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THE GALACTIC DISTRIBUTION OF BLACK HOLE CANDIDATES IN LOW-MASS X-RAY BINARY SYSTEMS

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ABSTRACT

We find that for black hole candidates (BHC) in low-mass X-ray binaries (LMXRB) the dispersion of their distances, z , to the Galactic plane is smaller than for LMXRB with neutron stars by more than a factor 2. This result indicates that any kick velocities that the black hole systems may have received at formation are substantially smaller than those of neutron star systems. We infer a value of 40 km s^{-1} for the radial-velocity dispersion of the BHC systems from their z dispersion, consistent with the value obtained directly from radial-velocity measurements. From the surface density of black hole X-ray transients (BHXT) in the solar vicinity, and an estimate for the typical recurrence time of $\sim 100 \text{ yr}$, we infer that the total number of BHXT in the Galaxy is ~ 500 .

Subject headings: binaries: close — galaxy: kinematics and dynamics — X-rays: general

1. INTRODUCTION

The dynamical evidence for accreting black holes in X-ray binaries now seems conclusive. In 10 systems (see Table 1) optical radial-velocity measurements have demonstrated that the mass of the compact object is greater than the maximum possible mass of a neutron star. In the past four years the number of systems has more than doubled; all the additions are X-ray transients with a late-type mass donor (the “secondary”). During the X-ray outbursts the optical counterparts to these black hole X-ray transients (BHXT) showed a large brightness increase, which decayed with the X-rays, usually on a timescale of several months. In quiescence the secondary could be detected, and the binary parameters were determined from optical spectroscopy (e.g., McClintock & Remillard 1986). In a previous paper (Van Paradijs & White 1995, hereafter PW) we considered the Galactic distribution of low-mass X-ray binaries (LMXRBs) containing neutron stars and found that the dispersion of their distances, z , to the Galactic plane is $\sim 1 \text{ kpc}$. This wide distribution requires that the neutron stars receive a kick velocity during their formation. In this paper we study the Galactic distribution of black hole candidates in LMXRB systems (BHC-LMXRB) and compare it to that of the LMXRB systems containing neutron stars (NS-LMXRB).

2. THE GALACTIC BLACK HOLE CANDIDATES

The measurement of the mass function from optical spectroscopy currently provides the only reliable way to identify a black hole in an X-ray binary. However, optical measurements are not always possible, e.g., if the system is highly reddened. X-ray binaries which show bursts or pulsations contain a neutron star. For other sources the X-ray spectrum has become a key indicator in determining if the compact object is

a BHC or a neutron star (White & Marshall 1984; White, Kaluziński, & Swank 1984; Sunyaev et al. 1991; Tanaka & Lewin 1995). X-ray binaries with dynamical evidence that the compact object is a black hole show a distinct two-component X-ray spectral signature. One component is *ultrasoft* with a characteristic temperature of $\sim 1 \text{ keV}$ that can be modeled by an optically thick accretion disk (e.g., Ebisawa et al. 1994). The other is an *ultrahard* power law that extends up to several hundred keV (e.g., Wilson & Rothschild 1983). This two-component spectrum has turned out to be a surprisingly good predictor for the presence of a black hole in an X-ray binary. Over the past decade 1–2 *ultrasoft/ultrahard* X-ray transients have been discovered each year (e.g., White et al. 1984) for which subsequent optical observations have confirmed that the X-ray source is a black hole candidate (e.g., Casares, Charles, & Naylor 1992).

Table 2 lists the X-ray binary systems that have exhibited an *ultrasoft* (US) and/or an *ultrahard* (UH) spectral component and have, or are suspected to have, late-type secondaries. We have indicated the observed spectral signature and also if dynamic (D) evidence for a black hole exists (Table 1). We have also included the two systems where relativistic jets (J) have been reported: GRO J1655–40 and GRS 1915+105. While most BHC-LMXRB are X-ray transients with a relatively rapid rise and a decline over several months, there are a minority that are either persistent sources or show extreme variability (see, e.g., Tanaka & Lewin 1995). In Table 2 we have classified the systems as transients, highly variable (meaning they show excursions in flux by a factor of 10 or more), and persistent (these show much less dramatic flux variations). These variable and persistent systems represent about 30% of the known BHC-LMXRB population but are likely to be a much smaller fraction as many BHXT remain to be discovered.

