Mon. Not. R. Astron. Soc. **000**, 1–13 (0000) Printed 20 June 2012 (MN LaTeX style file v2.2)

Investigating stellar-mass black hole kicks

Serena Repetto[1,2]⋆, Melvyn B. Davies[1] and Steinn Sigurdsson[3]
[1] *Lund Observatory, Department of Astronomy and Theoretical Physics, Box 43, SE−221 00 Lund, Sweden*
[2] *Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands*
[3] *Department of Astronomy & Astrophysics, Pennsylvania State University, 525 Davey Lab, University Park, PA 16802, USA*

20 June 2012

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 order $10-30$ $R_{\odot}$. We perform population synthesis calculations of these binaries, applying both kicks due to supernova mass-loss and natal kicks 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: X-rays: binaries – stars: neutron – supernovae: general – Galaxy: dynamics – binaries: general – black hole physics

1 INTRODUCTION

It has long been known that neutron stars receive kicks at birth in the range $\sim 200-400$ km/s (so called *natal kicks*), when they are formed in core-collapse supernovae, for example via proper motion studies of pulsars (Cordes et al. 1993, Lyne & Lorimer 1994). Whether stellar-mass black holes (for brevity, black holes hereafter) receive these kicks too is still a matter of debate. Black holes can be studied via interacting X-ray binaries which contain them. There are several known X-ray binaries which are known to contain black holes or contain black hole candidates (Jonker & Nelemans 2004, Özel et al. 2010). In these systems, the massive primary has evolved to form a black hole via a core-collapse supernova and material is currently flowing from the lower-mass secondary (typically via Roche-lobe overflow) onto the black hole 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 a supernova, 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 natal kick received by the black hole 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 natal kicks. A number of studies have considered the motion of individual binaries within the Galaxy.

Brandt et al. 1995 considered GRO J1655–40 (Nova Sco) and concluded that a natal kick more easily accounted for the high space velocity of the binary.

Nelemans et al. 1999 studied Cygnus X-1 and concluding that a natal kick was not necessary to explain its space velocity.

Willems et al. 2005 considered GRO J1655–40 and suggested that although a natal kick is not formally required to produce the system as observed today, the inclusion of a (modest) natal kick more readily explains the system. They also placed an upper limit on the natal kick of $\simeq 210$ km/s.

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 a natal kick when the black hole 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

⋆ E-mail: S.Repetto@astro.ru.nl

(Mirabel et al. 2001). Gualandris et al. 2005 concluded that for this system a black hole natal kick was *required*. More recently, Fragos et al. 2009 placed the value of the natal kick in the range 80 - 310 km/s.

Wong et al. 2010 considered Cygnus X-1. They found that in this case the black hole progenitor could have received a relatively small natal kick (few tens of km/s with an upper limit of 77 km/s). If the system originated in the Cyg OB3 association (Mirabel & Rodrigues 2003) , then the upper limit on a kick is reduced to 24 km/s.

In this Paper, we consider the population of black hole X-ray binaries as a whole (following the approach of White & van Paradijs 1996, Jonker & Nelemans 2004, Zuo et al. 2008) rather than consider the kinematics of an individual system. We synthesize a population of black-hole low-mass X-ray binaries (BH-LMXBs), using various natal kick distributions, and integrating the systems within the Galactic potential. We then compare their locations within the Galaxy to a catalogue of known black-hole 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 neutron stars or black holes 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 supernovae mass-loss kicks on binaries. In Section 5 we present the results of the binary population synthesis which we discuss in Section 6. The paper is concluded in Section 7.

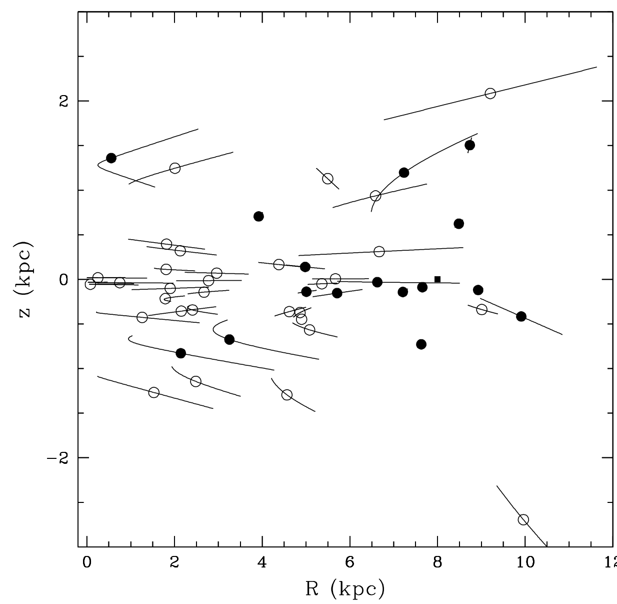

Figure 1. Galactic distribution of NS-LMXBs (open circles) and BH-LMXBs (filled circles). The radial distance from the Galactic centre is $R = \sqrt{x^2 + y^2}$, where x and y are the cartesian coordinates in the Galactic plane, whereas the distance from the plane of the Galaxy is $z = d \sin b$. Two neutron star binaries fall off the figure: XTEJ2123-058 and CygX-2. Solid lines account for the uncertainty of the distance from the Sun for each binary. The Sun is indicated as a square.

2 THE OBSERVED BINARIES

In our Galaxy there are 16 dynamically confirmed black holes in LMXBs and 33 NS-LMXBs, whose distance and Galactic position is known; see respectively Özel et al. 2010, Jonker & Nelemans 2004, and references therein (in particular, Jonker & Nelemans consider only NSs not found in globular clusters). 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 black hole binaries, uncertainty on the distance is taken from Özel et al.; for the neutron star 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.

