

# Resolved Jets and Long-Period Black Hole X-ray Novae

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## ABSTRACT

In this brief note we point out that the four spatially resolved relativistic jets among the 14 dynamically confirmed black hole X-ray novae are all in systems with long orbital periods. Many shorter period systems show transient radio outbursts which are attributed to jets, but these jets have not been spatially resolved. Super-Eddington accretion has been suggested as a requirement for jet formation and may be consistent with our compilation of luminosities, but some super-Eddington outbursts did not form spatially resolved jets. We speculate that some as yet unknown process (or combination of processes) favors formation of substantially larger jets in long period systems. Two short period systems show evidence for extent, but have not been resolved into multiple components as the long period systems have.

## 1. Introduction

The discovery of relativistic jets in SS433 (Margon et al. 1979, Margon 1984) brought the study of jets into the Galaxy from its previous extragalactic home. The speed of these  $v = 0.26c$  jets was emphatically exceeded with the discovery of  $v = 0.92c$  jets in GRS 1915+105 by Mirabel & Rodriguez (1994). This “microquasar” was the first galactic source to show apparent velocities exceeding the speed of light. This discovery led to a search for superluminal jets in other galactic X-ray binaries, and  $\sim$  a dozen examples have now been found (Mirabel & Rodriguez 1999).

Many X-ray binaries have been observed with radio interferometers (Hjellming & Han 1995). While most binaries are unresolved by these observations, the similarities in both rapid variability and the spectral indices between resolved and unresolved sources has led to the belief that relativistic jets are commonplace in X-ray binaries (Mirabel & Rodriguez 1999, Fender 2002). While it is clear that jets occur in X-ray binaries with both neutron star and black hole primaries, there is a trend

for the most relativistic jets (ie, those with  $v > 0.9c$ ) to be associated with black holes (Mirabel & Rodriguez 1999, Livio 1997, but see Fender 2002 for exceptions to this trend).

Soft X-ray transients (SXTs) are a subclass of X-ray binaries which, rather than being persistently bright at X-ray wavelengths, erupt from near invisibility to become among the brightest objects in the sky at X-ray wavelengths. They then fade away in  $\lesssim 1$  year. It is thought that most SXTs ( $\gtrsim 70\%$ ) contain black hole primaries (e.g. Charles 1998). In particular, there are 14 systems where dynamical mass estimates indicate the presence of compact objects that are too massive to be neutron stars (e.g. see the recent review by Orosz 2002). We will refer to these systems as the “dynamical confirmed” black hole X-ray nova (BHXN). Radio observations, which have the potential to detect and perhaps resolve relativistic jets, have been made of nearly all of these. Fender & Kuulkers (2001) present a thorough summary of these observations, noting which have been resolved. They include in addition the related fast transients and neutron star transients (their Table 1). By separating the sources into those containing neutron stars and those suspected of containing black holes, they show that the black hole systems are more radio loud than those containing neutron stars.

In what follows we concentrate on these 14 BHXN, because the dynamical data gives us insight into the nature (size, evolutionary state, mass transfer rate) of these systems which is less available for the other systems. We separate the systems into those having long and short orbital periods. Among these 14 systems, 6 have periods longer than a day. This is an important dividing line among the systems, as the nature of the secondary changes at this period. For periods less than a day the secondaries are close to the main sequence and the mass transfer is driven by gravitational radiation and/or magnetic braking, while at longer periods the secondaries have begun to evolve off the main sequence and the mass transfer is driven by the nuclear evolution of the secondary (which leads to higher time averaged mass transfer rates; Menou et al. 1999; King, Kolb, & Burderi 1996). These evolved secondaries include stars which are in the Hertzsprung gap (GRO J1655-40, Kolb, King & Ritter 1997) and low mass giants (GRS 1915+105, Greiner et al. 2001), and they all share the common property of being able to drive high mass transfer rates.

We note that by restricting our sample to dynamically confirmed BHXN, we may introduce an observational bias: the secondary must be bright enough to allow moderate S/N phase resolved optical spectra to be obtained, which will be difficult for systems at the greatest distances or with the smallest secondaries (ie, the shortest periods). However, 8 of the 14 systems in the sample are short period systems and their distances extend out to nearly the same range as the long period systems (eg, XTE J1859+226 with a period of 9.2 hours is at 11 kpc, see Table 1). The similar numbers and distances for long and short period systems indicates that the search for resolved jets is not biased by this effect.

## 2. Data

We have gathered observational data on dynamically confirmed BHXN from the literature and summarize it in Table 1. The list is ordered by orbital period (column 2), with the shortest period first (XTE J1118+480). The object with the longest period is GRS 1915+105, recently found to have a period of 33.5 days (Greiner, Cuby & McCaughrean 2001). This was also the first BHXN system found to have resolved relativistic jets (Mirabel & Rodriguez 1994).

The peak outburst luminosities (column 3) are generally from Narayan, Garcia & McClintock 1997 (hereafter NGM97) or Garcia et al. 1998 and references therein, but have been adjusted to approximate the bolometric ( $\sim 0.1$ -100 keV) luminosity, as this is likely of most interest to the theory of jet formation. As the NGM97 compilation covered the 1-40 keV range, this adjustment increases the luminosity by a factor of  $\sim 2$  for sources which show a “soft excess” (often modeled by multi-temperature disk black body) in their X-ray spectrum. We note that this adjustment is uncertain, as the low energy cutoff of the detectors (and the ISM) renders the flux below  $\sim 1$  keV unobservable for all but one (XTE J1118+480) of the sources in our sample. The distances (column 4) are taken from Lee, Brown & Wijers (2002), and the dynamical data (columns 5 and 6) is taken from Orosz 2002, unless noted as otherwise in the table footnotes. We have taken  $L_{Edd} = 1.1 \times 10^{38} (M_x/M_\odot)$ , appropriate for cosmic abundances and a moderate (neutron star like) redshift correction (Galloway et al. 2002). We assume a mass in the center of the range listed in column 5.

