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NEW EVIDENCE FOR BLACK HOLE EVENT HORIZONS FROM *CHANDRA*

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ABSTRACT

Previously we claimed that black hole X-ray novae (BHXNs) in quiescence are much less luminous than equivalent neutron star X-ray novae (NSXNs). This claim was based on the quiescent detection of a single short-period BHXN (A0620−00, $P_{\rm orb} = 7.8$ hr) and two longer period BHXNs (GRO J1655−40, $P_{\rm orb} = 62.9$ hr; V404 Cygni, $P_{\rm orb} = 155.3$ hr), along with sensitive upper limits. Here we announce the detection of two more short-period BHXNs (GRO J0422+32, $P_{\rm orb} = 5.1$ hr; GS 2000+25, $P_{\rm orb} = 8.3$ hr), an upper limit for a third that is improved by 2 orders of magnitude (4U 1543−47, $P_{\rm orb} = 27.0$ hr), and a new, much lower quiescent measurement of GRO J1655−40. Taken together, these new *Chandra* Advanced CCD Imaging Spectrometer measurements confirm that the quiescent X-ray luminosities of BHXNs are significantly lower than those of NSXNs. We argue that this provides strong evidence for the existence of event horizons in BHXNs.

Subject headings: binaries: close — black hole physics — stars: individual (A0620−00, GRO J0422+32, GRO J1655−40, GS 2000+25, V404 Cygni, 4U 1543−47) — stars: neutron — X-rays: stars

1. INTRODUCTION

The very low, but nonzero, quiescent X-ray luminosity of the black hole X-ray nova (BHXN) A0620−00 is difficult to understand in the context of standard viscous accretion disk theory (McClintock, Horne, & Remillard 1995), given the continued mass transfer from the companion evidenced by an optically bright disk. The observations can be explained by an advection-dominated accretion flow (ADAF) model (Narayan, McClintock, & Yi 1996). In an ADAF (see Narayan, Mahadevan, & Quataert 1998b and Kato, Fukue, & Mineshige 1998 for reviews), the energy released by accretion is stored as heat in a radiatively inefficient flow. Should the accreting object be a black hole (BH), this energy would be lost from view once it crosses the event horizon, but if the object has a solid surface, the energy would be released upon impact with that surface and radiated to infinity. Thus, for the same mass accretion rate, a BH would be significantly less luminous than a compact star with a surface (Narayan & Yi 1995). Such a comparison of otherwise similar systems is a promising method for proving the reality of event horizons (Narayan, Garcia, & McClintock 1997b, hereafter NGM97).

X-ray novae (XNs) containing BH and neutron star (NS) primaries are believed to be similar in many respects. Most importantly, the mass transfer rate from the secondary, measured in Eddington units of the primary, is believed to be comparable in BHXNs and neutron star X-ray novae (NSXNs) of similar orbital periods (Menou et al. 1999, hereafter M99). NGM97, Garcia et al. (1998, hereafter G98), and M99 showed that quiescent BHXNs are much less luminous in X-rays than quiescent NSXNs of similar orbital periods and argued that this provides direct evidence that BHXNs are able to "hide" their accretion energy behind an event horizon. However, their claims were based on a very small sample in which only one detected BHXN (A0620−00, $P_{\rm orb} = 7.8$ hr) had an orbital period similar to those of the comparison NSXNs. We report here new observations of six BHXNs with the *Chandra X-Ray Observatory* (Weisskopf & O'Dell 1997).

2. OBSERVATIONS AND ANALYSIS

The data described herein were obtained with the Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 1992) on board *Chandra*. The *Chandra*/ACIS combination is ~100 times more sensitive than previous X-ray observatories, making it ideal for studying the extremely faint quiescent state of BHXNs. The observations are listed in Table 1. Data were analyzed with a combination of the *Chandra* X-Ray Center (CXC) CIAO v1.1 software,[4] the HEASARC XSPEC v11.0 software,[5] and software written by A. Vikhlinin (Vikhlinin et al. 1998). Detected fluxes and count rates were restricted to a 0.3–7.0 keV energy band for ACIS-S observations, and 0.5–7.0 keV for ACIS-I observations, in order to reduce the instrumental background. The observed on-axis point-source response function is such that 95% of the source flux is contained in the 1.″5 radius source extraction circle (van Speybroeck et al. 1997[6]).

