Radbound Repository

Radboud University Nijmegen

PDF hosted at the Radboud Repository of the Radboud University Nijmegen

The version of the following full text has not yet been defined or was untraceable and may differ from the publisher's version.

For additional information about this publication click this link.
http://hdl.handle.net/2066/36697

Please be advised that this information was generated on 2019-05-25 and may be subject to change.

arXiv:astro-ph/0410381v1 15 Oct 2004

# What can we learn about black-hole formation from black-hole X-ray binaries?

Gijs Nelemans

*Institute of Astronomy, University of Cambridge, UK*
*and*
*Department of Astrophysics, Radboud University Nijmegen, NL*

**Abstract.** I discuss the effect of the formation of a black hole on a (close) binary and show some of the current constraints that the observed properties of black hole X-ray binaries put on the formation of black holes. In particular I discuss the evidence for and against asymmetric kicks imparted on the black hole at formation and find contradicting answers, as there seems to be evidence for kick for individual systems and from the Galactic $z$-distribution of black hole X-ray binaries, but not from their line-of-sight velocities.

## 1. Introduction: What do we want to learn?

We can study black holes only when they interact with other stars or material. For stellar mass black holes the only way to study them is when they reside in binaries and in particular when they accrete material from their (low-mass) companion stars in black-hole X-ray binaries (BHXBs). These binaries can be used to get information about the formation of black holes, of course with the caveat that strictly speaking they only constrain the formation of black holes *in binaries*. The formation of black holes from massive stars is poorly understood (e.g. Fryer & Kalogera 2001). The questions we would like to answer are:
i) Which stars form black holes? (What is the minimum mass of a main sequence star that forms a black hole, and does this depend on binarity/rotation etc?)
ii) Do black holes form in either direct collapse, a supernova explosion or either?
iii) How much mass is lost during the black hole formation? (which is important for the chemical enrichment of the interstellar medium)
iv) Is the black hole formation symmetric or asymmetric?
Here I will discuss only the last three questions.

## 2. Effects of the formation of a black hole on the binary

I discuss four ways in which the formation of a black hole in a binary can influence the companion and the binary as a whole (see Fig. 1)

**Pollution companion**

If the formation of the black hole is accompanied by explosive mass loss, part of this can be captured by the companion and, if enough is retained in layers near the surface, can cause the companion to show peculiar abundances (Israelian et al. 1999; Podsiadlowski et al. 2002; González Hernández et al. 2004)

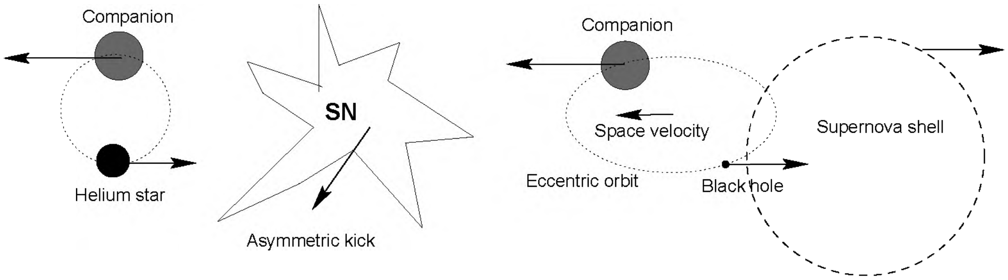


Figure 1. Effects of black hole formation on the binary (see text).

**Space velocity**
If mass is lost quickly it will carry linear momentum, causing the centre of mass of the remaining binary to move in the opposite direction. Furthermore, if the formation of the black hole is asymmetric a kick will be imparted on the black hole, which also causes a space velocity ($v_{\rm sys}$) of the binary.
**Eccentric orbit**
Both explosive mass loss and a kick induce an eccentricity ($e$)in the binary.
**Angle between $v_{\rm sys}$ and orbit**
If the kick on the black hole is directed out of the orbital plane, the direction of the resulting space velocity of the binary will make an angle with the orbital plane. Symmetric mass loss always results in a space velocity directed in the plane of the orbit.

