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A census of low mass black hole binaries

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Abstract. The six known low mass black hole binaries discovered as X-ray/Optical novae represent a relatively uniform source class. It is shown that the recurrence time for outbursts from these sources can be understood in the disk instability picture if magnetic braking is not active in the short period systems. An extrapolation from the discovery surveys gives an estimate of ~ 1700 such systems in the Galaxy as a whole. BATSE sky monitor observations should produce new candidate black hole transients at a rate of ~ 2/y. The population estimates also suggest that $\gtrsim 13$ optical outbursts of black hole binaries prior to 1975 should have been recorded in classical nova catalogues. Some strategies for discovery of more black hole binaries are discussed.

Key words: black hole physics – binaries: close – novae, cataclysmic variables – X-rays: stars – Galaxy: stellar content

1. Introduction

Of the ~10 interacting binaries with strong evidence for a black hole primary, the relatively uniform set of 'low mass' systems are particularly important. With $\lesssim 1\,M_\odot$ mass donors, and mass functions $f(M) \gtrsim 3M_\odot$, the accretors are clearly too massive for any realistic neutron star equation of state, and provide the best dynamical evidence for stellar mass black holes. These systems are discovered as X-ray/Optical (X/O) novae and are believed to be disk instability transients. Six of these binaries are now known, discovered over the past 20 years through their X-ray outbursts and confirmed some years after outburst by careful radial velocity studies of their companions in quiescence. Detailed reviews of the observations can be found in Tanaka & Lewin (1995) and Tanaka & Shibazaki (1996); some important properties are reviewed in Sects. 2-4 below. Since the known systems lie at distances of $\sim 2-3\,$kpc and since the outburst recurrence time seems to be many decades it is clear that many systems remain to be discovered. The goal of this paper will be to extrapolate from the observed sample an estimate of the total population of low mass black hole binaries (BHB) in the Galaxy.

In fact, Tanaka (1992) has already made an order of magnitude estimate of the number of black hole transients in the Galaxy. Updated, the argument is as follows: with sources detected to $\sim 3\,$kpc and ~ 15y of X-ray sky coverage, the total Galactic population is $N \sim 6\tau_R/15\mathrm{y}(10\mathrm{kpc}/3\mathrm{kpc})^2 \sim 500\tau_2$ for an average recurrence time of $\tau_R = 100\tau_2$y. Given that the sky monitoring was not complete and that dynamical measurements of primary mass are only available for a subset of the transient sources, it is likely that this number is a minimal estimate; in this paper attempts are made to improve the completeness corrections. In any case, this large number of BH systems is remarkable, as it exceeds the number of known neutron star low mass X-ray binaries. Such numbers were not entirely unexpected, since Romani (1992) followed common-envelope evolution scenarios similar to those producing neutron star low mass X-ray binaries (LMXB), arguing that with loss of angular momentum determining the accretion rates there should be several hundred short period BH systems in the Galaxy. While the higher mass primaries producing BH should indeed be less common than those producing neutron stars, the key idea in this study was that BH core collapse should be 'quiet', leading to small mass loss and small velocity kicks. In contrast to the neutron star case, a large fraction of the initial binaries should remain bound. These computations were extended by Romani (1996), where numbers as large as $\sim 10^3$ low mass BH systems and the existence of significant numbers of 'intermediate mass' BH systems (with donor mass $m_2 \sim 2-6M_\odot$) were discussed. However, even with long lifetimes for the BH systems, production of such large numbers through the 'He star' core collapse channel requires surprisingly high efficiencies for common envelope ejection. Portegies Zwart, Verbunt and Ergma (1997) for example, find that an application of the standard scenario underproduces the observed low mass BHB by a large factor unless the common envelope ejection efficiency is very high and unless black holes can form from moderate mass progenitors after appreciable narrowing of the orbital system. Large numbers of BH systems are certainly a challenge for evolution scenarios, and an improved census of the black hole population can provide useful constraints on the binary evolution physics.

Here the present sample of X-ray/optical transients is used to improve estimates of the number of Galactic interacting low mass BHB binaries. These computations can be compared with

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Send offprint requests to: R.W.Romani, Dept. of Physics, M.C. 4060, Stanford, CA 94350, USA the rate of X-ray transients being discovered by BATSE and similar sky surveys. An estimate is also made of the number of pre-1975 outbursts that went unobserved in X-rays but may have been recorded as interlopers in the sample of classical novae. Prospects for finding more BHB through continued X-ray observations and study of certain classical novae are also discussed. Such data will be very useful in constraining the outburst recurrence time and probing the BHB evolution.

2. Properties of low mass black hole binaries

It is useful to summarize the properties of the six X/O transients with low mass companions and mass functions indicating $M_1 \gtrsim 3M_\odot$. The properties most important to the present discussion are listed in Table 1, and are extracted from the observational reviews of Tanaka & Lewin (1995), Tanaka & Shibazaki (1996) and Zhang et al. (1997) and the references therein. Some synthesis and extrapolation to common energy bands has been made; for example the masses M_1 and M_2 are generally quite uncertain; when only one digit has been given the masses may be uncertain by $\sim 50\%$.

