ASCA Observations of Two Ultra-Luminous Compact X-Ray Sources in the Edge-On Spiral Galaxy NGC 4565

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Abstract

The edge-on spiral galaxy NGC 4565 was observed for ~ 35 ks with ASCA in the 0.5-10 keV energy band. The X-ray emission was dominated by two bright sources, which could be identified with two point-like X-ray sources seen in the ROSAT HRI image. The observed 0.5-10 keV fluxes of these sources, $1.7 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ and $0.7 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$, imply bolometric luminosities of $1.2 \times 10^{40}$ erg s$^{-1}$ and $4.6 \times 10^{39}$ erg s$^{-1}$, respectively. They exhibit similar spectra, which can be explained by emission from optically thick accretion disks with inner-disk temperature of 1.4-1.6 keV. One of them, coincident in position with the nucleus, shows too low absorption to be the active nucleus seen through the galaxy disk. Their spectra and high luminosities suggest that they are both mass-accreting black-hole binaries. However, the black-hole mass required by the Eddington limit is rather high (> 50$M_\odot$), and the observed disk temperature is too high to be compatible with the high black-hole mass. Several attempts have been made to solve these problems.

Key words: Black hole physics — Galaxies: individual (NGC 4565) — Galaxies: spiral — Galaxies: X-rays

1. Introduction

It has long been known (e.g., Fabbiano 1988) that a fair number of nearby spiral galaxies host extremely luminous X-ray sources with apparently point-like appearances, or “ultra-luminous compact X-ray sources” (hereafter ULXs). Their luminosities can reach $\sim 10^{40}$ erg s$^{-1}$ (e.g., Read et al. 1997), exceeding the Eddington limit for a 1.4 $M_\odot$ neutron star almost by two orders of magnitude. A general indication is that they are indeed mass-accreting compact objects associated with the host galaxies, rather than background or foreground contaminants (e.g., Fabbiano 1989). The extremely high luminosities of these objects are thought to indicate some of their extraordinary conditions.

Clarifying the nature of ULXs is of great importance, because they strongly influence our understanding of the X-ray emission from normal spiral galaxies. For example, a ULXs located close to the galaxy center would be mistaken for an active galactic nucleus (AGN) of low luminosity. However, the absence of ULXs in the Milky Way and M31 has hampered any clear identification of their nature.

Through observations with ASCA (Tanaka et al. 1994), 0.5-10 keV X-ray spectra have been accumulated on a fair number of ULXs (Petre et al. 1994; Takano et al. 1994; Reynolds et al. 1997; Okada et al. 1998; Uno 1997). Although these ASCA spectra exhibit a fair degree of variety, some of them have been fitted successfully with a so-called multi-color disk blackbody (MCD) model. Such examples include the center source (X-8) of M33 (Takano et al. 1994), the brightest source (source 1) in IC 342 (Okada et al. 1998), and the source X-6 in M81 (Uno 1997). The MCD model describes optically thick multi-temperature emission from a standard accretion disk (Shakura, Sunyaev 1973) around a black hole. It can be characterized by the highest disk temperature, $T_\text{in}$, and the size of the accretion disk (Mitsuda et al. 1984; Makishima et al. 1986).

Although these ASCA results provide an important clue to the understanding ULXs in terms of mass-accreting black holes, in some cases there remains a fundamental problem (Okada et al. 1998) that the measured values of $T_\text{in}$ are uncomfortably high (1.0-1.8 keV). In order to further examine this issue, it is essential to enlarge the sample of such spectral measurements. Accordingly, we here analyze the ASCA data of the nearby edge-on spiral galaxy NGC 4565. We show that it contains two ULXs, one nearly coincident in projection with its nucleus. Furthermore, we confirm that the spectra of these two sources can be described well by the MCD model with rather a high disk temperature.
2. Observations and Results

2.1. Observation and Data Reduction

NGC 4565 is a spiral galaxy with an almost perfectly edge-on geometry of inclination ~86° (Hummel et al. 1984). It is located at a high galactic latitude ($b = 86.°4$) and the distance is estimated as ~ 9.7 Mpc from the radial velocity corrected for inflow into the Virgo cluster (Tully 1988, where $H_0$ is assumed to be 75 km s$^{-1}$ Mpc$^{-1}$). Other distance indicators give similar results; for example 10.0$^{+1.3}_{-1.2}$ Mpc by the globular cluster luminosity function (Fleming et al. 1995), 10.4$^{+0.3}_{-0.4}$ Mpc by the surface brightness fluctuations (Simard, Pritchet 1994), and 10.5$^{+0.8}_{-1.0}$ Mpc by the planetary nebular luminosity function (Jacoby et al. 1996). Therefore, the distance to NGC 4565 can be said to be well determined, and it is regarded as a member of the Coma I group. In this paper, we assume the distance to NGC 4565 to be 10.4 Mpc, the weighted mean of the latter three indicators.