Using the values in Table 1 and Table 2, we plot the Galactic distribution of the binaries in Figure 1. In representing the observed system on the (R, z) plane we propagate the uncertainty on the distance into an uncertainty on R and on 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* 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 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 modeled as the superposition of three components due to the disc ($\Phi_{\rm d}$), the spheroid ($\Phi_{\rm s}$) and the halo ($\Phi_{\rm h}$), as given below

$$\Phi_{\rm d}(R,z) = -\frac{GM_{\rm d}}{\sqrt{R^2 + \left(a_{\rm d} + \sqrt{z^2 + b_{\rm d}^2}\right)^2}} \qquad (1)$$

where $a_{\rm d} = 3.7$ kpc, $b_{\rm d} = 0.20$ kpc, and $M_{\rm d} = 8.07 \times 10^{10} {\rm M}_\odot$.

$$\Phi_{\rm s}(R,z) = -\frac{GM_{\rm s}}{\sqrt{R^2 + \left(a_{\rm s} + \sqrt{z^2 + b_{\rm s}^2}\right)^2}} \qquad (2)$$

where $a_{\rm s} = 0.0$ kpc, $b_{\rm s} = 0.277$ kpc, and $M_{\rm s} = 1.12 \times 10^{10} {\rm M}_\odot$.

$$\Phi_{\rm h}(r) = \frac{GM_{\rm c}}{r_{\rm c}} \left[\frac{1}{2} \ln\left(1 + \frac{r^2}{r_{\rm c}^2}\right) + \frac{r_{\rm c}}{r} \arctan\left(\frac{r}{r_{\rm c}}\right)\right] \qquad (3)$$

Table 1. Observed properties of BH-LMXBs.

Name	l (deg)	b (deg)	d (kpc)	Δd (kpc)	R (kpc)	z (kpc)	Ref. (distance)
4U1543-47	330.0	+5.4	7.5	0.5	3.92	0.70	[1]
XTEJ1550-564	325.9	-1.8	4.4	0.5	5.0	-0.14	[2]
GROJ1655-40	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]
GRS1915+105	45.4	-0.2	9.0	3.0	6.62	-0.03	[6]
GS2023+338	73.1	-2.1	2.39	0.14	7.65	-0.09	[7]
GROJ0422+32	166.0	-12.0	2.0	1.0	9.91	-0.41	[8]
A0620-003	210.0	-6.5	1.06	0.12	8.92	-0.12	[9]
GRS1009-45	275.9	+9.4	3.82	0.27	8.48	0.62	[10]
XTEJ1118+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]
XTEJ1650-500	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]
XTEJ1859+226	54.1	+8.6	8.0	3.0	7.23	1.20	[10]
GS2000+251	63.4	-3.0	2.7	0.7	7.21	-0.14	[13]

References (from Özel et al. 2010): [1] Orosz 2010 private communication, [2] Orosz et al. 2010, [3] Hjellming & Rupen 1995, [4] Hynes 2005, [5] Orosz et al. 2001, [6] Fender et al. 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. 1999, [13] Barret et al. 1996.

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

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

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

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 a supernova are comparable to the circular orbital speed in the Galaxy (~ 200 km/s). 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 Gyrs (which is the typical main sequence MS-time of a sun-like star), using a 4th-order Runge-Kutta integrator developed by SR, and assuming 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, 200 km/s) and of the initial position $R_{t=0}$ over the plane, writing down the maximum z reached over the trajectory (see Figure 2). We see how z_{max} is a rather strong function of the initial position: for a fixed value of $v_\perp$, $z_{\rm max}$ 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 will be required in at least some of the observed systems shown in Figure 1.

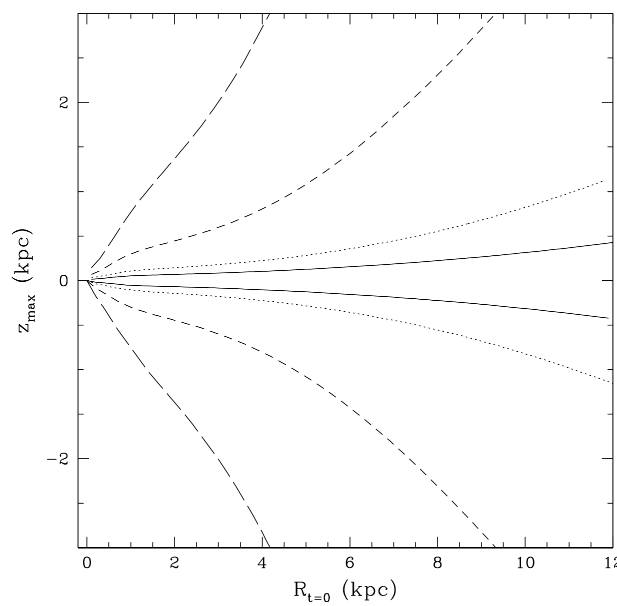

Figure 2. Maximum z reached by a binary over its trajectory. The object has been kicked perpendicularly to the Galactic plane, for four different magnitudes of the kick ($v_\perp$ = 20, 40, 100, 200 km/s).

Table 2. Observed properties of NS-LMXBs.

