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Published in:
Astrophysical Journal

DOI:
10.1086/423953

The Astrophysical Journal, 611:L121–L124, 2004 August 20

THE CORRELATION BETWEEN HARD X-RAY PEAK FLUX AND SOFT X-RAY PEAK FLUX IN THE OUTBURST RISE OF LOW-MASS X-RAY BINARIES

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Received 2004 January 5; accepted 2004 July 7; published 2004 July 20

ABSTRACT

We have analyzed *Rossi X-Ray Timing Explorer* pointed observations of the outbursts of black hole and neutron star soft X-ray transients in which an initial low/hard state, or "island" state, followed by a transition to a softer state was observed. In three sources—the black hole transient XTE J1550−564, the neutron star transient Aquila X-1, and the quasi-persistent neutron star low-mass X-ray binary 4U 1705−44—two such outbursts were found. We find that the flux of the soft X-ray peak, which lags the hard X-ray peak by a few days to several weeks, scales with the flux of the hard X-ray peak. We conclude that we are able to predict the soft X-ray outburst peak flux based on the "preceding" hard X-ray peak flux, implying an early setup of the outbursts. We also find that the X-ray luminosity corresponding to the peak of the hard X-ray flux, which corresponds to the X-ray luminosity of the start of the hard-to-soft state transition, varies by a factor of about 2. If the accretion geometry early in the outburst rise is composed of two flows (e.g., a hot sub-Keplerian halo flow and a Keplerian disk flow or an outflow and a Keplerian disk flow), the correlation indicates that the two flows are initially related, probably owing to processes in the outer part of the accretion disk. We discuss constraints on a single-flow model and a disk-jet model from these observations.

Subject headings: accretion, accretion disks — black hole physics — stars: individual (Aquila X-1, 4U 1705−44, XTE J1550−564) — stars: neutron

1. INTRODUCTION

When a black hole soft X-ray transient (SXT) evolves from quiescence to an outburst, it may go through a series of state transitions, from a low/hard state in the rising phase of its outburst to an intermediate state, a high/soft state, or even a very high state; which of these softer states a source reaches is probably related to the maximal mass accretion rate that an outburst achieves. For a neutron star low-mass X-ray binary (LMXB) system, the spectral/timing state transition is shown in the color-color diagram (Hasinger & van der Klis 1989) as movement from "island" state to "banana" state, with additional complicated movement toward/from lower X-ray luminosity (Muno et al. 2002; Gierlinski & Done 2002; Barret & Olive 2002). In both neutron star and black hole systems, *an apparent hard flare will be observed if there is an initial low/hard state associated with a state transition in the outburst rise*. Such hard flares were observed in the outbursts of black holes XTE J1550−564 (Wilson & Done 2001; Hannikainen et al. 2001; Dubath et al. 2003), 4U 1630−47 (Hjellming et al. 1999), XTE J1859+226 (Brocksopp et al. 2002; Hynes et al. 2002), and GRO 0422+32 (Ling & Wheaton 2003) and the neutron stars Cen X-4 (Bouchacourt et al. 1984) and Aquila X-1 (Yu et al. 2003), suggesting a common origin of state transitions among black hole and neutron star SXT outbursts. The hard flare precedes the soft X-ray maximum by an interval of several days to more than 10 days, corresponding to the time span of the hard-to-soft state transition and the rise of a soft state. The *most luminous* low/hard state occurs in the early outburst rise at the peak of the hard "preceding" flare for an individual outburst. This most luminous low/hard state is the best target to probe the spectral/timing properties of the low/hard state because of its high X-ray flux (Yu et al. 2003).

The rise and the decay of an outburst has been explained in terms of the accretion disk approaching and receding from the compact object. Such a picture is likely directly related to the hysteresis effect of state transitions during an outburst rise or decay (Miyamoto et al. 1995), where hard-to-soft and soft-to-hard state transitions are different—one corresponds to the disk approaching the center and the advection-dominated accretion flow (ADAF; Narayan & Yi 1995) or the corona collapses, and the other corresponds to a disk receding from the center perhaps because of disk evaporation (Meyer & Meyer-Hofmeister 1994; Meyer et al. 2000).

