CUTOFF IN THE HARD X-RAY SPECTRA OF THE ULTRALUMINOUS X-RAY SOURCES HOIX X-1 AND M82 X-1

S. Sazonov 1, A. Lutovinov 1, R. Krivonos 1,2

Submitted on August 23, 2013

Using data from the XMM-Newton and INTEGRAL observatories, we have detected a cutoff at energies above 10 keV in the X-ray spectra of the ultraluminous X-ray sources HoIX X-1 and M82 X-1. The spectra obtained can be described by a model of Comptonization of radiation in a gas cloud of moderate temperature \((kT \sim 2-3\) keV) and high optical depth \((\tau \sim 15-25)\). Such conditions can be fulfilled during supercritical accretion of matter onto a stellar-mass black hole accompanied by a strong gas outflow. The results of this work confirm the existence of a spectral state specific to ultraluminous X-ray sources, which is unlike any of the known spectral states in normal X-ray binaries.

Keywords: black holes, accretion, Comptonization, ultraluminous X-ray sources

INTRODUCTION

Ultraluminous X-ray sources (ULXs) are point-like X-ray sources observed in extra-nuclear regions of nearby galaxies, whose luminosities exceed \(\sim 2 \times 10^{39}\) erg/s. Their nature remains unknown. Two scenarios are being actively discussed: subcritical (at a rate below the Eddington limit) accretion onto a black hole of intermediate, \((10^2 - 10^4)\)\(M_\odot\), mass (IMBH, see, e.g., Miller et al. 2003) and supercritical accretion onto a black hole of stellar, less than a few tens of \(M_\odot\), mass (StMBH, see, e.g., Poutanen et al. 2007), possibly with substantial collimation of radiation toward the observer (e.g., King 2009). Both scenarios are of great interest, since in the former case, there appears an opportunity to explore the conditions that may reflect an intermediate phase of supermassive black hole growth, and in the latter case, an extreme regime of gas accretion onto black holes. It cannot be excluded that the former scenario is realized in some ULXs, while the latter in others.

So far, X-ray observations of ULXs have been carried out almost exclusively at energies below 10 keV, and many spectra measured in the 2–10 keV energy band could be described by a simple power law with a slope \(\Gamma \sim 2\) (see, e.g., Kajava, Poutanen 2009). Below 2 keV, an additional soft component with a color temperature of several hundred eV was sometimes detected. It was suggested that this component could be thermal emission from a geometrically thin, optical thick accretion disk around an IMBH, analogous to the hotter \((\sim 1\) keV) radiation observed from normal X-ray binaries in their soft/high state. If so, the lower temperature of the disk could imply a higher mass of the compact object in ULXs compared to X-ray binaries, whereas the power-law component in ULX spectra could be attributed to Comptonized radiation from an optically thin, hot corona of the accretion disk.

However, this picture faces certain difficulties. In particular, a number of ULX spectra obtained in long observations by Chandra and XMM-Newton are poorly described by a power law and have convex shape in the 2–10 keV energy band. If one describes such spectra in terms of blackbody radiation from a thin accretion disk, the temperature near its inner boundary proves to be 2–3 keV. Such values could be expected, at high accretion rates, for StMBHs, but certainly not for IMBHs. However, the measured ULX luminosities are \(10^{39} - 10^{40}\) erg/s, which exceeds the Eddington limit for a compact object of stellar mass. Therefore, an alternate scenario for ULXs has been actively discussed, namely supercritical accretion of matter onto a StMBH through a geometrically thick disk with a powerful gas outflow (see, e.g., Poutanen et al. 2007). In this case, the unusual X-ray spectral shape at energies above 2 keV is interpreted as the result of Comptonization of the relatively soft emission from the accretion disk in an optically thick corona and/or outflowing wind (Stobbart et al., 2006; Gladstone et al., 2006; Feng, Soria, 2011).

