The ultraluminous X-ray sources in the high-velocity system of NGC 1275

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ABSTRACT

We report the results of a study of X-ray point sources coincident with the high-velocity system (HVS) projected in front of NGC 1275. A very deep X-ray image of the core of the Perseus cluster, made with the Chandra X-ray Observatory, has been used. We find a population of ultraluminous X-ray sources [ULXs; seven sources with $L_X(0.5−7.0$ keV) $> 7 \times 10^{39}$ erg s$^{-1}$]. As with the ULX populations in the Antennae and Cartwheel galaxies, those in the HVS are associated with a region of very active star formation. Several sources have possible optical counterparts found on the Hubble Space Telescope (HST) images, although the X-ray brightest one does not. Absorbed power-law models fit the X-ray spectra, with most having a photon index between 2 and 3.

Key words: galaxies: clusters: individual: Perseus – galaxies: individual: NGC 1275.

1 INTRODUCTION

The study of ultraluminous X-ray sources (ULXs) has been greatly expanded by the high spatial resolution and spectral grasp of the Chandra and XMM–Newton observatories, respectively. ULXs (Fabbiano & White 2006; Miller & Colbert 2004) have 2−10 keV X-ray luminosities exceeding $10^{39}$ erg s$^{-1}$, and are found at some distance from the centres of galaxies; they are not active galactic nuclei (AGNs). Their luminosity exceeds that for a 10-M⊙ black hole accreting at the Eddington limit which radiates isotropically. X-ray luminosities exceeding $10^{39}$ erg s$^{-1}$, and are found at some distance from the centres of galaxies; they are not active galactic nuclei (AGNs). Their luminosity exceeds that for a 10-M⊙ black hole accreting at the Eddington limit which radiates isotropically and so has created much interest in the possibility that they contain even higher-mass black holes, such as intermediate mass black holes (IMBHs) of $\sim 10^3$ M⊙ (Makishima et al. 2000; Miller, Fabian & Miller 2004). Alternatively, they may appear so luminous because of beaming (Reynolds et al. 1999; King et al. 2001; Zezas & Fabbiano 2002) or due to super Eddington accretion (Begelman 2002).

ULXs are most common in starburst galaxies and in very active star-forming regions, such as in the Antennae and Cartwheel galaxies, where populations of tens of them are found (Zezas et al. 2002; Gao et al. 2003; Wolter & Trinchieri 2004). In some cases variability rules out the possibility that they are just clusters of lower-luminosity objects. The origin of IMBHs is unclear. They may form as a result of binary interactions in dense stellar environments (Portegies Zwart & McMillan 2002). A comparison of IMBH ULX candidates with a number of well-known stellar-mass black hole candidates (BHCs; Miller et al. 2004) demonstrates that the ULXs are more luminous but have cooler thermal disc components than standard stellar-mass BHCs. Therefore, ULXs in this sample are clearly different from the sample of stellar-mass BHCs, and are consistent with being IMBHs.

Here, we report on the discovery of a population of eight point X-ray sources to the N of the nucleus of NGC 1275, which is the central galaxy in the Perseus cluster. All exceed $10^{39}$ erg s$^{-1}$ in X-ray luminosity, and seven are formally ULXs, if they are at the distance of the cluster. The spatial region where they lie coincides with the high-velocity system (HVS) of NGC 1275. We assume that they are part of that system. We see no other point sources (apart from the nucleus) over the body of NGC 1275 (Fig. 1).

NGC 1275 is embedded in a complex multiphase environment. Optical imaging and spectroscopy first established the existence of two distinct emission-line systems towards NGC 1275: a low-velocity component associated with the galaxy itself at 5200 km s$^{-1}$ and a high-velocity component at 8200 km s$^{-1}$ projected nearby on the sky (Minkowski 1955, 1957). This latter component is associated with a small gas-rich galaxy falling into the cluster along our line of sight (Haschick, Crane & van der Hulst 1982). A merger scenario has been proposed (Minkowski 1955, 1957). However, interaction of the low-velocity system (LVS) and/or HVS with a third gas-rich galaxy or system of galaxies (Holtzman et al. 1992; Conselice, Gallagher & Wyse 2001), or influences from the surrounding dense intracluster medium (ICM) (Sarazin 1988; Boroson 1990; Caulet et al. 1992) have been discussed.