The above accretion geometry composed of a truncated accretion disk and a hot spherical ADAF or corona at the center has been challenged by the long-term monitoring observations of some black hole X-ray binaries, which favor an accretion geometry containing two accretion flows (Smith et al. 2002). In this Letter, we show evidence supporting two accretion flows *related in* $\dot{M}$. Our results also indicate that the X-ray luminosity corresponding to the hard-to-soft state transition during the outburst rise varies by a factor of 2.

2. OBSERVATIONS AND RESULTS

Using the same *Rossi X-Ray Timing Explorer* (*RXTE*) light-curve retrieval method we described in Yu et al. (2003), we analyzed the Proportional Counter Array and the High-Energy X-Ray Timing Experiment (HEXTE) pointed observations of some black hole and neutron star SXTs in the public archive before 2003 May. We followed Yu et al. (2003) to obtain daily average all-sky monitor (ASM; 2–12 keV) light curves and HEXTE (15–250 keV) light curves and found outbursts with a low/hard state preceding the soft X-ray maximum in the following sources: the black hole X-ray binaries XTE J1550−564 (JD 2,451,065 and 2,451,628), XTE J1859+226 (JD 2,451,460), 4U 1630−47 (JD 2,450,868), and XTE J1650−500 (JD 2,452,158), the neutron star X-ray binary Aql X-1 (JD 2,451,310 and

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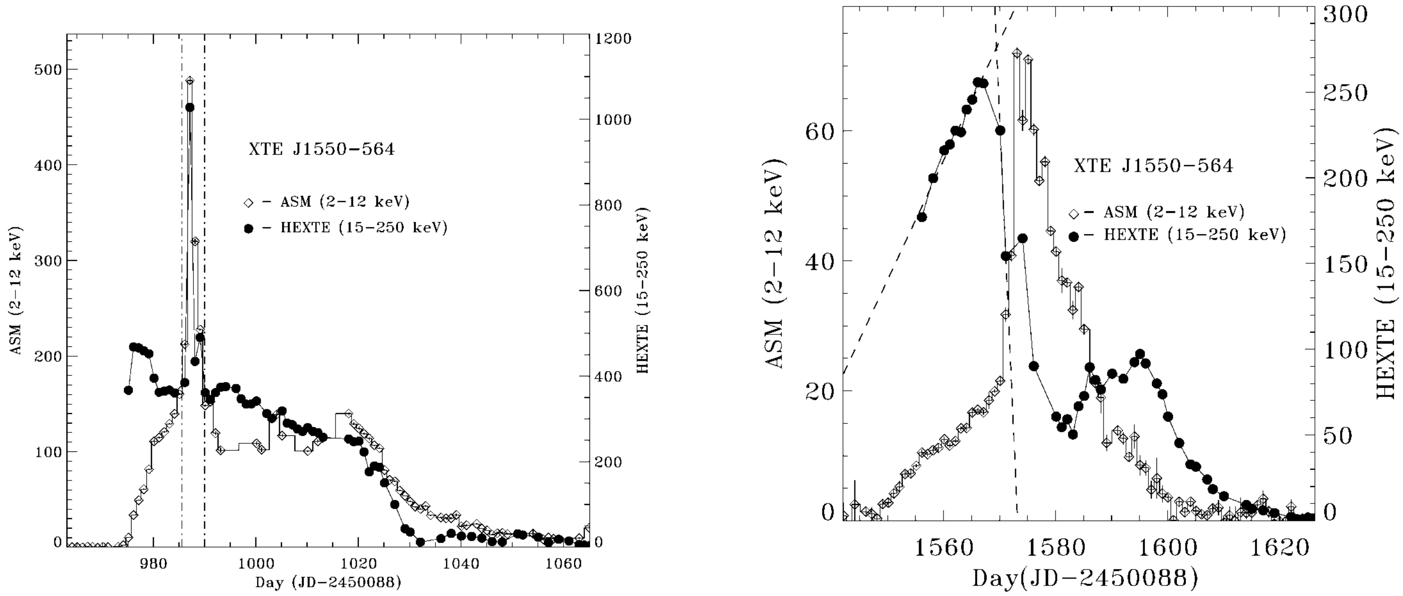