In column 7 we indicate if the system has been resolved into multiple components (MC). Throughout the following text we refer to resolved sources as those which have been separated into two (or more) spatially separate components. We note that this is qualitatively different from determining that a source is extended, ie, larger than the beam of the detector. Upper limits to the size of the radio counterparts are not always quoted in the literature. In these cases, we quote an upper limit (column 8) corresponding to the array beam size as listed in the on-line documentation for each telescope given the array configuration at the time of observation. The delay (column 9) is the time between the X-ray discovery and the first radio interferometric observations. Note that this time is shorter than the time required for the jets to reach the extent listed in the previous column.

We note that these observations span a large range of times after the outburst, sometimes beginning within days, other times within weeks of the outburst. The observations often extend for a year or more. If large scale jets fade to undetectable levels with a few days of an outburst they may be missed in some objects. For example, the September 1999 outburst of V4641 had an extraordinarily fast rise and fall at both X-ray and radio wavelengths. The resolved relativistic jet was visible only for the two days following the outburst, and the longer lasting (3 week) remnant might not have been associated with a jet if not for the prompt observations that detected the jet (Hjellming et al. 2000). However, relativistic jets have also been detected long after the initial X-ray discovery, for example GRS 1915+105 continues to show resolved jets many years after discovery (Fender et al. 1999); the resolved jets in GRO J1655-40 were found  $\sim 3$  weeks after the discovery

of the X-ray source (Zhang et al. 1994; Tingay et al. 1995; Hjellming & Rupen 1995); and those in XTE J1550-564 are visible several years after they were generated (Corbel et al. 2002). Therefore delays of a few days in the start of observations should not bias the sample against finding resolved, relativistic scale jets in the short (or long) period systems.

## 2.1. Notes on Individual Objects

### 2.1.1. Short Period Systems

XTE J1118+480: Approximately 1 month after the start of the outburst, high resolution imaging with MERLIN and a  $65 \times 35$  mas beam found the source unresolved (Fender et al. 2001). At approximately the same time, and in addition 2 months later, observations with the VLBA found the source unresolved at the  $\sim 1$  mas level (Mirabel et al. 2001). This provides the strongest upper limit to the size of any radio jet in a short period BHXN. Given the association of jets with outbursts near the Eddington luminosity, it is relevant to note that the outburst of XTE J1118+480 was unusually faint as compared to the other short period systems. The system never left the 'low-hard' state to enter the more luminous 'high-soft' state. Given the the observed power-law spectrum, the 1-160 keV luminosity from McClintock et al. (2001) is within  $\sim 5\%$  of that in our fiducial bolometric band of 0.1-100 keV.

GRO J0422+32: This BHXN was observed for over a year at the VLA in configurations ranging from D-array to A-array, and from 2 to 20 cm. There were no reports that the system was resolved, and it was well detected at 2 cm during A-array observations 3 months after the start of the X-ray outburst (Shrader et al. 1994). As the HPBW of this configuration is  $0.14''$ , we list this as the upper limit to the size of any jet. However, we note that the initial observation of the radio source  $\sim 10$  days after the X-ray outburst (Han & Hjellming 1992) had a HPBW of  $\sim 12''$  (VLA in D-array, detection at 6 cm wavelength).

The most complete coverage of the X-ray light curve was provided in the hard X-rays (20-200 keV) by CGRO/BATSE. Observations at  $\sim 1/2$  the peak luminosity with TTM allowed coverage down to 2 keV, and did not show the existence of an extra soft component. The maximum X-ray luminosity listed in Table 1 covers the 2-600 keV band and should be close to the bolometric luminosity (Esin et al. 1998).

GRS 1009-45: The 1993 outburst of GRS 1009-45 was not observed in the radio, and no post-outburst radio observations have been reported (Brocksopp et al. 2002, Masetti, Bianchini & Della Valle 1997). It is therefore not possible to search for radio jets in this source.

We use the same method and parameters as described in Barret et al. 2000 to estimate the distance to GRS 1009-45, but we use a new (fainter) measurement of the quiescent magnitude ( $R = 21.2 \pm 0.2$ ) from Filippenko et al. 1999. The largest uncertainty in the distance is due the lack of an accurate spectral type, and we find distances from 7.5 kpc to 12.8 kpc for M0 to K5 surface

fluxes. Assuming a K8 spectra type we find a nominal distance of 9 kpc.

