Özel F., Psaltis D., Narayan R., McClintock J. E., 2010, ApJ, 725, 1918
Paczynski B., 1990, ApJ, 348, 485
Pfahl E., Rappaport S., Podsiadlowski P., 2002a, ApJ, 573, 283
Pfahl E., Rappaport S., Podsiadlowski P., Spruit H., 2002b, ApJ, 574, 364
Portegies Zwart S. F., McMillan S. L. W., 2000, ApJ, 528, L17
Press W. H. et al., 1993, Numerical Recipes in C: The Art of Scientific Computing. Cambridge Univ. Press, Cambridge
Rasio F. A., Shapiro S. L., 1991, ApJ, 377, 559
Rasio F. A., Shapiro S. L., 1994, ApJ, 432, 242
Remillard R., Morgan E., Smith D., Smith E., 2000, IAU Circ., 7389, 2
Ritter H., Kolb U., 2003, A&A, 404, 301 (update RKcat7.18, 2012)
Rosswog S., Davies M. B., Thielemann F. K., Piran T., 2000, A&A, 360, 171
Ruffert M., Janka H.-Th., 2001, A&A, 380, 544
Sigurdsson S., Hernquist L., 1993, Nat, 364, 6436
Smale A. P., 1998, ApJ, 498, L141
Strohmayer T. E., Markwardt C. B., Swank J. H., in't Zand J. J. M., 2003, ApJ, 596, L67
Tauris T. M., van den Heuvel E. P. J., 2006, in Lewin W., van der Klis M., eds, Compact Stellar X-ray Sources. Cambridge Univ. Press, Cambridge, p. 623
Tawara Y. et al., 1984, ApJ, 276, L41
Tennant A. F., Fabian A. C., Shafer R. A., 1986, MNRAS, 221, 27
Tomsick J. A., Kaaret P., Kroeger R. A., Remillard R. A., 1999, ApJ, 512, 892
Verbunt F., Lewin W. H. G., 2006, in Lewin M., van der Klis M., eds, Compact Stellar X-ray Sources. Cambridge Univ. Press, Cambridge, p. 341

Webb N. A., Naylor T., Ioannou Z., Charles P. A., Shahbaz T., 2000, MNRAS, 317, 528
White N. E., van Paradijs J., 1996, ApJ, 473, L25
Wijnands R., Muno M. P., Miller J. M., Franco L. M., Strohmayer T., Galloway D., Chakrabarty D., 2002, ApJ, 566, 1060
Willems B., Henninger M., Levin T., Ivanova N., Kalogera V., McGhee K., Timmes F. X., Fryer C. L., 2005, ApJ, 625, 324
Wong T.-W., Willems B., Kalogera V., 2010, ApJ, 721, 1689
Wong T.-W., Valsecchi F., Fragos T., Kalogera V., 2012, ApJ, 747, 2
Zhang S. N., Cui W., Chen W., 1997, ApJ, 482, L155
Zhuge X., Centrella J. M., McMillan S. L. W., 1994, Phys. Rev. D, 50, 6247
Zuo Z.-Y., Li X.-D., Liu X.-W., 2008, MNRAS, 387, 121

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