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Maccarone, T.J.

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Do X-ray binary spectral state transition luminosities vary?

T. J. Maccarone⋆

Astrophysics Sector, Scuola Internazionale Superiore di Studi Avanzati, via Beirut, n. 2-4, 34014 Trieste, Italy
and
Astronomical Institute "Anton Pannekoek," University of Amsterdam, Kruislaan 403,1098 SJ Amsterdam, The Netherlands

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Abstract. We tabulate the luminosities of the soft-to-hard state transitions of all X-ray binaries for which there exist good X-ray flux measurements at the time of the transition, good distance estimates, and good mass estimates for the compact star. We show that the state transition luminosities are at about 1–4% of the Eddington rate, markedly smaller than those typically quoted in the literature, with a mean value of 2%. Only the black hole candidate GRO J 1655-40 and the neutron star systems Aql X-1 and 4U 1728-34 have measured state transition luminosities inconsistent with this value at the 1σ level. GRO J 1655-40, in particular, shows a state transition luminosity below the mean value for the other sources at the 4σ level. This result, combined with the known inner disk inclination angle (the disk is nearly parallel to the line of sight) from GRO J 1655-40's relativistic jets suggest that the hard X-ray emitting region in GRO J 1655-40 can have a velocity of no more than about $\beta = 0.68$, with a most likely value of about $\beta = 0.52$, and a minimum speed of $\beta = 0.45$, assuming that the variations in state transition luminosities are solely due to relativistic beaming effects. The variance in the state transition luminosities suggests an emission region with a velocity of $\sim 0.2c$. The results are discussed in terms of different emission models for the low/hard state. We also discuss the implications for measuring the dimensionless viscosity parameter α. We also find that if its state transitions occur at typical luminosities, then GX 339-4 is likely to be at a distance of at least 7.6 kpc, much further than typically quoted estimates.

Key words. accretion, accretion disks – binaries, close – stars: neutron – black hole physics

1. Introduction

Early on, it was discovered that the spectral energy distributions of X-ray binaries showed variations with luminosity. At low luminosities, these systems typically show hard X-ray spectra, dominated by a power-law like component with a photon spectral index of about 1.8 and a cutoff at a few hundred keV (the low/hard state). At higher luminosities, they typically show spectra dominated by a soft quasi-thermal component with a characteristic temperature of about 1 keV (the high/soft state). These quasi-thermal spectra are generally fairly well described by models of a geometrically thin, optically thick accretion disk (Shakura & Sunyaev 1973; Novikov & Thorne 1973). The low/hard state spectra are usually described in terms of thermal Comptonization models in a geometrically thick, optically thin medium (e.g. Shapiro et al. 1976). The optically thin region has an electron temperature of ∼70 keV, with the high temperature maintained either by magnetic reconnections (Haardt & Maraschi 1991; Nayakshin & Melia 1997; Di Matteo et al. 1999) or simply by inefficient cooling of the gas at particularly low accretion rates (e.g. Rees et al. 1982; Narayan & Yi 1994). Some recent work has suggested the alternative possibility that the X-ray emission in at least some of these objects may be dominated by synchrotron emission from a mildly relativistic jet (Markoff et al. 2001).

Most observed black hole X-ray binaries (as well as a smaller fraction of the observed neutron star binaries) show spectral state transitions between the low/hard and high/soft states. Furthermore, corresponding radio state transitions are seen as well, with the radio emission turning on in the X-ray low/hard state and off in the X-ray high/soft state (Tananbaum et al. 1972; Harmon et al. 1995; Fender et al. 1999). Finally the best fitting reflection parameters drop substantially as one goes from the high/soft state to the low/hard state (Zdziarski et al. 1999), which is usually interpreted as indicative of a "hole" developing in the accretion disk (e.g. Poutanen et al. 1997; Esin et al. 1997), but may also be explained by a mildly relativistic corona in the low/hard state beaming the hard x-rays away from the accretion disk (Beloborodov 1999), a jet doing the same thing (Markoff et al. 2003), or as a result of ionization effects which cause an artifical correlation between reflection fraction and spectral shape to appear (Done & Nayakshin 2001; Ballantyne et al. 2001). Understanding what happens during the state transitions thus holds great potential for helping us understand the radiation mechanisms and the accretion geometry in the individual spectral states (see e.g. Esin et al. 1997; Poutanen et al. 1997; Merloni 2003).

A systematic study of the luminosities at which these transitions occur and the possible variations in these luminosities

⋆ e-mail: tjm@science.uva.nl

is a necessary, but generally unavailable piece of the puzzle for understanding state transitions. Flux measurements at or near the state transitions and comparisons of the low/hard state and high/soft state luminosities have been presented for some individual sources (see e.g. Zhang et al. 1997; Zdziarski et al. 2002 as well as the observations discussed below), and the transition luminosity has been estimated in Eddington units for one source (Sobczak et al. 2000), but never before has a large sample been collected and analyzed in one place. The general lore has held that state transitions occur at about 8% of the Eddington luminosity (Esin et al. 1997), and that the state transition luminosities do not vary much. Recent work has shown hysteresis effects in many low mass X-ray binary systems, where the soft-to-hard state transitions occur at lower luminosities than the hard-to-soft state transitions (e.g. Miyamoto et al. 1995; Nowak et al. 2002; Barret & Olive 2002; Maccarone & Coppi 2003a). Furthermore, since some models for the low/hard state come from regions with bulk relativistic velocities away from the accretion disk (e.g. Beloborodov 1999; Markoff et al. 2001), while others come from regions without such motions (e.g. Shapiro et al. 1976; Rees et al. 1982; Narayan & Yi 1994), the presence of inclination angle effects on state transition luminosities may be an important diagnostic for understanding the accretion geometry of the low/hard states. With these aims in mind, we collect from the literature and/or derive from archival data the masses, distances, and state transition fluxes for all x-ray binaries where such data is available and reliable. We discuss the observations used in Sect. 2 and discuss the implications of the mean value, the variance in the values and the possible effects of inclination angle in Sect. 3.

2. Observations

We have compiled from the literature the data for the sources where the mass of the compact object, distance to the binary system, and state transition luminosity have all been measured. Where the distances come from optical measurements of the mass donor, we use the quoted errors. We have also included several neutron star sources whose distances have been measured from the luminosities of their type I bursts. For these sources, we have set the distance estimate errors to be 30% in accordance with the results of Kuulkers et al. (2003). The distance uncertainties are discussed in greater detail below. We also discuss below which sources which are known transients were not included in our sample and why they have not been included.

For a few additional sources, the data exist except for the state transition flux. In these cases, we have estimated the state transition flux, either from existing fits to the data or by downloading the appropriate data from HEASARC and fitting it. The sources of data for each system are discussed below, and the relevant parameters are all listed in Table 1.

We have, in general, chosen the data with the best temporal sampling among data sets capable of measuring the state transition. In some cases, this means using a narrower bandpass instrument than the most broadband instrument which observed the state transition. This choice is justified, however, by the fact that the luminosities can change rather quickly for X-ray transients, but the spectral shapes of low/hard state black hole accretors are rather constant. That is to say, the difference in luminosity caused by observing a source a week after its state transition is generally larger than the uncertainty introduced by extrapolating 2–20 keV data in order to measure the bolometric luminosity. There is greater variation in the spectral shapes of the neutron star accretors, but given that *RXTE* has generally provided the best broadband spectroscopy *and* the best temporal sampling, the choice need not be made for the neutron star sources included in our sample.