NGC 4565 was observed by ROSAT three times, once with the HRI and twice with the PSPC (Volger et al. 1996). The archival ROSAT HRI image shown in figure 1a is dominated by two point-like X-ray sources, one about 0.8 above the galaxy disk, while the other is coincident in position with the galaxy nucleus within a ROSAT position accuracy of ~ 4" (Volger et al. 1996; Rupen 1991).

We observed NGC 4565 with ASCA on 1994 May 28. The SIS (Solid State Imaging Spectrometer; Burke et al. 1994; Yamaishi et al. 1997) data were acquired in the 2CCD/FAINT mode, while the GIS (Gas Imaging Spectrometer; Ohashi et al. 1996; Makishima et al. 1996) data were taken in the standard PH mode.

The SIS data were selected using the following criteria: a) the time after passage through the South Atlantic Anomaly (SAA) be greater than 1 minute; b) the object be at least 10° above the night Earth’s limb; c) the object be at least 20° above the bright Earth’s limb; d) the cutoff rigidity (COR) of cosmic rays be greater than 6 GeV/c; and e) the time after day night transition be greater than 100 s. We also removed hot and flickering pixels. The GIS data were selected using the following criteria: a) the time after SAA be greater than 1 minute; b) the object be at least 10° above the Earth’s limb; and c) the cutoff rigidity (COR) be greater than 6 GeV/c. We also used the standard rise-time rejection and spread discrimination to remove particle events. After applying these criteria, we obtained ~ 31.5 ks of good SIS data, and ~ 35.5 ks of good GIS data. The galaxy was clearly detected at counting rates of 0.08 c s$^{-1}$ (in 0.5-10 keV) per SIS detector, and 0.05 c s$^{-1}$ (in 0.7-10 keV) per GIS detector.

2.2. X-Ray Images

Figure 1b shows an ASCA SIS (SIS 0 plus SIS 1) image of NGC 4565 after correcting the attitude data for known temperature effects. The ASCA image comprises two emission peaks with a separation of ~ 0.8, presumably corresponding to the two sources visible in the HRI image (figure 1a).

To confirm the presence of the two sources in the ASCA image, we have projected the SIS events inside the rectangle of figure 1b onto its longer side. The derived one-dimensional X-ray profiles are shown in figure 2, in three
representative energy bands. Each profile can be fitted well by the projected Point Spread Function (PSF) of the X-ray image convolved with the two point sources, of which the locations are fixed to those determined with the ROSAT HRI. We assumed constant background and determined the intensities of the two sources in the three energy bands, as tabulated in table 1. We can see that the intensity ratios of the two sources observed by ASCA are energy independent within the statistical errors. The discrepancy between the ASCA and ROSAT HRI ratios may be due to time variability.

2.3. Summed Energy Spectra

Now that the two sources have been confirmed to have similar spectra, we tentatively analyze their spectra together as a first-cut analysis. We hence accumulated the SIS and the GIS events over circular regions of radii 4′ and 6′, respectively, both centered on the off-center (brighter) source, and obtained the spectra shown in figure 3a. We subtracted the accumulated background spectra using a source-free region of the same dataset for the SIS, and blank-sky data for the GIS. We fitted these SIS/GIS spectra simultaneously with a common model; either a power-law, a thermal bremsstrahlung, a plasma emission (Masai 1984), a blackbody, or an MCD model. For the spectral fitting, we used the response function for a point source located at the off-center source.

The fit results are summarized in table 2. Thus, the blackbody model was unsuccessful. The power-law model gives a much better fit with \( \chi^2/\nu = 1.44 \), but the probability of this fit being acceptable is less than 1%. Residues to the power-law fit indicate that the observed spectra are more convex than a single power-law; even if the two
sources have different spectral slopes, their sum would not exhibit such a convex shape. We therefore rule out the power-law fit.

