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INITIAL MEASUREMENTS OF BLACK HOLE SPIN IN GX 339−4 FROM *SUZAKU* SPECTROSCOPY

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ABSTRACT

We report on a deep *Suzaku* observation of the stellar-mass black hole GX 339−4 in outburst. A clear, strong, relativistically shaped iron emission line from the inner accretion disk is observed. The broadband disk reflection spectrum revealed is one of the most sensitive yet obtained from an accreting black hole. We fit the *Suzaku* spectra with a physically motivated disk reflection model, blurred by a new relativistic line function in which the black hole spin parameter is a variable. This procedure yielded a black hole spin parameter of $a = 0.89 \pm 0.04$. Joint modeling of these *Suzaku* spectra and prior *XMM-Newton* spectra obtained in two different outburst phases yields a spin parameter of $a = 0.93 \pm 0.01$. The degree of consistency between these results suggests that disk reflection models allow for spin measurements that are not strongly biased by scattering effects. We suggest that the best value of the black hole spin parameter is $a = 0.93 \pm 0.01$ (statistical) $\pm$ 0.04 (systematic). Although preliminary, these results represent the first direct measurement of nonzero spin in a stellar-mass black hole using relativistic line modeling.

Subject headings: black hole physics — relativity — stars: individual (GX 339−4)

1. INTRODUCTION

X-ray emission from accreting black holes probes the innermost relativistic regime. Emission lines produced in the inner accretion disk are expected to bear the imprints of the strong Doppler shifts and gravitational redshifts natural to this region. Advances in X-ray spectroscopy have made it possible to exploit relativistic iron lines as probes of black hole accretion and even measures of black hole spin (for a review, see Miller 2007). Recently, relativistic line models have been developed in which black hole spin is a variable parameter that can be constrained through spectral fitting (e.g., Brenneman & Reynolds 2006); this marks another advance. *Suzaku* is a major step forward for relativistic spectroscopy of stellar-mass black holes: its CCD cameras retain a high live-time fraction even at high flux levels, and its bandpass covers both the relativistic iron line region and more subtle disk reflection curvature expected at high energy. The combination of new models and the capabilities of *Suzaku* provide the opportunity to obtain robust spin constraints in a number of stellar-mass black holes.

GX 339−4 is a recurrent black hole transient with a low-mass companion star. Its mass has been constrained to be greater than 5.8 $M_{\odot}$ (Hynes et al. 2004). The distance to GX 339−4 is likely to be greater than 6 kpc and may be as great as 15 kpc (Hynes et al. 2004); a value of 8 kpc may be most likely (Zdziarski et al. 2004). The radio jet observed in GX 339−4 and its X-ray properties argue for an inner disk inclination that may be as low as 15° (Gallo et al. 2004; Miller et al. 2004b). This inclination would imply a high black hole mass, but the inner disk and binary system need not have the same inclination.

Prior observations of GX 339−4 with *Chandra* and *XMM-Newton* have revealed lines suggestive of a black hole with a high spin parameter (Miller et al. 2004a, 2004b, 2006). Observations of XTE J1650−500 with *XMM-Newton* and *BeppoSAX* have also revealed skewed iron disk lines suggestive of high spin (Miller et al. 2002; Miniutti et al. 2004; Rossi et al. 2005). Spectroscopy of GRO J1655−40 has sometimes revealed relativistic iron lines suggestive of near-maximal black hole spin (Miller et al. 2005; Diaz Trigo et al. 2007). In contrast to these sources, iron lines observed in GRS 1915+105 do not require a high spin parameter (Martocchia et al. 2002).

In late 2006, GX 339−4 entered a new outburst with a slow rise phase (Swank et al. 2006). In the spring of 2007, we triggered an approved *Suzaku* TOO observation. Based on *RXTE* ASM monitoring, we observed GX 339−4 in an "intermediate" state (for a review, see Remillard & McClintock 2006). In the sections below, we detail how we reduced and analyzed the spectra, and discuss the strengths and weaknesses of our measurements and methods.