FIG. 1.—The 1998–1999 outburst (*left*) and the 2000 May outburst (*right*) of XTE J1550−564. ASM light curves (2–12 keV) and HEXTE light curves (15–250 keV) are shown as diamonds and filled circles, respectively. The initial most bright low/hard states are identified at the peaks of the preceding hard flares, corresponding to day 975 of the 1998–1999 outburst and day 1566 of the 2000 outburst, respectively. It is worth noting that the *RXTE* observations covered full turnover of the preceding hard flare peak in the 1998–1999 outburst on a daily scale. For the 2000 outburst, we may miss *RXTE* pointings at the turnover of the hard peak. We extrapolate the slopes of the rise and the decay to derive an upper limit of the HEXTE peak flux, about 14 counts s^{-1} higher than the peak rate observed (∼256 counts s^{-1}).

2,451,810), and the flares of the neutron star LMXB 4U 1705−44 (JD 2,451,235 and JD 2,451,370). We focus on XTE J1550−564, Aql X-1, and 4U 1705−44, the *only* sources in which we found more than one outburst/flare (i.e., two) showing that the hard X-ray peak precedes the soft X-ray peak (see below).

2.1. *ASM and HEXTE Daily Average Light Curves*

2.1.1. *XTE J1550−564*

The 1998–1999 and the 2000 April outbursts are shown in Figure 1 (*left and right, respectively*). The hard X-ray observation of the 1998 outburst with BATSE has been reported in Hannikainen et al. (2001) and Wu et al. (2002), while the BATSE detection of the 2000 outburst was reported in Masetti & Soria (2000) and Jain & Bailyn (2000). For the 1998–1999 outburst, the peak HEXTE flux of the preceding hard flare is 468 ± 1 counts s^{-1}. The peak ASM flux we use in the following analysis is 140 counts s^{-1}, estimated by excluding the very high state (VHS) interval marked by the dash-dotted lines for reasons explained below. We estimate the uncertainty of this flux to be ±10 counts s^{-1} based on the variation in ASM count rate during the primary outburst plateau. For the 2000 outburst, the peak HEXTE count rate recorded was 256 ± 1 counts s^{-1} (the true peak flux may have been 270 counts s^{-1}; see Fig. 1, *right*) and the peak ASM rate is 70 ± 1 counts s^{-1}. Here the count rate errors are rounded up to the nearest integers unless otherwise indicated. We exclude the VHS because we want to consistently compare the black hole SXT XTE J1550−564 with neutron star X-ray binaries, in which the characteristics of the VHS, i.e., a simultaneous high/soft X-ray flux and high/hard X-ray flux, have never been observed.

2.1.2. *Aql X-1*

We already reported that in the 1999 outburst and the 2000 outburst of Aql X-1, the hard X-ray flare precedes the soft X-ray outburst (Yu et al. 2003). The peak HEXTE count rates recorded are 56 ± 1 and 105 ± 1 counts s^{-1}, and the peak ASM count rates are 29 ± 1 and 50 ± 2 counts s^{-1}, respectively. The HEXTE pointings cover the hard peak of the 1999 outburst but may not cover that of the 2000 outburst, which by extrapolation may have reached about 120 counts s^{-1}, 15 counts s^{-1} higher than the observations.

2.1.3. *4U 1705−44*

The binary 4U 1705−44 is not a transient source. However, its long-term variability and detailed spectral evolution suggest that it probably undergoes the same state transitions as SXTs. In Figure 2, we show ASM and HEXTE light curves regarding the two flares of the source. The observed HEXTE peak count rates are 34 ± 1 and 48 ± 1 counts s^{-1}, and the peak ASM count rates are 21 ± 1 and 31 ± 1 counts s^{-1}, respectively.

