DETECTION OF X-RAY ELONGATED EMISSION FROM AN ULTRALUMINOUS X-RAY SOURCE IN THE INTERACTING PAIR OF GALAXIES NGC 5953/5954

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ABSTRACT

We present radio through X-ray observations of a bright (>10^{40} erg s^{-1} in the 0.5–8.0 keV band) ultraluminous X-ray source (ULX), CXOU J153434.9+151149, in the starburst, interacting pair of galaxies NGC 5953/5954. A Chandra image of this ULX shows that it is elongated. From HST/WFPC2/F606W data we have detected a counterpart of the ULX system with M_F606W \sim \sim 7.1 \pm 0.7 mag. This optical counterpart may be either an O-type supergiant star or a young star cluster. From our Fabry–Perot interferometric observations, we have detected Hα and [Nii] (6584 Å) diffuse emission, with velocity gradients up to 60 km s^{-1} at the astrometric corrected Chandra position of the ULX. Different scenarios have been invoked as to explain the possible nature of CXOU J153434.9+151149. Based on the observed X-ray morphology of the ULX, we estimate that the inclination of the line of sight to the observer and the direction of a possibly beamed outflow is \sim 53°. Beaming with this geometry from a stellar-mass black hole system will be inadequate to explain the observed X-ray luminosity of this ULX. Finally, we suggest that mild-beaming from a binary black hole with mass more than 50 M_⊙ associated with a young star cluster, is the most favorable scenario that describes the multiwavelength properties of this ULX. Future observations are definitely needed to determine the nature of this rare object.

Key words: galaxies: individual (NGC 5953, NGC 5954) – galaxies: interactions – X-rays: galaxies – X-rays: individual (CXOU J153434.9+151149)

Online-only material: color figure

1. INTRODUCTION

Theoretically, black holes (BHs) evolved from single stars have masses <20 M_⊙ (Fryer & Kalogera 2001; Heger et al. 2003). Galactic black hole systems are observed to radiate at luminosities of 10^{37} erg s^{-1} in X-rays and occasionally up to a few 10^{38} erg s^{-1} or several times the Eddington limit (McClintock & Remillard 2006; Remillard & McClintock 2006). Supermassive black holes at the centers of galaxies, on the other hand, have masses of 10^6–10^9 M_⊙ and luminosities of 10^{41}–10^{46} erg s^{-1}. The off-nuclear, point-like X-ray sources in external galaxies with observed luminosities in the range \sim 10^{39}–10^{41} erg s^{-1} in the 0.2–10 keV band are known as ultraluminous X-ray sources (ULXs). Even though, ULXs were first discovered in the 1980s with the Einstein Observatory (Helfand 1984; Fabbianio 1989) and have been extensively studied with subsequent satellites (Roberts & Warwick 2000; Colbert & Ptak 2002; Swartz et al. 2004; Liu & Mirabel 2005), their physical nature is still a subject of intense debate (for recent reviews, see Fabbianio 2006; King 2006; Fabbianio & White 2006). Present hypotheses to explain the ULX phenomenon fall into different broad categories: (i) accreting intermediate-mass black hole systems (IMBHs) with masses in the range 50–10^4 M_⊙ (Colbert & Mushotzky 1999; Makishima et al. 2000; Madai & Rees 2001; Ebisuzaki et al. 2001; Portegies-Zwart & McMillan 2002; Miller & Hamilton 2002; Ho et al. 2003; Mushotzky 2004; van der Marel 2004; Freitag et al. 2006), (ii) geometrically/mechanically– (King et al. 2001a; Fabrika & Mescheryakov 2001; Fabrika 2004; Poutanen et al. 2007) or relativistically beamed or super-Eddington accreting stellar-mass black hole systems (Körding et al. 2002; Georgopoulous et al. 2002; Abramowicz et al. 1980; Arons 1992; Gammie 1998; Begelman 2002, 2006; Grimm et al. 2002), (iii) supernovae and hypernovae (Terlevich 1992; Schlegel 1995; Paczynski 1998; Wang 1999; Li 2003), (iv) supersoft sources (Swartz et al. 2002; Kong & Di Stefano 2005), and (v) foreground/background objects, which mimic as ULXs (Arp et al. 2004; Gutiérrez & López-Corredoir 2006 and references therein).

