Optical Counterparts of ULXs and Their Host Environments in NGC 4490/4485

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Abstract

We report the identification of the possible optical counterparts of five out of seven ultraluminous X-ray sources (ULXs) in the galaxy pair NGC 4490/4485. Using archival Hubble Space Telescope (HST) imaging data, we identified a single optical candidate for two ULXs (X-4 and X-7) and multiple optical candidates for the other three (X-2, X-3, and X-6) within ~0″.2 error radius at the 90% confidence level. Of the two remaining ULXs, X-1 has no HST imaging data, and photometry could not be performed due to the position of X-5 in NGC 4490. Absolute magnitudes ($M_V$) of the optical candidates lie between $-5.7$ and $-3.8$. Color–magnitude diagrams have been used to investigate the properties of the counterparts and their environments. The locations of the counterparts of X-2, X-4, and X-6 suggest possible association with a nearby group of stars, while the others have no association with a star cluster or group of stars. For comparison purposes, we analyzed three previously unused archival XMM-Newton observations. The long-term X-ray light curves of the sources (except transient X-7) show variability by a factor of three on a timescale of more than a decade. The use of a disk blackbody model for the mass of the compact objects indicates that these objects most likely have masses in the range 10–15 $M_\odot$.

Key words: galaxies: individual (NGC 4490/4485) – X-rays: general

1. Introduction

Ultraluminous X-ray sources (ULXs) are non-nuclear point-like sources in external galaxies with an X-ray luminosity exceeding the Eddington limit for a stellar-mass black hole ($L_X \gtrsim 10^{39}$ erg s$^{-1}$). Few scenarios have been suggested to explain their high luminosities. According to two common ones, accretors in ULXs are either intermediate-mass black holes with standard accretion disks or stellar-mass black holes with supercritical disks. Recent studies promote stellar-mass black holes as accretors in ULXs (Liu et al. 2013; Motch et al. 2014; Fabrika et al. 2015). On the other hand, the recent discoveries of four ULXs that exhibited pulsed X-ray emission as expected from neutron stars, make their nature highly controversial (M82 X-2, Bachetti et al. 2014; NGC 5907 ULX-1, Israel et al. 2017a; NGC 7793 P13, Fürst et al. 2016; Israel et al. 2017b; and NGC 300 ULX1, Carpano et al. 2018).

Multiwavelength observations of ULXs have played a key role in investigations of their emission mechanisms and environments. In particular, identification of the possible optical counterparts of ULXs and their broadband photometry allow us to constrain the mass and spectral type of the companion star. It is known that the best way to determine the mass of compact objects in ULXs is through dynamical mass measurements of the binary system. However, it is difficult to obtain the radial velocity curve and measure the mass function because the counterparts of ULXs are faint sources in the optical band ($m_V = 21–24$; Tao et al. 2011). Using ground-based telescopes and the Hubble Space Telescope (HST), possible optical candidates of about 20 ULXs have been identified so far. Such studies may provide information about the donor star (e.g., age, mass, and spectral type), the host cluster and the origin of optical emission (from accretion disk and/or donor star; Kaaret et al. 2017).

Observations of the optical counterparts revealed that some of the ULXs are associated with young star clusters or star-forming regions (Kaaret 2005; Soria et al. 2005; Abolmasov et al. 2007a; Grisé et al. 2008, 2011, 2012; Avdan et al. 2016a, 2016b). These findings have been supported by identifying point-like counterparts of ULXs with blue colors that are indicative of early-type, OB stars (Liu et al. 2004; Soria et al. 2005; Roberts et al. 2008; Poutanen et al. 2013). These blue colors are consistent with emission from an irradiated accretion disk; however, it is noticed that the observed blue color may be partly due to contamination 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). However, in only one case (P13 in NGC 7793) have photospheric absorption lines been detected from the donor star in the blue part of the spectrum (Motch et al. 2014). Furthermore, the association between young star clusters and ULXs implies that some of the donor stars might be red supergiants and these donors could be identified in the near-infrared band. The systematic search for counterparts in the near-infrared (H band) revealed that they are bright sources (Heida et al. 2014, 2016; López et al. 2017). This could be important because the contribution of the accretion disk is lower in the near-infrared band than in the optical band. In addition, it is expected that the irradiation of donors of these binaries with large separations does not have a
significant effect on observed emission (Copperwheat et al. 2007; Heida et al. 2016).

