Another interpretation of the power-law-type spectrum of an ultraluminous compact X-ray source in IC 342

A. Kubota,1,2∗ C. Done2 and K. Makishima3

1Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan
2Department of Physics, University of Durham, South Road, Durham DH1 3LE
3Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

Accepted 2002 September 6. Received 2002 September 6; in original form 2002 July 3

ABSTRACT

The ultraluminous compact X-ray sources (ULXs) generally show a curving spectrum in the 0.7–10 keV ASCA bandpass, which looks like a high-temperature analogue of the disc-dominated high/soft-state spectra seen in Galactic black hole binaries (BHBs) at high mass accretion rates. Several ULXs have been seen to vary, and to make a transition at their lowest luminosity to a spectrum which looks more like a power law. These have been previously interpreted as the analogue of the power-law-dominated low/hard state in Galactic BHBs. However, the ULX luminosity at which the transition occurs must be at least 10–50 per cent of the Eddington limit assuming that their highest luminosity phase corresponds to the Eddington limit, while for the Galactic BHBs the high/soft–low/hard transition occurs at a few per cent of the Eddington limit. Here we show that the apparently power-law spectrum in a ULX in IC 342 can be equally well fitted over the ASCA bandpass by a strongly Comptonized optically thick accretion disc with a maximum temperature of ∼1 keV. Recent work on the Galactic BHBs has increasingly shown that such components are common at high mass accretion rates, and that this often characterizes the very high (or anomalous) state. Thus we propose that the power-law-type ULX spectra are not to be identified with the low/hard state, but rather represent the Comptonization-dominated very high/anomalous state in the Galactic BHBs.

Key words: galaxies: individual: IC 342 – galaxies: spiral – X-rays: binaries – X-rays: galaxies.

1 INTRODUCTION

Since the Einstein era, many ultraluminous compact X-ray sources (ULXs: Makishima et al. 2000) with X-ray luminosities $L_X \geq 10^{39–40}$ erg s$^{-1}$ have been found in spiral arms of nearby spiral galaxies (e.g. Fabbiano 1989). Such high values of $L_X$ exceed the Eddington limit, $L_E$, for a neutron star by several orders of magnitude, and instead suggest massive (30–100 M$_\odot$) accreting black holes (BHs). However, it is difficult to understand how such massive BHs could form: single massive stars have extreme mass loss throughout their life, and the maximum BH mass expected is of the order of 10–15 M$_\odot$ (e.g. Fryer & Kalogera 2001). Since there are no nearby systems either in our Galaxy or in M31 that could be easily studied, the nature of the ULXs has remained a mystery.

ASCA (Tanaka, Inoue & Holt 1994) data led to a breakthrough for these objects by providing the first moderate-resolution energy spectra. As reported by many authors (e.g. Makishima et al. 2000, and references therein), it is clear that the majority of the most luminous ULXs exhibit spectra which are well fitted by the multicolour disc model (MCD model: Mitsuda et al. 1984), similar to the case of Galactic/Magellanic BH binaries (BHBs) at high mass accretion rates, $M$ (e.g. Makishima et al. 1986; the review by Tanaka & Lewin 1995). This, together with the variability of these systems including periodic variation (Bauer et al. 2001; Sugih et al. 2001) and their general association with regions of ongoing star formation (Zezas, Georgantopoulos & Ward 1999; Roberts & Warwick 2000; Fabbiano, Zezas & Murray 2001), has led to their identification with BHBs.