We defer a discussion of the X-ray spectra of quiescent BHXNs, as determined by the ACIS, to a second paper (J. E. McClintock, M. R. Garcia, R. Narayan, & S. S. Murray 2001, in preparation). Here we assume that the spectra of all the sources are adequately described by a single power law with $\alpha \sim 2$ and absorption consistent with the optical extinction (Narayan, Barret, & McClintock 1997a). Our conclusions are unchanged for any reasonable assumption of the source spectra (e.g., Narayan et al. 1997a).

GRO J0422+32.—The GRO J0422+32 region was observed with the *Chandra* ACIS-I CCD array (Garmire et al. 1992) for 18.8 ks on 2000 October 10. The CCD array recorded

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[4] The CXC Data Manipulation User's Guide, Version 1.1; available at http://asc.harvard.edu/ciao/download/doc/manual_dm.ps.
[5] K. Arnaud & B. Dorman 2000, XSPEC, An X-Ray Spectral Fitting Package, Users Guide for Version 11; available at http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/index.html.
[6] See also the *Chandra* Proposers Observatory Guide, Version 2.0; available at http://asc.harvard.edu/udocs/docs/docs.html.

TABLE 1
CHANDRA OBSERVATIONS OF QUIESCENT BHXNS (DETECTED FLUXES AND LIMITS)

System	Instrument	Counts	Exposure (ks)	f_X (ergs s^{-1} cm^{-2})	L_X (ergs s^{-1})	D (kpc)	m_1 ($M_\odot$)	log N_H (cm^{-2})
GRO J0422+32	ACIS-I	16	18.8	6.6×10^{-15}	7.6×10^{30}	2.6	12	21.3
A0620−00 (XN Mon 75)	ACIS-S	123	38.3	1.8×10^{-14}	2.8×10^{30}	1.0	6.1	21.3
GS 2000+25 (XN Vul 88)	ACIS-I	5	21.5	2.4×10^{-15}	2.4×10^{30}	2.7	8.5	21.9
4U 1543−47	ACIS-I	<5	9.9	$<4.2 \times 10^{-15}$	$<3.0 \times 10^{31}$	6.1[a]	6[a]	21.6[b]
GRO J1655−40	ACIS-S	65	42.5	1.2×10^{-14}	2.4×10^{31}	3.2	7	21.8
V404 Cyg (GS 2023+338)	ACIS-S	1655	10.3	1.5×10^{-12}	4.9×10^{33}	3.5	12	22.0

NOTE.—Values of N_H are taken from G98 and NGM97; distances and primary masses are from M99, unless explicitly mentioned. Detected ACIS-S fluxes are over a 0.3–7.0 keV band, ACIS-I fluxes are over a 0.5–7.0 keV band, and emitted luminosities are over a 0.5–10.0 keV band.

[a] From J. Orosz et al. 2001, in preparation.

[b] N_H from Greiner, Predehl, & Harmon 1994 and van der Woerd, White, & Kahn 1989.

16 photons at a position consistent with the optical position of GRO J0422+32. Given the extremely low background of *Chandra* (<1 background count per target for every observation presented here), the recording of $\gtrsim$5 counts represents a detection of the target with greater than 99% confidence. Assuming a distance of 2.6 kpc (M99) and X-ray absorption corresponding to the optical extinction of $A_V = 1.2$ (Filippenko, Matheson, & Ho 1995; Predehl & Schmitt 1995), we derive an emitted luminosity of 7.6×10^{30} ergs s^{-1} (0.5–10.0 keV).

A0620−00.—The A0620−00 region was observed for 45 ks on 2000 February 29. We rejected 6.7 ks of this observation because of intervals of enhanced background (see Plucinsky & Virani 2000). A0620−00 was placed on the ACIS-S3 CCD (Garmire et al. 1992) in order to maximize the count rate from the possibly soft X-ray spectrum (Narayan et al. 1997a). The CCD recorded 123 photons at a position consistent with the optical position of A0620−00.

