Optical Counterparts of Ultra Luminous X-Ray Sources

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ABSTRACT

We present optical identification and characterization of counterparts of four objects previously catalogued as ultra-luminous X-ray sources. The objects were selected from the Colbert & Ptak (2002) catalogue. The optical counterparts are identified as point-like objects with magnitudes in the range $\sim 17–19$. The optical spectra of three of the sources (IXO 32, 37 and 40) show the presence of emission lines typical of quasars. The position of these lines allows a precise estimation of their redshifts (2.769, 0.567 and 0.789 for IXO 32, 37 and 40 respectively). The fourth X-ray source, IXO 35, is associated with a red object that has a spectrum typical of an M star in our Galaxy. These identifications are useful for building clean samples of ULX sources, selecting suitable targets for future observations and performing statistical studies on the different populations of X-ray sources.

Subject headings: galaxies: active - quasars: general - X-rays: galaxies

1. Introduction

One of the most intriguing astrophysical objects are the ultra-luminous X-ray sources (ULXs) that have been discovered around nearby galaxies by the X-ray satellites Einstein, ROSAT, Chandra and XMM. Assuming that they are at the same distance as their parent galaxies, their luminosities in the 0.1–2.4 keV band are in the range $10^{39}–10^{41}$ erg s$^{-1}$. Several explanations concerning the nature of these objects in terms of intermediate-mass black holes associated with globular clusters, HII regions, supernova remnants, etc. (Pakull & Mirioni 2002; Angelini et al. 2001; Gao et al. 2003; Roberts et al. 2003; Wang 2002), local QSOs (Burbidge et al. 2003), hypothetical supermassive stars or beamed emission (King et al. 2001; Körding et al. 2002) have been proposed. Studies with XMM-Newton (Jenkins et al. 2004) point to a heterogeneous class of objects whose spectral properties are similar to those of objects with lower X-ray luminosities. Detailed studies with Chandra and XMM and the identification of counterparts in other spectral ranges (optical/infrared/radio) are essential for making progress in the field. The number of such optical identifications is still limited.
Saveral major compilations of ULX sources exist, those by Colbert & Ptak (2002) (CP02 hereafter), Swartz et al. (2004), Liu & Mirabel (2005) and Liu & Bregman (2005) (LB05 hereafter). The statistical analysis of the objects in the CP02 catalogue made by Irwin et al. (2004) indicates considerable contamination by background sources. A direct confirmation of these and a better understanding on the nature of ULX sources can be achieved by identifying counterparts in other bands (in particular in the optical, as is widely recognized: see for instance the review by van der Marel 2004). This motivated us to start this study searching for such possible optical counterparts in the major existing optical surveys. For example, we have identified possible optical counterparts in the DSS plates for about ~50% of the objects compiled by CP02. The typical magnitudes of such objects are 17–20 in the $b$ band and are therefore bright enough targets for spectroscopic observations with 2 to 4 m telescopes. In previous work (Arp et al. 2004: Gutiérrez & López-Corredoira 2005) we have demonstrated the feasibility of such studies and present our first results with the identification and characterization of nine such ROSAT ULX sources. In eight cases the sources look point-like and turned out to be quasars at high redshift. The remaining object was in a spiral arm of NGC 1073 and is apparently embedded in an HII region. Here, we present further results with an analysis of the counterparts of four additional ULX sources.