### 2.1. Symmetric mass loss

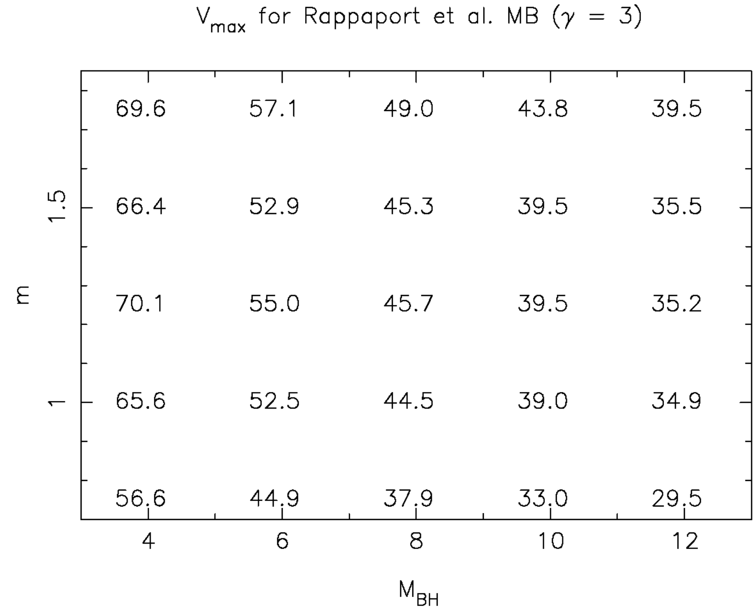
In the case of symmetric mass loss, so in absence of a kick, there is a unique relation betweem $v_{\rm sys}$ and $e$, as both are uniquely determined by the amount of mass loss[1]. If after the formation of the black hole the orbit of the binary is small enough that the companion will start mass transfer to the black hole (and thus we can observe the binary), the eccentric orbit quickly circularizes (e.g. Kalogera 1999), yielding the following relation between the space velocity of the binary and the observable parameters (cf. Nelemans et al. 1999)

$$v_{\rm sys} = 213\left(\frac{\Delta M}{M_\odot}\right)\left(\frac{m}{M_\odot}\right)\left(\frac{P_{\rm re-circ}}{\rm day}\right)^{-\frac{1}{3}}\left(\frac{M_{\rm BH}+m}{M_\odot}\right)^{-\frac{5}{3}} {\rm km\ s^{-1}}$$

Based on the properties of binaries that can reach this phase of mass transfer, a maximum space velocity can be derived for short period black hole binaries with low-mass companions (LMBBs), see Nelemans et al. (2004). The maximum velocities as a function of the system parameters *at the onset of mass transfer* (which generally is very different from the current parameters) is shown in Fig. 2.

---

[1] Be X-ray binaries, in which a neutron star accretes (periodically) from a Be star do not follow this relation, which is direct evidence that neutron stars do receive kicks at formation (van den Heuvel et al. 2000). Interestingly, there are no black-hole Be-X-ray binaries...



| | 4 | 6 | 8 | 10 | 12 |
|---|---|---|---|---|---|
| | 69.6 | 57.1 | 49.0 | 43.8 | 39.5 |
| 1.5 | 66.4 | 52.9 | 45.3 | 39.5 | 35.5 |
| | 70.1 | 55.0 | 45.7 | 39.5 | 35.2 |
| 1 | 65.6 | 52.5 | 44.5 | 39.0 | 34.9 |
| | 56.6 | 44.9 | 37.9 | 33.0 | 29.5 |

Figure 2. Maximum space velocities of LMBBs as function of their masses at the onset of mass transfer. From Nelemans et al. (2004)

## 3. Galactic $z$-distribution

For most systems it is not possible to determine the space velocity and the system parameters, let alone infer what they were at the onset of mass transfer. However, White & van Paradijs (1996) noticed that the average $z$-height of BHXBs was about half that of neutron star X-ray binaries (NSXBs) suggesting a lower average velocity of the BHXBs. They therefore concluded that there was no evidence for asymmetric kicks imparted on black holes, in contrast with neutron stars.