GS 2000+25.—The GS 2000+25 region was observed with the *Chandra* ACIS-I detector on 1999 November 5 for a total of 21.5 ks. The CCD array recorded 5 photons near the position of GS 2000+25, which is a weak but significant detection. In order to more accurately determine the position of this source, we cross-correlated the positions of all sources in the image with greater than 10 counts against an optical astrometric reference catalog (USNO-A2; Monet et al. 1996). We found four matches within a 2″ search radius. We then determined the astrometric solution for the X-ray image using these four stars. This solution has an rms position uncertainty of 0.″3 and shows that the position of this weak source is R.A. = $20^h02^m49^s.52$, decl. = +25°14′10.″34 (J2000). Our ability to determine the centroid of this source is limited by the low number of counts to ~0.″5. We determined the position of the optical counterpart of GS 2000+25 in a similar way, matching eight USNO-A2 stars against a *K*-band image of the field we acquired at the Lick 3 m telescope in California with the Gemini camera. This plate solution has an rms position uncertainty of 0.″2 and shows the position of the optical (IR) counterpart to be R.A. = $20^h02^m49^s.55$, decl. = +25°14′10.″94 (J2000). The offset between the two positions is 0.″7 ± 0.″8; thus, the position of the weak X-ray source is consistent with GS 2000+25.

4U 1543−47.—A 9.9 ks ACIS-I observation of 4U 1543−47 took place on 2000 July 26 and failed to detect even a single photon from this source. We compute a conservative upper limit to the luminosity by assuming that less than 5 photons were detected. This luminosity (see Table 1) is a factor of ~100 below the previous upper limit of 2×10^{33} ergs s^{-1} (M99).

GRO J1655−40.—A 42.5 ks ACIS-S observation of GRO J1655−40 took place on 2000 July 2 and detected 65 photons from this source. We note that this corresponds to a luminosity a factor of ~10 below the previously measured quiescent luminosity of 2.5×10^{32} ergs s^{-1} (G98). Given the quiescent variations seen in V404 Cygni (Wagner et al. 1994), this could simply be indicative of typical quiescent variations. Alternately, we note that the previous quiescent observations were in between two large outbursts separated by ~1 yr and therefore may not have been indicative of the true quiescent level. The *Chandra* observations reported here occurred ~4 yr after the last outburst, and therefore may measure the quiescent level more accurately.

V404 Cyg.—A 10.3 ks ACIS-S observation of V404 Cyg took place on 2000 April 26 and allowed detection of 1655 photons from this source.

3. DISCUSSION

We have collected in Table 2 the available quiescent X-ray luminosities and upper limits for BHXNs and NSXNs. We have supplemented our *Chandra* measurements with the recent quiescent detections of SAX J1808.4−3658 (Stella et al. 2000; Dotani, Asai, & Wijnands 2000) and included previous data compiled by M99. Figure 1 displays the Eddington-scaled luminosities as a function of orbital period P_{orb}. For calculating L_{Edd}, we used the BH mass estimates in Table 1 and assumed that all NSs have a mass of 1.4 $M_\odot$.

With the *Chandra* detections of GRO J0422+32 and GS 2000+25 reported here, three short-period BHXNs have now been detected in quiescence. A greatly improved upper limit for a fourth short-period system, 4U 1543−47, is nearly comparable to these detections. In addition, we find a new, 10 times fainter quiescent luminosity for GRO J1655−40, which has a period intermediate between the NSXNs and the long-period BHXN V404 Cyg.

The new data points significantly strengthen our earlier claim (NGM97; G98; M99) that BHXNs have much lower (roughly a factor of 100) quiescent luminosities than NSXNs. As explained in § 1, such a difference in luminosity is natural if quiescent accretion proceeds via a radiatively inefficient ADAF *and* if the primaries in BHXNs have event horizons. Thus, the new data bolster the evidence for event horizons in BHXNs.