By analogy with the X-ray spectra of Galactic black hole binaries, a multicolor disk (MCD) blackbody component with a temperature of around 100 eV (plus powerlaw) has been adopted to fit the soft X-ray component in ULX spectra, providing evidence for a cool accretion disk around an IMBH (Miller et al. 2003; Kaaret et al. 2003; Miller et al. 2004, 2004a; Cropper et al. 2004; Kong et al. 2004). In addition, quasi-periodic oscillations (QPOs) with periods \sim 20–170 mHz have been detected in some ULXs (Liu et al. 2005; Strohmayer & Mushotzky 2003; Soria et al. 2004; Strohmayer et al. 2007). Scaling these frequencies with the characteristic frequencies observed in the power density spectra of Galactic BH binaries (e.g. Belloni & Hasinger 1990) suggests the presence of IMBHs in these ULXs. However, the soft X-ray component in ULX spectra may be also fitted with other spectral models (King & Pounds 2003; Roberts et al. 2005; Stobbart et al. 2006; Goncalves & Soria 2006; Barnard et al. 2007). In addition, more detailed analysis of non-LTE accretion flows around IMBHs shows that the effects of black hole rotation and Compton scattering can easily generate hot accretion disks with temperatures up to kT \sim 1 keV (Hui et al. 2005), which is in sharp contrast to the conventional cool disk model. On the other hand, periodic intensity dips in the X-ray light curves of some
ULXs have been detected (Sugimoto et al. 2001; Bauer et al. 2001; Liu et al. 2002, 2005; Strohmayer & Mushotzky 2003; Pietsch et al. 2003; Pietsch et al. 2004; Stobbart et al. 2004; Weiskopf et al. 2004; Soria et al. 2004; Soria & Motch 2004; Mukai et al. 2005; Ghosh et al. 2006; Fabbiano et al. 2006). Assuming the observed dips are eclipses by the companion star, it has been suggested by the above authors that these ULXs may be stellar-mass black hole binaries, because ULX systems containing IMBHs are much less likely to display eclipses in their X-ray light curves (Pooley & Rappaport 2005). In addition, spectral curvatures have been detected in the X-ray spectra of a few luminous ULXs (Dewangan et al. 2004 and references therein), which may be more consistent with emission from stellar-mass black hole binaries. However, optical photometric and spectroscopic studies have revealed ionized nebulae around some ULXs. Some of these ionized nebulae are isotropic with huge energy content, which will be difficult to explain in the framework of beaming models. Furthermore, it may be mentioned that high signal-to-noise spectra of some ULXs obtained from very deep XMM-Newton observations appear to favor a high-mass solution for relativistic spectral models (Winter et al. 2007). Again, some ULXs are associated with luminous supernovae/hypernovae and supersoft X-ray sources.

All these results indicate that ULXs are not a homogeneous class of physical objects (Feng & Kaaret 2005). Similar studies were carried out by Winter et al. (2006, 2007) and they classified ULX spectra into low/hard and high/soft states. However, long-term monitoring of some ULXs displayed opposite results to what has been observed in Galactic X-ray binaries during their state transitions (Feng & Kaaret 2006; Roberts et al. 2006). In summary, no clear picture is emerging from X-ray studies. It is clearly evident that X-rays alone cannot differentiate between compact accretor models of ULXs and, in particular, cannot easily identify candidate IMBHs. Thus, studies of ULXs in other wave bands are essential.

Based on the results of optical imaging photometric studies, stars, star clusters, and ionized nebulae have been detected as the possible counterparts of some ULXs (Ghosh et al. 2001, 2005; Mucciarelli et al. 2005, 2007; Soria et al. 2005; Ptak et al. 2006; Ramsey et al. 2006). Optical spectroscopic studies on the local environments of some ULXs have also been carried out and different emission lines have been detected. It has been suggested that both shock excitations and photo-ionization processes are responsible for the formation of these emission lines. These results suggest that both stellar-mass black holes with beaming and IMBHs with strong radiation fields may be responsible for the ionization processes that occur in the ULX environment (Abolmasov et al. 2007a, 2007b; Kaaret et al. 2004; Zepf et al. 2007).

Recent surveys of ULXs have shown that the number of ULXs correlates with the star formation rates (SFRs) or far-infrared luminosities of the host galaxies (Swartz et al. 2004). During the process of interaction of two disc galaxies, gas transfer between the galaxies can cause strong star formation and multiple supernova explosions, which may trigger the formation of ULXs.

A luminous X-ray source has been discovered in the NGC 5953/5954 system. NGC 5953/5954 is an interacting pair of galaxies with high infrared luminosity \( L_{IR} \sim 10^{44} \text{ erg s}^{-1} \), with an estimated total SFR \( > 4.5 \ M_\odot \text{ yr}^{-1} \); Kennicutt 1998). Given the high SFR of this system and the correlation between the SFR of a galaxy and the number of ULXs hosted by that galaxy (Swartz et al. 2004), there should be, at least \( 3 \) to \( 4 \) ULXs in this galaxy pair. However, we have detected only one ULX, which is above the average luminosity \( L_X > 10^{40} \text{ erg s}^{-1} \). Thus, the expected ULX population of this galaxy is not present (Gilfanov et al. 2003). This indicates that either the missing ULXs are highly variable or they were below the detection limit at \( 2.7 \times 10^{39} \text{ erg s}^{-1} \), for ten source counts. Here we present multiwavelength results to study and explore the possible nature of the detected ULX. Multiwavelength observations, data analysis, and results are presented in Section 2. Discussion and conclusions are described in Section 3. We adopt a cosmology \( H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_M = 0.24, \Omega_L = 0.76 \) (Spergel et al. 2007). The cosmology corrected luminosity and angular-size distances are 28.9 Mpc and 28.5 Mpc, respectively.

2. MULTIWAVELENGTH OBSERVATIONS AND RESULTS

NGC 5953/5954, is a binary system with an \((S0/a + Scd)\) pair of galaxies (KPG 468 from Karachentsev 1972), which are transferring material (Domínguez et al. 2003; Hernández-Toledo et al. 2003). Both galaxies host an active nucleus: NGC 5953 is a Seyfert 2 and NGC 5954 is a LINER. These two galaxies are separated by a projected distance of 6.2 kpc (Hernández-Toledo et al. 2003).

