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# The distances to Galactic low-mass X-ray binaries: consequences for black hole luminosities and kicks

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**ABSTRACT**

We investigated the reported distances of Galactic black hole (BH) and neutron star low-mass X-ray binaries (LMXBs). Comparing the distances derived for the neutron stars Cyg X–2 and XTE J2123–058 using the observed Eddington limited photospheric radius expansion bursts with the distances derived using the observed radius and effective temperature of the companion star, we find that the latter are smaller by approximately a factor of 1.5–2. The latter method is often employed to determine the distance to BH LMXBs. A possible explanation for this discrepancy is that the stellar absorption lines in fast rotating companion stars are different from those in the slowly rotating template stars as was found before for early-type stars. This could lead to a systematic mis-classification of the spectral type of the companion star, which in turn would yield a systematic error in the distance. Further, we derive a distance of $4.0^{+2.0}_{-1.2}$ kpc for V404 Cyg, using parameters available in the literature. The interstellar extinction seems to have been overestimated for XTE J1550–564 and possibly for two other BH sources (H 1705–25 and GS 2000+25) as well. As a result of this, the distance to XTE J1550–564 may have been underestimated by as much as a factor three. We find that, using the new distances for XTE J1550–564 and V404 Cyg, the maximum outburst luminosity for at least five, but perhaps even seven, of the 15 BH soft X-ray transients exceed the Eddington luminosity for a 10-$M_{\odot}$ BH – showing that these systems would be classified as ultra-luminous X-ray sources had we observed them in other Galaxies. This renders support for the idea that many ultra-luminous X-ray sources are stellar-mass rather than intermediate-mass BHs. We find that the rms-value of the distance to the Galactic plane for BHs is consistent with that of neutron star LMXBs. This suggests that BHs could also receive a kick-velocity during their formation, although this has to be investigated in more detail. We find that the Galactic neutron star and BH *l*- and *b*-distributions are consistent with being the same. The neutron star and BH distribution is asymmetric in *l* with an excess of systems between $-30^\circ < l < 0^\circ$ over systems with $0^\circ < l < 30^\circ$.

**Key words:** black hole physics – binaries: close – stars: neutron – X-rays: binaries.

## 1 INTRODUCTION

Low-mass X-ray binaries (LMXBs) are binary systems in which a compact object – either a neutron star or a black hole – accretes matter from a low-mass companion star. Many of these systems are found to be transient, so-called soft X-ray transients (SXTs). Several hundreds have been found in our own Galaxy (see Liu, van Paradijs & van den Heuvel 2001) and many of the X-ray point sources in other Galaxies are likely to be LMXBs as well (Fabbiano 1995). However, some of these X-ray sources in other Galaxies have luminosities in excess of the Eddington limits of both neutron star and ten solar-mass black hole (BH) LMXBs (cf. Fabbiano 1989). These systems are thought to contain intermediate-mass BHs (Colbert & Mushotzky 1999) or stellar-mass BHs where the emission is anisotropic (King et al. 2001) or indeed super-Eddington (Begelman 2002).

Determining the distance to LMXBs is important for, for example, determining the peak or quiescent luminosity and determining if the compact object in LMXBs receives an (asymmetric) kick velocity at birth or not. Typically, a large distance to the Galactic plane implies the occurrence of a kick, unless the systems at large *z*-distances were formed in the halo.

In this Paper we collect distance estimates from the literature and discuss possible systematic trends related to the used distance

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estimation methods (Section 2). In Section 3 we discuss the implications for the Galactic distribution of (BH) LMXBs and the Galactic population of ultra-luminous X-ray sources (ULXs).

## 2 DISTANCES TO LMXBS

### 2.1 Black hole distances

For most BH SXTs it is not feasible to obtain a trigonometric parallax measurement. Instead, the distance is generally determined by comparing the derived absolute $V$-band magnitude with the (dereddened) apparent magnitude, taking into account a possible contribution from residual accretion (the distance derived using this method is sometimes called a photometric parallax). A first guess of the distance can be obtained by assuming that the absolute magnitude is that of a main sequence star of the observed spectral type, after determining the best-fit spectral type from the data, e.g. via the optimal subtraction technique (see Marsh, Robinson & Wood 1994 for a description of this technique). We call this method $A$. However, ideally the radius, spectral type and luminosity class are determined directly from the data. We denote this method $B$. The observations give the orbital period $P$, the radial velocity of the donor star $K_2$ and, by comparing the donor star spectrum with templates that are Doppler broadened, the rotational velocity of the donor ($v \sin i$). The inclination can be estimated from modelling the ellipsoidal variations in the light curve. From Kepler's third law and the assumptions that the donor fills its Roche lobe and is in co-rotation with the orbit, all system parameters can be determined as follows. The mass function and inclination relate the masses of the two components, while a combination of Kepler's law and the equation for the volume of the Roche-lobe gives $(v \sin i)/K_2 = 0.46[(1+q)^2 q]^{1/3}$ (see, for example, Wade & Horne 1988; $q$ is defined here as the mass of the secondary divided by the mass of the primary), giving an independent estimate of $q$ and thus providing the system parameters. The radius can be estimated from $v \sin i = (2\pi R \sin i)/P$. Alternatively, if $v \sin i$ or the inclination are not known, a quite good estimate of the radius can be obtained using the fact that the mean density of a Roche-lobe filling star depends only on the orbital period (Paczyński 1971). The radius of the donor star can be estimated via $R_2 \equiv R_{\rm Roche\,Lobe} = 0.234\, P_{\rm orb}^{2/3}\, M_2^{1/3}$ (where $P_{\rm orb}$ is in hours, $M_2$ in solar masses, and $R_2$ in units of solar radii).

In order to estimate the absolute magnitude, one either uses the surface brightness for the observed spectral type or colour, as given, for example, by Barnes & Evans (1976) and Popper (1980) or uses the determined radius and effective temperature, together with an appropriate bolometric correction. Alternatively, one uses the fact that for given surface brightness the observed flux scales with the angular diameter ($2R/d$), which together with the radius gives the distance. However, there are (small) differences in surface brightness for different luminosity classes of the same spectral type.

In the cases of GRO J1655–40 and GRS 1915+105, Hjellming & Rupen (1995) and Fender et al. (1999), respectively, determined limits on the distance from the observed proper motion for receding and approaching blobs, assuming the jet ejections are intrinsically symmetric and noting that the maximum velocity of the ejections is the speed of light. We list this method as method $C$. The distance can also be estimated using the interstellar absorption properties of the source. There are different ways to do this. For several interstellar absorption lines and diffuse interstellar bands, the observed equivalent width correlates with colour excess (cf. Herbig 1995). The colour excess can be converted in a distance estimate (e.g. using the calibration of Beals & Oke 1953). It is also possible to compare the observed extinction with that of (OB) stars in the observed field for which the distance is known or can be derived (see, for example, van Paradijs et al. 1986). The distance can also be constrained by using high-resolution spectroscopic observations of the interstellar absorption lines to trace individual gas clouds and their velocities. Assuming that the apparent velocities of the different gas clouds are projected Galactic rotation velocities, a lower limit on the distance of the object can be found (cf. Hynes et al. 2004). We refer to distances derived using the interstellar absorption properties as method $D$. Finally, we note here that various other methods for estimating the distance to BH SXTs have been proposed and used. We do not discuss these in detail but we merely mention some of them: Hynes et al. (2002) used the normalization of a model describing the accretion disc flux, Maccarone (2003) used the transition between the high/soft and low/hard X-ray states, and Jonker et al. (2004) proposed using the normalization of the radio–X-ray correlation in the low/hard state as a distance indicator.

In Table 1 we show the distance estimates in the literature based on method $A$, $B$, $C$ and $D$ for sources for which the best estimate of the mass of the compact object is above the upper limit of the neutron star mass of $\sim$3 M$_\odot$ (Rhoades & Ruffini 1974; Kalogera & Baym 1996). Below, we briefly discuss the sources listed in Table 1 for which disparate values for the distance exist in the recent literature.

(i) **1A 0620–00**. Marsh et al. (1994) report a distance of 485 pc for 1A 0620–00 whereas most other workers report a distance close to 1.2 kpc (for references, see Table 1). This is due to a numerical error of a factor of two in the result of Marsh et al. (1994; also Marsh, private communication). Hence, the distance Marsh et al. (1994) find is $912/\sin i$ pc. The correct equation for the stellar distance is

$$d = \frac{2R}{\theta} = 2\frac{0.46\, q^{1/3}\,(1+q)^{2/3}\, K_2\, P}{2\pi\theta \sin i} = 2\frac{P(v \sin i)}{2\pi\theta \sin i}, \qquad (1)$$

where $\theta$ is the stellar diameter.