The remaining three models all give acceptable fits to the data (at 98% confidence). However, the plasma-emission fit requires a very low metallicity; therefore, it is basically the same as the bremsstrahlung fit. The bremsstrahlung model, in turn, requires an intrinsic absorption greatly exceeding the galactic line-of-sight column density of N_H = 1.3 \times 10^{20} cm^{-2}. Such a moderately absorbed bremsstrahlung model is known to empirically approximate optically-thick emission arising from accreting non-magnetized compact objects (Makishima et al. 1989), rather than having its own physical meaning. We therefore regard the bremsstrahlung fit as essentially equivalent to the MCD fit, which is also acceptable. The MCD fit has yielded T_{\text{in}} \sim 1.4 \text{ keV}, and the 0.5–10 keV flux of the sum of the two sources becomes 2.3 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}. The flux is thought to be dominated by the two sources, because the contribution from the underlying ordinary X-ray binaries are estimated to be < 10\% by assuming that the f_X/f_B ratio is the same as that of M31 (Makishima et al. 1989), where f_X represents the X-ray flux and f_B represents the optical B-band flux.

Although the single MCD fit is acceptable, the observed spectra may contain an additional hard component. For example, if the two sources are low-mass X-ray binaries (LMXBs; close binaries involving non-magnetic neutron stars), we expect to detect a blackbody hard component of temperature \sim 2 \text{ keV}, arising from the neutron-star surface (Mitsuda et al. 1984). To examine this possibility, we refitted the SIS and GIS spectra with the MCD model plus a blackbody model, with the blackbody temperature fixed at 2.0 keV to ensure a stable fitting. The MCD parameters and the absorption were allowed to float again. However the data did not require the blackbody component, with its 0.5–10 keV flux being < 33\% (90\% confidence) of the total 0.5–10 keV flux. In short, the obtained spectra are considerably softer than those of LMXBs. The result of a bremsstrahlung fit given in table 2 also supports this interpretation, because the bremsstrahlung approximation to the ASCA spectra of LMXBs usually gives a considerably higher temperature.
Table 3. Estimates of the spectra of individual sources.

| Source | Absorption \((10^{21} \text{ cm}^{-2})\) | \(T_\text{in}\) (keV) | Bolometric flux\(^*\) |
|--------|---------------------------------|-----------------|-----------------|
| Off-center | \(\leq 0.2\) | 1.39±0.08 | 1.82 |
| Center | \(\leq 0.5\) | 1.59±0.32 | 0.72 |

\(^*\)The SIS/GIS spectra of NGC 4565 were fitted jointly with two MCD components, which are constrained to produce the center and off-center source spectrum.

Table 3, the two sources exhibit the same disk temperature within errors, which in turn agree with that derived in ta-

![Fig. 3. SIS and GIS spectra of NGC 4565, dominated by the two sources. The histogram shows the best-fit model and the crosses represent the observed spectra. (a) A fit with a single MCD model. (b) A fit with two MCD models, incorporating the constraints that each model can simultaneously reproduce the three-band spectrum (data points with wide bin) of the corresponding source. (c) Incident best-fit spectra corresponding to panel b. The dotted, dashed, and solid lines represent the spectrum of the off-center source, that of the center source, and the total spectrum, respectively.](image-url)
Neither source exhibits detectable absorption, again in agreement with table 2. We repeated the same fitting using different model combinations. When the off-center source spectrum is represented by a power-law, the overall fit becomes unacceptable at 98% confidence ($\chi^2/\nu = 159.1/124$). In contrast, the center source spectrum was described equally well ($\chi^2/\nu = 143.9/124$) when its MCD model was replaced by a power-law model of photon index $\Gamma = 1.55^{+0.28}_{-0.22}$. However, the absorption associated with this power-law model for the center source remained rather low ($\lesssim 2 \times 10^{21} \text{cm}^{-2}$), with the MCD parameters for the off-center source remained unchanged within the statistical errors.

3. Discussion

Using ROSAT and ASCA, we have detected two point-like luminous X-ray sources in the edge-on spiral galaxy NGC 4565. Their spectra have been successfully described by the MCD model with disk temperatures of $T_{\text{in}} = 1.4-1.6$ keV, although that of the center source can also be described with a power-law of $\Gamma = 1.55$.

