Optical Counterparts of ULXs in NGC 1672

S. Allak,1,3* A. Akyuz,2,3 E. Sonbas,4,5 K. S. Dhuga5
1Department of Physics, University of Çankale Onsekiz Mart, 17100, Çanakkale, Turkey
2Department of Physics, University of Çukurova, 01330, Adana, Turkey
3Space Science and Solar Energy Research and Application Center (UZAYMER), University of Çukurova, 01330, Adana, Turkey
4Adiyaman University, Department of Physics, 02040 Adiyaman, Turkey
5Department of Physics, The George Washington University, Washington, DC 20052, USA

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ABSTRACT

In this work, we deploy archival data from HST, Chandra, XMM-Newton, and Swift-XRT, to probe the nature of 9 candidate ULXs in NGC 1672. Specifically, our study focuses on using the precise source positions obtained via improved astrometry based on Chandra and HST observations to search for and identify potential optical counterparts for these ULXs. Unique optical counterparts are identified for two of the ULX candidates i.e., X2 and X6; for three of the candidates i.e., X1, X5 and X7, we found two potential counterparts for each source within the respective error radii. No optical counterparts were found for the remaining four sources. The spectral energy distribution of X2 is fitted to a blackbody spectrum with a temperature of ~ 10^4K and the spectral class of the source is determined to be B7–A3, a supergiant donor star. We used colour magnitude diagrams (CMDs) to investigate ages of the counterparts. Of all the sources studied, X9 exhibits the most variability whereby the X-ray flux varies by a factor of ~ 50 over a time period spanning 2004 to 2019, and also traces a partial q-curve-like feature in the hardness-intensity diagram, hinting at possible spectral transitions.

Key words: galaxies: individual: NGC 1672 - X-rays: binaries

1 INTRODUCTION

Ultraluminous X-ray sources (ULXs) are non-nuclear point-like sources in external galaxies. Their X-ray luminosities are above a threshold luminosity of L_X > 10^{39} erg s^{-1}, exceeding the Eddington limit for a typical 10 M_☉ stellar-remnant black hole (see review by Kaaret et al. 2017; Fabrika et al. 2021).

Several possibilities as to the nature of ULXs continue to be discussed in the literature: (a) an early model, though now seemingly less likely, poses the existence of BHs in the intermediate mass range of M ~ 10^2-10^5 M_☉, accreting at sub-Eddington rates (Colbert & Mushotzky 1999; Miller et al. 2004), (b) current models, based on recent data, tend to lean toward stellar-mass compact objects with a possible combination of effects such as geometric beaming, and/or accretion at super-Eddington limits (Begelman 2002; Roberts 2007; Poutanen et al. 2007; King 2009; Walton et al. 2018). Indeed, the recent detection of pulsations in a handful of ULX sources strongly argues in favor of at least a fraction of these sources hosting neutron stars (NSs) (Bachetti et al. 2014; Fürst et al. 2016; Israel et al. 2017a, b; Carpano et al. 2018; Sathyaprakash et al. 2019; Rodríguez Castillo et al. 2020).

With the current total of NS ULXs (with observed pulsations) standing at about a half-dozen, the question of the relative proportion of ULXs hosting a NS as opposed to a stellar-mass BH, has become a hotly debated topic (King & Lasota 2016; Middleton & King 2017; Wiktorowicz et al. 2019). In addition to the signature of coherent pulsations, NS ULXs also exhibit a large dynamic range in variability in their observed light curves. This feature has been suggested as a possible method of identifying NS ULXs in the absence of pulsations (Earnshaw et al. 2018). Indeed, a recent Swift-XRT monitoring campaign of M51 (Brightman et al. 2020) has yielded evidence for counterpart transient ULXs through the observation of long-term variability in their light curves. Likewise, the presence of a cyclotron resonance scattering feature in the X-ray spectrum of ULX-8 in M51, discovered by Middleton et al. (2019), provides strong evidence for the nature of the compact object i.e., a NS, and a measure of the associated magnetic field.

In the present work, we focus on NGC 1672, a late-type barred spiral galaxy at a distance of 16.3 Mpc (de Naray et al. 2000). This galaxy has been studied by Jenkins et al. (2011), who identified 28 X-ray sources within the D25 region of the galaxy. Among these sources, 9 were observed to have X-ray luminosities consistent with those associated with ULXs. Our primary goal is to search for and identify potential optical counterparts for these 9 candidate ULXs by deploying all available optical data. In addition, a secondary goal is to use the available Chandra, XMM-Newton and Swift archival data, to study the X-ray spectral and temporal variations of the candidate ULXs.

Optical studies provide valuable information regarding the nature of the donor star, disk geometry, and can place constraints on the mass of the accretor. Technically, the optical emission observed in ULX binaries can be due to the accretion disk, the donor star, and/or some combination of both. Many recent studies (Copperwheat et al. 2007; Patruno & Zampieri 2008; Tao et al. 2011; Grisé et al. 2012;
Soria et al. 2012a; Sutton et al. 2014; Ambrosi & Zampieri 2018; Yao & Feng 2019), focusing on optical variability, multi-band colors, and SED modeling, strongly suggest that the optical emission is likely contaminated or even dominated by reprocessed radiation from an irradiated accretion disk.

Unlike X-ray studies, the number of ULXs defined by optical observations is still limited since they are quite faint in the optical band (m_v > 21 mag.) and tend to be located in crowded star-forming regions. Therefore, identification of counterparts often requires the use of the Hubble Space Telescope (HST\(^1\)) for optical imaging. In addition, precise astrometry between high resolution Chandra X-ray and HST images is also essential (Patruno & Zampieri 2010; Grisé et al. 2011; Poutanen et al. 2013; Egorov et al. 2017; Urquhart et al. 2018; Allak et al. 2022). Identification of point-like (potential) counterparts of ULXs with blue colors are indicative of early-type, OB stars. This of course goes with the caveat that the observed blue color may result from dominant contributions from the X-ray irradiation of the accretion disk and/or the companion star facing the X-ray source (Patruno & Zampieri 2010; Jonker et al. 2012; Vinokurov et al. 2018). As a rare example, Motch et al. (2014) reported that photospheric absorption lines have been detected from the donor star in the blue part of the spectrum of P13 in NGC 7793. On the other hand, the systematic search for nearby ULX counterparts in the near-infrared (H band) revealed that they might be red supergiants (Heida et al. 2014, 2016; López et al. 2017, 2020). In these systems the contribution of the accretion disk is expected to be lower in the near-infrared than in the optical band and additionally, the irradiation of the donors is unlikely to be a significant effect on the observed emission because of the large separations of the companions (Copperwheat et al. 2007; Heida et al. 2015).

The layout of the paper is as follows: in section 2, we describe the data selection and the reduction procedures for both the optical and X-ray analysis, including the steps needed to perform astrometry, construct spectral energy distributions, hardness-intensity diagrams, color magnitude diagrams, and determine the spectral optical index. In section 3, we present our results of the optical analysis, astrometry, and X-ray spectral fits and temporal variability studies, as well as, the outcomes for particular sources. Finally, we summarize and conclude our main findings in section 4.

2 DATA REDUCTION AND METHODOLOGY

2.1 Optical

2.1.1 Astrometry

NGC 1672 was observed by HST in 2005 and 2019 using the ACS/WFC (Advanced Camera for Surveys/Wide Field Channel) and WFC3/UVIS (The Wide Field Camera 3), respectively. Details of the observations are given in Table 1.