(ii) **GRO J0422+32**. Webb et al. (2000) report a distance of 1.39 $\pm$ 0.15 kpc. However, besides the fact the best-fit spectral type they derived for the companion star was M4–5, later than that derived by, for example, Harlaftis et al. (1999) and Gelino & Harrison (2003) who found a M1–2 spectral type, they used method $A$ which is known to underestimate the radius of the companion star. In the distance determination Webb et al. (2000) use the absolute magnitude of a star with radius $R = 0.24$ R$_\odot$ (from Kirkpatrick et al. 1993 via the bolometric magnitude and the effective temperature), whereas the radius one would derive using the equation in the first paragraph of Section 2.1 would give $R = 0.53$ R$_\odot$.

For that reason, we prefer the distance derived using method $B$ by Harlaftis et al. (1999) and Gelino & Harrison (2003). However, Harlaftis et al. (1999) used the same erroneous equation as Marsh et al. (1994). If we correct for this error, Harlaftis et al. (1999) found a distance of $5.0 \pm 1.6$ kpc. Interestingly, Gelino & Harrison (2003) found a distance of $2.5 \pm 0.3$ kpc even though they also used method $B$. This is due to the fact that Harlaftis et al. (1999) use $(V-R)_0 \sim 1$ for an M1–2 star, while both Eaton & Poe (1984) and Cox (2000) give a value for the $(V-R)_0$ colour closer to 1.5 for a M2V star. Taking a $(V-R)_0$ of 1.5 for an M2 as in the relation of Eaton & Poe (1984) would yield a distance close to 2.5 kpc. Indeed, if we take the radius of the secondary and apparent $V$-band magnitude corrected for interstellar extinction and an accretion disc contribution as given by Harlaftis et al. (1999) but use the relation given by Popper (1980) for an M2 star we find a distance of 2.8 kpc. We conclude that the distance to GRO J0422+32 is likely to be 2.5–3.0 kpc.

(iii) **GX 339–4**. In the case of GX 339–4, the distance has been estimated to be $\sim$4 kpc using the equivalent width of the Ca II–K

**Table 1.** BH SXT distance estimates. We indicate whether method *A*, *B*, *C* or *D* has been used to derive the distance (see text). The *z*-values have been rounded to the nearest 25 pc.

| Name | $l$ | $b$ | Spectral type | $P_{orb}$ (hours) | Distance & method (kpc) | $z$ (pc) | References |
|---|---|---|---|---|---|---|---|
| GRO J0422+32 | 165.97 | −11.99 | K9–M2V | 5.09 | 2.5–3.0 (*B*) | −525 to −625 | [1,2] |
| 1A 0620–00 | 209.96 | −6.54 | K4–K5V | 7.75 | 1.2±0.4 (*B*) | −125 | [3,4] |
| GS 1009–45 | 275.88 | 9.35 | K6–M0V | 6.84 | 5.7±0.7 (*B*) | 925 | [5,6] |
| XTE J1118+480 | 157.66 | 62.32 | K5–M1V | 4.08 | 1.8±0.6 (*B*) | 1600 | [7,8] |
| GS 1124–684 | 295.30 | −7.07 | K3–K5V | 10.4 | 5.5±1.0 (*B*) | −675 | [9,10] |
| 4U 1543–47 | 330.92 | 5.43 | A2V | 26.8 | 7.5±0.5 (*B*) | 700 | [11,12] |
| XTE J1550–564 | 325.88 | −1.83 | G8IV–K4III | 37.0 | 5.3±2.3 (*B*) | −175 | [13] |
| GRO J1655–40 | 344.98 | 2.46 | F2–F6IV | 62.9 | 3.2 ± 0.2 (*C*) | 125 | [14,15,16,17] |
| GX 339–4 | 338.94 | −4.33 | ?? | 42.1 | >6 (*D*) | −450 | [18] |
| H 1705–250 | 358.59 | 9.06 | K0–K5V | 12.5 | 8.6±2 (*B*) | 1350 | [4,19,20] |
| SAX J1819.3–2525 | 6.77 | −4.79 | B9III | 67.6 | 9.6 ± 2.4 (*B*) | −800 | [21] |
| XTE J1859+226 | 54.05 | 8.61 | G5–K0V | 9.17 | 6.3 ± 1.7[a] | 950 | [22,23] |
| GRS 1915+105 | 45.37 | −0.22 | K–MIII | 34 (days) | $11^{+1}_{-4}$ (*C*) | −50 | [24,25,26] |
| GS 2000+25 | 63.37 | −3.00 | K3–K6V | 8.27 | 2.7 ± 0.7 (*B*) | −150 | [4,27,28] |
| GS 2023+338 | 73.12 | −2.09 | G8–K1IV | 6.47 (days) | $4.0^{+2.0}_{-1.2}$ (*B*) | −150 | [29,30, this work] |

Note. [a]A method for estimating the distance that has not been discussed here in detail has been used; see [23] for more info.

References: [1] Gelino & Harrison (2003); [2] Harlaftis et al. (1999); [3] Shahbaz, Naylor & Charles (1994a); [4] Barret, McClintock & Grindlay (1996); [5] Barret et al. (2000); [6] Filippenko et al. (1999); [7] McClintock et al. (2001); [8] Wagner et al. (2001); [9] Orosz et al. (1996); [10] Esin, McClintock & Narayan (1997); [11] Orosz et al. (1998); [12] Orosz et al. (2002b); [13] Orosz et al. (2002a); [14] Shahbaz et al. (1999); [15] Orosz & Bailyn (1997); [16] Tingay et al. (1995); [17] Hjellming & Rupen (1995); [18] Hynes et al. (2004); [19] Remillard et al. (1996); [20] Harlaftis et al. (1997); [21] Orosz et al. (2001); [22] Filippenko & Chornock (2001); [23] Hynes et al. (2002); [24] Mirabel & Rodriguez (1994); [25] Fender et al. (1999); [26] Greiner, Cuby & McCaughrean (2001); [27] Harlaftis, Horne & Filippenko (1996); [28] Callanan et al. (1996); [29] Wagner et al. (1992); [30] Shahbaz et al. (1994b).

interstellar line (see, for example, Cowley, Crampton & Hutchings 1987; see Buxton & Vennes 2003 for an overview). Recently, from high-resolution spectroscopic observations resolving the contributions to the interstellar Na D absorption lines, Hynes et al. (2004) found that the distance to GX 339–4 is likely to be more than 6 kpc. They explain that in order for the distance to be ∼4 kpc the line-of-sight towards GX 339–4 must be peculiar. The limit on the distance of GX 339–4 found by Maccarone (2003) indicates that $d >$ 7.6 kpc. In Table 1 we refer to the value derived by Hynes et al. (2004).

(iv) **GS 2023+338, a.k.a. V404 Cyg**. The distance to GS 2023+338 has been reported to be close to 3 kpc (Shahbaz et al. 1994b) or 8 kpc (White & van Paradijs 1996); even a distance of 11 kpc has been mentioned (Casares, Charles & Naylor 1992). King (1993) finds that if the secondary is a stripped giant, GS 2023+338 must have a distance 3.5–5.1 kpc. In an attempt to reconcile the different distances we recalculate the distance using method *B*. We used the relation between the absolute visual magnitude, spectral type and radius of the companion star given by Popper (1980). The spectral type of GS 2023+338 is K0 ± 1 (Casares et al. 1993). We take $R_2 = 6 \pm 1\ R_{\odot}$ for the radius of the companion star after Shahbaz et al. (1994b), who obtained this from modelling the ellipsoidal variations in the *K*-band light curve. From the relation of Popper (1980) we find for the absolute magnitude $1.8 \leqslant M_V \leqslant 3.0$. We further take $m_v = 18.7$ using the observed *V*-band magnitude of 18.42 and the fact that approximately 25 per cent of the light in the *V* band was estimated to come from the accretion disc, although the uncertainty in the accretion disc contribution is large (Casares et al. 1993). Here we took 25 ± 15 per cent for the accretion disc contribution to the light in the *V* band; from this we get for the observed *V*-band magnitude $18.5 \leqslant m_v \leqslant 19.0$. Together with an assumed interstellar absorption of $A_V = 3.3$, this yields a distance of $4.0^{+2.0}_{-1.2}$ kpc. Note that this calculation does not include an uncertainty in the interstellar absorption (see below). Since, as mentioned above, the accretion disc contribution is uncertain we also determined the distance assuming that there is no contribution of the accretion disc to the *K*-band flux (this assumption yields a lower limit to the distance). For a K0V/III star the $(V-K)_0$ colour is 1.96/2.31 (Cox 2000); using the relations between the $(V-K)_0$ colour and the surface brightness as determined by Bailey (1981) we get a lower limit to the distance of 2.7 kpc for a K0III and 3 kpc for a K0V companion star (again we used $R_2 = 6 \pm 1\ R_{\odot}$ after Shahbaz et al. 1994b) and we took $A_K = 0.4$.

