THE OPTICAL COUNTERPART OF NGC 1313 X-1

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ABSTRACT

We identify the optical counterpart of the ultraluminous X-ray source (ULX) NGC 1313 X-1 and discuss constraints on its physical nature from multiband optical spectra. There is a single object on Hubble Space Telescope images within the aspect-corrected Chandra X-ray error circle; a fainter, possibly extended, feature lies near the edge of the error circle. The brighter object showed prominent variation in the F555W band, but was constant in the F814W band. The spectrum was consistent with a single power law on 2003 November 17, but deviated from this on 2004 July 17, suggestive of more than one emission component. Based on the location, magnitudes, spectral shape, and variability of the bright object, it is likely the ULX counterpart. The red wing of the spectrum around F814W may be due to emission from the companion star, and the blue wing is likely from disk emission. The stellar population around X-1 has an age older than 30 Myr, without very blue stars or young clusters. This places a constraint on the companion mass of the ULX as no more than $10 M_\odot$.

Key words: accretion, accretion disks – black hole physics – X-rays: binaries – X-rays: individual (NGC 1313 X-1)

1. INTRODUCTION

Ultraluminous X-ray sources (ULXs) are variable, nonnuclear X-ray sources found in nearby galaxies with isotropic luminosities higher than $3 \times 10^{39}$ erg s$^{-1}$, the Eddington limit of a 20 $M_\odot$ black hole, roughly the most massive compact object that can be formed via core collapse of a single star with near solar metallicity (Belczynski et al. 2010). Growing evidence from observations of emission line nebulae around some ULXs indicates that their luminosity is truly high and the emission is not strongly beamed (Pakull & Mirioni 2003; Kaaret et al. 2004; Kaaret & Corbel 2009). This requires accretion onto intermediate mass black holes to explain the high luminosity if we assume sub-Eddington radiation. However, the Eddington limit could be violated under certain circumstances (Watarai et al. 2001; Begelman 2006) and mild beaming by a factor of a few is expected at high accretion rates (King et al. 2001). These two factors simultaneously could explain the majority of ULXs up to $10^{41}$ erg s$^{-1}$ as stellar mass black holes (Poutanen et al. 2007). The nature of ULXs is still uncertain.

NGC 1313 X-1 was among the first ULXs discovered with Einstein (Fabbiano & Trinchieri 1987). The source has shown significant spectral variability revealed by XMM-Newton observations. Using 12 XMM-Newton observations over a span of a few years, Feng & Kaaret (2006) reported a tight correlation between the X-ray luminosity and the power-law photon index of the source and a transition from the correlated phase to a soft state. This behavior is similar to that seen in some Galactic black hole X-ray binaries as well as ULXs like NGC 5204 X-1 and Holmberg II X-1 (Feng & Kaaret 2009), suggesting similar accretion physics, but contrary to some other ULXs like NGC 1313 X-2. Dewangan et al. (2010) demonstrated that NGC 1313 X-1 showed distinct temporal properties in different spectral states, manifesting a noisy high state and a quiet low state, interpreted as due to different accretion geometries. A distance of 4.1 Mpc for NGC 1313 is adopted in this paper (Méndez et al. 2002).

Optical observations of ULXs offer additional information regarding their nature, and could shed light onto the evolutionary history of the binary, disk geometry, and mode of the mass transfer (e.g., Madhusudhan et al. 2008; Feng & Kaaret 2008; Kaaret & Corbel 2009). Moreover, a conclusion to the stellar versus intermediate mass debate for ULXs would come from dynamical mass measurements, which require identification of optical counterparts. NGC 1313 X-1 is an important member of the ULX population, and has been extensively studied in X-rays. However, no optical counterpart of the source has been identified so far. Here, using data in the archive of the Hubble Space Telescope (HST) and Chandra X-Ray Observatory, we report the identification of the optical counterpart to NGC 1313 X-1 and discuss the physical implications.

2. ASTROMETRY AND THE OPTICAL COUNTERPARTS

NGC 1313 X-1 has been observed frequently with HST using the Advanced Camera for Surveys (ACS) and with Chandra using the Advanced CCD Imaging Spectrometer (ACIS). A log of HST observations used in the paper is shown in Table 1.