We note at the outset that our numbering scheme for the sources differs from that used by Jenkins et al. (2011); we label the candidate ULXs according to their increasing Chandra counts i.e., X1 (#25), X2 (#4), X3 (#5), X4 (#13), X5 (#24), X6 (#28), X7 (#7), X8 (#1) and X9 (#6). The numbers in parentheses correspond to the source numbers in Jenkins et al. (2011). We also mention that Liu (2011) identified four ULXs corresponding to our X1, X2, X3 and X4.

Figure 1 shows the location of the 9 ULX candidates on three-color (red, green and blue; RGB) images comprising the data from XMM-Newton, Chandra, Swift-XRT and HST.

Determining the optical counterparts of the ULXs requires accurate source positions provided by astrometric corrections. Chandra and HST images were used to obtain astrometric precision by following the method we used in our previous studies Allak et al. (2022) (and references therein). We chose deep Chandra ACIS-S (ObsID 5932) and HST ACS (ObsID j6n202010) images for astrometric corrections of the sources. We used wavedetect tool in CIAO and daofind tool in IRAF for source detection in both images, respectively. We found four reference point sources between Chandra and HST images. All of the matched sources are located on ACIS-S with a moderate offset from the optical axis in Chandra data. Properties of the reference sources are given in Table 2. The offsets between the reference sources were calculated with 95% confidence level. The astrometric errors between the Chandra and HST images were determined as 0.08 ± 0.03 in R.A. and 0.07 ± 0.03 in Dec. As a result, we found the positions of the optical counterparts of ULXs on the HST image within an error radius of 0.021 at 95% confidence level. The corrected HST coordinates of the ULXs are also given in Table 2. We searched for optical counterparts of all ULXs within their respective error radii.

We found unique optical counterparts for X2 (X2_1) and X6 (X6_1). Two potential counterparts each were found for X1 (X1_1 and X1_2), X5 (X5_1 and X5_2) and X7 (X7_1 and X7_2) respectively. The labels in parentheses indicate the corresponding optical counterparts. However, we could not identify any optical counterpart(s) for X3, X4 and X8 within their respective error radii: X9, unfortunately, was not observed by HST. The candidate optical counterparts are marked on the ACS/WFC/F814W image displayed in Figure 2.

2.1.2 Photometry

Point-Spread Function (PSF) photometry was performed with DOLPHOT v2.0 (Dolphin 2000) to determine the magnitudes of optical sources using the HST data. The ACSMASK task was used to remove pixels flagged as bad in images. For the next step, the tasks SPLITGROUPS and CALCSKY were run to split the image files into each chip and to create the sky background for each image, respectively. We then derived the magnitudes of sources using the set of parameters for the ACS/WFC and WFC3/UVIS recommended by DOLPHOT user’s guide. Obtained magnitude values were corrected with Galactic extinction A_V = 0.065 mag. (Schlafly & Finkbeiner 2011). The dereddened Vega magnitudes of optical counterparts are given in Table 3. We calculated the absolute magnitudes, M_V, for both UVIS/F555W (V) and WFC/F550M (∼V) with adopted distance of 16.3 Mpc. These values are given in Table 4. In addition, the calculated color indices to determine the spectral type of optical counterparts of ULXs are also given in Table 4.

2.1.3 Spectral energy distribution

Spectral energy distribution (SEDs) of the optical counterparts have been constructed to obtain the spectral characteristics of ULXs using the derived flux values given in Table 3. The wavelengths of the filters are selected as the pivot wavelength, obtained from PSYNPHOT\(^2\), in SED plots. The excess of the flux contaminated by continuum emission within the F658N filter is clearly visible compared to other filters. We applied the procedure as given by

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1. https://archive.stsci.edu/hst/search.php
2. https://psynphot.readthedocs.io/en/latest/
We attempt to constrain the nature of companions by fitting SEDs with a blackbody or a power-law \((F \propto \lambda^\alpha)\) spectrum. To obtain a blackbody spectrum, a publicly available code was used with \textsc{optimer} and \textsc{fminsearch} functions in \textsc{matlab}\(^3\). We found that SED fitting was only possible when data from more than three filter bands were available. On the other hand, of the eight counterparts identified, 4 are observed in only more than three filter band (see Table 3). The SED of \(X_1\) is adequately fitted by a power-law spectrum with \(\alpha = -2.13 \pm 0.16\). The \(X_2\) SED is well fitted by a blackbody spectrum with a temperature of \(10^4 \pm 113\) Kelvin (K) at 95% confidence level. This temperature corresponds to a late-type B supergiant donor (Straizys & Kurilene 1981). Additional extinction values were used to check for the possibility that SED would change to a power-law shape. For this, we increased the Galactic extinction value by two magnitude \(m_A\). It was found that SED is compatible with the SED of a late-type B supergiant donor. The reddening corrected SEDs of \(X_1\) and \(X_2\) are shown in Figure 3 and 4, respectively. No acceptable model-fits were obtained for the remaining optical counterparts.

2.1.4 Color-magnitude diagrams

In order to investigate the relation of the optical counterparts with their environments and estimate their ages, the color-magnitude diagrams (CMDs) were obtained assuming the optical emission of the donor stars dominate. Two CMDs, F435W (B) versus F550M (B-V) and F550M (V) versus F550M–F814W (V-I), were derived for optical counterparts and the field stars. The metallicity of [Fe/H]=−1.74 was used to obtain the corresponding PARSEC (Bressan et al. 2012) isochrones. The distance modulus was calculated as 31.06 magnitude using the adopted distance of 16.3 Mpc. The reddening in the direction of the galaxy was calculated as \(E(B-V) = 0.065\) mag. Also, synthetic spectra were normalised with Vega magnitude \(m_0\). It was found that \(X_1\) is compatible with the SED of a late-type B star. The reddening corrected SEDs of \(X_1\) and \(X_2\) are shown in Figure 3 and 4, respectively. No acceptable model-fits were obtained for the remaining optical counterparts.

2.1.5 X-ray-to-optical flux ratios

The ratios of X-ray to optical fluxes \((F_X/F_V)\) for the optical counterparts can be used to distinguish between ULXs and AGNs (Akyuz et al. 2020) (and references therein). Since we do not have simultaneous X-ray and optical observations, we calculated the ratio of \(F_X/F_V\) using 2006 \textit{Chandra} and 2005 \textit{HST}/ACS (J95801020) data. Where \(F_X\) is the flux observed in the range 2–10 keV and \(F_V\) is the optical flux in the F550M filter. According to a study by Aird et al. (2010), this ratio is defined in the range of 0.1–10 for AGNs. The calculated ratios for the optical counterparts of \(X_1\), \(X_2\), \(X_5\) and \(X_7\) are listed in Table 4.

2.1.6 X-ray-Ultraviolet Spectral Correlations

The distinct role played by the accretion disk in the emission process is well known for AGNs (Lusso et al. 2010; Vagnetti et al. 2013) and is well encapsulated in a X-ray-UV correlation cast in terms of the so-called optical spectral index \(\alpha_{ox}\) as defined by Tananbaum et al. (1979). The index is computed from the X-ray and UV flux densities at 2 keV and 2500Å respectively. This relation was recently exploited by Sonbas et al. (2019) to demonstrate an X-ray-UV correlation for a small sample of ULXs for which the optical counterparts are known. For comparison, we extracted \(\alpha_{ox}\) for the candidate ULXs in NGC 1672. These \(\alpha_{ox}\) values are listed in Table 4.

