Black Holes in our Galaxy: Observations By PHIL CHARLES

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This paper reviews the X-ray, optical, radio and IR observations of galactic X-ray binaries suspected to contain black hole compact objects, with particular emphasis on the supporting dynamical evidence.

1. Introduction

From just one object (Cyg X-1) 25 years ago, the number of strong black-hole candidates in the Galaxy has increased dramatically in the last decade. This is due to two main factors: (i) the provision of all-sky monitoring capabilities on the current generation of X-ray observatories, and (ii) the discovery of the class of low-mass X-ray binary (LMXB) known as soft X-ray transients (SXT). These are short-period (5hrs – 6days) binaries with mostly K-M type secondaries, and many similarities with dwarf novae. Their rare, dramatic X-ray outbursts (typically separated by decades) can reach very high luminosities ($> 10^{38} \text{erg s}^{-1}$) and are considered to be accretion disc instability events. Remarkably, a very high fraction of SXTs are black-hole candidates. This is largely because they are the only LMXBs for which accurate mass determinations are possible, through the ability to undertake dynamical studies of the secondary star during the long periods of quiescence. While Cyg X-1 has been joined by other high-mass X-ray binaries (HMXB) also believed to contain black-holes, they all suffer from the serious limitation that an accurate mass is required for the early-type mass donor before it is possible to precisely determine the compact object mass. Given their complex binary evolutionary path this is difficult to obtain.

It has been more than 30 years since the first X-ray binary was optically identified (Sco X-1), but a detailed knowledge of their binary parameters only started to come in the 1970s with the identification and study of Cyg X-1, Her X-1 and Cen X-3. However, these all have early-type companions, observable in spite of the presence in the binary of luminous X-ray emission (for a review see van Paradijs & McClintock 1995). Apart from Cyg X-1, most of these high-mass X-ray binaries (HMXRBs) had pulsating neutron star compact objects, thereby providing the potential for a full solution of the binary parameters since they were essentially double-lined spectroscopic binaries. From this has come the detailed dynamical mass measurements of neutron star systems which have recently been collated by Thorsett & Chakrabarty (1998), showing that they are all consistent with a mass of $1.35\pm0.04\mathrm{M}_{\odot}$.

However, when HMXRBs are suspected of harbouring much more massive compact objects (as is the case for Cyg X-1), the mass measurement process runs into difficulties. By definition, there will be no dynamic features (such as pulsations) associated with the compact object that can be observed. Hence all mass information must come from the mass-losing companion, and the mass of the compact object cannot be determined unless the companion's mass is accurately known.

The situation for low-mass X-ray binaries (LMXBs), such as Sco X-1, is completely different, in that their short orbital periods require their companion stars to be of low mass. This can be demonstrated quite simply as follows (see King 1988). Since these are interacting binaries in which the companion fills its Roche lobe, then we may employ the useful Paczynski (1971) relation

$$R_2/a = 0.46(1+q)^{-1/3} (1.1)$$

where the mass ratio $q = M_X/M_2$. Combining this with Kepler's 3rd Law yields the well-known result that the mean density, ρ (in g cm⁻³) of the secondary,

$$\rho = 110/P_{hr}^2 \tag{1.2}$$

And if these stars are on or close to the lower main sequence, then $M_2=R_2$ and hence $M_2=0.11P_{hr}$. Therefore short period X-ray binaries must be LMXBs and so the companion star will be faint. The major observational problem with this is that the optical light will then be dominated by reprocessed X-radiation from the disc (or heated face of the companion star; see van Paradijs & McClintock 1994). This is why the optical spectra of LMXBs are hot, blue continua (U–B typically -1) with superposed broad hydrogen and helium emission lines, the velocities of which indicate that they largely arise in the inner disc region, thereby denying us access to the dynamical information that is essential if accurate masses are to be determined. Hence, the evidence for the nature of the compact object in most bright LMXBs has come from indirect means, usually X-ray bursting behaviour (as few are X-ray pulsars) or the fast flickering first seen in Cyg X-1 (and hence used as a suggestion of the presence of a black hole). [Note, however, that while it is useful to employ the Paczynski relation in this way, it is only valid for q > 1, and there is a more accurate algorithm due to Eggleton (1983) which is valid for all q.]

To make real progress in determining the nature of compact objects in our Galaxy requires dynamical mass measurements of the type hitherto employed on neutron stars in HMXRBs. But without velocity information associated with the compact object, all that can be measured (in the case of Cyg X-1, and the other two HMXRBs suspected of harbouring black holes, LMC X-1 and LMC X-3) is the mass function

$$f(M) = \frac{PK^3}{2\pi G} = \frac{M_X^3 \sin^3 i}{(M_X + M_2)^2}$$
 (1.3)

where P is the orbital period and K is the radial velocity amplitude. And since $M_2 \ge M_X$, then M_X is not accurately known because M_2 has a wide range of uncertainty ($\sim 12-20 \rm M_{\odot}$) given the unusual evolutionary history of the binary. The compact object in Cyg X-1 almost certainly is a black hole, but an accurate mass determination is not possible from the available data which simply constrain it to be $>3.8 \rm M_{\odot}$ (Herrero et al 1995). This is close to the canonical maximum mass of a neutron star, based on the oft-quoted Rhoades-Ruffini Theorem (1974). However, there are a number of assumptions built into this which need careful examination in the light of the masses of the compact objects reviewed here (see e.g. Miller 1998 and Miller et al 1998).

For the LMXBs we clearly need to find systems in which the companion star is visible, which requires sources where the X-ray emission switches off for some reason. This is the basis of the new field of study of the soft X-ray transients, hereafter SXTs (and sometimes referred to as X-ray novae). Remarkably, of the ~ 23 currently known, only 6 (i.e. $\sim 25\%$) are confirmed neutron star systems (they display type I X-ray bursts), the remainder are all black-hole candidates, the highest fraction of any class of X-ray source.