While the success rate for identifying BHC based on spectral signatures is high, the signature is not fool proof. In the

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TABLE 1
BLACK HOLE BINARY CANDIDATES FROM RADIAL VELOCITY MEASUREMENTS

Name	ID	Date (yr)	Transient	Companion	P_{orb} (days)	$f(M)$ (M_{\odot})	M_X (M_{\odot})	Reference
HMXRb:								
Cyg X-1.....	HD226868	1972	No	O9.7 Iab	5.6	0.25	≥ 7	1, 2
LMC X-3.....		1982	No	B3V	1.7	2.3	≥ 7	3
LMC X-1.....		1983	No	O7-9 III(?)	4.2	0.12	≥ 2.6	4
LMXRb:								
A 0620-00.....	V616 Mon	1986	Yes	K5 V	0.32	2.91	≥ 2.9	5
GS 2023+338.....	V404 Cyg	1992	Yes	G9 V-K0 III	6.47	6.26	≥ 6.1	6
GS/GRS 1124-68.....	XN Mus 92	1992	Yes	K0 V-K4 V	0.43	3.1	≥ 2.9	7
GRO J0422+32.....	V518 Per	1995	Yes	M2	0.21	1.2	≥ 2.6	8, 9
GRO J1655-40.....	XN Sco 95	1995	Yes	F3-F6	2.60	3.16	≥ 3.2	10
GS 2000+25.....	QZ Vul	1995	Yes	K5 V	0.35	5.0	≥ 6.4	11, 12
H1705-25.....	XN Oph 77	1996	Yes	K3	0.52 (0.70)	4.0	≥ 3.4	13, 14

REFERENCES.— 1. Webster & Murdin 1972; 2. Bolton 1972; 3. Cowley et al. 1983; 4. Hutchings et al. 1987; 5. McClintock & Remillard 1986; 6. Casares et al. 1992; 7. McClintock, Bailyn, & Remillard 1992; 8. Filippenko, Matheson, & Ho 1995; 9. Casares et al. 1995b; 10. Bailyn et al. 1995; 11. Casares, Charles, & Marsh 1995a; 12. Filippenko, Matheson, & Barth 1995; 13. Remillard et al. 1996; 14. Martin et al. 1995.

case of one US system (4U 0142+61), previously classified as a BHC-LMXRB, low-amplitude pulsations were discovered by Israel, Mereghetti, & Stella (1995). This system is now thought to be a member of a new class of low-luminosity X-ray pulsar (Van Paradijs, Taam, & van den Heuvel 1995). During the last several years it has become clear that a hard power law spectrum is also emitted by atoll sources, i.e., LMXRB with weakly magnetized neutron stars, when their accretion rate is low. However, at high luminosities (greater than 10^{37} ergs s^{-1}) the UH and/or US components have been seen only for black hole systems, and this has turned out to be a reliable predictor of BHC-LMXRB systems, especially in the case of the BHXT (see Tanaka & Lewin 1995).

3. THE GALACTIC DISTRIBUTION

We compare in Figure 1 the Galactic longitude (l^{II}) and latitude (b^{II}) distributions for the current list of BHC-LMXRB (Table 2) and NS-LMXRB (from PW). White (1994) pointed out that there appears to be a deficit of BHC toward the Galactic center (GC) compared to the NS-LMXRB. The BHC-LMXRB l^{II} distribution in Figure 1 now shows a sharp peak within 5° of the GC, and away from this a flat distribution. In contrast the NS-LMXRB systems show a peak centered on the GC that is broader than that for the BHC-LMXRB. The b^{II} distribution of the BHC also appears to be broader than for the NS systems. While Figure 1 suggests a