We have focused here on the soft-to-hard state transitions. There are two major reasons for this. Firstly, the luminosities of X-ray binaries in outbursts often fit a fast-rise/exponential decay profile, so, with the source luminosity changing more slowly during the decaying than during the rising part of the outburst, errors in determining the exact time of the state transition will cause smaller errors in the overall luminosity. Secondly, hysteresis has been found to be ubiquitous in the state transition luminosities of X-ray binaries, with the transition from the hard state to the soft state occurring at a higher luminosity that the soft-to-hard state transition. Since one possible explanation for this hysteresis effect is that the soft-to-hard state transitions occur in quasi-equilibrium states, while the hard-to-soft occur in violently unstable states, there may be instrinsic variations in the hard-to-soft state transition luminosities that do not occur in the soft-to-hard state transition luminosities (Maccarone & Coppi 2003a).

Nova Muscae 1991. The measurement of the X-ray flux is taken from the *Ginga* All-Sky Monitor light curve of Kitamoto et al. (1992), with the state transition estimated to have occurred on day 135. The black hole mass and distance estimates come from Gelino et al. (2001).

XTE J 1550-564. The measurement of the X-ray flux comes from Sobczak et al. (2000), with the assumption that the state transition occurred at the luminosity measured in observation number 205. The black hole mass and distance estimate come from Orosz et al. 2002). The state transition luminosity was estimated by Sobczak et al. (2000) to occur at about 0.02 $L_{\rm EDD}$, but the estimate was made before the mass and distance of the black hole had been measured and bolometric corrections to that luminosity estimate were not made.

GS 2000+251. Like Nova Mus 91, the measurement of the X-ray flux is taken from the *Ginga* All-Sky Monitor light curve of Kitamoto et al. (1992), with the state transition estimated to have occurred on day 135. The black hole mass and distance estimates come from Callanan et al. (1996).

Cyg X-1. The X-ray flux measurements come from a fit to the spectral data from the September 2, 1996 data, the first low/hard state observed by RXTE after the high/soft state seen in the spring/summer of 1996. The 3–20 keV spectrum shows a flux of 1.5×10^{-8} ergs/s/cm^2 when a $\Gamma = 1.9$ absorbed power law plus Gaussian (to fit the iron emission line) model is fit. The mass measurement comes from Herrero et al. (1995), assuming an inclination angle of 30 degrees and the distance estimate comes from from Gies & Bolton (1986).

GRO J 1655-40. The measurement of the X-ray flux comes from Sobczak et al. 1991), with the state transition occurring

Table 1. The table of the source parameters – compact object mass in $M_\odot$, binary system distance in kpc, transition luminosity in ergs/s, assuming isotropic emission and the distance in the previous column, ratio of transiton luminosity to the Eddington luminosity, inclination angle, and fractional error on the state transition luminosity, assuming standard error propagation. The Aql X-1(C) refers to Aql X-1 using the distance estimate of Chevalier et al. (1999), Aql X-1(R) refers to Aql X-1 using the distance estimate of Rutledge et al. (1999).

Source	M (in $M_\odot$)	d (in kpc)	$L_{\rm trans}$ (in ergs/s)	$L_{\rm t}/L_{\rm E}$	i	σ_L/L
Nova Mus 91	7.0 ± 0.6	5.1 ± 0.7	3.0×10^{37}	0.031		0.35
XTE J 1550-564	10.0 ± 1.5	5.9 ± 2.8	4.8×10^{37}	0.034		0.98
GS 2000+251	8.5 ± 1.5	2.0 ± 1.0	7.4×10^{36}	0.0069		1.0
Cyg X-1	13.0 ± 3.0	2.5 ± 0.5	4.7×10^{37}	0.028		0.50
GRO J 1655-40	6.3 ± 0.5	3.3 ± 0.2	9.5×10^{36}	0.0095	85	.25
LMC X-3	9.5 ± 2.0	51 ± 1.0	2.0×10^{37}	0.014		0.29
Aql X-1(C)	1.4 ± 0.1	2.5 ± 0.5	7.0×10^{35}	0.004		0.45
Aql X-1(R)	1.4 ± 0.1	5.2 ± 1.2	1.8×10^{36}	0.019		0.51
4U 1608-52	1.4 ± 0.1	3.6 ± 1.8	8.1×10^{36}	0.042		0.64
4U 1728-34	1.4 ± 0.1	4.3 ± 2.2	9.6×10^{36}	0.050		0.64

on August 14, 1997. The mass estimates come from Greene et al. (2001). We note that the high proper motions seen in the relativistic jets of GRO J 1655-40 (Hjellming & Rupen 1995), place a firm upper limit on the distance of 3.5 kpc (Fender 2003). The distance determinations for this sources thus have two constraints – one from the optical measurements, which suggest that $d = 3.8 \pm 0.7$ kpc (Greene et al. 2001), and the other that $d < 3.5$ kpc (Fender 2003). We therefore combine these two pieces of information and find that $d = 3.3 \pm 0.2$ kpc.

LMC X-3. This source was long thought to be steadily in the high/soft state until the discovery of occasional, brief state transitions by Wilms et al. (2001). Luminosities are not quoted for the state transitions, but the dates during which the source was in the hard state are identified by Wilms et al. (2001). The hard state observation closest to the soft-to-hard transition was taken on May 29, 1998 (RXTE ObsID 30087-02-07-00). We have downloaded the data for this ObsID and fit an absorbed power law model to the PCA and HEXTE data from 3–200 keV, using the standard HEASARC screening criteria. The best fitting model gives a power law index of 1.8 ± 0.1 and a flux of 5.0×10^{-11} ergs/s/cm^2. The distance is assumed to be the standard distance to the Large Magellenic Cloud, 51 kpc (Keller & Wood 2002). As a persistent, high mass system, ellipsoidal light curve variations have not been measured in LMC X-3, so the system's inclination angle is not well-constrained. The black hole's mass estimates come from Cowley et al. (1983) and Paczynski (1983).

Aql X-1. This system is an accreting neutron star, and its mass is assumed to be the standard 1.4 $M_\odot$ values for neutron stars. The flux at the state transition comes from Maccarone & Coppi (2003a). The distance of this system is a debated point; the estimate in the paper presenting the first optical spectrum is 2.5 kpc (Chevalier et al. 1999) while other work has suggested a distance of 4-6.5 kpc (Rutledge et al. 2001). We have adopted the smaller value here as it is based entirely on optical measurements, but also present alternative calculations for the higher value.