Associations between ULXs and star clusters have also been studied in interacting galaxies. The latter are known to host a higher average number (>5) of ULXs. Therefore, they are good candidates in which to examine the properties of the population of ULXs. Poutanen et al. (2013) extensively examined the significant associations between ULXs and stellar clusters in the Antennae galaxies. Using data from HST and the Very Large Telescope supplemented with theoretical stellar isochrones, they estimated the ages of these clusters as <6 Myr. It was discussed that these ULXs were probably ejected from the cluster in the evolutionary process; thus these sources might be high-mass X-ray binaries instead of intermediate-mass black holes. Another well-known interacting galaxy is NGC 4490/NGC 4485 at a distance of 7.8 Mpc (Tully 1988). NGC 4490 is a late-type spiral galaxy and NGC 4485 is an irregular galaxy. Their linear sizes are 15 kpc for NGC 4490 and 5.6 kpc for NGC 4485. Radio observations show that star formation in NGC 4490 has been ongoing at a constant rate of \( \sim 4.7 M_\odot \text{yr}^{-1} \) (Clemens et al. 1999). Also, NGC 4490 has a giant H I envelope that probably originated from the star formation (Clemens & Alexander 2002). Our aim in this study is to identify the possible optical counterparts of ULXs in this galaxy pair and to investigate their associations with star groups or clusters. Previously, three ULXs in this pair were detected by ROSAT HRI observations (Roberts & Warwick 2000). Later, using a Chandra ACIS-S observation, three more ULXs were identified by Roberts et al. (2002). The calculated unabsorbed luminosities of six ULXs (in the 0.5–8 keV band) fall into the range (2.6–4.9) \( \times 10^{39} \text{erg s}^{-1} \). In addition, Roberts et al. noted that these ULXs appear to be spatially coincident with the star formation regions in the pair. Further, Fridriksson et al. (2008) searched for long-term variability of 38 X-ray sources in this galaxy pair using three Chandra observations. Eight of these sources were classified as ULXs in the luminosity range (0.6–3) \( \times 10^{39} \text{erg s}^{-1} \). One of them is a transient ULX detected in a single observation (ID 4726). Gladstone & Roberts (2009) investigated spectral and temporal features of seven ULXs (except for ULX X-5—this source was ignored because of its low luminosity of \( L_X \sim 6 \times 10^{38} \text{erg s}^{-1} \), which was given in Table 5 of Fridriksson et al. 2008) using the same Chandra and XMM-Newton data sets. The \( L_X \) values of these sources are given in the range (0.9–4) \( \times 10^{39} \text{erg s}^{-1} \) within the 0.5–8 keV energy band. Six of these seven sources (except the transient one, which is X-7 in this paper) were classified as ULXs by Swartz et al. (2011).

In the present work, the possible optical counterparts of these seven ULXs in the galaxy pair NGC 4490/4485 have been searched for extensively using archival HST and XMM-Newton data. The results from the analysis for the five optically identified ULXs (X-2, X-3, X-4, X-6, and X-7) are discussed. The optical spectra of the environment of ULXs obtained by the BTA 6 m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS) are also examined. A three-color Sloan Digital Sky Survey (SDSS) image of this galaxy pair with the approximate positions of seven ULXs (X-1 to X-7)\(^{10}\) is given in Figure 1.

The paper is organized as follows. Data reduction and results are described in Section 2. The details and results of the optical analyses are given in Sections 2.1–2.3. The X-ray observations are described in Section 2.4. Discussion of the physical properties of the ULXs and conclusions are given in Section 3.

2. Data Reduction and Results

2.1. HST Observations and Astrometry

Identification of the optical candidates of the ULXs in the galaxy pair requires precise source positions. For this, an intercomparision of Chandra, HST, and SDSS images was carried out to obtain improved astrometry. For the target astrometric correction, we have chosen a deep Chandra Advanced CCD Imaging Spectrometer (ACIS) observation (ID 4726) and two HST observations with the Advanced Camera for Surveys (ACS, data set j9h07020) and Wide Field Camera 3 (WFC3, icdm42060). The counterpart of X-2 was located on ACS images while other counterparts were located on the WFC3 image. Logs of HST observations are given in Table 1.

Source detections in the Chandra image were carried out using the WAVEDETECT task in CIAO. All ULXs are located on chip S3 of ACIS with a moderate offset to the optical axis from 1′59 to 2′3. Due to lack of the good X-ray/optical reference sources in the HST field, the offsets between Chandra and HST were corrected using the SDSS r-band image (Alam et al. 2015). Two relatively bright objects on the SDSS image were identified as the X-ray reference sources (given in Table 2). The brightest source s1 has 615 photons detected by Chandra with a statistical error radius of 0′6 at 90% confidence level (offset to the optical axis is about 1′/8). s2 has a large offset to the optical axis of 3′3, and for this source there only 62 photons detected by Chandra. Therefore, its positional uncertainty at 90% is about 0′5. Because of the big position error of s2 we derived the offset between ACIS and SDSS images using only s1 (Table 2). Nevertheless we note that both reference sources give nearly the same offset values.

Since the rotation of the X-ray image cannot be fixed with a single reference source, we used the estimation of rotation accuracy by Yang et al. (2011). From a few Chandra observations with multiple optically identified X-ray sources, the authors obtained a typical rotation about 2′ between Chandra and the Two Micron All Sky Survey. Using this value and distances between the ULXs and reference source s1 (about 200′), the typical error caused by rotation is about 0′1. Combining in quadrature these errors and the uncertainties of ULX positions on the ACIS image, and also the uncertainties of the s1 position on both ACIS and SDSS images, we estimate that the ULX positions corrected to SDSS have uncertainties of about 0′2/2 at the 90% confidence level (Table 2). On the other hand, using 10 bright isolated reference stars on each HST image, we derived shifts between SDSS and HST images with uncertainties better than 0′04 at 90%. The corrected positions of the ULXs relative to HST are shown in Table 2. The main uncertainty is between Chandra and SDSS, all other errors are significantly smaller.