Deep Chandra observations have clarified the position of the HVS. The depth of the observed X-ray absorption (e.g. Fig. 1) is not infilled by emission from hot gas projected along the line of sight, so the HVS must lie well in front of NGC 1275. Gillmon, Sanders & Fabian (2004) have estimated a lower limit on the distance of the HVS from the nucleus of 57 kpc. The LVSs and HVS are therefore not yet directly interacting. The HVS is, however, strongly interacting with the ICM of the Perseus cluster, which has triggered strong star formation. In this paper, we describe the detailed analysis of the X-ray spatial and spectral properties of the discrete sources in the HVS.

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This paper is organized as follows. In Sections 2 and 3, we present reduction and results from the imaging analysis and spectral analysis, respectively; in Section 4, we discuss the results, and Section 5 summarizes our findings.

Throughout this paper, we use a redshift of 0.018 and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. This gives a luminosity distance to the cluster of 80 Mpc; 1 arcsec corresponds to a physical distance of 370 pc.

2 IMAGING ANALYSIS

The Chandra data sets included in this analysis are listed in Table 1. The total exposure time, after removing periods containing flares, is 890 ks. To prepare the data for analysis, all of the data sets were reprocessed to use the latest appropriate gain file (acisD2000-01-29gain_citiN0003). Each of the data sets analysed used an aimpoint on the ACIS-S3 CCD. The data sets were filtered using the light curve in the 2.5–7 keV band on ACIS-S1 CCD, which is a back-illuminated CCD like the ACIS-S3. The CIAO LC_CLEAN tool was used to remove periods 20 per cent away from the median count rate for all the light curves. This procedure was not used for data sets 03209 and 04289 which did not include the S1 CCD; however, no flares were seen in these observations on the S3 CCD. Each of the observations was reprojected to match the coordinate system of the 04952 observation.

The 900-ks X-ray image covering the energy range 0.3–0.8 keV is shown in Fig. 2. The bright NGC 1275 nucleus is clearly seen at right ascension (RA) $3^h 19^m 48^s$ and declination (Dec.) $+41^\circ 30^\prime 42^\prime\prime$ (J2000) and the HVS is seen in absorption to the north of the nucleus.

The CIAO CELLDTECT source detection routine was then used on the reprocessed level 2 event data to produce a preliminary list of point sources. The cell size ranges from 4 to 8 pixels. This algorithm strongly depends on the local background, and the detection cell is not adjustable to the size of the source. As the X-ray diffuse emission of NGC 1275 is very strong, the source list may well include false detections in high background level regions. Therefore, problematic sources embedded in such regions have been excluded in our analysis. Moreover, as mentioned above, we only included sources associated with the HVS.

We have detected eight bright sources close to the nucleus of NGC 1275, located in the northern inner radio lobe of 3C 84. All of these sources are embedded in the same region as the HVS (see Fig. 1). There are no sources associated with the southern lobe (Fig. 1), thus we assume these sources are associated with the HVS.

Fig. 4 (left-hand panel) shows the smoothed ACIS-S3 image in the 0.3–7.0 keV band, including numbered labels of all the detected sources (top panel), centred on source labelled N3 (centre panel) and centred on source N5 (bottom panel).

All the point-like sources are listed in Table 2, showing their positions and count rates.
Table 1. Chandra observations included in this analysis. The exposure given is the time remaining after filtering the light curve for flares. All observations were taken with the aimpoint on the ACIS-S3 CCD. All positions are in J2000 coordinates.