The peak X-ray luminosity is uncertain due to the lack of continuous coverage below 20 keV. The 1-10 keV flux as reported by Tanaka et al 1993 during an ASCA observation  $\sim 2$  months after the X-ray peak corresponds to a luminosity of  $\sim 2 \times 10^{38} \text{erg s}^{-1}$  at the 9 kpc distance estimated by Filippenko et al. 1999. The 20-100 keV X-ray light curve (Chen et al. 1997) shows that the hard X-ray flux was down from the peak by a factor of 10 at the time of this ASCA observation, and also shows that the peak X-ray luminosity was  $1.8 \times 10^{38} \text{erg s}^{-1}$ . Scaling up the ASCA flux by  $10\times$  in order to account for the decay and adding in the observed 20-100 keV flux, we approximate the peak luminosity from 1-100 keV as  $\sim 2 \times 10^{39} \text{erg s}^{-1}$ , but note that the observed peak flux is only 10% of this. We note that soft excesses are often observed near the peak of XRN outbursts, so even though there is no data to confirm its presence at the peak of the GRS 1009-45 outburst such a component seems likely given its presence during the decay. We therefore approximate the bolometric luminosity in Table 1 as twice the 1-100 keV luminosity.

A0620-00: The 1975 outburst of A0620-00 pre-dated the VLA, but it was observed with the NRAO Green Bank Interferometer with a  $\sim 2'' \times 10''$  beam (Owen et al. 1976) and the Jodrell Bank MkII-III Interferometer (Davis et al. 1975). At the time, there were no reports that the radio source was resolved. A subsequent investigation of the hand drawn plots from Davis et al. (1975), along with a new estimate of the observational errors, may provide evidence that the outburst was resolved at  $\sim 3''$  size (Kuulkers et al. 1999).

At its peak, the  $\sim 2$ -100 X-ray spectrum of A0620-00 showed a soft component and a hard tail (Ricketts et al. 1975). The peak 1-18 keV X-ray luminosity was  $1.3 \times 10^{38} \text{erg s}^{-1}$  at 1 kpc (Elvis et al. 1975). From Figure 2 of Ricketts et al. (1975) we estimate the hard tail would contribute only  $\sim 10\%$  to this total. However, below 1 keV the soft spectrum could contribute an additional  $\sim 1.6 \times 10^{38} \text{erg s}^{-1}$  to the total luminosity, and we therefore list in Table 1 a peak bolometric luminosity of  $4 \times 10^{38} \text{erg s}^{-1}$  at a revised 1.1 kpc distance.

GS 2000+25: VLA observations 9 days after the start of the outburst failed to detect this source, but 22 to 60 days later it was detected as an unresolved source. The observations used the VLA C/D array, and detected the source at 1.49 Ghz to 14.9 Ghz (Hjellming et al 1988). We estimate a size of  $< 1.2''$  from the HPBW of the VLA C array at 2 cm.

The peak X-ray luminosity is taken from NGM97 (1-40 keV), but has been adjusted up by a factor of two to account for the soft component in the spectrum (Tsunemi et al. 1989, Terada et al. 2002).

XTE J1859+226: As in the case of A0620-00, this BHXN may prove to invalidate our suggestion that resolved relativistic jets are only seen in long-period systems. Observations of the 1999 outburst at the VLA show evidence of a faint structure  $\sim 0.7''$  in extent approximately 20 days after the X-ray outburst began (Brocksopp et al. 2002). Further details on this faint structure will appear in a forthcoming paper (Brocksopp et al. 2002).

The peak X-ray flux listed in Table 1 is the bolometric accretion disk flux calculated by Hynes et al. (2002) on 18 Oct 1999, but including the factor of  $\sim 2$  additional flux in the observed power-law component, corrected for the 11 kpc distance and scaled to the ASM peak of 1.5 Crabs seen two days earlier.

GRS 1124-683 (Nova Muscae 1991): Observations with the ACTA detected this BHXN during a phase of decaying radio emission 10 days after the outburst, and also during the rise of a second radio flare 20 days after the outburst (Ball et al. 1995). The source was not reported to be resolved, and from the HPBW at 2 cm for the 2.5 km maximum baselines used we estimate an upper limit to the source size of  $2''$ .

The maximum (bolometric) X-ray luminosity listed in Table 1 is the 1-40 keV luminosity listed in NGN97, adjusted for a distance of 5.1 kpc (Gelino, Harrison & McNamara 2001) and increased by a factor of 2 in order to include the observed soft component (Ebisawa et al. 1994, Greiner et al. 1994) that we assume extends below 1 keV.

H1705-250 (Nova Oph 1977): There were no radio observations of the only recorded outburst of this source in 1977 (Brocksopp et al. 2002). VLA observations of the source in quiescence during 1986 failed to detect it, yielding an upper limit of  $\sim 5$  mJy at 6 cm (Nelson et al. 1988).

The X-ray luminosity is the 1-40 keV luminosity from NGM97, but corrected by a factor of two in order to account for the bolometric luminosity likely present in the soft component of the observed X-ray spectrum (Cooke et al. 1984).

### 2.1.2. Long Period Systems

4U 1543-47: This BHXN has been observed to have outbursts in 1971, 1983, 1992, and most recently in 2002. The brightest of these outbursts was that in 1983 (Chen et al. 1997). Garcia et al. (1998) estimate that the peak luminosity of this outburst was  $4 \times 10^{39}$  (1-20 keV, at 8 kpc). The very soft X-ray spectrum (van der Woerd et al. 1989) would indicate a bolometric luminosity  $\sim 2\times$  larger. This, and the revised distance estimate of 7.5 kpc (Orosz et al. 2002c) would indicate a peak luminosity for this outburst of  $\sim 7 \times 10^{39}$  erg s $^{-1}$ . There were no radio observations of the 1992 outburst (Brocksopp et al. 2002). Observations during quiescence in 1998 did not detect a radio remnant from any of the previous outbursts (Hunstead & Webb 2002).