3.1. The Off-Center Source

The off-center source is the brighter of the two. It is located $\sim 2$ kpc above the galaxy disk. Since this exceeds the typical scale height ($\sim 0.2$ kpc) of the X-ray source distribution in our Galaxy, the source may be suspected to be a background AGN or a foreground object. However, the chance probability to find an X-ray source of $0.5-10$ keV flux exceeding $1 \times 10^{-12}$ erg s$^{-1}$ in a particular sky region encompassing NGC 4565, e.g., $2' \times 10'$ in size, is only $\sim 0.3\%$, as calculated from the log N-log S distribution for extragalactic X-ray sources (e.g., Ueda et al. 1998). Furthermore, none of AGNs are known to exhibit an MCD-type spectrum that has a mildly concave shape in a logarithmic plot. The chance probability of this source being a foreground galaxy object is also quite low, because of its location close to the galactic north pole. We therefore conclude that this source is associated with NGC 4565.

By applying a bolometric correction via the MCD model and employing the 10.4 Mpc distance, the bolometric luminosity of the off-center source becomes $2.3 \times 10^{40}$ erg s$^{-1}$ if the emission is isotropic, or $1.2 \times 10^{40} (\cos i_c)^{-1}$ erg s$^{-1}$ if assuming a flat disk geometry with an inclination of $i_c$. These values greatly exceed the Eddington limit for a $1.4 M_\odot$ neutron star.

The high luminosity and relatively large distance above the galaxy disk suggest that this source belongs to a globular cluster in NGC 4565. However, we would then need some $\sim 100$ or more LMXBs residing in one or a few globular clusters, with each LMXB radiating at a near-Eddington luminosity. Such a high concentration of luminous LMXBs has never been observed in the Milky Way or M31. Furthermore, due to the averaging effect, we would then observe a typical LMXB spectrum, with nearly equal luminosities in the MCD and blackbody components (Mitsuda et al. 1984). This contradicts our results derived in subsection 2.3, and is hence unlikely. We therefore conclude that the off-center source is a ULX.

3.2. The Center Source

At a distance of 10.4 Mpc, the bolometric luminosity of the center source is $9.3 \times 10^{39}$ erg s$^{-1}$ for isotropic emission, or $4.6 \times 10^{39} (\cos i_c)^{-1}$ erg s$^{-1}$ for disk-like emission, where $i_c$ is the inclination of this object. This also greatly exceeds the Eddington limit for a neutron star.

Then, together with its positional coincidence (within $\sim 0.2$ kpc) with the nucleus of NGC 4565, the simplest account of the source would be a low-luminosity AGN of NGC 4565. However, the clear detection of this source with the ROSAT HRI (figure 1a) and the ASCA spectral results (table 3) consistently indicate that the absorbing column density to this source is quite low ($\lesssim 0.5 \times 10^{21} \text{cm}^{-2}$ in terms of the MCD model). Even if we assume a power-law model for the center source, $N_H$ still remains rather low ($\lesssim 2.0 \times 10^{21} \text{cm}^{-2}$). On the other hand, judging from the inclination of 86° for NGC 4565 (Hummel et al. 1984), and scaling the absorption column to our Galaxy center of $\sim 5 \times 10^{22} \text{cm}^{-2}$ (Predehl et al. 1994), the column density along the galaxy disk to the nucleus of NGC 4565 would amount to at least $\sim 1 \times 10^{22} \text{cm}^{-2}$. Such a large absorption is ruled out by the data; therefore, the center source is not likely to be a low-luminosity AGN. The low absorption also certainly rules out this source being a background AGN. Judging from its particular position, this source is not likely to be a foreground object, either. Furthermore, the same argument as used in the previous subsection makes this source unlikely to be an assembly of luminous LMXBs. We therefore suggest that the center source is a second ULX in NGC 4565, located at the near-side edge of the disk of the galaxy.

3.3. The Nature of the Two Sources and Associated Problems

Taking it for granted that the two sources are both ULXs, a clue to their nature may be provided by their spectra. These objects cannot be very luminous Crab-like supernova remnants, since a power-law fit failed to describe the spectrum of the off-center source (subsection 2.4), and the photon index of $\Gamma = 1.55$ for the center source is inconsistent with the typical Crab-type slope of $\Gamma \sim 2.0$. As already discussed, the interpretation as...
an assembly of LMXBs is incompatible with the measured spectra. An X-ray pulsar with significant radiation beaming is also unlikely, because luminous galactic and Magellanic X-ray pulsars exhibit significantly flatter continua in the ASCA band, with typical photon indices in the range 0.5-1.2 (Nagase 1989).

