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1WGA J1216.9+3743: *CHANDRA* FINDS AN EXTREMELY STEEP ULTRALUMINOUS X-RAY SOURCE

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ABSTRACT

We report the discovery of a new ultraluminous X-ray source (ULX) in the nearby galaxy NGC 4244 from *Chandra* archival data. The source, 1WGA J1216.9+3743, is one of the least luminous and softest ULXs discovered so far. Its X-ray spectrum is the best available for a representative of the soft ULXs, a class of sources recently discovered by *Chandra* and *XMM-Newton*. 1WGA J1216.9+3743 appears pointlike in the *Chandra* image and has a complex spectral shape; a multicolor disk model, suitable for brighter ULXs, is inadequate for this source. The 1WGA J1216.9+3743 spectrum is heavily absorbed ($N_{\rm H} \sim 1$–4×10^{21} cm^{-2}) and very soft. The best-fit power-law model gives $\Gamma \sim 5$ and implies a luminosity $L_{(0.5–10\ {\rm keV})} \sim 10^{39}$ ergs s^{-1}. A comparison with previous detections shows that, despite the variability displayed by the source during the *Chandra* observation, the 1WGA J1216.9+3743 count rate, spectral shape, and absorption are practically unchanged over a 9 yr period. We also performed deep optical imaging of the field containing the X-ray source and found a possible $R \sim 23.7$ counterpart.

Subject headings: galaxies: individual (NGC 4244) — galaxies: spiral — stars: individual (1WGA J1216.9+3743) — X-rays: galaxies

1. INTRODUCTION

X-ray observations of nearby galaxies have shown that their X-ray emission comes from different classes of sources: X-ray binaries, supernova remnants, and the hot interstellar medium, in addition to possible background active galactic nuclei (AGNs; see, e.g., Fabbiano 1989 for a review). Some of the pointlike sources appear to radiate well in excess of the Eddington limit for a 1 $M_\odot$ object, with inferred luminosities in the range 10^{39}–10^{40} ergs s^{-1}. These objects are often referred to as ultraluminous X-ray sources (ULXs) or intermediate-luminosity X-ray objects (IXOs), inasmuch as their luminosity is between those of "normal" X-ray binaries and AGNs. Up to now, about 90 ULXs have been detected in more than 50 galaxies (see Colbert & Ptak 2002 for a recent catalog). ULXs seem to be preferentially located in the outskirts of the host galaxy, although some are found in the central regions (e.g., IXO 95 in NGC 6949). As pointed out by Colbert & Ptak (2002), starburst galaxies contain a comparatively large number of ULXs, but spiral galaxies seem not to be favored hosts with respect to elliptical galaxies. In a very recent paper, moreover, evidence was found for a ULX associated with a globular cluster in NGC 4565 (Wu et al. 2002). ULXs are often variable sources, and their X-ray spectrum may be quite soft (e.g., Makishima et al. 2000). No certain optical counterpart has been found for these sources yet, implying an extreme X-ray–to–optical flux ratio. Very recently, Pakull & Mironi (2002) reported the presence of emission nebulae at the position of some ULXs and suggested that they could actually be related to the episode that led to the ULX formation.

Thus far, no generally accepted model has been presented to explain the huge energy output of ULXs. Assuming that the Eddington limit is not exceeded and emission is isotropic implies that ULXs are powered by accretion onto an ≈50–100 $M_\odot$ black hole. Present evolutionary scenarios do not preclude such a possibility, and the fact that these are rare sources may be compatible with the mean number of ULXs per galaxy being only 1–2 (Colbert & Ptak 2002). Alternatively, ULXs may be interpreted as conventional black hole binaries ($M_{\rm BH} \lesssim 10\ M_\odot$) with modest beaming coming from a collimated X-ray emission ($b \sim 0.1$; King et al. 2001) or to a relativistically beamed emission. In this picture, the Galactic analogs of ULXs should be the microquasars, such as GRS 1915+105 and GRO 1655−40.