It is important to note that these systems have been discovered over a period of ∼20y with widely differing instrumental capabilities. Nevertheless, it has become clear that the low mass black hole binaries display many striking similarities and it is therefore appropriate to estimate the population of these sources as a homogeneous class. The class of X/O novae is larger than the six well-studied examples described below. In Tanaka & Lewin (1995) and Tanaka & Shibazaki (1996), $\gtrsim$12 other (generally fainter) X-ray transients with properties similar to the known low mass BHB are listed as possible BH systems, but do not have measured mass functions. Additionally, the transients GRO 1655-40, 1E1740.7-2491 and GRS 1915+105 are likely black holes. GRO 1655-40 is a dynamical BH candidate, but it is not considered here since it has an intermediate mass ($M > 1M_\odot$) secondary; further these three sources do not display the characteristic isolated outburst behaviour of the low mass systems. To complete the roster of BH candidates one should mention the classical persistent systems Cyg X-1, LMC X-1 and LMC X-3 which all have high or intermediate mass secondaries.

2.1. X-ray outbursts: fluxes and spectra

The X-ray outbursts of identified black holes have a rather similar appearance, with a rapid rise to a peak luminosity that can approach the Eddington limit in soft X-rays, followed by an exponential decay back to quiescence on a timescale $\tau_X \approx 25-75^{\rm d}$. There may be a faint precursor before the main outburst and the decay may be interrupted by smaller 'reflares' spaced by several τ_X. The similar basic behaviour has lead several authors to conclude that these are disk instability transients. For example, King, Kolb and Burderi (1996) have shown that LMXB transient behaviour corresponds well to predictions of the disk instability model. This picture is applied in Sect. 2.3.

Although these X/O novae are often referred to as 'Soft X-ray Transients', the spectral behaviour of the outbursts has been divided into two classes. The first class (UP) is indeed soft, with an ultra-soft (U) component dominating below 10keV at maximum and a variable high energy power-law (P) tail. In the late stages the burst often transitions to a hard state dominated by the P component. The high energy power-law index varies over an appreciable range ($\alpha \sim 1.7 - 2.5$). A second class of BH transients has been discovered, for which the U component is weak or absent and the luminosity is dominated by the power law component, even near burst maximum. In these cases the spectrum appears to be hard ($\alpha \sim 1.7$). Since sky monitors discovering X-ray transients survey in quite different bands, it is important to consider the hard and soft flux separately. In Table 1 the estimated soft (2-6keV) and hard (20-300keV) component fluxes of the six transients at maximum are listed, interpolated from data in Tanaka and Shibazaki (1996) and references therein. Note that for the UP class in particular the maximum fluxes in the two bands may occur at different times. For UP sources with poorly observed hard fluxes (*) the estimate $f_X(20-300) \approx 0.03 f_X(2-6)$ is used. For the P sources it is seen that $f_X(20-300) \approx 10 f_X(2-6)$. The fluxes are highly variable on short timescales, even at maximum.

2.2. Optical outbursts

The optical outbursts of the black hole transients are a product of reprocessed X-rays from the central accretion disk. This leads to light curves with characteristic decay constants of $\sim 2\tau_X$ (King and Ritter 1997). Modern outbursts of X/O novae confirm that the optical flux decays more slowly than the X-rays, although earlier outbursts of 2023+338 had T_3 (the time for a decay $\Delta m_V = 3$) of $\sim 1.5\times$ the 1989 τ_X rather than the $\sim 5-6\tau_X$ predicted by King & Ritter. There is a general correlation between the X-ray outburst flux and the optical peak magnitude, but apparently details of the disk affect the reprocessing of flux into blue optical light. Previous outbursts of two of these systems were recorded on archival sky survey plates (eg. Duerbeck 1987). For these sources an approximate recurrence time is thus known. The historical optical outbursts showed low amplitude and slow decay with brightness fluctuations (nova class Bb), similar to the optical outbursts observed during the modern X-ray selected events.

2.3. Recurrence times

These outbursts are held to be equivalent to the dwarf nova eruptions of white dwarf cataclysmic variables in the accretion disk instability model (e.g. Huang and Wheeler 1989, King & Ritter 1997). In this model the viscosity, and hence local energy release, of the disk is controlled by the ionization state of hydrogen. The system initiates an outburst when the largely neutral, low viscosity disk exceeds a local density threshold, causing a transition to a 'hot' high viscosity state with large mass flows. The energy released in accretion onto the central source irradiates the outer disk (King & Ritter 1997), ionizing the gas and