There are then three possibilities, first that these really are intermediate-mass BHs, formed perhaps via mergers of massive stars/BHs in a compact star cluster (e.g. Ebisuzaki et al. 2001). Alternatively, they could be ‘normal’-mass (≈10 M$_\odot$) stellar BHs accreting beyond the critical accretion rate at which the disc luminosity $L_{\text{disc}}$ reaches $L_E$. Recent work suggests that the Eddington limit can be violated by the disc becoming clumpy (e.g. Krolik 1998; Gammie 1998; Begelman 2002, and references therein), and it has long been known observationally that super-critical accretion can happen (e.g. Cir X-1). A third possibility is that these are ‘normal’-mass BHs, but that their X-ray luminosity is strongly anisotropic (beamed), so that the bolometric luminosity is overestimated. This beaming is highly unlikely to be the relativistic beaming seen in jet
sources, as this generally leads to a power-law (PL) type of spectrum (e.g. blazars), very unlike the curving spectrum seen by ASCA for the majority of the ULXs. However, strong anisotropy of the disc flux might be produced if the disc is geometrically thick in its inner regions. The radiation can then be strongly collimated by a funnel (e.g. Madau 1988), although the factor of 10–100 required (King et al. 2001) seems extreme. Such an extreme thick disc might be expected to form only under a super-critical accretion rate. So this is merely an addendum to the high-\(\dot{M}\) scenario, rather than an independent alternative.

All these alternatives involve an extreme of one kind – mass, radiation luminosity or disc shape. One way to test these is to compare the ULX spectra and spectral variability with those of Galactic BHBs. This has become much more feasible in recent years with the unprecedented volume of data from the Galactic BHBs gathered by RXTE. Here we use the bright Galactic BHB transient XTE J1550 – 564 to determine observationally the spectra and spectral variability of high-\(\dot{M}\) discs, and show that the ULXs are indeed compatible with being massive (30–100 M\(_\odot\)) BHs accreting at close to the critical accretion rate.

2 A COMPARISON OF THE ULXs WITH BHBs

Here we specify the puzzles in understanding ULXs as \(\sim 100\) M\(_\odot\) BHs. It has long been recognized that the Galactic/Magellanic BHBs reside in either of the two distinct spectral states, the high/soft state or the low/hard state. In the hard state, in which \(\dot{M}\) is generally low, the BHBs exhibit a hard PL spectrum in the 2–20 keV band. By contrast, the soft state is generally seen when \(\dot{M}\) is high, and it is characterized by the MCD spectrum, which approximates the optically thick standard accretion disc (Shakura & Sunyaev 1973).

Based on this viewpoint, the MCD-type ULXs have so far been regarded as residing in the usual soft state, even putting aside the issue of how to make the required \(\sim 100\) M\(_\odot\) BHs.

An increasing number of ULXs show spectral transitions from an MCD (curving) type of spectrum to one that is better described by a hard PL. This has been interpreted as the transition to the usual hard state (e.g. Kubota et al. 2001, hereafter Paper I; Mizuno 2000; La Parola et al. 2001). However, such a straightforward analogy between ULXs and BHBs presents the following puzzles.

(i) The ‘soft-state’ ULXs have inner disc temperatures \(T_\text{in}\) which are too high for their implied high masses. Equivalently, when the BH mass is estimated from the Eddington argument, \(R_\text{in}\) with reasonable correction for a boundary condition (Kubota et al. 1998) and spectral hardening factor (Shimura & Takahara 1995) falls much below the last stable orbit for a non-spinning BH, \(6R_g\), where \(R_g = GM/c^2\) is the gravitational radius (see e.g. Shapiro & Teukolsky 1983). This contrasts with soft-state BHBs, where \(R_\text{in}\) generally agrees with \(6R_g\).

(ii) The value of \(R_\text{in}\) is time-variable, in five bright ‘soft-state’ ULXs including the two in IC 342 (Mizuno, Kubota & Makishima 2001). This again makes a contrast with the case of soft-state BHBs, where \(R_\text{in}\) is approximately constant for each source.

(iii) Assuming that the ‘soft state’ corresponds to \(L_g\), the threshold luminosity for the spectral transition of ULXs (\(\sim 0.3L_g\)) Paper I) becomes much higher than is seen among BHBs, typically (0.01–0.03)L\(_g\). Of course, the MCD-state luminosity could be much below \(L_g\), but then the BH mass in ULXs would have to be even higher.