After astrometric correction, possible optical counterparts were identified for only five ULXs out of seven. While a single candidate each was found for X-4 and X-7, more than one candidate was identified for each of X-3, X-2, and X-6 within their error circles. Photometry could not be performed for X-5

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\(^{10}\) Sources are named from X-1 to X-6 in order of increasing R.A. as given in Table 1 of Swartz et al. (2011), and X-7 is named from Gladstone & Roberts (2009).
and X-1 because X-5 is located within the luminous part of the galaxy and X-1 has not been observed with HST.

The magnitudes of the counterpart candidates were calculated using the point-spread function (PSF) photometry. PSF was determined with DOLPHOT software (version 2.0, Dolphin 2000) for WFC3 and ACS data. Standard image reduction algorithms (bias and dark current subtraction, flat-fielding) have been applied to FITS files retrieved from HST data. The WFC3MASK, ACSMASK, and SPLITGROUPS tasks were used to mask out all the bad pixels and split the multi-image FITS files into a single file per chip. Then the DOLPHOT task was used for source detection, photometry, and photometric conversion. The magnitudes were derived in the VEGA magnitude system used for WFC3 and ACS data. The magnitudes of the counterparts were corrected for the total extinction determined from ratios of Balmer lines of several nebulae around the candidates. Therefore, the spectral data obtained from the 6 m BTA telescope were used to determine Balmer lines.

### 2.2. BTA Observations

The ground-based optical spectral observations of the stellar association were made with the SCORPIO instrument at the 6 m BTA telescope of the SAO RAS (Afanasiev & Moiseev 2005). The observations were carried out on 2011 January 4 (4800 s) for X-3 and X-6 and on 2016 March 13 (2400 s) for X-4. The VPHG550G grism (3500–7200 Å) and 1″ slit were used for all observations, where the seeing was about 2–3 arcsec.

The standard data reduction steps were carried out with IRAF software. Wavelength calibrations were done using neon lamps. The spectral data of the standard stars taken on the ground-based telescope were converted into 1D spectra using the APALL task in IRAF.

Strong emission lines such as Hβ (λ4861), [O III] (λλ4959, 5007), Hα (λ6563), and [S II] (λλ6717+6731) were identified in the whole spectral data set. We estimated an average redshift value from these emission lines as \( z \sim 0.0017 \). This value is compatible with the redshift of the galaxy NGC 4490 (\( z_{\text{ga}} \sim 0.0018 \); Strauss et al. 1992).

Several nebulae were identified around the ULXs within the different slit positions having strong Hβ, [O III], and Hα lines in the spectra. The Hα and Hβ fluxes of the nebulae were
measured to determine the observed Balmer decrement and corresponding reddening $E(B - V)$ value. To determine $E(B - V)$, the standard value of $\langle OH/H \rangle_{\text{int}} = 2.87$ for star-forming galaxies was adopted, which corresponds to an electron density $n_e = 10^2 \text{ cm}^{-3}$ and temperature $T = 10^4 \text{ K}$ for Case B of Osterbrock (1989) (Calzetti et al. 1994; Calzetti 2001). Finally, these values were converted to $A_V$ using the Cardelli law (Cardelli et al. 1989) in order to correct for reddening. These $A_V$ values and the distances of ULXs to the nebulae are given in Table 3. In these calculations, the uncertainties in the distances are estimated to lie in the range $\sim 0''5$–$0''8$ (38 pc/1″).

### 2.3. The Properties of Optical Counterparts

In this section, the individual optical properties of the possible counterpart candidates are given in detail.

X-2: This source was identified in several data sets listed in Table 1. By carefully examining all the images, X-2 seems to have a faint structure compatible with an extended source within the 0″15 error radius (see Figure 2). At about 2″ to the southeast of X-2, a small group of stars with an extent of $\sim 136$ pc diameter is indicated by a circle on the F814W image in Figure 2. As a result of PSF photometry of X-2, three optical sources have been identified as counterpart candidates within the error circle. Previously the optical counterpart of X-2 was studied by Roberts et al. (2008) using only HST data from the year 2005. They reported only one possible optical counterpart based on a $\sim 0''6$ error on the astrometric precision of the X-ray source position.

Dereddened magnitudes and color values of counterparts of X-2 obtained after photometric analysis are given in Table 4. To determine the ages and masses of counterpart candidates we constructed color–magnitude diagrams (CMDs) using isochrones from the Padova and Trieste Stellar Evolution Code (PARSEC; Bressan et al. 2012), on which extinction values ($A_V$ and $A_I$) from the calculated Balmer decrement (see Table 3) are overlaid using a distance modulus of 29.46 for NGC 4490 (Tully 1988). These values are kept fixed to create the CMDs. The metallicity value for NGC 4490 was taken as $Z = 0.005$ (Esposito et al. 2013). One of the resultant CMDs, F814W versus F606W, is given in Figure 3. The mean extinction in the direction of this source was calculated as $E(V - I) = 0.40$. The age and mass of candidate sources src1, src2, and src3 were obtained as $\sim 50, 80, \text{and } 90 \text{ Myr}$ and $\sim 7, 6, \text{and } 5 M_{\odot}$, respectively. Assuming the optical emission of the