The 2002 outburst also showed a very soft spectrum (Miller & Remillard 2002). It reached a peak rate in the ASM of  $\sim 320$  c/s (1 Crab = 73 c/s). Assuming the spectrum was similar to that measured by Tenma in 1983 (thermal bremsstrahlung with  $kT=1.6$  keV, Kitamoto et al. 1984) this corresponds to a bolometric luminosity of  $3.2 \times 10^{39}$  erg s $^{-1}$  at 7.5 kpc. Observations of this outburst with the MOST did detect a radio transient (Hunstead & Webb 2002). The source was not reported to be extended. The modest beam size of MOST therefore indicates a size  $\lesssim 1'$ . Table 1 lists these parameters for the 2002 outburst.

XTE J1550-564: Resolved ( $\sim 5''$ ) relativistic ( $v \sim 2c$ ) radio jets were observed shortly after the first strong X-ray flare in September 1998 (Hannikainen et al. 2001). Emission from material associated with these jets was observed in the radio and X-rays roughly 4 years later at angular separations from the source of  $\sim 20''$  (Corbel et al. 2002). In addition, Corbel et al. (2001) suggested that the radio spectrum and variability during the decay of the 1998 outburst indicated the presence of much smaller jets on a mas scale.

The X-ray flux of XTE J1550-564 reached a peak during a bright flare on 1998 Sept 19. The power law dominated the spectrum at this time, so it is not necessary to correct the bolometric flux for an additional soft component. Table 1 lists the 1-20 keV flux from Orosz et al. (2002b), which is within 20% of that computed by Sobczak et al. (2002) for the bolometric disk plus 2-100 keV power law component. We note that there is a strong soft component during the plateau immediately following the bright flare, but the bolometric flux at this time is substantially lower (Geirlnski & Done 2002).

GRO J1655-40: Radio emission was not detected until  $\sim 10$  days following the 27 July 1994 X-ray outburst of this source (Harmon et al. 1995, Zhang et al. 1994). The radio source was not resolved until  $\sim 3$  weeks after the X-ray outburst (Tingay et al. 1995). Nearly 3 months after the outburst it was visible at the VLA (1.3 cm) as a pair of jets separated by up to  $\sim 5''$  (Hjellming and Rupen 1995). At 20-100 keV energies, this outburst appeared as five (or more) discrete outbursts over more than 1 year. The first three of these has simultaneous radio flares, but the last two were very radio quiet (Rupen 2002). The 1997 outburst also produced a radio flare, but the VLA was in its most compact array (D) and was unable to resolve structures on the size seen in 1994 (Rupen 2002).

GRO J1655-40 is unusual among the long period systems in not reaching an outburst luminosity of  $\gtrsim 10^{39} \text{erg s}^{-1}$ . The 1994/5 outburst pre-dated the RXTE/ASM, so the entire outburst light curve was accessible only at energies above 20 keV as afforded by CGRO/BATSE. ASCA observations revealed the presence of a soft component in the X-ray spectrum containing  $\sim 40\%$  of the luminosity at a time when the bolometric luminosity was estimated to be  $\sim 10^{38} \text{erg s}^{-1}$  (Zhang et al. 1997, Zhang PC 2002). The rates in the BATSE band were 2-5 times below their peak during this ASCA observation (Zhang et al 1997). We therefore estimate that the bolometric luminosity at peak was  $5 \times 10^{38} \text{erg s}^{-1}$  and list this value in Table 1.

V4641 Sgr: The maximum luminosity during the very fast, 12 Crab X-ray flare lasting  $\lesssim 1$  hour was  $6 \times 10^{39} \text{erg s}^{-1}$  (2-100 keV), or  $3 \times 10^{39} \text{erg s}^{-1}$  (2-10 keV) (Orosz et al. 2001). This flare was observed only with the RXTE/ASM, so it is not possible to determine if there is an additional soft component which might increase the bolometric luminosity beyond that in the 2-100 keV band. At much lower flux levels (0.01 and 0.3 Crab) I'nt Zand et al. (1999) note the presence of an additional soft component, but Smith, Levine & Morgan (1999) note that the spectrum during the 12 Crab flare is "harder than the Crab". We therefore assume the 2-100 keV flux is close to bolometric, and list this in Table 1.

V4641 Sgr was observed with the VLA  $\sim 16$  hours following the bright 12 Crab flare, and was resolved into a jet with  $0.25''$  extent. Observations 2 days later showed that the jet had faded below the detection limit, but the core (presumed point of origin of the jets) was marginally resolved and remained visible for another 26 days (Hjellming et al. 2000).

GS 2023+338 (V404 Cyg): This very bright radio transient ( $\sim 1$  Jy) was not resolved at the VLA despite extensive observations using many array configurations (Han & Hjellming 1992). Because the source was not resolved, we take as an upper limit to its size the HPBW of the A-array at 2 cm which is  $\sim 0.14''$ . Rapid ( $\sim 5$  minute) fluctuations of the radio flux and the necessity to avoid the Compton catastrophe require a source size of  $\sim 0.2$  mas (Han & Hjellming 1992).

The outburst spectrum of GS 2023+338 was unusual in that it did not show an obvious soft thermal component (Tanaka 1989), instead being consistent with a power-law with photon index  $\sim 1.7$  (Terada et al 1994). Careful review of the GINGA spectrum shows that the  $\sim 1$  keV soft thermal component did make a brief appearance, perhaps at sub-peak luminosities, but was shrouded by heavy absorption and/or comptonization (Zycki, Done & Smith 1999).