2.1. X-ray Observations

NGC 5953/5954 was observed with the Chandra Advanced CCD Imaging Spectrometer (ACIS) operating in imaging mode on both 2002 June 11 (ObsID 2930) and 2002 December 29 (ObsID 4023) for 9.9 and 4.7 ks, respectively. These two data sets were retrieved from the Chandra archive and the Level 2 event lists were used to extract the events within the \( D_{25} \) isophotes of each galaxy. Both galaxies were fully within the back-illuminated CCD S3 field of view. Source detection and source and background light curves and spectra were extracted using the locally-developed software package lextect (see Tennant 2006). The entire data set was then cleaned of bad pixels and columns and the standard grade set and events in pulse invariant (PI) channels corresponding to 0.3–8.0 keV were selected for source detection. No periods of high particle background occurred during the observation.

The source finding method uses a circular Gaussian approximation to the point-spread function (PSF). This method assumes that a source is located at a given position and compares the distribution of detected events to the PSF. The algorithm first calculates the fraction of the PSF within each pixel within a detection region. Then, using the PSF fraction as the independent variable, it calculates an unweighted least-squares fit of a straight line to the counts detected in the pixels in the region. If a source is present, then the slope of the line will be positive and will represent the total number of counts from the source (integrated over the PSF). The line intercept is the background per pixel. A key value is the uncertainty in the slope and hence the number of source counts. The uncertainty is determined by applying the standard propagation of errors directly to the sums. The algorithm then calculates the estimated source counts (slope) and error at every pixel in the image. The estimated source counts divided by the uncertainty is the signal-to-noise ratio (S/N). If the S/N exceeds some threshold, then there is a source in the neighborhood. This threshold is as low as 2.5 for a source on-axis and as high as 3.0 for a source far off-axis. For the present analysis a constant value of 3.0 is used.

We have detected two sources within the \( D_{25} \) isophotes of both the galaxies in each observation. One is the nucleus of NGC 5953 and the other is the ULX. The detection limits for point sources in these two observations are \( \sim 5.9 \times 10^{38} \text{ erg s}^{-1} \) and \( \sim 6.7 \times 10^{38} \text{ erg s}^{-1} \) for NGC 5953 and 5954, respectively. This analysis confirms that there are more sources than just the-points sources, or the point sources could be the debris source.
Figure 1. The Chandra/ACIS-S3 image of NGC 5953/5954 obtained on 2002 June 11 with $D_{25}$ isophotes drawn on the respective galaxies. The galaxy with a bright nucleus surrounded with diffuse emission is NGC 5953. The ULX is located in between the two galaxies.

Figure 2. Left: close-up of the X-ray image of the ULX. The units are ACIS pixels 0.492″. Note its apparent elongation along the N–S direction. An arbitrary ellipse with major- and minor-axis diameters $\sim 2.5''$ and $\sim 1.5''$, respectively, has been drawn around the source and this identical ellipse will be plotted in the following figures to guide the eye. Center: close-up of the X-ray image of a point source in the field of the ULX. Although this source is further off-axis than the ULX (1.5′ vs. 0.5′) its image is more point-like and symmetric. Right: the radial profile of the ULX (square) is compared with that of the PSF, which clearly shows that the radial profile of the ULX is much broader than that of the PSF.

$\sim 1.2 \times 10^{40}$ erg s$^{-1}$, respectively, in the 0.5–8.0 keV band. An absorbed power-law of photon index $\Gamma = 1.8$, the Galactic absorption column along the line of sight ($N_H = 3.26 \times 10^{20}$ cm$^{-2}$), and a 10 counts detection limit were assumed to compute these luminosities. Figure 1 shows the Chandra image of the NGC 5953/5954 system with $D_{25}$ ellipses shown around each galaxy of the pair. An elliptical Gaussian profile, a utility of the {	t exrct} software package, was fitted to the spatial distribution of X-ray events, to determine the position of the ULX, which is $15^h34^m34.96^s +15^\circ11'49.3''$. Following the Chandra convention this ULX will be designated as CXOU J153434.9+151149. The estimated statistical uncertainty in the ULX position is 0.05″.

Figure 2 shows close-ups of the X-ray images of the ULX and of a point source located far from the center of the field of the observations. As one can see, the point source that is 1.5′ away from the optical axis has a symmetric image (center panel of Figure 2). On the other hand, the ULX image (nearer to the center of the field, where the image quality is better) appears elongated in the N–S direction. An ellipse with major- and minor-axis diameters $\sim 2.5''$ and $\sim 1.5''$, respectively, is also shown enclosing the elongated nature of the source in the left panel of Figure 2. In addition, we have compared the average radial profile, as the source has an elongated morphology, of the ULX with the PSF (model computed using the CIAO tool {	t mkpsf}) and results are shown in the right panel of Figure 2. It can be seen from this figure that these two profiles agree well up to 1.0″. However, the radial profile of the ULX clearly shows that it is broader beyond 1.0″ with respect to the PSF. This also indicates that the ULX is extended at least up to 4 pixels ($\sim 2.0''$). All these results suggest that the ULX is not a point-like, but an extended source. Indeed, we can suggest that the ULX image may consist of two point sources separated by 1.0″ (140 pc at the NGC 5953/5954 distance). However, it may be mentioned that the radial profile of this ULX clearly displays gradual decline of the normalized counts per pixel. Disabling pixel randomization may slightly improve the resolution of on-axis Chandra sources. However, in this particular case high S/N data are more crucial than the resolution. In addition, we will show in the next section that the probability of two sources
to be present within a separation of 1.0′, by random chance, is less than \(3.5 \times 10^{-6}\). Thus, the source is most likely an elongated object, even though two sources hypothesis cannot be completely ruled out with the existing data.