![Figure 2. HST/ACS F814W (2014 August 5) images of X-2 (the zoomed image has a size of $1''7 \times 1''2$) on the left and a nearby group of stars (the zoomed image has a size of $7''4 \times 6''3$) on the right. The red circle represents the corrected position of X-2 with an accuracy of $0''21$ radius. Three possible counterparts (black circles, the aperture of PSF fitting is $0''12$ radius) are found within the error radius. In the right panel, the black circle has a radius of $1''7$ and shows the group of stars. The ULX is located $\sim 2''$ away from center of the star group.](image-url)
donor star dominates, the spectral types of the candidate counterparts were determined as B9–A2 supergiant for src1, G0 supergiant for src2, and A7 supergiant for src3, where intrinsic colors and the absolute magnitudes of the Schmidt-Kaler table were used (Aller et al. 1982). The same assumption and procedures were followed to determine the spectral class of all counterpart candidates. In addition, only one of the CMDs created is shown due to the relatively large number of ULXs that have been examined.

The detected group of stars near X-2 does not indicate a homogeneous population. As seen in Figure 3, the CMD yielded diversity in the magnitudes and ages of the stars. However, the optical candidates of X-2 seem to be compatible with the oldest and faintest stars in this group. This may support the possibility that X-2 was ejected from the group.

X-3: After the astrometric correction, two faint candidates for the ULX X-3 were identified. These candidates are located near (~2") the star cluster also cataloged as a super-star cluster (Figure 4) based on the determination of the initial mass function with the data obtained from the SDSS (Dowell et al. 2008). CMDs for these two sources and the nearby super-star cluster are also produced and a diagram of F814W versus F555W is shown in Figure 5. The bright center of the cluster may consist of multiple unresolved sources in all available images of this source. For this reason, a small number of cluster members could be selected by PSF photometry. The HST dereddened magnitudes, colors, and absolute magnitudes of optical candidates are given in Table 5. Possible spectral type of optical candidates for X-3 seem to fall into the interval F2–G8 supergiant for src1 and G0 supergiant for src2.

There is a cataloged super-star cluster ~2" away from X-3. This is a notable feature because the high stellar densities within super-star clusters are the most promising location for the formation of intermediate-mass black holes via merging of massive stars (Kaaret et al. 2017). The core of the cluster is very bright, and therefore not many stars were identified using PSF photometry. The reddened magnitudes of the selected stars in the cluster are in the range $m_V \sim 21$–26 but the counterparts of X-3 are fainter ($m_V \sim 26.9; A_V = 1.5$). The obtained CMD (Figure 5) shows that, while stars in the cluster would have $(V - I)$ colors between $-0.2$ and $1.7$, the color values for the optical candidates are between 1.5 and 2. These values correspond to the upper limit of the color range of the stars. Using the isochrones from the PARSEC code (Bressan et al. 2012) and taking into account extinctions $E(B - V) = 0.48$ mag and $E(V - I) = 0.60$ mag based on the $A_V = 1.5$), we derive the age of the stars as $\leq 30$ Myr. However, the age and mass of the possible optical counterparts of X-3 were estimated as $40–63$ Myr and $\sim 7 M_{\odot}$, respectively. The determined age interval indicates that the possible candidates are quite old compared to the stars in the cluster. In addition to the age difference, the position of the counterparts on the isochrones and their derived spectral type (somewhat evolved F- or G-type supergiant) make it difficult for them to be members of the cluster.

X-4: As Figure 6 shows, a unique possible optical counterpart is visible for X-4. This bright source is clearly observable in all images, making it the most distinctly identified candidate. In its environment there is a small group of stars ~1” away from the source. We obtained CMDs to estimate the age of the candidate and the star group by using $A_V = 1$. The updated version of the code used to compute stellar tracks leads to unphysical mass loss and inconsistencies between the

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**Table 5**

|       | X-3            | X-4           | X-6            | X-7            |
|-------|----------------|---------------|----------------|----------------|
|       | src1 | src2 | src1 | src2 | src1 | src2 | src1 | src2 |
| WFC3/F275W | 24.68 ± 1.15 | * | 22.25 ± 0.04 | 22.44 ± 0.08 | * | 23.78 ± 0.23 | * |
| WFC3/F336W | *   | 24.49 ± 0.69 | 22.29 ± 0.04 | 22.54 ± 0.12 | * | 24.02 ± 0.24 | 24.33 ± 0.77 |
| WFC3/F438W | 25.67 ± 0.56 | 25.18 ± 0.24 | 23.74 ± 0.05 | 24.15 ± 0.11 | 26.67 ± 0.86 | 25.64 ± 0.34 | 24.07 ± 0.37 |
| WFC3/F555W | 25.40 ± 0.19 | 25.66 ± 0.23 | 23.74 ± 0.03 | 24.07 ± 0.05 | 25.08 ± 0.10 | 25.19 ± 0.11 | 23.88 ± 0.12 |
| WFC3/F814W | 24.25 ± 0.10 | 24.81 ± 0.17 | 23.62 ± 0.05 | 24.42 ± 0.16 | 23.83 ± 0.08 | 25.32 ± 0.25 | 23.91 ± 0.14 |

*These ratios were calculated in the wavelength range 4584–6209 Å for $F_{\text{opt}}$ and the energy band 2–10 keV for $F_X$.

