CHANDRA AND SWIFT FOLLOW-UP OBSERVATIONS OF THE INTERMEDIATE-MASS BLACK HOLE IN ESO 243-49

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ABSTRACT

The brightest ultra-luminous X-ray source HLX-1 in the galaxy ESO 243-49 provides strong evidence for the existence of intermediate-mass black holes (IMBHs). As the luminosity and thus the mass estimate depend on the association of HLX-1 with ESO 243-49, it is essential to confirm its affiliation. This requires follow-up investigations at wavelengths other than X-rays, which in turn needs an improved source position. To further reinforce the IMBH identification, it is necessary to determine HLX-1’s environment to establish whether it could potentially form and nourish a black hole at the observed luminosities. Using the High Resolution Camera on board Chandra, we determine a source position of R.A. = 01h10m28.3s and decl. = +46°04′22′′.3. A conservative 95% error of 0′.3 was found following a boresight correction by cross-matching the positions of three X-ray sources in the field with the Two Micron All Sky Survey catalog. Combining all Swift UV/Optical Telescopeuvw2 images, we failed to detect a UV source at the Chandra position down to a 3σ limiting magnitude of 20.25 mag. However, there is evidence that the UV emission is elongated in the direction of HLX-1. This is supported by archival data from GALEX and suggests that the far-UV emission is stronger than the near-UV. This could imply that HLX-1 may be situated near the edge of a star-forming region. Using the latest X-ray observations, we deduce the mass accretion rate of a 500 M⊙ black hole with the observed luminosity and show that this is compatible with such an environment.

Key words: accretion, accretion disks – X-rays: binaries – X-rays: individual (HLX-1)

1. INTRODUCTION

The brightest Hyper Luminous X-ray source (HLX-1) was discovered serendipitously with XMM-Newton on 2004 November 23 (Farrell et al. 2009) in the outskirts of the edge-on spiral galaxy ESO 243-49, at a redshift of 0.0224 (Afonso et al. 2005). Its 0.2–10 keV unabsorbed X-ray luminosity, assuming isotropic emission and the galaxy distance (95 Mpc), exceeded 1.1 × 1042 erg s−1. Follow-up observations with XMM-Newton and the Swift X-ray telescope (XRT) revealed that the source was variable in X-rays by more than 1 order of magnitude, and that luminosity changes were accompanied by changes in the spectral shape, in a way similar to Galactic black hole systems (Godet et al. 2009). As argued before, either super-Eddington accretion or beaming of the X-ray emission could account for X-ray luminosities up to ∼1040 erg s−1 for stellar mass black holes (10–50 M⊙), but would require extreme tuning to explain an X-ray luminosity of 1042 erg s−1. Hence, HLX-1 is an excellent intermediate-mass black hole (IMBH) candidate (Farrell et al. 2009).

To verify the IMBH nature, it is essential that its association with the host galaxy is confirmed. To do this, an improved position is crucial in order to carry out multi-wavelength follow-up observations. Subsequently, it is necessary to determine whether the source resides in an environment which can provide sufficient material to power such a massive black hole (e.g., Milosavljević et al. 2009). Again, multi-wavelength observations are the key to determining whether this object is in a star cluster, a star-forming region, or a globular cluster. As Ultra-luminous X-rays (ULXs) emit mostly in the X-ray domain, X-ray observations are thus the key to understanding how much material is required to feed the black hole as the luminosity is directly related to the mass accretion rate. Therefore, constant monitoring of the X-ray emission will allow us to place constraints on the quantity of material necessary in the neighboring environment.

Here we present Chandra observations of HLX-1 with the High Resolution Camera (HRC) accorded under the Directors Discretionary Time (DDT) program, which has allowed us to revise and improve the position of HLX-1, along with Swift XRT data revealing that the X-ray luminosity of this source remains above 1042 erg s−1, following its recent re-brightening in 2009 August (Godet et al. 2009). We discuss the mass accretion rate of HLX-1 using these observations. We also reveal evidence for the nature of the environment around HLX-1 through ultraviolet imaging with the Swift UV/Optical Telescope (UVOT), a finding independently supported by archival Galaxy Evolution Explorer (GALEX) observations.