2. X-ray/Optical Behaviour

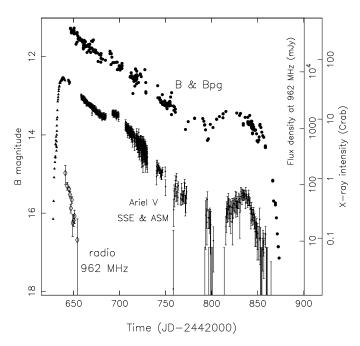


FIGURE 1. Optical, X-ray and radio outburst light curves of the prototype SXT A0620-00 (=Nova Mon 1975), adapted from Kuulkers (1998).

2.1. Outburst

The SXTs typically outburst every $\sim 10-20$ years. The first one (Cen X-2) was found by early rocket flights (Harries et al 1967), but the prototype of the class (due to its proximity and detailed multi-wavelength study) is widely considered to be A0620-00 (Nova Mon 1975), for several months the brightest X-ray source in the sky and peaking at 11th mag in the optical (Elvis et al 1975; see figure 1, taken from Kuulkers 1998). Their light curves tend to show a fast rise followed by an exponential decay (see Chen et al 1997 for a compendium of all SXT light curves), the optical amplitude of which has been shown by Shahbaz & Kuulkers (1998) to be related to the orbital period, and the precise form of the decay is related to the peak X-ray luminosity at outburst (King & Ritter 1997; Shahbaz et al 1998a).

It takes \sim 1 year for SXTs to reach optical/X-ray quiescence after an outburst, but note that there have been subsequent mini-outbursts in some systems (e.g. GRO J0422+32, Kuulkers 1998 and references therein) and erratic re-brightenings in others (e.g. GRO J1655-40). The observed properties of the 9 SXTs for which full dynamical analyses have been performed are summarised in table 1 and listed in order of orbital period, apart from separating the two SXTs which display a much earlier spectral type companion star.

At the time of outburst most (but not all) exhibit ultra-soft X-ray spectra with black-body colour temperatures of $kT\sim0.5-1 \text{keV}$ superposed on a hard power-law extending to much higher energies (see Tanaka & Lewin 1995). It is this characteristic that gives the SXTs their name, and effectively distinguishes them from the much harder Be X-ray transients that appear to be almost exclusively long-period neutron star systems. [Note also that the ultra-soft X-ray spectrum of SXTs is very different from the super-soft designation applied (mostly) to the (very) much cooler accreting white dwarf systems in the LMC and SMC (see Kahabka & van den Heuvel 1997).]

Source	Outbursts	P (hrs)	Sp. Type	E_{B-V}	$V \ (quiesc)$	K	$v\sin i \ (km/s)$	$K_2 \ (km/s)$
J0422+32	1992	5.1	M2V	0.3	22	16.2	<80	381
A0620-00	1917,75	7.8	K5V	0.35	18.3	6	83	433
GS2000+25	1988	8.3	K5V	1.5	21.5	17	86	518
GRS1124-68	1991	10.4	K0-4V	0.29	20.5	16.9	106	399
H1705-25	1977	12.5	K	0.5	21.5	-	\leq 79	448
Cen X-4	1969,79	15.1	K7IV	0.1	18.4	15.0	45	146
V404 Cyg	1938,56,89	155.3	K0IV	1	18.4	12.5	39	208.5
4U1543-47	1971,83,92	27.0	A2V	0.5	16.6	_	-	124
J1655-40	1994+	62.9	F3-6IV	1.3	17.2	-	-	228

Table 1. Optical/IR Properties of Soft X-ray Transients

Additionally the SXTs (e.g. GS2023+338) can show extremely erratic variability which is very similar to that displayed by Cyg X-1. Hence the X-ray spectrum and variability are used as key discriminators to hunt for black holes. However, it must be noted that, in certain circumstances, neutron star systems can mimic these properties (e.g. Cir X-1 and X0331+53), and so we must use only dynamical evidence in the final analysis as to the nature of the compact objects (McClintock 1991).

2.2. Quiescence

Even in quiescence, optical studies (see section 3) show that mass transfer continues in the SXTs, and indeed many have been detected by X-ray observatories (Einstein, EX-OSAT, ROSAT) as very weak sources (e.g. Verbunt et al 1994). However, the observed luminosities are substantially lower than expected for the continuing accretion rate, and this has led various groups (see e.g. Abramowicz et al 1995; Narayan et al 1997a) to propose that advective accretion is taking place. The inner disc at low accretion rates evaporates due to the X-radiation into a very hot low density corona. Such hot gas cannot radiate efficiently and transports most of its thermal energy onto the compact object (the advection process). (Such models can also account for the spectral shapes during outburst, see e.g. Chen et al 1995; Chakrabarti & Titarchuk 1995; Esin et al 1997 and Chakrabarti 1998.) If it is a black hole, then that energy is lost! But if it is a neutron star then the energy will be radiated from the neutron star's surface. The model therefore predicts that black-hole SXTs will be X-ray fainter in quiescence (relative to outburst) than neutron-star systems, and there is some evidence for this (see discussion in McClintock 1998).

2.3. X-ray Spectroscopy of BHXRBs

With Cyg X-1 as the first BH candidate, its X-ray properties were not surprisingly proposed as key indicators to help search for similar systems. Cyg X-1 exhibits 2 X-ray "states", a low, hard state with a power law spectrum extending to very high energies, and a high, soft state where the low energy data are well represented by a (multi-colour or disk) black-body spectrum at a temperature of $kT \sim 1$ keV. The power law can extend to hundreds of keV, sometimes to MeV. This is usually attributed to Comptonisation, in which case the highest energy photons require more scatterings, and hence an energy-dependent time delay would be expected. Such an effect is seen in Cyg X-1 (see van Paradijs 1998 and references therein) but it is complex.