Our argument relies on the reasonable assumption that the Eddington-scaled mass accretion rate is similar in quiescent BHXNs and NSXNs. At the short orbital periods characteristic of the NSXNs in our sample, angular momentum loss through gravitational radiation is expected to be the dominant mechanism driving mass transfer from the secondary. The Eddington-scaled mass transfer rates are then likely to be roughly similar

TABLE 2
QUIESCENT LUMINOSITIES

System (1)	P_{orb} (hr) (2)	log L_{min} (ergs s^{-1}) (3)
Neutron Star Primaries		
SAX J1808−365	2.0[a]	**32.0**,[b] **31.5**[c]
EXO 0748−676	3.82	34.1
4U 2129+47	5.2	32.8
Cen X-4	15.1	32.4
Aql X-1	19	32.6
H1608−52	**12**[d]	33.3
Black Hole Primaries		
GRO J0422+32	5.1	**30.9**, <31.6
A0620−00	7.8	**30.5**, 30.8[e]
GS 2000+25	8.3	**30.4**, <32.2
GS 1124−683	10.4	<32.4
H1705−250	12.5	<33.0
4U 1543−47	27.0	<**31.5**, <33.3
GRO J1655−40	62.9	**31.3**, 32.4
V404 Cyg	155.3	**33.7**, 33.1[f]

NOTE.—References are as in M99, unless otherwise noted. New and/or *Chandra* measurements are in boldface. Col. (2): Orbital period. Col. (3): Luminosity in quiescence in the 0.5–10 keV band (corrected for the revised distances).

[a] From Chakrabarty & Morgan 1998.

[b] From Stella et al. 2000; assuming $D = 2.5$ kpc.

[c] From Dotani et al. 2000.

[d] Wachter 2000 reports a new 12 hr period, intermediate between the previously reported 98.4 hr (Ritter & Kolb 1998) and 5 hr (Chen et al. 1998) periods.

[e] Recomputed for $\alpha = 2$ from NGM97.

[f] From Kong 2000.