4U 1608-52. The distance to 4U 1608-52 is estimated to be 3.6 kpc on the basis of radius expansion type I X-ray bursts (Nakamura et al. 1989). As a neutron star, the mass of the central object is assumed to be 1.4 solar masses. The flux is taken from the well-sampled RXTE PCA/HEXTE data set in the November 2001 outburst. The source was first observed in a hard spectral state early on 20 November 2001 (ObsID 60052-02-06-00). The first observed hard state flux is 2.7×10^{-9} ergs/s/cm^2 (2–20 keV); after correcting for neutral hydrogen absorption and making the bolometric spectral correction (the spectrum has a photon index $\Gamma = 1.72$, and a cutoff energy of 50.6 keV), we find that the bolometric flux is about 5.6×10^{-9} ergs/s/cm^2. At the quoted distance of 3.6 kpc, the luminosity is 8.1×10^{36} ergs/s, which corresponds to 4.2% of the Eddington luminosity for a 1.4 $M_\odot$ neutron star.

4U 1728-34. The distance to this source is estimated to be 4.3 ± 0.5 kpc on the basis of neutron star atmosphere modeling of a sample of Type I bursts (Foster et al. 1986 - FRF). The state transition with the best temporal sampling is found to have occurred on 22 February 1996. The flux at this transition is 2–200 keV flux at this transition is found to be 4.6×10^{-9} ergs/s/cm^2, with an optical depth of 0.75 and a temperature of 36 keV for the Comptonizing region. The bolometric luminosity is then 9.6×10^{36} ergs/s, corresponding to 5% of the Eddington luminosity, assuming that the model for the distance estimate is correct. Additional confidence in the distance estimate was ascribed to its consistency with the distance of a putative globular cluster associated with 4U 1728-34 (Grindlay & Hertz 1981), whose existence has since been refuted (van Paradijs & Isaacman 1989). Given the lack of this confirmation of the distance estimate and the fact that FRF did not consider the effects of changing the chemical composition of the accreted gas, we have increased the uncertainty in the distance estimate to this source to the 30% found by Kuulkers et al. (2003) to be the rough systematic error.

2.1. Sources not included

There are several soft X-ray transients with suspected black hole primaries which are not included in this work. The reasons vary – typically there is either no mass estimate, no distance estimate, or the X-ray data at the time of the state transitions lack either the necessary spectral or spatial resolution. We note that this is much more likely to be the case for neutron star systems than black hole systems; the state transitions and the changes in luminosity are much more rapid for neutron stars than for black holes, perhaps because the timescale for luminosity change scales with the mass of the accreting object; therefore, while sampling a few times a week may be sufficient to measure the state transitions of black hole systems, it will generally not be sufficient for the neutron star systems. This is compounded by the fact that the sampling of black hole systems has generally been better at the times of state transitions than the sampling of the neutron star systems, presumably because the black hole systems have been much brighter in the all-sky monitors and hence have attracted more attention. There are also several neutron star sources not included in the sample for various reasons – generally because a transition to a full low/hard state was not seen with sufficient temporal sampling, or because of extreme uncertainties in the source distance. Below we discuss the observations for all sources listed as atoll sources in the most recent "van Paradijs catalog" (Liu et al. 2001) that have not been included in the analysis as described above. Only the atoll sources are included because the Z sources are thought to all be accreting steadily at luminosities well above the soft/hard transition level and the unclassified neutron star sources are unclassified for the simple reason that they have not shown spectral state phenemenology.

2.1.1. Neutron stars not included

4U 1705-44. The transition flux for this source has been estimated to be between 7×10^{36} and 2.1×10^{37} ergs/s (Barret & Olive 2003), with the distance assumed to be 7.4 kpc (as estimated from non-radius expansion bursts by Haberl & Titarchuk 1995). However, it seems from the spectral fits to the data presented in this paper, that a full low/hard state is not reached; the optical depth in the Comptonization model (using the COMPTT model in XSPEC; Hua & Titarchuk 1995) never drops below 5.5 and the temperature never rises above 14.1 keV (compare, for example with Aql X-1 where the Comptonization model fits show a drop in the coronal optical depth to $\tau \approx 1$ and a rise in the coronal temperature to above 80 keV – Maccarone & Coppi 2003b). It is commonly held lore that the cutoff energies of neutron star spectra in hard states are typically lower than those for black hole spectra, and typically about 30 keV or less (Zdziarski et al. 1998). In fact, for many systems, the true low/hard state occurs and the spectrum takes a form quite similar to the low/hard states of black holes (Barret et al. 2000). While clearly substantial hardening to the spectrum has occured in 4U 1705-44, the spectrum has entered only an intermediate state, and after this point, the luminosity begins rising and the spectrum begins softening again. Based on this data, we can say only that the state transition luminosity should be less than about 7×10^{36} ergs/s. Furthermore, if the accreted material is helium rich, the distance estimate of Haberl & Titarchuk (1995) drops to 7.0 kpc, and the luminosity drops to 6.3×10^{36} ergs/s, which corresponds to 3.3% of the Eddington luminosity for a 1.4 $M_{\odot}$ neutron star. Because a full state transition is not seen, we do not include this source in either the table or any of the calculations based on the table.

4U 0614+09. There does not exist a particularly well-sampled state transition for this source, but evidence seems to suggest that the hysteresis effects for it are rather mild. Barret & Grindlay (1995) found that the source was in a low/hard type state during two EXOSAT observations where the flux was 1.1 and 1.2×10^{-9} ergs/s/cm^2 from 1–20 keV, in an intermediate state when the flux was 1.5×10^{-9} ergs/s/cm^2 and in a much softer state at 3.5×10^{-9} ergs/s/cm^2. We thus take the transition flux to be $1.3 \pm 0.2 \times 10^{-9}$ ergs/s/cm^2. The distance has only an upper limit of 3 kpc from sub-Eddington Type I bursts. When correcting to the bolometric luminosity, we assume that the spectrum has a cutoff energy of about 60 keV, in agreement with typical results from other neutron star systems, and use the measured power law photon index of $\Gamma = 1.9$. The bolometric luminosity is then $2 \times 10^{36}(d/3\ \mathrm{kpc})^2$ ergs/s, or less than about 1% of the Eddington luminosity.

4U 1820-30. This source has a known distance due to its association with the globular cluster NGC 6624. Its transition luminosity cannot be measured, however, because the sampling of the pointed RXTE observations of it is insufficient. It did appear to show a state transition in 1997, but the timespan between the last high/soft state observation and the first low/hard state observation was about 20 days, sufficient time for a rather large flux change. Given that the count rate did not continue decreasing after the source entered the low/hard state, one cannot even be certain that the transition flux is between the two observed fluxes. This source is a good candidate for future monitoring campaigns, as its distance is well known and it is known to exhibit state transitions.

SLX 1732-304. This system represents a similar case to 4U 1820-30. It is a globular cluster source, located in Ter 1 (Parmar et al. 1989), but has been poorly sampled by *RXTE*; only four observations have been made, all in a low flux state, and showing similar X-ray spectra (Molkov et al. 2001). Observations from *Granat* did show a spectral state transition, but there were only two observations made, a month apart in time, and a factor of four apart in flux (Pavlinsky et al. 2001). Using the typically quoted 5.2 kpc distance to the globular cluster (Ortolani et al. 1999), and the 3–20 keV fluxes of 6.95×10^{-10} and 1.64×10^{-10} erg/s/cm^2, the luminosities are found to be 2.25×10^{36} ergs/s and 5.0×10^{35} ergs/s respectively, indicating a state transition between 1% and 0.25% of the Eddington rate. However, no bolometric corrections have been made to these values, and given the rather large neutral hydrogen columns to the sources, the corrections are rather uncertain, but should be of order a factor of 2–4. Given that the spectral data and the sampling in time are insufficient to make accurate measurements, we choose not to include these transition luminosities in the analysis.