Name	l (deg)	b (deg)	d (kpc)	Δd (kpc)	R (kpc)	z (kpc)	Ref. (distance)
EXO0748-676	279.98	-19.81	7.95	2.3	9.96	-2.70	[1]
2S0918-54	275.85	-3.84	5.05	1.5	9.0	-0.34	[2]
Cir X-1	322.12	0.04	9.15	2.7	5.67	0.00	[3]
4U1608-522	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]
4U1636-53	332.91	-4.82	4.3	1.2	4.62	-0.36	[6]
4U1658-298	353.83	7.27	9.85	2.9	2.01	1.25	[7]
4U1702-429	343.89	-1.32	6.2	1.8	2.67	-0.14	[8]
4U1705-44	343.32	-2.34	8.4	2.4	2.40	-0.34	[8]
XTEJ1710-281	356.36	6.92	17.3	5.0	9.20	2.08	[8]
SAXJ1712.6-3739	348.93	0.93	6.9	2.0	1.81	0.11	[9]
1H1715-321	354.13	3.06	6.0	1.8	2.13	0.32	[10]
RXJ1718.4-4029	347.28	-1.65	7.5	2.2	1.79	-0.21	[11]
4U1728-34	354.30	-0.15	5.3	1.6	2.78	-0.01	[12]
KS1731-260	1.07	3.65	6.2	1.8	1.81	0.39	[13]
4U1735-44	346.05	-6.99	9.4	2.8	2.48	-1.14	[8]
GRS1741.9-2853	359.96	0.13	7.75	2.3	0.25	0.01	[14]
2E1742.9-2929	359.56	-0.39	8.05	2.3	0.08	-0.05	[8]
SAXJ1747.0-2853	0.21	-0.24	8.75	2.5	0.75	-0.04	[15]
GX3+1	2.29	0.79	5.05	1.5	2.96	0.07	[16]
SAXJ1750.8-2900	0.45	-0.95	6.1	1.8	1.90	-0.10	[17]
SAXJ1752.3-3138	358.44	-2.64	9.25	2.7	1.26	-0.43	[18]
SAXJ1808.4-3658	355.38	-8.15	3.15	0.9	4.90	-0.45	[19]
SAXJ1810.8-2609	5.20	-3.43	5.95	1.7	2.15	-0.36	[20]
4U1812-12	18.06	2.38	4.0	1.2	4.38	0.17	[21]
XTEJ1814-338	358.75	-7.59	9.6	2.8	1.53	-1.27	[22]
GX17+2	16.43	1.28	13.95	4.1	6.67	0.31	[23]
SerX-1	36.12	4.84	11.1	3.2	6.59	0.94	[8]
Aq1X-1	35.72	-4.14	5.15	1.5	4.86	-0.37	[24]
4U1857+01	35.02	-3.71	8.75	2.5	5.08	-0.57	[25]
4U1916-053	31.36	-8.46	8.8	2.6	4.56	-1.29	[26]
XTEJ2123-058	46.48	-36.20	18.35	5.3	10.96	-10.83	[27]
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 et al. 1986, [4] Murakami et al. 1987, [5] Bradshaw et al. 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. 2000, [14] Jonker & Nelemans 2004, [15] Natalucci et al. 2000, [16] Kuulkers et al. 2002, [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 et al. 1990, [26] Galloway et al. 2001, [27] Homan et al. 1999, [28] Smale 1998.

4 KICKS RECEIVED BY SURVIVING BINARIES

In this section we consider the effects of the supernova explosion on the binary. We will see how the rapid mass loss from the supernova alone could impart a kick on some systems whilst breaking others up. In addition, any kick imparted to the neutron star or black hole on its formation (i.e. a natal kick) 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 a supernova, 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 natal kick. In other words, where any kick is due solely to the rapid mass loss occurring during the supernova 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 below

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

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

$V_{\rm mlk}$ can't be too large, since the binary must remain bound after the supernova: 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 ~ 10 R$_\odot$, the resulting typical mass loss kicks for BH-LMXBs are of the order of $20-40$ km/s (for NS-LMXBs they are typically higher). Looking at figure 2, we immediately realize how kicks of this size cannot make the highest-z black hole binaries: in the optimal case of $V_{\rm mlk} \simeq 40$ km/s 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 neutron star or black hole produced in the supernova receives a natal kick. If we assume the orientation of the natal kick is random with respect to the orbital plane, the natal kick $V_{\rm nk}$ combines with the mass loss kick $V_{\rm mlk}$ as given below:

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

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 supernova explosion.

Many distributions to model neutron star natal kicks have been proposed. For example, Hansen & Phinney 1997 modeled the natal kick as a Maxwellian distribution peaked at 300 km/s. To solve the retention problem in globular clusters 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 et al. 2002a, Pfahl et al. 2002b).

We consider two different natal kick distributions here: one is the Hansen & Phinney distribution, the other is a bimodal distribution proposed by Arzoumanian et al. 2002 which has a lower peak at $\sim$ 100 km/s and the higher peak at $\sim$ 700 km/s. 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 black hole is the same as the momentum given to a neutron star 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$_\odot$ black hole receives a natal kick reduced by a factor of 5: for a neutron-star natal kick of 300 km/s, the black hole would receive a smaller kick of only 60 km/s. We show in figure 3 the natal kick distributions which we use.

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

Considering a population of binaries where $M_1 = 11$ M$_\odot$, $M_2 = 1.5$ M$_\odot$, $M_{bh} = 7.8$ M$_\odot$, $a = 10$ R$_\odot$ (M_1 is the mass of the progenitor of the black hole, M_2 is the companion star and a is the pre-SN orbital separation), we impart the BH of each binary a 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$_\odot$ neutron star is produced instead of a black hole (taking as the progenitor mass 3.5 M$_\odot$). A larger fraction of binaries remain bound for binaries containing black holes rather than neutron stars owing to the greater binding mass.

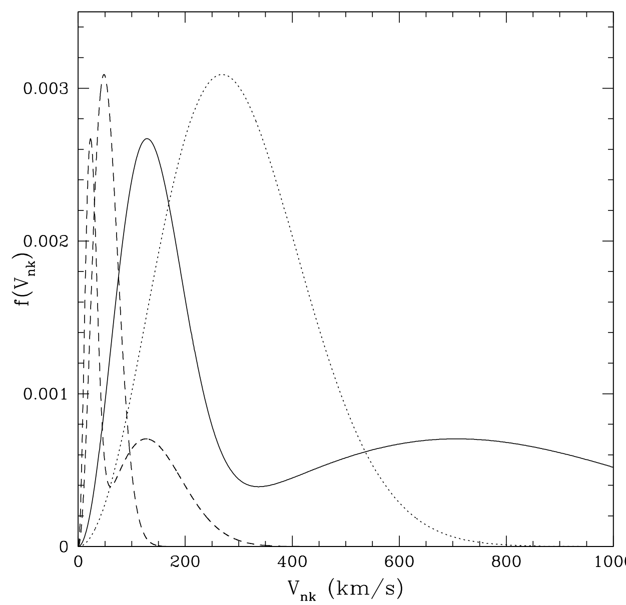

Figure 3. Natal Kick distributions used in our binary population synthesis calculations. Solid line corresponds to Arzoumanian distribution, dotted line to Hansen & Phinney and the two dashed lines to these two distributions but with kick speeds reduced, assuming that the momentum imparted to the black hole is the same as the momentum imparted to the neutron star.

