The Nature of Ultra Luminous X-ray Sources

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ABSTRACT

We present spectroscopic observations of six optical counterparts of intermediate luminosity X-ray sources (ULXs) around nearby galaxies. The spectra of the six objects show the presence of broad emission features. The identification of these allow us to classify all of the objects as quasars at higher redshift than their assigned parent galaxy. This is one of the first and largest identifications of such objects using unambiguous optical spectral features. These results, in conjunction with previous similar identifications of other sources, indicate that high redshift quasars represent an important fraction of catalogued ULX sources. We estimate the density of such sources and compare this with expectations for a population of randomly distributed background quasars.

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

1. Introduction

One of the most intriguing astrophysical objects are the ultraluminous X-ray sources (ULXs) discovered around nearby galaxies by the X-ray satellites Einstein, ROSAT, Chandra and XMM–Newton. Assuming that they are at the same distance as the galaxies that are apparently close to them on the sky, their luminosities in the 0.1–2.4 keV X-ray band are in the range $10^{39}$–$10^{40}$ erg s$^{-1}$, so that they are too luminous to be X-ray cataclysmic binary stars (Pakull & Mirioni 2002) and too faint to be compared with the typical luminosities of active galactic nuclei. Although much remains to be clarified, several explanations concerning the nature of these objects in terms of globular clusters, HII regions, etc. (Pakull & Mirioni 2002; Angelini, Loewenstein & Mushotzky 2001; Gao et al. 2003; Roberts, Goad, & Warwick 2003; Wang 2002), or of hypothetical supermassive stars or beamed emission (King et al. 2001; Kording, Falcke, & Markoff 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.
A catalogue of ULXs around bright nearby galaxies has been compiled (Colbert & Ptak 2002, CP02 hereafter) by cross-correlating public archive ROSAT HRI images with a selection of nearby \((cz \leq 5000 \text{ km s}^{-1})\) galaxies taken from the RC3 catalogue (de Vaucouleurs et al. 1991). The catalogue of ULXs (or IXOs, Intermediate X-ray Objects, in the notation of CP02) comprises 87 objects around 54 bright nearby galaxies. According to the analysis of the CP02 catalogue made by Irwin, Bregman & Athey (2004) ULXs with luminosities below \(\sim 2 \times 10^{39} \text{ erg s}^{-1}\) can be explained naturally by accretion on to black holes with masses \(\sim 10^{-20} M_\odot\). The analysis of objects with higher X-ray luminosities has revealed that only for parent galaxies of late types is the distribution of objects concentrated towards the galactic centre. Also, according to the analysis of these authors, the number of ULXs is smaller in early type parent galaxies and compatible with the expected number of foreground/background sources, while the number of ULXs around late-type galaxies is larger and requires the existence of a new class of objects within the parent galaxy. The contamination of background objects obviously increases with distance to the parent galaxy; in fact Ptak & Colbert (2004) have claimed that most of the ULXs listed in the CP02 catalogue at distances from the assumed parent galaxy \(\geq 0.5D_{25}\) are probably background objects.

These considerations on the nature of ULXs are based on indirect statistical evidence. The confirmation of this evidence with the identification of counterparts in other bands is essential. The number of such optical identifications is still small (e.g. Roberts et al. 2001; Wu et al. 2002; Maseti et al. 2003; Liu, Bregman & Seitzer 2004) and is usually restricted to single galaxies, making statistical studies very difficult. The study presented here includes sources in several galaxies and allows one of the first identifications based on unambiguous spectral features in the optical. We have looked for these counterparts of the ULX sources listed in the CP02 catalogue in the Digital Sky Survey (DSS) images and in the digitalized USNO catalogues. The typical magnitudes of such objects are 18–20 mag in the \(b\) band and are therefore bright enough targets for spectroscopic observations with 2 to 4 m telescopes. Previously we have presented (Arp, Gutiérrez & López-Corredoira 2004) an analysis of the first three objects observed; two of them (IXO 1 and 2), close to the galaxy NGC 720, resulted in quasars at much higher redshift (0.959 and 2.216 respectively) than the parent galaxy. Given the paucity of quasars in the sky, a misidentification is unlikely. The third one (IXO 5) was associated with an HII region at the redshift of the parent galaxy (NGC 1073). This last object was at the edge of a spiral arm of the parent galaxy, where there are many HII regions. If the identification is correct, these would confirm previous findings (Gao et al. 2003) claiming that many of the X-ray sources around the Cartwheel galaxy are associated with HII regions. In this paper, we present the results of new observations of six other cases, all of which also turn out to be quasars at higher redshift than their parent galaxies.
2. Observations and data analysis