Chandra observation 2950, with an exposure of 20 ks, is the deepest in this field and thus chosen for astrometry correction. The ULX is located on chip S3 of ACIS with a moderate offset to the optical axis of 2.4'. We performed source detection using the wavdetect tool in CIAO 4.1.2 on a flux-corrected image created using an exposure map assuming a power-law spectrum with a photon index of 1.7 modified by Galactic absorption with $N_H = 3.97 \times 10^{20}$ cm$^{-2}$. We then searched in HST images for possible optical counterparts to all X-ray sources detected on the S3 chip, and found one good candidate with both X-ray and optical emission, hereafter referred to as the reference object (see Figures 1 and 2).

The relative astrometry between Chandra and HST can be improved using the reference object. Due to the relatively small field of view of HST, the reference object and X-1 do not appear on any single ACS image. We thus created a mosaic image from two ACS observations with the Wide Field Channel.
with the F555W filter, data sets J8PH01030 and J8PH07020. These two observations have an overlap of about 6 arcmin$^2$. Stars in the overlap region were detected using the daofind task, cross identified using xymatch, then used to calculate a relative shift and rotation between the two images using geomap. Figure 1 shows a mosaic image created using the multidrizzle task with these parameters. The mosaic image was then aligned to stars in the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) using the Graphical Astronomy and Image Analysis Tool (GAIA; Draper et al. 2009). We find 11 2MASS counterparts that appear point-like, isolated, and bright (K $\lesssim$ 15) on the mosaic image. Fitting to them results in a root-mean-square average deviation less than 2 pixels ($\approx$0.1), and an absolute astrometric uncertainty of 0.07 at 90% confidence (also see Feng & Kaaret 2008). We note that this uncertainty does not influence the alignment of the X-ray and optical images.

The reference object appears as a saturated star on the HST image. Its optical position is estimated from the cross point of the diffraction spikes as R.A. = 03$^h$18$^m$18$^s$.858 decl. = $-$66$^\circ$32$'$29.92 (J2000.0) with a negligible statistic error of about 0.01. It has 82 photons detected on the Chandra image with a significance of 38$\sigma$ and an error radius of 0.17 at 90% confidence. Using MARX simulation, the systematic offset in the position calculated by wavdetect caused by asymmetry of the photon distribution is estimated as $\Delta$R.A. = 0.03 and $\Delta$decl. = $-$0.04. These values were used to correct the offset in the coordinates from wavdetect. In Figure 2, the optical image of the reference object is shown. The cross indicates the optical center of the source. The arrow points north and has a length of 1".

For X-1, there are 2968 photons detected with Chandra, and the statistic error radius is 0.04 at 90%. The systematic errors are $\Delta$R.A. = $-$0.08 and $\Delta$decl. = $-$0.02 and are taken into account. The corrected position of X-1 relative to HST is R.A. = 03$^h$18$^m$20$^s$.013 and decl. = $-$66$^\circ$29$'$10.79 (J2000.0). The uncertainty on this corrected position is similar to the statistic error radius absolute astrometry uncertainty of Chandra. The X-ray image can be registered onto the optical image by aligning the plus and the cross.

The Chandra astrometry is not discussed in any available Chandra documentation. We estimated the rotation accuracy from a few Chandra observations with multiple optically identified X-ray sources and obtained a typical rotation about 2' between Chandra and 2MASS. Taking this value into account, with a distance of $\approx$200" between the reference object and X-1, the error caused by rotation is about 0.1'. Combining the two errors, 0.1' and 0.17', in quadrature, we estimate that the corrected X-ray position has an uncertainty of about 0.2' at the 90% confidence level.

The F555W image around X-1 is shown in Figure 3, on which a large, dashed circle indicates the original Chandra

![Figure 1. Mosaic HST image in F555W containing X-1 and the reference object used for astrometry correction. The arrow points north and has a length of 1".](image1)

![Figure 2. Optical image of the reference object. The plus and the circle indicate the Chandra position and error circle of 0.6 radius, respectively. The cross indicates the optical center of the source. The arrow points north and has a length of 1".](image2)
Figure 3. HST images around NGC 1313 X-1 in different bands. On the F555W image the dashed and solid circles indicate, respectively, the original and corrected Chandra position errors of X-1. On F435W, the circle indicates a group of stars nearby. The horizontal bars point to the bright optical object in the corrected X-ray error circle. The F606W image is from the observation on 2004 October 30, and others are obtained from observations on 2003 November 17. All arrows point north and have a length of 1".