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

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

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

We show in figure 4 the distribution of kick velocities for BH-LMXBs that we obtain drawing from each of the four natal kick distributions. One should in particular note how the kick velocities for the momentum conserving kicks are typically lower than $\sim$ 100 km/s.

5 BINARY POPULATION SYNTHESIS

In this section we discuss the calculation of the synthetic population of black hole low-mass X-ray binaries. We produce a population of BH-LMXBs considering their formation within the Galactic disc at a range of radii. For each

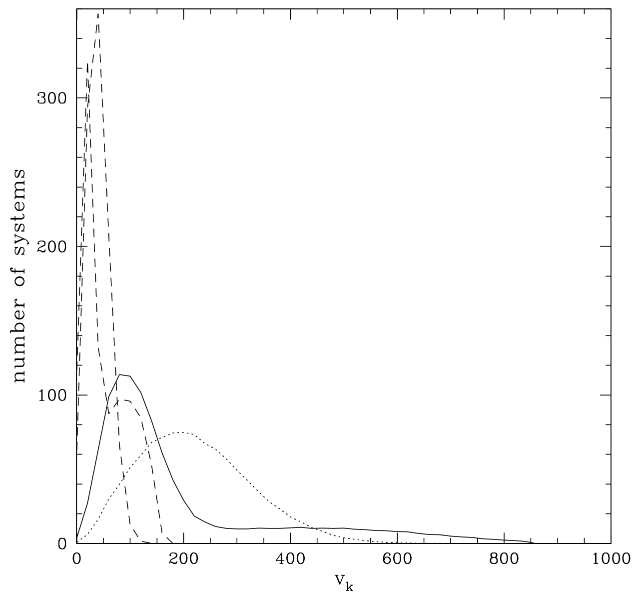

Figure 4. Peculiar velocity gained by the binary after an asymmetric supernova. Natal kicks have been drawn from Arzoumanian distribution (solid line), Hansen & Phinney distribution (dotted line), whereas the dashed lines correspond to the MCKs. The total number of systems for each curve has been normalized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

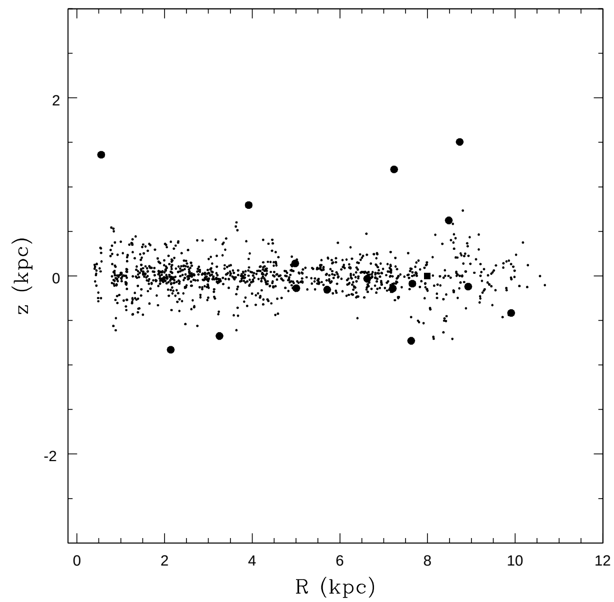

Figure 5. Binary population synthesis for a sample of BH-LMXBs. No natal kick has been imparted to the BH. Smaller dots correspond to the synthetic population, bigger ones to the observed binaries and the position of the Sun is denoted with a square.

binary, we randomly draw the black hole natal kick, considering five different natal kick distributions (including a zero natal kick) and give this kick a random direction which we then add to the mass-loss kick due to the supernova 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 $M_\odot$ 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 natal kick distributions for the black holes formed.

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

The population is formed by 100 binaries with the following parameters: $M_1 = 11$ $M_\odot$, $M_2 = 1.5$ $M_\odot$, $M_{\rm bh} = 7.8$ $M_\odot$, $a = 10$ $R_\odot$ (M_1 is the mass of the progenitor of the black hole, M_2 is the companion star and a is the pre-SN orbital separation). For the black hole mass, we choose the average mass of stellar black holes 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 supernova explosion of ~ 3 $M_\odot$ (see Fryer & Kalogera 2001), which delivers an associated mass-loss kick of ~ 20 km/s.

In addition, the black hole receives a natal kick drawn from one of the following five distributions: 1) a natal kick of zero km/s; 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 plot the positions of the 100 binaries -at random times of the trajectory- in Galactic cylindrical coordinates for zero black-hole natal kicks in Figure 5 and for the other four natal kick distributions in Figure 6. From Figure 5 it is clear that it is impossible to place BH-LMXBs seen at larger values of z when the black holes receive zero natal kicks. Either the Hansen & Phinney or the Arzoumanian distributions appear to fit the observed distribution of BH-LMXBs, whereas those produced by natal kick distributions with velocities reduced by a factor of $M_{\rm bh}/M_{\rm ns}$ (bottom panels in Figure 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 figure 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