The flux appeared to reach a maximum saturation level (perhaps equal to the Eddington limit) early on 30 May 1989, at which time the soft component showed a temperature of  $\sim 0.2$  keV. The bolometric luminosity at this time is computed to be  $\sim 3 \times 10^{39}$  erg  $s^{-1}$  (Zycki, Done & Smith 1999) and this value is listed in Table 1. We note that the that the 1.7-37 keV luminosity computed by Terada et al. (1994) assuming a simple power-law model is  $\sim 50\%$  below our adopted value.

GRS 1915+105: The first reported detection of the radio counterpart of this now prototypical microquasar was approximately 4 months after the X-ray outburst began (Mirabel et al. 1992). A large radio flare began  $\sim 1.5$  years after the discovery of the X-ray transient (Rodriguez & Mirabel 1993), which was subsequently resolved into relativistic jets (Mirabel & Rodriguez 1994).

The maximum X-ray luminosity during bright (10s) flares reaches an unabsorbed value of  $7 \times 10^{39}$  erg  $s^{-1}$  (1-200 keV). The bolometric luminosity (if the emission extends down to 0.1 keV) may be as high as  $6 \times 10^{40}$  erg  $s^{-1}$  (0.1-200 keV, Greiner et al. 1998), and we list this value in Table 1. This source continues to be active at X-ray and radio wavelengths and continues to generate relativistic jets (Fender et al. 1999).



Table 1: Multiple Component Radio Jets in BHXN

ID(outburst year)	Spectral Type	P <sub>orb</sub> hr	L <sub>max</sub> /L <sub>Edd</sub> erg s <sup>-1</sup>	D kpc	M <sub>X</sub> M <sub>⊙</sub>	<i>i</i>	MC?	Size	Radio Obs	Delay
Short Period Systems										
XTE J1118+480(00)	K7V-M0V	4.1	36.1(1)/38.9	1.9	6.5-7.2	81 ± 2	N	< 0.001''(3)	VLA, VLBA, Merlin,Ryle	1 month(2,3,4)
GRO J0422+32(92)	M0V	5.1	37.7(45)/38.7	2.6(4)	3.7-5.0	44 ± 2	N	< 0.14''(5)	VLA	10 days(6)
GRS 1009-45(93)	K6-M0	6.8	39.6?(7,8)/38.6	9(9,25)	3.6-4.7?	67?	N/A	N/A	NONE	N/A(10,11)
A0620-00(75)	K4V	7.8	38.6(12,13)/39.1	1.1(14)	8.7-12.9	40.8 ± 3	N(?)	≲ 3''	JB1,GB1	14 days(15,16)
GS 2000+25(88)	K5V	8.3	38.6(14,17)/38.9	2.7	7.1-7.8	64.0 ± 1.3	N	< 1.2''	VLA	9 days(18)
XTE J1859+226(99)	...	9.2	38.9(19)/39.0	11(20)	7.6-12.0?	high	N(?)	≲ 1''	VLA, Merlin	2 days(11)
GRS 1124-683(91)	K4V	10.4	38.9(14,21)/38.9	5.1(46)	6.5-8.2	54 ± 2	N	< 2''	ACTA, MOST	9 days(22)
H1705-250(77)	K3V	12.5	38.6(14,23)/38.9	8.6	5.6-8.3	> 60	N/A	N/A	VLA	11 years(24)
Long Period Systems										
4U 1543-47(02)	A2V	26.8	39.5(25)/39.0	7.5(26)	8.4-10.4	20.7 ± 1.5	N	< 1'	MOST	1.5day(27)
XTE J1550-564(98)	G8IV-K4III	37.2	39.2(28,29)/39.0	5.3	8.4-10.8	72 ± 5	Y	> 20''	VLA, ACTA MOST, VLBI, LBA	2 days(30,31)
GRO J1655-40(94)	F6III	62.4	38.7(32)/38.8	3.2	6.0-6.6	70.2 ± 1.2	Y	0.1''-5''	VLA, VLBA	10 days(33,34,35)
SAX J1819.3-2525(99) (V4641 Sgr)	B9III	67.6	39.8(36)/38.9	10	6.8-7.4	75 ± 2	Y	0.25''	VLA, Merlin	1 day(37)
GS 2023+338(89) (V404 Cyg)	K0IV	155	39.4(38,39)/39.1	3(40)	10.0-13.4	56 ± 4	N	~ 0.2mas	VLA	9 days(41)
GRS 1915+105(92)	K-MIII	804	39.8(42)/39.2	12.5	10.0-18.0	70 ± 2	Y	> 1''	VLA, Merlin	4 months(43,44)