X-ray light curves and spectra of the ULX and the background were extracted from a circle of radius 5′ and a circular annulus of 5′ and 10′ radii, respectively, at the position of the ULX. Background subtracted count rates of the ULX from the two Chandra observations were \((7.5 \pm 0.8) \times 10^{-3}\) and \((6.6 \pm 1.3) \times 10^{-3}\) cts s\(^{-1}\), respectively. This suggests that this ULX remained almost steady between the two observations. The X-ray light curves of the ULX were binned for 500 s and tested against the constant count rate hypothesis. In addition, we performed the Kolmogorov–Smirnov (K-S) test, which suggests this source did not vary during the observations. The spectrum of the ULX for ObsID 2930 was binned to obtain at least 10 counts per fitting bin. Spectral redistribution matrices and ancillary response files corresponding to the ULX were generated using CIAO, v3.3.0. XSPEC v13.1.2 was used to fit the spectrum of the ULX in the 0.5–8.0 keV energy band using either an absorbed powerlaw (PL) model or a bremsstrahlung (Brem) model. Table 1 lists the best-fitting parameters for both spectral models. It can be seen from this table that both models fit equally well to this spectrum. The Galactic hydrogen column density along that direction \((N_H)\) is only \(3 \times 10^{20}\) cm\(^{-2}\), so both measured columns exceed this value. The bremsstrahlung temperature of 13.5 keV is flatter than 1.78, which is close to the average value of 1.5, suggesting for a hard source. In addition to fitting models per fitting bin. Spectral redistribution matrices and ancillary response files corresponding to the ULX were generated using CIAO, v3.3.0. XSPEC v13.1.2 was used to fit the spectrum of the ULX in the 0.5–8.0 keV energy band using either an absorbed powerlaw (PL) model or a bremsstrahlung (Brem) model. Table 1 lists the best-fitting parameters for both spectral models. It can be seen from this table that both models fit equally well to this spectrum. The Galactic hydrogen column density along that direction \((N_H)\) is only \(3 \times 10^{20}\) cm\(^{-2}\), so both measured columns exceed this value. The bremsstrahlung temperature of 13.5 keV appears to be high and suggests for a hard source although the error is rather large. Similarly, the powerlaw photonindex \((\Gamma)\) of 1.5 is flatter than 1.78, which is close to the average value of the powerlaw index, for all candidate ULXs with statistically-acceptable powerlaw fits (Swartz et al. 2004). This flat powerlaw index suggests for a hard source. In addition to fitting models to the 0.5–8.0 keV spectrum of the ULX, the background subtracted X-ray counts were binned into three broad bands, defined as \(S (0.5–1.0\) keV), \(M (1.0–2.0\) keV), and \(H (2.0–8.0\) keV\); and the X-ray colors \((M – S)/T\) and \((H – M)/T\), where \(T = S + M + H\), were constructed following Prestwich et al. (2003). X-ray color analysis also shows that this ULX is an absorbed hard source.

A ROSAT HRI observation of NGC 5953/5954 was also carried out between 1996 August 16 and 25. The ULX was detected with a count rate of \((8.9 \pm 3.9) \times 10^{-3}\) cts s\(^{-1}\). This count rate was converted into flux using the PIMMS v3.9e and the bremsstrahlung model parameters of Table 1. The corresponding intrinsic luminosity in the 0.5–8.0 keV band is \((2.3 \pm 0.9) \times 10^{40}\) erg s\(^{-1}\). This result indicates that either the X-ray emission from the ULX has marginally decreased between the ROSAT and the Chandra observations or remained steady within the observational uncertainties.

### 2.2. Hubble WFPC2 Observations

**Hubble**/WFPC2 observations of NGC 5953/5954 were carried with F218W and F606W filters on 1996 September 23 and 1994 June 10 for 1200 s and 500 s, respectively. We could not use the data from the F218W filter, because we could not convincingly determine astrometric objects using USNO stars, Chandra and Hubble images. Astrometry between the Chandra and HST/F606W images was performed using the nucleus of NGC 5953 (central wavelength and halfwidth are 5997 and 1502 Å respectively). It was used to register the two images assuming that the F606W and X-ray band centroids coincide. The F606W band includes redshifted Hα and [NII] (6584 Å) lines, thus enclosing both the redshifted Hα and [NII] line-emission of the galaxy pair. The uncertainty of the best-fit elliptical Gaussian to the X-ray nucleus is \(\sim 0.05′′\) and we take this to be the registration uncertainty for the two Chandra sources (the nucleus and the ULX), which is much smaller compared to the Chandra absolute positional uncertainty, \(\sim 0.6′′\). This uncertainty is combined in quadrature with the (statistical) uncertainties in the X-ray positions of these two sources \((\sim 0.09′′)\) to give their final positional uncertainties. These two sources were on PC1 and WF3 CCDs, respectively, on the HST/WFPC2 image. We used the METRIC program to determine the relative positional errors \((\sim 0.27′′)\) between the PC1 and WF3 images (Ghosh et al. 2005). The resultant astrometric accuracy is less than 0.30′′. A potential optical counterpart was discovered within the resulting error circle at the Chandra position of the ULX candidate, which is shown in Figure 3. Within this error circle there may be multiple objects of single-pixel size. We have not considered these single-pixel size objects, because they are located at the boundary of the error circle and they may be just random fluctuations of the strong diffuse background emission. However, we have selected the brightest object of 2 × 2 pixels size, which is closest to the center of the error circle (shown with a black arrow in Figure 3). Photometry of this object was done with extract (Tennant 2006) using the current values of PHOTFLAM and ZeroPoint in the VEGAMAG system given in the Hubble data handbook for WFPC2. The apparent and absolute magnitudes of this object in the F606W band are 25.2 ± 0.7 and −7.1 ± 0.7 mag, respectively, assuming that it belongs to the galaxy pair.