The black-body component is explained as arising from the inner accretion disc around the compact object. Assuming that this could be approximated by a "multi-colour disc" (MCD) model which incorporates the temperature variation with disc radius, Mitsuda et al (1984) fitted the Ginga X-ray spectra to show that all those suspected (on other grounds) of being BHC had inner disc radii of $\sim 3r_S$, appropriate for stellar mass black hole candidates. r_S is the Schwarzschild radius, and ~ 3 times this value is the last stable orbit for matter around such an object. Interestingly, correcting the MCD model to allow for the effects of GR made no difference to the fitting of the continuum spectrum. However, it does affect the profiles of the spectral lines, and this is believed to have been seen in AGN (Tanaka et al, 1995; see accompanying article by Madejski), but not yet in XRBs (see Ebisawa 1997, although Życki et al (1997) have shown that such profiles are consistent with the X-ray outburst Fe line spectra obtained by Ginga). It has also recently been pointed out (Zhang et al 1997) that the BH spin can affect the size of r_S , from $\sim 1-9$ times the radius of the event horizon, and this will be discussed further below.

2.4. X-ray Spectral/Variability States

The presence of type-I X-ray bursts or pulsations immediately identifies the compact object as a neutron star, and detailed modelling of their light curves leads to constraints on the physical properties of the compact object. However, the discovery of rapid but non-periodic variability (quasi-periodic oscillations or QPOs) by EXOSAT in GX5-1 and other LMXBs (see Lewin, van Paradijs & van der Klis 1988) opened up new avenues of investigation into the physical processes occurring close to the interface between the accretion disc and compact object. Simultaneous analysis of the X-ray spectral and temporal variability led to the description of the behaviour of the source in terms of source "states" which could be understood as functions of the mass accretion rate (see review by van Paradijs 1998).

The 2-state behaviour of Cyg X-1 (with its low state, hard X-ray spectrum contrasting with the soft, high state) has been well-studied since the 1970s and is even considered as a possible black-hole diagnostic. Similar studies of the BHXRBs have extended these concepts and shown interesting correlations between their X-ray spectra and temporal variability. The presence of QPOs also reinforces their interpretation as a property of the inner accretion disc rather than the compact object. The SXT outbursts, when studied from peak to quiescence, cover a very large range in accretion rate onto the compact object, and detailed X-ray observations of N Mus 1991 by Ginga (van der Klis 1994, 1995; see figure 2) suggested that the change in its X-ray spectral and temporal behaviour was indeed a simple function of mass accretion rate. Table 2 summarises the key X-ray states observed so far in SXTs as defined by the temperature of the X-ray spectrum and variability characteristics displayed by the power density spectrum (PDS).

However, the fact that the IS has properties similar to the VHS indicate that the problem must be more complex than just a function of mass transfer rate. Care must also be taken in drawing comparisons between observations made in different energy bands, as can be seen by examining the decay light curves of Nova Mus 1991 by BATSE (see Ebisawa et al 1994).

It should also be noted that:

- the hard power law component in Cyg X-1 is very stable, it is the US component that can change on timescales of $\sim \text{day}(s)$:
 - the US component is *anti*-correlated with the radio emission:
- Barret et al (1996) proposed that observations are consistent with only the BHXRBs exhibiting both a hard power law component and a high L_X (but note the energy range concern);

BLACK-HOLE-CANDIDATE POWER SPECTRA

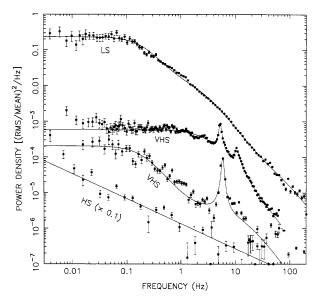


FIGURE 2. Power spectra of BHXRBs in various spectral states as observed by *Ginga*. The low state is of Cyg X-1, whereas the others are of Nova Mus 1991. From van der Klis (1995).

Table 2. X-ray Spectral and Temporal Properties of SXTs

Source State	X-ray Spectrum	Temporal Characteristics
Low (LS)	no ultra-soft (US) component	power law PDS, substantial variability
Intermediate (IS) High (HS)	US + steeper power law at high E US dominates (MCD model), very weak power law component	Lorentzian noise very little variability
Very high (VHS)	strong US + PL component	strong QPOs at $\sim 10 \text{Hz}$, Lorentzian noise

• LS BHXRBs and neutron star systems in the atoll state are very similar. Hence the presence of a solid surface and strong magnetic field makes little difference in this situation!

2.5. Light Curve Shapes

The X-ray light curves are reviewed by Tanaka & Shibazaki (1996), but are most comprehensively presented by Chen et al (1997). In spite of the similarity of GS2023+338, GS2000+25 and N Mus 1991, they do in fact exhibit a wide variety of outburst behaviour. Nevertheless the basic shape is that of a fast rise followed by an exponential decay, the latter being interpreted as a disc instability (see Cannizzo 1998, King & Ritter 1997). However, more recently Shahbaz et al (1998a) have shown that SXTs can exhibit both

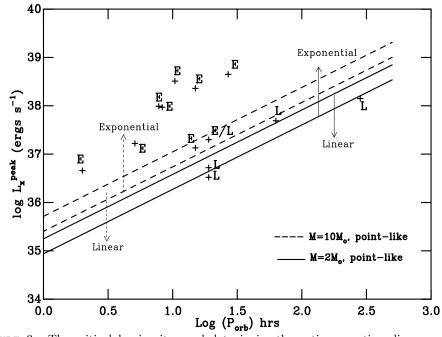


FIGURE 3. The critical luminosity needed to ionise the entire accretion disc, according to the calculations of Shahbaz et al 1998a. Results are shown for total masses of 2 and $10M_{\odot}$ corresponding to neutron star and black hole SXTs respectively. These luminosities are a factor 2 smaller for exponential decays compared to linear ones which is due to the difference in the circularisation and tidal radii of the disc. The SXTs shown are SAX J1808.4-3658, GRO J0422+32, A0620-00, GS2000+25, GS1124-68, Cen X-4, Aql X-1, 4U1543-47, GRO J1655-40 and GRO J1744-28. Observed decay shapes are designated E (exponential) and L (linear).

exponential and linear decays. As pointed out by King & Ritter (1998), the exponential decay is a natural consequence of the X-ray irradiation maintaining the disc in a hot (viscous) state, thereby producing outbursts that last much longer than in their dwarf nova analogues. If the SXT outburst is not bright enough to ionise the outer edge of the disc, then a linear decay will result. This is shown in figure 3 for those systems with known orbital period and whose decay light curve shape can be determined. Furthermore, Shahbaz et al show that the radius of the hot disc at peak of outburst is related to the time at which the secondary maximum is seen in the light curve, opening up the possibility of using the light curve as form of standard candle.