## 2.2 Neutron star LMXB distances

In order to compare the BH distances with the neutron star LMXB distances, we list in Table 2 the distances to neutron star LMXBs. We excluded sources in globular clusters since we want to compare the neutron star sample with that of BHs and (so far) BHs have not been found in globular clusters.

Some of the type I X-ray bursts, more specifically those showing evidence for photospheric radius expansion, can be used as a standard candle (van Paradijs 1978). Using the distance of the Galactic Centre and those of globular clusters to estimate the maximum peak luminosity for photospheric radius expansion bursts, van Paradijs (1981) found that the average peak luminosity of photospheric radius expansion bursts is $3 \times 10^{38}$ erg s$^{-1}$. Verbunt, Elson & van Paradijs (1984) used a more extensive sample of X-ray bursters in globular clusters and found an average peak luminosity of $(4.0 \pm 0.9) \times 10^{38}$ erg s$^{-1}$. Recently, Kuulkers et al. (2003) found a neutron star Eddington luminosity of $(3.79 \pm 0.15) \times 10^{38}$ erg s$^{-1}$ for the peak luminosity of radius expansion bursts in globular clusters. This luminosity is consistent with the Eddington luminosity of a 1.4-$M_{\odot}$, neutron star accreting helium-rich material. Kuulkers et al. (2003) also found that a few systems have a lower peak luminosity of

**Table 2.** Properties of the sample of neutron stars used in this paper. Distances derived from type I photospheric radius expansion bursts in both persistent and transient neutron star systems (excluding those in globular clusters) using a neutron star Eddington luminosity of 2.0 or $3.8 \times 10^{38}$ erg s$^{-1}$. The unabsorbed burst peak flux (0.1–100 keV) is indicated by (*i*) after the flux, and the bolometric peak burst flux is indicated by (*ii*) after the flux. The *z*-values are rounded to the nearest 25 pc.

| Name | $l$ | $b$ | $T/P^a$ | $P_{\rm orb}$ hours | Peak burst flux erg cm$^{-2}$ s$^{-1}$ | Distance 2.0–3.8$^c$ (kpc) | $z$ 2.0–3.8$^c$ (pc) | References |
|---|---|---|---|---|---|---|---|---|
| EXO 0748–676 | 279.98 | −19.81 | T | 3.82 | $3.8 \times 10^{-8}$ (*i*) | 6.8–9.1 | −2300 to −3075 | [1] |
| 2S 0918–54 | 275.85 | −3.84 | P | ? | $9.4 \times 10^{-8}$ (*ii*) | 4.3–5.8 | −300 to −400 | [18,19] |
| Cir X–1 | 322.12 | 0.04 | T/P? | 398 | $2.9 \times 10^{-8}$ (*i*) | 7.8–10.5 | 0 to 0 | [2,3] |
| 4U 1608–522 | 330.93 | −0.85 | T | 12.9? | $2.2 \times 10^{-7}$ (*i*) | 2.8–3.8 | −50 to −50 | [4] |
| Sco X–1 | 350.09 | 23.78 | P | 18.9 | parallax | $2.8 \pm 0.3$ | 1125 | [20] |
| 4U 1636–53 | 332.91 | −4.82 | P | 3.80 | $1.3 \times 10^{-7}$ (*i*) | 3.7–4.9 | −300 to −400 | [21] |
| 4U 1658–298 | 353.83 | 7.27 | T | 7.11 | $2.5 \times 10^{-8}$ (*ii*) | 8.4–11.3 | 1075 to 1425 | [5] |
| 4U 1702–429 | 343.89 | −1.32 | P | ? | $6.6 \times 10^{-8,b}$ (*ii*) | 5.3–7.1 | −125 to −175 | [32] |
| 4U 1705–44 | 343.32 | −2.34 | P | ? | $3.7 \times 10^{-8,b}$ (*ii*) | 7.2–9.6 | −300 to −400 | [32] |
| XTE J1710–281 | 356.36 | 6.92 | T | ? | $8.6 \times 10^{-9,b}$ (*ii*) | 14.8–19.8 | 1800 to 2375 | [32] |
| SAX J1712.6–3739 | 348.93 | 0.93 | T | ? | $5.1 \times 10^{-8}$ (*ii*) | 5.9–7.9 | 100 to 125 | [6] |
| 1H 1715–321 | 354.13 | 3.06 | P/T? | ? | $6.7 \times 10^{-8}$ (*ii*) | 5.1–6.9 | 275 to 375 | [22] |
| RX J1718.4–4029 | 347.28 | −1.65 | P/T? | ? | $4.3 \times 10^{-8}$ (*i*) | 6.4–8.6 | −200 to −250 | [23] |
| 4U 1728–34 | 354.30 | −0.15 | P | ? | $8.4 \times 10^{-8}$ (*i*) | 4.5–6.1 | 0 to −25 | [24,25] |
| KS 1731–260 | 1.07 | 3.65 | T | ? | $6.3 \times 10^{-8}$ (*ii*) | 5.3–7.1 | 325 to 450 | [7] |
| 4U 1735–44 | 346.05 | −6.99 | P | ? | $2.9 \times 10^{-8,b}$ (*ii*) | 8.0–10.8 | −975 to −1325 | [32] |
| GRS 1741.9–2853 | 359.96 | 0.13 | T | ? | $4.0 \times 10^{-8}$ (*i*) | 6.6–8.9 | 25 to 25 | [8] |
| 2E 1742.9–2929 | 359.56 | −0.39 | T/P? | ? | $3.7 \times 10^{-8,b}$ (*ii*) | 6.9–9.2 | −50 to −75 | [32] |
| SAX J1747.0–2853 | 0.21 | −0.24 | T | ? | $3.2 \times 10^{-8}$ (*ii*) | 7.5–10 | −25 to −50 | [9] |
| GX 3+1 | 2.29 | 0.79 | P | ? | $9.3 \times 10^{-8}$ (*i*) | 4.3–5.8 | 50 to 75 | [26] |
| SAX J1750.8–2900 | 0.45 | −0.95 | T | ? | $6.4 \times 10^{-8}$ (*ii*) | 5.2–7.0 | −75 to −125 | [10] |
| SAX J1752.3–3138 | 358.44 | −2.64 | P/T? | ? | $2.8 \times 10^{-8}$(*ii*) | 7.9–10.6 | −375 to −475 | [27] |
| SAX J1808.4–3658 | 355.38 | −8.15 | T | 2.0 | $2.5 \times 10^{-7}$ (*ii*) | 2.7–3.6 | −375 to −500 | [11] |
| SAX J1810.8–2609 | 5.20 | −3.43 | T | ? | $7.0 \times 10^{-8}$ (*ii*) | 5.1–6.8 | −300 to −400 | [12] |
| 4U 1812–12 | 18.06 | 2.38 | P | ? | $1.5 \times 10^{-7}$ (*ii*) | 3.4–4.6 | 150 to 200 | [28] |
| XTE J1814–338 | 358.75 | −7.59 | T | 4.27 | $2.6 \times 10^{-8}$ (*ii*) | 8.2–11.0 | −1075 to −1450 | [13] |
| GX 17+2 | 16.43 | 1.28 | P | ? | $1.2 \times 10^{-8}$ (*ii*) | 11.9–16.0 | 275 to 350 | [29] |
| Ser X–1 | 36.12 | 4.84 | P | ? | $2.1 \times 10^{-8,b}$ (*ii*) | 9.5–12.7 | 800 to 1075 | [32] |
| Aql X–1 | 35.72 | −4.14 | T | 19.0 | $9.1 \times 10^{-8,b}$ (*ii*) | 4.4–5.9 | −325 to −425 | [14] |
| 4U 1857+01 | 35.02 | −3.71 | T | ? | $3 \times 10^{-8}$ (*ii*) | 7.5–10 | −500 to −650 | [15] |
| 4U 1916–053 | 31.36 | −8.46 | P | 0.83 | $3.1 \times 10^{-8}$ (*ii*) | 7.5–10.1 | −1100 to −1475 | [30] |
| XTE J2123–058 | 46.48 | −36.20 | T | 5.96 | $7 \times 10^{-9}$ (*ii*) | 15.7–21 | −9275 to $-12.4 \times 10^3$ | [16,17] |
| Cyg X–2 | 87.33 | −11.32 | P | 236.2 | $1.35 \times 10^{-8}$(*ii*) | 11.4–15.3 | −2250 to −3000 | [31] |

Notes. $^a$T = transient; P = persistent. $^b$Corrected for the fact that RXTE fluxes are found to be higher by 20 per cent. $^c$Determined assuming an Eddington peak flux of 2.0 or $3.8 \times 10^{38}$ erg s$^{-1}$.

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

$\sim 2 \times 10^{38}$ erg s$^{-1}$, which can be interpreted as the Eddington luminosity for hydrogen-rich accreted material. Therefore, and for reasons explained in Section 2.3.4, we use both peak luminosities to calculate the distance to the neutron star LMXB.