Makishima et al. (2000) attribute the first puzzle to an extreme BH rotation, because the last stable orbit is then reduced to 1.23R\(_g\), although the other two problems remain unsolved. They suggested the scenario of Kerr BHs shining at \(L_g\) for ULXs. Following Makishima et al. (2000), Ebisawa et al. (2001) showed that, with standard Shakura–Sunyaev disc, even with Kerr BHs it is difficult to obtain the required high temperatures without super- (or near-) critical accretion rates. A more plausible explanation is that at high \(\dot{M}\) the disc structure changes from that of the standard disc as a result of the disc being so optically thick that radial advection of the radiation becomes important. These discs, called ‘slim discs’ (Abramowicz et al. 1988), are different in structure from the standard disc. Pressure support becomes important, so the material is not in Keplerian rotation. The inner edge of the optically thick accretion disc is then not necessarily at the last stable orbit, but can be closer to the BH (e.g. Abramowicz et al. 1988; Watarai et al. 2000). The small and changing inner disc radius [puzzles (i) and (ii)] could be explained in a Schwarzschild metric if the disc penetrates increasingly further into the plunging region at high \(\dot{M}\) rather than abruptly truncating at the last stable orbit, so Mizuno et al. (2001) and Watarai, Mizuno & Mineshige (2001) proposed that MCD-type ULXs may have slim accretion discs rather than standard ones.

The inner disc radius, however, is very dependent on the viscosity prescription. For small viscosity it can decrease to \(\sim 6R_g\) for super-Eddington luminosities, whereas for large viscosity it can be slightly larger than \(6R_g\) (e.g. Abramowicz et al. 1988; Artemova et al. 2001). Also, this mechanism for producing a decreasing radius can only be used for Schwarzschild BHs, as in extreme Kerr BHs there is so little space between the last stable orbit and the horizon.

The spectra of these slim discs have been calculated by Watarai & Mineshige (2001) (Schwarzschild, low viscosity) and Beloborodov (1998) (Schwarzschild and Kerr, high viscosity). Since some of the emission from the smallest radii is advected rather than radiated, the spectra have less high-temperature emission than a standard disc, but this can be somewhat compensated by the decrease in inner radius for the Schwarzschild, low-viscosity disc. Since the standard disc structure calculations have difficulty in producing the high temperatures observed from the ULXs even with Kerr BHs for sub-critical rates (Ebisawa et al. 2001), it seems unlikely that the slim disc will substantially help problems (i) and (ii) unless the accretion rate is super-critical.

Therefore it seems likely that the standard curving MCD-type ULX spectra are from super-critical accretion, in which case the third puzzle becomes acute. Recently, Kubota (2001) and Kubota, Makishima & Ebisawa (2001) have observationally suggested a novel understanding of high-luminosity accretion discs, using RXTE data on some Galactic BHBs. They have identified three distinct spectral regimes of the optically thick accretion discs in XTE J1550 – 564 and GRO J1655 – 40. [Fig. 1 shows their result on XTE J1550 – 564 (the distance and inclination angle are assumed to be 5 kpc and 60°, respectively).]

(1) The ‘standard regime’ where \(R_\text{in}\) remains constant when fitted with MCD models, i.e. \(L_\text{disc} \propto T_\text{in}^2\).

(2) The luminous ‘apparently standard regime’ where the disc luminosity rises slightly less quickly with temperature, \(L_\text{disc} \propto T_\text{in}^{-2}\), and the spectral shape is slightly distorted from the standard-disc one. In the literature, both this and (1) are identified as the soft state, with disc-dominated spectra.

(3) The intermediate ‘anomalous regime’, where the disc Comptonization suddenly increases and the spectrum becomes much harder. This is often termed the very high state in the literature (Miyamoto et al. 1991).