2. Sample selection and observations

2.1. Imaging

In this paper we consider the cases of IXO 32, 35, 37 and 40 (we follow the notation by CP02). Table 1 summarizes the main properties of such sources (taken from the compilation by CP02). We look for possible optical counterparts of these X-ray sources in the Digital Sky Survey (DSS) plates, the USNO catalogue, and the released Sloan Digital Sky Survey (SDSS) data. For the four cases we checked that there are point-like objects compatible with the X-ray positions. The last column in Table 1 lists the offset between the optical and X-ray coordinates. The fields around IXO 32, 35 and 37 were also observed with the IAC80
telescope\textsuperscript{1} in May 2004 and December 2005. For these objects we took single exposures of 1800 s in $BR$ for Ixo 32, 600 s in $BVRI$ for Ixo35, and 600 s in $R$ for Ixo 37. The observations were reduced using IRAF\textsuperscript{2} following a standard procedure. The nights were photometric and we use Landolt stars (Landolt 1992) to perform an absolute calibration with an uncertainty of $(2\sigma) \leq 0.05$ mag in each filter. Figure 1 shows the images with the identification of the optical counterpart. The images ($2' \times 2'$) are centred on the nominal X-ray positions. In one case (Ixo 32) there is another source slightly shifted (12 arcsec) from the X-ray coordinates.

2.2. Spectroscopy

The spectroscopic observations presented here were taken in February 2004 with the WHT\textsuperscript{3}. We used the blue and the red arms of the ISIS spectrograph with the R300B and R158R grisms. The slit width was 2 arcsec. We took a Cu–Ar and Cu–Ne lamp with a slitwidth of 1 arcsec at the beginning of the night for wavelength calibration. The stability of the wavelength calibration during the night and pointing was checked using the main sky lines. The sampling was 1.71 Å and 3.26 Å in the blue and red arms respectively. For each target, a single image was taken with exposure times of 1800 s for the counterparts of Ixo 32, 37 and 40, and 900 s for the counterpart of Ixo 35. The spectra were analysed following a standard procedure using IRAF of bias subtraction, extraction of the spectra and wavelength calibration. We used the standard spectroscopic star Feige 34 (Oke 1990) to correct for the response of the configuration to different wavelengths. The star was observed only three times during two nights and the slit for the targets was not positioned at parallactic angles, so this correction is only indicative. Given the prohibitive time needed to secure flat field images (specially in the blue part of the spectra), we did not correct for that effect. However, we have checked that this correction would be very small ($\leq 1\%$). None of these uncertainties is relevant for the analysis and results presented in this paper.

\textsuperscript{1}The IAC 80 is located at the Spanish Teide Observatory on the island of Tenerife and is operated by the Instituto de Astrofísica de Canarias

\textsuperscript{2}IRAF is the Image Reduction and Analysis Facility, written and supported by the IRAF programming group at the national Optical Astronomy Observatories (NOAO) in Tucson, Arizona.

\textsuperscript{3}The William Herschel Telescope (WHT) is operated by the Isaac Newton Group and the IAC in Spain’s Roque de los Muchachos Observatory
3. Analysis

The spectra of the four objects are presented in Figure 2. The four spectra show features that allow clear identification and characterization. Table 2 lists the main properties of these spectra. The analysis of each object is presented below.

3.1. IXO 32

This source is also listed in the LB05 catalogue as X06 (around the galaxy NGC 2775). The optical images show two point-like objects with a separation $\sim 7$ arcsec and distant $\sim 5$ and $\sim 12$ arcsec respectively from the nominal X-ray position. Only the brightest (the object at $\sim 12$ arcsec) is listed in the USNO catalogue. We put the slit crossing both objects. The spectrum of the bright object has typical absorption lines of a star being the most prominent absorption features, the H & K CaII, and the Balmer lines. The fainter is very blue and turn out to be an active galactic nuclei/quasar. Figure 2 shows the spectrum of this object in which the broad emission Ly-β+OVI, Ly-α, SiIV+OIV (1400 Å), CII (1549 Å) and CIII (1909 Å) lines are obvious. From the position of the line CII (1549 Å) we estimate a redshift $z = 2.769$. After the spectroscopic observations we discovered that the field has been observed with SDSS and that the object situated at 3.2 arcsecs from the nominal CP02 X-ray position has been catalogued as a star with with magnitudes $r = 18.62$ mag and $g = 18.86$ mag.