As mentioned earlier Shahbaz & Kuulkers (1998) have shown that the optical outburst amplitude ΔV is related to the system's orbital period (for periods <1 day) according to:

$$\Delta V = 14.36 - 7.63 \log P \tag{2.4}$$

where P is given in hours. This relation is shown along with the observed points in figure 4, and is essentially due to the brighter secondaries (which must be Roche-lobe filling) in longer period systems. This now provides the valuable function of being able to predict the orbital period providing the peak and quiescent magnitudes are known.

However, a key observational problem concerns SXTs' quiescent properties. Optical spectroscopy shows, in all cases strong $H\alpha$ emission, doppler tomography of which indicates continuing mass transfer into the accretion disc. However, the implied rate is not

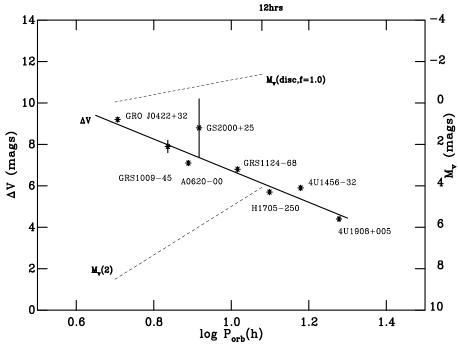


FIGURE 4. Visual outburst amplitude of SXTs as a function of orbital period, together with the least-squares fit (taken from Shahbaz & Kuulkers 1998). The dashed lines show the calculated M_V of the disk in an outbursting SXT and the M_V of the secondary star according to Warner (1995).

consistent with the very low observed quiescent X-ray fluxes. This led Narayan et al (1997b) to propose ADAFs as a means of accounting for this difference between the BH and NS systems. At low mass transfer rates, the temperature and density of gas in the inner disc region would be such as to produce a cooling time for the gas that exceeded the radial infall time. Hence the thermal energy of the gas would be advected into the black hole, and thereby lost to the observer. And while similar flows would occur in NS systems, the thermal energy would eventually be radiated from the NS surface, hence producing an apparently much higher L_X from the same rate of accreting matter.

2.6. Effect of Black Hole Spin

In spite of their observational title of SXT, there are two transients (GS2023+338 and GRO J0422+32) that do not show US components in their bright state, nor do Cyg X-1 and GX339-4 when in their hard (low) state. Both optical and X-ray studies show that this cannot be due to a high inclination in any of these. Zhang et al (1997) have calculated the disc emission from both Schwarzschild and Kerr BHs, allowing the specific angular momentum ($a_* = a/r_g$, where $r_g = GM/c^2$) to take values of 0 (non-spinning hole) and ± 1 (for maximal spin) where a negative value implies a retrograde spin. From this they inferred that we would observe a black-body (US) component whose colour temperature was a function of a_* .

Given the great distances of the SXTs (they are rare and spread throughout the galaxy), a key requirement of the US component is that it has $kT_{col} \ge 0.5$ –1 keV, in order for the emission not to be obscured by interstellar absorption. The calculations show that the highest kT_{col} (and most luminous US component) occur for $a_* = +1$, and

hence that GRO J1655-40 and GRS1915+10 must both have this value. And they are both jet sources!

Interestingly it can already be asserted that GRO J1655-40 cannot be a Schwarzschild BH as the dynamically determined $M_X = 7M_{\odot}$ requires the radius of the last stable orbit to be $2.3r_g$ and yet theoretically the minimum value required is $6r_g$.

3. Mass Measurements

3.1. Radial Velocity Curves

It is when they reach quiescence that the SXTs become such valuable resources for research into the nature of LMXBs. Their optical brightness has typically declined by a factor of 100 or more, with all the known SXTs having quiescent magnitudes in the range 17–23. The quiescent light is now dominated by the companion star and, while technically challenging, presents us with the opportunity to determine its spectral type, period and radial velocity curve (whose amplitude is the K-velocity). From the latter two we can calculate the mass function (equation 1.3) and the results for the same 9 systems (this time listed in order of their mass functions) are summarised in table 3, again separating out the two early spectral type systems as well as the single neutron star SXT, Cen X-4. Hence the enormous importance of the SXTs, since all are LMXBs which have $M_X > M_2$. The mass functions in table 3 represent the absolute minimum values for M_X since (for all of them) $i < 90^{\circ}$ and $M_2 > 0$, both of which serve only to increase the implied value of M_X . That is why the work of McClintock & Remillard (1986) on A0620-00 and Casares et al (1992) on V404 Cyg has generated so much interest.

It should also be noted that it can be possible to derive some dynamical information about the system even during outburst, providing spectroscopic data of sufficient resolution is obtained. Casares et al (1995) observed GRO J0422+32 during one of its subsequent "mini-outbursts" and found intense Balmer and HeII λ 4686 emission that was modulated on what was subsequently shown to be the orbital period. Furthermore, a sharp component of HeII displayed an S-wave that was likely associated with the hotspot.

However, to determine the actual value of M_X we need additional constraints that will allow us to infer values for M_2 and i.

3.2. Rotational Broadening

Since the secondary is constrained to corotate with the primary in short period interacting binaries, we can exploit our knowledge of its size by making assumption 1 that R_2 is given by equation (1). Hence the result (Wade and Horne, 1988)

$$v_{rot} \sin i = \frac{2\pi R_2}{P} \sin i = K_2 \times 0.46 \frac{(1+q)^{2/3}}{q}$$
 (3.5)

from which q can be derived if v_{rot} is measurable. Typical values are in the range $40-100 \text{ km s}^{-1}$ and clearly require high resolution and high signal-to-noise spectra of the secondary.