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Notes: Asterisks (*) in the table indicate that the source is not seen. $F_X/F_{\text{opt}}$ of X-7 is not presented since the source was not detected in XMM-Newton data.

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**Figure 3** CMD for the possible counterparts, group of stars, and field stars around X-2. The red, blue, and green circles represent src1, src2, and src3, respectively. The black dots represent field stars within a 2" region around the source, and the magenta dots show the stars in the group. The isochrones have been corrected for extinction of $A_V = 1.0$ mag. The black arrow shows the reddening line.

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**Figure 4** CMD for the possible counterparts, group of stars, and field stars around X-2. The red, blue, and green circles represent src1, src2, and src3, respectively. The black dots represent field stars within a 2" region around the source, and the magenta dots show the stars in the group. The isochrones have been corrected for extinction of $A_V = 1.0$ mag. The black arrow shows the reddening line.
mass and spectral type of the donor star (1.4–3 $M_\odot$ indicates a B6–B9 supergiant). These results may be due to the high extinction and hence high reddening of $E(B - V) = 0.31$ mag toward X-4. To cope with this issue we estimated another $A_V$ in the following way. The interstellar reddening values of the stars have been derived by aligning the PARSEC isochrones with the reddening line in the F555W–(F438W − F555W) CMD. The corresponding color excesses are applied to the diagram of F814W versus F555W − F814W by using the standard interstellar extinction laws (Pandey et al. 2003). The best fit $A_V$ and $A_I$ values are determined as 0.5 and 0.24, corresponding to $E(B - V) = 0.16$ and $E(V - I) = 0.2$ respectively. Dereddened magnitudes of the possible optical counterpart of X-4 are given in Table 5, and a created CMD is shown in Figure 7 for F814W versus F555W − F814W. The age and the mass of the candidate star from both CMDs were estimated based on the lower extinction value as 28 Myr and $9 M_\odot$, respectively. The spectral type of the possible donor of X-4 is determined as an A1–A3 supergiant. It is seen that the values estimated using the lower absorption yielded much more reasonable results.

There is also a group of stars that is ~1.7′ away from X-4. The $(V - I)$ colors of the majority of stars in this group are in the range from −0.5 to 1.5 and the absolute magnitudes are $-3.5 < M_V < -6$. These stars may be late O-type or early B-stars evolving toward the supergiant phase. It is seen from the CMD (Figure 7) that the candidate counterpart of X-4 may belong to these nearby OB associations. Several ULXs that were found to be associated with OB stars are well studied in the literature (Abolmasov et al. 2007b; Liu et al. 2007; Grisč et al. 2012). By comparing the counterpart’s position on the diagrams with Padova stellar models, we found that the possible optical counterpart has an age of 28 Myr from its $B$ (F435W) and $V$ (F555W) magnitudes after correction for $E(B - V) = 0.16$ mag and has the same age from its $V$ (F555W) and $I$ (F814W) magnitudes after correction for $E(V - I) = 0.20$. We note that almost all of the stars in the group are probably older than the candidate and are located near the 25−75 Myr isochrones for both CMDs. However, the high probability that several ULXs have been ejected from nearby star cluster prompts us to keep our attention on this association between ULXs and the star group.

**X-6**: Three possible optical counterparts were identified for this source within its error circle (Figure 8). A group of stars with an extent of about 76 pc is located ~1′.3 to the west of X-6. Similar inconsistencies between the mass and spectral type of the donor star were observed for X-6, probably due to a high extinction of $A_V = 1.7$ (corresponding to a high reddening of $E(B - V) = 0.55$). Thus, the procedure described for the
source X-4 was applied. As a result, $A_V = 0.85$ and $A_I = 0.41$ were determined for the possible donor star of X-6, and these extinction values yield $E(B - V) = 0.28$ and $E(V - I) = 0.34$. Extinction-corrected magnitudes of the possible optical counterparts are given in Table 5. A CMD for possible counterparts and nearby stars is given in Figure 9 for F814W versus F555W. Then the ages of the sources were estimated as 22 Myr, 36 Myr, and 50 Myr for src1, src2, and src3, respectively. Also the mass values were estimated as $10 M_\odot$, $8 M_\odot$, and $7 M_\odot$, respectively. The spectral types of the possible optical counterparts are found to be B1–A3 type supergiant for src1, G8–K3 supergiant for src2, and O–B6 supergiant for src3.

The group of stars near X-6 contains both blue and red stars. According to the CMD (Figure 9), the ages of these stars are $>22$ Myr, the $(V - I)$ color value is in the range from $-0.5$ to 2, and the $(V - I)$ colors of the candidates are 0.1–1.7. The age and color values of the optical candidates of X-6 and the stars in the group are compatible with each other.

X-7: This is the only ULX source identified as a transient in our ULX list. Two sources are seen in the error circle in the HST/WFC3 F814W image of X-7 (Figure 10). The fainter one, which is in the center of the red circle, was not determined in other filters. Therefore, the source seen in all filters was taken as the possible optical candidate of X-7. The dereddened magnitudes of the candidate are given in Table 5. The source is in a very crowded location. There is no significant star cluster structure. Therefore, a region of bright stars 25 away to the north of X-7 is selected. The resultant CMD obtained for F814W versus F555W – F814W is given in Figure 11. The age and mass of the companion star are derived as 28–32 Myr and $9 M_\odot$. The spectral type of optical candidate is determined to be an A3–F0 supergiant.