Table 1. Properties of low mass BHB transients

		Outburst data						Quiescence data							
Name	Nova	D[a]	Sp[a]	f^b_{soft}	f^b_{hard}	τ^c_X	m^c_{OB}	$m^{\rm d}_R$	$A^{\rm d}_V$	$d^{\rm d}$	Sp$^{\rm d}_2$	$P^{\rm e}_b$	$f^{\rm e}_M$	$M^{\rm e}_2$	$M^{\rm e}_1$
0422+32	Per92	B	P	-8.2^*	-7.3	40	13.2	21.2	0.9	2.0	M2V	0.21	1.21 ± 0.06	0.4	$\gtrsim 9^{\rm f}$
0620−003	Mon75(17)	A	UP	-6.2	-7.7^*	24	11.5	17.6	1.3	0.9	K4V	0.32	2.91 ± 0.08	0.7	~ 7
1124−684	Mus91	G	UP	-7.0	-8.5	30	13.5	19.5	0.9	3.0	K2V	0.43	3.01 ± 0.15	0.8	~ 7
1705−250	Oph77	A	UP	-7.7	-9.2^*	70	16.6	20.6	1.6	3.0	K3V	0.52	4.0 ± 0.8	0.7	~ 6
2000+250	Vul88	G	UP	-6.9	-8.2	30	16.4	21.2	3.5	2.0	K5V	0.34	4.97 ± 0.10	0.7	~ 9
2023+338	Cyg89(38, 59)	G	P	-7.3	-6.3	40	11.6	19.6	3.0	3.5	K0IV	6.48	6.08 ± 0.06	0.9	12.5

[a] The discovery survey (A=Ariel 5, G=Ginga, B=BATSE) and the X-ray spectral class of the outburst.

[b] Log of estimated source fluxes f_s=2-6keV, f_h=20-300keV in $\mathrm{erg/cm^2/s}$. Entries with (*) are extrapolated from standard hard/soft ratios (see text).

[c] X-ray decay time constant in days and visual magnitude of the nova at maximum.

[d] The quiescence R magnitude, estimated visual extinction, source distance in kpc and companion spectral type.

[e] Orbital period (d), mass function, and estimated secondary and primary mass in $M_\odot$.

[f] Fillipenko, et al. 1995 estimate $M_1 \approx 3.6 M_\odot$ based on disk radial velocity estimates; Beekman et al. (1997) find $M_1 > 9 M_\odot$ from ellipsoidal modulation.

forcing the disk to remain in the high $\dot{M}$ state until the ionized zone is depleted of mass and the disk can return to its quiescent 'cool' configuration. In this picture the 're-flares' of the disk occur when heated outer regions accrete through the central zone on a viscous timescale. Neutron star accretors do not generally show this behaviour as the hot central object continues to irradiate the disk even as the accretion decreases so that the disks remain in the hot outburst state. In this way the presence of an event horizon (i.e. a black hole) is central to the existence of large amplitude X/O outbursts.

Since, according to King & Ritter (1997), the heated disk must be accreted for the outburst to cease, a simple prescription for the recurrence time is

$$\tau_R = M_h/(-\dot{M}_2) \approx 50 R_{11}^3 (\dot{M}_{-10})^{-1} \mathrm{y} \qquad (2.1)$$

where the disk mass $M_h \approx \pi (h/R) \rho R^3$ (with $\rho \sim 3 \times 10^{-8} \mathrm{gcm^{-3}}$ the pre-outburst disk density, a typical disk radius $10^{11} R_{11}$cm and $h/R \sim \alpha \sim 0.1$) is replenished on a timescale τ_R by mass transfer from the secondary M_2 at rates near $10^{-10} M_\odot$/y. The disk radius can be related to the binary parameters; since the average Roche lobe radius is $R_L/a = 0.38 + 0.2 \log(M_1/M_2) \approx 0.6$ for these high mass ratio systems and the disk around the primary extends to $\sim 0.75 R_L$, one has a disk radius $R_{11} \approx 1.3 M_T^{1/3} P_d^{2/3}$, where M_T is the total system mass in solar mass units and P_d is the binary period in days. In long period BHB, however, King & Ritter (1997) note that the outer disk may not be sufficiently heated by the central flux to become ionized and achieve high viscosity. For $h/R \sim 0.1$, an Eddington-limited mass accretion rate of $\sim 10^{-8} M_1 M_\odot$/y and standard parameters for a BH irradiated disk, their estimates give a maximum heated radius of $R_h \sim 7 \times 10^{10} M_1$cm. This is larger than the full disk radius for all of the observed systems except GS 2023+33. As there is good evidence that this X/O nova reached an Eddington-limited luminosity in outburst, in this system R_{11} is taken to be R_h.