This paper presents a multiwavelength study of a new ULX, 1WGA J1216.9+3743, found in NGC 4244. This source is one of the 16 peculiar *ROSAT* PSPC sources selected for their extremely high X-ray–to–optical flux ratio (Cagnoni et al. 2002). 1WGA J1216.9+3743 is a bright ($F_{(0.1–2.4\ {\rm keV})} > 10^{-13}$ ergs cm^{-2} s^{-1}) WGA Catalog (White, Giommi, & Angelini 1994)[5] source with blank fields, i.e., no optical counterparts on the Palomar Observatory Sky Survey to $O = 21.5$. The extreme $f_{\rm X}/f_V$ ratio that follows is incompatible with all major and common classes of extragalactic sources, including normal quasars, AGNs, normal galaxies, and nearby clusters of galaxies (Maccacaro et al. 1988). Possibilities for the nature of these "blanks" (Cagnoni et al. 2002) include (1) quasar 2s, i.e., high-luminosity, high-redshift, heavily obscured quasars, the bright analogs of Seyfert 2s; (2) low-mass Seyfert 2s, AGNs powered by a low-mass obscured black hole (i.e., obscured narrow line Seyfert 1); (3) AGNs with no big blue bump, e.g., low radiative efficiency flows; (4) isolated neutron stars (e.g., Treves et al. 2000); (5) γ-ray burst X-ray afterglows or fast variable/transient sources; (6) failed clusters, in which a

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[5] Additional information on WGACAT can be found at http://heasarc.gsfc.nasa.gov/W3Browse/all/wgacat.html.

large overdensity of matter has collapsed but has not formed galaxies (Tucker, Tananbaum, & Remillard 1995); (7) high-redshift clusters of galaxies; and, most relevant to this paper, (8) ULXs in nearby galaxies.

Using X-ray archival data (*ROSAT* and *Chandra*) and the information obtained from optical and IR follow-ups, we present strong evidence that 1WGA J1216.9+3743 is indeed a ULX in NGC 4244, a $B = -18.4$ (Olling 1996) edge-on spiral galaxy (Hubble type Scd) at a distance of ~3.6 Mpc (Fry et al. 1999).

We present the X-ray, optical, and IR observations in § 2 and discuss the results in § 3. Errors in the paper represent 90% confidence levels, unless explicitly stated otherwise.

2. OBSERVATIONS

2.1. *ROSAT*

1WGA J1216.9+3347 was serendipitously observed by *ROSAT* PSPC in 1991 November, and the results of this observation are reported in Cagnoni et al. (2002); we summarize the main findings here. During the 9 ks PSPC observation (600179n00), a total of 135 net photons were collected between 0.07 and 2.4 keV. We extracted a spectrum and fitted it with both an absorbed power law and an absorbed blackbody model. Despite the scanty statistics and the large error bars, both fits agree on the extreme softness of 1WGA J1216.9+3743 emission ($\Gamma = 4.90^{+5.10}_{-1.74}$ for the power law and $kT \sim 200$ eV for the blackbody models, respectively) and, in the presence of absorption, a factor of 10–30 in excess of the Galactic value in this direction ($N_{\rm H\,Gal} = 1.69 \times 10^{20}$ cm^{-2}; $N_{\rm H} \sim 4.5$ and $\sim 1.5 \times 10^{21}$ cm^{-2} for the power-law and blackbody models, respectively). The source absorbed flux in the 0.5–2.0 keV band is $\sim 1.2 \times 10^{-13}$ ergs cm^{-2} s^{-1}, which corresponds to an absorbed luminosity of $\sim 2 \times 10^{38}$ ergs s^{-1} and to an unabsorbed luminosity of $\sim 10^{39}$ ergs s^{-1} for both the power-law and blackbody models at NGC 4244 distance. The *ROSAT* PSPC light curve is consistent with the source being constant during the observation (65% probability).

The 1WGA J1216.9+3743 region was observed by the HRI instrument on board *ROSAT* in 1996 June for ~8.5 ks, but the source was not detected, consistent with the extrapolation in the HRI band of the best-fit absorbed power law. The 3 σ upper limit on the count rate in a 24$''$ circle is 0.0023 counts s^{-1}.