We recently repeated this analysis, using new distances and newly discovered systems and found that the current situation is that there is no difference anymore $z_{\mathrm{rms,BH}} = z_{\mathrm{rms,NS}} \approx 1$ kpc (Jonker & Nelemans 2004, see Fig. 3). This in principle suggests that black holes do get kicks at birth, but there are a number of selections effects that complicate the comparison. Firstly, the black hole systems are relatively close by (as one needs to see the companion in order to measure its radial velocity and thus determine the mass of the compact object). This means the BHXBs are farther from the Galactic centre and thus move in a lower potential. Secondly, there are differences in formation between NSXBs and BHXBs, that can give rise to quite different velocities, even if the mass loss was symmetric.

As a simple experiment, I plot in Fig. 3 (top right) the $R - z$ distribution of the subset of systems that are LMBBs (solid circles), and in the bottom two panels their expected distributions in case of symmetric mass loss, i.e. with velocities as in Fig. 2 (bottom left panel) and in case they receive a kick of 110 km/s (bottom right panel). Except for the system close to the Galactic centre, all seem to be consistent with symmetric mass loss.

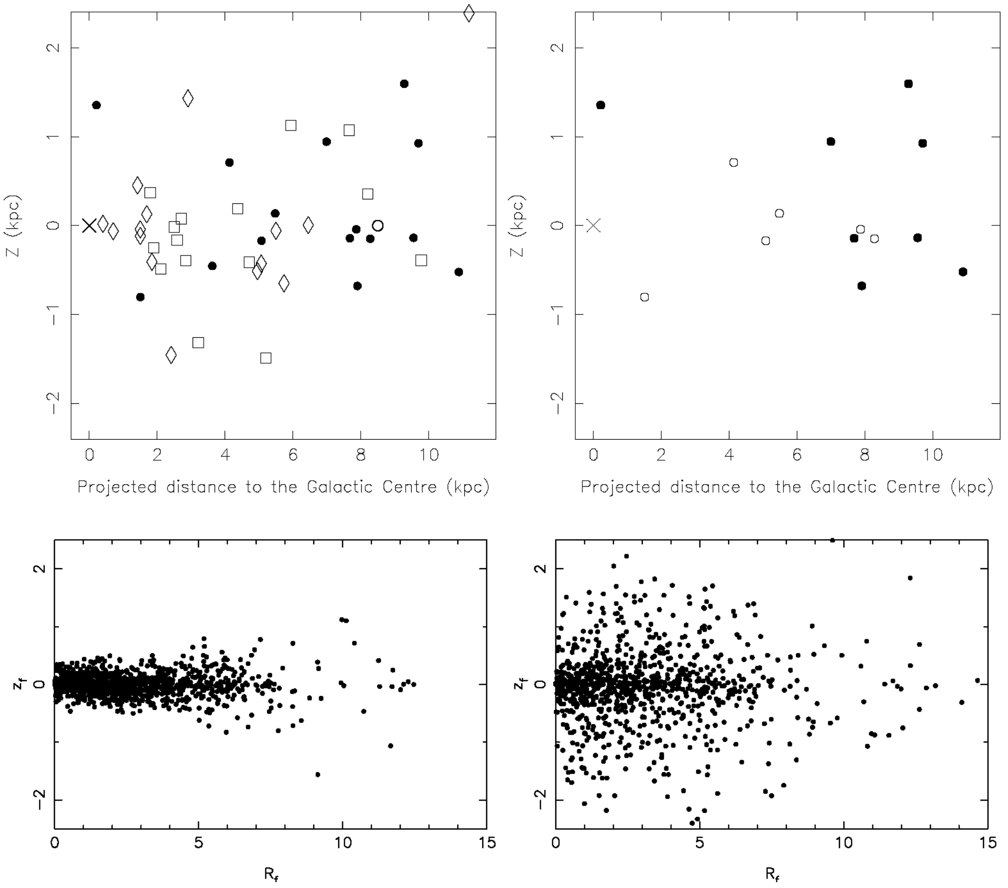


Figure 3. Top left: distances from the Galactic centre and the Galactic plane of BHXBs (solid circles) and NSXBs (open symbols), from Jonker & Nelemans (2004). Top right: only LMBBs. Bottom: comparison between expected $R - z$ distribution of LMBBs with velocities according to Fig. 2 (left) and with kick of 110 km/s (right).