Measurements in the hard X-ray range could help advance the understanding of the nature of ULXs. However, such observations were impossible until recently, because even the brightest ULXs have X-ray fluxes of less than 1 mCrab in the 2–10 keV energy band and are often located in sky regions with high number density of X-ray sources. The capabilities of the INTEGRAL observatory (Winkler et al., 2003), namely the combination of relatively high sensitivity and good angular resolution, have made it possible to overcome these difficulties for the first time. However, even in this case very long exposures are required. Beginning in late 2009, following our proposal, within the Russian share of observing time, INTEGRAL has been performing deep observations at energies above \(\sim 20\) keV of a
Table 1. Observations of HoIX X-1 and M82 X-1 with INTEGRAL and XMM-Newton

| Program   | Revolution or observation | Dates             | Exposure (ks) |
|-----------|---------------------------|-------------------|---------------|
| INTEGRAL  |                           |                   |               |
| Archive   | 131–133, 179, 180, 250    | 10–17.11.2003,2–6.4. | 750           |
| 0720010   | 856–862, 868–872, 932, 933, 977 | 30–31.10.2004 | 1930          |
| 0820030   | 1029,1031,1033,1036,1037,1042,1046,1048,1049,1051,1092,1093,1111,1112,1114,1115 | 17.10.–6.12.2009, 1–5.6, 15–16.10.2010 | 1540 |
| 0920014   | 1225,1226,1228–1231,1233,1234,1237–1241,1244,1254 | 26.10.2012–20.1.2013 | 1690          |
| XMM-Newton|                           |                   |               |
| 065780 (HoIX X-1) | 2001                | 24.03.2011        | 28            |
|           | 1601                     | 17.04.2011        | 21            |
|           | 1801                     | 26.09.2011        | 25            |
|           | 2201                     | 23.11.2011        | 24            |
|           | 0101                     | 18.03.2011        | 27            |
|           | 1701                     | 9.04.2011         | 24            |
|           | 1901                     | 29.04.2011        | 28            |
|           | 2101                     | 24.09.2011        | 23            |
| 065780 (M82 X-1) | 2301                | 21.11.2011        | 24            |

sky region containing the M81 group of galaxies. The targets of these observations are the nucleus of the M81 galaxy and two well-known ULXs: HoIX X-1 (also known as M81 X-9) and M82 X-1. Interestingly, both of these ULXs are among the brightest over the whole sky in terms of both flux and luminosity, they are located within one degree of each other. Up to now, data for nearly 6 Ms worth of observations have been accumulated. Within the same scientific program, the XMM-Newton X-ray observatory performed a series of observations of HoIX X-1 and M82 X-1 in 2011. The main goal of the coordinated observations by INTEGRAL and XMM-Newton was to build the X-ray spectra of the aforementioned ULXs in a broad energy range from $\sim 200$ eV up to several tens of keV. In the present paper, we report the results of these observations.

In what follows, we adopt the distance to HoIX X-1 to be 3.6 Mpc, which is the distance to the M81 galaxy (Freeman et al., 1994), whose satellite is the HoIX dwarf galaxy, and that to M82 X-1 to be 3.5 Mpc (the distance to the M82 galaxy, Jacobs et al., 2009).

Observations of the M81 field started in the 7th cycle of INTEGRAL observations (AO-7) and were continued in the 8th and 9th cycles (AO-8 and AO-9). Another series of observations of this region of the sky is planned to take place in late 2013, within the 10th observational cycle of the INTEGRAL observatory (AO-10). In Table 1 information about the dates and duration of the observations performed so far is collected. The total accumulated exposure is $\approx 6$ Ms (nominal exposure, uncorrected for the decrease in efficiency for off-axis observations of the sources) for the IBIS/ISGRI instrument. This time includes $\approx 750$ ks of archival data obtained in 2003–2004, when HoIX X-1 and M82 X-1 occasionally fell into the outer regions of the field of view (7–9 deg off-axis) of the ISGRI detector. These archival data were taken into account in our analysis, although they barely increase the detection significance of the studied objects.

**OBSERVATIONS**

In 2011, the XMM-Newton observatory carried out two series of observations of HoIX X-1 and M82 X-1, consisting of 4 and 5 pointings, respectively, with a duration of about 25 ks each. Table 1 contains some key information about these observations. These observations were performed in time intervals that approximately coincided with the INTEGRAL observations (of much longer duration) performed during AO-8, hence one can regard the X-ray and hard X-ray observations carried out in 2011 as quasi-simultaneous.