2. OBSERVATIONS AND DATA REDUCTION

We observed GX 339−4 with *Suzaku* on 2007 February 12 starting at 05:33:31 (UT). The nominal observation duration was 100 ks, but different exposures were obtained due to observing constraints and the instrument modes chosen. The XIS pointing was used. In order to prevent photon pileup, the XIS units were operated using the 1/4 window mode using a 0.3 s burst option. In general, XIS on-source times of approximately 70 ks were achieved. This resulted in dead-time-corrected net 3 × 3 editing mode exposures of 10.3, 9.3, and 16.9 ks for the XIS0, XIS1, and XIS3 cameras, respectively. The HXD/PIN and HXD/GSO cameras were operated in their default modes. A net exposure time of 87.9 ks was achieved using the HXD/PIN.

We reduced version 2–processed data. It is important to note that the XIS burst modes are not yet calibrated as well as more standard modes. As reproducibility is even more important when nonstandard modes are used, we chose to use the XIS

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and HXD pipeline spectra. For the XIS, these products include both source and background spectra from each camera; for the HXD/pin, the pipeline products include only the source spectrum. We generated XIS redistribution matrix files (RMFs) and ancillary response files (ARFs) using the tools `xisrmfgen` and `xissimarfgen` available in the HEASOFT version 6.4 reduction and analysis suite. The `xissimarfgen` tool generates a response using a simulation; we generated the recommended 400,000 photons in creating each ancillary response. (XIS spectra oversample the true energy resolution of the instrument, as do the *XMM-Newton* spectra treated in later sections. Although RMF files account for this, the reader should be aware that the resolution is oversampled.) To create an HXD/PIN background file, we simulated non-X-ray background and cosmic X-ray backgrounds in XSPEC[8] version 11.3 as per the instruction in the *Suzaku* ABC guide. The standard PIN response file for XIS-nominal pointings was used.

The spectra from XIS0 and XIS1 matched each other closely, while the spectrum from XIS3 has somewhat larger residuals (in the Si band, for instance). In order to focus on relativistic spectroscopy rather than calibration uncertainties, we restricted our analysis to XIS0 and XIS1. For all plausible continuum models, these spectra show strong residuals below 0.7 keV and above 10.0 keV; we therefore restricted our XIS fitting range to the 0.7–10.0 keV band. Similarly, the HXD/PIN shows strong residuals below 12 keV. The source is strong throughout the HXD/PIN bandpass, so we considered the 12.0–70.0 keV band when fitting this spectrum. All spectral fits reported in this work were made using XSPEC 11.3. Errors reported in this work are 1 σ errors obtained using the "error" command.

3. ANALYSIS AND RESULTS

The high sensitivity of our *Suzaku* spectra provides an unprecedented chance to study a relativistic disk reflection spectrum, and this is the focus of our analysis. Especially given that the absolute flux calibration in our modes is still being refined, and given that contamination affects the effective area below 0.7 keV in ways that could affect disk continuum spectroscopy, focusing only on the residuals to fiducial continua is particularly pragmatic. Indeed, this is a general advantage of line and reflection spectroscopy over disk continuum spectroscopy.

Figure 1 shows the *Suzaku* spectra of GX 339−4 fit with a simple model consisting of disk blackbody (`diskbb`) and power-law components, modified by interstellar absorption (`phabs`). The continuum is the best-fit continuum for each individual camera (the parameters were not linked during the fit). A Gaussian emission line was added at 2.26 keV to account for an instrumental response defect. The 4.0–7.0 keV and 15.0–40.0 keV ranges were ignored when fitting the data in order to show the disk reflection signatures clearly, and then restored when forming the data/model ratio shown in Figure 1 (as per Miniutti et al. 2007).

Fits to the continuum with this simple model reveal a relativistic iron emission line (Miller et al. 2004a, 2004b, 2006) and a Compton backscattering hump. The asymmetric shape of the broad line is exactly that predicted by relativistic disk line models, and the curvature of the Compton reflection hump is clearly revealed in the HXD spectrum. The broadband relativistic disk spectrum is very similar to that revealed in *Suzaku*