2.2. *Correlation between the HEXTE Peak Flux and the ASM Peak Flux*

In Figure 3, we plot the *observed* HEXTE peak flux versus the ASM peak flux for the outbursts or flares of XTE J1550−564, Aql X-1, 4U 1705−44, and several other sources. The uncertainties of peak flux because of lack of coverage are very small. The plot shows a proportionality between the hard X-ray peak flux and the delayed soft X-ray peak flux for each source. The data corresponding to the three sources are also roughly consistent with a single linear proportionality, indicating similar *observed* energy spectra among these sources. Deviation from the proportionality may come from different Galactic or intrinsic absorption among sources.

Because the energy spectra corresponding to the hard state of the same source for different outbursts are very similar (XTE J1550−564: Sobczak et al. 2000; Aql X-1: Yu et al. 2003; 4U 1705−44: Barret & Olive 2002), the X-ray luminosity corresponding to the start of the hard-to-soft state transition is roughly described by either the ASM rate or the HEXTE rate at the peak

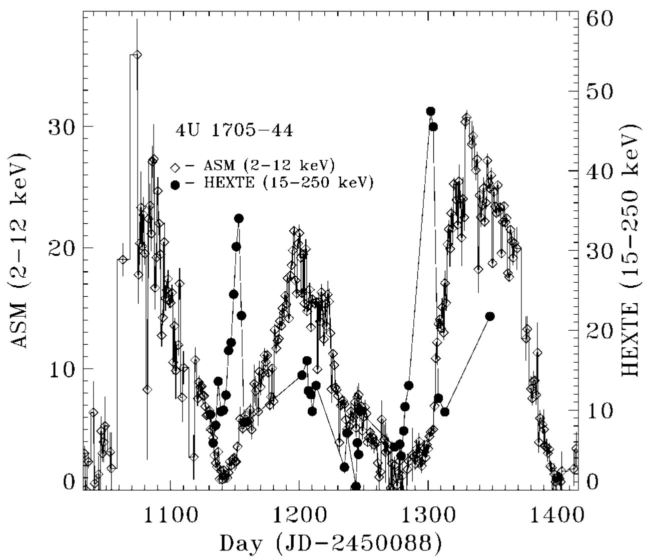

Fig. 2.—ASM light curves (2–12 keV) and HEXTE light curves (15–250 keV) of 4U 1705−44, shown as diamonds and filled circles, respectively. It is worth noting that on a daily scale, the HEXTE pointings roughly covered the hard peak of the first flare but probably not the later ones. Notice that the ASM peaks lag the HEXTE peaks for 30–50 days, much longer than observed in Aql X-1 (Yu et al. 2003).