| Observation ID | Sequence | Observation date | Exposure (ks) | Nominal roll (°) | Pointing RA | Pointing Dec. |
|---------------|----------|-----------------|---------------|-----------------|-------------|--------------|
| 3209          | 800209   | 2002-08-08      | 95.8          | 101.2           | 3:19:46.86  | +41:31:51.3  |
| 4289          | 800209   | 2002-08-10      | 95.4          | 101.2           | 3:19:46.86  | +41:31:51.3  |
| 6139          | 800397   | 2004-10-04      | 51.6          | 125.9           | 3:19:45.54  | +41:31:33.9  |
| 4946          | 800397   | 2004-10-06      | 22.7          | 127.2           | 3:19:45.44  | +41:31:33.2  |
| 4948          | 800398   | 2004-10-09      | 107.5         | 128.9           | 3:19:44.75  | +41:31:40.1  |
| 4947          | 800397   | 2004-10-11      | 28.7          | 130.6           | 3:19:45.17  | +41:31:31.3  |
| 4949          | 800398   | 2004-10-12      | 28.8          | 130.9           | 3:19:44.57  | +41:31:38.7  |
| 4950          | 800399   | 2004-10-12      | 73.4          | 131.1           | 3:19:43.97  | +41:31:46.1  |
| 4952          | 800400   | 2004-10-14      | 143.2         | 132.6           | 3:19:43.22  | +41:31:52.2  |
| 4951          | 800399   | 2004-10-17      | 91.4          | 135.2           | 3:19:43.57  | +41:31:42.6  |
| 4953          | 800400   | 2004-10-18      | 29.3          | 136.2           | 3:19:42.83  | +41:31:48.5  |
| 6145          | 800397   | 2004-10-19      | 83.1          | 137.7           | 3:19:44.66  | +41:31:26.7  |
| 6146          | 800398   | 2004-10-20      | 39.2          | 138.7           | 3:19:43.92  | +41:31:32.7  |

Figure 2. The central region of NGC 1275 in the 0.3–0.8 keV band. Pixels are 0.49 arcsec in dimension and the entire image is 1.77 × 0.89 arcmin². North is to the top and east is to the left-hand side in this image. The HVS is seen in absorption to the north of the bright nucleus which is at RA 3 h 19 m 48 s and Dec. +41° 30′ 42″.

We have used the archival Hubble Space Telescope (HST) observations of NGC 1275 in order to search for optical counterparts. The galaxy was imaged with the WFPC2 camera on HST using the F814W (∼I, on 2001 November 6 with an exposure time of 1200 s) and F702W (∼R, on 1994 March 31 with an exposure time of 140 s) broad-band filters. Several coincidences between X-ray sources and optical knots of emission (F814W) can be seen in Fig. 4 (right-hand panel), showing the same regions as Fig. 4 (left-hand panel).

The HST image shows many highly absorbed features. When we compare in detail, sources N7 and N8 are located in star-forming regions, while N2 and N6 have a point-like counterpart. Sources N1, N3, N4 and N5 have no optical identification. Therefore, we have found a possible correlation between compact X-ray sources and the regions of vigorous star formation. The implications are discussed later.

In order to investigate the emission mechanism of these ULXs, the X-ray to optical flux ratios have been computed between the F702W and F814W HST broad-bands and 1.0–7.0 keV X-ray band. Preliminary processing of the raw images, including corrections for the flat fielding, was done remotely at the Space Telescope Science Institute through the standard pipeline. For each frame, cosmic rays were removed by image combination, using the IMCOMBINE routine in IRAF. After cosmic ray removal, the frames were added using the task WMOSAIC in STSDAS package. Photometric measurements were made with PHOT task, within the NOAO package. Finally, the fluxes and magnitudes have been determined using the photometric zero-point information in the header of the calibrated image files.

These results are shown in Table 3, including the X-ray to optical flux ratios from the F814W and F702W broad-band filters, and the magnitude determinations from the same filters. In the cases where an optical counterpart has not been found (N1, N3, N4 and N5), the magnitudes and fluxes are just a lower limit.
Table 2. Positions of sources detected near the NGC 1275 centre and displayed in Fig. 4 (column 2) and count rate in the energy range between 0.5 and 7.0 keV (column 3).

| N   | Position (J2000) | Count rate (count ks$^{-1}$) |
|-----|-----------------|------------------------------|
| 1...| 03:19:48.736 +41:30:47.25 | 0.34±0.05                  |
| 2...| 03:19:48.166 +41:30:46.64 | 1.69±0.06                  |
| 3...| 03:19:48.090 +41:31:01.88 | 2.60±0.08                  |
| 4...| 03:19:47.994 +41:30:52.30 | 1.42±0.09                  |
| 5...| 03:19:47.925 +41:30:47.50 | 1.19±0.09                  |
| 6...| 03:19:47.602 +41:30:47.01 | 0.74±0.06                  |
| 7...| 03:19:47.422 +41:30:51.93 | 0.95±0.08                  |
| 8...| 03:19:47.214 +41:30:47.62 | 1.28±0.08                  |

Table 3. Optical analysis. X-ray to optical ratios (columns 2 and 3) and magnitude determinations (columns 4 and 5) for the filters F814W and F702W, respectively, with the X-ray flux between 1.0 and 7.0 keV.