## 4. Observations of 3D velocities

For most systems we know their period, system radial velocity, their masses and the binary inclination. In addition sometimes a radio or optical proper motion is know (Mirabel et al. 2001, 2002; Mirabel & Rodrigues 2003). In principle this can be used to get a 3D velocity by combining the proper motion with the (generally very uncertain) distance to get the transverse velocity and the radial velocity plus local standard of rest (which again depends on the distance) to get the peculiar radial velocity. In order to constrain the black hole formation one also needs to estimate the age of the system, in order to trace the orbit back in the Galactic potential to find the system parameters after the formation of the black hole. A number of systems have recently been analyzed in this way

**XTE J1118+480**

Gualandris et al. (2004) studied the formation of XTE J1118+480 and traced back its orbit. They show that the memory of its initial position is quickly lost. However, Fig. 4 shows that even after 5 Gyr, the peculiar velocity of the

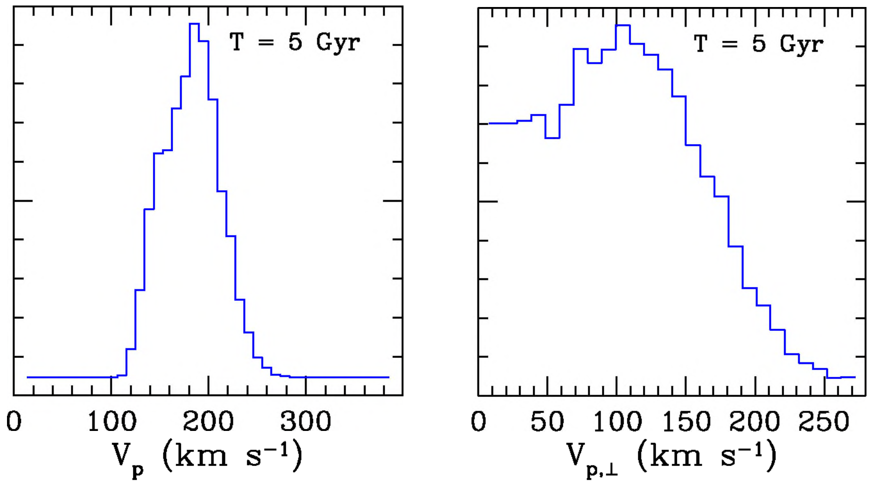


Figure 4. Peculiar velocity of XTE J1118+480 after the formation of the black hole, and its component perpendicular to the orbital plan based on the current system parameters (from Gualandris et al. 2004).

binary after the formation of the black hole is still quite well constrained and is significantly above the maximum velocity that can be reached with symmetric mass loss for any of the system parameters leading to LMBBs (cf. Fig. 2). Also the component of the peculiar velocity perpendicular to the orbital plane is likely non-zero (Fig. 4). Both findings suggest the black hole received a kick.

**GRO J1655-40**

Kalogera & Willems (in prep.) performed a similar analysis of the intermediate mass X-ray binary GRO J1655-40 and found solutions without kick, but only when allowing the binary to get circularized very quickly after the formation of the black hole (for details see Kalogera & Willems, in prep.).

## 5. Radial velocities

Finally, if kicks of the order of 100 km/s or higher indeed are commonly imparted on black holes, one would expect the current peculiar line-of-sight velocities (i.e. compared to their local standard of rest) to be at least several tens of km/s. In Table 1 I show the line-of-sight velocities of BHXBs, together with rough values of the system parameters (see e.g. Orosz 2003; Charles & Coe 2004; McClintock & Remillard 2004, for recent reviews). These velocities are remarkably low and to me suggest that certainly not all BHXBs received (large) kicks.