Kubota (2001) and Kubota et al. (2001) suggested a picture for this, in which the ‘standard regime’ is where the accretion
flow is described by the Shakura–Sunyaev geometrically thin disc approximation. As the disc luminosity increases, this approximation breaks down, and the disc becomes slim. This theoretical picture explains both the change in spectral shape (as the hotter, inner disc emission is preferentially advected rather than radiated) and the different $T_{\text{in}}$–$L_{\text{disc}}$ relationship (Watarai et al. 2000) seen in the ‘apparently standard regime’, although for the likely mass/distance of XTE J1550 − 564 the transition threshold appears at 0.1$L_{\text{E}}$, rather than at the predicted $L_{\text{E}}$. It should be noted that, though Comptonization in the disc can shift the apparent disc temperature/radius as measured by MCD models, the effect of this is less important at high $M$ than at low $M$ (Merloni, Fabian & Ross 2000), opposite to the observed behaviour on the $T_{\text{in}}$–$L_{\text{disc}}$ plane.

The clear observational result is that the high-$M$ Galactic BHBs show a variety of spectral shapes, which correlate fairly well with $L_{\text{disc}}/L_{\text{E}}$. Overlaid on the BHB data in Fig. 1 are the results from fitting several spectra from the ULX IC 342 source 1 with the MCD model (as in Mizuno et al. 2001, except that an inclination angle of 60° is assumed). We thus notice a clear similarity between the ULX behaviour and that of XTE J1550 − 564 in its apparently standard regime. This similarity argues for a slim disc interpretation of ULX spectra, as first suggested by Mizuno et al. (2001). As to the MCD-type spectrum of ULXs, we here simply point out its similarity to the apparently standard regime of BHs, although to get the same temperature from a much more massive BH requires that the disc should be accreting at a correspondingly larger fraction of the critical rate. Overlaid on Fig. 1 is the standard disc $T_{\text{in}}$–$L_{\text{disc}}$ relation for 10-, 30- and 100-M⊙ Schwarzschild and Kerr ($a = 0.55$) black holes.

In Fig. 1, the horizontal dotted line indicates the 0.7–10 keV luminosity of IC 342 source 1 in 2000, when it made a spectral transition into the PL-type spectrum. The extrapolated 1–30 keV luminosity in the PL-type spectrum is close to $L_{\text{disc}}$ in the dimmest MCD spectral state (the 1993 data). This illustrates the problem (iii) above: if we require that the ULX is shining at close to $L_{\text{E}}$, then this PL-type state also has a luminosity close to $L_{\text{E}}$, so it is unlike a usual low/hard state for the stellar BHBs, even though it has a characteristic PL spectral shape of the low/hard state.

Here we propose instead that the PL-type spectrum seen in the ULX marks a transition to the Comptonized ‘anomalous regime’ rather than the usual low/hard state.

3 REANALYSIS OF PL-TYPE SPECTRA

In recent years, our understanding of both ULXs and stellar BHBs has thus made rapid progress observationally and theoretically. This makes it possible to reconsider the PL-type ULXs and solve the third puzzle presented in Section 2. Accordingly, we re-examine the gas imaging spectrometer (GIS) data of IC 342 source 1 in 2000, the longest observation among the PL-type ULXs. The observational details are given in Paper I and Sugiho et al. (2001).

3.1 Characteristics of the spectrum

The overall GIS spectrum is well described by an absorbed PL of $\Gamma = 1.73 \pm 0.06$ (Paper I). In order to investigate whether this is truly a simple PL shape, we fit the low- and high-energy bands separately. The 0.7–4 keV GIS data give a flatter power-law index, $\Gamma = 1.54 \pm 0.12$, modified by a low-energy absorption of $N_{\text{H}} = 5.2 \pm 0.3 \times 10^{21}$ cm$^{-1}$, than that obtained from fitting the 5–10 keV data with a single PL, where $\Gamma = 2.4 \pm 0.3$. Fig. 2 shows the extrapolation of the 0.7–4 keV spectral fit to the full GIS energy band, clearly showing that the spectrum is slightly curved. This could be due to spectral complexity around the iron line and edge energies as suggested in Paper I. However, the low/hard-state PL spectra of Galactic BHBs usually show the opposite curvature, with the 5–10 keV spectrum becoming harder than the 0.7–4 keV spectrum because of frequently observed soft excess softening the low-energy spectrum, and some reflection hardening the higher energy bandpass.