KS 1731-260. This source has been assumed to lie at the Galactic Center. Neutron star model atmospheres for this source in quiescence are consistent with a distance of about 8 kpc, but the best fitting value is half that distance, assuming a neutron star radius of 12 km (Rutledge et al. 2000). We adopt a distance of 4 ± 2 kpc for this source based on the neutron star model atmospheres. Its transition appears to have occured at a luminosity of about 3.3×10^{36} ergs/s, based on the PCA/HEXTE measurements taken on May 25, 1999. However, with the distance uncertainty of a factor of ~2, we do not include this source in calculations.

4U 1636-53. State transitions were first seen in 4U 1636-53 with EXOSAT (e.g. Prins & van der Klis 1987), but only the hard-to-soft transition was seen in these data. A more recent campaign (RXTE proposal 60032) shows some evidence that a soft-to-hard state transition probably occurred between 17 September 2001 and 30 September 2001, as the count rate is dropping and the spectrum is hardening in the well sampled region of the lightcurve leading up to 17 September 2001. The spectrum on 17 September 2001 is well represented by a thermal Comptonization model with a temperature of 3.7 keV and an optical depth of 4.7, so the source is clearly still in an intermediate state. Unfortunately, no observations were taken between 17 and 30 September, and the count rate had again started rising by September 30, so the transition cannot even be said to have occurred in a flux range bracketed by the values of the fluxes on these dates. We can thus estimate only an upper limit on the transition flux for this source of the 1.5×10^{-9} ergs/s/cm^2 seen on 17 September 2001. Given the 5.5 kpc distance to the source, estimated from radius expansion Type I bursts (van Paradijs et al. 1986; van Paradijs & White 1995), we estimate that the state transition luminosity occurs at no more than 4.8×10^{36} ergs/s, implying that the Eddington fraction of the state transition is less than 2.5%.

Cir X-1. Circinus X-1 is an extremely unusual system. It has been tentatively classified as an atoll source (Oosterbroek et al. 1995), but shows much larger luminosity variations than most systems in its class. Furthermore, its mass accretion rate seems to vary due to the eccentricity of its orbit, and not due to disk or mass transfer instability effects that affect most other neutron star systems.

GX 3+1. This system has not been the subject of a regular, finely sampled monitoring campaign by *RXTE*. The only regular monitoring, in Proposal 60022, was roughly monthly.

4U 1735-44. This system is thought to be at a distance of 9.2 kpc (van Paradijs & White 1995) from Type I X-ray bursts, but again there are no well sampled state transitions observed. Furthermore, the ASM lightcurves show that the luminosity, assuming this distance, seems not to drop below about 15% of the Eddington rate, so in fact, it seems likely that no state transition has occurred during the *RXTE* mission.

The persistently bright Galactic Center sources. Four atoll sources near the Galactic Center, GX 3+1. GX 9+1, GX 9+9, and GX 13+1 have generally been found only in the banana branches after rather detailed studies (see Homan et al. 1998 and references within). These sources hence do not undergo state transitions, and some have even sometimes been classified as Z sources rather than as atoll sources (see e.g. Schulz et al. 1989). These sources are thus rather similar to 4U 1735-444.

XTE J 2123-058. This source is a new transient first detected with *RXTE* in June of 1998. It was observed with the pointed instruments on *RXTE* five times, including on either side of a state transition. Unfortunately, the flux dropped by a factor of 15 between the lowest soft state and highest hard state points (Tomsick et al. 1999). Given the flux measurements of 1.1×10^{-9} and 7.3×10^{-10} respectively, along with the distance estimate of 8 ± 3 kpc (Zurita et al. 2000), we find that the transition occurred between 14% and 0.2% of the Eddington rate (accounting for both the distance and flux uncertainties). This range is not particularly useful, so we exclude this source.

XTE J1806-276. This source has no reliable distance estimate; there is a only a tentative association with an X-ray burster (Marshall et al. 1998), and there is only a "likely" optical counterpart (Hynes et al. 1998).

4U 1915-05. This system was monitored by *RXTE* with quite good sampling in May of 1996, but the well sampled part of the light curve showed only the upper and lower banana states (Boirin et al. 2000). The other data for this source is sampled typically monthly. Thus no state transition has been observed in a well sampled data set.

4U 1724-30. This system is in Terzan 2, a globular cluster about 9.5 kpc away. During the *RXTE* mission it reached a rather large luminosity (about 10% of the Eddington rate), where it was observed rather frequently (P20170, PI:Jung), but did not show a state transition; the spectrum always remained hard, even at the peak (as determined from the long-timescale lightcurve in Emelyanov et al. (2002), being well fit by a thermal Comptonization model with an optical depth of about 0.5 and a temperature of about 45 keV.

4U 1746-37. This is another globular cluster system lacking a well-sampled state transition luminosity measurement. There are two well sampled *RXTE* campaigns on this source, P30701 (PI:van Paradijs) and P60044 (PI:Smale), but P30701 has been shown to be in the island state all the time (Jonker et al. 2000), and an inspection of the data from P60044 has shown that the same is true here. An additional set of observations, P10112, that was less well sampled showed the source only in an island state, and occurred well before the other two campaigns (Jonker et al. 2000).

2.1.2. Black hole sources with insufficient optical data

GX 339-4. GX 339-4 is in some ways the best candidate for studying state transitions - it is one of the few sources which has been well studied in the X-rays in all the canonical spectral states. However, its optical counterpart is very faint, and its lowest luminosity observations are still dominated by the accretion flow in the optical and infrared. Thus no mass measurement has been possible and the distance measurements to this source are based primarily on the absorbing medium. Recent optical studies (Hynes et al. 2003) of the source in outburst have allowed the measurement of a *mass function*, i.e. a lower limit on the mass, which are sufficient to prove that the primary is a black hole under the standard assumptions about the neutron star equation of state, but the mass and distance estimates remain insufficient for estimating the Eddington luminosity of the state transitions.

XTE J 1859+226. This source lacks an inclination angle estimate, a distance estimate, and is the subject of a debated period. The mass function is hence uncertain and regardless of its certainty, it cannot be converted to a mass measurement.

GRS 1009-45. Three problems exist for this source. The inclination angle is extremely uncertain, so the conversion from mass function to mass is likewise uncertain.

The Hα emission does not follow the spectroscopic phase in the conventional manner, suggesting that the orbital period may be in error. Finally, the spectral type of the mass donor is highly uncertain, so there is no distance estimate (Fillipenko et al. 1998).

2.1.3. Black hole sources with insufficient X-ray data

4U 1543-47. This source is a dynamically confirmed black hole candidate, and has shown three strong X-ray outbursts. Unfortunately, the first occurred in 1971, when it was monitored once a month over the entire outburst, the second in 1983, when it was monitored more frequently, but only during the high/soft state, and the third occurred in 1992, where the only publicly available data set comes from BATSE, which is not well-suited to measuring the bolometric luminosity, and whose data results are available only as 1 week averages. It is currently in its fourth outburst, and the current outburst is likely to provide useful data.