Figure 5 (second from top) shows the Casares & Charles (1994) WHT summed spectrum of V404 Cyg after doppler correcting all individual spectra into the rest-frame of the secondary. The bottom spectrum is a very high S/N spectrum of a K0IV star which was used as a template, and which clearly has much narrower (actually they are unresolved) absorption lines. The template is broadened by different velocities (together with the effects of limb darkening), subtracted from that of V404 Cyg and the residuals χ^2 tested. This gave $v_{rot} \sin i = 39 \pm 1 \text{ km s}^{-1}$ and hence $q = 16.7 \pm 1.4$. The full details

Source	$f(M) \ (M_{\odot})$	$ (g \ cm^{-3})$	$(=M_X/M_2)$	i	$M_X \ (M_{\odot})$	$M_2 \ (M_{\odot})$	Ref.
V404 Cyg G2000+25 N Oph 77 N Mus 91 A0620-00 J0422+32	6.08 ± 0.06 5.01 ± 0.12 4.86 ± 0.13 3.01 ± 0.15 2.91 ± 0.08 1.21 ± 0.06	0.005 1.6 0.7 1.0 1.8 4.2	$ \begin{array}{c} 17\pm 1 \\ 24\pm 10 \\ >19 \\ 8\pm 2 \\ 15\pm 1 \\ >12 \end{array} $	55 ± 4 56 ± 15 60 ± 10 54^{+20}_{-15} 37 ± 5 $20-40$	$12\pm 2 10\pm 4 6\pm 2 6^{+5}_{-2} 10\pm 5 10\pm 5$	0.6 0.5 0.3 0.8 0.6 0.3	[1-2] [3-5] [6-9] [13-15] [16-18] [19-20]
J1655-40 4U1543-47 Cen X-4	3.24 ± 0.14 0.22 ± 0.02 0.21 ± 0.08	0.03 0.2 0.5	3.6±0.9 - 5±1	67 ± 3 $20-40$ 43 ± 11	6.9 ± 1 5.0 ± 2.5 1.3 ± 0.6	2.1 2.5 0.4	[10–12] [21] [22–23]

Table 3. Derived Parameters and Dynamical Mass Measurements of SXTs

Casares & Charles 1994; [2] Shahbaz et al 1994b; [3] Filippenko et al 1995a; [4] Beekman et al 1996; [5] Harlaftis et al 1996; [6] Filippenko et al 1997; [7] Remillard et al 1996; [8] Martin et al 1995; [9] Harlaftis et al 1997; [10] Orosz & Bailyn 1997; [11, 12] van der Hooft 1997, 1998; [13] Orosz et al 1996; [14] Casares et al 1997; [15] Shahbaz et al 1997; [16] Orosz et al 1994; [17] Marsh et al 1994; [18] Shahbaz et al 1994a; [19] Filippenko et al 1995b; [20] Beekman et al 1997; [21] Orosz et al 1998; [22] McClintock & Remillard, 1990; [23] Shahbaz et al 1993.

can be found in Casares & Charles, and Marsh et al (1994). It should also be noted that while the accretion disc around the compact object might be expected to provide some velocity information, there are serious difficulties with this. The H α line in figure 5 is extremely broad ($\geq 1000 \text{ km s}^{-1}$) and yet the compact object's motion in such high q systems will be very small (typically $\leq 30 \text{ km s}^{-1}$). Nevertheless such motions have been seen (e.g. Orosz et al 1994), but their interpretation is not straightforward as there is a small phase offset relative to the motion of the companion star, and so they cannot be used as part of the dynamical study.

Having determined q, the range of masses consistent with the observed f(M) is plotted in figure 6, where the only remaining unknown is the orbital inclination i. To date, none of the SXTs is eclipsing (although GRO J1655-40 shows evidence for a grazing eclipse), and so it is the determination of i that leads to the greatest uncertainty in the final mass measurement. Nevertheless there are methods by which i can be estimated.

Note also, that high mass ratios for these systems is also implied by the work of O'Donoghue & Charles (1996) which demonstrates the *superhumps* have been seen in SXT optical light curves during outburst decay. Such features had been seen before during the *superoutbursts* of the SU UMa subclass of dwarf novae and are attributed as arising from tidal stressing of the accretion discs in high mass ratio interacting binaries. Their calculation of system parameters based on this model provides satisfactory confirmation of these values.

3.3. Ellipsoidal Modulation

We exploit one more property of the secondary, it's peculiarly distorted shape responsible for the so-called *ellipsoidal modulation* as we view the varying projected area of the secondary around the orbit. This leads to the classical double-humped light curve, as

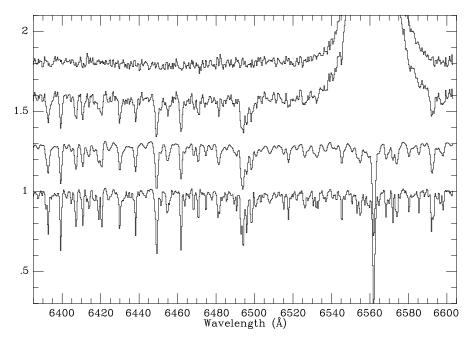


FIGURE 5. Determining the rotational broadening in V404 Cyg. From bottom to top: the K0IV template star (HR8857); the same spectrum broadened by 39 km s⁻¹; doppler corrected sum of V404 Cyg (dominated by intense $H\alpha$ emission from the disc); residual spectrum after subtraction of the broadened template (from Casares and Charles, 1994).

shown for A0620-00 in figure 7. If the secondary's shape is sufficiently well-determined by theory (i.e. the form of the Roche lobe) then the observed light curve depends on only 2 parameters, q and i. In several cases (as described in the previous section) q is already determined, but in practice the ellipsoidal modulation is largely insensitive to q for values q > 5. Details of the light curve modelling can be found in Shahbaz et al (1993), and the collected results are in table 3.