In the present work, we used only the data of the IBIS/ISGRI detector (Ubertini et al., 2003) from all the data obtained by INTEGRAL. We have also analyzed the data from the JEM-X instrument, but this has not provided any additional strong constraints on the X-ray flux from HoIX X-1 and M82 X-1 at energies above 10 keV. We therefore built our analysis upon comparison of the XMM and ISGRI data.

**DATA REDUCTION, X-RAY IMAGES**

**INTEGRAL**

Initial reduction of the ISGRI data consisted of reconstruction of sky images of the M81 field in a number of energy bands (20–30, 30–45, 45–65, ... keV) using the standard algorithm (Krivonos et al., 2010) utilized in a number of our previous studies. Calibration
Fig. 1. Image of the M81 group of galaxies in the 20–30 keV energy band obtained by IBIS/ISGRI aboard INTEGRAL over the whole period of observations. Plotted is the signal to noise ratio, with the contours being 1, 2, 3, and 4σ. Denoted are the positions of HoIX X-1, M82 X-1, and the nucleus of the M81 galaxy. The distance between HoIX X-1 and M81 is 13″.

The reduction of the data obtained by the MOS1, MOS2, and pn instruments aboard XMM-Newton was done using the standard software SAS v.1.\footnote{http://xmm2.esac.esa.int/sas/} Since there were no strong proton flares during our observations, data filtering was done in a standard way.

At a distance of just 13 arcmin from HoIX X-1, there is a relatively bright hard X-ray source whose position is consistent with that of the nucleus of the M81 galaxy. This object belongs to the class of low-luminosity active galactic nuclei and its study in the hard X-ray range is of great interest but beyond the scope of the present work. Because of the proximity to M81, studies of HoIX X-1 in the hard X-ray range were practically impossible before the advent of INTEGRAL. The angular resolution of the BAT telescope aboard Swift is also insufficient for this purpose.

| MJD | HoIX X-1 (mCrab) | M82 X-1 (mCrab) |
|-----|------------------|-----------------|
| 53000 | 0.25             | 0.25            |
| 54000 | 0.25             | 0.25            |
| 55000 | 0.25             | 0.25            |
| 56000 | 0.25             | 0.25            |

Fig. 2. Light curves of HoIX X-1 and M82 X-1 in the 20–30 keV energy band over the whole period of INTEGRAL observations.
Fig. 3. X-ray images of the sky (shown are counts in the 0.2–13 keV energy band) near HoIX X-1 and M82 X-1 obtained using data of the pn detector aboard XMM-Newton in individual observations (on March 24 and 18, 2011, respectively). The spectral analysis was based on the counts recorded within the 13'-radius circles shown in the figure.

during the analysis of the M82 X-1 X-ray spectrum obtained from the XMM-Newton data.

For the subsequent spectral analysis, we used the counts recorded within the circles of 13' radius around HoIX X-1 and M82 X-1 (see Fig. 3). This region contains \( \sim 70\% \) of all the photons from a point source, and this aperture coefficient was taken into account during the spectral analysis. To estimate the background unrelated to the emission of the host galaxy, we used regions located at distances \( \sim 1–3' \) from the studied objects. Because M82 X-1 is located in the central region of the M82 galaxy, even the compact (13') spectrum-extraction region contains a number of other fairly bright X-ray sources, known from arcsec-resolution observations with the Chandra telescope. Unfortunately, it is impossible to remove the contribution of these sources during the analysis of the XMM-Newton data. However, the Chandra data suggest that this contribution is unlikely to exceed \( \sim 30\% \) [Matsumoto et al., 2001].

SPECTRAL ANALYSIS

**HoIX X-1**

Figure 4 shows the X-ray spectra of HoIX X-1 measured with XMM-Newton during the four observations carried out in 2011 (see Table 1), as well as the hard X-ray fluxes in the 20–35 and 35–50 keV energy bands obtained using the ISGRI data for the whole period of INTEGRAL observations.

We first carried out a spectral analysis of the XMM-Newton data only, in the 0.2–13 keV energy band. To this end, we used the XSPEC package [Arnaud, 1996]. A given model was fitted simultaneously to the data from all three X-ray cameras, pn, MOS1, and MOS2, allowing the model normalization to differ between the detectors. The resulting differences in the normalization proved to be less than 10\%, and the data of the three detectors showed a good mutual agreement. Each of the four spectra shown in Fig. 4 is the result of averaging over the pn, MOS1, and MOS2 data; a similar averaging was done for the corresponding spectral models.