The majority of the stars detected near ULX X-7 are bright blue stars. The absolute magnitudes of these stars are in the range $-8.5 > M_V > -6$ while the magnitude of the possible optical counterpart of X-7 is $M_V = -5.5$. According to the obtained CMD (Figure 11), these bright stars in the region are younger than the candidate. The differences in the magnitude and age values do not support the association of the ULX with the group.

2.4. X-Ray Observations

The NGC 4490/4485 pair has been observed three times with Chandra from 2000 to 2004 and four times with XMM-Newton from 2002 to 2015. Previously, the detailed spectral
analyses for all ULXs (except the transient one) were carried out by Gladstone & Roberts (2009) and Yoshida et al. (2010) using the available data sets (Chandra data: ObsID 1579, 4725, 4726; and one XMM-Newton data set: ObsID 0112280201). In the present study, we used three archival XMM-Newton data sets (taken in 2008 May: ObsID 0556300101; 2008 June: ObsID 0556300201; and 2015 June: ObsID 0762240201) that were not used before. These data sets were analyzed for four sources (X-2, X-3, X-4, and X-6) since X-7 was detected only by one Chandra observation (ObsID 1579). In addition, we also reanalyzed all the older data sets mentioned.

As the standard data analysis for XMM-Newton we used SCIENCE ANALYSIS SOFTWARE (SAS version 13.05). The event files were created using EPCHAIN and EMCHAIN tasks in SAS. Two 2008 observations were affected significantly by several background flarings, which were excluded from the analysis. This process reduced the 2008 data exposures by about half. The files for the source and background spectra were obtained using the EVSELECT task and grouped to have a minimum of 20 counts per bin prior to fitting.

In all three XMM-Newton observations, the source X-2 was significantly contaminated by a nearby source located ∼12″ away. This contaminating source was not seen in previous XMM-Newton (ObsID 0112280201) or the other two Chandra observations (ObsID 1579 and 4725). In order to minimize the contamination circular regions of 5″ radius were used for source apertures. This aperture value is in line with the aperture that Gladstone & Roberts (2009) used for the ULXs (in NGC 4490/4485). Besides, circular regions of 15″ radius were used to obtain source and background spectra of X-6.

We performed spectral fittings using XSPEC software (version 12.9.1). EPIC pn and MOS spectra were fitted simultaneously in the 0.3–10 keV energy band and a constant scaling factor was introduced in order to consider the cross-calibration differences between the instruments. The absorbed flux and luminosity values were calculated in the 0.5–8 keV energy band to compare with previous results. The obtained best-fitting model parameters for a power law (PL) and a disk blackbody (DISKBB) for ULXs are given in

Figure 8. HST/WFC3 F814W image of X-6 (left) and a true-color HST image of the star group near the source (red: F814W, green: F555W, blue: F438W; right). In the left panel, the red circle represents the corrected position of X-6 with an accuracy of 0″.19 radius. Three optical candidates (black circles, the aperture of PSF fitting is 0″.12 radius) are found within the error circle. The zoomed image has a size of ∼2″ × 1″.7. In the right panel, the white circle (2″ diameter) represents the group of stars ∼1″.3 away from X-6. The optical candidates are marked with white bars. The RGB image has a size of ∼4″.8 × 4″.2.

Figure 9. CMD for the possible counterparts, the group of stars, and field stars around X-6. The red, blue, and green circles represent src1, src2, and src3 respectively. The black and magenta dots represent the field stars within the 2″ region around X-6 and stars in the group, respectively. The isochrones have been corrected for extinction of $A_V = 0.85$ mag and the black arrow shows the reddening line.
3. Discussion and Conclusions

The optical properties of seven ULXs in the galaxy pair NGC 4490/4485 were studied for the first time using HST archival data. Possible optical counterparts were found for only five of them (X-2, X-3, X-4, X-6, and X-7). For two ULXs (X-4 and X-7) we identified a single candidate; the remaining three (X-2, X-3, and X-6) have more than one counterpart. Furthermore, we have studied the environments around these five ULXs in the NGC 4490/4485 galaxies. The correlation between ULX source positions and stellar clusters has already been noticed in the literature (see Kaaret et al. 2004; Abolmasov et al. 2007b; Grisé et al. 2012; Avdan et al. 2016a). Several authors have suggested that some ULXs might have their clusters already dispersed due to their ages (Liu et al. 2007; Poutanen et al. 2013).