For Aql X–1 we determined the burst peak flux in a 0.25 s bin from a photospheric radius expansion burst detected with the *RXTE* satellite in the observation starting on MJD 51364.834069 (Terrestrial Time). In this we subtracted the average persistent emission 5–105 s before the burst. The bolometric burst peak flux is $1.1 \times 10^{-7}$ erg cm$^{-2}$ s$^{-1}$. We corrected the Aql X–1 flux for the fact that fluxes derived using the RXTE satellite are found to be systematically higher by about 20 per cent than the X-ray fluxes in the same band found by other satellites (cf. Tomsick et al. 1999a; Barret et al. 2000; Kuulkers et al. 2003). Finally, we use the distance for Sco X–1 as determined from radio parallax measurements ($d = 2.8 \pm 0.3$ kpc, Bradshaw, Fomalont & Geldzahler 1999).

### 2.3 Systematics and uncertainties in distance estimates

Orosz & Kuulkers (1999) derived a distance of $7.2 \pm 1.1$ kpc for Cyg X–2, using method *B* (they used the spectral type of the companion derived by Casares, Charles & Kuulkers 1998). From the radius expansion burst (Smale 1998) we find a distance of 15.3 kpc, approximately a factor of two larger. The large differences in these distance estimates are difficult to explain. Even if the radius expansion bursts are hydrogen-rich and hence the burst peak luminosity is lower (see Section 2.3.4), there would still be a difference in distance estimates of a factor 1.5. However, due to the large photon rate, deadtime effects could lower the apparent burst peak flux. The bolometric burst peak flux corrected for deadtime effects was $1.5 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ (Smale 1998; compare this with the value in Table 2). This makes the distance smaller by ∼4 per cent. On the other hand, correcting the observed fluxes for the fact that the RXTE/PCA fluxes are generally found to be 20 per cent higher than fluxes determined using other satellites would make the radius expansion burst distance larger. Furthermore, if Cyg X–2 is a halo object with a low metallicity the absolute $V$-band magnitude would be smaller than that of a star with solar metallicity in order to explain the observed spectral type, making the discrepancy even bigger. A possible solution for the distance discrepancy could be that the neutron star in Cyg X–2 is lighter than the canonical value of 1.4 $M_\odot$ (although this would also affect the optically determined distance). However, this is at odds with the findings of Casares et al. (1998) and Orosz & Kuulkers (1999) who find that the mass of the neutron star in Cyg X–2 is $> 1.88$ $M_\odot$ and $1.78 \pm 0.23$ $M_\odot$, respectively.

From spectroscopic observations of XTE J2123–058 in quiescence, Casares et al. (2002) determined a best-fit spectral type for the companion star of K7V (they ruled out spectral types earlier than K3 and later than M1). Shahbaz et al. (2003) report a quiescent $V$-band magnitude for XTE J2123–058 of $22.65 \pm 0.06$, a reddening in the $V$ band of 0.37 mag, and that the companion star contributes approximately 77 per cent of the flux in the $R$ band. Here we assume that the companion star contributes 70 per cent of the flux in the $V$ band. Again using the relation of Popper (1980) to estimate the absolute $V$-band magnitude gives $M_V = 7.97$ for the observed mass ratio of 0.49 and assuming a neutron star mass of 1.4 $M_\odot$ (had we assumed a neutron star mass of 2.0 $M_\odot$ we would have obtained $M_V = 7.72$). We again assumed that the companion star fills its Roche lobe. From this we derive a distance of 8.7/9.6 kpc for a neutron star mass of 1.4/2.0 $M_\odot$, respectively (see also Tomsick et al. 2004 and references therein). The distance derived using the radius expansion burst is 15.7–21 kpc (see Table 2; deadtime effects are negligible in the case of XTE J2123–058). For the limiting spectral types of the companion star (K3/M0V) the distance would be 14/7 kpc for a 1.4-$M_\odot$, neutron star. So, even for an assumed K3 spectral type the distance is lower than that derived using the radius expansion burst. Again, as in the case of Cyg X–2, correcting the parameters we used in the distance calculations either for the fact that the RXTE/PCA fluxes are generally found to be 20 per cent higher than fluxes determined using other satellites or for the fact that XTE J2123–058 might be a halo object with a low metallicity would make the discrepancy between the photospheric radius expansion burst distance and the method $B$ bigger.

Even though the sample of neutron star sources for which we can compare the distances derived using radius expansion bursts and those derived using the properties of the companion star is small (so far this is only possible for two sources), this could mean that distances derived using method $B$ are too low, or that the distance derived using the radius expansion burst is too large. Below we will investigate in some detail possible effects responsible for the observed discrepancy in distance estimate between method $B$ and the radius expansion burst method.

### 2.3.1 *Systematics in the companion star radius determination and residual accretion*

As mentioned earlier, under the assumption that the companion star fills its Roche lobe, a first estimate of the radius of the companion star can be obtained (cf. White & van Paradijs 1996). Given the fact that mass accretion must take place in order to explain the multiple outbursts for some of the systems, the assumption that the secondary (nearly) fills its Roche lobe seems justified. However, if the temperature distribution on the surface of the star is uneven, for example owing to the effects of irradiation, then the luminosity is not determined by the full size of the companion star. Depending on whether the determined temperature is that of the hotter or colder part of the star this yields an overestimate or an underestimate of the distance.

An underestimate of the amount of light contributed due to residual accretion would lead to an underestimate of the distance and vice versa.

### 2.3.2 *Systematics in the companion star temperature determination*

Besides the radius, the temperature of the companion star is important for its luminosity. The temperature is derived from the observed spectral type. A systematic mis-classification of one spectral type for a fixed radius (e.g. using a K1V instead of a K0V star) already results in a distance error of ∼15–25 per cent for late-type stars (see Fig. 1). The difference in derived distance between using the surface brightness of main sequence stars or giants (for fixed radius) is also given in Fig. 1. The giant surface brightnesses lead to smaller absolute magnitudes, i.e. smaller distances.

The best-fit spectral type can be determined using the optimal subtraction method (Marsh et al. 1994), which is quite robust. However, this method is rarely applied fully. The broadband spectral energy distribution can also be used to determine the spectral type (cf. Gelino, Harrison & McNamara 2001 and Gelino & Harrison 2003 for recent use of this method). However, disentangling the effects of fast rotation, reddening, a possible accretion disc contribution, and the spectral type is difficult with only a few data points. This makes the uncertainty in the temperature of the companion star an important contributor to the uncertainty in the distance. For XTE J2123–058, a spectral type of K2 (just outside the determined range) would already make the two different distance estimates consistent. For Cyg X–2, a spectral type of A0 is needed while the determined type is A9 ± 2. However, from the effects discussed above, there

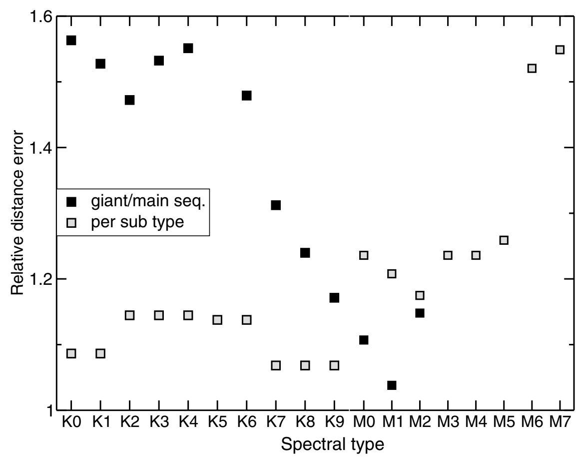


**Figure 1.** Grey squares: the fractional error one would make in the distance estimate if the spectral classification were off by one sub-class is plotted as a function of spectral type for late-type stars. Black, filled squares: the fractional error in the distance estimate if one were to take a main sequence spectral class companion instead of a giant of the same spectral type for the same radius. In both cases it is assumed that the radius of the companion star is known and accurate (in the calculations we used the results from Popper 1980).

is no reason to expect a systematic underestimation of the effective temperature of the companion star that would lead to a systematic underestimation of the distance using method *B*.

In using method *B* as described above, an implicit assumption about the temperature of the companion star has been made. This is due to the fact that the effective temperature of the companion star is in most cases assumed to be that of a main sequence star of the observed spectral type. Besides a small variation in temperature with luminosity class, there is also a difference in bolometric correction for stars that have the same spectral type but a different luminosity class. Comparing the observed surface gravity with that of different luminosity classes of the observed spectral type, the effective temperature of the companion star can be determined. These then determine the bolometric correction, and thus the distance. However, the error in the distance from neglecting the difference in bolometric correction between the luminosity classes is small.