As can be seen from Fig. 4, the X-ray spectrum of HoIX X-1 varied significantly over 2011. The first spectrum, obtained on March 24, exhibits a local maximum near 1 keV and a power-law continuum at higher energies. This spectrum is well fit (see Table 2) by a sum of a model of blackbody radiation from a multi-temperature accretion disk and a power law.
with an exponential cutoff at high energies, modified by absorption along the line of sight, i.e., by the \( \text{wabs}(\text{diskbb}+\text{cutoffpl}) \) model in XSPEC. However, the statistical significance of the detection of a cutoff is low: replacement of the \text{powerlaw} model by \text{cutoffpl}, i.e., addition of one degree of freedom, leads to a decrease of the \( \chi^2 \) value by only 6. The parameters of the \text{diskbb} model are a normalization and the temperature \( (kT_{\text{in}}) \) at the inner boundary of the multicolor disk. Our analysis assumed that the disk is observed along its axis.

In the subsequent XMM-Newton observation (April 17, 2011), the blackbody component is barely detected (the detection significance is just above 2\( \sigma \)), nor is detected a high-energy cutoff of the power-law continuum. Hence, this spectrum can be described, over the 0.2–13 keV energy band, by a simple power law with absorption. In the latest two observations (September 26 and November 23, 2011), the soft blackbody component is again barely detected (the detection significance is \( \sim 3-4 \sigma \) when the temperature at the inner boundary of the disk is fixed at 0.3 keV), however a rollover of the power-law continuum becomes evident above \( \sim 5-10 \) keV (see Fig. 4 and Table 2).

Table 2 summarizes, for all four XMM-Newton observations, the unabsorbed fluxes and luminosities of the blackbody and power-law (with a cutoff) spectral components in the 0.2–10 keV energy band \( (F_{\text{bb}}, \, F_{\text{pl}}, \, L_{\text{bb}}, \, L_{\text{pl}}) \). The total luminosity of HoIX X-1 in this energy range increased over the observing campaign from \( \sim 1.5 \times 10^{40} \) to \( \sim 3 \times 10^{40} \) erg/s, the luminosity of the blackbody component being \( \sim (2-4) \times 10^{39} \) erg/s. The deduced line-of-sight absorption columns, \( N_H \sim (1.5-2) \times 10^{21} \) cm\(^{-2} \), somewhat exceed the corresponding value for the interstellar absorption through the Galaxy in the direction of the M81 group of galaxies, \( \sim 5 \times 10^{20} \) cm\(^{-2} \) (Kalberla et al., 2005), indicating the presence of cold gas near HoIX X-1.

The presence of a strong cutoff in the spectrum of HoIX X-1 at energies above \( \sim 5-10 \) keV becomes evident from comparison of the XMM-Newton data with the upper limits on the hard X-ray flux in the 20–30 and 30–45 keV energy bands obtained with the ISGRI detector aboard INTEGRAL (see Fig. 3). Joint fitting of the data of both observatories allows us to fully exclude a power-law spectral model from consideration and reliably establish the position of the cutoff in the hard X-ray spectrum: \( E_{\text{cut}} \sim 8 \) keV (see Table 2). Reasonable values of \( \chi^2 \) per degree of freedom obtain when the ISGRI data are fitted jointly with any of the four XMM-Newton spectra. However, one should keep in mind that the latter data, obtained in individual observations lasting less than a day, are here compared with ISGRI measurements averaged over several Ms and accumulated in various years.

A natural mechanism to explain power-law spectra with a high-energy cutoff is Comptonization of soft radiation on hot electrons. We thus tried to describe the XMM-Newton spectra of HoIX X-1 by a model that, together with a blackbody component, includes a component of Comptonized radiation emergent from a cloud of hot gas (Sunyaev, Titarchuk, 1980) – the \text{wabs}(\text{diskbb}+\text{compst}) model in XSPEC. This model describes the data well, albeit somewhat worse than the \text{wabs}(\text{diskbb}+\text{cutoffpl}) model (see Table 2). The resulting gas temperature is \( \sim 2-3 \) keV and the optical depth of the cloud is \( \sim 15 \).