### 2.3. Scanning Fabry–Perot Optical Interferometry

Fabry–Perot observations of NGC 5953/5954 were carried out at the f/7.5 Cassegrain focus of the 2.1 m telescope of the Observatorio Astronómico Nacional in San Pedro Mártir, B.C., Mexico (OAN-SPM) using the scanning Fabry–Perot interferometer PUMA (Rosado et al. 1995). A 1024 × 1024 Tektronics CCD detector was used with a pixel size of 0.58″. Two Fabry–Perot (FP) velocity cubes at Hα (6563 Å) and [NII] (6584 Å) were obtained on 1998 June 25 and 1997 May 6, respectively. The exposure time was 2900 s for each observation. The sampling spectral resolution is 0.41 Å (19.0 km s\(^{-1}\) at Hα) and the field of view of the Hα and [NII] FP cubes is 5′ and 3′, respectively. Results on the [NII] kinematics of this galaxy pair derived from the [NII] data cubes and further details on the observations have been presented in Hernández-Toledo et al. (2003).

FP data reduction and analysis were done using the ADHOCw software (developed by J. Boulesteix, http://www.oamp/adhoc/adhocw.html) and the CIGALE software (Le Coarer et al. 1993). Further description of PUMA FP observations and data

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**Table 1**

X-ray Spectral Parameters of the ULX

| Model | \(N_H\) (10\(^{22}\) cm\(^{-2}\)) | \(\Gamma\) | \(T_e\) (keV) | \(\chi^2\) (dof) |
|-------|-------------------------------|--------|-------------|---------------|
| PL\(^a\) | \(0.6^{+0.4}_{-0.3}\) | 1.5^{0.8}_{-0.6} | 1.1 ± 0.2 | 1.9(5) |
| Brem\(^b\) | \(0.6^{+0.4}_{-0.3}\) | 13.5^{+20}_{-10} | 1.0 ± 0.2 | 1.8(5) |

**Notes.**

\(^a\) PL: power-law and Brem: bremsstrahlung model.
\(^b\) In units of 10\(^{23}\) cm\(^{-2}\).
\(^c\) In units of 10\(^{40}\) erg s\(^{-1}\) in the 0.5–8.0 keV band.

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5 http://stdas.stsci.edu/cgi-bin/gethelp.cgi?metric.hl.
6 http://www.stsci.edu/instruments/wfpc2/Wfpc2_dhb/wfpc2_ch52.html # 1902177.
The most likely counterpart of the ULX. The object with four-pixel size within the circle (marked with a black arrow) is the most likely counterpart of the ULX.

Figure 3. HST/WFC2/F606W image around the ULX. An error circle of radius 0.3′′ is shown at the astrometric corrected Chandra position of the ULX. The object with four-pixel size within the circle (marked with a black arrow) is the most likely counterpart of the ULX.

reductions are described in Fuentes-Carrera et al. (2004). The Chandra and FP images were registered using the nucleus of NGC 5953. In the case of the FP images, we also used several stars detected in the PUMA field of view in order to do the astrometry.

Figure 4 shows a close-up of the velocity map at +1825 km s\(^{-1}\) obtained from the H\(_\alpha\) FP velocity cubes. As discussed below, the nebulous at the ULX position has a peak near this velocity. This close-up displays part of the southern spiral arm of the Scd galaxy NGC 5954. The H\(_\alpha\) position is marked with an ellipse that has the same size and orientation as shown in Figure 2. Also marked in Figure 4 are the positions of two H\(_\text{II}\) nebular complexes (#5 and #9), which were detected by González-Delgado & Pérez (1996). These authors give positions as an offset from the nucleus but due to irregularities in the emission near the center of the galaxy, the nuclear position is uncertain at the arcsec level. We have adjusted this fiducial point so that the two brightest H\(_\text{II}\) regions (#16 and #18), identified by those authors, are centered on the brightest spots in our data. This implies a shift of (2.73 ± 0.67)″ between the nuclear position given by González-Delgado & Pérez (1996) and the position of the nucleus as detected in our FP images. Consequently, in Figure 4 we have marked the black ellipse corresponding to the shifted Chandra position and the red one which corresponds to the astrometric corrected Chandra position of the ULX obtained applying the 2.73″shift.