3.2. IXO 35

This object is also listed in the LB05 catalogue and denoted as NGC 3226 X03. The USNO catalogue lists an object with magnitudes $b = 18.8$ mag and $r = 17.2$ mag at 2.8 and 2.1 arcsec from the CP02 and LB05 X-ray positions respectively. The observations taken with the IAC80 telescope show a point-like object with magnitudes 18.87, 17.97, 16.65 and 14.79 in the B, V, R and I bands respectively. The nearest neighbour listed in the USNO catalogue and detected with the IAC80 at $R = 19.3$ mag is $\sim 27$ arcsec SE. The source is also listed in 2MASS with magnitudes 13.24, 12.70 and 12.39 in the $J$, $H$ and $K$ bands respectively. According to the maps by Schlegel et al. (1998), possible corrections for galactic extinction are below 0.1 mag in the blue band.

The optical spectrum of this object is dominated by strong absorption bands (VO, Na and TiO) typical of a cold star. We detect also the Ca H and K and Balmer emission lines ($H\alpha$, $H\beta$, $H\gamma$, $H\delta$ and $H\epsilon$), although some of them are in the middle of absorption bands,
making the estimation of equivalent widths uncertain. Following the calibration by Hawley et al. (2002), based on several photometric and spectroscopic indices, we classify the object as an M3–6 star. From this and with the magnitude in the J band it is possible to estimate the distance and then the X-ray luminosity. The resulting distance is in the range 41 pc (for an M6 type) to 157 pc (for an M3 type), which corresponds to X-ray luminosities of $8.6 \times 10^{27}$ and $1.3 \times 10^{29}$ erg s$^{-1}$ respectively. These luminosities are within the range found by Schmitt & Liefke (2004) for a volume-limited sample of nearby M stars.

### 3.3. IXO 37

The object is also listed in the LB05 catalogue with the name X02 around the galaxy IC 2597. A possible counterpart at a distance of $\sim$4 arcsec from the X-ray source appears in the optical images having a magnitude of 19.44 in R in the observations at the IAC80 telescope. The spectrum is shown in Fig. 2. We identify the forbidden narrow emission line OII($\lambda\lambda$ 3727 Å) and OIII($\lambda\lambda$ 4959, 5007 Å) as the most important features. The redshift is $z = 0.567$. At this redshift the H$\beta$ lies at $\sim$7617 Å, which we identify as a bump in the middle of a telluric line. We also identify H$\alpha$ at 10294 Å in a spectral region (not shown in the figure) of low sensitivity of the detector and severely contaminated by sky emission lines. Other emission lines in the red arm are from NeIII ($\lambda$3869). Correcting the spectrum for redshift, we detect in the blue arm the MgII($\lambda$2799 Å) emission line. The impossibility to measure the flux of the H$\beta$ and H$\alpha$ lines precludes the application of the common diagnostic diagrams. However, based on the X-ray emission, we classify this object as a Seyfert I, AGN.

### 3.4. IXO 40

DSS plates show only a possible optical counterpart of this ULX at $\sim$2 arcsec from the nominal X-ray position and with magnitudes 17.9 and 19.1 in r and b respectively. The optical spectrum shows emission lines typical of AGN/QSOs. The main features are broad emissions of CIII(1909 Å) and MgII (2799 Å) in the blue arm. OII($\lambda\lambda$ 3727 Å), NeIII($\lambda$3869 Å) and possibly OIII($\lambda\lambda$ 4959, 5007Å) are detected in the red. The resulting redshift is $z = 0.789$. 

4. Discussion and conclusions

The poor spatial resolution of ROSAT images is irrelevant for the optical identifications presented here. In fact, as discussed in Gutiérrez & López-Corredoira (2005), the low density of bright quasars (∼2-3 per square degree brighter than 19 mag) makes unlikely a chance projection between the X-ray sources and the quasars identified as the optical counterparts of IXO 32, 37 and 40. A similar argument can be applied in the case of IXO 35: from the local density of M stars (Martini & Osmer 1998), we have estimated that the probability to have randomly a source at ∼ 3 arcsecs from the X-ray nominal position is below ∼ 10^{-6}. These simple arguments confirm the reliability of our identifications. The sample analyzed in this paper suffer of several biases and then can not be considered as statistical representative of the whole sample of ULXs listed in the CP02 catalogue. In fact, the objects selected are restricted to those with a bright point-like optical counterpart (∼ 19 mag). So, for instance we have excluded a priori the possibility to detect X-ray binary stars within the parent galaxy. The objects were also selected to be in relatively isolated regions that allow an unambiguous identification. This is against the detection of objects within star forming complexes. The statistical implications of these and other identifications are in progress and will be addressed in a forthcoming paper (López-Corredoira & Gutiérrez A&A submitted). In any case the results presented here reinforce the importance of multiwavelength studies of these X-ray sources as one of the most promising ways to disentangle the nature of these objects and for the construction of clean samples of ULX sources for further studies.
Acknowledgements