2.2 X-ray

2.2.1 Spectral fitting

NGC 1672 was observed by \textit{XMM-Newton} and \textit{Chandra} in 2004 and 2006, respectively. In addition, it was observed 17 times by \textit{Swift-}\textit{XRT} between 2006 and 2020. The log of observations is given in Table 1.

The \textit{Chandra} ACIS (Advanced CCD Imaging Spectrometer) data were analyzed by using \textsc{ciao} v4.12 software with its calibration package \textsc{caldb} \(^5\) v4.9. The source and background photons were extracted with \textsc{specextract} task using circles with radii of \(6''\) and \(12''\), respectively.

The \textsc{XMM-Newton} data reductions were carried out using the \textsc{sas} (Science Analysis Software version 18.0). The \textit{epchain} and \textit{emchain} tasks were used to obtain EPIC-pn and MOS event files. The events corresponding to \textsc{pattern}\(\leq 12\) and \textsc{pattern}\(\leq 4\) with \textsc{flag}=0 were selected for EPIC-pn and MOS detectors, respectively. Source and background spectra of the candidate ULXs were extracted using the \textit{evselect} task, with appropriate circular regions of radii \(10'' - 15''\) and \(20'' - 30''\), respectively. The background regions were selected from source free regions on the same chip containing the ULXs. However, since the X9 source is localized on the EPIC-pn chip gap, we used only the MOS data for spectral fitting. For the other ULXs, EPIC-pn and MOS spectra were fitted simultaneously in the 0.3–10 keV energy band and a constant scaling factor was taken in order to consider the cross calibration differences between the instruments. The files for the source and background spectra were obtained using the \textsc{dmgroup} task.

The \textit{Swift-}\textit{XRT} data sets were processed with \textsc{HEASoft} v6.29\(^6\), the tool \textsc{xrtpipeline} and calibration files \textsc{caldb} v4.9. Data used were taken in Photon Counting (PC) mode in the range of 0.3–10 keV. The source and background photons were extracted circular regions of radii \(18''\) and \(36''\) respectively. Appropriate ancillary response files were generated with the task \textsc{xrtmkarf}. We combined

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\(^3\) https://www.mathworks.com/matlabcentral/fileexchange/20129-fit-blackbody-equation-to-spectrum

\(^4\) https://cxc.cfa.harvard.edu/ciao/

\(^5\) https://cxc.cfa.harvard.edu/caldb/

\(^6\) https://heasarc.gsfc.nasa.gov/docs/software/heasoft/
the data taken in the same year (e.g. six datasets in 2012) for spectral fitting due to the short exposure time and low data statistics.

Jenkins et al. (2011) fitted the X-ray spectra with a power-law model and obtained reasonable fits. In order to explore whether these fits could be improved, the spectra for the ULX candidates which have sufficient statistics were grouped at least 15 counts per energy bin. We then fit the grouped spectra by using the package, xspec v12.11 (Arnaud 1996) with the following models (in addition to the power-law): several single component models such as the absorbed multicolor disk blackbody (diskbb), diskpbb and cutoffpl respectively. We also fitted the spectra with the frequently used two-component models such as power-law + diskbb and diskbb + compt.

In Table 5, the well-fitted spectral model parameters for X1, X2 and X6 (deploying the Chandra data only) are given with unabsorbed flux values. The unabsorbed flux was calculated in the 0.3–10 keV energy band using the convolution model cflux available in xspec and corresponding luminosity was calculated using a distance of 16.3 Mpc (de Naray et al. 2000). The acceptable model-fits were selected according to null hypothesis probability. We consider all fits with $P > 0.05$ corresponding to a confidence level $\geq 95\%$. We found the diskbb model fits to be statistically better than the other single component models at the $3\sigma$ confidence level. The absorption component was left as a free parameter in the fitting procedure. Inclusion of two component models for these sources did not improve the fits significantly compared to diskbb model. The unfolded energy spectra of the best model-fits, for X1, X2 and X6, are shown in Figure 8.

The ULX candidates with low data statistics (i.e X5, X7, X8 and X9) were also fitted with the same single component models using C-statistics. However, none of the models gave reasonable results therefore the power-law model parameters are the accepted in our final calculations as given in the study of Jenkins et al. (2011). This is partially due to the lack of sufficient data for these sources leading to poor statistics. On the other hand, the XMM-Newton and Chandra data statistics are reasonable for X3 but a satisfactory fit was not achieved with one or two-component models. More complex combinations of models were not pursued as it further deteriorates the interpretation of the extracted parameters. We note that X4 is detected as a distinct source only in the Chandra observation. In the XMM-Newton and Swift-XRT observations, the source is not resolved from the galaxy center, and as such was not considered for further spectral analysis.

2.2.2 Long-term and Short-term X-ray Variability

We used all the available X-ray data to examine the long-term variability of the candidate ULXs. Fluxes of XMM-Newton and Chandra observations were obtained by using the power-law model in 0.3–10 keV energy band at 1–$\sigma$ confidence level. As the Swift-XRT observations do not have enough statistics, we combined the event files for each observation within a given year. This was applied to all the data taken in the years 2007, 2012, 2017 and 2019 respectively (see Table 1). Unfortunately even the combined statistics proved insufficient thus in this case, we obtained the Swift-XRT fluxes from the respective count rates using WebPIMMS. We used the power-law model parameter, $\Gamma$, and $N_H$ obtained from the Chandra observation of each ULX. The source X5 was not detected in XMM-Newton and 2019 Swift-XRT so its flux values were calculated at the $3\sigma$ upper limit. The light curves of the sources which have optical counterparts are shown plotted in Figure 9. The source X9 seems to exhibit more variability than the others.

We also performed a periodicity search for all of the candidate ULXs except X4. The background subtracted X-ray light curves of Chandra and XMM-Newton data were sampled at 0.1 s and 3.2 s, respectively, in the 0.3–10 keV energy band. The light curves were divided into six time intervals and the power spectrum density (PSD) of each interval was computed via a Fourier transform. The six PSDs were averaged to probe for temporal features. Our results showed no evidence for any significant periodicity $\geq 1.5\sigma$ in any of the sources examined.

2.2.3 Hardness–Intensity and Hardness-Ratio Diagrams

In order to probe possible state transitions in the ULXs, we constructed hardness-intensity diagrams (HIDs) and hardness ratio diagrams (HRDs) for the sources that have optical counterparts. We included X9 in this group largely because of its X-ray variability although it has no identified optical counterpart. The observations used in determining the hardness ratios (HRs) are listed in Table 1. The HRs are calculated as the ratio of counts in the hard-to-soft energy bands where the respective bands are as follows: 0.3 - 2.0 keV (Soft) and 2.0 - 10.0 keV (Hard). For the HIDs, the fluxes specified in section 2.2.2 were used. The HIDs of the sources that have one optical counterpart are shown in the left panel of Figure 10; the right panel of the figure depicts the HIDs of the sources that have two optical counterparts. The HID for X9 is displayed in Figure 11. The HRDs of these sources are displayed in Figure 12.

3 RESULTS AND DISCUSSION

3.1 Optical

The problem with identifying the donor star in the optical emission of ULXs is that the flux contribution from the accretion disk, either directly or irradiated, is mostly unknown.