For all of these binaries we have $M_1 \gg M_2$. For the short period systems mass transfer is driven by loss of angular momentum. Considering first GR losses one has

$$\dot{M}_{GR} = 2 \times 10^{-12} M_1 M_2^2 M_T^{-1/3} P_d^{-8/3} M_\odot/\mathrm{y} \qquad (2.2)$$

with the stellar masses in $M_\odot$, and P_d the orbital period in days. In many short period binary systems, 'magnetic braking' (Verbunt and Zwaan 1981) is also believed to play a role, giving

$$\dot{M}_{MB} \approx 5 \times 10^{-9} M_T^{1/3} M_2^{7/3} M_1^{-1} P_d^{-2/3} M_\odot/\mathrm{y}. \qquad (2.3)$$

At longer periods the system is driven by nuclear evolution of the secondary. King, Kolb and Burderi (1996) give the convenient expression

$$\dot{M}_{ev} \approx 4 \times 10^{-10} M_2^{1.47} P_d^{0.93} M_\odot/\mathrm{y} \qquad (2.4)$$

for secondaries well off the main sequence.

GS 2023+338 clearly has mass transfer driven by evolution of the secondary. For the systems with $P \lesssim 8$h angular momentum losses should be driving them to shorter periods. If the secondary mass is near the low end of the allowed range, however, significant mass loss must have occurred. Further, it is also clear that for 1705-250 and 1124-683, at least, the secondaries must be somewhat evolved to maintain Roche lobe contact. It is generally assumed that nuclear evolution ceases at initial Roche lobe contact, but there will be a range of periods for which modest evolution of the secondary can occur before angular momentum capture and spiral-in. The orbital period would be reduced below that normally expected for the evolved star core mass, and the nuclear evolution-driven transfer rate should provide an upper limit in this case. Detailed models are needed to compute precise transfer rates.

Table 2. Recurrence timescale estimates

Name	τ_{GR}	τ_{MB}	τ_{NE}	τ_{obs}
0422+32	$^\dagger 52$	11.6	–	> 64
0620−003	119	6.6	–	$^\dagger 58$
1124−683	369	11	$^\dagger 120$	–
1705−250	1116	19	$^\dagger 154$	–
2000+250	$^\dagger 167$	11	–	–
2023+338	–	–	39	$^\dagger 26$

† Adopted recurrence timescale; all times in years.

Following the discussion above, the model outburst recurrence times can be computed for the low mass BH binary systems. Table 2 lists τ_R (in y) for the mass transfer rates (2.2)-(2.4). For objects with earlier outbursts recorded on sky survey plates, the observational τ_R estimate is also listed. In the case of GS 2023+338, nuclear evolution-driven transfer is assumed to replenish the inner heated disk. For the binaries with $P_b < 0.4^{\rm d}$ it is clear that standard magnetic braking of the form above gives unacceptably small τ_R, since observations indicate that typical recurrence times must be at least several decades. As an example, for 0422+32 Castro-Tirado et al. (1993) find $\tau_R > 64$y by searching for similar outbursts on archival sky survey plates. On the other hand for the slightly evolved systems, the GR-driven recurrence times are quite long; MB, especially with somewhat reduced efficiency, may be acceptable. To be conservative the standard τ_R will be determined by the observed recurrence time where available, or by GR losses for the short period systems and nuclear evolution-driven recurrence rates for $P_b > 0.4^{\rm d}$. Some check on the disk replenishment picture can be obtained from estimates of average mass transfer rates. McClintock et al. (1995) estimate a continued transfer rate of $10^{-10} M_\odot$/y for A0620-003 from the accretion disk emission, about $1.3\times$ the rate for the τ_{GR} estimate above.

It is interesting to speculate why MB appears to be inefficient in the short period systems – with the high primary mass and large mass ratio, tidal forces may suppress convection in secondaries with normally convective envelopes, reducing any associated magnetic wind. An examination of secondary spectra for evidence of coronal activity may provide opportunities for testing this idea.

3. Galactic distribution, extinction

To extrapolate from a local X/O nova rate to a galactic population of low mass BHB systems, one needs a distribution model. Here it is assumed the black holes are distributed similarly to other high mass star products at birth, namely the Galactic neutron stars. To minimize the extrapolation to the Galactic center, the BH systems are distributed according to the model of Johnston (1994) for the pulsar Galactic surface density

$$\Psi(R) \propto \exp(-R^2/2R_0^2), \qquad R > 3.7\,{\rm kpc}$$

$$\propto 0.734 \times \exp(-[R-3.7]^2/2R_i^2), \qquad R < 3.7\,{\rm kpc} \qquad (3.1)$$

with $R_0 = 4.8$ kpc and $R_i = 1.5$ kpc, which provides a good fit to the observed pulsar distribution, and avoids a large excess inside the ~ 3.7 kpc molecular gas ring. The thickness z of this disk is modeled as a Gaussian distribution with $\sigma = 100$pc. This model follows recent high mass star formation; it might be argued that this under-counts old systems produced by the bulge. For example, in Sect. 6 the classical novae are considered, which have a significant bulge population. These are observed to follow the distribution of light in external galaxies, so Shafter (1997) models the Galactic population as

$$\Psi_{disk} \propto \exp(-R/R_D), \qquad R_D = 5\,{\rm kpc}$$

$$\rm{Log}\Psi_{bulge} \propto -3.33[(R/R_e)^{1/4} - 1], \qquad R_e = 2.7{\rm kpc} \qquad (3.2)$$

The scale heights of these populations are 100pc and 200pc respectively (Warner 1995) and, following the surface brightness distribution, 12% of the systems are found in the bulge.