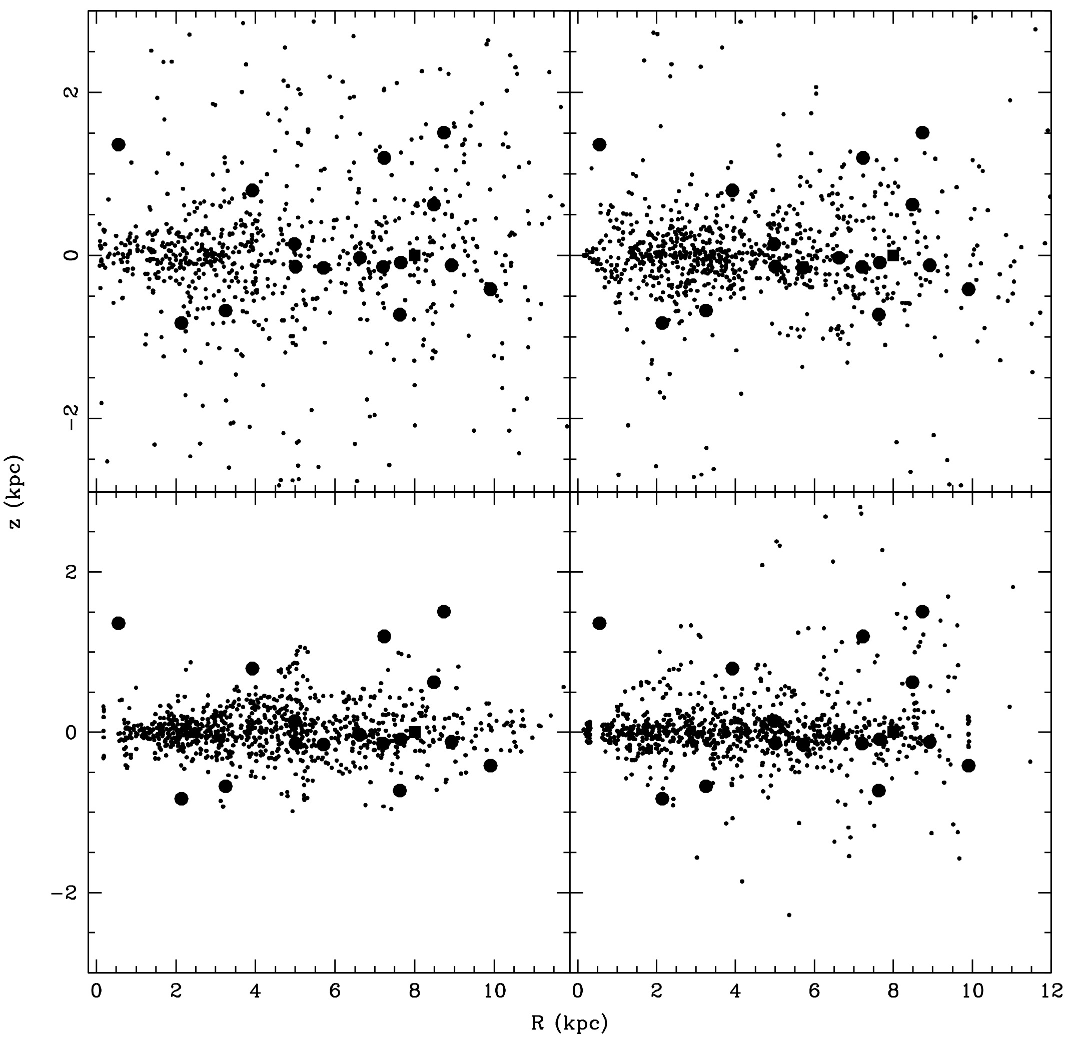

Figure 6. Binary population synthesis for a sample of BH-LMXBs. Natal kicks have been drawn from Hansen & Phinney (top left) distribution, a bimodal distribution (top right), whereas the bottom figures correspond to the reduced natal kicks. Smaller dots correspond to the synthetic population, bigger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

of the BPS for which no NK has been imparted to the black hole.

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 the 0.5%. With a reduced Arzoumanian NK the percentage gets higher ($\sim 6\%$), though the fit remains unsatisfactory (see table 4). It then turns out to be very difficult, with a momentum conserving kick, to reproduce the binaries XTEJ118+480, 1705-250, XTEJ1859+226, which are located respectively at $z = 1.5$, 1.36, 1.20 kpc. Section 6 is dedicated to the detailed study of these sources.

We are aware that the integration time we chose ($\sim 3\times10^9$ years) 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 ($M_2 \sim 3$ $M_\odot$, see the updated catalogue Ritter & Kolb 2003). We then carry out other two synthesises for the BH-LMXBs, integrating their trajectories for $\sim 10^8$ years and for $\sim 5\times10^8$ years. In the first integration, the percentage of binaries that reach z higher than 1 kpc is 0% for a reduced Hansen & Phinney NK and 1% for an Arzoumanian reduced NK. In the second integration, the percentages are respectively are 0.2% and 2.2%. Concerning the KS-test, the resulting probabilities get 1 or 2 order of magnitudes lower when choosing a reduced integration time; this is easily explained, since the binary doesn't 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 com-

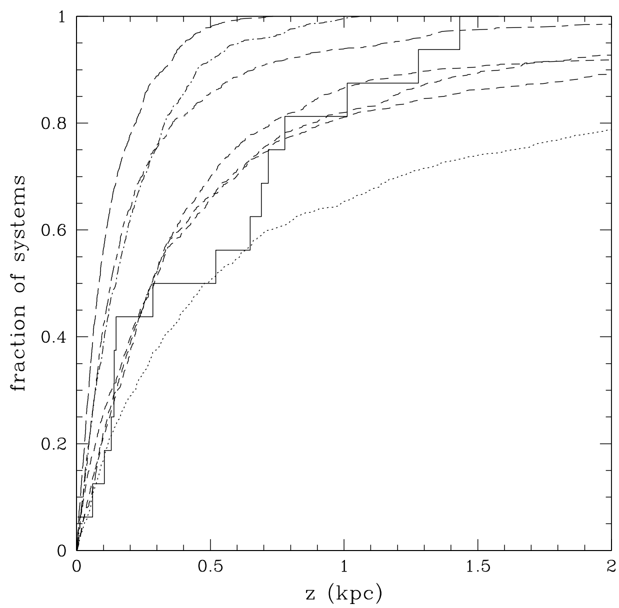

Figure 7. Cumulatives which show the fraction of BH-LMXBs versus the distance from the Galactic plane, for the four different natal kicks (dotted line is for an Hansen & Phinney NK, dotted-dashed line is for a reduced Hansen & Phinney NK, short-long-dashed is for a reduced Arzoumanian NK, whereas a zero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