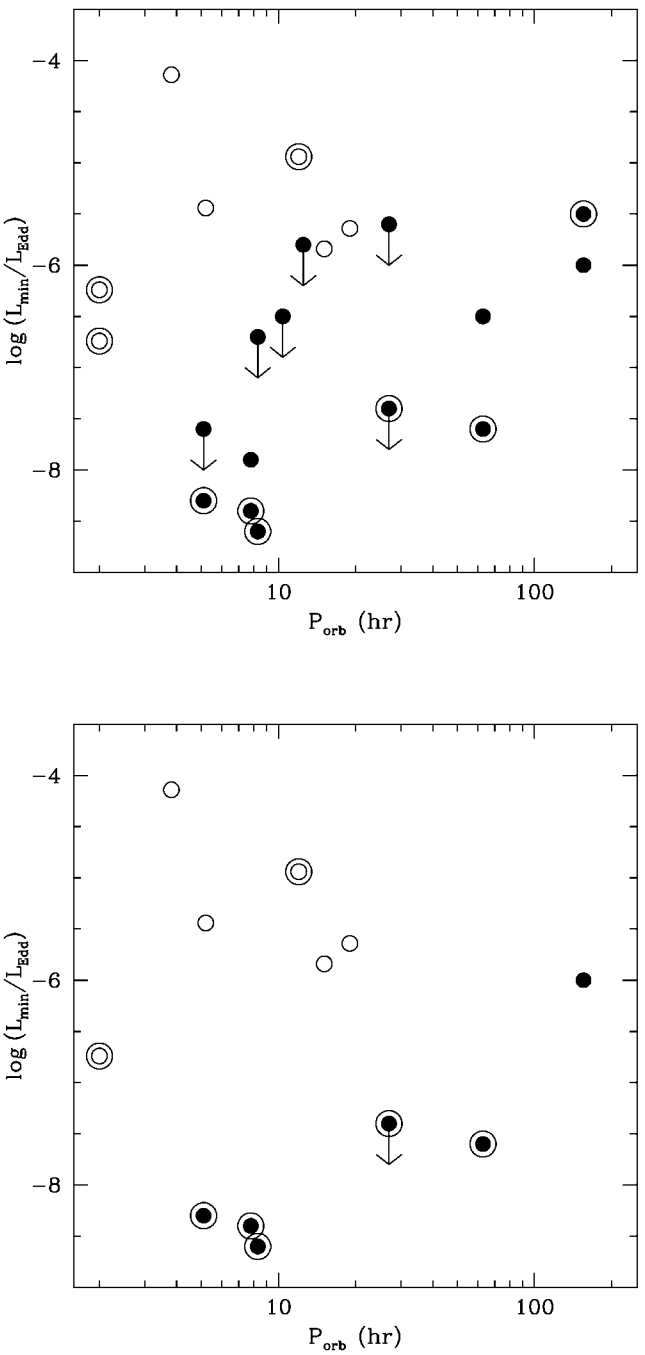

FIG. 1.—*Top*: Quiescent luminosities of BHXNs (*filled circles*) and NSXNs (*open circles*) from Table 2. Data points not included in M99 are circled. Multiple quiescent detections are included. *Bottom*: Only the lowest quiescent detections or *Chandra* upper limits.

in BHXNs and NSXNs of similar P_{orb} (M99). At the long periods of V404 Cyg and perhaps GRO J1655−40, nuclear evolution is expected to drive the mass transfer rate to substantially higher values, and so these systems are less useful for our purposes. Moreover, the lack of NSXNs with similar P_{orb} limits the usefulness of these systems for the comparisons made here.

We also assume that f_*, the fraction of matter transferred from the secondary that actually reaches the central star, is the same in BHXNs and NSXNs. Outflowing winds from an ADAF (Narayan & Yi 1994, 1995; Blandford & Begelman 1999; M99) tend to reduce f_*, but there is no reason to expect winds to be stronger (by a factor of 100) in BHXNs than in NSXNs. In fact, a centrifugal propeller and/or radio pulsar action could reduce f_* in NSXNs without affecting BHXNs (NGM97; M99). Therefore, we expect f_* to be lower in NSXNs than in BHXNs rather than the other way round. This strengthens the case for event horizons in BHXNs.

In this connection, we note that SAX J1808.4−3658 is the least luminous of the NSXNs. It also may have a time-averaged mass transfer rate that is lower than that typical of XNs, perhaps due to the action of the radio pulsar on the secondary (Chakrabarty & Morgan 1998) or due to the possible extreme evolution of the secondary (King 2000; Dotani et al. 2000). Given that SAX J1808.4−3658 is the only example of an NSXN that shows permanent coherent pulsations, it seems possible that it may also have an unusually efficient "propeller." Despite all these anomalies, this NSXN is ~60 times brighter than our three short-period BHXNs (see Fig. 1).

Campana & Stella (2000) argue that it is not correct to compare only X-ray luminosities, as we have done, but that we should include also the quiescent nonstellar optical and UV luminosity. This point is not obvious since the origin of the optical/UV luminosity is presently unclear. Within the ADAF model, it depends on the poorly known radius at which the inner edge of the accretion disk evaporates into the ADAF (e.g., Narayan et al. 1996, 1997a). It also depends on the strength of winds from the ADAF (Quataert & Narayan 1999). If the nonstellar optical/UV luminosity originates in the outer accretion disk, or in the hot spot where the mass transfer stream from the secondary impacts the disk, then the fact that the optical/UV luminosities of BHXNs and NSXNs are similar (Campana & Stella 2000) provides observational confirmation

that the mass transfer rates in the two kinds of system are similar, as we have assumed. A 0.25 mag modulation in the far-UV flux of A0620−00 on an orbital timescale suggests that the far-UV flux may be modulated with the orbital phase (McClintock 2000), which indicates an origin in the hot spot.