position with an absolute error of 0.6", while a small, solid circle indicates the corrected relative position with a radius of 0.2". The astrometry correction successfully rules out a few objects as possible counterparts to X-1, but leaves one relatively bright object within the corrected relative error circle and another faint feature just to the east of the circle. Even if the error radius of the corrected Chandra position is 2.5 times larger, i.e., 0.5", this conclusion does not change. All available HST images of X-1 in other bands (F330W, F435W, F606W, and F814W) are also displayed with the same scale as the F555W image. Horizontal bars are plotted pointing to the bright object in the error circle. The bright object is obvious in all bands. The faint feature is more significant at shorter wavelength.

At about 2" to the southwest of X-1, a group of stars with an extent of about 1.5" (30 pc) are obviously seen, indicated by a circle on the F435W image. A few bright objects in the group may consist of multiple unresolved sources, especially on images of long wavelength.

3. PHOTOMETRY

3.1. Flux and Variability of the Counterpart

The region around X-1 on the HST images is crowded, so we decided to perform aperture photometry with an aperture radius of 0.1", in order to reduce contamination from nearby sources. To test the aperture correction for this relatively small aperture, we selected nearby isolated bright objects and performed photometry using both small and large apertures. We found a typical uncertainty around 0.02 mag, which is added into the uncertainty in our reported magnitudes. We note that point-spread function (PSF) photometry in this circumstance does not offer more reliable measurement, as features near the source have somewhat complex morphology and are not point-like. Background levels were estimated from a concentric annulus where no sources appear; if a couple dim sources could not be avoided, we then chose a background region as large as possible to depress the source contribution. The intrinsic source flux or magnitude was calculated using the SYNPHOT package using the count rate obtained from photometry corrected to an infinite aperture (Sirianni et al. 2005) and Galactic reddening $E(B-V) = 0.11$ (Schlegel et al. 1998). The PSF may vary slightly with temperature, causing a systematic shift about 0.02–0.05 mag between observations with such a small aperture. Several nearby isolated bright stars were used to calculate a zero-point shift to correct for this effect using the magnitudes measured on 2003 November 17 as reference. The extinction corrected fluxes at different bands were fitted to a power-law spectrum, $F_\nu \propto \nu^\alpha$, where $\nu$ is the pivot frequency of the filter in Hz and $F_\nu$ is the flux in erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$. The same power-law spectrum was assumed during the conversion from rate to flux; a couple cycles of iteration were needed here to produce a consistent power-law index before and after the conversion.

5 http://www.stsci.edu/hst/acs/documents/isrs/isr0712.pdf
Table 2

| Band   | 2003 Nov 17 | 2004 Feb 22 | 2004 Jul 17 | 2004 Oct 30 |
|--------|-------------|-------------|-------------|-------------|

ST Magnitudes in HST Bands

| F330W  | 22.26 ± 0.03 | ...         | ...         | ...         |
| F435W  | 23.00 ± 0.03 | ...         | ...         | ...         |
| F555W  | 23.65 ± 0.04 | 23.68 ± 0.04| ...         | ...         |
| F606W  | ...         | ...         | ...         | ...         |
| F814W  | 24.92 ± 0.06 | ...         | ...         | ...         |

ST Magnitudes Corrected for Galactic Extinction of the Bright Optical Object in the Corrected Error Circle of X-1

| Band   | 2003 Nov 17 | 2004 Feb 22 | 2004 Jul 17 | 2004 Oct 30 |
|--------|-------------|-------------|-------------|-------------|