The author is especially grateful to M. López-Corredoira, a close collaborator in this project, for useful suggestions and comments. We thank also J. A. Caballero for useful hints about the properties of the M star identified as possible counterpart of IXO 35. The author was supported by the *Ramón y Cajal* Programme of the Spanish science ministry.
REFERENCES

Liu, J. F. & Bregman, J. N. 2005


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Table 1. Optical and X-ray properties of ULXs

<table>
<thead>
<tr>
<th>ID</th>
<th>RA (J2000) (hh:mm:ss.s)</th>
<th>Dec (J2000) (°,′,″)</th>
<th>log ($L_X$) (erg s$^{-1}$)</th>
<th>ID Gal.</th>
<th>Type</th>
<th>$D$ (Mpc)</th>
<th>$d$ (arcmin)</th>
<th>$d/R_{25}$</th>
<th>$\Delta$ (arcsec)</th>
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<td>1.6</td>
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<td>IC 2597</td>
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<td>1.8</td>
<td>1.4</td>
<td>4</td>
</tr>
<tr>
<td>IXO 40</td>
<td>11 50 57.9</td>
<td>−28 44 02</td>
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<td>4.4</td>
<td>1.2</td>
<td>2</td>
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</table>

*1. Identification of the ULXs; 2-3. RA (J2000) and Dec (2000) positions; 4. Log of luminosity in the band 0.1-2.4 KeV assuming that the X-ray sources are at the distance of the parent galaxy; 5-7. Identification, morphological type and distance of the parent galaxy; 8-9. Angular distance (in arcmin and in units of $R_{25}$ of the central galaxy) between these galaxies and the X-ray source; 10. Difference in arcsecs between X-ray and optical nominal coordinates. Columns 1-9 have been taken from Colbert & Ptak (2002).
Table 2. Properties of optical counterparts

<table>
<thead>
<tr>
<th>ID</th>
<th>Magnitudes</th>
<th>Main Features</th>
<th>Counterpart</th>
<th>Redshift</th>
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<td>IXO 32</td>
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<td>M star</td>
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<td>19.44</td>
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<td>AGN</td>
<td>0.567</td>
</tr>
<tr>
<td>IXO 40</td>
<td>17.9</td>
<td>CIII, MgII, OII, NeIII,OIII</td>
<td>QSO</td>
<td>0.789</td>
</tr>
</tbody>
</table>

*1. Identification of the ULXs following the Colbert & Ptak (2002) notation; 2. Magnitude of optical counterparts in the $R$ band (except for IXO 40 which are photographic magnitude in the red plates of DSS); 3. Main spectral features; 4. Type: 5. Redshift (or distance for the case of IXO 35).
Fig. 1.— Optical images of 2 square arcminutes centred on X-ray positions of the sources analysed in this paper. For object IXO 40 the image corresponds to the red filter of the DSS plates; the other images were obtained with the IAC80 telescope in the \( R \) (IXO 32 and 37), and \( I \) (IXO 35) filters respectively. The small lines identify the optical counterpart of the X-ray sources. Names according to the notation by Colbert & Ptak (2002) are indicated. North is up and east to the left.
Fig. 2.— Optical spectra of the counterpart of ULX sources analysed in this paper. The $y$-axis is the flux in arbitrary units. The absorption features centered at $\sim 6875$ and $\sim 7610$ Å are telluric bands due to molecular oxygen.