The observed low mass BHB transients are discovered in X-rays, but confirmed via radial velocity studies in the optical. The quiescent counterparts are generally very faint, and optical extinction is a serious impediment to their study (Table 1). Extinction will, of course affect their outburst magnitudes and can be a very significant limit on detectability, even for systems with $d \lesssim 3$ kpc. To follow the distribution of optical extinction with *l*, *b* and d in the Solar neighborhood, one may use the compilation of Galactic reddening from stellar observations described in Guarinos (1992). From this compilation of ~15,500 measurements one may extract stars close to any given $(l,\, b)$ and follow the increase of A_v with d to model the local extinction. In practice, regions of radius $\sim 1 - 3°$ were used along the Galactic plane, and the top tercile of A_v in each distance bin was selected to minimize bias against rare high A_v lines of sight. These data allowed estimates out to $d \sim 2 - 3$ kpc in the plane. When A_V were needed at larger d than covered by the data for a given line of sight, an exponential dust disk of height 100pc and mean extinction in the plane of ${\rm d}A_V/{\rm d}r = 1$ mag/kpc was assumed (cf. Burton and Deul 1987). There are, of course, long interarm regions that are relatively dust free in the galaxy. To model this 10% of the nominal disk's dust density was assigned randomly to 0.2 of the lines of sight beyond the local 2-3 kpc. This turned out to have a very small effect on the BHB statistics. This extinction model was checked against a number of measured extinctions, giving adequate estimates. While rare lines of sight through very large A_V molecular clouds are not followed, the results should be reasonable for modeling of the nearby outburst sample.

4. Survey sensitivity and coverage

Three main X-ray surveys are considered that have discovered or co-discovered all of the known low mass BHB transients and that dominate the historical sky coverage. These are the Ariel 5 ASM survey, the Ginga ASM survey and the ongoing BATSE survey of the high energy sky, for which only discoveries before mid-1995 are considered. Estimating the effective sensitivities

Table 3. X-ray sky surveys

Survey	Range	Dates	T_{obs}	$f_{th}(\mathrm{erg/cm^2/s})$
Ariel 5	$2-6\mathrm{keV}$	$1974.9-1980.2$	5.3	1.5×10^{-9}
Ginga	$1.5-6\mathrm{keV}$	$1987.2-1991.9$	4.7	7.0×10^{-9}
BATSE	$20-300\mathrm{keV}$	$1991.4-$	3.1	7.0×10^{-9}

of these surveys for the discovery of isolated transients with sufficient significance that they received detailed study is quite difficult. Certainly this is well above the threshold for monitoring fluctuations or detecting low intensity recurrences of known sources. It is also well above the flux limit of the faintest transients that have been detected; in particular archival analysis of these sky survey data sets can reveal fainter outbursts. Further, for these satellites pointed observations were also able to detect sources at substantially lower fluxes — these however add little to the integrated sky coverage. Even for the sky survey components of these missions the on-time for coverage of the Galactic plane is not always 100%; e.g. for the Ginga ASM an effective coverage of ∼30% is estimated (Tanaka, private communication). However for bursts similar to the identified BH transients, the relatively long decay time (Table 1) makes it probable that the source can be caught in a high state and decreases the incompleteness due to the partial temporal coverage.

In this paper the sky survey sensitivity is estimated from the flux at the first reported detection of a number of new transients (eg. 1524-617, Kaluzienski et al. 1975; GS 2000+250, Makino 1988; GRO 1915+05, cf. Grindlay et al 1996). The epochs of the surveys, the modeled duration and the estimated threshold sensitivity referenced to the appropriate soft (2-6keV) or hard (20-300keV) band are listed below (Table 3). For Ariel 5, confusion in the inner Galaxy seriously decreased the source sensitivity (Warwick et al. 1981); the sensitivity for $|l| < 45^\circ$ is decreased to $4\times10^{-9}\mathrm{erg/cm^2/s}$.

5. The number of galactic low mass BHB systems

These results are now used to estimate the number of low mass interacting BHB in the galaxy. The philosophy will be similar to that used in early estimates of the population of millisecond pulsars (Kulkarni and Narayan 1988; Kulkarni, Narayan & Romani 1989); one assumes that the observed sample of X/O novae is representative of the underlying population and estimates the volume (in $\mathrm{kpc^3 y}$) covered by the major surveys that discovered these objects. For each observed source i one integrates over the Galactic plane distribution (3.1) to find the fraction of the Galaxy $f_{\rm Gal}$ in which the source could have been detected (and confirmed optically, including the Galactic extinction Sect. 3) in the survey j. The extrapolated number of similar binaries of type i in the Galaxy as a whole is then

$$N_i = \frac{\tau_{R,i}}{\Sigma_j f_{{\rm Gal},ji} T_{{\rm obs},j}} \qquad (5.1)$$

Table 4. BHB numbers

Object Type	$\tau_R^{\rm a}$	N_X	$N_{X,opt}$	$\dot N_{\rm BATSE}$	$N^{\rm b}_{\rm Nova}$
0422+32	52	73	443	1.46	4.8
0620−003	58	18	137	0.03	1.6
1124−683	120	24	208	0.04	1.4
1705−250	154	116	444	0.01	0.4
2000+250	167	51	426	0.05	1.0
2023+338	26	3.8	13	0.51	4.2
Total		285	1670	2.1	13.4

[a] Adopted recurrence time (y).