We took spectroscopy in January 2004 for the optical counterparts of sources (following the notation of the CP02 catalogue) IXO 33, 45, 58, 69, 71 and 84. The observations were conducted at the William Herschel Telescope (WHT). We used the red arm of the ISIS spectrograph with the R158R grism. The slit width was between 1.20 and 1.45 arcsec. We used Cu–Ar and Cu–Ne lamps for wavelength calibration. This provides a sampling of 1.62 Å pixel$^{-1}$ and an effective resolution of 8–10 Å (depending on the slit width used and atmospheric seeing). A single image with an exposure time of 1800 s was taken for each object. The spectra were analysed following a standard procedure using IRAF that comprises bias subtraction, extraction of the spectra and wavelength calibration. We used the standard spectroscopic stars Feige 67 (Oke 1990), and BD+26 2606 (Oke & Gunn 1983) to correct approximately for the response of the configuration to different wavelengths. Given the prohibitive time needed to obtain flat-field images (especially in the blue part of the spectrum), we did not correct for that effect. However, we have checked that this correction would have been very small ($\leq 1\%$) and would not have affected any of the identifications of the main spectral features reported here.

Figure 1 shows the DSS images with the identification of the optical counterpart. Figure 2 presents the spectra taken for these objects. Spectra of four of the objects (IXO 45, 58, 69 and 71) are rather flat while the other two (IXO 33 and 84) rise slightly towards red wavelengths. The main lines in the spectra of objects IXO 33 and 71 are wide Balmer lines ($H_α$ and $H_β$) and narrow forbidden OII ($λλ$3727 Å) and OIII ($λλ$4959, 5007 Å) lines, while the spectra of the other four (objects IXO 45, 58, 69 and 84) are dominated by the wide emission line of Mg II (2798 Å). All these features are characteristic of quasar spectra. The position of the main emission lines allows unambiguous determination of the redshifts of the objects. The uncertainties in the determination of redshift are $\sim 0.001$ for objects in which we detect the MgII lines and $\sim 0.0002$ for the rest. Table 1 presents a summary of the main properties of the objects and the estimated redshifts.

Other objects in the slit

In three of the cases (IXO 33, 58 and 84) there is more than one object in the DSS very close to the main object and whose position is marginally compatible with that of the X-ray

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1The William Herschel Telescope is operated by the Isaac Newton Group and the IAC in Spain’s Roque de los Muchachos Observatory. The observations were done in service time.

2IRAF 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.
source. In all these cases we positioned the slit crossing these objects also. These are:

- Second object near IXO 33: This object, not listed in the USNO catalogue, is nevertheless visible in the DSS plates. It is at a distance $\sim 18$ arcsec from the main object. The spectra has absorption features typical of a local cold star.

- Second object near IXO 58: According to the USNO catalogue, this object has 18.8 and 18.5 mag in $b$ and $r$ bands respectively and is at a distance of $\sim 14$ arcsec from the main object. We have identified weak Balmer H$\delta$, H$\gamma$, H$\beta$ and H$\alpha$ lines at $z=0.317$ in its continuum, which has no strong features. We tentatively identify the spectra as a BL Lac type object.