TABLE 2
BLACK HOLE CANDIDATES IN LOW-MASS X-RAY BINARIES

Name	Type	Signature	l^{II}	b^{II}	d (kpc)	z (pc)	d Reference
GRO J0422+32 (V518 Per).....	Transient	D/UH	165.9	-11.9	2.5	-516	1
A 0620-00 (V616 Mon).....	Transient	D/US	210.0	-6.5	0.8	-91	2
GRS 1009-45 (XN Vel 93).....	Transient	UH	275.9	9.3	...	...
GRS 1124-68 (GU Mus).....	Transient	D/US/UH	295.3	-7.1	3.9	-482	3
GS 1354-645 (Cen X-2).....	Transient	US/UH	310.0	-2.8	...	...
A 1524-62 (TrA X-1).....	Transient	US/UH	320.3	-4.4	...	...
4U 1543-47.....	Transient	US/UH	330.9	5.4	4	376	4
4U 1630-47 (Nor X-1).....	Transient	US/UH	336.9	0.3	...	...
GRO J1655-40 (XN Sco 94).....	Transient	D/US/UH/J	345.0	2.5	3.2	140	5
GX 339-4 (4U1658-48).....	Variable	US/UH	338.9	-4.3	4	-300	6
H 1705-25 (V2107 Oph).....	Transient	US/UH	358.6	9.1	6	950	7,8
GRO J1719-24 (GRS 1716-249).....	Transient	UH	0.1	7.0	...	...
KS 1730-312.....	Transient	UH	356.7	1.0	...	...
1E 1740.7-2942.....	Variable	UH	359.1	-0.1	8.5	-15	6
H 1743-32.....	Transient	US/UH	357.1	-1.6	...	...
SLX 1746-331.....	Transient	US	356.8	-3.0	...	...
4U 1755-338.....	Persistent	US	357.3	-4.9	...	...
GRS 1758-258.....	Variable	UH	4.5	-1.4	...	...
GS 1826-24.....	Variable	UH	9.3	-6.1	...	...
EXO 1846-031.....	Transient	US/UH	30.0	-0.9	10	-157	9
GRS 1915+105.....	Variable	UH?/J	45.3	-0.9	12.5	-196	10
4U 1957+11.....	Persistent	US	51.3	-9.3	...	...
GS 2000+25 (QZ Vul).....	Transient	D/US/UH	63.4	-3.0	2.5	-131	6
GS 2023+33 (V404 Cyg).....	Transient	D/UH	73.2	-2.1	8	-293	11

REFERENCES.— 1. Shrader et al. 1994; 2. Oke 1977; 3. West 1991; 4. Chevalier 1989; 5. Hjellming & Rupen 1995; 6. Tanaka & Lewin 1995; 7. Griffiths et al. 1978; 8. Martin et al. 1995; 9. Parmar et al 1993; 10. Mirabel & Rodriguez 1994; 11. Wagner et al. 1992.