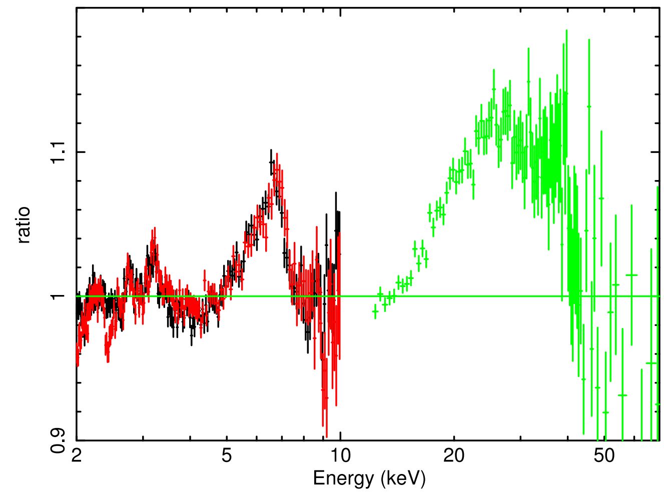

FIG. 1.—Data/model ratio obtained when the *Suzaku* spectra of GX 339−4 are fitted with a phenomenological disk plus power law model. The 4.0–7.0 keV and 15.0–40.0 keV regions were ignored when fitting the model. The curvature at high energy is a clear signature of disk reflection.

spectra of the Seyfert 1 AGN MCG −6-30-15 (Reeves et al. 2006; Miniutti et al. 2007). It must be noted that residuals remain in the 2–3 keV band. These residuals are not physical, but rather related to aspects of the instrument response (e.g., Si and Au edges) that are not yet modeled correctly by the response files.

Owing to the quality of the spectra line and reflection spectra, we made fits with a physically motivated model suited to constraining the spin of the black hole in GX 339−4. The model included a disk blackbody component, a power-law component, and the constant-density ionized disk (CDID) reflection model (Ballantyne et al. 2001). This disk reflection model includes line emission, and was convolved with the `kerrdisk` line function using the `kerrconv` model (Brenneman & Reynolds 2006). We have chosen to use the `kerrdisk` model because radii are parameterized in terms of the innermost stable orbit for a given spin parameter; other line models predict very similar profiles but differ in some details (see Dovciak et al. 2004; Beckwith & Done 2004). In all fits, the outer reflection radius is assumed to be 400 times the innermost stable circular orbit. The CDID reflection model is particularly well suited to high ionization regimes, and explicitly measures the inner disk ionization parameter ($\xi = L/nr^2$). The CDID model is an angle-averaged model, and does not include the disk inclination as a variable parameter.

This model provides a very good description of the spectra (see Fig. 2 and Table 1), although the fit is not formally acceptable. A high inner disk ionization parameter of $\log(\xi) = 4.1(2)$ is measured; this is broadly consistent with prior results obtained in "intermediate" states (e.g., Miller et al. 2004a). The most important result obtained with this spectral model is the black hole spin parameter: $a = 0.89(4)$.

GX 339−4 is special in that excellent spectra have been obtained in each of the spectral states where relativistic lines are expected. We next fit each of these spectra jointly to obtain the best possible constraint on the black hole spin parameter.

This procedure also ensures that state-specific changes (such as disk ionization) are not driving any spin constraints. Using the same model, we jointly fit our *Suzaku* XIS spectra, the "very high" state spectrum obtained with the *XMM-Newton* EPIC-pn camera, and the "low/hard" state spectra obtained with

[8] XSPEC (K. A. Arnaud & B. Dorman, 2000) is available via the HEASARC online service, provided by NASA/GSFC.

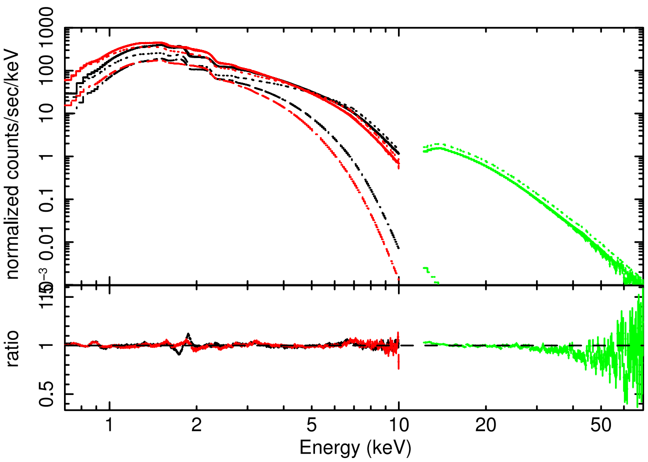

FIG. 2.—*Suzaku* spectra of GX 339−4 fitted with a simple disk model and a constant-density ionized disk model (suited to highly ionized disks) convolved with the `kerrdisk` line function.