However, it is possible that the observed spectral types are systematically shifted to later spectral types because of effects on the lines and continuum induced by the fast rotation of the companion star. Single late-type stars have rotational velocities of less than a few kilometres per second due to the onset of a magnetic-brake in stars later than typically F5 (see Kraft 1967). However, the late-type companion stars in LMXBs are likely in co-rotation with the orbit. Therefore, the rotational velocities range from several tens of kilometres per second for long-orbital-period systems (see, for example, GRS 1915+105; Harlaftis & Greiner 2004) to hundred or more kilometres per second for the short-orbital-period systems. Studies of rapidly rotating early-type stars found that a fast rotation causes a slight increase in absolute magnitude of stars with spectral type later than B5 (the stars are intrinsically less luminous than the non-rotating stars of the same spectral type by typically several tenths of a magnitude; only stars up to F8 were studied; Collins & Sonneborn 1977). Additionally, it is known that limb and gravity darkening effects on the line change the equivalent widths of stellar photospheric absorption lines (see, for example, Shajn & Struve 1929; Collins & Sonneborn 1977).[1] Generally, the lines in the spectrum resemble the lines of a later spectral-type star (Collins & Sonneborn 1977). However, this depends on the behaviour of the equivalent width of the used lines as a function of the effective temperature. Broadening of template star spectra in the optimal subtraction technique does not take into account these physical changes in the lines. In early-type stars the decrease in luminosity of the star due to rotation is outweighed by the apparent shift in spectral type. Hence, the distance estimation method *B* using the spectra of non-rotating template stars to estimate the spectral type applied to fast-rotating early-type stars would probably lead to a net underestimation of the distance, the effect being bigger the later the spectral type of the star (at least up to spectral type F8).

Unfortunately, there are no detailed model atmosphere calculations showing the physical effects of rotation on the absolute magnitude and the lines of stars later than F8 available in the literature. However, the effects of limb darkening are larger in late-type stars than in early-type stars. Furthermore, extrapolating the findings for early-type stars, the spectral appearance is probably more affected than the true source luminosity – meaning that the distances to the sources would be underestimated using non-rotating template stars to determine the spectral type.

### 2.3.3 *Systematics in the interstellar absorption estimates*

If the interstellar extinction $A_V$ is systematically overestimated, this would yield an underestimate of the distance, or vice versa, since $m_V - A_V - M_V = 5\log d - 5$. The interstellar extinction caused by scattering of light off dust grains is traced by the optical/UV spectrum – through $E(B-V)$ and/or the strength of the absorption feature at λ2175. Spectral fits to the X-ray data trace interstellar absorption caused by neutral hydrogen and absorption (above ∼0.5 keV) by K/L-shell electrons of mostly O and Fe (Predehl & Schmitt 1995). Finally, interstellar absorption lines from ions such as Na I and Ca II trace low-ionization interstellar gas (Sembach & Danks 1994). Over the years, relations between $A_V$ and these different sources of interstellar extinction have been established. For example, Predehl & Schmitt (1995) reported a relation between $N_H$ and $A_V$. Rieke & Lebofsky (1985) give a relation between $E(B-V)$ and $A_V$:

$$R \times E(B-V) = A_V, \tag{2}$$

with $R \approx 3.1$. Herbig (1995) gives relations between the equivalent widths of the Na I and Ca II absorption lines and $E(B-V)$. However, the line-depth of some absorption lines saturates quickly leading to an overestimate of the distance. Furthermore, for systems out of the Galactic plane the equivalent width of the interstellar absorption features does not increase much with distance once the system has a $z$-distance larger than the scale-height of the interstellar material (e.g. the scale-height of Ca II is approximately 800 pc whereas that of Na I is approximately 400–500 pc; Sembach & Danks 1994).

In addition, determining $A_V$ from the observed $N_H$ or from the observed equivalent width of interstellar absorption lines one implicitly assumes that the sight-line for the SXT under investigation has the same gas-to-dust ratio, i.e. $N_H/E(B-V)$, as the sight-lines for which the relations between $A_V$ and $N_H$ or between the equivalent widths of the Na I and Ca II absorption lines and $E(B-V)$ have been established. It is known that this is not always the case; e.g. the sight-line towards the Gould belt (i.e. Orion, Ophiuchus and Perseus; Burstein & Heiles 1978) has a low gas-to-dust ratio. Similarly, the sight-line towards the Galactic Centre, where most LMXBs are located, has, in general, a low $R$ ($R < 3.1$; Udalski 2003). This caveat has to be kept in mind.

In Table 3 we show the $A_V$ as derived from optical/UV and X-ray data. As was found before (see, for example, Vrtilek et al. 1991), the extinction derived using X-ray data is systematically larger than that based on optical/UV data. There are two possible reasons for this. Predehl & Schmitt (1995) used the $N_H$ values derived from fitting an absorbed power-law model to *ROSAT* X-ray data. Using an absorbed Bremsstrahlung or a blackbody model to fit the data gave systematically lower values for $N_H$. However, in the $N_H$ estimates in Table 3 in most cases a power-law model has been used as well.

Another possibility is that local absorbing material is present during outbursts. Since most of the X-ray observations that are sensitive enough to determine $N_H$ are done during outburst this could lead to a

[1] For example, the ratio between equivalent widths of the hydrogen lines and those of weak metallic atoms also changes among other things owing to the fact that the strong hydrogen lines respond differently to the rotational effects (Collins, Truax & Cranmer 1991). Orosz et al. (2001) found that the companion star in V4641 Sgr (a.k.a. SAX J1819.3–2525) is rapidly rotating ($v \sin i \sim 123$ km s$^{-1}$). In fact, for an assumed B9III spectral type observed at an inclination close to 60° (Orosz et al. 2001), the star is rotating at 80–90 per cent of its break-up speed (cf. Collins & Sonneborn 1977). The fact that the lines of stars with large rotational velocities are similar to the lines in stars of later spectral types (Collins & Sonneborn 1977) can explain the unusually strong Mg II line in V4641 Sgr. Bildsten & Rutledge (2000) noted that the peculiar Li abundances observed in the companion stars of several BH SXTs could also result from the fact that the companion stars are fast rotators similar to RS CVn stars.

**Table 3.** The interstellar extinction $A_V$ for the sample of BH SXTs determined using optical/UV or X-ray data. For some sources a range of values corresponding to the different values found by the different references is given whereas for others an error bar is given. We used $R = 3.1$ in $A_V = R \times E(B - V)$. We used the $N_H$ value obtained using a power-law model where available since the correlation $N_H = 1.79 \times 10^{21}$ cm$^{-2}A_V$ was derived using power-law fits to *ROSAT* data (see Predehl & Schmidt 1995). An 'X' denotes that the value has not been determined.

| Name | $A_V$ optical | $A_V$ X-ray | Refs Opt – X-ray |
|---|---|---|---|
| GRO J0422+32 | 0.6–1.2[a] | <2.8 | [1] – [2] |
| 1A 0620–00 | 1.09–1.24 | 1.3±0.7 | [3,4] – [5] |
| GS 1009–45 | 0.6±0.2 | X | [6] – [X] |
| XTE J1118+480 | X | 0.041±0.004[d] | [X] – [7] |
| GS 1124–684 | 0.9±0.1 | 1.28±0.06 | [8] – [9] |
| 4U 1543–47 | 1.55±0.15 | 2.4±0.1 | [10] – [11] |
| XTE J1550–564 | 2.5[e] | 4.88±1.15 | [12] – [13] |
| GRO J1655–40 | 3.7±0.3 | 4.8±2.8 | [14] – [5] |
| GX 339–4 | >2.8 | 3.9±0.5 | [15] – [16] |
| H 1705–250 | X | 1.7±0.5 | [X] – [17] |
| SAX J1819.3–2525 | 1.0±0.3[b] | X | [18] – [X] |
| XTE J1859+226 | 1.80±0.37 | 4.47[c] | [19] – [20] |
| GS 2000+25 | 3.5[b] | 6.4±1.0 | [21] – [22] |
| GS 2 Section 023+338 | 3.3–4.0 | 3.9±0.4 | [23,24] – [5] |

Notes. [a]See the discussion and references in Beekman et al. (1997). [b]The uncertainty is large since the value is derived assuming $(B - V)_0 = 0$. [c]No error bars given. [d] $N_H$ from EUVE observations. [e]Sánchez-Fernández et al. (1999) report 2.2 ± 0.3. We prefer the value derived using the DIB since the Na D line may have been saturated.