| N   | $F_X/F_{F814W}$ | $F_X/F_{F702W}$ | $M_{F814W}$ | $M_{F702W}$ |
|-----|----------------|----------------|-------------|-------------|
| 1...| >26.5          | >16.2          | >22.6       | >22.1       |
| 2...| 25.4           | 23.6           | 20.4        | 20.3        |
| 3...| >18 800        | ...            | >26.8       | ...         |
| 4...| >1081          | >800           | >24.5       | >24.2       |
| 5...| >123           | >60.6          | >22.6       | >21.9       |
| 6...| 26.2           | 28.4           | 21.7        | 21.7        |
| 7...| 76.7           | 51.4           | 22.3        | 21.9        |
| 8...| 134            | 90.1           | 22.2        | 21.7        |

3 SPECTRAL ANALYSIS

We extracted spectra for all the detected sources close to the HVS, using extraction regions defined to include as many of the source photons as possible, but at the same time minimizing contamination from nearby sources and background. The background region was either a source-free circular annulus or several circles surrounding each source, in order to take into account the spatial variations of the diffuse emission and to minimize effects related to the spatial variation of the CCD response.

For each source, we extracted spectra from each of the data sets. These spectra were summed to form a total spectrum for each source. Response and ancillary response files were created for each source in each of the observations using the CIAO MKACISRMF and MKWAF tools. The responses for a particular source were summed together, weighting according to the number of counts in each observation.

The spectra were fitted using XSPEC v11.3.2. In order to use the $\chi^2$ statistic, we grouped the data to include at least 20 counts per spectral bin, before background subtraction. In spectral fitting, we excluded any events with energies above 7.0 keV or below 0.5 keV.

Table 4 summarizes our spectral results in terms of the absorbing column density and photon index.

The sources have been modelled with an absorbed power-law slope with photon index between $\Gamma = 1.78$ and 5.56 and an equivalent column density of $N_H = (2.05-4.03) \times 10^{21}$ cm$^{-2}$. In all the cases, the single-component power-law model gives satisfactory fits. The column density of source N1 has been fixed due to the low count rate. The fitted $N_H$ values are consistent with the intrinsic absorption measured, for example, in the optical band the value of $A_V = 0.54$ corresponds to $N_H \sim 1.1 \times 10^{21}$ cm$^{-2}$, assuming $A_V = N_H \times 5.3 \times 10^{-22}$ for $R_V = 3.1$ (Bohlin, Savage & Drake 1978). This value should be a lower limit to the fitted $N_H$ value to be consistent, as is seen in Table 4.

As an example of our spectral fits, the brightest source, N3, has been fitted with a power law with spectral index of 2.08 and an absorption of $N_H = 2.5 \pm 0.4 \times 10^{21}$ cm$^{-2}$ (see Fig. 3).

In Table 5, we list the 0.5–7 keV flux and (absorption-corrected) luminosities of the individual sources based on the best-fitting power-law model.

The lower limit of the luminosity of point sources in the image, if at the distance of NGC 1275, is $L_X(0.5-7.0 \text{ keV}) = 3.2 \times 10^{34}$ erg cm$^{-2}$ s$^{-1}$.

Figure 3. ACIS-S spectrum of source N3. The solid line corresponds with a power-law model with a spectral index of $\Gamma = 2.08$ and an absorption of $N_H = 2.5 \times 10^{21}$ cm$^{-2}$. The fit residuals are presented in the lower panel.

Table 5. Fluxes (observed and $k$-corrected) and luminosities assuming a cosmological model with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $z = 0.018$.