This final stage in the SXT orbital solutions has made 2 key assumptions: assumption 2, that the secondary in quiescence fills its Roche lobe; assumption 3, that the light curve is not contaminated by any other light sources. It is felt that the former is reasonable since there is strong evidence through doppler tomography (e.g. Marsh et al 1994) for continued mass transfer in quiescence from the secondary. However, the principal (and potentially significant) uncertainty is the problem of any other contaminating light sources. This would mainly be the accretion disk, but residual X-ray heating and starspots on the surface of the secondary might also be present. It is for this reason that this work has been performed in the K band whenever possible. The disc contamination has been measured in the optical around $H\alpha$ (as a by-product of the spectral type determination by searching for excess continuum light) and is typically <10%. It should therefore be even less in the IR given the blue colour of the disc. However, the outer disc edge has been found to be an IR emitter in CVs (Berriman et al 1985) and the light curves might be contaminated, as was suggested in the case of V404 Cyg by Sanwal et al (1996). This is potentially an important effect, since a contaminating (and presumably steady) contribution will reduce the amplitude of the ellipsoidal modulation, which will lead to a lower value of i being inferred, and hence a higher mass for the compact object.

For this reason Shahbaz et al (1996, 1998b) undertook IR K-band spectroscopy of the

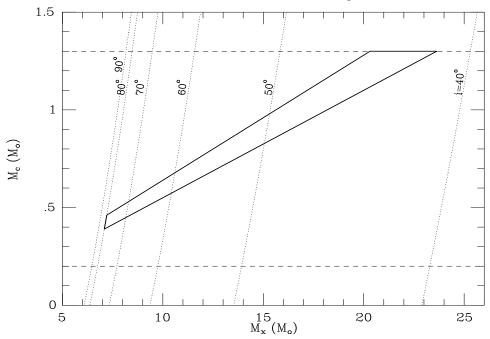


FIGURE 6. Constraints on M_X and M_2 for a range of values of i in V404 Cyg based on the radial velocity curve (f(M)) and determination of q (from the rotational broadening). It is the limited constraint on i (absence of eclipses) that leads to a wide range of M_X (from Casares and Charles, 1994).

two brightest and best studied SXTs, V404 Cyg and A0620-00. Only upper limits were derived in both cases, showing that any contamination must be small and hence the masses derived can (at most) be reduced by only small amounts. It is also interesting to note that, in their study of the non-orbital optical variability in V404 Cyg, Pavlenko et al (1996) found that (as first noted by Wagner et al 1992) the ellipsoidal modulation could be discerned underlying the substantial flickering in the light curve. Interpreting the flickering as a completely independent component, Pavlenko et al showed that the lower envelope of this light curve (rather than the mean) produced an ellipsoidal light curve which, when fitted as described above, gave essentially identical results to those obtained from the K-band analysis, thereby providing further weight to the significance of the mass determinations.

The results of these analyses are collected together in figure 8, which contains all neutron star and black hole mass measurements. It should also be noted that the value for Cen X-4 (one of only two neutron star SXTs, identified on the basis of its type I X-ray bursts) has been derived exactly by the method outlined here (Shahbaz et al 1993) and yields a value of $1.3M_{\odot}$, in excellent accord with that expected for a neutron star.

4. Lithium in the Companion Stars

One of the remarkable by-products of our high resolution radial velocity study of V404 Cyg was the discovery of strong LiI λ 6707 absorption in the secondary star (Martı́n et al 1992). This was, of course, not present in any of the template stars which we were using for the spectral fitting, since Li is a characteristic feature of young, premain sequence and T Tau objects. Subsequent convection in late type stars leads to the

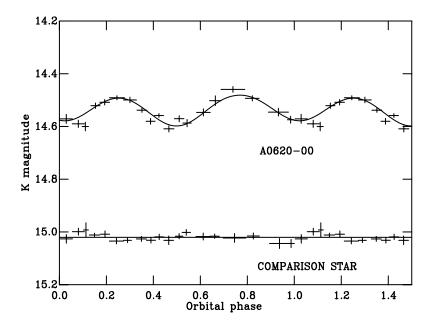


Figure 7. IR light curve of A0620-00 showing the classical double-humped modulation (from Shahbaz et al, 1994a).

destruction of lithium, and observed abundances in normal stars (like the Sun) are a thousand times lower. Similar Li enhancements have since been identified in A0620-00, J0422+32, GS2000+25, N Mus 1991 and Cen X-4 (see Martín et al 1996), the latter indicating that this phenomenon is not confined solely to the BHC.

Li is an important element in galactic chemical abundances because galactic material is found to be enriched in Li relative to the halo, and the source of this enrichment is a subject of current research. Since the SXTs are clearly highly evolved objects which are extremely unlikely to have retained such high Li abundances, then we must find mechanisms create Li within the structure of an SXT. Those systems in which Li has been detected cover a wide range of period and secondary size, but they all display high luminosity, recurrent X-ray outbursts. Martín et al (1994) therefore suggested that spallation processes during these outbursts produce Li in large quantities close to the compact object. Subsequent large mass outflows result in the transfer of some of this Li to the secondary, the energetics of which are considered by Martín et al (1994). Support for this suggestion is cited as the interpretation of the 476keV γ -ray line that was observed during the N Mus 1991 outburst (Sunyaev et al 1992; Chen et al 1993). Originally interpreted as the gravitationally redshifted e^--e^+ 511keV line, it might instead be associated with the 478keV line of ⁷Li. The temporal behaviour of this line (it only lasted for about 12 hours) could give insight into the spallation mechanism. That high luminosities are needed, whatever the mechanism, is indicated by the absence of Li in CVs of comparable spectral type to the SXTs, nor has Li been detected in the nova GK Per (Martín et al 1995).

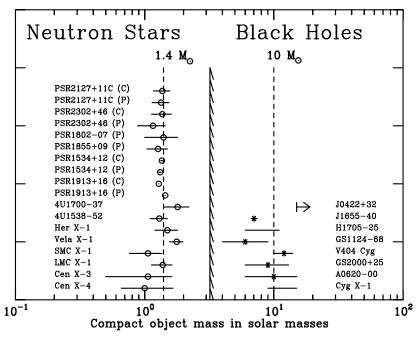


FIGURE 8. The mass distribution of neutron stars and black holes. Note the remarkably narrow spread of neutron star masses, and the large factor by which the BHXRB masses exceed the (canonical) maximum mass of $3.2M_{\odot}$.