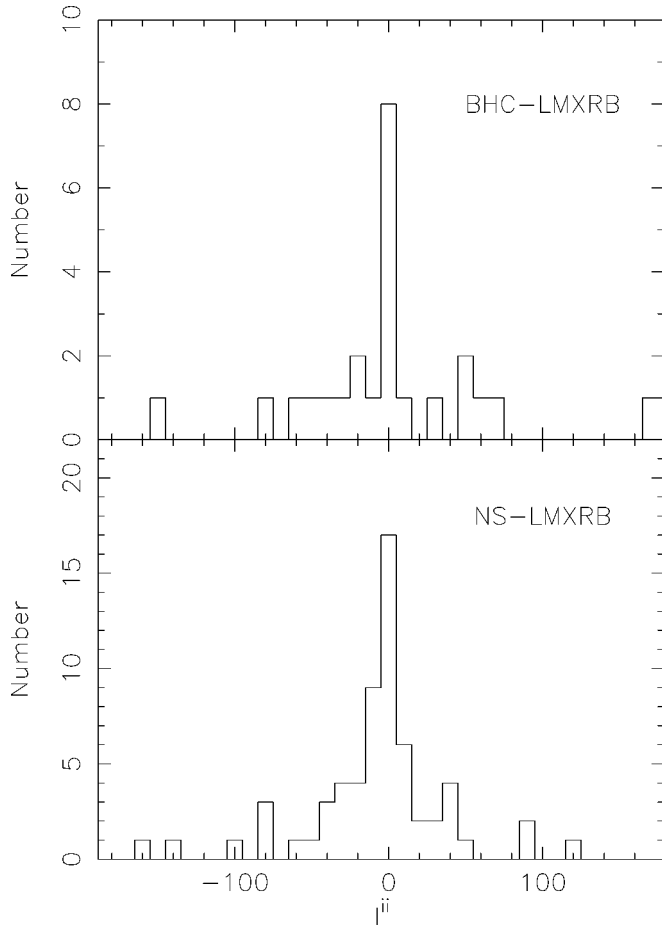


FIG. 1a

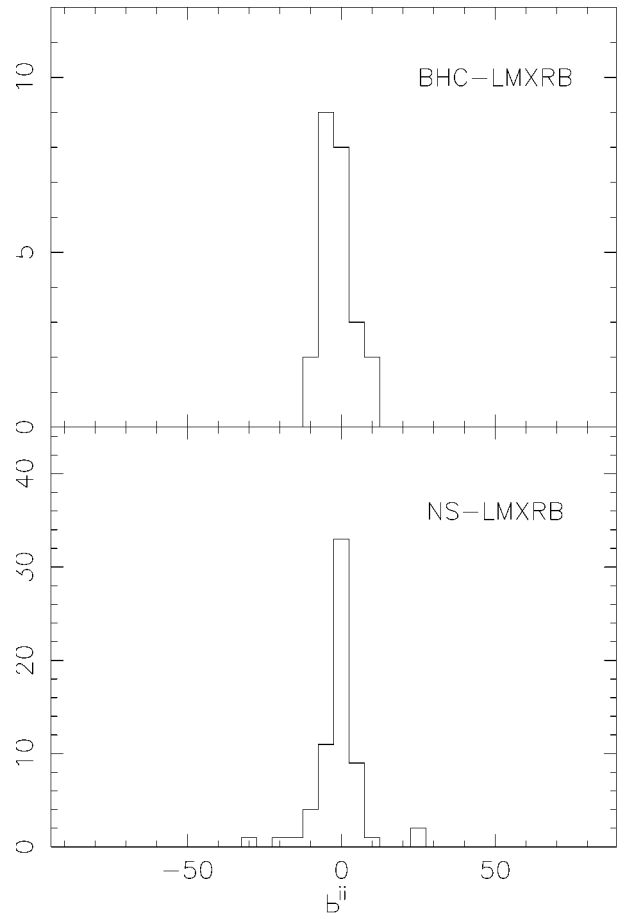


FIG. 1b

FIG. 1.—Galactic longitude (l^{II}) and latitude (b^{II}) distributions of the black hole candidates in low-mass X-ray binaries (BHC-LMXRB) and neutron stars in low-mass X-ray binaries (NS-LMXRB). The data are binned in 10° and 5° bins for the l^{II} and b^{II} distributions, respectively. The NS-LMXRB distribution uses the sample given in PW and excludes most sources that are less than $10 \mu\text{Jy}$ because their nature is unclear. The BHC-LMXRB distribution comes from the sample listed in Table 2.

concentration of BHC in the GC region, selection effects may distort the distribution. The GC region has been more often observed by sensitive medium-to-hard X-ray imaging instruments (e.g., Skinner et al. 1990), and this has probably caused a bias toward detecting fainter BHC (and NS-LMXRB systems) within $\sim 5^\circ$ of the GC. The PW sample excludes sources fainter than $10 \mu\text{Jy}$ because their nature is uncertain. These sources (which were included by White 1994) are mostly located within 5° of the GC and also result in a spike similar to that seen from the BHC-LMXRB (cf. White 1994). A K-S test shows that there is a 22% and 28% chance, respectively, that the l^{II} and b^{II} locations of the BHC-LMXRB and NS-LMXRB are drawn from the same distribution (this is also the same when only the BHXT systems are considered). If, however, we exclude the central 5° around the GC, then this probability drops to 5×10^{-3} for l^{II} (suggesting a significant difference), while it increases to 89% for b^{II} .

For BHC-LMXRB with known orbital period and spectral type of the secondary the distance can be estimated. The spectral type, which is a measure of the V -band surface brightness of the secondary, and the optical V magnitude (corrected for interstellar extinction) together provide an estimate of the angular radius R_2/d of the secondary (see, e.g., Popper 1980). The density of the (Roche lobe filling) second-

ary is proportional to the orbital period, so its radius, R_2 , is determined up to a factor $M_2^{1/3}$ which can be reasonably assumed to within an accuracy of several tens of percents. The resulting distances (and the corresponding distances, z , to the Galactic plane) are listed in Table 2. We have also included in Table 2 several other distance estimates from the literature but, except for 1915+105 and 1740.7–2941, we consider these estimates less accurate.