2.2. *Chandra*

1WGA J1216.9+3347 was serendipitously observed by *Chandra* ACIS-S on 2000 May 20 during a ~50 ks observation of the nearby galaxy NGC 4244. 1WGA J1216.9+3743 is 6 kpc away from the NGC 4244 center and is detected as a pointlike source on ACIS-S S2 front-illuminated chip with a total of 1948 counts between 0.3 and 10 keV with peak position at $\alpha = 12^{\rm h}16^{\rm m}56^{\rm s}.927$, $\delta = +37^\circ43'35''.89$ (J2000.0).

We reprocessed *Chandra* archival data using the CXC analysis package CIAO 2.2.1 (M. Elvis et al. 2003, in preparation) and CALDB 2.9. The source position determination was improved by using the new geometry parameter file added to CALDB 2.9 and by removing the pixel randomization of ±0.5 pixels introduced by the standard *Chandra* pipeline processing (e.g., Garcia et al. 2001). We corrected the data for bad pixels and checked for high particle background times during the observation. The observation is not affected by any significant background flare. The 1WGA J1216.9+3743 average count rate during this observation is $(3.92 \pm 0.98) \times 10^{-2}$ photons s^{-1} between 0.3 and 10 keV, for a total of 1948 counts in the ~49 ks of net exposure. In a conservative test to confirm whether any background flare might affect our results, we have excluded the time intervals with background count rate a factor 1.2 larger or smaller than the mean value during the observation, as suggested by CIAO 2.2.1 Science Threads.[6] This would reduce the useful exposure time to 42 ks and to 1653 net photons (0.3–10 keV) for 1WGA J1216.9+3743. A detailed comparison shows that the count rate, spectrum, and light curves are fully consistent with those extracted from the total observation.[7]

We extracted a spectrum for the source using a circle with radius $17''.5$ (35 pixels) and a local background in an annular region with radii of 20$''$ and 50$''$ (40 and 100 pixels), respectively, from which a circle of 15$''$ centered on a nearby source was excluded. We binned the spectrum to have a minimum of 30 counts per bin and fitted it with SHERPA between 0.3 and 10.0 keV with an absorbed power-law model and an absorbed disk blackbody. Both models proved to be a poor representation of the data, and the results are unchanged when the ACIS quantum efficiency degradation is taken into account. We tried with more complex models, such as an absorbed power-law + disk blackbody, an absorbed power-law + a Raymond-Smith thermal plasma, and an absorbed broken power law, and they are all acceptable. The spectrum and the residuals to an absorbed power-law model are reported in Figure 1, and the results of all the fits are reported in Table 1. We also report in Table 1 the 0.5–10 keV absorbed fluxes and the 0.5–10 keV absorbed and unabsorbed luminosities of the source. It is clear from Table 1 that (1) the 1WGA J1216.9+3743 spectrum is extremely soft ($\Gamma \sim 4.90^{+0.42}_{-0.36}$), (2) simple models give an unacceptable fit to the data, (3) all but the broken power-law model predict a high column density (~ 1–7×10^{21} cm^{-2}) in the 1WGA J1216.9+3743 direction, and (4) the 1WGA J1216.9+3743 unabsorbed 0.5–10 keV luminosity is $\geq 10^{39}$ ergs s^{-1} (for all but the broken power-law model, which could mimic the absorption with a flatter low-energy slope and for the disk blackbody model, which is the statistically worst model).

We extracted light curves for the source and background between 0.3 and 10 keV using the same circular and annular regions used for the spectral analysis. The background subtracted light curve of 1WGA J1216.9+3743 binned over 5000 s is shown in Figure 2, and the source displays a factor of 1.5 variability. A fit with a constant model gives a ~0.5% probability for constant emission, indicating that 1WGA J1216.9+3743 is variable on timescales of ≤ 5000 s. We have confirmed the variability by an independent method using a Bayesian block analysis to the unbinned data, which has recently been developed for the *Chandra* Multiwavelength Project (J. Drake 2002, private communication; D.-W. Kim et al. 2003, in preparation).

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[6] Note that all the points lie within a factor 1.3. For additional information, see http://asc.harvard.edu/ciao/threads/acisbackground/.