In contrast, we have reproduced their 0.5-10 keV spectra successfully by the MCD model (or its empirical approximation by an absorbed thermal bremsstrahlung model). Furthermore, the MCD model is applicable to the ASCA spectra of three other ULXs, as mentioned in section 1. These results indicate that the X-ray emission from these two ULXs, and possibly from some other ULXs too, originate from optically-thick accretion disks in these objects. These ULXs are therefore inferred to be mass-accreting black holes in the high state, wherein the MCD emission from the accretion disk dominates in the X-ray band. However, as discussed below, this interpretation involves two serious problems.

An immediate problem associated with the black-hole interpretation of ULXs is that the black-hole mass required to satisfy the Eddington limit is quite high. In fact, for the off-center and the center sources to be radiating below the Eddington limit, their black-hole mass has to be

\[ M_0^{\text{ED}} > 84 \left( \cos i_0 \right)^{-1} M_{\odot}, \quad M_c^{\text{ED}} > 33 \left( \cos i_c \right)^{-1} M_{\odot}, \]  

respectively. Black holes as massive as \( M_0^{\text{ED}} \) have never been observed, and invoking such objects may contradict our current understanding of stellar evolution.

The other, more delicate problem is that the measured values of \( T_{\text{in}} \) of the two ULXs are rather high compared to those of galactic and Magellanic black-hole binaries (typically 0.5-1.2 keV; Tanaka, Lewin 1995). As first pointed out by Okada et al. (1998) with respect to the ULX in IC 342, this implies a serious self-inconsistency in the black-hole interpretation of ULXs; below, we describe this issue.

The bolometric luminosity of an MCD emission may be described as (Mitsuda et al. 1984; Makishima et al. 1986)

\[ L_{\text{bol}} = 4\pi (R_{\text{in}}/\xi)^3 \sigma (T_{\text{in}}/\kappa)^4, \]  

where \( R_{\text{in}} \) is the innermost radius of the optically-thick accretion disk, \( \sigma \) is the Stefan–Boltzmann constant, \( \kappa \sim 1.7 \) (Shimura, Takahara 1995) is ratio of the color temperature to the effective temperature, and \( \xi = (3/7)^{1/2} (6/7)^2 = 0.41 \) (Kubota et al. 1998) is a correction factor. By substituting the bolometric luminosities of the two sources, and assuming \( \kappa = 1.7 \) and \( \xi = 0.41 \), we may solve equation (2) to obtain \( R_{\text{in}} = 185^{+23}_{-17} (\cos i_0)^{-1/2} \) km and \( R_{\text{in}} = 89^{+28}_{-26} (\cos i_c)^{-1/2} \) km for the off-center and the center sources, respectively.

After previous studies (e.g., Dotani et al. 1997), we may identify \( R_{\text{in}} \) as the radius inside which stable Kepler orbits no longer exist. This radius becomes 3 \( R_S \) for a non-spinning black hole of mass \( M \), where \( R_S = 2GM/c^2 = 9.0(M/M_{\odot}) \) km is the Schwarzschild radius, with \( G \) the constant of gravity and \( c \) the light speed. We then obtain \( M_0 = 20.5^{+2.6}_{-1.9} (\cos i_0)^{-1/2} M_{\odot} \) for the off-center source, and \( M_c = 9.9^{+3.1}_{-2.7} (\cos i_c)^{-1/2} M_{\odot} \) for the center source. These values considerably fall short of the mass lower limits imposed by equation (1), even if taking the most favorable case of \( i_0 = i_c = 0 \). This severe self-inconsistency arises because \( T_{\text{in}} \) is too high, and hence \( R_{\text{in}} \) is too small for the large black-hole mass required by the high luminosities. Essentially the same problem has been reported by Okada et al. (1998) on the brightest ULX in IC 342.

### 3.4. Possible Solutions to the Problems

We here attempt to solve the two problems raised in subsection 3.3, that the inferred black-hole mass is too high, and that the disk is too hot. One simple way around these problems is to assume that the black-hole has a reasonable mass, e.g., 10–20 \( M_{\odot} \), and that the observed high X-ray flux is due to radiation beaming toward us. This hypothesis has often been employed by various authors in a rather ad-hoc way when discussing the nature of ULXs. However, none of them have successfully presented mechanisms to produce such radiation beaming. Consequently, we do not appeal to this solution.