[b] Estimate of novae *recorded* 1895-1975.

which can then be summed to obtain the total Galactic population.

Note that inclusion of low mass BHB in this study requires both X-ray detection and an optical radial velocity study. The estimated number of Galactic systems thus depends on the completeness of this optical confirmation. These radial velocity studies are generally done in the R band, to mitigate against Galactic extinction and to increase sensitivity to the cool late type secondaries. For the standard estimate, it is assumed that the X-ray selected X/O novae with quiescence magnitudes brighter than $m_R = 20.5$ have been well studied. Some fainter low mass BHB have been observed, but other excellent candidates at brighter magnitudes remain to be dynamically confirmed (*e.g.* 1009-45=Vel93 at $m_R \lesssim 20$ – note that Beekman et al. 1997 list this as a highly likely BH system). The sensitivity to this assumption is noted below. For the standard assumptions (Ψ from Eq (3.1), optical limit $m_R = 20.5$) the Galactic population of systems like each of the known objects are listed in Table 4.

Assuming that none of the other X-ray detected X/O novae is a low mass BHB, and ignoring the constraints imposed by optical confirmation, one gets the estimates N_X. Including the (more severe) requirement that an optical mass function has been measured raises the numbers to $N_{X,opt}$. The estimates indicate that roughly $(N_{X,opt}/N_X\ -1)\times 6 \sim 30$ X/O novae should have been detected over the past 20y by the various sky surveys and should be awaiting dynamical (optical) confirmation. The actual number of good candidates listed by Tanaka & Lewin (1995) and Tanaka & Shibazaki (1996) from X-ray spectra and light curves is roughly 1/2 this value. This suggests that either the optical confirmation cut is too restrictive or that a good X-ray spectral study and BH candidate ID of an X/O nova requires even larger threshold fluxes (esp. for Ariel 5 and Ginga detections) than assumed in Sect. 4. Thus the accuracy of the completeness limits and temporal coverage in Sect. 4 are major remaining uncertainties in the population estimate; further study of the ASM survey data may reduce this. Interestingly, BATSE detection rates can also provide a check on the population estimates: at present sensitivities BATSE detects candidate BH X/O transients at a rate of ∼ 2/y (Tanaka and Shibazaki

1996). Thus, estimation of the rate of BATSE detections predicated on the larger $N_{X,opt}$ numbers (column 4) provides a useful check on the population numbers. This estimated BATSE rate is independent of the adopted recurrence times, but since P sources (especially 0422+32-like BHB) dominate the BATSE detections, the computation of this rate is rather sensitive to the estimated luminosities of these binaries. If the BATSE transient peak sensitivity can be reduced to $\lesssim$ 100mCrab for the entire plane as discussed by Grindlay et al. (1996), one would expect a discovery rate of $\sim$ 4.7/y.

Population estimates of this sort are most useful when the dependence on various assumptions are tested. If, for example, the optical confirmation limit is $m_R = 21$ the total number of systems is then 1220; however the predicted BATSE rate is somewhat low at 1.5 transients per year. On the other hand if the confirmation limit is as bright as $m_R = 20$, the total galactic population rises to $\sim$ 2300. If the classical nova Galactic distribution with a bulge population (3.2) is adopted for the BH novae the observed systems extrapolate to a galactic population of 2420 low mass BHB. Thus the estimate of the total number of Galactic low mass BHB systems may be uncertain by as much as a factor of ~ 2.

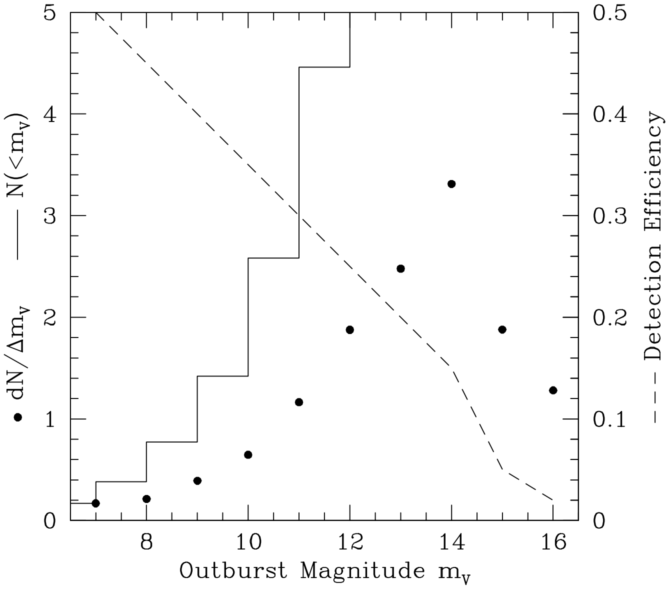

Fig. 1. Differential and cumulative numbers of X/O transient low mass BH systems expected in the historical nova catalogues covering 1895-1975. The dashed line gives the presumed recovery efficiency as a function of magnitude (right hand scale).