Bildsten & Rutledge (2000; but see Lasota 2000) suggest that the X-rays in many BHXNs may be produced by a rotationally enhanced stellar corona in the secondary. The detection of GRO J0422+32 with a luminosity of nearly 10^{31} ergs s^{-1} rules out the coronal interpretation for this system but is consistent with the prediction of the ADAF plus disk instability model of Lasota (2000). Similarly, the luminosity of V404 Cyg is ~60 times larger than the coronal model predicts but within a factor of 10 of the ADAF model (Lasota 2000). The luminosities of the remaining four sources in Table 1 are consistent with both models. If some (or all) of the X-ray emission in BHXNs were coronal, then the accretion luminosities of the BHs would be even lower than our estimates and the argument for event horizons would be further strengthened.

A critical element in our comparison of NSXN and BHXN quiescent luminosities is the assumption that the quiescent X-ray luminosities of NSXNs result from accretion. Brown, Bildsten, & Rutledge (1998) have suggested that the luminosity could be due to crustal heating of the NS during outburst followed by cooling in quiescence. The rapid variability of the prototypical NSXN Cen X-4 (Campana et al. 1997) is hard to explain in a cooling model and shows that at most approximately one-third of the quiescent luminosity of this source is due to crustal cooling (M99). In addition, Cen X-4 and Aql X-1 have substantial power-law tails in their spectra (carrying about half the total luminosity), and it is hard to explain this spectral component with a cooling model. It thus seems reasonable to assume that accretion accounts for a substantial fraction of the quiescent X-ray luminosity in most NSXNs. The optical variability of NSXNs in quiescence (McClintock & Remillard 2000; Jain et al. 2000; Ilovaisky & Chevalier 2000) provides ample evidence that accretion continues during quiescence.

Regardless of the caveats mentioned above, ultimately the dramatic difference in quiescent X-ray luminosities of BHXNs and NSXNs needs to be explained. Any explanation is likely to require a fundamental difference in the nature of the primaries in BHXNs and NSXNs. In our view, any straightforward explanation, whether based on ADAFs or not, will require postulating an event horizon in BHXNs.

The Eddington-scaled luminosities of some supermassive black holes (SMBHs) in galactic nuclei (e.g., Garcia et al. 2000; Baganoff et al. 2000) are much smaller than those of the "stellar mass" BHs discussed here. Could this be evidence for the event horizon (Narayan et al. 1998a)? Unfortunately, the mass accretion rates of SMBHs are difficult to determine observationally (DiMatteo et al. 2001b; DiMatteo, Carilli, & Fabian 2001a; Quataert, Narayan, & Reid 1999), and one cannot exclude the possibility that the low luminosities of SMBHs are simply the result of extremely low accretion rates. In the case of quiescent BHXNs, we have the luxury of a control sample of NSXNs. By comparing quiescent BHXNs and NSXNs with similar orbital periods, we eliminate the uncertainty in the mass accretion rate and thus obtain more secure evidence for the event horizon.