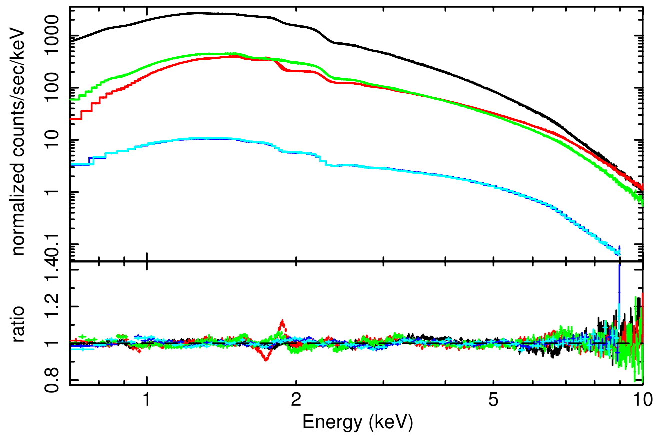

FIG. 3.—Spectra of GX 339−4 in the very high (*black*; *XMM-Newton*), intermediate (*red and green*; *Suzaku*), and low/hard (*light and dark blue*; *XMM-Newton*) states, fitted with a simple disk model and a constant-density ionized disk model (suited to highly ionized disks) convolved with the `kerrdisk` line function.

the *XMM-Newton* MOS1 and MOS2 spectra in revolution 782. (The HXD spectrum considered above was omitted as its response is complex and drives up computation times.) The same spectral and response files used in Miller et al. (2004b, 2006) were employed in this effort. All spectra were fit in the 0.7–10.0 keV band except the low/hard state spectra, which were fit in the 0.7–9.0 keV band. For simplicity, an ionization parameter of $\log(\xi) = 4.0$ was assumed for the intermediate state (see above), and a value of $\log(\xi) = 2.8$ was assumed for the low/hard state as per the results of modeling described in Miller et al. (2006). While each camera was again allowed to have its own continuum parameters, the spin parameter and inclination were determined by the joint fits.

This joint fit across states measures a spin parameter of $a = 0.93(1)$ (see Fig. 3). This is very similar to the result obtained using the broadband *Suzaku* spectra of the intermediate state alone, and suggests that scattering in the disk atmosphere—an effect expected to change across states—can accurately be accounted for with good reflection models. The very high state spectrum required an enhanced inner line emissivity [$q = 6.0(1)$ within $6GM/c^2$; $q = 3.0$ at larger radii]; this is common in the very high state (Miller et al. 2002, 2004b; Diaz Trigo et al. 2007). Once again, the overall fit is not statistically acceptable in a formal sense, but this is driven by narrowband calibration problems.

4. DISCUSSION AND CONCLUSIONS

We have analyzed *Suzaku* spectra of the well-known recurrent black hole transient GX 339−4 in outburst. Motivated by the quality of the broadband spectra obtained, we fit the data with models capable of measuring the black hole spin parameter. Fits with a relativistically blurred disk reflection model give a spin parameter of $a = 0.89(4)$. As a check on this result, we jointly fit the *Suzaku* XIS spectra with CCD spectra in the "very high" and "low/hard" states obtained with *XMM-Newton*. This procedure yields a commensurate spin parameter of $a = 0.93(1)$. We therefore suggest that the best value of the spin parameter in GX 339−4 is $a = 0.93 \pm 0.01$ (statistical) $\pm$ 0.04 (systematic), where the systematic error aims to account for the error associated with considering a single state. Relativistic iron emission lines previously detected using *Chandra* and *XMM-Newton* also suggested a similar spin parameter, but were not fit with models wherein spin is a variable parameter (Miller et al. 2004a, 2004b).

We do not regard the apparent changes in line-of-sight col-

TABLE 1
SPECTRAL FIT PARAMETERS

Spectra	N_H (10^{21} cm^2)	kT (keV)	Norm. (10^3)	a (cJ/GM^2)	i (deg)	q	$\log(\xi)$	Γ	Norm.	Refl. Norm. (10^{-26})	χ^2/ν
Suzaku	6.4(1)	0.81(1)	1.05(1)	0.89(4)	18(1)	3.0(1)	4.1(2)	1.92(4)	0.57(2)	2.5(1)	11860/5076
Joint fits:											
XMM VH	5.1(1)	0.80(1)	1.63(1)	0.93(1)	19(1)	6.0(1)	5.0(2)	2.73(5)	1.43(5)	3.1(2)	16190/7992
Suzaku IS	6.4(1)	0.81(1)	1.00(1)	…	…	3.00(6)	4.0	1.99(3)	1.22(2)	2.4(1)	…
XMM LH	4.3(1)	0.44(1)	0.47(1)	…	…	…	2.8	1.39(4)	0.25(1)	9.0(6)	…