Thus the subtle downwards curvature of the spectrum makes it look different from the BHB low/hard state. In order to characterize...
Table 1. Spectral parameters of IC 342 source 1 with 90 per cent confidence limits.

| Epoch     | Model | Range (keV) | $N_H^a$ | $\Gamma$ or $\Gamma^b$ | $T_{in}$ (keV) | Flux$^b$ | $\chi^2$/d.o.f. |
|-----------|-------|-------------|---------|------------------------|---------------|---------|-----------------|
| 2000      | PL    | 0.7–4       | 5.2 ± 0.3 | 1.54 ± 0.12            | —             | 4.0     | 71.7/57         |
| 2000      | PL f  | 5–10        | —        | 2.4 ± 0.3              | —             | 6.1     | 14.4/19         |
| thcomp    | 0.7–10| 3.2 ± 0.4   | 2.2 ± 0.4 | 1.1 ± 0.3              | 3.3           | 102.2/86 |                 |
| PL$^c$    | 0.7–10| 6.4 ± 0.7   | 1.73 ± 0.06 | —                     | 3.7           | 101.1/86 |                 |
| PL$^d$    | 0.7–10| 6.8 ± 0.7   | 1.78 ± 0.06 | —                     | 3.9           | 119.4/88 |                 |
| MCD$^e$   | 0.7–10| 1.9 ± 0.4   | —        | 2.06 ± 0.08            | 2.4           | 120.5/88 |                 |
| 1993 (faintest phase) | MCD | 0.7–10 | 3.4$^{+2.1}_{-1.8}$ | — | 1.30$^{+0.19}_{-0.16}$ | 6.4 | 23.1/33 |

$^a$Column density for absorption assuming solar abundances, in units of $10^{21}$ cm$^{-2}$.

$^b$The 0.7–10 keV source flux at the top of the atmosphere, in units of $10^{-12}$ erg s$^{-1}$ cm$^{-2}$. Taken from Paper I. An ionized Fe K edge at 8.4 ± 0.3 keV is applied, with an optical depth of 0.9 ± 0.5.

$^c$Fit result by a single PL with absorption column. Taken from Paper I.

the spectral shape from another viewpoint, we compare the PL-type spectrum in 2000 with the faintest MCD-type spectra seen from the same source in 1993 (using the same data selection as Mizuno et al. 2001). As shown in Table 1, the faintest 1993 GIS data are well fitted with the MCD model of $T_{in} = 1.3$ keV modified by a low-energy absorption column of $N_H = 3.4 \times 10^{21}$ cm$^{-2}$. These parameters are consistent with those in Mizuno et al. (2001). Fig. 3 shows the ratio of the PL data in 2000 with the best-fitting MCD model to the 1993 faintest data. This is remarkably flat below 3 keV, showing that the shape of the low-energy spectrum does not change. A better explanation of the PL-type spectrum could be that it is not a simple PL but has a soft component which is a fainter version of that in the faintest MCD state, together with a Comptonized tail, similar to the anomalous-type (or very high-state) spectra seen in XTE J1550 — 564 and GRO J1655 — 40.