- Objects near IXO 84: An object at $\sim 18$ arcsec from the main one has a very weak continuum in which we detect a narrow emission line at 6843 Å, which we were unable to identify. By chance, the slit also crosses another object at a distance of $\sim 64$ arcsec from the main object. It has a spectrum typical of an HII region resulting a redshift of $z = 0.0525$. The object is extended and, given its redshift and its location near an arm of the galaxy NGC 5774, it seems to be an HII region of this galaxy.

3. Discussion and conclusions

In the following analysis we also include the three objects IXO 1, 2 and 5 that were observed with the same set-up and presented in Arp et al. (2004). The ULXs analysed here have X-ray luminosities in the range $\sim 1-6 \times 10^{39}$ erg s$^{-1}$ (assuming that the X-ray sources are at the distance of the putative parent galaxy) and are at projected distances in the range $\sim 0.7-1.9 \times D_{25}$ from the centre of such galaxies, six of them in elliptical galaxies and three in spirals. All except for one (IXO 5) turn out to be quasars at higher redshift than the assumed parent galaxy. These results extend the findings of Foschini et al. (2002) and Maseti et al. (2003), who also found optical counterparts of ULXs at a higher redshift than that of the assigned host galaxy, and that other objects obeying the observational criteria used to define ULXs were not included in the CP02 compilation because they were previously known high redshift quasars (see the discussion on this in Arp et al. 2004). Because our targets were selected among those visible in the DSS, it should be reasonable to deduce that an important fraction (the majority in the case of early-type parent galaxies) of the ULX sources with optical counterparts in the range $\sim 18-20$ mag must also be quasars. The only object that has a redshift similar to that of the assigned parent galaxy is IXO 5, which is in a star forming region of the spiral galaxy NGC 1073.
It is interesting to compare these results with the statistics of quasars in the field. This analysis is difficult because of the characteristics in terms of completeness, coverage, etc., of the CP02 catalogue and the small size of our sample. A simplistic and rough calculation can be made by considering the optical magnitudes of the quasars detected, and the area surveyed by CP02. The total area enclosed in a circle centred on the parent galaxy and enclosing the ULXs found in our sample is \( \sim 500 \) square arcmin. According to the study by Ptak & Colbert (2004) only \( \sim 10\% \) of the RC3 galaxies observed with HRI have at least one ULX, so that the total area surveyed in which the quasars have been found is \( \sim 1.5 \) square degrees. From the 2dF Quasar Survey (Croom et al. 2004) and the fit presented by López-Corredoira & Gutiérrez (2004) to the Boyle et al. (2000) data, there are about 0.2, 3, and 17 quasars per square degree brighter than 18, 19 and 20 mag, respectively, in the \( b \) band. So, in principle, the inferred distribution of quasars from our measurements is roughly in agreement with expectations for a purely random distribution of background quasars. This would confirm the statistical analysis by Irwin et al. (2004) and Ptak & Colbert (2004), who claimed that the distribution of ULXs around early-type galaxies is compatible with expectations from the background population of objects. However, an accurate assessment of this would require a direct comparison with the density of X-ray selected background quasars. In any case, searching for optical counterparts of ULXs and taking their spectra seems to be one of the most promising and unambiguous methods of unravelling the true nature of such objects.

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REFERENCES


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Fig. 1.— Images of the Digital Sky Survey in the blue filter of 1 square arcminute centred on optical counterparts of the ultraluminous X-ray sources analyzed in this paper. Names according to the notation by Colbert & Ptak (2002) are indicated. North is up and East to the left. The small dark line indicate the position of such objects. The grey wide lines indicate the orientation of the slit.
Fig. 2.— Optical spectra (for clarity, corrected by redshift) of the sources marked on Figure 1. The y-axis is the flux in arbitrary units. The main spectral features and the redshifts estimated for each object are indicated. The gaps in the spectra correspond to the position of the telluric A band.
Table 1. Optical counterpart of ULX sources