| N   | $F_{\text{obs}}$ (0.5–7.0 keV) erg cm$^{-2}$ s$^{-1}$ | $F_{\text{corr}}$ (0.5–7.0 keV) erg cm$^{-2}$ s$^{-1}$ | $\log L_X$ (0.5–7.0 keV) |
|-----|---------------------------------------------------|---------------------------------------------------|--------------------------|
| 1...| $2.09 \times 10^{-15}$                           | $4.34 \times 10^{-15}$                           | 39.51                    |
| 2...| $7.59 \times 10^{-15}$                           | $9.97 \times 10^{-15}$                           | 39.86                    |
| 3...| $1.64 \times 10^{-14}$                           | $2.28 \times 10^{-14}$                           | 40.22                    |
| 4...| $7.76 \times 10^{-15}$                           | $1.10 \times 10^{-14}$                           | 39.91                    |
| 5...| $5.36 \times 10^{-15}$                           | $1.07 \times 10^{-14}$                           | 39.90                    |
| 6...| $3.02 \times 10^{-15}$                           | $9.23 \times 10^{-15}$                           | 39.84                    |
| 7...| $4.28 \times 10^{-15}$                           | $1.18 \times 10^{-14}$                           | 39.95                    |
| 8...| $7.67 \times 10^{-15}$                           | $1.16 \times 10^{-14}$                           | 39.93                    |
10^{39} \text{ erg s}^{-1}, which is already well above the Eddington limit for a neutron star binary ($L_X \sim 3 \times 10^{38} \text{ erg s}^{-1}$) and is also above the limit of canonical ULXs, that is, $>10^{39} \text{ erg s}^{-1}$.

The brightest point source has a luminosity of $L_X(0.5–7.0 \text{ keV}) = 1.67 \times 10^{40} \text{ erg s}^{-1}$, and is one of the brightest individual sources found in a galaxy. A ULX more luminous than the entire X-ray luminosity of a normal galaxy has been found in the Cartwheel system with a luminosity of at least $L_X \sim (2–4) \times 10^{40} \text{ erg s}^{-1}$ (Gao et al. 2003; Wolter & Trinchieri 2004). They explain this luminosity with a high-mass X-ray binary source (HMXB). The high X-ray luminosity suggests either a single extremely bright source, or a very dense collection of several high-$L_X$ sources, which would be even more peculiar. Evidence of time variability might suggest that this is a single high-$L_X$ source.

Time-variability analysis has been performed. The observations span about 2 yr. Two data files were observed on 2002 August 8 and 10, and the other 11 data files were observed from 2004 October 4 to 2004 October 20, giving an almost daily coverage. The exposure times are between 22 and 143 ks. The data characteristics allow us to determine short variation in 16 d (second period) and long-term variability of 2 yr. Because of the low count rates of the sources in NGC 1275 (see Table 2), it is very hard to search for short-term variability. We extracted light curves, using DME XTRACT CIAO task for the two brightest sources (N3 and N4) (net count rate greater than 0.98 count s$^{-1}$) binned with bin sizes of 500, 1000, 2500 and 5000 s. In both the cases, the points were consistent with the respective mean values and variability has not been found. Furthermore, the mean values between 2002 and 2004 are the same, including errors bars. Therefore, evidence of time variability has not been found during the whole set of observations.

4 DISCUSSION

Chandra has revealed significant populations of ULXs in the interacting systems of the Antennae (NGC 4038/9; Zezas et al. 2002) and the Cartwheel ring galaxy (Gao et al. 2003; Wolter & Trinchieri 2004), where dramatic events have stimulated massive star formation. We have reported here on another example (Fig. 4, left-hand panel) in the HVS of NGC 1275 which is interacting with the ICM of the Perseus cluster.

The sources are spatially associated with the distribution of absorbing clouds seen in soft X-ray (Fig. 2) and optical (Fig. 3) images. Two sources (N7 and N8) are directly linked with dust knots and another two (N2 and N6) have an optical point-like counterpart (Fig. 4, bottom panel). Similar correspondence has been found in the Cartwheel galaxy with the outer ring (Wolter & Trinchieri 2004) and in the Antennae galaxies with 39 X-ray sources within the WFPC2 field (Zezas et al. 2002). The optical brightness of the counterparts in the HVS is too high to be individual stars and so may be associated with young star clusters. Following the discussion of young star clusters in NGC 1275 given by Richer et al. (1993), an object of magnitude 22 corresponds to a cluster mass of about $10^6 M_\odot$ if its age is about $10^7$ yr. The HVS system travels at least 30 kpc in $10^7$ yr so if a strong interaction with the core of the Perseus galaxy cluster has triggered star cluster formation in the HVS, then the clusters should have ages less than $10^8$ yr.

Our interpretation of the spatial correspondence with star clusters is that the regions are especially active, indicating a real link between ULXs and star-forming regions, and meaning they are young objects. However, the optical limits on sources N3 and N4 rule out any association with massive clusters in those cases (the limit on the absolute magnitude is about $-8$).