The ULX is located between complexes #9 and #5. The sizes of complexes #5 and #9 are 151 pc and 165 pc, in radius, respectively, and their H\(_\alpha\) luminosities are \(~1.6 \times 10^{39}\) erg s\(^{-1}\) with an estimated rms electron density of 3.1 cm\(^{-3}\) (González-Delgado & Pérez 1996). In our FP velocity maps, the emission of nebular complex #9 extends beyond its reported diameter, while for complex #5 the emission lies within the reported diameter. An inspection of our H\(_\alpha\) and [N\(_\text{II}\)] velocity maps shows that no conspicuous point-like emission is visible at the ULX position; however, extended, diffuse emission is detected. The H\(_\alpha\) luminosity of the diffuse emission at the ULX position has been computed by extracting total counts from a circle of 0.5″ radius at the Chandra position of the ULX candidate and by subtracting the equivalent background taken from annuli of 0.5″ and 1.0″ radii of the same image, where no emission is observed. These counts were converted into H\(_\alpha\) flux using the H\(_\text{II}\) complex #5 as the H\(_\alpha\) flux calibrator (González-Delgado & Pérez 1996). The computed H\(_\alpha\) luminosity of the ULX is \(~1 \times 10^{38}\) erg s\(^{-1}\). Although similar counts were obtained for the [N\(_\text{II}\)] emission, implying a similar luminosity, we are unable to determine its absolute value, because there is no absolute flux calibrator for the [N\(_\text{II}\)] line, within the field of view of our observations. Thus, approximately, we may consider that the [N\(_\text{II}\)] line-ratio will be around one, which is consistent with the [N\(_\text{II}\)]/H\(_\alpha\) line-ratios of most of the H\(_\text{II}\) complexes in the galaxies NGC 5954 and NGC 5953 (González-Delgado & Pérez 1996).

Given the diffuse appearance of the line emission at the ULX position, we have extracted the velocity profiles integrated over a square window of 5 × 5 pixels (linear extension of 315 pc at the assumed distance) centered at the location of the ULX. The profiles show two components whose heliocentric velocity values are confirmed from both H\(_\alpha\) and [N\(_\text{II}\)] observations: (1) the brighter one at +1821 km s\(^{-1}\) (for H\(_\alpha\)) and +1814 km s\(^{-1}\) (for [N\(_\text{II}\)]), and (2) a weaker component at +1760 km s\(^{-1}\) (for H\(_\alpha\)) and +1763 km s\(^{-1}\) (for [N\(_\text{II}\)]) at about 1.5″ away from the ULX location. Thus, within the uncertainties of ±5 km s\(^{-1}\) in the determination of the peak velocities, both the H\(_\alpha\) and the [N\(_\text{II}\)] observations show the same velocity components separated by 60 ± 7 km s\(^{-1}\), suggesting possible expansion at a velocity of 30 ± 7 km s\(^{-1}\) or simple superpositions along the line of sight of nebulae at different velocities, while the neighboring H\(_\text{II}\) complexes show only a single velocity component at about +1800 km s\(^{-1}\). The velocities, diffuse appearance and the [N\(_\text{II}\)]/H\(_\alpha\) line-ratio are consistent with the idea that this ULX could be associated with an emission-line nebula. Emission nebulae (a few hundred parsecs in diameter) with both low- and high-ionization emission lines have been detected around some ULXs (Wang 2002; Pakull & Mirioni 2003). Higher spatial resolution and high S/N observations will be able to detect the morphology and kinematics of the nebulous at the position of the ULX.

An interesting remark regarding the galactic location of ULX is that both ULX and the H\(_\text{II}\) complexes #5 and #9 are located in a spiral arm of NGC 5954. This spiral arm has a strange appearance because part of it is not curved but straight, this distortion probably being an effect of tidal interaction with the companion Sa galaxy NGC 5953. The ULX and the mentioned complexes are located where the spiral arm bends becoming straight.

### 2.4. Near-infrared and Radio Observations

Near-infrared images of NGC 5953/5954 were retrieved from the Two Micron All Sky Survey (2MASS) archive. Astrometry between the 2MASS and the Chandra images was done using the nucleus of NGC 5953 (offset in R.A. is 0.00′′ and in decl. 0.3′′). Although there are 2MASS sources in the area, they do not match peaks in our H\(_\alpha\) data. No point-like 2MASS sources were detected at the ULX position at the detection limit of 20 mag.
Figure 4. Close-up of the Hα scanning Fabry–Perot velocity map at +1825 km s$^{-1}$ of the galaxy pair NGC 5953/5954 showing part of the southern spiral arm of the Scd galaxy NGC 5954. Astrometry between the Fabry–Perot Hα image and the Chandra was done using the nucleus of NGC 5953 (not shown in this image). The ULX position is marked with an ellipse of the same dimensions as in Figure 2. The black ellipse corresponds to the shifted Chandra position whereas the red one corresponds to the astrometric corrected Chandra position of the ULX obtained applying a $(2.73 \pm 0.67)''$ shift derived from matching the positions of the H\textsc{ii} regions with those of González-Delgado & Pérez (1996). The approximate positions of the nearby H\textsc{ii} complexes #5 and #9 catalogued by González-Delgado & Pérez (1996) are marked with circles whose diameter is about the dimensions reported by those authors (see the text for further details).

(A color version of this figure is available in the online journal)

Figure 5. FIRST image of NGC 5953/5954. The black ellipse is the same as in Figure 2 and shows the location of the ULX candidate.

The NRAO Very Large Array–Faint Images of the Radio Sky at Twenty centimeters (VLA–FIRST, Becker et al. 1995) image of NGC 5953/5954 field is shown in Figure 5. The peak flux densities at the nuclei of NGC 5953 and NGC 5954 are 16.72 and 2.95 mJy beam$^{-1}$, respectively, with an rms of 0.15 mJy. Once again, to help guide the eye, we plot the ellipse at the Chandra position of the ULX. This shows that no radio emission was detected at the position of the ULX during the FIRST observation although there is a weak radio source nearby with integrated flux density around 0.7 mJy.