6. BH X/O transients masquerading as classical novae

Discoveries based on the optical outbursts have not yet been considered. As previously mentioned, X/O novae appear optically similar to classical novae with moderate amplitude, slow decay and post-maximum fluctuations (type Bb or similar). In fact, 2023+338/V404Cyg appeared in earlier nova catalogues as Nova Cyg38 and A0620-003/V616 Mon was detected in its 1917 outburst at $m_V \sim 11.5$ on archival plates and claimed to be a normal recurrent nova (Eachus, et al. 1976). Clearly outbursts can be detected in the optical, but the historical nova surveys must be very incomplete at these magnitudes. Again assuming that the X-ray selected, dynamically confirmed objects provide a fair sample of absolute luminosities at outburst, one can use the modeled distribution of low mass BHB to predict the rate of optical BHB transients as a function of magnitude and then estimate the number appearing in optical novae catalogues (eg Duerbeck 1987; Downes, Webbink & Shara 1997). It is particularly interesting to estimating the number of X/O novae recorded in the period between 1895 and 1975, when the nova discovery rate was fairly constant (Shafter 1997), but there was little or no X-ray sky coverage.

The absolute magnitudes of the recent X/O novae cluster around $M_V \sim +1$ with the exception of 2023+336 which was very luminous at $M_V \sim -4$. This is likely a consequence of the fact that the disk area in this system is $\sim$ 30 times larger than that of the other binaries. This leads us to speculate that optical outburst selection may preferentially find BHB with large P_b. Certainly an appreciable number of X/O novae prior to 1975 should have $m_V \lesssim 15$ and may be detected on archival plates. Some fraction will have been noted at outburst as novae.

Estimating this fraction, the completeness of faint nova discovery, is surprisingly difficult. Duerbeck (1984) argues that for $m_V < 3-4$ the nova discoveries are ‘complete’, while for fainter novae only $\sim 0.4-0.5$ of the potentially observable systems are discovered. The completeness clearly drops off to even fainter magnitudes, with a modern sample collected by Liller (1987) suggesting a fraction ~ 0.3 of novae (mostly brighter than $m_V = 11$) are discovered. From the (<1975) nova discovery rates as a function of magnitude listed in Warner (1995) and Shafter (1997) and a census of pre-1975 novae in Downes, et al. (1997) extending fainter than $m_V = 10$, one can attempt to use the population distribution and extinction model of Sect. 3 to estimate the discovery completeness. To do this, the absolute luminosity distribution is extracted from the bright ($m_V < 3$) novae in Shafter (1997) with measured A_V and secure distances from either nova shell expansion or detailed observations at maximum. The model novae are drawn from this parent M_V distribution, distributed according to (3.2), subject to extinction and binned into apparent luminosity ranges. Since historical novae are discovered visually or on sky survey plates, here V magnitudes and extinctions are used to more closely approximate the selection effects. Comparison of the model outburst frequency with the observed detection rate, normalized to the bright nova rate, should give the completeness. In practice the model completeness is non-monotonic with estimated discovery fractions ~ 0.7 at $m_V = 7-8$ and lower rates at $m_V = 4-6$ and at faint magnitudes. This is probably due to an insufficient number of clear sight-lines to the galactic bulge in the model (where novae at $m_V \sim 7-8$ start to appear) as a result of unmodeled small scale inhomogeneity in the ISM. However, it seems that discovery rates remain greater than ~20% to a limiting magnitude $m_V \sim 14$. A rough check of the estimates was obtained by comparing the values of $\langle A_V \rangle$ and $\langle d \rangle$ for well-studied novae at $m_V = 7-10$ against the model predictions, finding generally good agreement. It will be very difficult to improve the completeness estimates, so for now a conservative efficiency is adopted, falling smoothly from 0.5 at $m_V = 7-8$ to 0.15 for $m_V = 14$ and dropping rapidly to near 0 at $m_V = 17$ (Fig. 1). This predicts, for example, a discovery fraction 0.25 in the bin $m_V = 11-12$. This is lower than the discovery fraction of ∼0.5 implied by the fact that of the two post-1975 X-ray selected X/O novae now known to be present on archival plates at $m_V \sim 11.5$, one was noticed as a classical nova. While the estimates above are designed to be conservative, they must still be considered uncertain by a factor of ~ 2.

