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Estimates of black hole natal kick velocities from observations of low-mass X-ray binaries

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ABSTRACT

The birth kicks of black holes, arising from asymmetric mass ejection or neutrino emission during core-collapse supernovae, are of great interest for both observationally constraining supernova models and population-synthesis studies of binary evolution. Recently, several efforts were undertaken to estimate black hole birth kicks from observations of black hole low-mass X-ray binaries. We follow up on this work, specifically focusing on the highest estimated black hole kick velocities. We find that existing observations do not require black hole birth kicks in excess of approximately 80 km s^{-1}, although higher kicks are not ruled out.

Key words: binaries: close – stars: black holes – Galaxy: kinematics and dynamics – X-rays: binaries.

INTRODUCTION

Unlike neutron-star supernova-induced birth kicks, which are constrained from pulsar proper motion observations (Hobbs et al. 2005), black hole birth kicks are poorly known (e.g. Repetto, Davies & Sigurdsson 2012). They are, none the less, of great interest to stellar and binary astrophysicists. Black hole birth kicks play a key role in the evolution of massive stellar binaries and predictions of compact-binary merger rates observable through their gravitational-wave signatures (e.g. Abadie et al. 2010). For example, in a population-synthesis study of binary evolution, Dominik et al. (2012) find that varying black hole kicks from zero to the distribution used for neutron stars decreases the rate of binary black hole mergers by two orders of magnitude, as a significant fraction of potential binary black hole systems are disrupted by large supernovae kicks. Birth kicks are also of interest in supernova modelling as constraints on the supernova explosion mechanism. For example Janka (2013) uses the high kicks inferred by Repetto et al. (2012) to support a supernova model in which a neutron star is initially formed and converted into a black hole after a delay during which ejecta fall back asymmetrically, contributing further momentum to the black hole.

Black-hole X-ray binaries provide a promising tool for measuring black hole birth kicks. Typically, measuring the birth kicks requires the knowledge of the position and velocity of the X-ray binary in the Galaxy. This information makes it possible to integrate the trajectory of the binary backwards in the Galactic potential until it intersects the Galactic plane, where the binary is assumed to have been born. This assumption is consistent with both the observed birth locations of massive stars in a thin disc in the Galactic plane (e.g. Urquhart et al. 2014), and more specifically the finding that metal abundances in the secondary in black hole X-ray binaries is consistent with a thin-disc origin (e.g. González Hernández et al. 2008). Binary evolution can then be modelled in order to include the contribution of Blaauw kicks (Blaauw 1961) from mass-loss during the supernova and constrain the range of supernova-induced natal kicks required to preserve the binary with current orbital parameters.

This approach has been applied to several black hole X-ray binaries. Willems et al. (2005) find that a birth kick of a few tens of km s^{-1} (and no more than around 200 km s^{-1}) was given in the supernova that formed GRO J1655−40. Wong et al. (2012) find that Cygnus X-1 likely received a non-zero birth kick (cf. Nelemans, Tauris & van den Heuvel 1999), but with a velocity no larger than around 80 km s^{-1}. Wong et al. (2014) find that the birth kick of IC10 X-1 was smaller than 130 km s^{-1}. Fragos et al. (2009) find the largest black hole birth kick inferred from systems with both position and velocity measurements in XTE J1118+480, which they conclude must be between 80 and 310 km s^{-1}.

However, the number of black hole X-ray binaries with accurate position and velocity measurements is very limited (Miller-Jones 2014). This motivated Repetto et al. (2012) and Repetto & Nelemans (2015) to extend the approach above to the analysis of black hole low-mass X-ray binaries with a position measurement but without a 3D velocity measurement. They model binary evolution to argue that, without natal supernova kicks, such binaries cannot achieve overall initial velocities in excess of ∼50 km s^{-1} – the maximum velocity that could be attributed to the Blaauw kick from mass-loss during a supernova, as larger mass ejection would disrupt the binary.