References: [1] Beekman et al. (1997); [2] Sunyaev et al. (1993); [3] Oke & Greenstein (1977); [4] Wu et al. (1983); [5] Kong et al. (2002); [6] della Valle et al. (1997); [7] Hynes et al. (2000); [8] Cheng et al. (1992); [9] Greiner et al. (1994); [10] Orosz et al. (1998); [11] van der Woerd, White & Kahn (1989); [12] Sánchez-Fernández et al. (1999); [13] Tomsick, Corbel & Kaaret (2001); [14] Hynes et al. (1998); [15] Hynes et al. (2004); [16] Gallo, Fender & Corbel (2003); [17] Griffiths et al. (1978); [18] Orosz et al. (2001); [19] Hynes et al. (2002); [20] dal Fiume et al. (1999); [21] Chevalier & Ilovaisky (1990b); [22] Tsunemi et al. (1989); [23] Wagner et al. (1991); [24] Casares et al. (1993).

systematic overestimation of $N_H$. The fact that for XTE J1859+226 the value derived from X-ray spectral fits is higher than that derived using the UV data even though both the *HST* UV and the BeppoSAX X-ray observations were made during outburst can be explained by the fact that the UV and X-ray observations are sensitive to different sources of interstellar extinction. If the extra absorbing material is indeed local to the source, the temperature may be too high for dust to form, on the other hand neutral hydrogen may well be present explaining the difference in derived $A_V$. This all suggests that the $A_V$ derived from $N_H$ from X-ray spectral fitting systematically provides an overestimate for $A_V$. Hence, their use would yield an underestimation of the distance.

In all BH distance estimates in the literature the $A_V$ derived using optical or UV data has been used, except in the case of XTE J1550–564, H 1705–25 and GS 2000+25. The diffuse interstellar bands (DIBs) used by Sánchez-Fernández et al. (1999) to estimate the $A_V$ for XTE J1550–564 do not suffer from saturation at relatively low values of $E(B - V)$. Given the fact that the factor with which the distance to the source changes goes as $d_2/d_1 = 10^{(A_{V1}-A_{V2})/5}$, the distance to XTE J1550–564 may have been underestimated by a factor ∼3! Although, as explained above, the sight-line could have properties different from the properties of the sight-line used in deriving the relation between the $A_V$ and the equivalent width of the DIB leading to an anomalously low $A_V$ as derived from the DIB. In the case of GS 2000+25, an $A_V$ of 4.4 has been used. However, since the optically derived value for $A_V$ for GS 2000+25 does not seem to be very accurate (it has been determined assuming the intrinsic $B - V$ colour of the source during outburst is 0) it is unclear whether this is an overestimation or not. Unfortunately, it is not possible to estimate whether the distance to H 1705–225 is overestimated or underestimated, since there is no optically derived $A_V$ available.

### *2.3.4 Systematics in the radius expansion burst method*

It has been suggested that the burst flux could be anisotropic (Kuulkers et al. 2002). However, given the good agreement between the globular cluster distances and the distances to the LMXBs in these globular clusters derived from the photospheric radius expansion burst properties (Kuulkers et al. 2003) that seems unlikely. Furthermore, Galloway et al. (2003) showed that, considering the burst peak fluxes of 61 photospheric radius expansion bursts in the atoll source 4U 1728–34, the degree of anisotropy in the burst emission in less than 2 per cent.

Two out of the eight neutron star systems studied by Kuulkers et al. (2003) have a photospheric radius expansion peak burst luminosity that is lower than that of the other six. This lower peak luminosity is consistent with the Eddington luminosity limit for hydrogen rather than helium–rich material for a neutron star mass of 1.4 $M_\odot$. So, for some of the neutron star systems in our list we could have overestimated the distance by a factor $\sim\sqrt{1.8}$. If we take a 1:4 ratio as was found by Kuulkers et al. 2003, this would affect eight systems in our sample. As was noted by Kuulkers et al. (2003) the two sources whose peak luminosity is consistent with hydrogen accretion have an orbital period characteristic for normal LMXBs, rather than ultra-compact X-ray binaries with periods less than ∼1 h (which necessarily accrete hydrogen-poor material; see, for example, Verbunt & van den Heuvel 1995). Because the fraction of ultra-compact X-ray binaries in globular clusters might be higher than in the field, the ratio between the number of sources with a hydrogen-rich, low Eddington burst luminosity and the number of sources with a helium-rich, high Eddington burst luminosity could be higher. It is unlikely, however, that the distances to *all* neutron star LMXBs in our sample have been overestimated. For example, in the long-period LMXBs 4U 1636–53 and KS 1731–26, the photospheric radius expansion burst was consistent with a helium-rich explosion (Sugimoto, Ebisuzaki & Hanawa 1984; Muno et al. 2000, respectively, see also Cumming & Bildsten 2000).

## 3 IMPLICATIONS AND DISCUSSION

Using the data set compiled above, leaving the distances derived using method *B* as they are, keeping the discrepancy in the distance estimate between method *B* and the radius expansion burst method in mind, we investigate the Galactic distribution of neutron star and BH LMXBs and the peak luminosity of BHs.

### 3.1 Galactic distribution of LMXBs

The authors van Paradijs & White (1995) investigated the Galactic $z$-distribution of neutron star LMXBs and concluded that neutron stars should receive an asymmetric kick at birth from the fact that the rms-value of the $z$-distribution was ∼1 kpc. We obtain rms $z$-values of 1025 and 1125 pc for persistent and transient neutron star LMXBs, respectively (we round rms $z$-values to the nearest 25 pc).

In this we have excluded XTE J2123–058 since with a $z$-value of $-12.4$ kpc it would dominate the outcome and Casares et al. (2002) show that the systemic velocity is consistent with its being a halo source. It can be argued on the basis of the large $z$-values that Cyg X–2 and EXO 0748–676 are also halo sources although this is much less clear. For example, Kolb et al. (2000) argue that if Cyg X–2 is at a distance of ∼11.6 kpc it could have originated in the Galactic plane. However, when we also exclude Cyg X–2 and EXO 0748–676 we find rms $z$-values for the persistent and transient neutron star LMXBs of 700 and 850 pc, respectively. The authors van Paradijs & White (1995) found an rms $z$-value of ∼500 pc when they excluded Cyg X–2 and EXO 0748–676 from their sample. Since we have used $3.8 \times 10^{38}$ erg s$^{-1}$ for the Eddington luminosity for the radius expansion peak luminosity for all neutron stars, the rms $z$-value we derived for neutron star LMXBs corresponds to an upper limit. If we use $2.0 \times 10^{38}$ erg s$^{-1}$ as the photospheric radius expansion peak burst luminosity we find rms $z$-values of 775 and 850 pc for persistent and transient neutron star LMXBs, respectively (here we only excluded XTE J2123–085; if we also exclude Cyg X–2 and EXO 0748–676 we find 550 and 650 pc for persistent and transient neutron star LMXBs, respectively) – i.e. our findings confirm the result of van Paradijs & White (1995).

In a follow-up paper, White & van Paradijs (1996) investigated the differences between the rms-values of the neutron star and BH LMXBs $z$-distributions. They found that the rms-value for the BHs was substantially lower than that for the neutron star $z$-distribution (more than a factor of two). Using the distances of the BHs given in Table 1 we now find an rms-value of ∼625 pc (we took a distance of 2.5 kpc for GRO J0422+32; we excluded the likely halo object XTE J1118+480, see Wagner et al. 2001 – although note that some of the evidence leading to the suggestion that XTE J1118+480 is a halo object was based on the low rms $z$-value White & van Paradijs 1996 found for BH LMXBs), i.e. close to the upper limit we find for the neutron star systems. Increasing the distance of XTE J1550–564 by a factor of three does not significantly increase the rms-value of the BH population. The main reason for the difference between the findings of White & van Paradijs (1996) and our findings is that the distance estimates for most BHs have gone up. The conclusion drawn by White & van Paradijs (1996) that BHs receive a significantly smaller kick than neutron stars is no longer tenable.

We plotted the $z$-values for transient and persistent neutron star LMXBs (open diamonds and squares, respectively) and BHs (black dots) using the distances from Tables 1 and 2 as a function of their projected distance to the Galactic Centre in Fig. 2. It is interesting that the rms-value for the projected distance to the Galactic Centre for the neutron stars and BH is 4.8 and 7.0 kpc, respectively – excluding the (probable) halo sources. Because the Galactic potential in the $z$-direction decreases with increasing Galactocentric radius (see, for example, Carlberg & Innanen 1987) the larger scale-height of BHs can partly be due to this effect, rather than a kick velocity. For example, for neutron star systems van Paradijs & White (1995) estimate an rms-value of the $z$-distribution near the Sun of 650 pc. Furthermore, the symmetric kick velocity (imparted due to mass loss in the supernova) scales with the companion mass and the mass lost in the supernova (see, for example, Nelemans, Tauris & van den Heuvel 1999) both can be (much) larger in the case of BH systems, but it scales inversely with the total mass of the remaining binary. Lastly, for large asymmetric kick velocities the binary is more likely to have been disrupted in case of a neutron star than a BH. A detailed investigation of all the possible explanations for the high rms-value for the BHs is needed in order to draw firm conclusions and we defer this to a later paper.