The efficiency of nova discovery represents a substantial uncertainty, but the number of nova in historical catalogues depends on the nova rate and, like the predicted BATSE detection rate, is not subject to uncertainties in the low mass BHB recurrence time or total population. Fig. 1 also shows, for the adopted efficiency, the number of low mass BHB expected in Duerbeck (1987) in each magnitude bin over the 80y span (1895-1975). The histogram shows the cumulative number for the brighter limiting magnitudes; the total expected in the catalogue to $m_V \sim 16$ is 13. Again this total is probably conservative, since a naive extrapolation of two systems selected during the ~ 13y of X-ray coverage extrapolated to 80y (<1975) and a recovery rate of 1/2 gives a prediction of 6 X/O novae detected brighter than 11.5. The adopted efficiencies predict 3 such X/O novae. Interestingly, more than half of the expected recoveries are from P-type systems (Table 4), which are relatively luminous and have short recurrence times. One can thus expect a modest number of X/O novae to be recovered in historical catalogues. These represent a substantial fraction ($\gtrsim 20\%$) of the recorded novae *fainter* than $m_V = 11$ at maximum.

7. Conclusions

In this paper, the X/O novae dynamically confirmed as $M_1 > 3M_\odot$ black hole candidates with low mass secondaries have been studied as representatives of the Galactic source population. This relatively homogeneous class seems to be a dominant component of the Galactic X-ray transients. It was shown that reasonable recurrence times for these systems can be derived by assuming the disk instability model with mass transfer driven by nuclear evolution of the secondary or by gravitational radiation loss of orbital angular momentum. Magnetic braking of the form commonly assumed for close binaries does not seem to operate in these systems, at least for $P_b \lesssim 0.4^{\rm d}$.

An extrapolation to the Galactic population of such systems confirms simple estimates, giving under fairly conservative assumptions a total Galactic number of ~ 1700 low mass BHB that appear as X/O novae. No one system dominates the extrapolated population numbers, so this estimate is relatively immune to uncertainties in the parameters or evolution of any one observed system. Plausible changes to the model assumptions may allow numbers to range from $\sim 1200-2400$. This substantially exceeds the number of known neutron star LMXB (∼200), most of which are persistent. There are several transient neutron star LMXB known (Tanaka & Lewin 1995, Tanaka & Shibazaki 1996). Excluding the large number of Galactic Be X-ray binaries, it seems likely that the transients will not dominate the neutron star LMXB population, both from evolutionary arguments (King & Ritter 1997) and from the smaller numbers, larger typical distance and shorter recurrence time of the detected neutron star transients compared to the BH X/O novae. A quantitative assesment of the transient contribution to the neutron star LMXB population of the sort made here for the BH systems is needed, but it seems that even including these systems there will be appreciably more BH LMXB than those containing neutron stars. Given the expectation that BH progenitors are much rarer, this presents a challenge for models of binary evolution and may place particular pressure on scenarios forming high mass ratio binaries after a common envelope phase.

The modeled X/O nova rate provides good agreement with the BATSE detection rate of X-ray transients. BATSE's hard band sensitivity prevents it from seeing most UP systems. In fact, hard spectrum objects like 0422+32 should dominate BATSE's future detections, giving a rather biased view of the BHB population. Nevertheless, follow-on radial velocity studies of X/O novae in quiescence, requiring in many cases 10m-class telescopes, should produce a steadily increasing number of sources of this class.

A similar prediction can be made for the occurrence of optical detections of X/O novae in classical nova catalogues; $\gtrsim 13$ should be present in compilations of novae recorded before 1975 in the pre-X-ray survey era. Any recovery of a BH binary from a historical nova will be particularly valuable for constraining the outburst recurrence time and the physics of the accretion disk during quiescence. More detailed study of the archive plates would, of course, turn up many more BH candidate systems. Searches of the historical novae will also be especially interesting as the selected systems will tend to be relatively bright, and hence nearby (although a possible bias towards large P_b binaries with evolved companions has been noted; roughly half of the systems with outburst magnitudes $m_v < 11$ are expected to be similar to 2023+338). The exciting possibility of discovering a system substantially closer than the closest known BH (A0620-003) is a further reason to search for historical X/O novae.

For a total population of 1670 systems, the closest example should be at $\lesssim 0.23$kpc. With an outburst frequency-weighted absolute magnitude in quiescence of $M_R = 7.7$, such a system would appear at $m_R \approx 14.7$. The average (nearest) systems will have long recurrence times, so only $\sim 20\%$ would be present in historical nova catalogues. Nevertheless, the nearest recovered system would then be relatively close and bright at ~ 0.4kpc, even disregarding the optical bias towards recovering the brightest nearby outbursts. The possibility of finding many more BH binary systems, including close, bright examples and eclipsing systems, raises the hope that one may be able to subject newly detected black hole binaries to a number of high precision studies. The prospect of closely studying the physics of the accretion disk and even of probing the space-time metric near the central holes themselves (eg. Zhang et al. 1997) makes the future study of low mass black hole binaries particularly appealing.

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