3.2 Fit with the Comptonized model

We re-fit the same PL-type GIS spectrum incorporating Comptonization. We use the same model as for XTE J1550 — 564 in the anomalous regime (Kubota 2001), i.e. an approximate model for thermal Comptonization based on the Kompaneets equation (thcomp: Zdziarski, Johnson & Magdziarz 1996; Zyci, Done & Smith 1999). We choose a disc blackbody as the seed photon distribution, and include a separate un-Comptonized MCD the temperature of which is tied to that of the seed photons, as the thcomp model only calculates the Comptonized component. We do not include reflection as the statistics are not sufficient to constrain the fit. The fit parameters are the maximum temperature of the disc blackbody seed photon spectrum $T_{in}$, the electron temperature $T_e$, the photon index $\Gamma$ which expresses the spectral shape of the thcomp below $T_e$, and the normalizations of the Comptonized and un-Comptonized disc photons. We cannot constrain the values of $T_e$ with the 0.7–10 keV GIS data. Therefore we fix $T_e$ at 20 keV as seen in XTE J1550 — 564 (Wilson & Done 2001).

We show the best-fitting thcomp parameters in Table 1. The thcomp model with a low-energy absorption can successfully reproduce the observed spectrum, with $\chi^2$/d.o.f. = 102/86. The obtained value of $T_{in} = 1.1$ keV is slightly below the temperature of 1.3 keV seen in the dimmest MCD-type spectrum in 1993. Although the direct MCD component was added to the spectral model, the data do not require it with a 90 per cent upper limit to the direct disc emission being less than 25 per cent of the total 0.7–10 keV energy flux. The lack of a direct MCD component is consistent with the optical depth of $\tau \sim 3$ inferred from the $\Gamma^b$ and (fixed) $T_e$.

4 DISCUSSION

In Section 3, we have shown that the apparently PL-type spectra seen from IC 342 in 2000 are most probably not related to the low/hard spectra in Galactic BHBs. It shows significant deviations from a PL shape, in the sense that the spectrum softens at higher energies. This is opposite to the behaviour of the Galactic BHBs in the low/hard state. We propose that the PL-type spectra are instead the analogue of the anomalous-regime (also termed the very high-state) spectra seen in the Galactic BHs at high luminosities. We demonstrate this by fitting Comptonization models, thcomp, to the PL-type data, and show that they can indeed give as good a fit to the data as a PL continuum plus ionized edge (Paper I). If the ionized edge is not incorporated, the PL fit is significantly inferior to the thcomp fit (Table 1), because of the intrinsic concaveness of the spectral shape.

Additionally, the validity of this interpretation can be tested by investigating the location of the obtained result on the $L_{disc}$–$T_{in}$ plane (Fig. 1). There, we also show the 0.1–100 keV thcomp luminosity, $L_{disc} = 1.1 \times 10^{36}$ erg s$^{-1}$ cm$^{-2}$, extrapolated from the best-fitting model assuming isotropic emission. If the Comptonization is from overheating of the disc (Beloborodov 1998) then this represents the disc luminosity. If instead it is from a separate corona, then the disc luminosity is amplified by Comptonization. However, at this low Compton $\gamma$-parameter the amplification is rather low (less than a factor of 2), so we use the thcomp luminosity as our estimate for the disc luminosity and plot this with the seed photon temperature in Fig. 1. The PL-type spectrum then lies nicely on the same luminosity–temperature relation as defined by the MCD-type spectra. This predicts a ULX mass between 30 $M_\odot$ ($a = 0$) and 150 $M_\odot$ ($a = 0.998$) if the PL-type spectrum marks the break between the
standard and apparently standard (slim disc) regimes. This break then appears at $\sim(1-2)L_E$. If instead the break is at $\sim(0.1-0.2)L_E$ as in J1550$-$564 then this implies a mass of 50$-$250 $M_\odot$.

Based on these observational results, including spectral softening at higher energies, X-ray luminosity, and disc temperature within the framework of the disc Comptonization, we conclude that the PL-type spectra of IC 342 source 1 in 2000 are related to the standard MCD-type disc with a strong disc Comptonization state rather than to the low/hard state, and that the transition between 1993 and 2000 is probably an apparently standard to anomalous transition, rather than the canonical high/soft to low/hard transition.

ACKNOWLEDGMENTS

AK is supported by Japan Society for the Promotion of Science Postdoctoral Fellowship for Young Scientists. The present work is supported in part by a Sydney Holgate Fellowship at Grey College, University of Durham.