In the present study, we identified the possible optical counterparts of the ULXs in the galaxy NGC 1672 with precise astrometric calculations based on Chandra and HST data. Using HST UV/optical observations, we investigated in detail the optical variability, color and SED features of the optical counterparts to analyze their possible contribution to the observed optical emission.

Examining all the optical images listed in Table 1, we identified a unique counterpart for X2 and X6, and two potential optical counterparts for X1, X5 and X7 respectively within the error radius of 0.′′21 at 95% confidence level. It is noteworthy that X3 and X8, located in a spiral arm, and X4 located very close to the center of the galaxy, apparently have no optical counterparts or more likely, the counterparts are just not bright enough to be visible in the observations considered here. Unfortunately, X9 was not in the field of view of the HST archival observations and hence we are not in position to make any statement regarding its potential counterpart(s).

The absolute magnitudes, ($M_V$), of the optical counterparts are listed in Table 4, and are seen to lie in the range $-5 < M_V < -7.5$. This range is compatible with the values ($-4$ to $-9$) noted by Gladstone et al. (2013). In addition, we also note that the observed counterparts appear to be faint in the $V$-band magnitude ($m_V < 23.5$) similar to most of the known ULXs (Tao et al. 2011; Gladstone et al. 2013; Vinokurov et al. 2018). As a part of this study, we also examined the...
environment in the vicinity of the target ULXs to investigate if there were any associations between the ULXs and nearby star groups or clusters. Widely scattered star groups are located near X1 and X7 sources. Results of optical photometry indicate that these nearby bright stars have similar properties (such as colors and magnitudes) to the counterparts of X1 and X7. Also, when we examined the F658N image to search for existing star forming regions and check for possible ULX nebulae, we noticed that X1 is located in a HII region; the region is shown in Figure 7.

Of course, an intrinsic property of particular interest for any optical counterpart is its mass. The mass of the donor (M_d) (in an accreting system for example) is useful in not only categorizing the binary system (i.e., a low-mass X-ray binary (LMXB) or a high-mass X-ray binary (HMXB) etc) but is fundamentally important in determining many of the emission processes associated with the binary system. Although a consistent mass range of the donor is not provided in the literature, we adopt the mass scale given in the recent studies of Johns Mulia et al. (2019); Chandar et al. (2020); Hunt et al. (2021), i.e., M_d > 8 M_⊙ for a HMXB; 3 M_⊙ < M_d < 8 M_⊙ for an intermediate X-ray binary, and M_d < 3 M_⊙ for a LMXB. When optical emission is observed in the positional uncertainty of an ULX, it is potentially an optical counterpart. The optical counterparts of the ULXs given in Table 3 are likely donor stars of HMXBs since they have been detected at least in the one of HST filters. For X3, X4 and X8, we were not able to identify any optical counterparts, probably because they are too faint; see studies by Hunt et al. (2021); Rice et al. (2021), and references therein, who suggest an HST observation threshold for stars with a mass < 3 M_⊙ at a distance of ~ 10 Mpc.

As a check to determine whether any of the target sources are possibly background AGNs, we determined the F_X/F_V ratios. These ratios range from ~ 11 to 50, which confirms that these sources are unlikely to be AGNs for which the ratio falls in a significantly lower range i.e., (0.1 < (F_X/F_V) < 10, Aird et al. (2010)). In addition, we extracted the spectral optical index (Tananbaum et al. 1979), α_ox, which has been shown (Sonbas et al. 2019) to exhibit a distinctly different correlation for ULXs as compared to AGN. The extracted values of α_ox are listed in Table 4 and they agree well with the typical values found for other well-studied ULXs.

In the remaining part of this section, we mention some of the salient features of the optical counterparts identified for each of the ULX candidates:

- X2 and X6: A unique counterpart was identified for both X1 and X6 within the 0.21 astrometric error radius. The optical counterparts are shown in the F814W image in Figure 2. Dereddened magnitudes and flux values of the counterparts in each filter are given in Table 3. X2_1 appears to be a faint source in the V-band and is relatively bright in the UV band. Interestingly X6_1 was detected only in the I-band with 25.33 ± 0.11 mag.

  The intrinsic colors of X2_1 are as follows: (B-V)_0 = 0.03 and (V-I)_0 = 0.05. Using the Schmidt–Kaler table, the spectral class of X2_1 was determined to be B8–A3, a supergiant donor star. We also tried to confirm the spectral class of X2_1 using the reddening corrected SED as given in Figure 4. The SED for the source is adequately fitted (a χ² value of 0.93 (df=5) at 95% confidence level) with a blackbody model and a temperature of 10^4 ± 113 K. In this case assuming the majority of the emission arises from the donor star, the temperature and the luminosity of X2_1 correspond to a B7 type supergiant according to the table given in Straizys & Kuriliene (1981). We also determined the same spectral type of X2_1 based on the CK04 standard stellar spectra templates. On the other hand, the blackbody emission could also originate from irradiation of the accretion disk. Therefore, both X-ray and optical variability need to be investigated. While X2 is quite variable in the X-ray range (factor of ~ 8), it is difficult to comment on the optical variability considering we have only two observations 14 years apart, F550M in 2005 and F555W in 2019. Even in these two observations no optical variability was seen.

- X1, X5 and X7: Two possible optical counterparts are identified for each of these ULX candidates; see Figure 2. The calculated dereddened magnitudes and fluxes of the counterparts are given in Table 3. A careful examination of all the HST images shows the counterparts X1_1, X5_1 and X7_1 to be brighter in the UV (m_F275W_F336W > 22) compared to the other filters. On the other hand X1_2 is only visible in the I-band filter (m_I = 24.22 mag). It is possible that this source is similar in nature to X6_1. We note that X5_1 is detected in all images taken between 2005 to 2019 while X5_2 is only seen in the 2019 UVIS images. This suggests that X5_1 is a persistent source whilst X5_2 is a variable source. As noted in Table 3, X7_2 is detected in three ACS filters. This source appears reddish in color in the HST true color image depicted in Figure 6. It is possible this source is a red supergiant.

The CMD, deploying the filters F435W versus (F435W-F550M), was used to investigate the association of optical counterparts to nearby stars or group of stars. For this case, X1_1 and X7_1 are the best candidates, as seen in the top panels of Figures 5 and 6. If we consider the age intervals of the star groups close to the counterparts, then X1_1 and X7_1 can be associated with stars with ages (10-13) Myr and (25-30) Myr, respectively. We also derived color indices for the counterparts (see Table 4) then using intrinsic colors and the absolute magnitudes of the Schmidt–Kaler table (Aller et al. 1982), the spectral types were determined to be early type B–A supergiants.

Optical counterparts X1_1 and X1_2 are located within a HII region as seen in the F658N image (see Fig. 7). Source X1_2 is not resolved in the F658N band and it is only detected in the F814W filter. Using a circular region with a radius of 0.21 (and following the procedure given in section 2.1.3), we calculated the total F658N flux as 1.01x10^{-18} erg cm^{-2} s^{-1} Å^{-1}. This calculated F658N flux was determined to be ~ 40% of the total flux (F658N+continuum background).

The SED for the optical counterparts X1_1 is adequately fitted with power-law, F = a x^n, with a photon index, a = 2.13 ± 0.16 at 95% confidence level. The χ² value is found as 0.87 with 4 dof. The reddening corrected SED of X1_1 is shown in Figure 3. If the optical emission originates mostly from an accretion disk then the optical SED should have a roughly power-law form with a photon index of a about -2.3 and significant optical variability (Tao et al. 2011). The extracted a is consistent with the expected value within errors. Thus, for this source, the optical emission may be dominated by an intrinsic emission from an accretion disk. The m_F336W ~ 0.6 mag. variability detected in the UVIS/F336W images for this source, over an interval of about 1.5 years, further supports this scenario.