2. DATA ANALYSIS

2.1. The First HRC-I Observation

We obtained a 1 ks DDT observation of HLX-1 with the HRC-I camera on board Chandra on 2009 July 4 (ObsID: 10919). We extracted all the events in the detector (i.e., the background) and plotted the number of counts per energy channel (PI) with the CIAO v4.1.1 task WAVDETECT. Between PI = 25 and 120, the background is lower and the sensitivity of the instrument is higher (see, e.g., Cameron et al. 2007). We thus filtered the event list to include only these energies and performed source detection with WAVDETECT utilizing an exposure map. No source is detected within the XMM-Newton error circle of HLX-1, and only two sources are detected in the field of view. The two sources that are detected correspond to known XMM-Newton sources: 2XMM J011050.4-460013 which was similar in flux to the XMM-Newton detection of...
Figure 1. Swift-UVOT unsmoothed $uvw2$ image of ESO 243-49. The white contours show the orientation of the galaxy in the $J$ band (N. A. Webb et al. 2010, in preparation). The black circle indicated by the white arrow is centered on the Chandra position of HLX-1, with the radius representing the 95% error bounds.

HLX-1, and 2XMM J010953.9-455538. These sources have, respectively, 17 and 6 counts in the HRC-I image, which gives 0.018 and 0.006 count s$^{-1}$. Therefore, HLX-1 must have dropped in flux down to at most 0.006 count s$^{-1}$ (the faintest source detected), compared to 0.03 count s$^{-1}$ expected from the flux in the most recent XMM-Newton observation. This faint flux is confirmed using Swift observations taken one month later (Godet et al. 2009).

2.2. The Second HRC-I Observation

Following the re-brightening of HLX-1 (Godet et al. 2009), we obtained a second deeper DDT observation of 10 ks with the Chandra HRC-I on 2009 August 17 (ObsID: 11803). We generated several images of the HRC-I field of view with a binning of 4, 8, 16, and 32 pixels, and performed source detection using WAVDETECT. A total of 11 sources were detected, including a source consistent with the position of HLX-1 with a net count rate of 0.098 ± 0.003 count s$^{-1}$. We cross-matched the entire source list with the Two Micron All Sky Survey (2MASS) catalog (Skrutskie et al. 2006) and found three matching objects which appear to be the real counterparts to the X-ray sources. A boresight correction was applied to the X-ray image which lead to a small shift of 0.030, and the rms of the alignment of the X-ray image on the 2MASS reference stars (0.030). Combining these errors, a total 95% error of $0.3''$ was derived.

2.3. The Swift UVOT Data

The Swift UVOT observed the field of ESO 243-49 on 2009 August 5, 6, 16, 18, 19, and 20 for a total exposure of 38 ks. Observations were performed in the $uvw2$ ($\sim1600$–$2500$ Å) filter only. Data reduction and analysis of the data were done using the software release HEADAS 6.6.2 and version 20090630 of the UVOT calibration files. At the location of the core of ESO 243-49 there is an extended object (Figure 1), with some hints of an elongated emission toward the position of HLX-1. No other source is observed above the flux level of this galaxy at the Chandra position of HLX-1.

We cannot determine an upper limit from subtracting the galaxy contribution at that position as we do not know when or even if HLX-1 stops emitting in the $uvw2$ wavelength range. A source at the X-ray position would only be discernible from the galaxy if the source is significantly brighter than the emission at that position. Therefore, to determine an upper limit to the detection of the ULX above the flux of the galaxy, we first co-added the individual observations. We then placed seven circular apertures of 3'' radius on the image, one at the location of the X-ray source and six others around an ellipse on the galaxy of similar galaxy isophotal brightness to the region containing the source. Then, using a background region of 20'' located in a source-free region close to the galaxy, we determined the magnitude of the galaxy in each aperture using the Swift tool UVOTSOURCE. To be compatible with the calibration, which is determined for a 5'' aperture (Poole et al. 2008), we applied an aperture correction to the count rate using a table of aperture correction factors contained within the calibration files. We determined the standard deviation of the magnitudes determined from the seven apertures to be 0.10 mag. We then took the 3σ upper limit for detecting a source at the Chandra position to be the magnitude determined from the source region located at the Chandra position minus three times the standard deviation, which gives a 3σ upper limit of 20.25 mag.