A0620-00. This source was well observed for two months during its outburst, but its spectrum only softened throughout the outburst. This softening is generally consistent with the decrease in temperature of an accretion disk which is dominating the X-ray spectrum. Hence the state transition was not observed in the well-sampled portion of the light curve and the transition flux cannot be estimated.

XN Oph 77. This system was monitored during its outburst by Ariel V, but the published results present only count rates. Hence the state transition cannot be detected and its flux cannot be estimated.

V 404 Cyg. This source was observed only by *Ginga*. The data are not public, and the published results (Kitamoto et al. 1989) are insufficient for determining a time of the state transition. It appears that the time resolution of the observations is regardless insufficient for determining a transition luminosity.

2.1.4. Black hole sources which do not show the necessary state transitions

A handful of black hole X-ray transients have not shown the full phenomenology of spectral states seen in the typical soft X-ray transients. As a result, there is no soft-to-hard state transition for these systems, so the measurement obviously cannot be made.

GRO J 0422+32 and XTE J 1118+480. Both these systems exhibited "mini-outbursts" in which the luminosity never reached a high enough level to trigger a high/soft state.

V4641 Sgr. This source was seen to spend a large amount of time in the low/hard state in the period before a very rapid, very bright outburst on September 15–16, 1999. It may have entered the high/soft state on the way down from the $\sim L_{\rm EDD}$ peak, but the luminosity decay was so rapid that even the several pointings per day from the *RXTE* All Sky Monitor provide insufficient time resolution to determine whether, or at what luminosity, a state transition occurred.

GRS 1915+105. Since its discovery by *Granat* (Castro-Tirado et al. 1992), GRS 1915+105 has shown a luminosity consistently sufficient to place it in the high/soft state, the very high state, or an unstable flaring state. In fact, its *lowest* luminosity observations are those in the high/soft state. At times, it enters into a state commonly referred to as its "low/hard" state, but the spectral index of the power law component in this state is typically about $\Gamma = 2.5$, much softer than any of the other low/hard states. It has been suggested that at high fractions of the Eddington luminosity, flows with high viscosities may see a large fraction of their energy dissipated in a hot corona (Merloni 2003); in this picture, in fact, two solutions, a disk-dominated and a corona dominated one, are possible at every accretion rate above a critical fraction of the Eddington rate which is a function of the viscosity parameter α. The properties of these corona are still not well studied, but the presence of an alternative means of explaining a power-law dominated spectrum at high accretion rates lends credence to the suggestion that the GRS 1915+105 "low/hard" state is fundamentally different than that seen in other systems.

2.2. Bolometric corrections

Bolometric corrections are applied to the data assuming a spectrum of $\frac{dN}{dE} \sim E^{-1.8} \exp^{-E/200\ \rm keV}$, and that this functional form applies from 0.5 keV to 10 MeV, with no power outside this range. This model provides a phenomenologically good fit to the broadband spectra observed from low/hard state objects, and this correction is essential for correctly estimating the observed luminosities in the low/hard state (see e.g. Zdziarski et al. 2002). Changes in the spectral index by 0.1 or changes in the high or low energy cutoff by factors of two induce only 10% errors in the bolometric luminosity, so the errors in the bolometric luminosity correction are likely to be small compared to the other errors in the problem. We note that because the errors in the bolometric corrections are likely to be rather small, good temporal coverage of the state transitions becomes more important for estimating the transition luminosity than good broadband spectral coverage. Thus, when multiple data sets exist for measuring the most recent state transition from a given system, we have chosen the data set with the best temporal sampling of the source, rather than the one with the best broadband spectroscopy.

2.3. Reliability of optical distance measurements

To make a distance estimate of a black hole or a neutron star from the properties of its optical counterpart, one needs accurate measurements of the period and inclination angle of the binary system, as well as the spectral type of the optical star and the reddening along the line of sight to the X-ray binary. The radius of the mass donor is then assumed to be that at which it exactly fills its Roche lobe (its mass having been estimated from its spectral type). The absolute magnitude is then computed from the spectral shape for the companion star and the radius estimates, and the distance is estimated from comparing the observed apparent magnitude with the estimated absolute magnitude. The models also include a correction for the optical flux contributed by the accretion flow. A good discussion of converting optical measurements into masses and distances can be found in Orosz & Bailyn (1997).

The reliability of optical distance measurements has been studied by Barret et al. (1996). They find that the largest source of uncertainty in the mass and distance measurements typically comes from the uncertainties in the inclination angle. They found that using the method above, the uncertainties in the mass are typically ∼10% for inclination angle errors of about 10 degrees. They tested this claim by using an alternative model to estimate the size of the mass donor – the period density relation from Frank et al. (1992). They confirmed that the scatter in the distance measurements was about 15%, but at least some of this error may be due to the fact that the mass donors were assumed to be 0.4 $M_\odot$ in order to apply this technique.

Given improvements in both the quality of the photometric light curves and the techniques of the ellipsoidal modulation modeling in the last 7 years, the largest uncertainties often come from other considerations, typically the reddening or spectral type of the mass donor; typical errors in the inclination angle are now less than 5 degrees (see e.g. Gelino et al. 2001; Orosz et al. 2002). For the three sources in our sample where the uncertainties in the optical distance estimate are greater than 20%, the distance errors are largely due to the uncertainties in the spectral type of the companion star, and not due to errors in the inclination angle.

2.4. Reliability of burst distance measurements

Several of the neutron star source distances were measured using Type I bursts. It has long been believed that these bursts should be Eddington limited and hence the brightest bursts observed from a particular source should be a standard candle. Recently, this claim has been tested systematically by examining the luminosity distribution of Type I bursts in globular cluster X-ray binaries. In the globular clusters, of course, the distances can be measured by main sequence fitting of the optical stars. It was found that distances measured from Type I bursts have systematic biases of up to 50%, depending, for example on whether the accreted material is hydrogen rich or hydrogen poor, and on whether the truly "brightest" radius-expansion burst from a particular system has been observed (see Kuulkers et al. 2003). Given that the errors can be as large as 50%, but that only a fraction of the sources are likely to have errors this large, we estimate the typical distance errors due to using the Type I burst method to be 30%.

3. Discussion

3.1. Variations of the transition luminosities

We have performed averages of the state transition luminosities in Eddington units weighted by the inverses of their standard deviations, and also estimate their standard deviation. We perform the statistical analyses for three cases – one where Aql X-1 is eliminated (because, as a neutron star system, its state transitions may depend differently on luminosity than those of the dynamically confirmed black hole candidates), one where Aql X-1 is included and the 2.5 kpc distance of Chevalier et al. (1999) is used, and one where Aql X-1 is included and the 4.0 kpc distance of Rutledge et al. (1999) is used.