Table 2

The intrinsic fluxes in different bands from different epochs are plotted in Figure 4, where the solid lines indicate the best power-law model fitted to the spectrum on 2003 November 17. As shown in Figure 4, the fluxes measured on 2004 July 17 and October 30 show a deviation from the best-fit power law obtained from 2003 November 17, except in the F814W band. The largest variation is seen in the F555W filter with a magnitude increase, Δm = 0.25 ± 0.06 (here the aperture correction error is not included as we are considering relative shifts for the same filter), for the observation on 2004 July 17 with respect to that on 2003 November 17. Fitting to a constant with the three F555W magnitudes results in χ² = 23.4 for 2 degrees of freedom (dof). To investigate whether the variation is intrinsic or instrumental, we selected eight sources with similar magnitude in F555W within 10′ of X-1, and checked their magnitude variation (again, without considering the aperture correction error), shown in Figure 5. All these 8 sources show a light curve consistent with a constant, with χ² = 0.3–3.3 for 2 dof. Also, the multiband spectra of these 8 sources are closely consistent between the two observations on 2003 November 17 and 2004 July 17. Therefore, we conclude that the variation in the F555W band for the counterpart is intrinsic. We also checked the variability in F435W and F814W for the ULX and comparison sources in the same way. Within the photometric errors, there is no evidence for variability of the ULX. However, the data in the F435W band are incompatible with the level of variability seen in the F555W band only at the 90% confidence level.

For the faint object to the east of the corrected error circle, it has a reddening corrected ST magnitude of 25.3 ± 0.1 in F555W on 2003 November 17. Interestingly, there seems to be an extended feature connecting it to the bright object, as one can see at long wavelengths, in particular in F814W, while the object itself, at the tip of this extended feature, becomes invisible in F814W. This faint object shows a constant flux within errors. Due to the deepness of HST observations, such a faint object has a relatively high chance probability to show up in any circle of 0.2 radius. We currently cannot constrain its nature or rule out the possibility that it is not the physical counterpart to X-1. However, due to two facts we prefer the bright object as the better candidate of the counterpart to X-1. First, its magnitude and spectral shape are similar to the optical counterparts of most other ULXs that have a unique identification in optical (Tao et al. 2011). Also, variability is expected for an accreting source.

3.2. X-ray to Optical Flux Ratio

Two sets of HST observations used here have simultaneous Chandra observations. Unfortunately, X-1 caused severe pileup on the CCD with about 25% of events being piled from multiple photons in these observations, hampering us from obtaining reliable spectra and fluxes. Based on the recorded X-ray count...
Figure 6. Color–magnitude diagram for objects within 10′′ (200 pc) of NGC 1313 X-1. Dashed lines are theoretical isochrones at ages of $10^{7.2}$, $10^{7.5}$, and $10^{8.3}$ yr, respectively. Filled circles are for objects in the nearby group of stars, i.e., inside the circle on F435W in Figure 3.

3.3. Color–Magnitude Diagram

The magnitudes for objects within 10″ of X-1 (about 200 pc correspondingly) were calculated using the DAOPHOT package in the Interactive Data Language (IDL). A total number of 123 bright sources with a flux 4σ above the background were detected using daofind from observations on 2003 November 17 in the F435W and F555W bands. All these sources have a local fit $\chi^2 < 3$ to exclude extended sources and image defects. We performed PSF photometry for these sources and created a color–magnitude diagram shown in Figure 6, for F555W versus F435W–F555W. The magnitudes are computed assuming an A0 spectrum based on their mean color, normalized to VEGA zero point, and corrected for the Galactic extinction. Typical errors are 0.03 for magnitudes and 0.05 for colors. For the nearby group of stars, eight bright, point-like sources are detected and displayed in the figure as filled circles.

Observations of H II regions in NGC 1313 suggest a flat distribution of oxygen abundance with $12 + \log(O/H) = 8.4$ across the disk (Walsh & Roy 1997), converting to a metallicity of $Z = 0.006$ based on standard solar composition (Grevesse & Sauval 1998). Theoretical isochrones of stars with the same metallicity at ages of $10^{7.2}$, $10^{7.5}$, and $10^{8.3}$ yr are plotted (Marigo et al. 2008). As one can see, most objects are older than $10^{7.5}$ yr, and almost none of them is younger than $10^{7.2}$ yr. In the diagram, stars in the nearby group do not appear differently from field sources. We also checked the diagram between F555W and F814W and obtained the same conclusion.

4. DISCUSSION

We have demonstrated the identification of the optical counterpart of NGC 1313 X-1 as the brighter object in the corrected error circle. Deviation from a single power-law spectrum on 2004 July 17 may suggest that at least two components are responsible for the optical emission. Due to a constant flux in F814W and variability in F555W, the red wing of the spectrum is possibly dominated by emission from the companion star and the blue wing is likely dominated by disk radiation.