Repetto & Nelemans (2015) estimate the minimum initial velocity of the binaries from their current observed position in Galactic spherical coordinates (ρ, z) as follows. They consider a binary that starts out on the Galactic plane and moves directly out of the Galactic plane, with an initial velocity pointed perpendicular to the Galactic plane, until it reaches the present observed location. They use the difference in the Galactic potential at the observed spherical

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coordinate position (ρ, z) and assumed starting position $(\rho, z = 0)$ to infer the minimal initial velocity of the binary from the conservation of energy (see section 3.3 of Repetto & Nelemans 2015):

$$v_{\mathrm{initial}} = \sqrt{2[\Phi(\rho, z) - \Phi(\rho, 0)]}. \quad (1)$$

Repetto & Nelemans (2015) analyse seven black hole low-mass X-ray binaries. They find that several of them must have had initial velocities in excess of what is possible without natal kicks, most notably H1705−250 (for which they estimate an initial binary velocity between 360 and 440 km s^{-1}) and, to a lesser extent, XTE J1118+480 (for which they estimate an initial binary velocity of $\gtrsim$ 70 km s^{-1})[1], with lower initial velocities for other systems. This provides evidence for significant natal kicks.

We follow up on this work below, particularly focusing on the ultrafast kick required for H1705−250. We re-evaluate the required initial velocities, and consider the contribution of uncertainties in the observations and modelling, in order to critically evaluate the claimed evidence for black hole kicks of order ∼400 km s^{-1}. We conclude that existing observations do not require the existence of black hole birth kicks above the minimum value of 80 km s^{-1} inferred by Fragos et al. (2009) from the analysis of XTE J1118+480 based on 3D velocity measurements.

INITIAL VELOCITY ESTIMATION

Equation (1) converts the extra energy necessary to get the binary up to the observed height above the Galactic plane into a constraint on the initial kinetic energy, and, hence, the natal velocity of the binary following the black hole supernova. For example, equation (1) evaluated using the Galactic potential described by model 2 of Irrgang et al. (2013, see below) indicates that the potential difference between the claimed location of H1705−250 (ρ = 0.5 kpc, z = 1.35 kpc) and its projection on to the Galactic plane (ρ = 0.5 kpc, z = 0 kpc), corresponds to a requirement of $v_{\mathrm{initial}} \geq 370$ km s^{-1} on the initial velocity.

However, the potential difference between the observed location and its projection on to the Galactic plane is not an accurate indication of the necessary initial velocity. The gradient of the potential has a significant component in the direction perpendicular to the Galactic plane, so a displacement in this direction is energetically unfavourable and requires a high initial velocity. Moreover, a purely vertical displacement does not correspond to a physical solution; a velocity that is initially perpendicular to the Galactic plane would not, in general, yield a purely vertical displacement in the Galactic potential. In fact, if the potential difference between initial and observed location were sufficient to determine the necessary initial velocity, then starting the binary at a location with a potential similar to that at its present location would yield very low requirements on the initial velocity. For example, starting the binary (ρ = 3.5 kpc, z = 0 kpc) would yield a required initial velocity of only 10 km s^{-1}.

On the other hand, motion along equipotential lines is not, in general, possible. An additional complication is that the Galactic disc, in which the binary is assumed to be born (see below), is rotating with a large velocity roughly independent of radius, ∼225 km s^{-1}; therefore, we must consider the initial velocity of the binary relative to the velocity of the disc. In effect, the need for conservation of angular momentum in the $\hat{z}$ direction means that in order to find a binary such as H1705−250 close to a position directly above the Galactic centre, at $\rho \to 0$, it must first receive a kick roughly cancelling its azimuthal velocity if it was born in the disc at larger cylindrical radii, thereby setting the $\hat{z}$ component of its angular momentum to zero. This kick should be accompanied with a smaller component necessary to move to high Galactic latitudes, therefore we expect that a minimal initial velocity just above ∼225 km s^{-1} would be required.

[1] XTE J1118+480 has a measured 3D velocity (Mirabel et al. 2001), not used in the analysis of Repetto & Nelemans (2015).