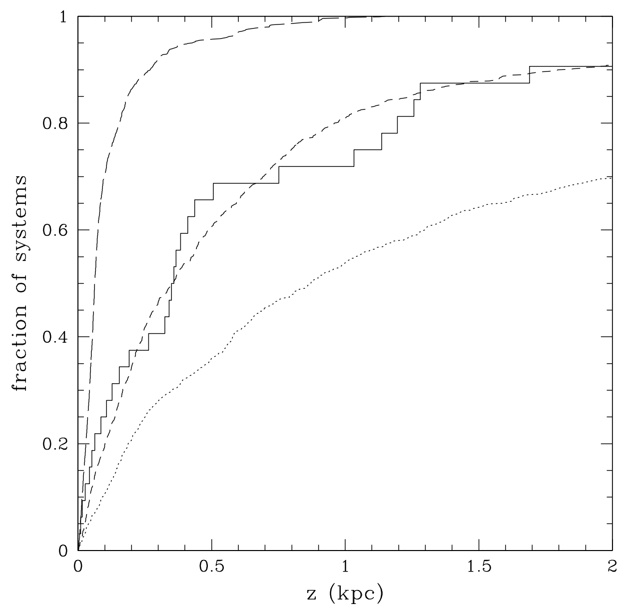

Figure 8. Cumulatives which show the fraction of NS-LMXBs versus the distance from the Galactic plane, for the four different natal kicks (dotted line is for an Hansen & Phinney natal kick, short-dashed line is for an Arzoumanian natal kick, whereas a zero natal kick scenario corresponds to the long-dashed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

panion mass. It is believed that in the SN event the Helium star loses no more than $3-4$ M$_\odot$ (before exploding as a SN, the Helium star suffers from strong WR winds after the common envelope phase, see for example 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 following parameters, $M_1 = 11$ M$_\odot$, $M_2 = 3.0$ M$_\odot$, $M_{\rm bh} = 7.8$ M$_\odot$, $a = 6$ R$_\odot$, give a recoil velocity $V_{\rm mlk}$ of ~ 40 km/s. We then perform two synthesises in which we fix the mass loss kick to ~ 40 km/s, testing the two types of reduced natal kicks. 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 synthesises has been set to $\sim 3\times10^{9}$ years; decreasing the integration time would make the KS probabilities even lower.

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

Table 4. KS probabilities for the BPS.

KS probabilities		
	BH-BPS	NS-BPS
Integration time 3×10^9 years		
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 years		
Hansen MCK	7×10^{-4}	-
Bimodal MCK	5×10^{-3}	-
Integration time 10^8 years		
Hansen MCK	4×10^{-4}	-
Bimodal MCK	6×10^{-4}	-

6 DISCUSSION

We now aim at deriving the minimum natal kick 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, black-hole 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 natal kick 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 traveling in the Galactic potential, assuming the binary is born right over the Galactic plane at some radius R_0. Thus

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

where Φ is the gravitational potential of the Galaxy.

We show in Table 5 the minimum perpendicular kick $V_{\perp}$ and minimum natal kick $V_{\rm nk}$ required for those BH-LMXB systems which have relatively well-constrained binary properties. One should understand that the natal kick value quoted in Table 5 is the absolute lower limit, assuming that the natal kick occurred in the perfectly optimal direction. In practice, the natal kick 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 natal kick to reproduce the current location of XTE J1118+480 is up to 300 km/s (as was also seen in Fragos et al. 2009).

The minimum peculiar velocity is normally greater than 80 km/s for binaries that are located at $z > 1$ kpc, or for binaries that are closer in towards the Galactic center and at $z > 0.6$ kpc. Particularly, for systems that are located at $R \lesssim 3$ kpc from the Galactic center, typical required velocities are greater than 100 km/s for 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 black hole natal kick broadly in the range $100 - 500$ km/s. For other systems, the current location could be reached with the black hole having received no natal kick. 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 natal kick. 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 both launching the binary out of the disc 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, while in the second case a velocity $V_{\perp} \sim 250$ km/s is needed. These velocities require a minimum natal kick of 440 km/s and of 260 km/s respectively. Our results might have been affected by the choice of a spherically symmetric bulge (i.e. $a_{\rm s} = 0.0$ kpc, see equation 2 for the potential of the spheroid); we then take a *pseudobulge* with $a_{\rm s} = 1.0$ kpc. The resulting $V_{\perp}$ is ~ 320 km/s for $R = 0.5$ kpc and $V_{\perp} \sim 220$ km/s for $R = 2.0$ kpc. The associated minimum natal kicks are 340 and 230 km/s respectively. For both of the two model 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 natal kick 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 Orosz et al. 2002, Orosz et al. 2001, Gelino et al. 2006, Barret et al. 1996). 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 binaries distance, we computed the minimum required natal kick, the distance being 10, 25, 50, 100 % larger than the nominal value. We perform the computation for our four candidates of BHs receiving the same NK as NSs. The required minimum NK decreases in all the cases except for XTEJ1118+480. This is easily explained since a larger distance would move the binary further out the Galactic potential well. The binaries 4U1543-47, 1819.3-2525, 1705-250 require a minimum natal kick of 45, 22, 92 km/s, respectively, when the distance is increased of the 100%. XTEJ1118+480 shows instead an increase of the minimum NK up to ~ 100 km/s 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 globular clusters (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 globular clusters (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 black holes might be retained in a globular cluster has been largely discussed in the literature (e.g., Kulkarni et al. 1993, Sigurdsson & Hernquist 1993, Portegies Zwart & McMillan 2000, Miller & Hamilton 2002). It is generally thought that black holes 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 timescale shorter than $\sim 10^9$ years. In case one black hole 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 et al. 2004 and reference therein). Stars the BH is interacting with have a typical mass $\lesssim 1\ M_{\odot}$ at this stage of the life of the GC. It has been shown that the two-body tidal capture scenario between a NS and a low-mass star is likely to result in a merger (Davies et al. 1992, Kumar & Goodman 1996, McMillan et al. 1990, Rasio & Shapiro 1991). Specifically, Davies et al. 1992 showed that an encounter between a NS and a red-giant would result in a merger in some 70%

of the cases, and some 50% for an encounter between a NS and a MS-star. For a BH, tidal forces are expected to be much larger, so that a 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 and we follow their motion in the Galactic potential for $\sim 3\times10^9$. 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 globular cluster 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. A natal kick 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 black hole to neutron star masses.