NOTES.—The results of fitting models to the *Suzaku* spectra of GX 339−4 and joint fits to different outburst states are tabulated above. *Suzaku* spectra from XIS0, XIS1, and the HXD/PIN were fit jointly. The model consists of a simple `diskbb` model plus a constant-density ionized disk reflection model convolved with the `kerrdisk` function. Relativistic line and reflection parameters were linked while continuum parameters were allowed to vary between cameras. Parameters for XIS0 are quoted above in the *Suzaku* line; parameters obtained for other cameras generally differ by less than 10%. Joint fits to *XMM-Newton* spectra in the very high (VH) state, the *Suzaku* XIS spectra of the intermediate state (IS), and *XMM-Newton* spectra of the low/hard (LH) state are presented below the *Suzaku* line. The spin parameter and inclination were linked across all spectra and states, and ionization parameters were linked within states. The parameters for the EPIC-pn, XIS0, and MOS1 camera are listed, and once again the parameters for other cameras in each state generally differ by less than 10%. The line/reflection emissivity index is parameterized by q, assuming $J(r) \propto r^{-q}$. The normalization of the reflection model is simply related to the number of photons detected; it is a small number because distance dilution is not included. All errors quoted above are 1 σ errors obtained using the `error` command in XSPEC.

umn density and inner disk radius in Table 1 as robust. The changes are more likely due in part to differences in flux calibration between *XMM-Newton* and *Suzaku*. The apparent changes may also reflect real differences in disk ionization that falsely mimic radius variations (Merloni et al. 2000). Relativistic lines are also likely to be affected by such changes, especially Compton scattering in the disk atmosphere. Disk reflection models attempt to account for these effects. Making joint fits to different states allows us to obtain a measure of the spin parameter in a way that is reasonably independent of changing scattering effects.

To achieve a maximal spin parameter, a black hole must accrete approximately half of its mass (Volonteri et al. 2005). It is unlikely, then, that black holes in low-mass X-ray binary systems can achieve maximal spin through accretion alone. The short life span of massive stars also makes it unlikely that black holes in high-mass binaries can achieve a maximal spin parameter through accretion. Factoring in these constraints and the range of black hole spins likely to be generated in supernova/GRB events, Gammie et al. (2004) suggest that stellar-mass black holes should have spins of $a \leq 0.95$. The results we have obtained are consistent with this prediction.

Accretion disks are necessarily an indirect measure of black hole spin, and the accuracy of all such measurements depends on how strong the contrast is between the inner edge of the accretion disk and the plunging region within the innermost stable circular orbit. The most advanced 3D general relativistic MHD simulations of accretion disks are beginning to bear on this problem, although the case of a standard thin accretion disk has not yet been treated (Krolik & Hawley 2002; Krolik & Hirose 2004). The case of a thin disk has been treated simply by Shafee et al. (2007); however, the most advanced and physically realistic treatment is given by Reynolds & Fabian (2008). The latter work makes use of sophisticated disk simulations and concludes that the contrast between the disk and plunging region is relatively high and that relativistic line diagnostics are robust. This work partially validates the implicit assumption of a geometrically thin disk with Keplerian orbits.

Although the relativistic modeling performed in this Letter has permitted a significant advance over many prior efforts to characterize relativistic lines in stellar-mass black holes, our results must still be regarded as preliminary. In certain respects, disk reflection models are like stellar atmosphere models: the physics is known and the problems are tractable, but refinements can always be made. The CDID model we have used is excellent and well suited to highly ionized disks (Ballantyne et al. 2001), but astrophysical disks have a vertical density structure. Moreover, averaging over viewing angle may act to wash out important angle dependencies. At the time of writing, improved reflection models that assume vertical structure according to hydrostatic equilibrium and a hot thermal midplane spectrum are becoming available (Ross & Fabian 2007; Reis et al. 2008). All current reflection models assume a single ionization zone; however, the fact that only the inner radii contribute strongly to the red wing make this a robust simplification.