### 3.2 X-ray

The values given in Table 5 show the well–fitted spectral model parameters for X1, X2, and X6. The unfolded energy spectra of these sources obtained via the use of the diskitb model are shown in Figure 8. These sources tend to exhibit relatively high values for the inner disk temperature (i.e., T_{in} > 1.2 keV). This is a known feature of ULX spectra.

We revisit X9 when we consider the long-term variability of the ULXs. Nonetheless, the fits for the other sources are in reasonable agreement.
(statistical) agreement with those found by Jenkins et al. (2011) but given the limited statistics, we refrain from drawing firm conclusions regarding the choice of spectral models and the extracted parameters.

The HID is a proven diagnostic tool in tracking spectral transitions in the case of BH binaries. These transitions typically trace out a q-shape contour in the HID as the binary transitions from the low-hard state through the hard-intermediate, soft-intermediate, and finally back down to the low-hard state, and in some cases, into the lowest intensity state corresponding to the quiescent state (e.g., Barnard et al. 2003; Done & Gierliński 2003; Remillard & McClintock 2006; Belloni 2010). We constructed HIDs using the hardness ratios determined from the count rates in the soft (0.3 - 2.0 keV) and hard states (2.0 - 10.0 keV) respectively, in order to probe similar transitions in the ULX candidates (Soria et al. 2012b). The HIDs of X2 (empty circles), X6 (filled triangles) are given in the left panel of Figure 10, and the HIDs of X1 (filled circles), X5 (empty squares) and X7 (empty triangles) are displayed in the right panel of Figure 10. Furthermore, the HID of X9 is given in Figure 11. Although a complete q-shape contour is not discernible, X9 does, however, hint at a partial loop in the HID plane, thus suggesting possible transitions between spectral states.

We explore this variability more systematically by constructing long-term light curves for the selected ULXs using all available Swift-XRT, XMM-Newton, and Chandra observations. The light curves of the sources that have optical counterparts are displayed in Figure 9. In each case, the solid line indicates the mean value of the X-ray flux; a measure of the variability is provided by the ± 3σ levels shown as dotted lines. As is clear from the Figure 9, the flux for X9 varies almost a factor 50 ± 18 between the different observations. In addition to the X9, the transient source X5 also exhibits high degree variability (almost a factor of 30) in the long-term. It should be noted that while the source was undetected in the 2004 XMM-Newton and 2019 Swift-XRT observations, it has the highest flux from the longest exposure in 2012 Swift-XRT data. The occurrence of high flux variability in ULXs may provide some evidence for exhibiting bi-modal flux distributions as might be expected for sources related to propeller transitions. As discussed in several studies, probing some ULX transient systems with such a bi-modal flux distribution may be a way to identify a ULX hosts a NS without detecting pulsations (Earnshaw et al. 2018; Song et al. 2020; Allak et al. 2022). However, we note that the statistics for the X5 and X9 sources are very low and the bi-modal nature is not evident in all the datasets we used.

Song et al. 2020 e.g. SRC 279969) for X5 and X9 these distributions consistent with bi-modality. We calculated the variability factor as the ratio of maximum to minimum fluxes; this factor is found to be 5 ± 0.4, 8 ± 2.9 and 5 ± 1.9 for X1, X2 and X7 respectively. For the remaining sources, i.e., X3, X6 and X8, the factor is ≤4. From this it is readily transparent that sources X5 and X9 show significant variability and thus are potential candidates for additional long-term monitoring. The corresponding long-term variation of the hardness ratio (HR) of X1, X2, X5, X6, X7 and X9 is displayed in Figure 12. The HR too shows variability among the sources but is not as striking as that exhibited by the flux.

Finally, we note that we extracted the optical spectral index $\alpha_{OX}$ for the candidate ULXs that have optical counterparts. The values are listed in Table 4, and are in good agreement with those reported by Sonbas et al. (2019). Importantly, these indices are quite different from those reported for AGN (see Lusso et al. (2010); Vagnetti et al. (2013)) and thus this distinction provides another possible criterion for distinguishing ULXs from AGN.

4 SUMMARY AND CONCLUSIONS

A recent multiwavelength study of NGC 1672 identified multiple bright X-ray sources including 9 ULX candidates. In this study, we performed an optical, spectral, and a temporal analysis of those 9 ULX candidates. We deployed archival optical data from HST, and X-ray data from Chandra, XMM-Newton, and Swift-XRT. Specifically, our study focuses on using the precise source positions obtained via improved astrometry based on the Chandra and HST observations to search for and identify potential optical counterparts for the ULX candidates. We summarize our main findings as follows:

(i) We identified unique optical counterparts for X2 and X6.

(ii) In the case of X1, X5 and X7, we were able to isolate two optical counterparts for each source.

(iii) No optical counterparts were found for X3, X8 and X4 within the respective error circles. The source X9, unfortunately did not have any HST data, so it could not be investigated further.

(iv) Photometric results of bright star groups in the vicinity of X1 and X7 suggest that their counterparts have similar properties to the nearby stars.

(v) We constructed CMDs to estimate the age of the optical counterparts ($X1_1$ and $X7_1$). The extracted age values of $X1_1$ are the order of ≤ 20 Myr, whereas $X7_1$ is somewhat older i.e., 25-30 Myr.

(vi) The absolute magnitudes ($-5 <M_V < -7.5$) and spectral types (B-A) of the identified optical counterparts in NGC 1672 are compatible with optical companions of ULXs in other galaxies; see Gladstone et al. (2013) and Tao et al. 2011. Moreover, the optical counterparts appear to be faint in the V-band and relatively brighter in the UV band.

(vii) The SED for the counterpart $X1_1$ is well-fitted with power-law, $F_{\lambda} \propto \lambda^{\alpha}$, with a photon index, $\alpha = -2.13$ and also shows 0.6 mag. variability in UV. These findings are consistent with optical emission arising primarily from an accretion disk. Furthermore, the SED of $X2_1$ is adequately fitted with a blackbody model and a temperature of $10^5$ K. In this case, the emission could come from the donor star and/or result from irradiation of the disk.

(viii) The sources X5 and X9 exhibit high X-ray variability, with the flux varying by factor of ~ 30 and 50 times, respectively, over observations spanning a time period of 2004 to 2019. Due to the sparse coverage of the data, it is difficult to interpret that the high variability exhibits bi-modal flux distribution that could indicate the propeller effect. This level of variability together with the fact that X9 displays a partial q-curve track in the hardness-intensity diagram (possibly indicating spectral transitions) makes it an interesting source for further investigation.

ACKNOWLEDGEMENTS

This research was supported by the Scientific and Technological Research Council of Turkey (TÜBİTAK) through project number 119F315. ES and KD acknowledge support provided by the TÜBİTAK through project number 119F334.
Figure 1. Three-color X-ray (upper left XMM-Newton, upper right Chandra and lower left Swift-XRT) and HST (lower right) images of the NGC 1672 galaxy. For X-ray images, red, green and blue (RGB) represent 0.3–1 keV, 1–2.5 keV and 2.5–8 keV emissions, respectively and images smoothed with a 5" Gaussian. The ULX candidates are indicated with dashed white circles. Red circles represent the positions of 8 ULXs on the HST RGB image (R:F814W, G:F550M and B:F435W). The X9 is not in the field of view of the HST images. All X-ray images are the same scale.