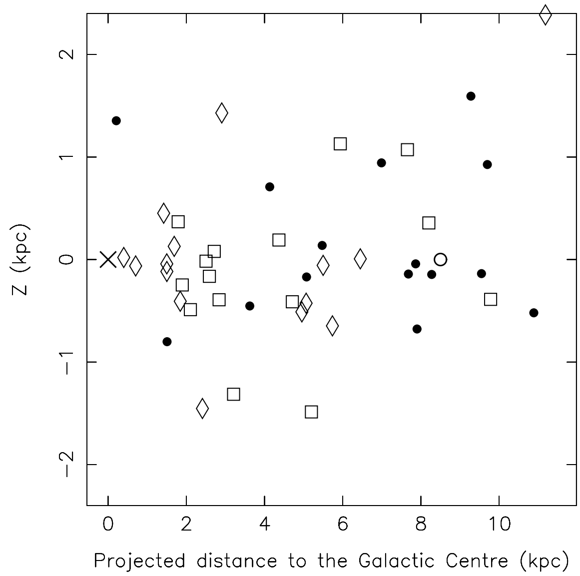


**Figure 2.** The $z$-distribution of the Galactic persistent (open squares) and transient (open diamonds) neutron star LMXBs for which a radius expansion burst has been detected, and BH LMXBs (filled circles) for which a dynamical mass has been derived as a function of the projected distance to the Galactic Centre. The projected distance is $\sqrt{x^2 + y^2}$, where $x$ and $y$ are the Cartesian coordinates in the Galactic plane (see Fig. 4). The location of the Sun at an assumed distance of 8.5 kpc is indicated with an open circle, and the location of the Galactic Centre is indicated with a cross. Four neutron star systems fall off the figure (EXO 0748–676, $z = -3.1$ kpc, XTE J2123–058, $z = -12.4$ kpc, XTE J1710–281, $D_{GC} = 19.7$ kpc, and Cyg X–2, $D_{GC} = 15$ kpc). In this figure we use the neutron star distances derived assuming the Eddington peak burst luminosity was $3.8 \times 10^{38}$ erg s$^{-1}$.

After White & van Paradijs (1996) we also compare the distribution of the $l$ and $b$ coordinates of the neutron star and BH LMXBs. We first compare the $l$ and $b$ coordinates of neutron star LMXBs in Table 2 with those of the BHs listed in Table 1. A K–S test shows that the probability that the distributions are the same is 18 per cent for the $l$-coordinate and 52 per cent for the $b$-coordinate (the K–S D-values are 0.33 and 0.24, respectively. Here and below, the effective number of data points is always larger than 10 so that the probabilities we quote are quite accurate, cf. Press et al. 1992). To investigate this further and to minimize selection effects, we plot the $l$- and $b$-coordinates of *all* neutron star systems, e.g. systems where a burst was found, and pulsars listed in Liu et al. (2001) (solid line histogram in Fig. 3). We compare this with the BH sources listed in Table 1 *and* the BH candidates for which no mass estimate based on a radial velocity study exist (systems in table 3 in McClintock & Remillard 2004; the dashed line histogram in Fig. 3). A one-dimensional K–S test shows that the probability that the neutron star and BH distributions in $l$ are drawn from the same distribution is 37 per cent whereas the probability that $b$-values are drawn from the same distribution is 90 per cent (the K–S D-values are 0.19 and 0.12, respectively). Hence, using a larger sample of neutron stars and BHs makes the probability that the neutron star and BH distributions are the same larger. The probabilities we derive are higher than those derived by White & van Paradijs (1996); a difference we attribute to the fact that White & van Paradijs (1996) had fewer BH systems in their study. We conclude that there is no evidence for a difference in the $l$- and $b$-distributions of neutron star and BH LMXBs.

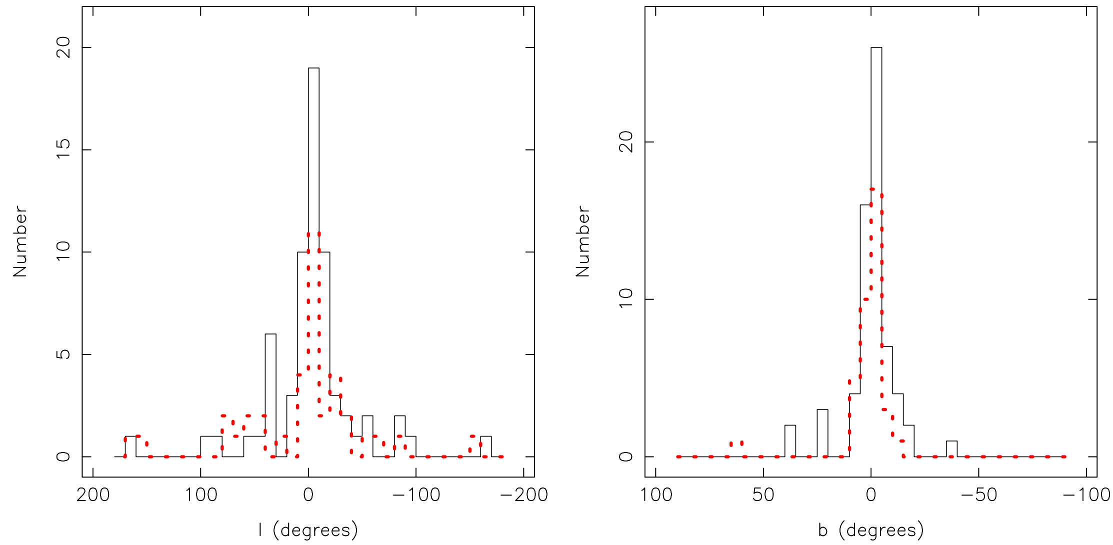


**Figure 3.** Left-hand panel: the *l*-distribution of the neutron stars (solid line histogram; all sources showing bursts or pulsations listed in Table 2 and Liu et al. 2001) in bins 10° wide. The *l*-distribution of the BHs listed in Table 1 and McClintock and Remillard 2004 (dotted line histogram). Right-hand panel: the *b*-distribution for the same sources and using the same symbols as in the left-hand panel in bins 5° wide.

Interestingly, there seems to be an excess of 12 out of a total of 22 BH and an excess of 19 out of a total of 45 neutron star systems with $-30° < l < 0°$ over systems with $0° < l < 30°$. There is an excess of five out of 35 BH and 13 out of 53 neutron star systems with $-10° < b < 0°$ and $0° < b < 10°$ (see Fig. 3). The expected mean number of systems with a positive/negative *l* of a symmetric distribution around $l = 0°$ is $N/2$, with *N* the total number of systems. The variance on this number is $\sqrt{N/4}$. Comparing this with the observed number of systems yields significances of the observed asymmetries of 2.8$\sigma$ for the neutron star distribution in *l*, 3.0$\sigma$ for the BH distribution in *l*, and 3.8$\sigma$ for the combined neutron star and BH distribution in *l*. The combined significance for the neutron star and BH distribution in *b* is 1.9$\sigma$ only, so we do not discuss this apparent asymmetry in *b* further.

The asymmetry in the *l*-distribution is not an obvious observational selection effect. For instance, the BeppoSAX WFC monitoring the Galactic Centre region had a field of view of 40° × 40° centred on the Galactic Centre (in't Zand 2001). The dust maps from Schlegel, Finkbeiner & Davis (1998) do not show a large dust asymmetry around the Galactic Centre. It seems that the neutron star and BH LMXB distribution in *l* is symmetric around $l = -5°$. Possibly this asymmetry is related to the bar structure in the inner part of our Galaxy. It is known that the bar causes asymmetries in the stellar and gas distributions around $(l, b) = (0, 0)$ (for example, see the recent review by Merrifield 2004). Furthermore, Gilfanov (2004) found that the distribution of LMXBs follows the stellar mass distribution, and hence not the spiral arm structure.

Using the distances listed in Tables 1 and 2 we also plot in Fig. 4 the Galactic *x*–*y* distribution of the neutron stars for which a photospheric radius expansion burst was observed and the BHs for which a dynamical mass estimate has been derived. The Galactic spiral arm structure according to the model described in Taylor & Cordes (1993) has been overplotted. It is clear that few LMXBs at the other side of the Galactic Centre have been detected, especially if the Eddington limit for hydrogen-rich material for a 1.4-$M_\odot$, neutron star is applicable to the peak burst flux of most photospheric radius expansion bursts (see also Grimm, Gilfanov & Sunyaev 2002). There also seems to be a paucity of nearby neutron star LXMBs (this was also noted by Verbunt 2001). In order to try to quantify this we performed a two-dimensional Kolmogorov–Smirnov (K–S) test (Press et al. 1992) to test whether the neutron star and BH populations are the same. The K–S test gives a *D* of 0.45 and a probability that the two populations are the same of 3.8 per cent. If we decrease the distance of all neutron star systems by a factor $\sim\sqrt{1.8}$ the probability that the distributions are the same increases only slightly to 5.2 per cent ($D = 0.44$). It is possible that the discrepancy in the spatial distribution of the neutron stars and BHs is a selection effect. Since we only included BHs for which a mass limit larger than 3 $M_\odot$ has been derived, the optical counterpart must have been detected in quiescence, hence this favours nearby systems.