[7] For example, the 42 ks spectrum fitted with an absorbed power-law model gives values perfectly in agreement with those reported in Table 1 $N_{\rm H} = 4.46^{+0.51}_{-0.47} \times 10^{21}$ cm^{-2}, $\Gamma = 4.91^{+0.28}_{-0.25}$, normalization $= 3.37^{+0.54}_{-0.44} \times 10^{-4}$ photons cm^{-2} s^{-1} keV^{-1}, and reduced $\chi^2 = 1.32$ for 39 degrees of freedom (dof). Errors represent 1 σ confidence here.

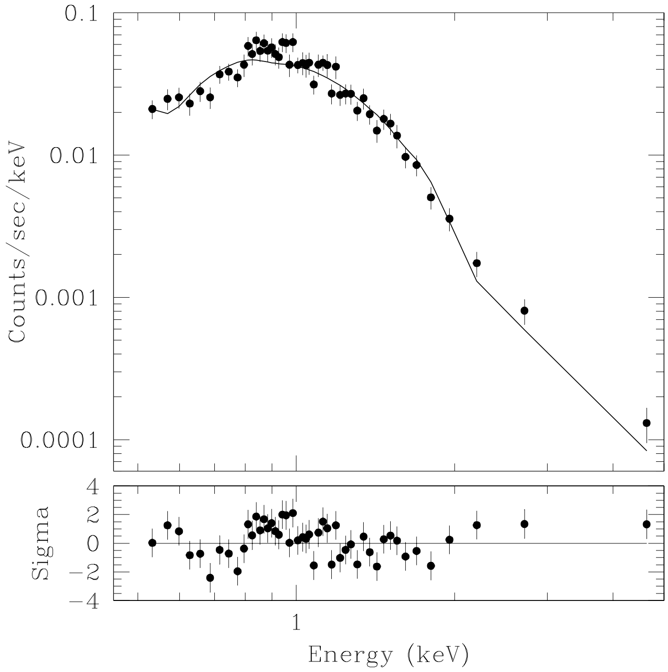

FIG. 1.—Spectrum and residuals to an absorbed power-law fit. The residuals show that a more complex model is needed to model 1WGA J1216.9+3743 emission.

2.3. *Optical and Infrared*

We obtained deep IR imaging in the *K* band (to $K \sim 18$) with NSFCAM at the NASA Infrared Telescope Facility (IRTF) on 2000 January and deep *R*-band imaging (to $R \sim 25$) with MOSAIC at KPNO 4 m in 2001 February. We performed standard imaging reduction using IRAF version 2.11.3 and calculated accurate astrometric solutions for the data using the Digitized Sky Survey.

The *Chandra* error box (0″.67 at 95% confidence level for ~1000 net photons at 6′ off-axis; D.-W. Kim et al. 2003, in preparation) contains only one object (at 0″.6 from *Chandra* central position), which appears stellar on the *R* image (Fig. 3). The 1WGA J1216.9+3743 counterpart lies in the optical extent of NGC 4244, at ~6 kpc from the galaxy center, and it is thus likely to be associated with the galaxy (we exclude a possible AGN in the background in § 3).

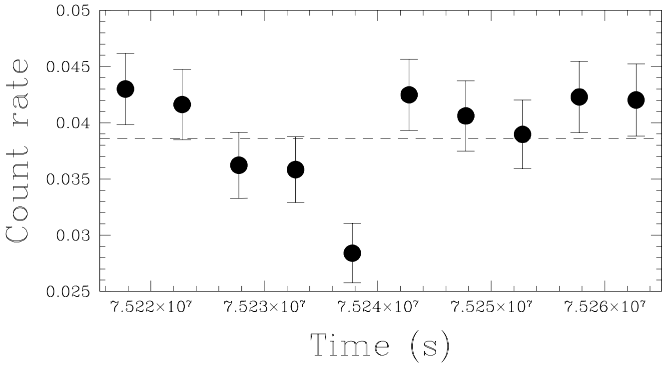

FIG. 2.—*Chandra* 0.3–10.0 keV light curve of 1WGA J1216.9+3743 binned over 5000 s. The dashed line represents the mean count rate during the observation (i.e., 3.86×10^{-2} counts s^{-1}).