DATA AVAILABILITY

The scientific results reported in this article are based on archival observations made by the Chandra8, XMM-Newton9 and Swift-XRT10 X-ray Observatories. This work has also made use of observations made with the NASA/ESA Hubble Space Telescope, and obtained from the data archive at the Space Telescope Science Institute11.

REFERENCES

Aird J., et al., 2010, MNRAS, 401, 2531
Akyuz A., Avdan S., Allak S., Aksaker N., Akkaya Oralhan I., Balman S., 2020, MNRAS, 499, 2138
Allak S., et al., 2022, MNRAS, 510, 4355
Aller L. H., et al., eds, 1982, Landolt-Börnstein: Numerical Data and Functional Relationships in Science and Technology - New Series “ Group/Group 6 Astronomy and Astrophysics ” Volume 2 Schaifers/Voigt: Astronomy and Astrophysics / Astronomie und Astrophysik ” Stars and Star Clusters / Sterne und Sternhaufen
Ambrosi E., Zampieri L., 2018, MNRAS, 480, 4918
Arnaud K. A., 1996, in Jacoby G. H., Barnes J., eds, Astronomical Society of the Pacific Conference Series Vol. 101, Astronomical Data Analysis Software and Systems V. p. 17
Bachetti M., et al., 2014, Nature, 514, 202
Barnard R., Kolb U., Osborne J. P., 2003, A&A, 411, 553
Begelman M. C., 2002, ApJ, 568, L97
Belloni T. M., 2010, in Belloni T., ed., , Vol. 794, Lecture Notes in Physics, Berlin Springer Verlag. p. 53, doi:10.1007/978-3-540-76937-8_3
Bressan A., Marigo P., Girardi L., Salasnich B., Dal Cero C., Rubele S., Nanni A., 2012, MNRAS, 427, 127
Brightman M., et al., 2020, ApJ, 895, 127
Carpano S., Habel F., Maitra C., Vasilopoulos G., 2018, MNRAS, 476, L45
Castelli F., Kurucz R. L., 2004, A&A, 419, 725
Chandar R., Johns P., Mok A., Prestwich A., Gallo E., Hunt Q., 2020, ApJ, 890, 150
Colbert E. J. M., Mushotzky R. F., 1999, ApJ, 519, 89
Copperwheat C., Cropper M., Soria R., Wu K., 2007, MNRAS, 376, 1407
Dolphin A. E., 2000, PASP, 112, 1383
Done C., Gierliński M., 2003, MNRAS, 342, 1041
Earnshaw H. P., Roberts T. P., Sathiyaparakash R., 2018, MNRAS, 476, 4272
Egorov O. V., Lozinskaya T. A., Meosev A. V., 2017, MNRAS, 467, L1
Fabrika S. N., Atapin K. E., Vinokurov A. S., Sholukhova O. N., 2021, Astrophysical Bulletin, 76, 6
Fürst F., et al., 2016, ApJ, 831, L14
Gladstone J. C., Copperwheat C., Heinke C. O., Roberts T. P., Cartwright T. F., Levan A. J., Goad M. R., 2013, ApJS, 206, 14
Gris F., Kaaret P., Pakull M. W., Moc H., 2011, ApJ, 734, 23
Gris F., Kaaret P., Corbel S., Feng H., Cseh D., Tao L., 2012, ApJ, 745, 123
Heida M., et al., 2014, MNRAS, 442, 1054
Heida M., et al., 2015, MNRAS, 453, 3510
Heida M., Jonker P. G., Torres M. A. P., Roberts T. P., Walton D. J., Moon D. S., Stern D., Harrison F. A., 2016, MNRAS, 459, 771
Hunt Q., Gallo E., Chandar R., Johns Muliya P., Mok A., Prestwich A., Liu S., 2021, ApJ, 912, 31
Israel G. L., et al., 2017a, Science, 355, 817
Israel G. L., et al., 2017b, MNRAS, 466, L48
Jenkins L. P., et al., 2011, ApJ, 734, 33
Johns Muliya P., Chandar R., Rangelov B., 2019, ApJ, 871, 122
Jonker P. G., et al., 2012, ApJ, 758, 28
Kaaret P., Feng H., Roberts T. P., 2017, ARA&A, 55, 303
King A. R., 2009, MNRAS, 393, L41
King A., Lasota J.-P., 2016, MNRAS, 458, L10
Liu J., 2011, ApJS, 192, 10
López K. M., Heida M., Jonker P. G., Torres M. A. P., Roberts T. P., Walton D. J., Moon D. S., Harrison F. A., 2017, MNRAS, 469, 671
López K. M., Heida M., Jonker P. G., Torres M. A. P., Roberts T. P., Walton D. J., Moon D. S., Harrison F. A., 2020, MNRAS, 497, 917

8 https://cda.harvard.edu/chaser/
9 http://nxsa.esac.esa.int/nxsa-web/
10 https://www.swift.ac.uk/swift_portal/
11 https://mast.stsci.edu/portal/Mashup/ clients/Mast/Portal.html
Table 1. The log of optical and X-ray observations.

| Instrument       | ObsID     | Date (YYYY-MM-DD) | Exp (ks) | Filter |
|------------------|-----------|-------------------|----------|--------|
| **Optical observations** |           |                   |          |        |
| ACS/WFC         | j95801010a | 2005-08-01        | 2.44     | F435W  |
| ACS/WFC         | j95801020a | 2005-08-01        | 2.44     | F550M  |
| ACS/WFC         | j95801040a | 2005-08-01        | 2.44     | F658N  |
| ACS/WFC         | j95801030a | 2005-08-01        | 2.44     | F814W  |
| WFC3/UVIS       | idxr12040b | 2019-06-24        | 2.87     | F275W  |
| WFC3/UVIS       | idxr12030b | 2019-06-24        | 2.48     | F336W  |
| WFC3/UVIS       | idxr12050b | 2019-06-24        | 1.50     | F555W  |
| WFC3/UVIS       | idxr13040c | 2019-06-25        | 2.87     | F275W  |
| WFC3/UVIS       | idxr13030c | 2019-06-25        | 2.48     | F336W  |
| WFC3/UVIS       | idxr12050c | 2019-06-26        | 1.50     | F555W  |
| WFC3/UVIS       | ieb336020b | 2020-11-27        | 0.71     | F336W  |
| **X-ray observations** |       |                   |          |        |
| XMM-Newton      | 0203880101 | 2004-11-27        | 49.91    |        |
| Chandra          | 5932      | 2006-04-30        | 40.00    |        |
| Swift-XRT       | 35882001  | 2006-12-19        | 1.84     |        |
| Swift-XRT       | 35882002  | 2007-03-18        | 2.43     |        |
| Swift-XRT       | 35882003  | 2007-10-31        | 1.01     |        |
| Swift-XRT       | 46271001  | 2012-01-14        | 0.77     |        |
| Swift-XRT       | 46271002  | 2012-09-06        | 1.11     |        |
| Swift-XRT       | 46271003  | 2012-09-08        | 0.49     |        |
| Swift-XRT       | 46271004  | 2012-09-13        | 0.55     |        |
| Swift-XRT       | 46271005  | 2012-10-07        | 8.87     |        |
| Swift-XRT       | 46271006  | 2012-10-12        | 7.56     |        |
| Swift-XRT       | 35882005  | 2017-08-16        | 1.99     |        |
| Swift-XRT       | 35882006  | 2017-08-17        | 1.85     |        |
| Swift-XRT       | 35882008  | 2017-08-20        | 2.23     |        |
| Swift-XRT       | 35882009  | 2017-08-21        | 2.96     |        |
| Swift-XRT       | 95188001  | 2019-07-16        | 0.65     |        |
| Swift-XRT       | 95188002  | 2019-07-22        | 0.88     |        |
| Swift-XRT       | 95188004  | 2019-12-04        | 0.69     |        |

*a These observations cover the eight ULXs (X1-X8), b X1, X5 and X6 c X2, X3, X4, X7 and X8 positions.