When only the black hole candidates are considered, the weighted mean state transition luminosity is 1.9 ± 0.2%, and the excess deviation (i.e. the square root of the weighted variance minus the weighted errors) is about 0.57%, indicating that there are ≈30% variations in the state transition luminosity. For the purposes of computing the excess deviation, the error in the state transition flux has been assumed to be 20%. With the neutron stars included, the mean state transition luminosity drops to 2.2 ± 0.2% (regardless of which distance estimate is chosen for Aql X-1), with a fraction excess variance of 42% of the mean if the 5.2 kpc distance is used and of 48% of the mean if the 2.5 kpc distance is used. Thus there is some suggestive evidence that the state transitions vary based on the sample as a whole, although if the 20% estimate of the systematic error on the state transition flux is a severe underestimate, then the sample could conceivably be consistent with measurement errors. Furthermore, the errors in estimating the variance are likely to be quite large since there are only 6 black hole candidates in the sample and the errors on the measurements are quite large themselves. If the sources are distributed uniformly in the cosine of the inclination angle i and the variations in the transition luminosity are entirely due to bulk relativistic motions of the X-ray emitting region, then one would expect 30–35% variations in the state transition luminosity for a value of β between 0.18 and 0.22 (where β is defined as the jet velocity divided by the speed of light).

An interesting question would be whether there is a systematic difference between the state transition luminosities of black hole and neutron star accretors. In fact, the weighted mean state transition luminosity for the neutron stars is larger than that of the black holes by a rather substantial margin. However, we note that there are only 3 neutron stars with suitable measurements for inclusion in the sample, so random variations are likely to be quite important. Furthermore, there are two more neutron stars with upper limits for the state transition luminosity that are substantially below those of the neutron stars included in the sample. At this time the data are insufficient for making a strong statement on this question.

Stronger evidence of real variations may be found by looking at individual sources. In particular, the source GRO J 1655-40 has a state transition at a luminosity 4σ below the mean state transition luminosity. This system has one of the lowest observed state transition luminosities in the sample, and has the smallest observational errors, largely due to strong constraints on the distance given by the combination of the relativistic jet kinematics and the optical distance measurement, and the strong constraints on the orbital inclination angle given by the combination of strong ellipsoidal modulations and the lack of an eclipse (Greene et al. 2001). Furthermore, it has a well constrained jet inclination angle of 85 degrees (Hjellming & Rupen 1995). While the errors listed in Hjellming & Rupen (1995) are likely to be underestimated, it has been shown that the observed jet proper motions are incompatible with the minimum distance constraints from optical measurements of 3.1 kpc if the jet's inclination angle is less than about 82 degrees (Fender 2003).

Because the inner accretion disk of GRO J 1655-40 is so close to being edge-on, if beaming effects are important, GRO J 1655-40 is likely to have its hard X-ray luminosity de-beamed, and hence to have a lower transition luminosity than the mean. We define the approaching beam's Doppler factor $\delta_{\rm app}$ to be $[\Gamma(1-\beta\cos\theta_i)]^{-1}$ and the receeding beam's Doppler factor $\delta_{\rm rec}$ to be $[\Gamma(1+\beta\cos\theta_i)]^{-1}$. We average the beaming factor $\delta_{\rm app}^{2.8}+\delta_{\rm rec}^{2.8}$ (from assuming a $\Gamma = 1.8$ spectral index and a continuous flow of material into the emission region and applying the appropriate formula from the review of Mirabel & Rodriguez 1999), over angles to determine the ratio between the intrinsic rest frame and mean observed fluxes. We find that for the most likely value of the GRO J1655-40 state transition luminosity of 0.95% $L_{\rm EDD}$, $\beta = 0.62$. For the lowest reasonable value, where all the errors are set to the 1σ value in the direction where this acts most strongly to reduce the inferred transition luminosity of GRO J 1655-40, we find that $\beta = 0.71$, making this value the upper limit on the velocity of the emission region. Taking instead the maxmimum value for the distance and the minimum value for the mass, and assuming the state transition flux was *overestimated* by about 20%, we find that the state transition luminosity was still no more than about 1.4% of the Eddington luminosity. If the variations in state transition luminosity are then solely due to relativistic beaming, we would expect the outflow velocity to be at least $\beta = 0.51$.

We note that there has been a recent challenge to the standard distance estimate for GRO J 1655-40 (Mirabel et al. 2002). These authors have argued most strongly that the optical distance constraints may not be valid, as one cannot be sure that a star in an interacting binary has the same luminosity as a single star of the same spectral type. They have furthermore suggested that perhaps the relativistic jet and the outer accretion disk in this system are aligned with one another, which would place the source at a distance of about 0.9 kpc assuming that the proper motions of the jet have been measured accurately. Then, however, the state transition for GRO J 1655-40 would occur at about $7\times10^{-4}L_{\rm EDD}$, and if the differences were solely due to beaming effects, the X-ray emission region's Lorentz factor in the low/hard state would have to be about $\Gamma > 3.0$, large enough to violate severely the beaming constraints based on the radio luminosity to X-ray luminosity correlation of Gallo et al. (2002). Additionally, a higher beaming factor in the low/hard state would be implied than in the "superluminal" jets if the source were at such a small distance, in seeming contradiction to the observation that the jets of the low/hard state systems tend to be slower than those seen in the high luminosity flaring states (e.g. Stirling et al. 2001). Finally, it seems unlikely that a single source would be separated from the sample as a whole by a factor of ~20 in state transition luminosity while the rest of the sample is clustered within a factor of three of the mean, despite rather large measurement errors which should lead to larger dispersion in their transition luminosity values.

Finally, we point out that while the X/γ-ray luminosities of most sources with superluminal non-steady jets are very close to the Eddington limit at the time of the jet event, GRO J 1655-40 was emitting at only about 70% of $L_{\rm EDD}$ when its jet was ejected (Sobczak et al. 2000). It is not clear, however, whether this represents evidence for relativistic motions in the very high state. The X/γ-ray spectrum of sources in this state have a substantial contribution from a geometrically thin, optically thick component, so simple geometric projection effects can lead to changes in flux received as a function of the observer's inclination angle.

3.2. Implications for theoretical models

The present observational constraints cannot distinguish among existing theoretical models. Three broad classes of geometries exist for explaining the emission. One class, that of Comptonization in a geometrically static, optically thin medium (e.g. Shapiro et al. 1976 and other similar solutions such as ADAFs) predicts that there should be no variations in the state transition luminosities due to geometric effects – a static optically thin medium emits isotropically. In this picture, the state transition luminosity should show no variations. Our finding that GRO J 1655-40 shows evidence for such variations casts some doubt on the validity of this model. Given that only one black hole candidate shows such clear evidence for variations in the luminosity of the state transition, at this point, we cannot rule out the possibility that this observational result is due to intrinsic variations in the state transition luminosities rather than due to relativistic beaming. Nonetheless, the case of GRO J 1655-40 seems to suggest that the most likely cause of the variations are inclination angle effects on the state transition luminosities.