Another obvious solution to the issue is to presume that the employed distance to NGC 4565, \( D = 10.4 \) Mpc, was significantly over-estimated. However, we do not have a large degree of freedom for changing \( D \), since various distance estimates consistently yield \( D \sim 10 \) Mpc, as already mentioned in subsection 2.1. Here, let us take a rather extreme assumption of \( D = 5.2 \) Mpc instead of 10.4 Mpc, and also assume \( i_0 = i_c = 0 \). Then, the bolometric luminosities of the two sources become \( 2.9 \times 10^{39} \) erg s\(^{-1} \) and \( 1.2 \times 10^{39} \) erg s\(^{-1} \), and hence the mass limits of equation (1) become

\[ M_0^{\text{ED}} > 21 M_{\odot}, \quad M_c^{\text{ED}} > 8 M_{\odot}. \]  

These values may be reasonable for stellar-mass black holes. Thus, the issue of too high a black-hole mass might be solved by assuming that the distance to NGC 4565 is over-estimated by a factor of 2, and that the two objects are both face-on systems.

Under these assumptions and from equation (2), we obtain \( R_{\text{in}} = 92.6^{+11.4}_{-8.6} \) km and \( R_{\text{in}} = 44.5^{+14.9}_{-12.1} \) km for the off-center and the center sources, respectively, because \( R_{\text{in}} \) is directly proportional to \( D \). By identifying these again with 3 \( R_S \), we then obtain \( M_0 = 10.3^{+1.3}_{-1.0} M_{\odot} \) for the off-center source, and \( M_c = 4.9^{+1.6}_{-1.3} M_{\odot} \) for the center source. These values still remain inconsistent with the lower mass limits imposed by equation (3).
To solve the remaining inconsistency, we notice that the estimates of \( \kappa \) or \( \xi \) may be modified, because these values must be subject to considerable uncertainties. For this purpose, let us consider Cygnus X-1, the most well studied black-hole binary that is thought to have \( D = 2.5 \) kpc and \( i \sim 30^\circ \) (Dotani et al. 1997). By employing \( T_m = 0.43 \) keV and \( L_{bol} = 2.4 \times 10^{37} \) erg s\(^{-1} \) measured with ASCA (Dotani et al. 1997), together with \( \kappa = 1.7 \) and \( \xi = 0.41 \), and equating again \( R_m \) with \( 3 \) \( R_s \), we obtain the black-hole mass of Cygnus X-1 to be \( \sim 10 M_\odot \). This agrees well with the optically estimated mass, \( 10.1^{+4.6}_{-5.3} M_\odot \) (Herreo et al. 1995). From this result, we infer that the combination of \( \kappa \times \xi^2 = 1.18 \) which we have been using in equation (2) is reasonable to within an accuracy of \( \sim \pm 50\% \).

Given the above argument, let us increase \( \kappa \times \xi^2 \) by 50\%, from 1.18 to 1.77. (If \( \kappa \) is kept constant, this implies \( \kappa = 2.55 \).) Because the mass estimate through equation (2) is directly proportional to \( \kappa \times \xi^2 \), we will then obtain \( M_\odot = 15.5^{+11.5}_{-10.6} M_\odot \) and \( M_\odot = 7.4^{+2.4}_{-1.8} M_\odot \). Although the mass of the center source becomes consistent with the mass lower limit in equation (3), that of the off-center source still remains inconsistent.

Thus, the second problem pointed out in subsection 3.3 cannot be solved despite a series of compromising assumptions described above. Of course, the problem would be solved if we appeal to more extreme assumptions, e.g., \( D = 3 \) Mpc. However, we consider such attempts to be too artificial. Furthermore, the issue of too high a disk temperature (or too low a black-hole mass derived via \( R_m \)) is found in other ULXs, including IC 342 source 1 (Okada et al., 1998), and M81 X-6 (Uno 1997) of which the distance is accurately known (Freedman et al. 1994). Essentially the same problem has also been reported from a few galactic jet sources (Zhang et al., 1997), of which accurate estimates on \( D, i \), and the black-hole mass are available.

These arguments suggest that, in some black holes, the disk temperature can become significantly and systematically higher than is predicted by the standard accretion-disk picture. Zhang et al. (1997) propose that such black holes are spinning rapidly, and the accretion disks are prograde to their rotation; in such cases, the disk can get closer to the black hole, and hence become hotter, just as has been observed. Therefore, the ULXs may be mass-accreting Kerr black holes with several tens of solar masses. A further examination of this scenario will be presented elsewhere.