### 3.2 The black hole outburst peak luminosity

The BH distances are important for the maximum observed BH luminosity. We found a somewhat larger distance for V404 Cyg than often used previously. Shahbaz et al. (1994b) found an upper limit on the distance of V404 Cyg of 3.7 kpc assuming the peak outburst source luminosity was Eddington limited taking their 90 per cent confidence upper limit to the mass of the BH of 15 $M_\odot$. The distance of $4.0^{+2.0}_{-1.2}$ kpc we find shows that the maximum observed luminosity exceeds the Eddington luminosity for a 10-$M_\odot$ BH (the limit often quoted to decide whether a source is a ULX or not). The distance derived for XTE J1550–564 may have been underestimated by as much as a factor three: its distance could be as large as $3 \times 5.3 = 15.9$ kpc, although the uncertainties are large. For this distance the outburst peak luminosity in the 2–20 keV band alone would be $7 \times 10^{39}$ erg cm$^{-2}$ s$^{-1}$ (taking the flux from Sobczak et al. 1999). For 4U 1543–47, SAX J1819.3–2525 and GRS 1915+105, systems for which the distance was determined by method *B*, *B* and *C*, respectively, it was noticed earlier that the outburst peak luminosities are super-Eddington for the best-fit BH masses (cf. Revnivtsev et al. 2002; McClintock & Remillard 2004). Garcia et al. (2003) show that the peak outburst of GRO J1009–45 most probably also exceeded the Eddington luminosity for a for $\sim 10 = M_\odot$ BH (even if the distance is 5.7 instead of the 9 kpc they favoured). It seems

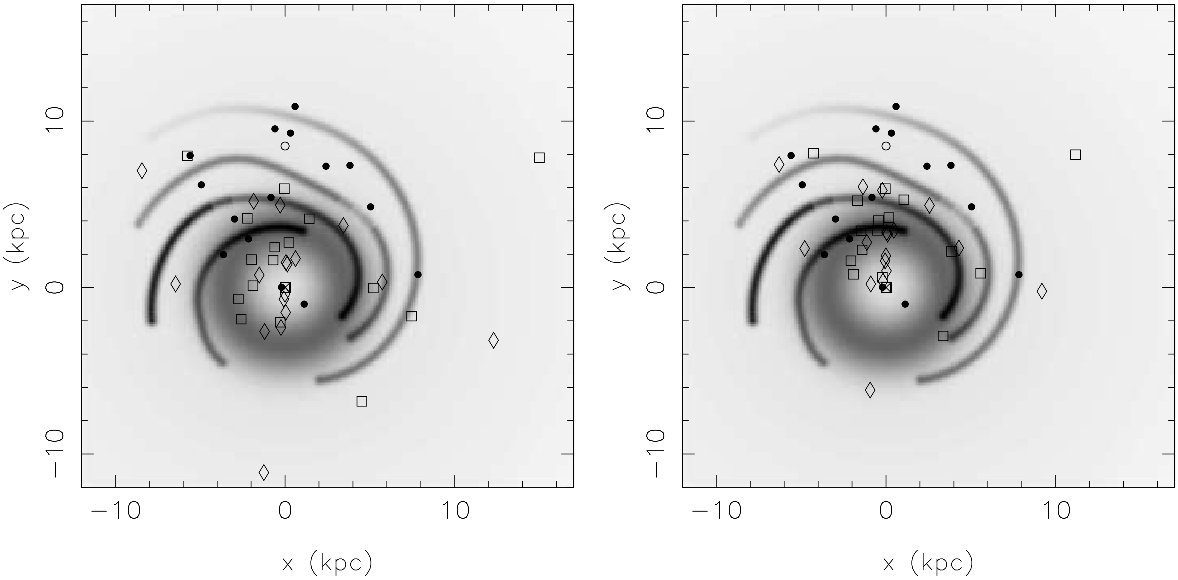


**Figure 4.** Left-hand panel: the *x*–*y* distribution of the Galactic persistent (open squares) and transient (open diamonds) neutron star LMXBs for which a photospheric radius expansion burst has been detected, and BH SXTs (filled circles) for which a dynamical mass has been derived. The location of the Sun is indicated with an open circle, and the location of the Galactic Centre at an assumed distance of 8.5 kpc is indicated with a cross. It is clear that there is a paucity of nearby neutron star systems compared with nearby BH SXTs. The neutron star distances were derived assuming that the Eddington peak burst luminosity was $3.8 \times 10^{38}$ erg s$^{-1}$. Overplotted is the spiral structure and the free-electron density according to the model of Taylor & Cordes (1993). Right-hand panel: same as the left-hand panel except that the neutron star distances have been derived assuming that the Eddington peak burst luminosity was $2.0 \times 10^{38}$ erg s$^{-1}$.

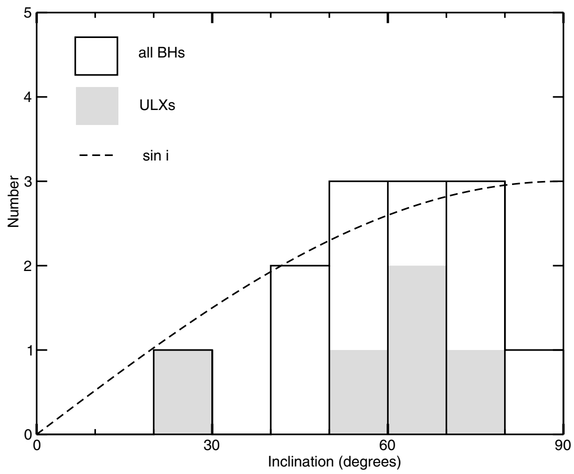


**Figure 5.** Inclination distribution for the dynamically confirmed BH SXTs (all the inclinations are taken from Orosz 2003). The shaded bins indicate the five systems that would have been classified as ULX had we observed them in another galaxy at their outburst peak luminosity. XTE J1550–564 ($i \sim 72° \pm 5°$) is possibly also a ULX (see text).

therefore likely that there are several sources in our own Galaxy that we would classify as transient ULXs had we observed them in other Galaxies. For these sources a mass determination has shown that they are not intermediate-mass BHs but rather 5–15 $M_\odot$ BHs. Furthermore, the fact that LMXB sources (an old population) seem to be capable of producing super-Eddington luminosities could also help explain the presence of ULXs in elliptical Galaxies. Assuming that most ULXs are stellar-mass BHs the fact that many ULXs are found a few arcseconds away from young stellar clusters could be caused by kick velocities received at BH formation.

If super-Eddington luminosities were to be explained by effects of 'mild-beaming' (cf. King et al. 2001) then one would naively expect the inclinations of the sources with the highest luminosities to be lowest. In Fig. 5 we plot the inclination distribution for 13 BH SXTs in Fig. 5 (the inclinations for GX 339–4 and XTE J1859+226 are not well known and those sources have therefore not been included; inclinations from Orosz 2003). Although the amount of sources is low we see that the inclination distribution of the BH ULX sources is not skewed to low inclinations but instead clusters around the fiducial 60° point. We did not include XTE J1550–564 ($i \sim 72° \pm 5°$) and GRO J0422+32 ($i \sim 41° \pm 3°$) as ULXs.

## 4 CONCLUSIONS

We studied the distance estimates for BH SXTs in detail. We note that the uncertainties in the distance estimates due to, for example, uncertainties in the spectral type (i.e. temperature) of the companion star are probably large. Comparing the distances derived for the neutron stars Cyg X–2 and XTE J2123–058 using the distance estimation method *B*, which is used for most BH SXTs, with the photospheric radius expansion burst method, we find that the latter gives larger distances. This could mean that for some reason method *B* systematically underestimates the distance. Possibly this is related to an erroneous spectral classification of the companion star caused by its fast rotation. If this is indeed the case this would have important consequences for the reported difference in quiescent X-ray luminosities of BH and neutron star SXTs, for the BH SXT peak outburst luminosities, for the BH masses, and for the Galactic distribution of BH LMXBs. We find that the distance towards XTE J1550–564 may have been underestimated by as much as a factor three because the interstellar extinction could have been overestimated in that case. As was noticed before, several BH SXTs observed in our Galaxy would be classified as ULXs had we observed them in another Galaxy (at least five, but perhaps even seven, out of the 15 dynamically confirmed BH SXTs). This suggests that many (transient) ULXs in other Galaxies could well be stellar-mass BHs.

A re-evaluation of the distance to the Galactic plane of neutron star and BH LMXBs shows that there is no longer evidence for a smaller rms-value of the *z*-distribution for BH systems. Such a difference had been interpreted as evidence for the absence of asymmetric kicks during BH formation. However, before firm conclusions can be drawn about the similarities or differences between neutron stars and BH kicks the details of the formation and Galactic distribution have to be investigated. Finally, we found that the *l*-distribution of Galactic LMXBs is asymmetric around $l = 0°$.

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