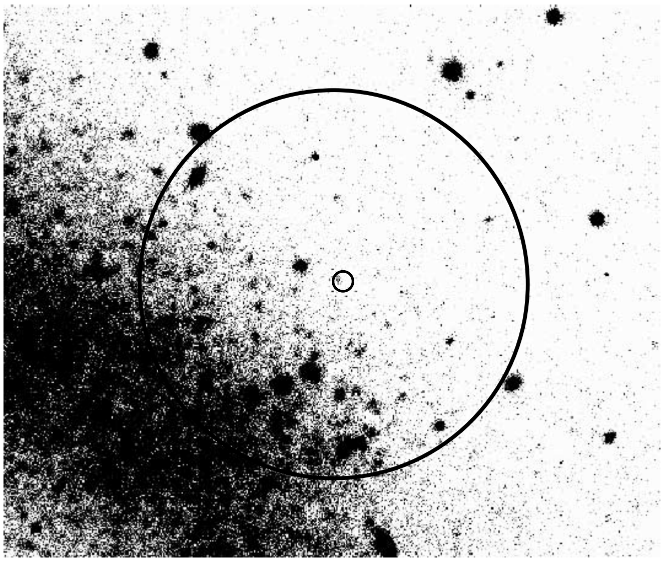

FIG. 3.—*ROSAT* PSPC ($r = 39''$) and *Chandra* (enlarged to $r = 2''$ for clarity) error circles on 1WGA J1216.9+3743 positions. North is up, and east is to the left in the image.

Since the night was not photometric, we obtained an estimate of the source magnitude rescaling from the United States Naval Observatory catalog sources in the 17.0–20.0 *R* magnitude range falling on the CCD. The estimated *R*-band magnitude is $\sim 23.7 \pm 0.5$, while the source is not visible in the *K*-band image down to $K \sim 18$. The X-ray over *R*-band flux ratio, defined as in Hornschemeir et al. (2001), is ~170.

We searched for radio counterparts from the Faint Images of the Radio Sky at Twenty-Centimeters and the NRAO VLA Sky Survey, but none were found within 30″ of the *Chandra* position, setting an upper limit of ~1 mJy at 1.4 GHz.

3. DISCUSSION

The properties of 1WGA J1216.9+3743 indicate that it is a ULX in NGC 4244. The source absorbed flux in the 0.5–2.0 keV band derived from *Chandra* data ($\sim 1.8 \times 10^{-13}$ ergs cm^{-2} s^{-1}) is consistent within the errors with that measured with *ROSAT* ($\sim 1.2 \times 10^{-13}$ ergs cm^{-2} s^{-1}), so the source appears not to have significantly varied between the two observations (~9 yr). The unabsorbed luminosity of 1WGA J1216.9+3743 at NGC 4244 distance is $\sim 2 \times 10^{39}$ ergs s^{-1} for the absorbed power-law model. Note however, that the 50 ks *Chandra* observation provides evidence for variability on a much shorter timescale (~5000 s). We also found that the spectral shape did not change from the *ROSAT* observation and, although no simple emission model gives a satisfactory fit, the X-ray continuum appears to be very soft and can be roughly described by a very steep absorbed power law with $\Gamma \sim 5$ but not with thermal emission. A complex spectral shape was also found for the stacked spectra obtained from the ULXs in the Antennae galaxies by Zezas et al. (2002a; see their Fig. 2); the spectrum presented here for 1WGA J1216.9+3743 suggests that the complexity might not be the effect of the superposition of different types of ULX spectra, but it is intrinsic to each source.