Notes for Table: The dynamical data (periods, masses, inclinations) are taken from Orosz (2002). Distances and spectral types are from Lee, Brown & Wijers (2002), unless otherwise noted. Maximum outburst luminosities are from Garcia et al 1998 or NGM97 unless otherwise noted, but have been adjusted to be bolometric. The X-ray energy bands listed below correspond to the range covered by the observations. Radio data is from a variety of sources, often multiple. The 'Delay' refers to time between X-ray discovery and first radio interferometric observations. Additional refs: (1)1-160 keV, McClintock et al. 2001,(2)Fender et al. 2001,(3)Mirabel et al. 2001,(4)Pooley & Waldram 2000;(5)Shrader et al. 1994,(6)Han & Hjellming 1992;(7)Chen et al. 1997,(8)Tanaka et al. 1993,(9)Filippenko et al. 1999,(10)Masetti et al. 1997,(11)Brocksopp et al. 2002;(12)2-18 keV, Elvis et al. 1975,(13)2-80 keV, Ricketts et al. 1975,(14)NGM97,(15)Davis et al. 1975,(16)Kuulkers et al. 1999;(17)Terada et al. 2002,(18)Hjellming et al. 1998;(19)Hynes et al. 2002,(20)Zurita et al. 2002;(21)Greiner et al. 1994,(22)Ball et al. 1995;(23)Cooke et al. 1984,(24)Nelson et al. 1988;(25)This work, (26)Orosz 2002c,(27)Hunstead and Webb 2002;(28)Orosz et al. 2002b,(29)Sobczak et al. 2000,(30)Hannikainen et al. 2001,(31)Corbel et al. 2002;(32)Zhang et al. 1997, Zhang P.C. 2002,(33)Harmon et al. 1995,(34)Tingay et al. 1995,(35)Hjellming & Rupen 1995;(36)Orosz et al. 2001,(37)Hjellming et al. 2000;(38)Tanaka 1989,(39)Zycki, Done & Smith 1999, (40)Shahbaz et al. 1994,(41)Han & Hjellming 1992b;(42)Greiner et al. 1998,(43)Mirabel et al. 1992,(44)Mirabel & Rodriguez 1994(45)2-600 keV, Esin et al. 1998,(46) Gelino, Harrison & McNamara 2001

### 3. Discussion

From Table 1 we see that the four systems with well resolved (multiple component) relativistic jets are XTE J1550-564, GRO J1655-40, V4641 Sgr, and GRS 1915+105, which all have orbital periods  $\gtrsim 1$  day. The data also suggests that the radio counterparts of two short period systems (A0620-00 and XTE J1859+226) may be larger than the beam size. However, the data is unequivocal only in the case of these four long period systems. That is, relativistic jets have so far only been resolved into two separate, moving components in long period systems. It appears that a long orbital period and bright outbursts are necessary, but not sufficient, to give rise to resolved jets. For example, the long period systems V404 Cyg and 4U 1543-47 both have had super-Eddington outbursts, but resolved jets have not been found in either.

Given the small number of sources in the sample, we should ask what the odds are that this apparent trend is merely a coincidence. In doing so, we should leave GRS 1009-45 (not observed) and H1705-250 (not detected) out of consideration, as there are no observational constraints on them. This leaves equal numbers of long and short period systems. Depending upon exactly how one asks the question, the probability is  $= 0.5^4 = 6.3\%$  (assuming each detection of a resolved jet is equivalent to a trial with 50% probability of selecting a long or short period system) or  $(6 \text{ pick } 4)/(12 \text{ pick } 4) = 3\%$  (from the combinatorics of selecting 4 jets out of the 6 long period systems vs. the number of ways to select 4 jets out of all 12 systems). In either case the significance of the correlation is suggestive ( $3\% \sim 1.8\sigma$ ) but certainly not overwhelming.

Could observational biases lead to this correlation? Certainly the distances of the two classes of sources are not systematically biased, so any observed differences in jet angular scales would indicate physical size differences. The resolved jets in the long-period systems are typically  $\gtrsim 1''$  (V4641 Sgr, GRO J1655-40, GRS 1915+105) or even more ( $\gtrsim 20''$  in the case of XTE J1550-564). Most of the upper limits to jets sizes in the short-period systems are of a similar scale, ie,  $\lesssim$  a few arcsec (GS 2000+25, A0620-00, XTE J1859+226, GRS 1124-683), but the limits for GRO J0422+32 and XTE J1118+480 are factors of  $\sim 10$  and  $\sim 1000$  smaller. However, the peak luminosities of these two systems were  $\sim 0.1$  and  $\sim 0.001$  of Eddington, so neither had the very bright outburst apparently required to produce resolved jets.

Radio jets can be associated with the transition from a quiescent to outbursting state and may fade in a few days, (ie, V4641 Sgr, Hjellming et al. 2000) in which case prompt observations are required to detect them. The delay between the X-ray outburst and the first interferometric radio observations (column 10) ranges from 1 (2) days to 4 months (11 years) with a median of 5 (10) days for the long (short) period systems. However, jets may also be visible for years after the outburst has faded (ie, XTE J1550-564, Corbel et al. 2002) indicating that prompt observations are not always required. Brocksopp et al. (2002) tabulate the radio observations of 13 of the 14 sources in our sample, and note that the initial rise was observed in the radio in only two systems, one with a short period (XTE J1859+226) and one with a long period (XTE J1550-564).

There are several possible physical reasons to expect and/or explain the correlation which may

be present. We discuss some of these possibilities below, but conclude that the situation is currently unclear.

Could this difference be related to the smaller physical size of the short period binary orbits? Certainly the jets in AGN are larger than those in microquasars. Assuming similar black hole masses, GRO J0422+32 and XTE J1118+480 (the two shortest period systems, also with the tightest limits to jet size) have orbital separations  $\sim 5x$  smaller than V4641 Sgr and GRO J1655-40 (which have periods near the median for the long-period sample). If the longer period systems have higher masses (Lee, Brown & Wijers 2002) this difference would be further enhanced, but even if we make the extreme assumption that they have twice the mass of the short-period systems the orbital scales are only  $\sim 6$  times larger. This difference is not negligible and might explain an order of magnitude difference in the apparent jet sizes. Orbital dimensions alone cannot account for the factor of  $\gtrsim 1000$  difference in the size of the jets in the long period systems when compared to the best limit among the short period systems (that in XTE J1118+480, of  $< 0.001''$ ), but given the very low outburst luminosity of XTE J1118+480 this comparison may not be appropriate.