<table>
<thead>
<tr>
<th>ID</th>
<th>RA (J2000)</th>
<th>Dec (J2000)</th>
<th>log ($L_X$)</th>
<th>ID Gal.</th>
<th>d</th>
<th>$d/R_{25}$</th>
<th>$z_g$</th>
<th>z</th>
<th>Object</th>
</tr>
</thead>
<tbody>
<tr>
<td>IXO 1</td>
<td>01:52:49.7</td>
<td>−13:42:11</td>
<td>39.1</td>
<td>NGC 720</td>
<td>3.0</td>
<td>1.3</td>
<td>0.0058</td>
<td>2.216</td>
<td>QSO</td>
</tr>
<tr>
<td>IXO 2</td>
<td>01:53:02.9</td>
<td>−13:46:53</td>
<td>39.7</td>
<td>NGC 720</td>
<td>2.6</td>
<td>1.1</td>
<td>0.0058</td>
<td>0.959</td>
<td>QSO</td>
</tr>
<tr>
<td>IXO 5</td>
<td>02:43:38.3</td>
<td>+01:24:13</td>
<td>39.1</td>
<td>NGC 1073</td>
<td>1.8</td>
<td>0.7</td>
<td>0.0040</td>
<td>0.0037</td>
<td>HII</td>
</tr>
<tr>
<td>IXO 33</td>
<td>09:10:27.0</td>
<td>+06:59:10</td>
<td>39.5</td>
<td>NGC 2775</td>
<td>3.6</td>
<td>1.7</td>
<td>0.0045</td>
<td>0.253</td>
<td>QSO</td>
</tr>
<tr>
<td>IXO 45</td>
<td>12:15:15.7</td>
<td>+33:10:20</td>
<td>39.0</td>
<td>NGC 4203</td>
<td>2.7</td>
<td>1.6</td>
<td>0.0036</td>
<td>0.967</td>
<td>QSO</td>
</tr>
<tr>
<td>IXO 58</td>
<td>12:29:27.9</td>
<td>+08:06:34</td>
<td>39.4</td>
<td>NGC 4472</td>
<td>8.1</td>
<td>1.6</td>
<td>0.0033</td>
<td>1.194</td>
<td>QSO</td>
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<tr>
<td>IXO 69</td>
<td>12:43:36.8</td>
<td>+11:30:06</td>
<td>39.4</td>
<td>NGC 4649</td>
<td>3.2</td>
<td>0.8</td>
<td>0.0037</td>
<td>1.195</td>
<td>QSO</td>
</tr>
<tr>
<td>IXO 71</td>
<td>12:44:09.2</td>
<td>+11:33:36</td>
<td>39.7</td>
<td>NGC 4649</td>
<td>7.1</td>
<td>1.9</td>
<td>0.0037</td>
<td>0.401</td>
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<tr>
<td>IXO 84</td>
<td>14:53:44.7</td>
<td>+03:33:30</td>
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<td>NGC 5775</td>
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<td>1.5</td>
<td>0.0056</td>
<td>1.365</td>
<td>QSO</td>
</tr>
</tbody>
</table>

*1. Identification of the ULXs following the Colbert & Ptak (2002) notation; 2-3. RA (J2000) and Dec (2000) position of the optical counterpart according to the DSS plates and USNO catalogues; 4. Luminosity in the band 0.1-2.4 KeV (in units of erg s$^{-1}$) assuming that the X-ray sources are at the distance of the parent galaxy; 5. Identification of the parent galaxy; 6-7. Angular distance (in arcmin and in units of $R_{25}$ of the central galaxy) between these galaxies and the X-ray source; 8 Redshift of the parent galaxy (taken from the literature); 9. Redshift of the X-ray source as computed in this work. 10. Type of the optical counterpart. The analyses of objects IXO 1, IXO 2 and IXO 5 was presented in Arp et al. (2004).