TABLE 1

Fit to the 0.3–10 keV *Chandra* Spectrum with SHERPA

Model	$N_{\rm H}$ (10^{21} cm^{-2})	Parameter Values (E_b, kT in keV)	χ^2_ν/dof	Absorbed $F_{\rm X}$ (10^{38} ergs cm^{-2} s^{-1})[a]	Absorbed $L_{\rm X}$ (10^{38} ergs s^{-1})[b]	Unabsorbed $L_{\rm X}$ (10^{38} ergs s^{-1})[b]
A...........	$4.19^{+0.75}_{-0.67}$	$\Gamma = 4.90^{+0.42}_{-0.36}$, $K = (3.38^{+0.82}_{-0.61}) \times 10^{-4}$	1.38/47	2.31	3.6	21.6
B...........	$0.85^{+0.51}_{-0.47}$	$kT = 0.300^{+0.030}_{-0.027}$, $K = 3.15^{+2.70}_{-1.42}$	1.91/47	2.19	3.4	4.6
C...........	$7.43^{+2.46}_{-1.51}$	$\Gamma = 6.88^{+1.68}_{-0.71}$, $K_{\rm pow} = (6.91^{+5.92}_{-2.91}) \times 10^{-4}$, $kT = 0.712 \pm K_{\rm diskbb} = 0.016^{+0.087}_{-0.015}$	1.28/45	2.11	3.3	104.5
D	0.169[c]	$\Gamma_1 = 0.22^{+0.46}_{-0.53}$, $\Gamma_2 = 3.85^{+0.20}_{-0.18}$, $E_b = 0.94 \pm 0.04$ $K = (1.71^{+0.29}_{-0.22}) \times 10^{-4}$	0.89/46	2.15	3.3	3.5
E...........	$2.91^{+1.25}_{-0.96}$	$\Gamma = 4.26^{+0.86}_{-0.56}$, $K_{\rm pow} = (1.36^{+0.81}_{-0.48}) \times 10^{-4}$, $kT = 0.835^{+0.052}_{-0.079}$, Abundances = 0.3[d], $K_{\rm RS} = (1.53^{+0.56}_{-0.44}) \times 10^{-4}$	1.05/45	2.14	3.3	9.4

Note.—Model A, absorption × power law. Model B, absorption × disk blackbody. Model C, absorption × (power law+disk blackbody). Model D, absorption × broken power law. Model E, absorption × (power law+Raymond-Smith).

[a] Between 0.5 and 10 keV.

[b] Between 0.5 and 10 keV.

[c] The absorption was fixed to the Galactic value in 1WGA J1216.9+3743 direction; if left as a free parameter, it tends to zero.

[d] Similar values are obtained for Raymond-Smith abundances equal to the solar value.

Using the X-ray flux at 1 keV from the absorbed power-law fit, the *R*-band magnitude, and the upper limit at 1.4 GHz, we computed 1WGA J1216.9+3743 broadband spectral indices according to the formula

$$\alpha_{x_1 x_2} = -\frac{\log[f(x_2)/f(x_1)]}{\log[\lambda(x_1)/\lambda(x_2)]} \ . \qquad (1)$$

We used the canonical 1 keV, *V*-band (5500 Å), and 5 GHz points by extrapolating the *R*-band flux density to the *V*-band and the 1.4 GHz flux density to 5 GHz assuming a flat spectral shape, and we obtain $\alpha_{RO} \geq 0.60$, $\alpha_{OX} = 0.23$, and $\alpha_{RX} \geq 0.47$. Such values place 1WGA J1216.9+3743 out of the region occupied by AGNs in the α_{RO}-α_{OX} plane (e.g., Caccianiga et al. 1999) since not even the most extreme BL Lac objects can reach such values (e.g., Costamante & Ghisellini 2002). Taking absorption into account would make the situation even more extreme (e.g., an absorbing column of $\sim 4 \times 10^{21}$ cm^{-2} with a Galactic dust-to-gas ratio would enhance the X-ray flux by a factor of ~10 and the optical flux by a factor of ~6). We can thus exclude the possibility of 1WGA J1216.9+3743 being a background AGN.

We can also exclude the possibility of 1WGA J1216.9+3743 being a supernova remnant for the short timescale variability displayed in the *Chandra* observation and by the lack of a significant fading in the 9 yr between the *ROSAT* and the *Chandra* observations.

Even if the best-fit model for 1WGA J1216.9+3743, a convex absorbed broken power law, is usually used to describe the synchrotron peak observed in beamed sources such as blazars, the sharp change in the power-law shape of 1WGA J1216.9+3743 ($\Gamma_1 = 0.22$, $\Gamma_2 = 3.85$) is difficult to reconcile with the smoothly curving blazar synchrotron peak (e.g., $\Gamma_1 = 2.1$, $\Gamma_2 = 2.8$, measured for Mrk 421 by Guainazzi et al. 1999).