The two other possibilities, those of synchrotron emission from jets, and of magnetic flares in a corona above an accretion disk, are also optically thin solutions. However, both these models have bulk relativistic accretion flows, and the resulting relativistic beaming can have an effect on the observed luminosity. In the case of a corona powered by magnetic reconnections, the bulk outflow velocity has been estimated on the basis of the relative weakness of the Compton reflection component in the low/hard state (i.e. the correlation between the spectral index and the reflection fraction found by Zdziarski et al. 1999). Given that $R/2\pi \sim 0.3$ in the low/hard state, Beloborodov (1999) estimated that the corona would have an outflow velocity of $\beta \sim 0.3$. This is in relatively good agreement with the observational results presented here, as the value of β falls between that suggested by the GRO J 1655-40 data alone and that suggested by the sample as a whole.

The final mechanism proposed for the emission from low/hard state objects is emission from a relativistic jet. In the models of Markoff et al. (2001), the typical beaming factors inferred are $\Gamma \sim 2.0$, which is equivalent to $\beta \approx 0.85$–0.9 (S. Markoff, private communication), which is somewhat larger than the minimum value of Γ suggested by the VLBI measurements of Stirling et al. (2001) for Cygnus X-1 in its low/hard state. Such beaming factors are marginally too large to be in agreement with the observational data on state transition luminosities, and if the current results hold up as a larger sample of sources is examined, inclination angles of the jets of more systems are measured and smaller error bars are placed on the masses and distances of the sources, then this result will present fairly strong evidence against the X-ray jet model in its current form. Such models, could, however, be modified (for example by adding the effects of Compton drag, which should slow the jet). At the present, the discrepancy is not large enough to allow for a strong conclusion.

There are no strong constraints on the inclination angles of the jets, and hence on the inner disks of systems other than GRO J 1655-40. The inclination angles of the binary planes of these systems are generally constrained within about 20 degrees, but the inner disks are subject to warping due to, among other effects, the Bardeen-Petterson effect, and the timescale for the black hole spin to realign itself with the binary plane is often longer than the lifetime of the binary system (Maccarone 2002). It would thus be of great use to measure the inclination angles of jets from more of these systems, but such measurements are typically only possible during flaring events where proper motions can be observed. Such measurements are, of course, the key to determining whether the suggestive results from GRO J 1655-40 are truly an indication of an inclination angle effect on state transition luminosities (and hence beaming), or just a coincidence.

If one of the established mechanisms for producing the spectral state transitions can be successfully adopted, then the value of α might be measured using the state transition luminosities. In the case of advection dominated accretion flows, the state transition luminosity occurs at a luminosity of $1.3\alpha^2 L_{\rm EDD}$ (Narayan & Yi 1995), so the observations that the state transitions occur at 0.022 $L_{\rm EDD}$ would indicate that $\alpha = 0.13$. The magnetic corona model of Merloni & Fabian (2002), on the other hand, suggests that the state transitions should depend very weakly on α, but should always be at luminosities slightly higher than 2%. Other models do not predict such a clear correlation between α and the state transition luminosity.

3.3. A new distance indicator?

We have found that the state transition luminosity for X-ray binaries, and particular for the black hole systems is constant to within about 40%. This in turn means that given perfect flux and mass measurements, the state transition flux could be used as a distance indicator within about 20% accuracy. Recent work on X-ray binaries in bright states has made it possible to estimate their masses in outbursting states when the stellar spectrum cannot be estimated accurately (Steeghs & Casares 2002; Hynes et al. 2003). In particular, GX 339-4, whose distance has not been reliably measured, but is generally assumed to be about 4 kpc on the basis of its kinematics and its hydrogen column measurements (Zdziarski et al. 1998), has had its mass function measured by this method; the mass is found to be at least 5.8 $M_\odot$. Its state transition flux, $F_{\rm trans}$ has been measured by Nowak et al. (2002), and is found to be 2.7×10^{-9} ergs/s/cm^2. If the state transition luminosity is 2.2% of the Eddington limit, then it should be at least 1.8×10^{37} ergs/s for a black hole with $M > 5.8 M_\odot$. This distance should be $d > \sqrt{(}L/4\pi F_{\rm trans})$, or greater than 7.6 kpc. Given a likely 40% systematic error on the state transition luminosity in Eddington units, a 20% error on the flux measurement, and a 9% error on the mass function measurement, the errors on the distance are likely to be about 22%, so we find that the distance to GX 339-4 is at least 7.6±1.8 kpc by this method. Applying a similar argument to the recent very strong flare of GX 339-4, where the source reached a flux of 1.4×10^{-7} ergs/s/cm^2 (as estimated from the *RXTE* All Sky Monitor flux on 16 July 2002), and assuming that it reached the Eddington luminosity for a > 5.8 $M_\odot$ black hole, we find a distance that must be at least 7.1 kpc. A distance of more than 7 kpc is perhaps not surprising considering that the source lies along a line of sight that passes near to the Galactic Center.

3.4. Prospects for future improvements

Finally, we note that these results underscore an additional important point – the need for more accurate distance measurements of X-ray binaries. The largest uncertainties in the problem are almost always those in the distance. As there will always be some systematic uncertainty in determining the appropriate spectral type for a Roche lobe overflowing star, an additional method for measuring distances would be of great benefit. Parallax distance estimates from planned interferometers such as SIM, and from VLBI measurements hold great potential for improving our measurement accuracy of the state transition luminosities. Many X-ray binaries approach high enough radio flux levels in their low/hard states for VLBI measurements to be made (see e.g. Bradshaw et al. 1999), and hopefully a large fraction will be observed by SIM. Great improvements in understanding the state transition luminosities of neutron star systems could result from improved temporal sampling of the outburst cycles of globular cluster X-ray sources since the distance estimates for most globular clusters are substantially more accurate than those for the individual stellar companions in X-ray binaries and are free of the systematic uncertainties that cause problems for Type I burst distance measurements. A more sensitive all sky monitor in X-rays would be a key for such work, since the ASM on *RXTE* is not sensitive enough to easily detect outbursts from the faint sources in the more distant globular clusters.

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Note added in proof: Eric Kuulkers has pointed out that a more detailed analysis of A 0620-00 did show a hardening in the decay at roughly 1 Crab (Kuulkers 1998). This is consistent with our other results within the uncertainties of the Ariel V data set.

References

Ballantyne, D. R., Ross, R. R., & Fabian, A. C. 2001, MNRAS, 327, 10
Barret, D., McClintock, J. E., & Grindlay, J. E. 1996, ApJ, 473, 963
Barret, D., Olive, J. F., Boirin, L., et al. 2000, ApJ, 533, 329
Barret, D., & Grindlay, J. E. 1995, ApJ, 440, 841
Barret, D., & Olive, J.-F. 2002, ApJ, 576, 391