3. DISCUSSION AND CONCLUSIONS

From Chandra observations of NGC 5953/5954 we have detected a bright ULX, which is most likely an elongated object...
around 350 pc long. Both power-law and bremsstrahlung models fit equally well to the Chandra spectrum of this ULX. Possible optical counterpart of this ULX system is an object of absolute magnitude $-7.1 \pm 0.7$ mag. We do not know the color of this object. Considering the very high optical luminosity, we thus expect that it may be a massive, O-type supergiant. However, the possibility of a young star cluster (Wyder et al. 2000) cannot be ruled out, especially considering that some ULXs have been detected in the vicinity of young star clusters (Zezas et al. 2004; Krauss et al. 2005). From Fabry–Perot observations, we have detected excess diffuse He and [N II] (6584 Å) emissions, above the ambient background, at the astrometric-corrected Chandra position of the ULX. Fabry–Perot velocity maps also show that this ULX is most likely associated with an emission nebula, which is expanding at a rate of $30 \pm 7$ km s$^{-1}$. Counterparts of this ULX are not detected in the 2MASS and VLA/FIRST data.

Based on these results, different scenarios can be invoked to describe the possible nature of the ULX system: (1) a foreground star, (2) a background object, (3) a gravitational lens system, (4) ULX consisting of two ULXs, (5) an X-ray transient, (6) a supernova remnant, and (7) an X-ray beamed system. Here we discuss these possibilities in detail.

The ratio between the X-ray and the optical fluxes ($F_X/F_O$) is around 140, which is extremely large for any stellar object. The value of this ratio for stars ranges between $10^{-4}$ and 0.1 (Maccacaro et al. 1988). In addition, the value of the hydrogen column density is more than an order of magnitude higher than that of the Galactic value (Table 1). Thus, we can rule out the foreground origin of this ULX.

Similarly, the value of $F_X/F_O$ for normal galaxies, clusters of galaxies, and active galactic nuclei (AGNs) is much lower than the observed value of around 140 (Maccacaro et al. 1988; Stocke et al. 1991). For blazars, this ratio could be up to 50. Even if we assume that the ULX is an X-ray selected blazar with $F_X/F_O \sim 140$, then the expected radio flux density at 1.4 GHz, assuming synchrotron emission from the same population of electrons responsible for the optical emission, the expected flux density would be more than 50 mJy (Stocke et al. 1991; Landt et al. 2001), which is far above the emission detected from the nearby, weak radio source located at 5″ from the Chandra position of the ULX (Figure 5). Thus, we can confidently rule out that the ULX is a background object.

If the elongated image of the ULX is due to double sources, then it may be possible that it is a gravitational lens system. In this scenario, we expect two optical objects at the positions of the two X-ray sources. However, from the HST image we do not see a second object within the astrometric-corrected error circle at the Chandra position. Thus, we rule out this possibility.

It may be possible that the elongated shape of the ULX is due to the presence of two ULXs separated by an arcsecond. With the available data we can neither rule out nor establish this hypothesis. However, it can be mentioned that the radial profile, i.e., the radial distribution of the counts per pixel at the position of the ULX, gradually declines up to a radial distance of 4.5 pixels and then merges with the background. This is shown in the right panel of Figure 2. In addition, we would like to mention that the chance probability of detecting two ULXs separated by an arcsec among 4000 sources detected in more than 100 galaxies observed with Chandra (Swartz et al. 2004) is extremely low, less than $3.5 \times 10^{-6}$. These results suggest that the Chandra image of CXOU J153434.9+151149 is elongated.

Extremely low values of the ratio of radio to X-ray fluxes ($F_R/F_X$) have been detected in X-ray transients (Fender & Kuulkers 2001) and also in the ULX candidate in NGC 5408 (Kaaret et al. 2003). Non-detection of radio emission at the position of the ULX suggests that the $F_R/F_X$ for the ULX candidate in NGC 5953/5954 is consistent with those of X-ray transients. However, this ULX was detected three times in three observations. Thus, it may not be an X-ray transient.

Extended X-ray morphology of the ULX indicates that a young supernova remnant (SNR) may explain the properties of this ULX. Typically, young SNRs have X-ray luminosities of $\sim 10^{38}$ erg s$^{-1}$, which is two orders of magnitude lower than the X-ray luminosity of ULXs. However, some Type IIn supernova (SNe IIn) explosions are extremely powerful and can produce X-ray luminosities up to $10^{41}$ erg s$^{-1}$ (Fabian & Terlevich 1996). These rare events occur only in late-type galaxies, mainly in Sc galaxies, and are thought to be due to the explosion of a massive star in a very dense circumstellar medium, probably ejected in a previous evolutionary phase of the supernova progenitor, i.e., during its red giant phase. These SNRs evolve faster in comparison with the normal evolution of SNRs in less dense media and enter into the radiative phase bypassing the Sedov phase. They reach maximum luminosity in less than 20 years after the SN explosion, when their radii are small ($R < 0.1$ pc). Her luminosities and expansion velocities of these SNRs could reach up to $10^{40}$ erg s$^{-1}$ and thousands of km s$^{-1}$, respectively. In fact, the evolution and duration of the X-ray bright phase of Type IIn SNe is very uncertain, which is detected up to 25–30 years after explosion (Fabian & Terlevich 1996; Lenz & Schlegel 2007).