2.4. The GALEX Data

Given the possible detection of extended emission in the $uvw2$, we retrieved archival data taken by GALEX in the near-UV (NUV; $\sim1800$–$2800$ Å) and far-UV (FUV; $\sim1500$–$2000$ Å) bands. The field of HLX-1 was observed by GALEX as part of the deep survey on 2004 September 27 for $\sim 13$ ks in the NUV and $\sim 8$ ks in the FUV. A clear extension toward the location of HLX-1 from the bulge of ESO 243-49 can be seen in both images (see Figure 2), with the dominant emission occurring in the FUV. No point source was detected coincident with the position of HLX-1 in either band. In order to determine magnitude upper limits, we measured the counts within regions centered on the Chandra position with radii corresponding to the 80% encircled energy radius (3'' and 4'' for the NUV and FUV, respectively). The total count rate inside six similar-sized regions located around the galaxy, at the same isophotal brightness as the location of HLX-1, was also determined. Using a source-free area of the image near the galaxy with radii of 6'' and 8'' for the NUV and FUV, respectively, we measured the total background rates. These were scaled to the same extraction region size as used for the source regions. All the count rates (both source and background) were then corrected for the wings of the point-spread function (PSF) outside the extraction region. Net count rates were calculated by subtracting the background rates from the source rates. Magnitudes were then calculated for the net rates using the zero points given in Morrissey et al. (2007). The standard deviation for the magnitudes from each of the seven regions were 0.3 mag and 0.2 mag for the NUV and FUV, respectively. We then determined the 3σ upper limits as the magnitudes derived for the region centered on the HLX-1 Chandra position minus three times the standard deviation, in the same way as for the UVOT data. This gives upper limits of 20.4 mag and 21.4 mag for the NUV and FUV, respectively.
3. DISCUSSION AND CONCLUSIONS

Using Chandra observations of HLX-1, we have determined an improved position with a 95% confidence error radius of 0.3′. This is sufficiently small that we should eventually be able to identify the source at other wavelengths, and eventually perform broadband spectroscopic observations.

Although no point-like source is detected with UV observations at this position, HLX-1 appears to be situated near the edge of a region of UV excess stretching from the nucleus of ESO 243-49 toward the Chandra position. However, it is not yet certain that this emission is related to HLX-1, but the fact that no similar extended emission is seen in the radio, infrared, optical, or X-ray domains (Farrell et al. 2009; N. A. Webb et al. 2010, in preparation) makes it unlikely that this is either a foreground or background source. Follow-up observations with a higher resolution instrument would also help to confirm the association and the extended nature, as the low resolution of GALEX (5′′ full width at half-maximum, FWHM) and the UVOT (better at 2′′ FWHM) would mean that it would be difficult to resolve a source at the center of the galaxy and a second toward the position of HLX-1. However, the fact that this emission appears to be stronger in the FUV could hint toward star formation taking place in that region, as the UV flux primarily originates from the photospheres of O- through later-type B-stars (M > 3 M⊙), and
thus measures star formation averaged over a $\sim 10^8$ yr timescale (e.g., Lee et al. 2009). Starburst environments are thought to be able to generate IMBHs through runaway collisions and mergers of massive stars (Freitag et al. 2006). Further, the massive stars present in such environments can supply the necessary material to be accreted onto the black hole to provide the luminosities observed if one is captured by the black hole and then proceeds to main-sequence Roche-lobe overflow (Hopman et al. 2004). An alternative situation is described by Sun et al. (2010) where a trail of star formation could be created by ram-pressure stripping of gas and stars from a dwarf galaxy which has recently interacted with ESO 243-49. In this case HLX-1 could have been an IMBH which was once at the center of the dwarf galaxy, but has now had most of the gas and stars stripped from it via the gravitational interaction with ESO 243-49. This may resemble a globular cluster if detected in the optical domain.

To determine whether accretion from the medium around the stripped galaxy is possible, we use the latest X-ray observation of HLX-1, which has a 0.2–10 keV unabsorbed luminosity of $1.9^{+3.5}_{-0.4} \times 10^{42}$ erg cm$^{-2}$ s$^{-1}$ if we fit with a PL model. This is the highest luminosity that we have observed over the last five years while this source has been bright (previous observations with ROSAT in the early nineties gave non-detections, confirming that the source was more than a factor of 10 fainter than in these observations; N. A. Webb et al. 2010, in preparation). HLX-1 is not bright in the radio, infrared, optical, or NUV domains (Farrell et al. 2009; N. A. Webb et al. 2010, in preparation), so we can assume that the majority of the emission in the X-rays and we can use this luminosity ($L$) to deduce the approximate mass accretion rate ($\dot{M}$), where $L = \eta \dot{M} c^2$ and $\eta = GM/Rc^2$ ($M$ is the mass of the black hole and $R$ is the innermost stable circular orbit, i.e., six times the Schwarzschild radius, therefore supposing a non-rotating black hole). We assume a mass of 500 $M_\odot$. We find $\dot{M} \sim 2.1 \times 10^{-4} M_\odot$ yr$^{-1}$. This is well within the ranges of the matter available for accretion predicted by Sun et al. (2010), therefore supporting the idea that HLX-1 could be embedded in a star-forming region and that it may have originated from a stripped dwarf galaxy.

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Facilities: CXO, Swift, GALEX

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