**M82 X-1**

We carried out a similar analysis for M82 X-1. There is a significant difference with respect to the previous case, namely that the spectra obtained with XMM-Newton contain an unsubtracted contribution from the background emission associated with the host galaxy M82. The presence of a large number of strong emission lines clearly suggests that this additional emission is thermal radiation from an optically thin, hot plasma. We have thus added an \text{APEC} (Smith et al., 2001) component into the spectral model, assuming Solar chemical composition and further restricted our consideration by energies above 1 keV, since at lower energies the contribution of the background emission becomes dominant and does not enable reliable
### Table 2. Results of spectral analysis for Hol X-1

| Parameter          | XMM2001 (+ISGRI) | XMM1601 (+ISGRI) | XMM1801 (+ISGRI) | XMM2201 (+ISGRI) |
|--------------------|------------------|------------------|------------------|------------------|
| $\Gamma$           | 1.47 ± 0.04 (1.55 ± 0.03) | 1.81 ± 0.09 (1.89 ± 0.03) | 1.871 ± 0.017 (1.872 ± 0.010) | 1.863 ± 0.019 (1.921 ± 0.019) |
| $\chi^2$ (d.o.f.)  | 2 (1305.4/1221)  | 2 (1308.6/1222)  | 2 (1308.6/1222)  | 2 (1308.6/1222)  |
| $N_H$, 10$^{22}$ cm$^{-2}$ | 0.179 ± 0.015 | 0.15 ± 0.03 | 0.193 ± 0.004 | 0.204 ± 0.005 |
| $F_{18}$, erg/s/cm$^2$ | 2.50 ± 0.15 | 2.8 ± 1.2 | 1.4 ± 0.4 | 1.7 ± 0.5 |
| $L_{20}$, 0.2-10 keV, erg/s | 4.0 ± 0.2 | 4.3 ± 1.9 | 2.2 ± 0.6 | 2.7 ± 0.7 |
| $kT_{\text{cgs}}$, keV | 0.29 ± 0.03 | 0.48 ± 0.06 | 0.3 (fixed) | 0.3 (fixed) |
| $F_{\text{pl}}$, 0.2-10 keV, erg/s/cm$^2$ | 7.5 ± 0.3 | 12.9 ± 1.9 | 16.9 ± 0.3 | 18.2 ± 0.4 |
| $E_{\text{cut}}$, keV | 1.0 ± 0.2 (1.01 ± 0.17) | 1.1 ± 0.6 (1.2 ± 0.3) | 1.28 ± 0.08 (1.29 ± 0.08) | 1.33 ± 0.10 (1.35 ± 0.09) |
| $\chi^2$ (d.o.f.) | 941.1/935 (941.7/937) | 641.3/625 (641.9/627) | 1454.8/1463 (1456.1/1465) | 1242.7/1272 (1243.7/1274) |
| $\Gamma$           | 16.9 ± 1.6 (16.4 ± 1.5) | 10 ± 5 (13 ± 4) | 14.7 ± 0.6 (14.4 ± 0.6) | 14.5 ± 0.7 (14.5 ± 0.7) |
| $\chi^2$ (d.o.f.)  | 944.4/935 (946.2/937) | 641.5/625 (642.6/627) | 1473.5/1463 (1478.2/1465) | 1248.1/1272 (1250.3/1274) |