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REFERENCES

Baganoff, F., et al. 2000, AAS HEAD Meeting, 32, 02.10
Bildsten, L., & Rutledge, R. E. 2000, ApJ, 541, 908
Blandford, R. D., & Begelman, M. C. 1999, MNRAS, 303, L1
Brown, E. F., Bildsten, L., & Rutledge, R. E. 1998, ApJ, 504, L95
Campana, S., Mereghetti, S., Stella, L., & Colpi, M. 1997, A&A, 324, 941
Campana, S., & Stella, L. 2000, ApJ, 541, 849
Chakrabarty, D., & Morgan, E. H. 1998, Nature, 394, 346
Chen, W., et al. 1998, in AIP Conf. Proc. 431, Accretion Processes in Astrophysical Systems: Some Like It Hot!, ed. S. S. Holt & T. R. Kallman (Woodbury: AIP), 347
DiMatteo, T., Carilli, C. L., & Fabian, A. C. 2001a, ApJ, 547, 731
DiMatteo, T., Johnstone, R. M., Allen, S. W., & Fabian, A. C. 2001b, ApJ, 550, L19
Dotani, T., Asai, K., & Wijnands, R. 2000, ApJ, 543, L145
Filippenko, A. V., Matheson, T., & Ho, L. C. 1995, ApJ, 455, 614
Garcia, M. R., McClintock, J. E., Narayan, R., & Callanan, J. 1998, in ASP Conf. Ser. 137, Wild Stars in the Old West, ed. S. Howell, E. Kuulkers, & C. Woodward (San Francisco: ASP), 506 (G98)
Garcia, M. R., Murray, S. S., Primini, F. A., Forman, W., & Jones, C. 2000, ApJ, 537, L23
Garmire, G. P., et al. 1992, in AIAA Space Programs and Technologies Conf. (Reston: AIAA), 8
Greiner, J., Predehl, P., & Harmon, B. A. 1994, in AIP Conf. Proc. 304, Proc. Second Compton Symp., ed. C. E. Fichtel, N. Gehrels, & J. P. Norris (New York: AIP), 314
Ilovaisky, S. A., & Chevalier, C. 2000, IAU Circ. 6025
Jain, R., et al. 2000, IAU Circ. 7429
Kato, S., Fukue, J., & Mineshige, S. 1998, Black Hole Accretion Disks (Kyoto: Kyoto Univ. Press)
King, A. R. 2000, MNRAS, 315, L33
Kong, A. 2000, Ph.D. thesis, Oxford Univ.
Lasota, J. P. 2000, A&A, 360, 575
McClintock, J. E. 2000, in Rossi2000: Astrophysics with the *Rossi X-Ray Timing Explorer*, ed. T. E. Strohmayer (Greenbelt: NASA/GSFC), 89
McClintock, J. E., Horne, K., & Remillard, R. A. 1995, ApJ, 442, 358
McClintock, J. E., & Remillard, R. R. 2000, ApJ, 531, 956
Menou, K., Esin, A. A., Narayan, R., Garcia, M. R., Lasota, J. P., & McClintock, J. E. 1999, ApJ, 520, 276 (M99)
Monet, D., et al. 1996, The USNO-A2.0 Catalog (Washington, DC: USNO)
Narayan, R., Barret, D., & McClintock, J. E. 1997a, ApJ, 482, 448
Narayan, R., Garcia, M. R., & McClintock, J. E. 1997b, ApJ, 478, L79 (NGM97)
Narayan, R. Mahadevan, R., Grindlay, J. E., Popham, R. G., & Gammie, C. 1998a, ApJ, 492, 554
Narayan, R., Mahadevan, R., & Quataert, E. 1998b, in Theory of Black Hole Accretion Disks, ed. M. A. Abramowicz, G. Bjornsson, & J. E. Pringle (Cambridge: Cambridge Univ. Press), 148
Narayan, R., McClintock, J. E., & Yi, I. 1996, ApJ, 457, 821
Narayan, R., & Yi, I. 1994, ApJ, 428, L13
———. 1995, ApJ, 444, 231
Plucinsky, P. P., & Virani, S. N. 2000, Proc. SPIE, 4012, 669
Predehl, P., & Schmitt, J. H. M. M. 1995, A&A, 293, 889
Quataert, E., & Narayan, R. 1999, ApJ, 520, 298
Quataert, E., Narayan, R., & Reid, M. J. 1999, ApJ, 517, L101
Ritter, H., & Kolb, U. 1998, A&AS, 129, 83
Stella, L., Campana, S., Mereghetti, S., Ricci, D., & Israel, G. L. 2000, ApJ, 537, L115
van der Woerd, H., White, N. E., & Kahn, S. M. 1989, ApJ, 344, 320
van Speybroeck, L., Jerius, D., Edgar, R. J., Gaetz, T. J., Zhao, P., & Reid, P. B. 1997, Proc. SPIE, 3113, 89
Vikhlinin, A., McNamara, B. R., Forman, W., Jones, C., Quintana, H., & Hornstrup, A. 1998, ApJ, 502, 558
Wachter, S. 2000, in 1999 Pacific Rim Conference on Stellar Astrophysics, ed. K. S. Cheng (Dordrecht: Kluwer), 451
Wagner, M. R., Starrfield, S. G., Hjellming, R. M., Howell, S. B., & Kreidl, T. J. 1994, ApJ, 429, L25
Weisskopf, M. C., & O'Dell, S. L. 1997, Proc. SPIE, 3113, 2