King (1998) suggested that jets appear in systems with 'Hertzprung gap' secondaries, leading to super-Eddington mass transfer. Others (ie, Mirabel & Rodriguez 1999, Fender 2001) have also suggested that the presence of jets is related to super-Eddington mass transfer. The data in Table 1 provides some support for this, in that the peak X-ray luminosities of 3 of the 4 resolved sources are super-Eddington. The fourth (GRO J1655-40) is apparently not super-Eddington, although it did reach within  $\sim 70\%$  of its Eddington luminosity. However, given the lack of continuous coverage below 20 keV one must allow the possibility that this system did reach (unobserved) super-Eddington luminosities. While the data allows that it may be necessary to reach super-Eddington luminosities in order to produce resolved jets, it does not appear to be sufficient. The long period systems V404 Cyg (39.5), 4U1543-47 (39.5) both were super-Eddington and did not display resolved jets. The short period systems GRS 1124-683 (38.9) and XTE J1859+226 (38.9) both reached, but apparently did not exceed, the Eddington luminosity.

Under low luminosity conditions, the inner edges of BHXN accretion disks may be truncated long before they reach the last stable orbit by evaporation of the disk into an advection or convection dominated flow (Narayan et al. 1996, Hameury et al. 1997, Liu et al. 1999, Meyer-Hofmeister & Meyer 2001). It has been suggested that the rapid filling of this cavity in the inner regions of the accretion disk is necessary to generate relativistic jets (Mirabel & Rodriguez 1999). There is some evidence that the size of this cavity may scale with mass, and that the mass of the BH in the long period BHXN is larger than that in the short period systems (Bailyn et al. 1998, Orosz et al. 2002b, Lee, Brown & Wijers 2002). However, V4641 Sgr shows a strong Fe-line in quiescence which may show the signature of relativistic broadening in the inner disk, indicating that this BHXN does not have a large cavity in the accretion disk during the low state (Miller et al. 2002).

Could the spins be higher in the long period systems, and could this cause larger jets? Blandford & Znajek (1977) demonstrated that it is possible, at least in principle, to extract rotational

energy from a black hole with high angular momentum through magnetic field lines threading the horizon. Observationally, magnetic connections to gas in the plunging region (the region inside of which there are no stable orbits) may be quite similar. This may provide an energy source for powering jets from black holes (see, e.g., Blandford 2001). This has some observational appeal: VLBI observations of M87 constrain the point of jet collimation in this AGN to be within 100 Schwarzschild radii (Junor, Biretta & Livio 1999); this suggests a fairly compact region is involved in forming the jet. Moreover, this source is well-described by ADAF models (e.g., Di Matteo et al. 2003), so the jet is not likely driven by a disk in this source.

Evidence for significant angular momentum (or, black hole spin) has also been implied in many Galactic black holes and black hole candidates, but it is not yet clear if the spin has been accurately measured in any source. This evidence has been found through a variety of methods: measurements of the inner disk radius using continuum X-ray spectroscopy (Zhang, Cui & Chen 1997), via measurements of rapid QPOs (Remillard et al. 2002), and via measurements of relativistically broadened Fe emission lines (Miller et al. 2002).

The first method used to estimate the spin in a substantial number of BHXN was to measure the inner radius of the disk via fitting the continuum spectra to multi-color disk black body (MCBD) models (Mitsuda et al. 1984). Using this method Zhang, Cui & Chen (1997) found nearly maximal spins ( $a \sim 1$ ) for GRO J1655-40 and GRS 1915+105 and near zero spins ( $a \sim 0$ ) for GS 1124-68 and GS 2000+25. Hynes et al. (2002) derive an inner disk radius from MCBD fits to XTE data that is consistent with a low spin for XTE J1859+226.

The MCBD method has some uncertainties that are not shared by the other two methods. Not only does the measured inner disk radius depend on the distance to the source and the inclination of the inner disk (which may be different from the system inclination), but the model itself may fail to account for changing opacities due to Comptonization effects (see Shimura & Takahara 1995; see also Merloni, Fabian, & Ross 2000). Regardless of the uncertainties in the theory, the varying dominance of different spectral components may make it difficult to do the spectral deconvolutions necessary to measure the inner disk temperature and radius. For example, while Zhang et al. (1997) find a nearly maximal spin ( $a = 0.93$ ) based on ASCA spectroscopy of GRO J1655-40, Sobczak et al. (1999) apply the same method to a much larger RXTE dataset on the same source and find a much lower spin ( $a = 0.5$ ) and a lower limit consistent with zero spin.

As the Keplerian orbital frequency at the marginally stable circular orbit around a non-spinning black hole scales roughly as  $\nu \simeq 220\text{Hz}(10 M_{\odot}/M_{BH})$ , the observation of QPOs at similar frequencies in systems with mass constraints may also provide a means of measuring black hole spin. Evidence for spin has been revealed via this means in GRO J1655-40 (Strohmayer 2001,  $0.15 < a < 0.5$ ), in XTE J1550-564 (Remillard et al. 2002,  $0.1 < a < 0.6$ ; Miller et al. 2001  $a > 0$ ), GRS 1915+105 (Morgan et al. 1997, Strohmayer 2001b, Remillard et al. 2002,  $a > 0$ ), and perhaps XTE J1650-500 (Homan et al. 2002).