### Table 3. Results of spectral fitting for M82 X-1

| Parameter          | XMM1001 (+ISGRI) | XMM1701 (+ISGRI) | XMM1901 (+ISGRI) | XMM2201 (+ISGRI) |
|--------------------|------------------|------------------|------------------|------------------|
| $\Gamma$           | 0.21 ± 0.09       | −0.15 ± 0.12     | 0.58 ± 0.12      | −0.05 ± 0.13     |
| $E_{\text{cut}}$, keV | 4.4 ± 0.4         | 3.4 ± 0.3        | 6.2 ± 0.9        | 3.5 ± 0.3        |
| $\chi^2$ (d.o.f.)  | 1547.9/1941       | 1315.4/1326      | 1433.2/1270      | 1294.8/1219      |
| $N_H$, 10$^{22}$ cm$^{-2}$ | 1.15 ± 0.03       | 1.22 ± 0.04      | 1.20 ± 0.02      | 1.25 ± 0.03      |
| $F_{\text{spec}}$, 1-10 keV, erg/s/cm$^2$ | 5.2 ± 0.2         | 5.8 ± 0.3        | 6.7 ± 0.2        | 7.1 ± 0.3        |
| $kT_{\text{cgs}}$, keV | 0.800 ± 0.015     | 0.923 ± 0.019    | 0.922 ± 0.013    | 0.947 ± 0.014    |
| $\tau$             | 24.2 ± 0.8        | 28.5 ± 1.3       | 21.0 ± 1.0       | 25.5 ± 1.2       |
| $\chi^2$ (d.o.f.)  | 1506.9/1491       | 1297.6/1326      | 1389.6/1290      | 1275.7/1219      |
| $kT_{\text{in}}$, keV | 3.41 ± 0.07       | 3.59 ± 0.10      | 3.36 ± 0.10      | 3.23 ± 0.08      |
| $\chi^2$ (d.o.f.)  | 1541.5/1492       | 1336.6/1327      | 1425.2/1271      | 1298.8/1220      |
| $kT_{\text{out}}$, keV | 3.41 ± 0.07       | 3.59 ± 0.10      | 3.36 ± 0.10      | 3.23 ± 0.08      |
| $\chi^2$ (d.o.f.)  | 1541.5/1492       | 1336.6/1327      | 1425.2/1271      | 1298.8/1220      |

The tables provide the results of spectral analysis and fitting for Hol X-1 and M82 X-1, including parameters such as hydrogen column density ($N_H$), flux density ($F_{18}$), luminosity ($L_{20}$), cut-off energy ($E_{\text{cut}}$), and other parameters relevant to the spectral fitting of X-ray sources.
The derived broad-band X-ray spectra can be well described by a model of Comptonization of radiation in a cloud of gas of moderate temperature and large optical depth: $kT \sim 2.5$ keV, $\tau \sim 15$ for HoIX X-1, and $kT \sim 2$ keV, $\tau \sim 25$ for M82 X-1. These values indicate that the Comptonization takes place in a nearly saturated regime (the Comptonization parameter $y = (4kT/m_e c^2)\tau^2 \sim 4-10$, see, Sunyaev, Titarchuk [1980]). Such conditions are quite unusual for the hot coronae of accretion disks in normal X-ray binaries (where accretion onto a StMBH at a subcritical rate occurs), but can be fulfilled during supercritical accretion of matter onto an IMBH accompanied by a strong outflow of gas from the central regions (Shakura, Sunyaev, 1973; Ohsuga et al., 2003; Poutanen et al., 2007).

In this case, the soft emission component with a characteristic temperature of $kT_{\text{in}} \sim 0.3$ keV detected from HoIX X-1 by XMM-Newton can be related to regions of a thin accretion disk that are open to the observer (beyond the spherization radius of the accretion flow) or with the photosphere of the wind outflowing from the disk.

Therefore, the reported results of XMM-Newton and INTEGRAL observations confirm the existence of a spectral state (Stobbart et al. 2006; Gladstone et al., 2009), specific to ultraluminous X-ray sources, which is unlike any of the spectral states known for normal X-ray binaries.

For M82 X-1, we have found an indication of an additional hard X-ray emission component. This radiation may hint at the presence in the inner part of the supercritical accretion flow of a hot corona similar to the coronae of accretion disks in X-ray binaries. However, this excess may also be associated with the unsubtracted contribution of other fairly bright X-ray sources in the central region of the starforming galaxy M82, which are resolved by Chandra (Matsumoto et al., 2001).

Given the findings of this study, we are awaiting with great interest the upcoming announcement of the results of hard X-ray observations of a number of ULXs by the new-generation observatory NuSTAR, whose high sensitivity and angular resolution enable detailed studies of ULX spectral properties at energies above 10 keV for the first time.

This research was partially supported by the Ministry of Science and Education of the Russian Federation (contract 8701), Russian Foundation for Basic Research (grant 13-02-01365), programs P-21 and OFN-17 of the Presidium of the Russian Academy of Sciences, and program NSh-6137.2014.2 for support of leading scientific schools in Russia. The research made use of data obtained from the Russian INTEGRAL Data Center and XMM-Newton Data Center. The authors are grateful to Eugene Churazov for developing the methods of analysis of INTEGRAL/IBIS data and
providing the software.