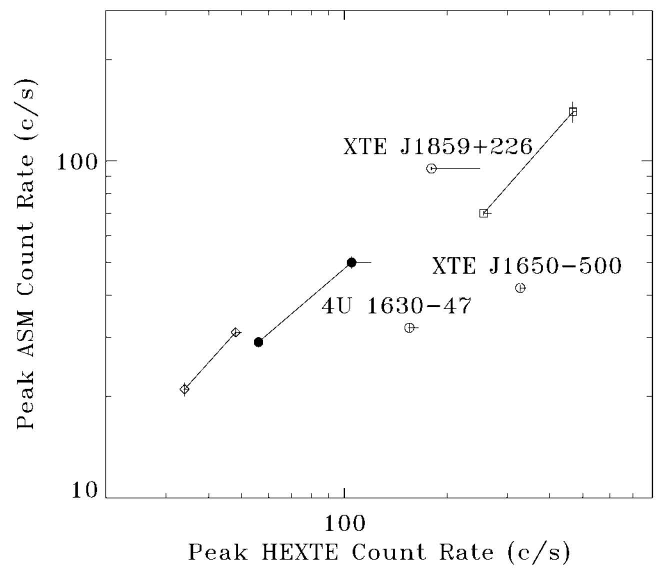

Fig. 3.—Correlation between HEXTE (15–250 keV) and ASM (2–12 keV) peak flux in the outbursts or flares of XTE J1550−564 (*squares*), Aql X-1 (*filled circles*), and 4U 1705−44 (*diamonds*) discussed in the text. The lack of coverage by the HEXTE pointed observations on a daily basis will introduce an underestimate of the peak HEXTE fluxes, but assuming a linear rise and decay, the effect of the underestimate is small. This is shown as error bars of the HEXTE peak flux. The outbursts in 4U 1630−47, XTE J1650−500, and XTE J1859+226 are also shown as open circles.

of the preceding hard flare of an outburst (see Yu et al. 2003). Using the same spectral model for the same source (4U 1705−44 and Aql X-1: same model as used in Barret & Olive 2002; XTE J1550−564: blackbody+cutoff power law+Gaussian line at 6.4 keV), we have derived the unabsorbed peak X-ray flux at the peak of the hard flare. The flux, or the X-ray luminosity, can vary by a factor of 2.5. This suggests that the hard-to-soft state transition does not occur at a constant X-ray luminosity for the same source.

3. DISCUSSION AND CONCLUSION

We have investigated the *RXTE* pointed observations of the outbursts of the black hole transient XTE J1550−564 and the neutron star transient Aql X-1, together with those of the flares of the quasi-persistent neutron star LMXB 4U 1705−44. Two instances of a preceding hard X-ray flare were observed in each source. (Note that the outbursts discussed here are only those in which the source could reach the point of state transition in the outburst rise. The low-amplitude low/hard state outbursts are out of the scope of this Letter.) We find that the HEXTE peak flux is proportional to the ASM peak flux, which the source reached a few days to several weeks later. We show that the X-ray luminosity corresponding to the hard-to-soft state transition can vary by a factor of more than 2 for the *same* source.

If the X-ray luminosity is an indicator of the mass accretion rate on the outburst timescale, a varying X-ray luminosity of the hard-to-soft state transition shows that the transition is not solely determined by the mass accretion rate. We have demonstrated that for an individual source, the brighter the initial low/hard state of the outburst is, the brighter the later high/soft state will be. This is contrary to what is predicted by models that attribute the state transition to a change in a single mass accretion rate (examples of such models are, e.g., Esin et al. 1998; Meyer et al. 2000). In the disk-instability model of SXT outbursts, the energy reservoir of the X-ray outburst is the material accumulated in the accretion disk during "quiescence." If an outburst consumes almost all the material in the disk, the outburst size should correlate with the disk mass. The more massive the disk is, the bigger the outburst will be, and the bigger both the hard and the soft flares will be. Disk mass provides the additional parameter that determines the state transition. If this also holds for the state transition during the outburst decay, it should occur at a lower X-ray luminosity than that during the rise because of a less massive disk (assuming the same physics applies). This agrees with the observations—the so-called hysteresis effect (Miyamoto et al. 1995).

The correlation between the hard X-ray peak flux and the soft X-ray peak flux of the outbursts indicates that the outbursts are set up early. At the time when the hard-to-soft state transition occurs and the hard X-ray peak flux is known, the soft X-ray peak flux of the outburst can already be predicted as the entire outburst scales with the hard peak flux.