The rms distance from the Galactic plane, z_{rms} , for the sample of 10 sources with good distance estimates, equals 410 pc, with an estimated uncertainty of ~ 50 pc. For the BHXT alone it equals 500 pc. This result is influenced by H 1705–25, which has an extreme $z \sim 950$ pc. Excluding H 1705–25 results in a lower z_{rms} of ~ 300 pc. The z_{rms} estimate excludes most of the systems that are in the vicinity of the GC region, where there are no direct distance estimates. If we assume that the BHC-LMXRB within 7° of the GC are at a distance of 8.5 kpc, we obtain for them z_{rms} of ~ 470 pc.

4. DISCUSSION

4.1. Comparison with Neutron Star Systems

The z dispersion of the BHC-LMXRB (~ 400 pc) is more than a factor of 2 smaller than the value found for LMXRB

with neutron stars (PW). This difference is the more striking since the neutron star systems are more strongly concentrated toward the GC than the BHC-LMXRB systems. When the distances are taken into account then only 2 (of 18) of the NS-LMXRB systems with known distances are at galactocentric distances, r_{GC} , larger than 7 kpc, whereas half of the BHC-LMXRB systems exceed that distance. Since the perpendicular deceleration to the Galactic disk diminishes with r_{GC} , one would expect that if both classes had the same kinematic properties, then the BHC-LMXRB would have a wider z distribution, contrary to what is observed.

The observed large z_{rms} of the NS-LMXRB systems requires that they have undergone a kick velocity, most likely during the formation of the neutron star, in addition to the velocity acquired by mass loss from the system alone (PW). The narrower z distribution of the BHC-LMXRB systems shows that any kick velocities that these may have received are substantially smaller than those of the NS-LMXRB systems. This result supports the conclusion of Brandt, Podsiadlowski, & Sigurdsson (1995) that the two-stage black hole formation by the delayed collapse of an initially formed neutron star cannot be a dominant formation mechanism.

4.2. Estimate of the Space Velocities of BHC Systems

The z distribution of the BHC-LMXRB systems can be compared with those of normal stellar disk populations, as given by Mihalas & Binney (1981). The latter are represented in terms of a scale height β for assumed exponential distributions, $\rho(z) \propto \exp(-z/\beta)$, for which $z_{rms} = \beta 2^{1/2}$. The corresponding scale height β_{BHC} is in the range 280 to 350 pc. This range corresponds to a disk population of an intermediate age.

There is a strong correlation between β and the dispersion, σ_z of the z velocity distribution; according to the results compiled by Mihalas & Binney (1981) the expected value of σ_z for BHC is $16.5 \pm 2 \text{ km s}^{-1}$. We can relate this value to an expected dispersion of radial velocities by using the fact that the BHC are all located close to the Galactic plane. Therefore, the square of the radial velocity dispersion σ_{rad} equals the sum of the dispersions squared of the u and v components of the space velocity. For intermediate disk populations the ratio σ_{rad}/σ_z then equals 2.3 ± 0.4 , and thus the expected σ_{rad} equals $40 \pm 8 \text{ km s}^{-1}$. Accordingly, the dispersion in the space velocities of BHC-LMXRB systems is $42 \pm 8 \text{ km s}^{-1}$. Another way to study the velocity distribution of these systems is to use their systemic (radial) velocities, corrected for differential Galactic rotation and solar motion. From such results (excluding the one high-velocity BHC-LMXRB system GRO J1655–40) by Brandt et al. (1995) we infer $\sigma_{rad} = 22 \text{ km s}^{-1}$, with an estimated uncertainty of 9 km s^{-1} . This is somewhat smaller than, but consistent with, our result.