REFERENCES

1. K.A. Arnaud, Astronomical Data Analysis Software and Systems V 101, 17 (1996).
2. G.C. Dewangan, V. Jithesh, R. Misra, C.D. Ravikumar, Astrophys. J. 771, L37 (2013).
3. H. Feng and R. Soria, New Astron. Reports 55, 166 (2011).
4. W.L. Freedman, S.M. Hughes, B.F. Madore, J.R. Mould, M.G. Lee, P. Stetson, R.C. Kennicutt, A. Turner, L. Ferrarese, H. Ford, J.A. Graham, R. Hill, J.G. Hoessel, J. Huchra, G.D. Illingworth, Astrophys. J. 427, 628 (1994).
5. J.C. Gladstone, T.P. Roberts, C. Done, Mon. Not. R. Astron. Soc. 397, 1836 (2009).
6. F. Grisé, P. Kaaret, M.W. Pakull, C. Motch, Astrophys. J. 734, 23 (2011).
7. B.A. Jacobs, L. Rizzi, R.B. Tully, E.J. Shaya, D.I. Makarov, L. Makarova, Astron. J. 138, 332 (2009).
8. J.J.E. Kajava and J. Poutanen, Mon. Not. R. Astron. Soc. 398, 1450 (2009).
9. P.M.W. Kalberla, W.B. Burton, D. Hartmann, E.M. Arnal, E. Bajaja, R. Morras, W.G.L. Pöppel, Astron. Astrophys. 440, 775 (2005).
10. A.R. King, Mon. Not. R. Astron. Soc. 393, L41 (2009).
11. R. Krivonos, M. Revnivtsev, S. Tsygankov, S. Sazonov, A. Vikhlinin, M. Pavlinsky, E. Churazov, R. Sunyaev, Astron. Astrophys. 519, A107 (2010).
12. H. Matsumoto, T.G. Tsuru, K. Koyama, H. Awaki, C.R. Canizares, N. Kawai, S. Matsushita, R. Kawabe, Astrophys. J. (Letters) 547, L25 (2001).
13. J.M. Miller, G. Fabbiano, M.C. Miller, A.C. Fabian), Astrophys. J. 585, L37 (2003).
14. R. Miyawaki, K. Makishima, S. Yamada, P. Gandhi, T. Mizuno, A. Kubota, T.G. Tsuru, H. Matsumoto, Publ. Astron. Soc. Japan. 61, 263 (2009).
15. K. Ohsuga, M. Mori, T. Nakamoto, S. Mineshige, Astrophys. J. 628, 368 (2005).
16. J. Poutanen, G. Lipunova, S. Fabrika, A.G. Butkevich, P. Abolmasov, Mon. Not. R. Astron. Soc. 377, 1187 (2007).
17. N.I. Shakura and R.A. Sunyaev, Astron. Astrophys. 24, 337 (1973).
18. R.K. Smith, N.S. Brickhouse, D.A. Liedahl, J.C. Raymond, Astrophys. J. 556, L91 (2001).
19. A.M. Stobbart, T.P. Roberts, J. Wilms, Mon. Not. R. Astron. Soc. 368, 397 (2006).
20. R.A. Sunyaev and L.G. Titarchuk, Astron. Astrophys. 86, 121 (1980).
21. P. Ubertini, F. Lebrun, G. Di Cocco, A. Bazzano, A.J. Bird, K. Broeystad, A. Goldwurm, G. La Rosa, C. Labanti, P. Laurent, I.F. Mirabel, E.M. Quadrini, B. Ramsey, V. Reglero, L. Sabau, B. Sacco, R. Staubert, L. Vigroux, M.C. Weisskopf, A.A. Zdziarski, Astron. Astrophys. 411, L131 (2003).
22. C. Winkler, T. J.-L. Courvoisier, G. Di Cocco, N. Gehrels, A. Giménez, S. Grebenev, W. Hernsken, J.M. Mas-Hesse, F. Lebrun, N. Lund, G.G.C. Palumbo, J. Paul, J.-P. Roques, H. Schnopper, V. Schönfelder, R. Sunyaev, B. Teegarden, P. Ubertini, G. Vedrenne, A.J. Dean, Astron. Astrophys. 411, L1 (2003).