REFERENCES

Abramowicz M. A., Czerny B., Lasota J. P., Szuszkiewicz E., 1988, ApJ, 332, 646
Artemova I. V., Bisnovatyi-Kogan G. S., Igumenshchev I. V., Novikov I. D., 2001, ApJ, 549, 1050
Bauer F. E., Brandt W. N., Sambruna R. M., Chartas G., Garmire G. P., Kaspi S., Netzer H., 2001, AJ, 122, 182
Beloborodov A. M., 1998, MNRAS, 297, 739
Ebisawa K., Kubota A., Mizuno T., Zycki P., 2001, Proc. Fourth INTEGRAL Workshop, Exploring the Gamma-Ray, Universe. ESASP, 459, 415 (astro-ph/0106034)
Ebisuzaki T. et al., 2001, ApJ, 562, L19
Fabbiano G., 1989, A&A, 27, 87
Fabbiano P., Zezas A., Murray S. S., 2001, ApJ, 554, 1035
Fryer C. L., Kalogera V., 2001, ApJ, 554, 548
Gammie C. F., 1998, MNRAS, 297, 929
King A. R., Davies H. B., Ward M. J., Fabbiano G., Elvis M., 2001, ApJ, 552, L109
Krolik J., 1998, ApJ, 498, L13
Kubota A., 2001, PhD thesis, University of Tokyo
Kubota A., Tanaka Y., Makishima K., Ueda Y., Dotani T., Inoue H., Yamaoka K., 1998, PASJ, 50, 667
Kubota A., Mizuno T., Makishima K., Fukazawa Y., Kotoku J., Ohnishi T., Tashiro M., 2001, ApJ, 547, L119 (Paper I)
Kubota A., Makishima K., Ebisawa K., 2001, ApJ, 560, L147
La Parola V., Peres G., Fabbiano G., Knin D. W., Bocchino F., 2001, ApJ, 556, L47
Madau P., 1988, ApJ, 327, 116
Makishima K., Maejima Y., Mitsuda K., Bradt H. V., Remillard R. A., Tuohy I. R., Hoshi R., Nahagawa H., 1986, ApJ, 308, 635
Makishima K. et al., 2000, ApJ, 535, 632
Merloni A., Fabian A. C., Ross R. R., 2000, MNRAS, 313, 193
Mitsuda K. et al., 1984, PASJ, 36, 741
Miyamoto S., Kimura K., Kitamoto S., Dotani T., Ebisawa K., 1991, ApJ, 383, 784
Mizuno T., 2000, PhD thesis, University of Tokyo
Mizuno T., Kubota A., Makishima K., 2001, ApJ, 554, 1282
Roberts T., Warwick B., 2000, MNRAS, 315, 98
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337
Shimura T., Takahara F., 1995, ApJ, 445, 780
Sugimoto M., Kotoku T., Makishima K., Kubota A., Mizuno T., Fukazawa Y., Tashiro M., 2001, ApJ, 561, L73
Tanaka Y., Inoue H., Holt S., 1994, PASJ, 46, L37
Tanaka Y., Lewin W. H. G., van der Heuvel E. P. J., eds, X-ray Binaries. Cambridge Univ. Press, Cambridge, p. 126
Watarai K., Mineshige S., 2001, PASJ, 53, 915
Watarai K., Fukue J., Takeuchi M., Mineshige S., 2000, PASJ, 52, 133
Watarai K., Mizuno T., Mineshige S., 2001, ApJ, 549, L77
Wilson C. D., Done C., 2001, MNRAS, 325, 167
Zezas A. L., Georgantopoulos I., Ward M., 1999, MNRAS, 308, 302
Zdziarski A. A., Johnson W. N., Madejski G., 1996, MNRAS, 283, 193
Zycki P. T., Done C., Smith D. A., 1999, MNRAS, 309, 561

This paper has been typeset from a TEX/LATEX file prepared by the author.