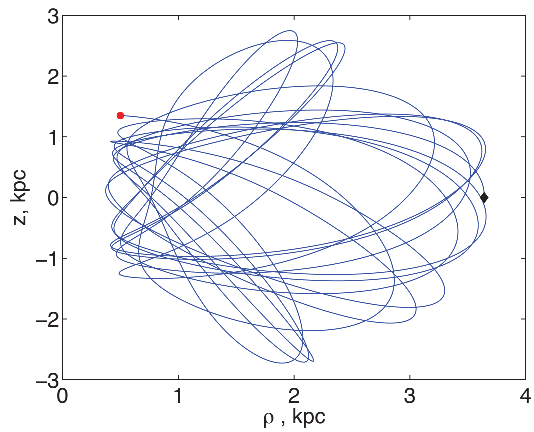

Figure 1. The trajectory of a binary in the Galactic potential, integrated backwards from the claimed observed position of H1705−250 (ρ = 0.5 kpc, z = 1.35 kpc), indicated with a red circle. Motion in the azimuthal ϕ direction is not shown. At the Galactic plane crossing indicated by the black diamond, the total velocity relative to the Keplerian disc is 230 km s^{-1}.

This is what we find when we determine the minimum initial velocity by integrating the binary's motion backwards in the Galactic potential from its current observed position, noting the binary's velocity at crossings of the Galactic plane, z = 0, under the assumption that the binary was born in the plane of the disc. Performing this integration requires specifying the unknown velocities at the observed position of the binary. A possible trajectory passing through (ρ = 0.5 kpc, z = 1.35 kpc) is illustrated in Fig. 1. The velocity at the Galactic plane crossing is then compared to the Keplerian orbital velocity of the disc in which the binary is born. Minimizing the initial velocity relative to the disc for this position via a grid over the 3D velocity at the observed location yields an initial velocity of only $v_{\mathrm{initial}} \approx 230$ km s^{-1}, only 60 per cent of the required $v_{\mathrm{initial}} \geq$ 370 km s^{-1} estimated from equation (1). The binary navigates this trajectory in well under 1 Gyr, consistent with the possible age of a low-mass X-ray binary [the donor star in H1705−25 has a mass of $\lesssim 1\,\mathrm{M}_{\odot}$ (Martin et al. 1995), so could have an age of $\gtrsim$ 10 Gyr].

UNCERTAINTY IN THE OBSERVED POSITION

The distance to low-mass X-ray binaries is difficult to measure precisely. Remillard et al. (1996) provide distance estimates of 6–10 kpc for H1705−250, which are used by Repetto & Nelemans (2015) to provide error bars on the initial binary velocity (these error bars do not correctly account for the full range of uncertainty; Repetto, private communication). Meanwhile, Martin et al. (1995) claim distance estimates of 2–8.4 kpc. If the lower boundary of 2 kpc is taken from the Martin et al. (1995) estimate, the binary H1705−250 could be located only ∼0.3 kpc away from the Galactic plane. This is consistent with the scaleheight of the thick disc naturally arising from dynamical relaxation processes.

Of course, energy equipartition implies that more massive objects, such as black hole binaries, will relax to a smaller scaleheight. The binary H1705−250 is about ∼10–15 times heavier than the typical star, so its expected scaleheight from relaxation at a radial Galactic distance of ∼6 kpc would be ∼80 pc. While an observed position at ($\rho = 6$ kpc, $z = 0.3$ kpc) would still be marginally inconsistent with dynamical relaxation alone, a trajectory evolution like that described in the previous section indicates that an initial velocity of $\lesssim 30$ km s^{-1} relative to the Galactic disc is sufficient to bring the binary to this observed position from a birth location in the thin disc. This velocity is consistent with the Blaauw kick from mass-loss alone, obviating the need for a black hole birth kick.