1WGA J1216.9+3743 luminosity falls at the lower end of the ULX range. Some emission models imply $L_{\rm X} < 10^{39}$ ergs s^{-1} (see Table 1). In particular, the absorbed power-law plus Raymond-Smith model and the absorbed broken power-law models, which have the lowest χ^2, give a luminosity of only few times 10^{38} ergs s^{-1}. This would make 1WGA J1216.9+3743 an ordinary X-ray binary in NGC 4244. However, optically thin bremsstrahlung emission is typical of extended sources, such as clusters of galaxies, and we found no evidence for a diffuse nature of this source in *Chandra* data, and the broken power-law model does not have a straightforward physical interpretation. The relatively low luminosity of 1WGA J1216.9+3743 may still suggest that this source is an X-ray binary with a $M \approx 10\ M_\odot$ black hole, of the Cyg X-1 type. The X-ray spectrum, however, strongly argues against this possibility, being much softer of those of Galactic black hole candidates (BHCs). BHC spectra in the high state are thermal and soft but peak around a few keV and extend up to ~10 keV.

The extreme softness of the X-ray spectrum makes this source rather peculiar among the ULXs. In fact, while very soft spectra have been already detected from other ULXs with *ROSAT*, successive observations over a wider energy range showed a harder component. An example of this behavior is MS 0317.7−6647, which has been first associated with an isolated neutron star by Stocke et al. (1995) on the basis of its soft, thermal spectrum. The source was later identified with a ULX by Makishima et al. (2000) when *ASCA* data convincingly showed a hard tail ($\Gamma \sim 2$), possibly associated with a multicolor disk blackbody. Before the advent of *Chandra*, the ULXs seen by *ROSAT* and *ASCA* were consistent with emission from a multicolor disk blackbody (e.g., Makishima et al. 2000); *Chandra* is now discovering a new class of steep ULX (e.g., out of the 30 ULX of Zezas et al. 2002b, nine have a steep spectrum). 1WGA J1216.9+3743 is the source for which the best *Chandra* spectrum is available so far. In the study of the Antennae galaxies, Zezas et al. (2002a) find steeper spectra for the least luminous ULX; 1WGA J1216.9+3743 seems to fit in this picture, interpreted with the possible presence of undetected diffuse hot interstellar medium in the proximity of the source. Alternatively, one could consider that the indication of a luminosity-dependent spectral shape is due to different accretion properties. The steep ULXs could be the "galactic" analog of narrow-line Seyfert galaxies (a steep version of the Seyfert galaxies), which are thought to be powered by a lower mass black hole accreting at a higher rate, compared with "normal" Seyfert galaxies.

Follow-up optical observations allowed us to discover a possible counterpart of 1WGA J1216.9+3743 at 0″.6 from the *Chandra* position. The association is based only on the positional coincidence. The *Chandra* error box is quite small (95% confidence radius greater than 1″; D.-W. Kim et al.

2003, in preparation), and the background field is not very crowded (see Fig. 3), so the possibility of a chance alignment appears unlikely, albeit it cannot be ruled out on the basis of present data. The optical counterpart has $R \sim 23.7$; if this source is a star in NGC 4244, it has to be a red star, or its bolometric correction would imply a luminosity not compatible with even the most luminous stars known. The most likely possibility is that the suggested counterpart is a late-type giant/supergiant, like an M5 II-III; for this spectral range, the source luminosity, corrected for extinction, would be $L \approx 7 \times 10^{37}$ ergs s^{-1}, about $10^4\ L_\odot$. The $R-K < 5.7$ derived from the IR nondetection is not stringent, and it is satisfied by the red stars.

ULXs are one of the most interesting class of sources that are now being investigated by the X-ray satellites *Chandra* and *XMM-Newton*. We presented in this paper the best spectrum (~2000 photons) available so far for a steep-spectrum ULX. Steep ULXs, such as 1WGA J1216.9+3743, appear to be related to the least luminous objects of the ULX class (e.g., Zezas et al. 2002a) and were essentially unknown before the launch of *Chandra* and *XMM-Newton*. Future investigations are needed to understand the emission mechanisms powering these sources and to confirm and explain a possible luminosity dependence of the spectral shape.

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