Lusso E., et al., 2010, A&A, 512, A34
Middleton M. J., King A., 2017, MNRAS, 470, L69
Middleton M. J., Brightman M., Pintore F., Bachetti M., Fabian A. C., Fürst F., Walton D. J., 2019, MNRAS, 486, 2
Miller J. M., Fabian A. C., Miller M. C., 2004, ApJ, 614, L117
Motch C., Pakull M. W., Soria R., Grisé F., Pietrzyński G., 2014, Nature, 514, 198
Patruno A., Zampieri L., 2008, MNRAS, 386, 543
Patruno A., Zampieri L., 2010, MNRAS, 403, L69
Poutanen J., Lipunova G., Fabrika S., Butkevich A. G., Abolmasov P., 2007, MNRAS, 377, 1187
Poutanen J., Fabrika S., Valeev A. F., Sholukhova O., Greiner J., 2013, MNRAS, 432, 506
Remillard R. A., McClintock J. E., 2006, ARA&A, 44, 49
Rice J. R., Rangelov B., Prestwich A., Chandar R., Boldt C., 2021, ApJ, 922, 178
Roberts T. P., 2007, Ap&SS, 311, 203
Rodríguez Castillo G. A., et al., 2020, ApJ, 895, 60
Sathyaprakash R., et al., 2019, MNRAS, 488, L35
Schlafly E. F., Finkbeiner D. P., 2011, ApJ, 737, 103
Sonbas E., Dhuga K. S., Göğüş E., 2019, ApJ, 873, L12
Song X., Walton D. J., Lansbury G. B., Evans P. A., Fabian A. C., Earnshaw H., Roberts T. P., 2020, MNRAS, 491, 1260
Soria R., Hakala P. J., Hau G. K. T., Gladstone J. C., Kong A. K. H., 2012a, MNRAS, 420, 3599
Soria R., Kunz K. D., Winkler P. F., Blair W. P., Long K. S., Placinski P. P., Whitmore B. C., 2012b, ApJ, 750, 152
Straizys V., Kurilene G., 1981, ApSS, 80, 353
Sutton A. D., Done C., Roberts T. P., 2014, MNRAS, 444, 2415
Tananbaum H., et al., 1979, ApJ, 234, L9
Tao L., Feng H., Grisé F., Kaaret P., 2011, ApJ, 737, 81
Tikhonov N. A., Galazutdinova O. A., 2020, Astrophysical Bulletin, 75, 384
Urquhart R., Soria R., Johnston H. M., Pakull M. W., Motch C., Schoewe A., Miller-Jones J. C. A., Anderson G. E., 2018, MNRAS, 475, 3561
Vagnetti F., Antonucci M., Trevese D., 2013, A&A, 550, A71
Vinokurov A., Fabrika S., Atapin K., 2018, ApJ, 854, 176
Walton D. J., et al., 2018, ApJ, 857, L3
Wiktorewicz G., Lasota J.-P., Middleton M., Belczynski K., 2019, ApJ, 875, 53
Yao Y., Feng H., 2019, ApJ, 884, L3
de Naray P. J., Brandt W. N., Halpern J. P., Iwasawa K., 2000, AJ, 119, 612

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### Table 2. Coordinates of the X-ray/optical reference sources and ULXs.

| Source number | Chandra R.A. (hh:mm:ss.sss) | Chandra Dec. (° : ′ : ″) | Net Counts<sup>a</sup> | HST R.A. (hh:mm:ss.sss) | HST Dec. (° : ′ : ″) | Offset<sup>b</sup> (") |
|---------------|-----------------------------|---------------------------|------------------------|------------------------|------------------------|----------------------|
| Ref.1         | 4:45:53.305                | -59:15:28.02              | 70.65 ± 8.54           | 4:45:53.313            | -59:15:27.95           | 0.17                 |
| Ref.2         | 4:45:44.536                | -59:15:35.21              | 37.62 ± 6.25           | 4:45:44.541            | -59:15:35.14           | 0.13                 |
| Ref.3         | 4:45:36.973                | -59:16:54.91              | 13.87 ± 3.87           | 4:45:36.989            | -59:16:54.76           | 0.35                 |
| Ref.4         | 4:45:29.833                | -59:15:07.04              | 62.54 ± 8.06           | 4:45:29.847            | -59:15:07.05           | 0.20                 |

**Chandra** and corrected optical coordinates of optical counterparts

| X1            | 4:45:52.823                | -59:14:56.15              | 1305.25 ± 36.51        | 4:45:52.834            | -59:14:56.08           | 0.21                 |
| X2            | 4:45:31.603                | -59:14:54.68              | 955.95 ± 31.26         | 4:45:31.612            | -59:14:54.59           | 0.21                 |
| X3            | 4:45:33.965                | -59:14:42.03              | 771.71 ± 28.07         | 4:45:33.975            | -59:14:41.93           | 0.21                 |
| X4            | 4:45:42.166                | -59:14:52.17              | 480.53 ± 29.91         | 4:45:42.175            | -59:14:52.08           | 0.21                 |
| X5            | 4:45:50.996                | -59:14:22.96              | 214.59 ± 14.83         | 4:45:51.006            | -59:14:22.87           | 0.21                 |
| X6            | 4:45:54.289                | -59:14:10.44              | 144.52 ± 12.29         | 4:45:54.299            | -59:14:10.35           | 0.21                 |
| X7            | 4:45:35.078                | -59:14:12.68              | 125.82 ± 11.40         | 4:45:35.087            | -59:14:12.59           | 0.21                 |
| X8            | 4:45:28.453                | -59:14:33.39              | 105.65 ± 10.39         | 4:45:28.463            | -59:14:33.30           | 0.21                 |
| X9<sup>d</sup> | 4:45:34.317                | -59:12:55.95              | 61.70 ± 8.00           | ...                    | ...                    | ...                 |

**Position uncertainty (")**:  

- <sup>a</sup>The Chandra counts are given in the 0.3-10 keV energy range with 1-σ errors using XSPEC.
- <sup>b</sup>Offsets are given at 95% confidence level of the Chandra/HST reference sources.
- <sup>c</sup>Position uncertainties (error radius) are given at 95% confidence level.
- <sup>d</sup>X9 was not observed by HST.