Beloborodov, A.M. 1999, ApJ, 510, L123
Blandford, R.D., & Begelman, M. C. 1999, MNRAS, 303, L1
Boirin, L., Barret, D., Olive, J.F., et al. 2000, A&A, 361, 121
Bradshaw, C. F., Fomalont, E. B., & Geldzahler, B. J. 1999, ApJ, 512, L121
Callanan, P. J., Garcia, M. R., Fillipenko, A. V., et al. 1996, ApJ, 470, L57
Castro-Tirado, A. J., Brandt, S., & Lund, N. 1992, IAU Circ. 5590
Chevalier, C., Ilovaisky, S. A., Leisy, P., et al. 1999, A&A, 347, L51
Cowley, A. P., Crampton, D., Hutchings, J. B., et al. 1983, ApJ, 272, 118
Di Matteo, T., Celotti, A., & Fabian, A. C. 1999, MNRAS, 304, 809
Done, C., & Nayakshin, S. 2001, ApJ, 546, 419
Emelyanov, A. N., Revnivtsev, M. G., Aref'ev, V. A., & Sunyaev, R. A. 2002, AstL, 28, 12
Esin, A. A., McClintock, J. E., & Narayan, R. 1997, ApJ, 489, 865
Gelino, D. M., Harrison, T. E. & McNamara, B. J. 2001, AJ, 122, 971
Fender, R., Corbel, S., Tzioumis, T., et al. 1999, ApJ, 519, L165
Fender, R. P. 2003, MNRAS, 340, 1353
Foster, A. J., Ross, R. R. & Fabian, A. C. 1986, MNRAS, 221, 409
Frank, J., King, A. & Raine, D. 1995, Accretion Power in Astrophysics (Cambridge: Cambridge University Press)
Gelino, D. M., Harrison, T. E., & McNamara, B. J. 2001, AJ, 122, 971
Gies, D. R., Bolton, C. T. 1986, ApJ, 304, 371
Greene, J., Bailyn, C. D., Orosz, J. A. 2001, ApJ, 554, 1290
Grindlay, J. E., & Hertz, P. 1981, ApJ, 247, 17
Haardt, F., & Maraschi, L. 1991, ApJ, 380, L51
Haberl, F., & Titarchuk, L. 1995, A&A, 299, 414
Harmon, B. A., Wilson, C. A., Zhang, S. N., et al. 1995, Nature, 374, 703
Herrero, A., Kudritzki, R.P., Gabler, R., et al. 1995, A&A, 297, 556
Homan, J., van der Klis, M., Wijnands, R., et al. 1998, ApJ, 499, 41
Hjellming, R. M., & Rupen, M. P. 1995, Nature, 375, 464
Hynes, R. I., Steeghs, D., Casares, J., et al. 2003, ApJ, 583, 95
Hynes, R. I., Roche, P., & Haswell, C. A., 1998, IAU Circ. 6905
Jonker, P. G., van der Klis, M., Homan, J., et al. 2000, ApJ, 531, 453
Keller, S. C., & Wood, P. R. 2002, ApJ, 578, 144
Kitamoto, S., Tsunemi, H., Miyamoto, S. & Hayashida, K. 1992, ApJ, 394, 609
Kuulkers, E. 1998, New Astron. Rev., 42, 1
Kuulkers E., den Hartog, P.R., in't Zand, J. J. M., et al. 2003, A&A, 399, 663
Liu, Q. Z., van Paradijs, J., & van den Heuvel, E. P. J. 2001, A&A, 368, 1021
Maccarone, T. J. 2002, MNRAS, 336, 1371
Maccarone, T. J., & Coppi, P. S. 2003a, MNRAS, 338, 189
Maccarone, T. J., & Coppi, P. S. 2003b, A&A, 399, 1151
Markoff, S., Falcke, H., & Fender, R. 2001, A&A, 372, 25
Markoff, S., Nowak, M., Corbel, S., et al. 2003, A&A, 397, 645
Marshall, F., Strohmayer, T. & Remillard, R. 1998, IAU Circ. 6891
Merloni, A., 2003, MNRAS, 341, 1051
Mirabel, I. F., Mignani, R., Rodrigues, I., et al. 2002, A&A, 395, 595
Mirabel, I. F., & Rodriguez, L. F. 1999, ARA&A, 37, 409
Miyamoto, S., Kitamoto, S., Hayashida, K., & Egoshi, W. 1995, ApJ, 442, 13
Molkov, S. V., Grebenev, S. A., & Lutovinov, A. A. 2001, Ast, 27, 363
Nakamura, N., Dotani, T., Inoue, H., et al. 1989, PASJ, 41, 617
Narayan, R., & Yi, I. 1994, ApJ, 428, 13
Nayakshin, S., & Melia, F. 1997, ApJ, 490, L13
Novikov, I. D., & Thorne, K. S. 1973, in Black Holes, ed. C. DeWitt & B. DeWitt (Paris: Gordon and Breach), 343
Nowak, M. A., Wilms, J., & Dove, J. B. 2002, MNRAS, 332, 856
Oosterbroek, T., van der Klis, M., Kuulkers, E., et al. 1995, A&A, 297, 141
Orosz, J. A., Groot, P. J., van der Klis, M., et al. 2002, ApJ, 568, 845
Orosz, J. A. & Bailyn, C. D. 1997, ApJ, 477, 876
Ortolani, S., Barbuy, B., Bica, E., et al. 1999, A&A, 350, 840
Paczynski, B. 1983, ApJ, 273, L81
Parmar, A. N., Stella, L., & Giommi, P. 1989, A&A, 222, 96
Pavlinsky, M. N., Grebenev, S. A., Lutovinov, A. A., et al. 2001, Ast, 27, 297
Poutanen, J., Krolik, J. & Ryde, F. 1997, MNRAS, 292, L21
Prins, S., & van der Klis, M. 1987, A&A, 319, 498
Rees, M. J., Phinney, E. S., Begelman, M. C., & Blandford, R. D. 1982, Nature, 295, 17
Rutledge, R. E., Bildsten, L., Brown, E. F., et al. 2001, ApJ, 559, 1054
Rutledge, R. E., Bildsten, L., Brown, E. F., et al. 2002, ApJ, 580, 413
Schulz, N. S., Hasinger, G., & Trümper, J. 1989, A&A, 225, 48
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Shapiro, S. L., Lightman, A. P., & Eardley, D. M., 1976, ApJ, 204, 187
Sobczak, G. J., McClintock, J. E., Remillard, R. A., et al. 2000, ApJ, 544, 993
Stirling, A. M., Spencer, R. E., de la Force, C. J., et al. 2001, MNRAS, 327, 1273
Tananbaum, H., Gursky, H., Kellogg, E., Giacconi, R., & Jones, C., 1972, ApJ, 177, L5
Tomsick, J. A., Halpern, J. P., Kemp, J., & Kaaret, P. 1999, ApJ, 521, 341
van Paradijs, J., Sztajno, M., Lewin, W. H. G., et al. 1986, MNRAS, 221, 617
van Paradijs, J., & White, N. 1995, ApJ, 447, L33
van Paradijs, J., & Isaacman, R. 1989, A&A, 222, 129
Wilms, J., Nowak, M. A., Pottschmidt, K., et al. 2001, MNRAS, 320, 327
Zdziarski, A. A., Lubinski, P., & Smith, D. A. 1999, MNRAS, 303, 11P
Zdziarski, A. A., Poutanen, J., Mikolajewska, J. et al. 1998, MNRAS, 301, 435
Zdziarski, A. A., Poutanen, J., Paciesas, W. S., & Wen, L. 2002, ApJ, 578, 357
Zhang, S. N., Cui, W., Harmon, B.A., et al. 1997, ApJ, 477, L95
Zurita, C., Casares, J., Shahbaz, T., et al. 2000, MNRAS, 316, 137