5. The Superluminal Transients

In 1994 there were two new X-ray transients discovered, GRS1915+105 and GRO J1655-40, that brought an entirely new type of behaviour to this field. As with many of the transient outbursts, they also emitted strongly in the radio, but VLA and VLBI observations showed that these objects also exhibited ejection events that were "superluminal" (Mirabel & Rodríguez 1994; Hjellming & Rupen 1995), the first time that such phenomena had been observed within the Galaxy. Further dynamical studies of GRS1915+105 are severely hampered by (a) its extremely high interstellar extinction ($A_V \sim 26$), leaving only a variable, K \sim 14 IR counterpart, and (b) its continuing and extremely variable X-ray activity that is totally unlike any of the "classical" SXTs. It is not even clear that GRS1915+105 is an LMXB (see Mirabel et al 1997), and it demonstrates an extraordinarily rich variety of X-ray variability (e.g. Morgan & Remillard 1996, Belloni et al 1997).

GRO J1655-40 (N Sco 1994), on the other hand, is optically the brightest in quiescence of all the SXTs, and so has extremely well-determined photometric light-curves, and is an excellent candidate for a dynamical study. The companion also has one of the earliest (confirmed) spectral types (mid-F) of the SXTs which means that, in quiescence, the effects of the accretion disk are very small, almost negligible. And the high γ -velocity led to the suggestion (Brandt et al 1995) that J1655-40 could be an example of a NS system that had suffered accretion-induced collapse. However, J1655-40's behaviour is not at all typical of other SXTs, with quiescent studies severely hampered by its return to activity in 1996. This return was fortuitously observed by Orosz et al (1997) who found that the optical brightening began \sim 6 days before the X-ray activity began. They (and Hameury et al 1997) interpreted this as an "outside-in" outburst of the accretion

disc, with the substantial delay arising due to the ADAF flow (in quiescence) having evaporated the inner disc, and which needed to be re-filled before accretion onto the compact object could take place. Subsequent multi-wavelength (UV/optical/X-ray with HST and RXTE) observations of this period of activity (Hynes et al 1998) demonstrated two interesting properties. They found that the X-ray and optical variations were, at times, correlated, but with the optical variations lagging the X-ray by ~ 19 secs. With the known size of the binary from its orbital period, this lag is too short to be due to irradiation of the secondary, and hence must be associated with the accretion disc. Furthermore, Hynes et al found that as the outburst progressed, the optical/UV emission declined as the X-rays increased! They suggested that this might arise through the driving of a large corona early in the outburst which can then allow subsequent upscattering of hard X-rays later on. However, this requires much more extensive and detailed multi-wavelength studies to be undertaken throughout an outburst in order for it to be fully tested.

The orbital system parameters have been derived from several photometric studies of J1655-40 by van der Hooft et al (1997), Orosz & Bailyn (1997) and van der Hooft et al (1998). Figure 9 shows the van der Hooft et al light curve together with the system schematic of Orosz & Bailyn. The values recorded in table 3 are those from the latter paper due to their more conservative error analysis. J1655-40 is unusual in this class in that it has a low mass ratio of $q\sim3$ (but this has not yet been obtained from a rotational broadening study, due to its return to activity shortly after its initial outburst). At such a value, the ellipsoidal modulation is sensitive to both q and i (the latter also being tightly constrained here as a result of its grazing eclipse). Hence, once it becomes possible to spectroscopically determine the rotational broadening of the F star (when it re-enters an extended period of quiescence) it will then be possible to perform a check of the entire basis on which the quiescent SXT light curves have been modelled and used to determine i. It has also been suggested (Kolb et al 1997) that the secondary star is in a very interesting evolutionary state in which it is crossing the Hertzsprung gap and about to ascend the giant branch. This is what is driving the much higher mass transfer rate than in the other SXTs, but temporary drops in M return it to the transient domain.

6. Outburst Mechanisms

Over the last 10 years there has been the same debate over the mechanism for SXT outbursts as had been taking place over the cause of dwarf nova outbursts, with the same two competing models, namely enhanced mass transfer from the secondary star (as a result of X-ray heating) and the thermal (viscous) instability in the accretion disc itself (both are discussed by Lasota 1996). However, as a result of much more sensitive quiescent X-ray observations of SXTs by ROSAT (Verbunt 1996) it is clear that these levels of X-ray emission (as low as $2.5 \times 10^{30} \mathrm{erg \ s^{-1}}$ for A0620-00) are incapable of heating the secondary star sufficiently to generate the mass transfer necessary to account for the observed outbursts. And whilst there have been models proposed (e.g. Chen et al 1993; Augusteijn et al 1993) that combine elements of both the mass transfer and disc instability explanations, these have not yet been supported by observations.

Strong support for the disc instability model has appeared in papers by van Paradijs (1996) and King et al (1996). They point out that, when calculating whether the disc instability mechanism will occur in an SXT disc (which requires that the temperature somewhere in the disc be below the ionisation temperature of hydrogen, 6500K), it is necessary to take into account the effects of (time-averaged over outbursts) X-ray heating.

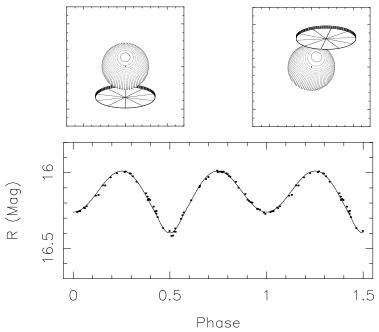


FIGURE 9. R-band light curve of GRO J1655-40 taken by van der Hooft et al (1997) when the source was quiescent. To obtain acceptable fits (shown) it was necessary to add partial obscuration by a cool accretion disc at phase 0.5, as demonstrated in the system schematic (above) taken from Orosz & Bailyn (1997).