Assuming that the red component is mainly due to star light from the companion, we can place constraint on its absolute magnitudes $M_V \gtrsim -4.1$, $M_I = -4.5$, and color $(V - I)_0 \gtrsim 0.4$, where the values are translated from F555W and F814W on 2004 July 17 and the inequality accounts for the fact that the F555W flux of the red component is lower than the observed value. A K5–M0 I bright giant would match the $I$-band magnitude and be consistent with the color. The F814W flux on 2003 November 17 should also be due to the companion emission under this hypothesis, and the single power law is then a composition of two components. The distinct optical spectra between 2003 November 17 and 2004 July 17 indicate that the disk emission has a varying break frequency $\nu_b \approx (5–8) \times 10^{14}$ Hz, corresponding to a break temperature $T_b = h\nu_b/k \approx 3 \times 10^4$ K, where $h$ and $k$ are the Planck and Boltzmann constants, respectively.

Disk emission in the optical can be decomposed into two origins, one from intrinsic viscous release of the multicolor disk, and the other from X-ray reprocessing (irradiation) in the outer regions of the disk. The intrinsic emission of a standard thin disk has the spectral form of $I \propto \nu^{1/3}$ at frequencies above $kT_{out}/h$, where $T_{out}$ is the disk temperature at the outermost radius, and then breaks to $\nu^{2}$ at much lower frequencies. The two point power-law index between the F555W and F435W fluxes on 2004 July 17 is $\alpha = 1.4 \pm 0.3$ corrected for Galactic extinction; if additional extinction exists in NGC 1313, $\alpha$ would be even larger.

Thus, the blue wing of the spectrum is steeper than $1/3$ and cannot be explained by intrinsic disk emission only, unless the disk is truncated with $\beta_{out} = 1.00–2000$, suggesting the presence of a relatively narrow disk, as has been proposed for NGC 6946 X-1 (Kaaret et al. 2010) and SS 433 (Perez & Blundell 2010). Otherwise, if disk irradiation is dominant, it is expected to have an effective temperature $T_{irr} \approx T_b$ with a surface area around $10^{35}$ cm$^2$ to reach
observed flux density. Therefore, a disk size about $10^{12}$ cm is inferred.

As optical fluxes at different bands were not obtained simultaneously, an alternative explanation of the non-power-law spectrum seen on 2004 July 17 could be due to short-term variation of the disk emission. The last sub-exposure of F435W started in advance of the F555W observation by 544 s, which, corresponding to a light cross distance over $10^{13}$ cm, is sufficiently long to respond to the rapid X-ray variation. Strong, fast optical variations have been found for both LMXBs and ULXs (Bradt & McClintock 1983; Grisé et al. 2008), and NGC 1313 X-1 is highly variable in X-rays at short timescales (Dewangan et al. 2010). Simultaneous X-ray and optical observations in the future could test different scenarios.

The properties of the companion star could be constrained by comparing the observed $M_V$ and $(B-V)_0$ with theoretical values derived from binary evolution (Patruno & Zampieri 2008, 2010). The data can be best-fitted with a donor of $10^{-15}$ $M_{\odot}$ derived from binary evolution (Patruno & Zampieri 2008, 2010).

The color–magnitude diagram and isochrones reveal a stellar population around NGC 1313 X-1 with most stellar ages greater than $10^{15}$ Myr. The nearby region (within 100 or 200 pc) lacks very blue stars and young star clusters. This places a constraint on the mass of the companion star as no more than $10 M_{\odot}$. Also, it can be ruled out that the donor starts to fill the Roche lobe during the giant phase if the black hole mass is greater than $20 M_{\odot}$ (Patruno & Zampieri 2010).

The ULX is close to a group of stars, which has an extent of about 30 pc and has a similar age to field stars. Whether or not the ULX belongs to the star group is unknown. This is different from the environment around NGC 1313 X-1 with most stellar ages greater than $10^7$ Myr. The nearby region (within 10$^9$ or 200 pc) also lacks very blue stars and young star clusters. This places a constraint on the mass of the companion star as no more than $10 M_{\odot}$. This is consistent with the hypothesis above that the companion may be a late type bright giant.

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