In M31 and the Milky Way (Grimm, Gilfanov & Sunyaev 2003), XRBs have luminosities consistent with the Eddington limit of a $\sim 2 M_\odot$ accreting object. They produce luminosities $\sim 3 \times 10^{39} \text{ erg s}^{-1}$, about one order of magnitude below the limiting luminosity in our sample ($3.2 \times 10^{39} \text{ erg s}^{-1}$). It is possible that our ULXs consist of at least 15 (or 130, in the case of the brightest source found) ‘normal’ XRBs clustered together, perhaps in a young star cluster. However, in other objects, we know that variability requires the presence of intrinsically luminous X-ray sources (e.g. M82; Griffiths et al. 2000; Kaaret et al. 2001). Alternative possibilities are that black hole sources, with masses in the range of galactic black hole binaries, are mildly beamed (Reynolds et al. 1999; King et al. 2001). Spectral and timing features, however, rule out this possibility in some ULXs (e.g. Strohmayer & Mushotzky 2003).

Finally, we recall the IMBH model which has spectral support from some sources (Miller et al. 2004; the level of absorption in NGC 1275 is too high for any soft excess to be observed). They may form in dense star clusters.

Our optical studies have clearly shown that the ULXs have very high X-ray to optical flux ratios. X-ray selected AGNs from the ROSAT all-sky survey tend to have $\log(F_X/F_{opt}) \sim 1$. Thus, the ULXs do not have the expected optical properties if there were simple extensions of AGNs (IMBH, as low-luminosity limit). However, low-mass X-ray binaries in the Milky Way have $F_X/F_{opt} \sim 100–1000$ (Mushotzky 2004).

The results found in our system indicate that we have a mixed group of objects (see Table 3). At least four out of eight sources (N3, N4, N5 and N8) have high X-ray to optical flux ratios. At least three out of eight (N1, N2 and N6) have lower X-ray to optical ratios, possibly because they lie in star clusters.

Our data are consistent with no significant variability, similar to the result obtained on NGC 3256 by Lira et al. (2002). Time variability is frequently observed in ULXs (e.g. IC 342, Sugihiro et al. 2001 or M51 X-1, Liu et al. 2002), arguing that most of them are single compact objects, rather than a sum of numerous lower-luminosity objects in the same object. While most ULXs vary, many show low-amplitude variability on long time-scales (e.g. the Antennae galaxies, Zezas et al. 2002), which is very different from galactic black holes. Portegies Zwart, Dewi & Maccarone (2004) find that a persistent bright ULX requires a donor star exceeding $15 M_\odot$. The search for characteristic frequencies is one of the most productive way of determining the nature of the ULXs.

5 CONCLUSIONS

We have described the detailed analysis of the spatial and spectral properties of the discrete X-ray sources detected with a deep Chandra ACIS-S observation around NGC 1275. Our results are summarized below.

(i) We have detected a total of eight sources to the north of NGC 1275 nucleus.

(ii) The sources are spatially coincident with the HVS and thus probably associated with it. They are therefore ULXs.

(iii) Four of the sources have an optical counterpart in the $i$ and $R$ bands (from the HST images); two of which are point-like sources and the other two are associated with star-forming regions.

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Figure 4. Top left-hand panel: broad-band (0.5–7.0 keV) X-ray smoothed image with sources labelled. Top right-hand panel: HST/WFPC2 F814W broad-band image. Centre left-hand panel: broad-band (0.5–7.0 keV) X-ray smoothed image centred in source 3. Centre right-hand panel: HST/WFPC2 F814W broad-band image centred in source 3. Bottom left-hand panel: broad-band (0.5–7.0 keV) X-ray smoothed image centred in source 5. Bottom left-hand panel: HST/WFPC2 F814W broad-band image centred in source 5.

(iv) In all the cases a single-component power law gives satisfactory fits, with spectral index of $\Gamma = (1.78–3.51)$ and an equivalent column density of $N_H = (2.05–4.03) \times 10^{21} \text{ cm}^{-2}$.

(v) The minimum luminosity is $L_X(0.5–7.0 \text{ keV}) = 3.2 \times 10^{39} \text{ erg s}^{-1}$ (source N1), which is already above the limit of canonical ULXs.

(vi) No variability was detected in the two brightest sources found.

Our results add to the growing evidence that some episodes of rapid star formation lead to the production of ULXs. Young, massive, star clusters may be involved in some, but not all of the sources.
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