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**Figure 2.** The identified optical counterparts of the five ULXs are shown on the F814W images. Red dashed circles indicate the astrometric error radius of the optical counterparts given in Table 2. Blue dashed circles represent the center coordinates of each optical counterpart. North is up and east is left in all panels. Panels (a-e) are the same scale. In panel f shows positions of ULXs which have optical counterparts on the DSS image.
### Table 3. The calculated dereddened Vega magnitudes and fluxes of the possible optical counterparts.

| Source | UVIS/F275W | UVIS/F336W | UVIS/F555W | ACS/F435W | ACS/F550M | ACS/F658N | ACS/F814W |
|--------|------------|------------|------------|-----------|-----------|-----------|-----------|
|        | Vega Magnitude         |            |            |            |            |            |            |
|        | Flux \(10^{-18}\) (erg cm\(^{-2}\) s\(^{-1}\) \(\text{Å}^{-1}\))     |            |            |            |            |            |            |
| \(X_1\) | 22.37 ± 0.05 | 22.63 ± 0.04 | 24.16 ± 0.04 | 23.90 ± 0.03 | 23.93 ± 0.05 | 23.12 ± 0.44 | 24.01 ± 0.17 |
| \(X_1\) | ...         | ...         | ...         | ...         | ...         | ...         | ...         |
| \(X_2\) | 22.84 ± 0.04 | 22.46 ± 0.03 | 23.58 ± 0.03 | 23.64 ± 0.02 | 23.61 ± 0.04 | 23.33 ± 0.20 | 23.56 ± 0.03 |
| \(X_5\) | 24.19 ± 0.51 | 24.37 ± 0.11 | 25.99 ± 0.33 | 24.77 ± 0.08 | 24.85 ± 0.23 | 24.80 ± 0.43 | 24.74 ± 0.18 |
| \(X_7\) | 25.27 ± 0.17 | 24.48 ± 0.12 | 24.95 ± 0.16 | ...         | ...         | ...         | ...         |
| \(X_8\) | ...         | ...         | ...         | ...         | ...         | 25.33 ± 0.11 | ...         |
| \(X_6\) | 23.75 ± 0.11 | 24.12 ± 0.08 | 25.72 ± 0.10 | 24.63 ± 0.07 | 24.78 ± 0.12 | 24.95 ± 0.65 | 24.97 ± 0.13 |
| \(X_7\) | 25.84 ± 0.85 | 24.40 ± 0.41 | 24.12 ± 0.13 | ...         | ...         | ...         | ...         |

### Table 4. Properties of optical counterparts

| Optical counterparts | \(M_V^{\text{ACS}}\) (1) | \(M_V^{\text{UVIS}}\) (2) | (B-V)
|----------------------|-----------------|-----------------|-----------------|
| \(X_1\)             | -7.13 ± 0.05    | -6.90 ± 0.4     | -0.03           |
| \(X_2\)             | -7.45 ± 0.04    | -7.48 ± 0.3     | 0.03            |
| \(X_5\)             | -6.21 ± 0.23    | -5.10 ± 0.35    | -0.08           |
| \(X_7\)             | -6.16 ± 0.12    | -5.34 ± 0.11    | -0.15           |
| \(X_8\)             | -5.22 ± 0.85    | ...             | ...             |

### Table 5. The diskbb model parameters of three ULXs from the Chandra observation

| Source | \(N_H\) (1) | \(N_d\) (2) | \(T_{\text{in}}\) \(\text{k}\) (3) | \(F_{\text{umb}}\) (4) | \(L_X\) (5) \(\text{ergs}\) (6) | \(P\) (7) |
|--------|------------|------------|-----------------|-----------------|-----------------|---------------|
| \(X_1\) | 0.08 ± 0.02 | 2.94 ± 1.57 | 1.50 ± 0.02     | 3.10 ± 0.14     | 9.8 ± 0.46      | 0.73          |
| \(X_2\) | 0.01 ± 0.01 | 3.30 ± 1.56 | 1.28 ± 0.02     | 1.81 ± 0.10     | 5.7 ± 0.51      | 0.63          |
| \(X_6\) | 0.84 ± 0.22 | 1.07 ± 0.62 | 1.25 ± 0.05     | 0.57 ± 0.08     | 1.82 ± 0.27     | 0.76          |

Notes: Absolute magnitudes were obtained (1) from ACS/WFC (2) from ACS/UVIS data with adopted distance 16.3 Mpc (de Naray et al. 2000). (3) and (4) Color values obtained from F435W-F550M (B-V) and F550M-F814W (V-I) filters, respectively. (5) Spectral types estimated from the color values. (6) The \(F_X/F_V\) ratios. (7) X-ray-UV correlation cast in terms of the so-called optical spectral index \(\alpha_{OX}\).
Figure 3. The reddening corrected SED of X1_1. The power-law model is shown by blue solid line. All data are shown with dark circles and their respective errors with bars. The power-law model has $\alpha = -2.13 \pm 0.16$. The units of y and x axes are erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ and Å, respectively.

Figure 4. The reddening corrected SED of X2_1. The blackbody model is shown by blue solid line. All data are shown with dark circles and their respective errors with bars. The blackbody has a temperature of $\sim 10^4$ K. The units of y and x axes are erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ and Å, respectively.

Figure 5. Upper: Optical counterparts of X1 and their environments are shown on the HST RGB image. Two large groups of stars are indicated by two white rectangles (C1 and C2) with the size of (2.0"×5") on the image. Zoomed view of the optical counterparts for clarity is given upper right. Lower: CMD for the X1_1, two group of stars and field stars around X1_1. The red star, black and gray dots represent the X1_1, field stars within C1 and C2, respectively. The isochrones have been corrected for extinction of $A_V = 0.065$ mag and the black arrow shows the reddening line.
Figure 6. Upper: Optical counterparts of X7 and their environments are shown on the HST RGB image. A large group of stars is indicated by a white circle with 2.5" radius. Zoomed view of the optical counterparts for clarity is given upper right. Lower: CMD for the X7, a large group of stars, and field stars around X7. The red square and black dots represent the X7 and field stars within the given region. The isochrones have been corrected for extinction of $A_V = 0.065$ mag and the black arrow shows the reddening line.

Figure 7. HST/WFC F658N filter image showing the Hα Nebula around ULX X1. The position of X1 is shown within the astrometric error radius (green circle). White contour levels are plotted on the image.
Figure 8. Energy spectra of X1 (upper), X2 (center) and X6 (lower) by using Chandra data in the 0.3–10 keV energy range. The spectra were fitted with an diskbb model. The units of delchi is (data-model)/error.

Figure 9. Upper: The long-term X-ray light curve for the ULX candidates which have optical counterparts. The vertical arrows represent 3σ upper limits when the source is not detected. Lower: The long-term X-ray light curve of X9. In both panels the solid line indicates the mean value of the X-ray flux; a measure of the variability is provided by the ± 3σ levels shown as dotted lines. Observations are from XMM-Newton (2004), Chandra (2006) and Swift-XRT (2007; 2012;2017 and 2019).
**Figure 10.** Left panel: The hardness-intensity diagram (HID) for X2 (empty circles) and X6 (filled triangles). Right panel: The HID for X1 (filled circles), X5 (empty squares) and X7 (empty triangles). The downward arrows indicate the $3\sigma$ upper limits where the X5 source cannot be detected. In both panels, black, blue and red colors represent *Chandra*, *XMM-Newton* and *Swift-XRT* observations, respectively.

**Figure 11.** The HID for X9 suggestive of a partial q-curve pattern.
Figure 12. The long-term variation of the hardness ratios of X1, X2, X5, X6 and X7 (upper) and X9 (lower). The downward arrows indicate the 3σ upper limits where the X5 source cannot be detected. Observations are from XMM-Newton (2004), Chandra (2006) and Swift-XRT (2007; 2012, 2017 and 2019). The same symbols given in Figure 9 are used.