The correlation between the hard X-ray peak flux and the soft X-ray peak flux requires a link between an earlier accretion flow/outflow that generates the hard X-ray flare and a later accretion flow that produces the soft X-ray outburst. In the single-flow Comptonization models for the low/hard state that are composed of disk and corona (for a recent review, see Nowak 2002), the correlation requires the hard X-ray photons to originate from inverse Comptonization of low-energy photons in ultraviolet or optical from the disk flow farther away from the central compact object, which produces the soft X-ray outburst peak at a later time when it propagates to the center. This requires future observations to confirm a correlation between the ultraviolet or optical flux and the hard X-ray flux in the rise of the low/hard state, as required by the inverse Comptonization models. On the other hand, our results support a two–accretion-flow geometry at the beginning of an SXT outburst; at the start of the outburst rise, a nondisk flow arrives earlier from the outer disk and generates the hard X-ray flux, while the optically thick disk flow propagates inward on a viscous timescale (in a model involving a halo flow being an ADAF flow or a corona flow, the disk's propagation inward may be also related to a simultaneous collapse or contrast of the central ADAF or corona). The time lag between the two flows depends on the initial inner disk radius at the start of the outbursts. This is consistent with the model proposed by Chakrabarti & Titarchuk (1995). A sub-Keplerian corona flow originating from disk evaporation moving above the disk rather than comoving with the disk flow in the ADAF+disk+corona model (e.g., Meyer et al. 2000) may also explain the observations. Smith et al. (2002) discussed supporting evidence for such two simultaneous, independent accretion flows in several black hole X-ray binaries. Our study is on the outburst rise, different from the count rate decrease discussed in Smith et al. (2002), and includes both black hole and neutron star X-ray binaries. Furthermore, our study indicates that *the two accretion flows are related in* $\dot{M}$; the two accretion flows are supplied with approximately *proportional* amounts of matter among the outbursts of the same source. It is worth noting that a similar two related accretion-flow geometry was used to interpret the "parallel tracks" in the plot of kilohertz quasi-periodic oscillation frequency and the X-ray flux in neutron star LMXBs (van der Klis 2001). As all the three sources in our study are known to be LMXBs, this relation may only apply to LMXB outbursts.

The two–accretion-flow geometry suggests that the accretion state depends on which accretion flow dominates. If the observed accretion state is solely a consequence of the competition of the two flows, the critical X-ray luminosity corresponding to the appearance of the "propeller" regime for accreting neutron stars (Lamb et al. 1973; Illarionov & Sunyaev 1975) is not expected to be a constant but to vary with the composition of the two accretion flows. This implies that during the outburst rise, if the X-ray luminosity is below the level of the hard-to-soft state transition, the X-ray luminosity corresponding to the propeller state might relate to the propeller state of the halo flow, while during the outburst decay, if the X-ray luminosity is above the level of the soft-to-hard state transition, the X-ray luminosity corresponding to the propeller state might relate to the propeller state of the disk flow. The difference between the two accretion flows probably also introduces differences in the energy spectrum in the propeller state. The competition of the two accretion flows and the propeller mechanism may jointly contribute to the complexities of the spectral variation at low X-ray luminosity ranges (see, e.g., the color-intensity diagram of Aql X-1 shown in Muno et al. 2002).

The association of the preceding hard X-ray flux with a halo flow rather than a disk flow can also put some constraints on the viscosity of the hot halo flow compared with the disk flow. The rise of the preceding hard flare from the quiescent level in these sources has a timescale of several days to several weeks (T_1), while the rise of the soft X-ray outburst has a timescale of several weeks (T_2). The ratio between T_2 and T_1 is about $2:3$. Thus, if the two–accretion-flow model is correct, then the non-disk flow is a sub-Keplerian flow rather than a free-fall flow. Assuming that T_2 and T_1 are related with the viscous timescales $t_{\rm visc} \sim R^2/\nu$, and the viscosity of either the halo flow or the disk flow is similar among sources, T_2 and T_1 may reflect the size of the central hole in the disk and the disk size at the start of an outburst, respectively.

Our results may also support the accretion geometry composed of an inner jet/outflow and an outer disk flow in which the jet/outflow generates the hard X-rays and the disk flow generates the soft X-rays (e.g., Markoff et al. 2001). In this case, the correlation we found requires that the base of the jet is related to the disk flow and there is a close relationship between the peak powers of the two. The more massive the disk is, the stronger the jet will be (see also Garcia et al. 2003). This might suggest that the lifetime of the jet/outflow is more sensitive to the inner radius of the disk flow than the disk flow luminosity. Fender & Kuulkers (2001) show that soft X-ray peak luminosity also correlates with the radio peak luminosity. Thus, our results predict that the radio peak flux correlates with the hard X-ray peak.