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References

Burke E.B., Mountain R.W., Daniels P.J., Cooper M.J., Dolat V.S. 1994, IEEE Trans. Nucl Sci. 41, 375

Dotani T., Inoue H., Mitsuda K., Nagase F., Negoro H., Ueda Y., Makishima K., Kubota A. et al. 1997, ApJ 485, L87

Fabbiano G. 1988, ApJ 325, 544

Fabbiano G. 1989, ARA&A 27, 87

Fleming D.E.B., Harris W.E., Pritchet C.J., Hanes D.A. 1995, AJ 109, 1044

Freedman W.L., Hughes S.M., Mould J.R., Lee M.G., Stetson P., Kennicutt R.C., Turner A. et al. 1994, ApJ 427, 628

Herreo A., Kudritzki R.P., Gabler R., Vilchez J.M., Gabler A. 1995, A&A 297, 556

Hummel E., Sancisi R., Ekers R.D. 1984, A&A 133, 1

Jacoby G.H., Ciardullo R., Harris W.E. 1996, ApJ 462, 1

Kubota A., Tanaka Y., Makishima K., Ueda Y., Dotani T., Inoue H., Yamaoka K. 1998, PASJ 50, 667

Makishima K., Maejima Y., Mitsuda K., Bradt H.V., Remillard R.A., Tuohy I.R., Hoshi R., Nagakawa M. 1986, ApJ 308, 635

Makishima K., Ohashi T., Hyashida K., Inoue H., Koyama K., Takano S., Tanaka Y., Yoshida A. et al. 1989, PASJ 41, 697

Makishima K., Tashiro M., Ebisawa K., Ezawa H., Fukazawa Y., Gunji S., Hirayama M.,Ideways M. et al. 1996, PASJ 48, 171

Masai K. 1984, Ap&SS 98, 367

Mitsuda K., Inoue H., Koyama K., Makishima K., Matsuoka M., Ogawara Y., Shibazaki N., Suzuki K. et al. 1984, PASJ 36, 741

Nagaese F. 1989, PASJ 41, 1

Ohashi T., Ebisawa K., Fukazawa Y., Hiyoshi K., Horii M., Ikebe Y., Ikeda H., Inoue H. et al. 1996, PASJ 48, 157

Okada K., Dotani T., Makishima K., Mutsukawa K., Mihara T. 1998, PASJ 50, 25

Petre R., Okada K., Mihara T., Makishima K., Colbert E.J.M. 1994, PASJ 46, L115

Predehl P., Trümper J. 1994, A&A 290, L29

Read A.M., Pumman T.J., Strickland D.K. 1997, MNRAS 286, 626

Reynolds C.S., Loan A.J., Fabian A.C., Makishima K., Brandt W.N., Mizuno T. 1997, MNRAS 286, 349

Rupen M.P. 1991, AJ 102, 48

Shakura N.I., Sunyaev R.A. 1973, A&A 24, 337

Shimura T., Takahara F. 1995, ApJ 445, 780

Simard L., Pritchet C.J. 1994, AJ 107, 503

Tanaka M., Mitsuda K., Fukazawa Y., Nagaese F. 1994, ApJ 436, L47

Tanaka Y., Inoue H., Holt S.S. 1994, PASJ 46, L37

Tanaka Y., Lewin W.H.G. 1995, in X-ray Binaries, ed W.H.G. Lewin, J. van Paradijs, W.P.J. van den Heuvel (Cambridge University Press, Cambridge) p126

Tully R.B. 1988, Nearby Galaxies Catalogue (Cambridge University Press, Cambridge)

Ueda Y., Takahashi T., Inoue H., Tsuru T., Sakano M., Ishisaki Y., Ogazaka Y., Makishima K. et al. 1998, Nature 391, 866

Uno S. 1997, PhD Thesis, Gakushuin University

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Volger A., Pietsch W., Kahabka P. 1996, A&A 305, 74
Zhang S.N., Ebisawa K., Sunyaev R., Ueda Y., Harmon B.A.,
Yamashita A., Dotani T., Bautz M., Crew G., Ezuka H.,
Sazonov S., Fishman G.J., Inoue H. et al. 1997, ApJ 479,
Gendreau K., Kotani T., Mitsuda K. et al. 1997, IEEE
Trans. Nucl Sci. 44, 847