From table 5 we see that natal kicks exceeding 70 km/s are required for several systems: 4U1543-47, 1819.3-2525, XTEJ1118+480 and 1705-250. These binaries provide us with evidence that *black holes receive natal kicks of the same size as those received by neutron stars.* One might have expected the black hole natal kicks to carry the same momentum as those for neutron stars if, for example, a neutron star formed first (and having received a kick) and then a black hole formed later as a result of fall-back material within the supernova. In particular, the magnitude of the natal kick imparted to the BH depends on the competition between two timescales: the fall-back timescale τ_{fb} and the timescale of the mechanism leading to the natal kick τ_{nk}. If $\tau_{fb} > \tau_{nk}$, we expect the fall-back material not to receive the same natal kick has the proto neutron star; the BH natal kick will then be reduced by the ratio M_{ns}/M_{bh}. In case $\tau_{fb} \lesssim \tau_{nk}$, we expect the BH to receive a full natal kick. 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 binary population synthesis, is surprising. However, one should note the large natal kick speeds obtained by the black hole in some of the supernova 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 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 natal kicks received by neutron stars, some of which will also apply to black holes, especially those forming through the subsequent fall-back of material onto a proto neutron star. 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 et al. 1995, Janka & Mueller 1996, and the recent work by Nordhaus et al. 2011) or by over-stable oscillation modes of the progenitor core (Goldreich et al. 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 neutron star has formed: the off-centre rotating dipole impart the neutron star a kick (Harrison & Tademaru 1975, Lai et al. 2001). For a review of neutron star natal kicks, 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 black hole or neutron star. This secondary will rapidly spiral-in towards the primary. If the secondary is a neutron star, then it may transfer mass to the primary until it reaches the minimum mass for a neutron star at which point it will explode potentially giving the primary a kick (Colpi & Wasserman 2002, Davies et al. 2002b). In case both objects are black holes, then a merger kick may result from the asymmetric emission of gravitational waves (see Rosswog et al. 2000, Zhuge et al. 1994, Rasio & Shapiro 1994, Ruffert & Janka 2001). In both cases, the kick received can be several hundreds km/s. Or else, when the disc on collapse forms directly around a BH, it might release its energy as a powerful jet: if this jets 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 Zhang et al. 1997, Laor 1991 and also Fender et al. 2010). Ruling out the accretion of matter from a low-mass companion as origin of the BH spin (see McClintock 2006), a BH-BH merger might well fit 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 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 for a mass ratio q in the range $0.2 - 0.4$.

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

Name	$V_\perp$ (km/s)	$V_{\rm nk}$ (km/s)	R (kpc)	z (kpc)
3 4U1543-47	95	80	3.92	0.70
XTEJ1550-564	22	10	5.0	-0.14
GROJ1655-40	36	0	4.98	0.13
1659-487	113	-	3.25	-0.67
1819.3-2525	160	190	2.14	-0.82
GRS1915+105	5	0	6.62	-0.03
GS2023+338	10	0	7.65	-0.09
GROJ0422+32	25	10	9.91	-0.41
A0620-003	10	0	8.92	-0.12
GRS1009-45	40	15	8.48	0.62
XTEJ1118+480	80	70	8.73	1.50
1124-683	50	40	7.63	-0.73
XTEJ1650-500	20	-	5.71	-0.15
1705-250	420	450	0.55	1.36
XTEJ1859+226	80	-	7.23	1.20
GS2000+251	15	0	7.21	-0.14

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

7 CONCLUSIONS

In this Paper, we have considered the distribution of low-mass X-ray binaries containing black holes (BH-LMXBs) within the Galaxy as a function of the distribution of natal kicks given to the black holes. We have synthesized a BH-LMXB population by forming systems randomly throughout the Galactic citealt, weighted by stellar surface density of the disc. We have given each binary a mass-loss kick due to the supernova explosion of the primary and added to this kick a black hole natal kick drawn from one of five kick distributions: 1) a natal kick of zero km/s; 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 black holes only rarely receive a natal kick is ruled out at very high significance. The computed distribution is most similar to the observed distribution when the black hole natal kicks are drawn from the same velocity distribution as for neutron stars. Although we are unable to rule out that black holes receive smaller kicks than neutron stars, in a number of cases the required natal kick is very likely to exceed the maximum possible kicks in the reduced-velocity distributions (i.e. distributions 4 and 5 above).

ACKNOWLEDGMENTS

This work was supported by the Swedish Research Council (grants 2008–4089 and 2011–3991). We thank the anonymous referee for helpful comments that improved our paper. SR is thankful to the University of Pavia for the Erasmus grant and Andrea De Luca for helpful suggestions. MBD and SS gratefully acknowledge the hospitality of the Aspen Center for Physics.

REFERENCES

Arras P., Lai D., 2002, 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
Blaauw A., 1961, Bull. Astron. Inst. Netherlands, 15, 265
Bradshaw C. F., Fomalont E. B., Geldzahler B. J., 1999, ApJ, 512, L121
Binney J., Tremaine S., Freeman K., 1988, Galactic Dynamics, Princeton University Press
Brandt N., Podsiadlowski P., 1996, MNRAS, 274, 46
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
Cadolle Bel M., Ribó M., Rodriguez J., Chaty S., Corbel S., Goldwurm A., Frontera F., Farinelli R., D'Avanzo P., Tarana A., Ubertini P., Laurent P., Goldoni P., Mirabel I.F., 2007, ApJ, 659, 549
Cantrell A.G., Bailyn C.D., Orosz J.A., McClintock J.E., Remillard R.A., Froning C.S., Neilsen J., Gelino D.M., Gou L., 2010, ApJ, 710, 1127
Casares J., Orosz J.A., Zurita C., Shahbaz T., Corral-Santana J.M., McClintock J.E., Garcia M.R., Martínez-Pais I.G., Charles P.A., Fender R.P., Remillard R.A., 2009, ApJS, 181, 238
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, Memorie della Società Astronomica Italiana, 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., in't Zand J.J.M., 2001b, A&A, 378, L37
Davies M.B., Benz W., Hills J.G., 1992, ApJ, 401, 246
Davies M.B., King A., Ritter H., 2002a, MNRAS, 333, 463
Davies M.B, King A., Rosswog S., Wynn G., 2002b, ApJ, 579, L63