## 6. Conclusions

By analyzing the properties of BHXBs a number of things can be learned about the formation of black holes. The first is that some BHs are formed in a supernova, with (quite some) mass loss. Secondly, the $z$-distribution BHXBs and NSXBs are similar, which naively suggests kicks are imparted on black holes as

| Name | $P$ (hr) | $\mathrm{M_{BH}}$ | $\mathrm{M_{comp}}$ | $z$ pc | $v_{\mathrm{sys,los}}$ km/s |
|---|---|---|---|---|---|
| XTE J1118+480 | 4.08 | 7 | 0.25 | 1600 | −7.2 |
| GRO J0422+32 | 5.09 | 4 | 0.3 | −525 | 24.2 |
| GS 1009-45 | 6.84 | 5 | 0.7 | 925 | 10.8 |
| A0620-00 | 7.75 | 11 | 0.6 | −125 | −9.5 |
| GS 2000+25 | 8.27 | 8 | 0.5 | −150 | −3.5 |
| XTE J1859+226 | 8.61 | 8 |  | 950 |  |
| GS 1124-683 | 10.4 | 7 | 0.8 | −675 | 36.3 |
| H1705-250 | 12.5 | 7 | 0.3 | 1350 | 166.7 |
| 4U 1543-47 | 26.8 | 9 | 2.5 | 700 | 17.7 |
| XTE J1550-564 | 37 | 10 | <1 | −175 | 12.9 |
| GX339-4 | 42.1 | >2 |  | −450 |  |
| GRO J1655-40 | 62.9 | 6 | 2.8 | 125 | −116.8 |
| SAX J1819.3-2525 | 67.6 | 7 | 3.1 | −800 | −2.2 |
| GS 2023+338 | 155.3 | 12 | 0.6 | −150 | −6.2 |
| GRS 1915+105 | 816 | 14 | 1.2 | −50 | −16.6 |
| Cyg X-1 | 134.4 | 8 | 15 | 100 | −12.6 |

Table 1. Rough system parameters and observed velocities of BHXBs. Top rows are LMBBs, middle have higher companion masses and/or longer periods, while Cyg X-2 has a high-mass companion.

well as on neutron stars but this needs detailed investigation. The measurement of 3D velocities opens the possibility to study BH formation in *detail* and the first results indicate that black holes were formed in a supernova and received an asymmetric kick. However, line-of-sight velocities of BHXBs are generally low, suggesting not all black holes receive a kick.

## References

Charles P., Coe M., 2004, in Lewin W., van der Klis M., eds., Compact Stellar X-Ray Sources, CUP

Fryer C.L., Kalogera V., 2001, ApJ, 554, 548

González Hernández J.I., Rebolo R., Israelian G., et al., 2004, ApJ, 609, 988

Gualandris A., Colpi M., Zwart S.P., Possenti A., 2004, ApJ, in press, astro-ph/0407502

Israelian G., Rebolo R., Basri G., Casares J., Martín E.L., 1999, Nat, 401, 142

Jonker P.G., Nelemans G., 2004, MNRAS, in press

Kalogera V., 1999, ApJ, 521, 723

McClintock J., Remillard R.A., 2004, in Lewin W., van der Klis M., eds., Compact Stellar X-Ray Sources, CUP

Mirabel I.F., Rodrigues I., 2003, Science, 300, 1119

Mirabel I.F., et al., 2001, Nature, 413, 139

Mirabel I.F., Mignani R., Rodrigues I., et al., 2002, A&A, 395, 595

Nelemans G., Tauris T.M., van den Heuvel E.P.J., 1999, A&A, 352, L87

Nelemans G., van den Heuvel E.P.J., Bhattacharya D., 2004, in van den Heuvel , Kaper, Rol, Wijers, eds., *ASP conf. ser.* 308, ASP, San Francisco, p. 155

Orosz J.A., 2003, in IAU Symposium 212, p. 365

Podsiadlowski P., Nomoto K., Maeda K., et al., 2002, ApJ, 567, 491

van den Heuvel E.P.J., Portegies Zwart S.F., Bhattacharya D., Kaper L., 2000, A&A, 364, 563

White N.E., van Paradijs J., 1996, ApJ, 473, L25