The authors thank A. R. King for mentioning the jet/outflow and Frederick K. Lamb for very useful comments. This work was supported mainly by the Netherlands Organization for Scientific Research under grant 614.051.002 and partly by NASA grants NAG 5-12030 and NAG 5-8740 and NSF grant AST 0098399 and has made use of data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/Goddard Space Flight Center.

REFERENCES

Barret, D., & Olive, J. 2002, ApJ, 576, 391
Bouchacourt, P., et al. 1984, ApJ, 285, L67
Brocksopp, C., et al. 2002, MNRAS, 331, 765
Chakrabarti, D., & Titarchuk, L. 1995, ApJ, 455, 623
Dubath, P., Revnivtsev, M., Goldoni, P., von Kienlin, A., Lund, N., Grebenev, S., & Kuulkers, E. 2003, IAU Circ. 8100
Esin, A. A., Narayan, R., Cui, W., Grove, J. E., & Zhang, S.-N. 1998, ApJ, 505, 854
Fender, R. P., & Kuulkers, E. 2001, MNRAS, 324, 923
Garcia, M. R., Miller, J. M., McClintock, J. E., King, A. R., & Orosz, J. 2003, ApJ, 591, 388
Gierlinski, M., & Done, C. 2002, MNRAS, 331, L47
Hannikainen, D., et al. 2001, in Exploring the Gamma-Ray Universe, ed. A. Giminez, V. Reglero, & C. Winkler (ESA SP-459; Noordwijk: ESA), 291
Hasinger, G., & van der Klis, M. 1989, A&A, 225, 79
Hjellming, R. M., et al. 1999, ApJ, 514, 383
Hynes, R. I., Haswell, C. A., Chaty, S., Shrader, C. R., & Cui, W. 2002, MNRAS, 331, 169
Illarionov, A. F., & Sunyaev, R. A. 1975, A&A, 39, 185
Jain, R., & Bailyn, C. 2000, IAU Circ. 7400
Lamb, F. K., Pethick, C. J., & Pines, D. 1973, ApJ, 184, 271
Ling, J. C., & Wheaton, Wm. A. 2003, ApJ, 584, 399
Markoff, S., Falcke, H., & Fender, R. 2001, A&A, 372, L25
Masetti, N., & Soria, R. 2000, IAU Circ. 7399
Meyer, F., Liu, B. F., & Meyer-Hofmeister, E. 2000, A&A, 354, L67
Meyer, F., & Meyer-Hofmeister, E. 1994, A&A, 288, 175
Miyamoto, S., Kitamoto, S., Hayashida, K., & Egoshi, W. 1995, ApJ, 442, L13
Muno, M. P., Remillard, R. A., & Chakrabarty, D. 2002, ApJ, 568, L35
Narayan, R., & Yi, I. 1995, ApJ, 444, 231
Nowak, M. A. 2002, in New Views on Microquasars, ed. Ph. Durouchoux, Y. Fuchs, & J. Rodriguez (Kolkata: Center for Space Physics), 3
Smith, D. M., Heindl, W. A., & Swank, J. H. 2002, ApJ, 569, 362
Sobczak, G. J., McClintock, J. E., Remillard, R. A., Cui, W., Levine, A. M., Morgan, E. H., Orosz, J. A., & Bailyn, C. D. 2000, ApJ, 544, 993
van der Klis, M. 2001, ApJ, 561, 943
Wilson, C. D., & Done, C. 2001, MNRAS, 325, 167
Wu, K., et al. 2002, ApJ, 565, 1161
Yu, W., Klein-Wolt, M., Fender, R., & van der Klis, M. 2003, ApJ, 589, L33