OPTICAL COUNTERPARTS OF ULTRALUMINOUS X-RAY SOURCES

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Received 2005 December 1; accepted 2006 February 2; published 2006 February 21

ABSTRACT

We present the optical identification and characterization of counterparts of four objects previously cataloged as ultraluminous X-ray (ULX) sources. The objects were selected from the E. Colbert & A. Ptak catalog. The optical counterparts are identified as pointlike objects with magnitudes in the range of $17-19$. 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

Online material: color figure

1. INTRODUCTION

Some of the most intriguing astrophysical objects are the ultraluminous x-ray (ULX) sources that have been discovered around nearby galaxies by the x-ray satellites Einstein, ROSAT, Chandra, and XMM-Newton. If we assume that they are at the same distance as their parent galaxies, their luminosities in the 0.1–2 keV band are in the range $10^{39}-10^{41}$ ergs s$^{-1}$. Several explanations concerning the nature of these objects in terms of intermediate-mass black holes associated with globular clusters, H ii regions, supernova remnants, etc. (Pakull & Mirioni 2002; Angelini et al. 2001; Gao et al. 2003; Roberts et al. 2003; Wang 2002), local QSOs (Burbridge 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 (e.g., Roberts et al. 2001; Wu et al. 2002; Liu et al. 2004). Some of these counterparts have revealed objects at higher redshift than the putative parent galaxies (Maseti et al. 2003; Clark et al. 2005) and are viewed in standard bg cosmology as contaminated background objects.

Several major compilations of ULX sources exist: those by Colbert & Ptak (2002, hereafter CP02), Swartz et al. (2004), Liu & Mirabel (2005), and Liu & Bregman (2005, hereafter LB05). The statistical analysis of the objects in the CP02 catalog made by Irwin et al. (2004) indicates considerable contamination by background sources. A direct confirmation of these and a better understanding of 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 Digitized Sky Survey (DSS) plates for $\sim$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 2–4 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 pointlike 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 H ii 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 Letter, 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 DSS plates, the US Naval Observatory (USNO) catalog, and the released Sloan Digital Sky Survey (SDSS) data. For the four cases, we checked that there are pointlike objects compatible with the X-ray positions. Column (10) 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$^2$ in 2004 May and 2005 December. For these objects, we took single exposures of $1800$ s in $BR$ for IXO 32, $600$ s in $BVRI$ for IXO 35, and $600$ s in $R$ for IXO 37. The observations were reduced using IRAF$^3$ 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 centered on the nominal X-ray positions. In one case (IXO 32), there is another source slightly shifted ($12'')$ from the X-ray coordinates.

$^2$ The IAC80 is located at the Spanish Teide Observatory on the island of Tenerife and is operated by the Instituto de Astrofísica de Canarias.

$^3$ IRAF is the Image Reduction and Analysis Facility, written and supported by the IRAF programming group at the National Optical Astronomy Observatory in Tucson, Arizona.
Fig. 1.—Optical images of 2′ × 2′ centered on X-ray positions of the sources analyzed in this Letter. 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 in CP02 are indicated. North is up, and east is to the left.

2.2. Spectroscopy

The spectroscopic observations presented here were taken in 2004 February with the WHT. We used the blue and the red arms of the Intermediate dispersion Spectrograph and Imaging System (ISIS) spectrograph with the R300B and R158R grisms. The slit width was 2″. We took a Cu-Ar and Cu-Ne lamp with a slit width of 1″ 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 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 analyzed using IRAF according to a standard procedure 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 (≤1%). None of these uncertainties are relevant for the analysis and results presented in this Letter.

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 catalog as X06 (around the galaxy NGC 2775). The optical images show two pointlike objects with a separation of ~7" and distance of ~5" and ~12", respectively, from the nominal X-ray position. Only the brightest (the object at ~12") is listed in the USNO catalog. 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 and K Ca ii, and the Balmer lines. The fainter is very blue and turns out to be an active galactic nucleus (AGN)/quasar. Figure 2 shows the spectrum of this object in which the broad emission Lyβ+O vi, Lyα, Si iv+O iv (1400 Å), C ii (1549 Å), and C iii (1909 Å) lines are obvious. From the position of the line C ii (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 32' from the nominal CP02 X-ray position has been cataloged as a star with magnitudes \( r = 18.62 \) mag and \( g = 18.86 \) mag.

3.2. IXO 35

This object is also listed in the LB05 catalog and denoted as NGC 3226 X03. The USNO catalog lists an object with magnitudes \( b = 18.8 \) mag and \( r = 17.2 \) mag at 27" and 21' from the CP02 and LB05 X-ray positions, respectively. The observations taken with the IAC80 telescope show a pointlike object with magnitudes 18.87, 17.97, 16.65, and 14.79 in the B, V, R, and I bands, respectively. The nearest neighbor listed in the USNO catalog and detected with the IAC80 at \( R = 19.3 \) mag is ~27" southeast. The source is also listed in the Two Micron All Sky Survey 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 (Hα, Hβ, Hγ, Hδ, and He), 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 from 41 pc (for an M6 type) to 157 pc (for an M3 type), which corresponds to X-ray luminosities of \( 8.6 \times 10^{37} \) and \( 1.3 \times 10^{39} \) ergs 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 catalog with the name X02 around the galaxy IC 2597. A possible counterpart at a distance of ~4" 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 Figure 2. We identify the forbidden narrow emission lines O ii (\( \lambda 3727 \)) and O iii (\( \lambda 4959, 5007 \)) as the most important features. The redshift is \( z = 0.567 \). At this redshift, the Hα line lies at ~7617 Å, which we identify as a bump in the middle of a telluric line. We also identify Hβ 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 Ne iii (\( \lambda 3869 \)). Correcting the spectrum for redshift, we detect in the blue arm the Mg ii (\( \lambda 2799 \)) emission line. The impossibility to measure the flux of the Hβ and He lines precludes the application of the common diagnostic diagrams. How-

| Identification | Magnitudes | Main Features | Counterpart | Redshift |
|----------------|------------|---------------|-------------|----------|
| IXO 32 …… | 18.47 | Lyβ+O vi, Lyα, C ii, Si iv+O iv, C iii | QSO | 2.769 |
| IXO 35 …… | 16.65 | Molecular bands | M star | 41–157 pc |
| IXO 37 …… | 19.44 | O ii, O iii, Mg ii | AGN | 0.567 |
| IXO 40 …… | 17.9 | C iii, Mg ii, O ii, Ne iii, O iii | QSO | 0.789 |

Notes.—Col. (1): Identification of the ULX sources following the CP02 notation. Col. (2): Magnitude of optical counterparts in the \( R \) band (except for IXO 40, which are photographic magnitude in the red plates of DSS). Col. (3): Main spectral features. Col. (4): Type. Col. (5): Redshift (or distance for the case of IXO 35).
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 deg⁻² 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 of having randomly a source at ∼3" from the X-ray nominal position is below ∼10⁻⁶. These simple arguments confirm the reliability of our identifications. The sample analyzed in this Letter suffers from several biases and then cannot be considered as a statistical representative of the whole sample of ULX sources listed in the CP02 catalog. In fact, the objects selected are restricted to those with a bright pointlike optical counterpart (∼19 mag). So, for instance, we have excluded a priori the possibility of detecting 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 2006). In any case, the results presented here reinforce the importance of multi-wavelength 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.

4. DISCUSSION AND CONCLUSIONS

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 a possible counterpart of IXO 35. The author was supported by the Ramón y Cajal program of the Spanish science ministry.

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