These considerations indicate that it is unlikely that BHC-LMXRB as a group are as old as the oldest Galactic disk population ($\sim 10^{10}$ yr). They may be substantially younger, if their current velocity dispersion contains a significant contribution from kick velocities caused by sudden loss of mass at the formation of the black hole. For example, let us assume that the progenitors of BHC-LMXRB are Population I objects, for which the space velocity dispersion is 17 km s^{-1} (Mihalas & Binney 1981). To obtain the observed dispersion of $42 \pm 8 \text{ km s}^{-1}$ one requires a dispersion of the systemic kick velocities of $38 \pm 8 \text{ km s}^{-1}$. In relating the systemic kick velocity v_{sys} to the fraction f of total system mass lost we will

use the approximate relation (PW) $v_{sys} = v_x(1-f)/f$, where v_x is the orbital velocity of the black hole: $v_x = (M_2/M)(GM\omega_{orb})^{1/3}$ (Here M_2 and M are the secondary and system mass, respectively, and ω_{orb} is the orbital angular frequency). In estimating v_x we have taken $M = 10 M_\odot$ and $M_2/M \lesssim 0.1$. For the sample of BHC-LMXRB with known orbital period we then obtain $v_x \lesssim 60 \text{ km s}^{-1}$ as a typical value. We then find $f \lesssim 0.6$, i.e., one requires that a substantial fraction of the black hole progenitor mass be lost in a supernova explosion. Current models of black hole formation are consistent with this requirement (Woosley & Timmes 1996). A more precise analysis of the age of the BHC-LMXRB systems would require a detailed analysis of the evolution of the progenitor binary systems, and of black hole formation, and exceed the scope of this Letter.

4.3. The Total Number of BHXT in the Galaxy

Tanaka (1992) estimated that the total number, N_{BHXT} of BHXT in the Galaxy (which dominate the BHC-LMXRB population) is in the range 600–3000. We have made a new estimate of N_{BHXT} using the local surface density, σ_{BHXT} , of BHXT in the solar vicinity as inferred from the distance estimates presented in Table 2. In estimating σ_{BHXT} we have limited ourselves to systems at distances less than 3 kpc from the Sun, where we find 4 (out of 9) BHXT with known distances. There are another 8 BHXT without known distances; we assume that the same fraction of these is located within ~ 3 kpc. This leads to a local value $\sigma_{BHXT} = 0.25 \text{ kpc}^{-2}$. These BHXT were observed during the last ~ 25 yr; according to the analysis of Chen, Schrader, & Livio (1997) the average sky coverage during these years has been 70%. The corresponding local “production rate” of BHXT is therefore $\sim 0.015 \text{ kpc}^{-2} \text{ yr}^{-1}$. To estimate the total number of BHXT per year in the Galaxy we assumed that the latter can be approximated by a uniform circular disk with radius 10 kpc, leading to a Galactic production rate of $\sim 4.6 \text{ yr}^{-1}$.

Estimating the average recurrence time between outbursts of BHXT is fraught with uncertainty. Several BHXT have recurred at intervals ranging between 1.6 and 58 yr. There is good evidence that the instability that gives rise to the outbursts of BHXT is a disk instability similar to that operating in dwarf novae (see Van Paradijs & Verbunt 1984; Howell, Kuulkers, & Van Paradijs 1996). X-ray heating has a stabilizing effect on the mass flow in accretion disks, and, as a result, LMXRB can undergo disk instabilities only if the mass transfer rate is very low; the critical rate below which a BHXT will occur is of order several $10^{-11} M_\odot \text{ yr}^{-1}$ and depends primarily on the orbital period and on the mass of the compact star (Van Paradijs 1996). Gravitational radiation will sustain a minimum mass transfer rate which is not far below this critical rate (King, Kolb, & Burderi 1996). The corresponding range in time-averaged mass transfer rates in BHXT is less than 1 order of magnitude (from $\sim 10^{-11} M_\odot \text{ yr}^{-1}$ at $P_{orb} \sim 10$ hr, to $\sim 10^{-10} M_\odot \text{ yr}^{-1}$ at $P_{orb} \sim 100$ hr), comparable to the observed time averaged accretion rates in those BHXT systems that have recurred (e.g., White et al. 1984). A disk instability occurs when the surface density in the outer parts of the disk exceeds some critical value; with the mass transfer rate within a limited range, the interval required to build up to the critical surface density should not show a large range. We therefore consider it unlikely that the BHXT have average outburst intervals above 100 yr.

Based on the above reasoning and the observed intervals (between 1.6 and 58 yr) we assume 100 years to be the maximum for the average interval between BHXT outbursts. With this average interval, and the above estimated outburst rate of 4.6 per year we find that the total number

of BHXT in the Galaxy is about 500. This estimate is consistent with the low end of the range estimated by Tanaka (1992). If the average outburst interval is shorter than 100 years, then the number of BHXT in the galaxy will be less.

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