INITIAL LOCATION OF THE BINARY

The scaleheight of the Galactic disc is ∼0.3 kpc. Since the Galactic potential has a minimum in the Galactic plane among all points at a fixed cylindrical coordinate ρ, it requires the most kinetic energy for the binary to rise from an initial location in the Galactic plane. Therefore, assuming that the binary is initially located away from the Galactic plane reduces the initial velocity required to reach an observed height away from the Galactic plane.

However, massive stars which can give rise to a black hole in a low-mass X-ray binary appear to be born in a much thinner disc of only 20–30 pc (e.g. Urquhart et al. 2014). Variations in initial position by only a few tens of parsecs do not lead to an appreciable change in the required initial velocity. On the other hand, a somewhat larger scaleheight – and, critically, a lower azimuthal velocity – may be possible in the bulge itself; if H1705−250 is really located above the bulge, this could reduce the necessary orbital velocity by a further ∼10–20 per cent, depending on assumptions.[2]

UNCERTAINTY IN THE GALACTIC POTENTIAL

The Galactic mass density and potential (Paczynski 1990) are not known perfectly. Most of the uncertainty is confined to the halo, despite improved measurements which rely on masers and hypervelocity stars (e.g. Irrgang et al. 2013). Therefore, we do not expect the uncertainty in the Galactic potential to significantly impact our findings. We use the three models presented in Irrgang et al. (2013), all of which fit the observed data well, to estimate that uncertainty in the potential models should contribute at most at the ∼10–20 per cent level to the inferred binary velocities.

CONCLUSION

We have discussed several sources of uncertainty in the inference on black hole birth velocities from the observed positions of black hole low-mass X-ray binaries. Other complications include the possibility that the initial kick comes from a dynamical interaction (and subsequent ejection of the binary from its host cluster) rather than a supernova-induced kick (Repetto et al. 2012). We also note that a small fraction of binaries could get significant kicks of many tens to a few hundred km s^{-1} from strong three-body interactions in the Galactic disc, with interlopers approaching to within the semimajor axis of the binary. However, we estimate that this mechanism would apply to $\lesssim 0.1$ per cent of all binaries, and so is an unlikely explanation for the observed systems.

When accurate position and velocity measurements of low-mass X-ray binaries are available (Miller-Jones 2014), the binary's trajectory can be integrated backward in the Galactic potential to deduce the velocity of the binary at birth, assuming that it was born in the Galactic plane. This calculation for XTE J1118+480, which yields a minimal birth kick of 80 km s^{-1} (Fragos et al. 2009), provides a firm lower bound on the maximum black hole kick.

In the absence of such a measurement, statistical inference is, in principle, possible. For example, the small (few tens of km s^{-1} according to Remillard et al. 1996) line-of-sight velocity of H1705−250 might suggest that a high total current velocity is less likely. The small number of observations and the uncertain selection effects make reliance on statistical arguments precarious. A statistical analysis of all observed black hole X-ray binaries with position measurements was undertaken by Repetto et al. (2012), who considered a sample of 16 black hole X-ray binaries to argue that their distribution was consistent with black holes receiving similar birth kicks to neutron stars. However, this conclusion again largely relied on two systems requiring particularly strong kicks, most notably H1705−250.

We found that the potential difference between the current observed position of a low-mass X-ray binary and the projection of that position on to the Galactic plane is not an accurate conservative estimate of the minimal initial velocity of the binary. Moreover, inference on initial velocities is significantly compromised by the uncertainty in observed positions of some low-mass X-ray binaries.[3] We conclude that existing observations of only the spatial locations of low-mass X-ray binaries are not sufficient to confidently deduce the existence of strong black hole supernova kicks of order 400 km s^{-1}, as claimed by Repetto & Nelemans (2015). Upcoming high-precision position and velocity observations, such as those enabled by *Gaia*, should improve our ability to infer black hole birth kicks.

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[2] Under the most optimistic assumptions, H1705−250 may have been born near its present location in (ρ, z), making a black hole birth kick unnecessary; this appears relatively unlikely given the present-day massive-star formation, but could be consistent with an older bulge population.

[3] For a further discussion of the impact of position uncertainty, see Belczynski et al. (2015).

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