We also use the available high-quality Hα image from the HST/WFC3 archive in order to probe the current star formation regions and check for possible ULX nebulae, which might supply important information about the intrinsic photon luminosity and wind/jet power (Feng & Soria 2011). The positions of ULXs on the F657N image show that only a nebular structure appeared around the source X-7. ULX X-7 appears almost to the south of the nebular structure, whose diameter is θ = 200 pc (∼6″). We have examined the northern (brighter) and southern parts of the nebula near the ULX X-7 (Figure 13). Aperture photometry was performed to find the absolute Hα flux with the apphot package in IRAF for the F657N image from HST/WFC3/UVIS (data set no: ICNK19010). We have measured the total flux of both parts of the nebula with stars in a circular aperture of radius 45 pixel (1.78′). For the background calculation an annulus (with inner radius of 80 pixel and outer radius of 150 pixel) around the circular region was chosen and the contribution of stars (with 2 pixel aperture) was removed to obtain the continuum-subtracted nebular flux. The calculated continuum-subtracted flux values from the northern and southern parts of the nebula are ∼5.20 × 10⁻¹⁶ erg cm⁻² s⁻¹ and 2.73 × 10⁻¹⁶ erg cm⁻² s⁻¹, respectively. After the reddening corrections (for AV = 2.1), the flux values are 2.53 × 10⁻¹⁵ erg cm⁻² s⁻¹ for the northern nebula and 1.33 × 10⁻¹⁵ erg cm⁻² s⁻¹ for the southern one. These reddening-
Figure 12. Long-term light curves for X-2, X-3, X-4, X-6, and X-7. Triangles and circles represent *Chandra* and *XMM-Newton* data, respectively. The flux values are unabsorbed and calculated in the 0.5–8 keV energy band.

Table 6

| ObsID       | Model | $N_{\text{H}}$ ($10^{22}$ cm$^{-2}$) | $\Gamma$ | $kT_{\text{in}}$ (keV) | $\chi^2$/dof | $L_X$ (10$^{39}$ erg s$^{-1}$) |
|-------------|-------|-------------------------------------|----------|------------------------|--------------|---------------------------------|
| 0556300101  | PL    | 0.24$_{-0.03}^{+0.05}$              | 2.04$^{+0.23}_{-0.08}$ | ...                    | 47.36/63     | 4.00$^{+0.26}_{-0.26}$          |
|             | DISKBB| 0.03$^{+0.02}_{-0.02}$              | ...       | 1.28$^{+0.08}_{-0.08}$ | 60.74/63     | 2.84$^{+0.19}_{-0.18}$          |
| 0556300201  | PL    | 0.27$_{-0.03}^{+0.04}$              | 2.23$^{+0.12}_{-0.12}$ | ...                    | 34.00/32     | 2.76$^{+0.25}_{-0.25}$          |
|             | DISKBB| 0.04$_{-0.03}^{+0.03}$              | ...       | 1.13$^{+0.11}_{-0.09}$ | 34.09/32     | 1.87$^{+0.16}_{-0.16}$          |
| 0556300101  | PL    | 0.81$_{-0.05}^{+0.05}$              | 1.80$^{+0.09}_{-0.07}$ | ...                    | 114.17/106   | 5.21$^{+0.28}_{-0.28}$          |
|             | DISKBB| 0.45$_{-0.04}^{+0.04}$              | ...       | 1.86$^{+0.12}_{-0.11}$ | 117.35/106   | 3.53$^{+0.18}_{-0.18}$          |
| 0556300201  | PL    | 1.24$_{-0.09}^{+0.09}$              | 2.17$^{+0.09}_{-0.09}$ | ...                    | 78.98/84     | 6.05$^{+0.38}_{-0.43}$          |
|             | DISKBB| 0.71$_{-0.09}^{+0.09}$              | ...       | 1.51$^{+0.12}_{-0.12}$ | 86.80/84     | 3.47$^{+0.25}_{-0.25}$          |
| 0762240201  | PL    | 0.80$_{-0.06}^{+0.06}$              | 2.14$^{+0.09}_{-0.09}$ | ...                    | 47.04/57     | 6.42$^{+0.45}_{-0.39}$          |
|             | DISKBB| 0.41$_{-0.05}^{+0.05}$              | ...       | 1.40$^{+0.10}_{-0.09}$ | 43.97/57     | 4.06$^{+0.27}_{-0.27}$          |
| 0556300101  | PL    | 0.51$_{-0.04}^{+0.04}$              | 2.05$^{+0.08}_{-0.08}$ | ...                    | 79.73/79     | 3.28$^{+0.19}_{-0.20}$          |
|             | DISKBB| 0.22$_{-0.03}^{+0.03}$              | ...       | 1.41$^{+0.09}_{-0.08}$ | 96.77/79     | 2.19$^{+0.13}_{-0.12}$          |
| 0556300201  | PL    | 0.74$_{-0.05}^{+0.05}$              | 2.20$^{+0.09}_{-0.09}$ | ...                    | 96.24/94     | 4.90$^{+0.34}_{-0.32}$          |
|             | DISKBB| 0.36$_{-0.05}^{+0.05}$              | ...       | 1.29$^{+0.10}_{-0.10}$ | 126.23/94    | 2.95$^{+0.20}_{-0.21}$          |
| 0762240201  | PL    | 0.70$_{-0.05}^{+0.06}$              | 2.22$^{+0.10}_{-0.10}$ | ...                    | 53.86/49     | 5.31$^{+0.38}_{-0.38}$          |
|             | DISKBB| 0.35$_{-0.05}^{+0.05}$              | ...       | 1.23$^{+0.09}_{-0.08}$ | 44.26/49     | 3.29$^{+0.24}_{-0.22}$          |
| 0556300101  | PL    | 0.49$_{-0.05}^{+0.04}$              | 2.05$^{+0.09}_{-0.09}$ | ...                    | 92.77/82     | 3.82$^{+0.38}_{-0.38}$          |
|             | DISKBB| 0.24$_{-0.04}^{+0.04}$              | ...       | 1.23$^{+0.08}_{-0.08}$ | 75.28/82     | 2.54$^{+0.25}_{-0.25}$          |
| 0556300201  | PL    | 0.64$_{-0.04}^{+0.04}$              | 2.27$^{+0.07}_{-0.07}$ | ...                    | 120.74/130   | 5.52$^{+0.33}_{-0.29}$          |
|             | DISKBB| 0.32$_{-0.03}^{+0.03}$              | ...       | 1.18$^{+0.06}_{-0.06}$ | 104.80/130   | 3.46$^{+0.18}_{-0.19}$          |
| 0762240201  | PL    | 0.63$_{-0.05}^{+0.05}$              | 2.35$^{+0.09}_{-0.09}$ | ...                    | 60.78/61     | 4.85$^{+0.31}_{-0.32}$          |
|             | DISKBB| 0.30$_{-0.04}^{+0.04}$              | ...       | 1.16$^{+0.09}_{-0.09}$ | 66.53/61     | 2.96$^{+0.17}_{-0.22}$          |