Dehnen W., Binney J., 1998, MNRAS, 294, 429
Dhawan V., Mirabel I.F., Ribó M., Rodrigues I., 2007, ApJ, 668, 430
Eggleton P.P., 1983, ApJ, 268, 368
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., 2009, 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
Goldreich P., Lai D., Sahrling M., 1996, Unsolved Problems in Astrophysics, eds. J.N. Bahcall and J.P. Ostriker, Princeton Univ. Press
Gottwald M., Haberl F., Parmar A. N., White N. E., 1986, ApJ, 308, 213
Gelino D.M., Balman Ş., Kızıloğlu Ü., Yılmaz A., Kalemci E., Tomsick J.A., 2006, ApJ, 642, 438
Gualandris A., Colpi M., Zwart S.P., Possenti A., 2005, ApJ, 618, 845
Hansen B.M.S., Phinney E.S., 1997, Lewin W. H. G., 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, 339
Hernandez J.I.G., Rebolo R., Israelian G., Filippenko A.V., Chornok R., Tominaga N., Umeda H., Nomoto K., 2008, ApJ, 679, 732
Hoffman J. A., Cominsky L., Lewin W. H. G., 1980, ApJ, 240, L27
Hjellming R. M., Rupen M. P., 1995, Nat, 375, 464
Herrmann F., Hinder I., Shoemaker D., Laguna P., 2007, ApJ, 661, 430
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
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. et al., 2001, ApJ, 553, 335
Jonker P.G., Nelemans G., 2004, MNRAS, 354, 355
Jonker P.G. et al., 2011, ApJS, 194, Issue 2
Jonker P.G., Miller-Jones J.C.A., Homan J., Tomsick J., Fender R.P., Kaaret P., Markoff S., Gallo E., 2012, arXiv:1204.4832
Kaaret P., in't Zand J.J.M., Heise J., Tomsick J. A., 2002, ApJ, 575, 1018
Kalamkar M. et al., 2010, ATEL, 2881
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
Kolb U., Davies M.B., King A., Ritter H., 2000, MNRAS, 317, 438
Kuulkers E., Homan J., van der Klis M., Lewin W.H.G., Méndez M., 2002, A&A, 382, 947
Kuulkers E. et al., 2012, arXiv:1204.5840
Kulkarni S.R., Hut P., McMillan S., 1993, Nat, 364, 421
Kumar P., Goodman J., 1996, ApJ, 466, 946
Lai D., Qian Y.Z., 1998, ApJ, 505, 844
Lai D., Chernoff D.F., Cordes J.M., 2001, ApJ, 549, 1111
Lai D., 2004, Cosmic explosions in three dimensions : asymmetries in supernovae and gamma-ray bursts, Cambridge University Press
Laor A., 1991, ApJ, 376, p. 90-94
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 et al., 2006, ApJ, 652, 518
McMillan S.L.W., Taam R.E., McDermott P.N., 1990, ApJ, 354, 190
McMillan P.J., 2011, MNRAS, 414, 2446
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., Dhawan V., Mignani R.P., Rodrigues I., Guglielmetti F., 2001, Nat, 413, 139
Mirabel I.F., Rodrigues I., 2003, Science, 300, 1119
Muno M. P., Fox D. W., Morgan E. H., Bildsten L., 2000, ApJ, 542, 1016
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., 2011, arXiv1112.334
Orosz J.A., Kuulkers E., van der Klis M., McClintock J.E., Garcia M.R., Callanan P.J., Bailyn C.D., Jain R.K., Remillard R.A., 2001, ApJ, 555, 489
Orosz J. A., Polisensky E.J., Bailyn C.D., Tourtellotte S.W., McClintock J.E., Remillard R. A., 2002, American Astronomical Society, 201st AAS Meeting
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, Issue 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., 2002, ApJ, 573, 283
Pfahl E., Rappaport S., Podsiadlowski P., Spruit H., 2002, ApJ, 574, 364
Podsiadlowski P., Pfahl E., Rappaport S., 2005, Binary Radio Pulsars, ASP Conference Series, Vol. 328
Pollney et al., 2007, Physical Review D 76
Portegies Zwart S.F., McMillan S.L.W., 2000, ApJ, 528, L17
Press W.H., Teukolsky S.A., VetterlingW.T., Flannery B.P., Teukolsky S.A., Vetterling W.T., Flannery B.P., Lloyd C., Rees P., 1993, Numerical recipes in C: the art of scientific computing, Cambridge University Press
Ramadevi M.C., Seetha S., 2007, MNRAS, 378, 182
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 RKcat7.16, 2011)
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, Compact stellar X-ray sources, Cambridge Astrophysics Series, No. 39 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., Phinney E.S., 1995, A&A, 296, 709
Verbunt F., Lewin W.H.G., 2006, Compact stellar X-ray sources, Cambridge Astrophysics Series, No. 39 p. 341
Webb N.A., Naylor T., Ioannou Z., Charles P.A., Shahbaz T., 2000, MNRAS, 317, 528
Willems B., Henninger M., Levin T., Ivanova N., Kalogera V., McGhee K., Timmes F.X., Fryer C.L., 2005, ApJ, 625, 324
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, ApJl, 566, 1060
Wong T-W, Willems B., Kalogera V., 2010, ApJ, 721, 1689
Wong T-W, Valsecchi F., Fragos T., Kalogera V., 2012, ApJ, 747, Issue 2
Zhang S.N., Cui W., Chen W., 1997, ApJ, 482, L155
Zhuge X., Centrella J.M., McMillan S.L.W., 1994, Physical Review D, 50, 6247
Zuo Z.-Y., Li X.-D., Liu X.-W., 2008, MNRAS, 387, 121
Zurita C., Durant M., Torres M.A.P., Shahbaz T., Casares J., Steeghs D., 2008, ApJ, 681, 1458