However, uncertainty in exactly what causes the QPO (ie, Homan et al 2001, Remillard et

al. 2002) leads to uncertainty in the derived spin, and values as high as  $a > 0.9$  may be allowed for XTE J1550-564 (Remillard et al. 2002) and GRO J1655-40 (Strohmayer 2001, Remillard et al 2002). With multiple QPOs in many systems, comparative measures of the spin among different systems should likely be done by comparing the systems when they are in similar luminosity and spectral states (Mendez, Belloni & van der Klis 1998).

Broad Fe  $K_\alpha$  emission lines – sometimes asymmetrically skewed and plausibly explained as emission lines produced at the inner accretion disk – can also provide evidence of spin. At present, this technique has produced strong evidence of spin only in XTE J1650-500 (Miller et al. 2002,  $a \sim 1$ ). While we do not include XTE J1650-500 in Table 1 because its binary parameters are not yet well known, this BHXN has a short orbital period of 0.212 days (Sanchez-Fernandez et al. 2002). A measurement of the Fe-line in V4641 Sgr at a low flux level ( $\sim 10^{-3} L_{Edd}$ ) finds a line consistent with zero spin, but which does allow moderate spin (Miller et al. 2002b).

At least one of each of the three methods discussed above has been applied to each of the four jet systems in order to estimate its spin. While the estimates do not always agree, there is evidence for moderate to high spin in three of the four jet systems. The spin in V4641 Sgr may be somewhat lower. Do the two long period systems without resolved jets (V404 Cyg and 4U 1543-47) have even lower spin? V404 Cyg did not show a strong soft disk component at the peak of its outburst (Tanaka 1989), and while they did not fit MCBBD models to the spectra, Zhang, Cui & Chen (1997) suggest that this lack of a disk component may indicate a retrograde spin. However, reanalysis of the Ginga spectrum shows brief periods when there was a strong soft component hidden beneath strong low energy absorption (Zycki et al 1999). The spectrum during each of the four recorded outbursts of 4U 1543-47 has contained a strong soft excess (van der Woerd 1989), but thus far multi-color disk blackbody models have not been fit to the spectrum.

Conversely, do the short period systems (where there are no resolved jets) show evidence for lack of spin? All of the systems except for XTE J1118+480 and GRO J0422+32 show a soft component in outburst, indicative of an accretion disk possibly amenable to multi-color disk black model fits. The most interesting systems to explore would be GS 2000+25, XTE J1859+226, and GRS 1124-683, as they reached at least  $\sim 1/2$  of their Eddington luminosities and had  $\sim 1''$  resolution radio imaging within about a week of their outbursts. Hynes et al. (2002) found an inner disk radius of  $\sim 90\text{km} \sim 6R_g$  for the  $10M_\odot$  black hole in XTE J1859+226. While the spectra did not allow tight constraints on this radius, it is indicative of zero spin. Zhang, Cui & Chen (1997) have previously noted that the X-ray spectra of GRS 1124-683 and GS 2000+25 are indicative of near zero spin. However, XTE J1650-500 ( $P_{orb} = 0.212$  days) has a highly skewed Fe line indicating a very high spin ( $a \sim 1$ , Miller et al. 2002). Thus it is unclear if the short period systems have uniformly lower spin than the long period systems.

As evidence for spin is often found in the systems with resolved jets, it may be productive to explore whether the fastest jets observed may be due to the highest spin parameters (Fabian & Miller 2002). At present, robust measures of black hole spin are difficult to make. Further

observations of black holes with high time resolution and high spectral resolution instruments may be able to make more robust measurements. It is possible that magnetic connections between the disk and either the black hole or matter in the plunging region are favored at high mass accretion rates in Galactic black holes; if this is the case, spinning black holes may act to drive jets more often in the more luminous long-period binaries.

#### 4. Summary

In order to focus discussion, we have deliberately excluded several resolved relativistic jets in galactic sources which are not dynamically confirmed BHXN. In addition, it may not be fair to compare the jets even amongst this smaller sample, as they may not all be due to the same phenomena: the  $> 20''$  X-ray and radio jets in J1550-564 may be powered by deceleration, while the rapidly evolving jets from V4641 Sgr must be powered by relativistic electrons. However, the data we present do suggest that long period BHXN produce larger jets than short period systems, an observation which may provide insight into the jet formation mechanism. The data in Table 1 are consistent with the suggestion that an outburst luminosity  $\gtrsim$  Eddington is necessary but not sufficient to produce resolved, relativistic jets. Measurements of black hole spin are not yet sufficiently robust to determine the role it plays in the formation of resolved jets. As has been often noted (ie, Mirabel & Rodriguez 1999), the human time-scale of the evolution of micro-QSO jets may allow insights that are difficult to gain from the much more slowly varying extra-galactic jets.

We thank the Aspen Center for Physics for its hospitality during the summer of 2002 which allowed work on this paper to begin. MRG acknowledges the support of NASA/LTSA grant NAGW-10889 and NASA contract NAS8-39073. JMM acknowledges support from the NSF through its Astronomy and Astrophysics Postdoctoral Fellowship Program. JEM acknowledges the support of NASA ADP grant NAG5-10813. ARK gratefully acknowledges a Royal Society Wolfson Research Merit Award.

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