Note.

- The luminosities were calculated in the 0.5–8 keV energy band.

Corrected fluxes correspond to luminosities of $\sim 1.84 \times 10^{37}$ and $9.65 \times 10^{38}$ erg s$^{-1}$ at a distance of 7.8 Mpc. Statistical errors of the flux values are about or less than 2%. It needs to be noted that the background level can vary considerably depending on the selected region. This could ultimately lead to an uncertainty in measuring the nebular flux at the level of 30%. In case of X-7, we do not observe a brightening of the nebula near the ULX position as observed in the nebulae around NGC 6946 ULX-1 (Abolmasov et al. 2008), HolmbergII X-1 (Lehmann et al. 2005), and NGC 5408 X-1 (Grisé et al. 2012). Note also that these sources and their nebulae are very bright and compact (a few tens of parsecs). On the other hand, the ULX nebulae of IC 342 X-1 and HolmbergIX X-1 are very large (up to 500 pc). The common feature of these nebulae is that they have high luminosity (about $10^{38}$ erg s$^{-1}$ in H$\alpha$ and more than about $10^{39}$ erg s$^{-1}$ bolometric; Abolmasov et al. 2007a). The X-7 nebula has a size of about 200 pc, but its H$\alpha$ line luminosity is less by a factor of 3–10 (compared to the sources listed in Table 2 in Abolmasov et al. 2007a).
We think that the UV luminosity of the young nearby star cluster is enough to photoionize the gas of this nebula, but the contribution from the ULX source is not clear. We also keep in mind that if there is time-dependent illumination and ionization (X-7 is a transient source), it may not show the characteristics of the other brighter Hα nebulae around ULXs. This matter requires more study in future work. In particular, we need a spectrum of the nebula to model with the CLOUDY spectral synthesis code.

On the other hand X-ray data analyses provide us with good fits for PL and DISKBB models to explain their spectra. The estimated average values of the ratio $F_X/F_{\text{opt}}$ for well-studied ULXs are ~1600 (Avdan et al. 2016b and references therein). Even though only two of the ULXs (X-3 and X-6) have values higher than this average ratio, the remaining sources still have values higher than 100.

An alternative definition of X-ray to optical flux ratio has been proposed as $\xi$ to distinguish between low-mass and high-mass X-ray binaries. This ratio is defined as $\xi = B_0 + 2.5 \log F_X$, where $F_X$ is the observed X-ray flux density in 2–10 keV in units of $\mu$Jy and $B_0$ is the dereddened $B$ magnitude (van Paradijs 1981). To determine $\xi$, the flux densities were calculated using the XMM-Newton observations on the closest date available in the archives. $F_X$ values obtained for X-3, X-4, and X-6 are 0.066 $\mu$Jy, 0.051 $\mu$Jy, and 0.047, respectively. Thus, the $\xi$ values were found to be $\sim$20–23 for X-3, $\sim$20 for X-4, and $\sim$20–22 for X-6. $\xi$ was not calculated for X-7 because the source was not detected in any XMM-Newton data. The color ratios are given in the range of 12–18 for high-mass X-ray binaries and 21–22 for low-mass X-ray binaries (van Paradijs 1981). For the given $\xi$ values, X-3 and X-4 might be identified as low-mass X-ray binaries like most of the ULXs studied so far (Tao et al. 2011; Kaaret et al. 2017). As discussed in Tao et al. (2011), this does not mean that ULXs actually have low-mass companions; instead it may suggest that the optical spectra of ULXs are dominated by emission from the disk but not from the companion star.

As discussed in the related studies, the optical emission from the ULXs could arise from the accretion disk or the donor star or both. Assuming that the light from the optical counterpart is dominant, then the optical variability should be $\leq 0.1$ mag and consistent with a single spectral type in all observations. On the other hand, if the optical emission is dominated by the accretion disk, then it may exhibit significant variability.
Unfortunately, there are not sufficient optical data to discuss these conditions for the sources examined in this study.

In order to improve our understanding of the nature of these sources, more sensitive photometric and spectroscopic observations should be performed.

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