In this way they derive an expression for the X-ray luminosity (as a function of period) that separates the steady and transient sources:

$$\log L_X = 35.8 + 1.07 \log P \tag{6.6}$$

and find that this is very well supported by the observations. Indeed, the continued activity of GRO J1655-40 has brought it very close to this line, indicating that it is in fact "almost" a steady source. The average SXT mass transfer rate from the secondary is found to be:

$$\langle M_2 \rangle = -4 \times 10^{-10} P_d^{0.93} M_2^{1.47} M_{\odot} y^{-1}$$
 (6.7)

giving values $\sim 10^{-10} \rm M_{\odot} \rm y^{-1}$ for most SXTs, but about $3 \times \rm higher$ for GRO J1655-40.

7. Population Size and Distribution

Important questions for current and future surveys for X-ray transients, such as those likely to be undertaken with AXAF and XMM in nearby galaxies (M31 and M33), concerns the number of quiescent systems, the chance of their being observed if they do outburst, and their distribution through the galaxy. The largest uncertainty in such calculations is the typical recurrence time of an SXT. Following Tanaka & Shibazaki (1996), the current sample's outburst properties (table 1) show that this can range from less than a year to ~ 50 years. However, the average is likely to be around 10–20 years, with typically 2 SXTs being observed per year (with regular all-sky coverage by CGRO and RXTE). With $\sim 90\%$ of SXTs located within a galactic longitude range of $\pm 80^{\circ}$,

this implies that they lie within 8kpc of the Galactic Centre, but distance estimates for the current sample suggest they are all <5kpc from us. Hence, we are only detecting $\sim 10\%$ of the transients that occur within our galaxy (due to a combination of interstellar absorption and sensitivity), and the total number of SXTs is $\sim 200-1000$ for assumed recurrence times of 10 and 50 years respectively. Long-term surveys of nearby galaxies will allow these estimates to be more rigorously examined, as well as deriving more accurate luminosities and galactic distribution information.

White & van Paradijs (1996) have examined and compared the distribution in galactic latitude and longitude of the BHC LMXBs and the NS systems. They find that the BHC have a dispersion in z of $\sim 400 \, \mathrm{pc}$, whereas the NS are $\sim 1 \, \mathrm{kpc}$, interpreting the difference as an indication that the kick velocities received in BH formation are less than in NS. The corrolary of this is that the BHC LMXBs are not formed by the accretion-induced collapse of a NS (except possibly GRO J1655-40) where the higher NS kick would be inherited by the resultant BH.

8. Nature of the Compact Object

Since the existence of compact objects with masses $\geq 10 M_{\odot}$ can now be taken as secure, the question arises as to what are they. Or, more importantly, what is the maximum mass of a neutron star? This is usually quoted as $3.2 M_{\odot}$ on the basis of the *Rhoades-Ruffini Theorem* (1974). But there are a number of assumptions built into this theorem that, if relaxed, can lead to a very different result (see Miller 1997 and references therein).

In particular, the assumption of causality (which requires the sound speed to be less than c) is only applicable in a non-dispersive medium. Also, the density up to which the equation of state is well-defined may be optimistically high. Both these effects, together with significant rotation of the compact object, can lead to the maximum mass of the neutron star only being constrained to be $<14M_{\odot}!$ Nevertheless, it should be recognised that current models of neutron star equations of state are compatible with the original $3.2M_{\odot}$ limit.

However, an alternative suggestion that such compact objects may be Q-stars has been made by Bahcall et al (1990). In such objects, the strong force confines neutrons and protons at densities below nuclear density, leading to a very different equation of state (in which the Q stands for conserved Quantity, the baryon number). They can be very compact and hence consistent with our current understanding of the properties of neutron stars. But Miller, Shahbaz & Nolan (1998) have shown that if this model is to be applied to V404 Cyg (i.e. that it is a Q-star of $12M_{\odot}$), then it requires that the threshold density for this effect must be $\sim 10 \times$ below that of nuclear density, which is considered to be too implausible given the results of current experiments. In which case, we conclude that V404 Cyg and related objects must be black holes.

9. Conclusions

The dramatic advances in the field of galactic black-hole studies have come about during this decade for 2 main reasons: (i) the almost continuous monitoring of the X-ray sky that is now provided by all-sky monitors such as those on CGRO and RXTE has provided a steady stream of new X-ray transients for subsequent ground-based observations once they reach quiescence, and (ii) the availability of high performance optical spectrographs with good red sensitivity on 4m and larger telescopes. With these facilities we have obtained more detailed information about the nature of both components of LMXBs than was hitherto possible. In particular, the discovery of the mass function of

V404 Cyg has revolutionised attitudes concerning the existence of compact objects that must be heavier than the canonical maximum mass of a neutron star. And while there are useful indicators from X-ray observations as to the possible presence of black holes in X-ray binaries, the ultimate diagnostic has to be the dynamical study that has been described here. The next major advances will come from observing the many quiescent transients that are too faint for current 4m class telescopes and require access to the about to be completed VLT and Gemini telescopes in the southern hemisphere.

10. Future Work

The SXTs are providing a very fertile hunting ground for BH candidates, and with CGRO and RXTE both having all-sky monitors there should be a steady stream of new transients discovered over the next decade. Key questions to be addressed include:

- are there any low-mass ($<5M_{\odot}$) BHs?
- i.e. formed in 2 stages via accretion-induced neutron star collapse (see Brown et al. 1996).
 - or any very high-mass (>20 M_{\odot}) BHs?
- i.e. from massive stars that succeeded in retaining most of their mass until the time of collapse.
 - or are they all formed from He stars at the end of the W-R phase?
- therefore we need at least a dozen *accurate*, *i.e.* < 10% mass determinations, which will require exploiting the new generation of 8–16m class telescopes.
 - can advective flows demonstrate the existence of the Event Horizon in the BHXRBs?
- or high resolution X-ray spectroscopy of Fe emission line profiles reveal the distorted shape expected due to General Relativity?

The observations have now securely established compact objects with masses in the $5{\text -}15{\rm M}_{\odot}$ range, and if they are *not* BHs then this has profound implications for particle physics (and general relativity). Once thought impossible, SXTs allow perhaps the cleanest study of the BH environment.

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