The use of relativistic lines to measure spin parameters in stellar-mass black holes holds enormous promise and some specific advantages over other techniques. To obtain spin constraints using the accretion disk continuum, the black hole mass, distance, and mass accretion rate must be known. The uncertainty on the mass can be as high as 30% (Remillard & McClintock 2006), and the accretion rate can be uncertain by a factor of a few. As an observational rather than empirical science, astronomy is poorly suited to absolute flux (luminosity) measurements, and the difficulties with continuum spectroscopy are merely a special case of the general problem. Iron lines have the advantage of harnessing dynamical imprints to estimate the inner disk radius and black hole spin parameter. A remaining difficulty for relativistic iron line measurements is that the geometry of the hard X-ray source illuminating the disk is unknown; however, this is effectively encoded by the line emissivity index and can be determined observationally.

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REFERENCES

Ballantyne, D., Iwasawa, K., & Fabian, A. C. 2001, MNRAS, 323, 506
Beckwith, K., & Done, C. 2004, MNRAS, 352, 353
Brenneman, L. W., & Reynolds, C. S. 2006, ApJ, 652, 1028
Diaz Trigo, M., Parmar, A. N., Miller, J. M., Kuulkers, E., & Caballero-Garcia, M. D. 2007, A&A, 462, 657
Dovciak, M., Karas, V., & Yaqoob, T. 2004, ApJS, 153, 205
Gallo, E., Corbel, S., Fender, R. P., Maccarone, T. J., & Tzioumis, A. K. 2004, MNRAS, 347, L52
Gammie, C. F., Shapiro, S. L., & McKinney, J. C. 2004, ApJ, 602, 312
Hynes, R. I., Charles, P. A., van Zyl, L., Barnes, A., Steeghs, D., O'Brien, K., & Casares, J. 2004, MNRAS, 348, 100
Krolik, J. H., & Hawley, J. F. 2002, ApJ, 573, 754
Krolik, J. H., & Hirose, 2004, Prog. Theor. Phys. Suppl., 155, 140
Martocchia, A., Matt, G., Karas, V., Belloni, T., & Feroci, M. 2002, A&A, 387, 215
Merloni, A., Fabian, A. C., & Ross, R. R. 2000, MNRAS, 313, 193
Miller, J. M. 2007, ARA&A, 45, 441
Miller, J. M., Fabian, A. C., Nowak, M. A., & Lewin, W. H. G. L. 2005, in Proc. Tenth Marcel Grossmann Meeting, ed. M. Novello, S. Perez Berliaffa, & R. Ruffini (Singapore: World Scientific)
Miller, J. M., Homan, J., Steeghs, D., Rupen, M., Hunstead, R. W., Wijnands, R., Charles, P., & Fabian, A. C. 2006, ApJ, 653, 525
Miller, J. M., et al. 2002, ApJ, 570, L69
———. 2004a, ApJ, 601, 450
———. 2004b, ApJ, 606, L131
Miniutti, G., Fabian, A. C., & Miller, J. M. 2004, MNRAS, 351, 466
Miniutti, G., et al. 2007, PASJ, 59, 315
Reeves, J. N., et al. 2006, Astron. Nachr., 327, 1079
Reis, R., Fabian, A. C., Ross, R., Minniutti, G., Miller, J. M., & Reynolds, C. 2008, MNRAS, in press (arXiv:0804.0238)
Remillard, R. A., & McClintock, J. E. 2006, ARA&A, 44, 49
Reynolds, C. S., & Fabian, A. C. 2008, ApJ, 675, 1048
Ross, R. R., & Fabian, A. C. 2007, MNRAS, 381, 1697
Rossi, S., Homan, J., Miller, J. M., & Belloni, T. 2005, MNRAS, 360, 763
Shafee, R., Narayan, R., & McClintock, J. E. 2007, ApJ, 676, 549
Swank, J., Smith, E. A., Smith, D. M., & Markwardt, C. B. 2006, ATel 944
Volonteri, M., Madau, P., Quataert, E., & Rees, M. J. 2005, ApJ, 620, 69
Zdziarski, A. A., Gierlinski, M., Mikolajewska, J., Wardzinski, G., Smith, D. M., Harmon, B. A., & Kitamoto, S. 2004, MNRAS, 351, 791