From our FP observations we have found that the nebula around the ULX could be expanding at a rate of 30 km s$^{-1}$, which is too small compared to those of SNIIn/SNls (Fabian & Terlevich 1996). In addition, the major-axis diameter of the ellipse drawn on the X-ray image of the ULX (left panel of Figure 2) is $\sim 2.5''$, which corresponds to $\sim 350$ pc. This is extremely large compared to $\sim 0.2$ pc (Fabian & Terlevich 1996). Thus, the observed properties of the ULX in NGC 5953/5954 are different from those of SNIIn/SNls.

HST/WFC2 results suggest that the possible counterpart of the ULX in NGC 5953/5954 may be either an O-type supergiant star or a young star cluster. In addition, steady emissions have been detected from this ULX on all three occasions in excess of $10^{40}$ erg s$^{-1}$. Observed, persistent X-ray emissions may originate from stable accretion disks, which are generally formed through the thermal time scale mass transfer (King et al. 2001a). It has also been shown that both stellar-mass black hole and IMBH binaries can have persistent X-ray emissions (Kalogera et al. 2004). Thus, the luminous X-ray emission from CXOU J153434.9+151149 can be explained in the framework of both a beamed, stellar-mass black hole and an IMBH system (Begelman 2006; Copperwheat et al. 2007; Mizuno et al. 2007; Patruno & Zampieri 2007).

It is very likely that high-mass binary stars will form in the environment of strong OB-associations on the spiral arm of the galaxy, where the ULX is located. Fast evolution of these binary stars will lead to high-mass X-ray binaries. Beaming from a stellar-mass black hole binary with an O-type supergiant star can emit X-rays in excess of $10^{40}$ erg s$^{-1}$ (King et al. 2001b). If we assume that the maximum mass of a stellar-mass black hole is $20 M_\odot$, which is accreting at the Eddington rate, then the beaming has to enhance the emission by a factor of 10 to produce the observed luminosity of the ULX. If such beaming is
due to the inverse-Compton process from a continuous jet with photons from an external source, e.g. from the companion star, then this amplification factor can be expressed as $\delta^{3+2\epsilon}$ (Kaaret et al. 2003), where the Doppler factor, $\delta = 1/[\gamma (1 - \beta \cos \theta)]$, $\gamma$ is the Lorentz factor of the outflow, $\beta$ is the three velocity of the outflow in units of the velocity of light, $\alpha_x$ is the spectral index ($\alpha_x = 0.5$, Table 1), and $\theta$ is the inclination angle to the outflow (Lind & Blandford 1985). In order to obtain an amplification factor of 10, the value of $\delta$ will be 1.78. This value of $\delta$ can be achieved when the values of $\theta$ are $0^\circ$, $15^\circ$ and $30^\circ$ and the corresponding $\beta$ values are 0.6, 0.64 and 0.9, respectively. These results demonstrate that to enhance the intrinsic X-ray intensity by a factor of 10, the outflow has to be viewed by the observer, at least, within $30^\circ$. However, the projected minor-to-major axial ratio of the ellipse (Figure 2) is roughly around $1.5''/2.5'' = 0.60$. This suggests that the inclination angle to the elongated emission is $\sim53^\circ$, assuming that the thickness of the elongated emission is sufficiently small. With this value of $\theta$, we have computed a range of values of $\delta$ for different values of $\beta$ between 0.1 and 0.9 and find that the maximum possible enhancement of the X-ray emission will be only by a factor 3.1 with the value of $\beta$ equal to 0.6. Thus, the observed X-ray morphology of CXOU J153434.9+151149, which constrains the inclination angle, indicates that the observed X-ray luminosity cannot be explained with beaming from a stellar-mass black hole binary. However, changes by one pixel in the minor- or major-axis diameters of the X-ray elongated emission will lead to the inclination angle close to $30^\circ$. Then, beaming from the stellar-mass black hole binary system will be able to produce the observed X-ray brightness of CXOU J153434.9+151149 with $\beta$ equal to 0.9. It is important to mention here that elongated emission from a ULX system can be seen when the inclination angle is sufficiently large but, at the same time, it has to be viewed at a narrow angle, if large amplifications of intrinsic X-rays are to be produced due to the relativistic beaming. This rules out the possibility that most of the ULXs can be seen under such a special orientation. To the contrary, the ULX in NGC 5953/5954 is the only known object with elongated X-ray emission, which is consistent with the expectations of only a few such systems with a special geometry. Thus, a high S/N Chandra image of this ULX is essential to accurately determine its morphology. In addition, kinetic energy of such a highly relativistic outflow (velocity = 0.9 c) will inflate the local environment and will form a special spatial structure. Ionized nebulae with bubble-like morphology have been detected around some ULXs (Roberts et al. 2003; Pakull & Mirioni 2003; Pakull et al. 2006). These bubbles are several hundred parsec in diameter with expansion velocities around 50–80 km s$^{-1}$ (Rosado et al. 1981, 1982; Valdez-Gutiérrez et al. 2001). It has been suggested that the expansion could be due to the combined action of energetic supernova explosions and stellar winds, or to continuous inflation by geometrically-beamed jets (Chu & Mac Low 1990; Miller 1995; Valdez-Gutiérrez et al. 2001; Wang 2002; Pakull & Mirioni 2003; Pakull et al. 2006). Some nebulae show barrel-type shapes or enhanced emission along opposite directions that could be interpreted as excitation from a beamed source (Roberts et al. 2003; Pakull & Mirioni 2003). However, some nebulae have displayed a spur-shape, which requires an isotropic flux of energetic photons to explain the observed He ii flux (Kaaret et al. 2004; Pakull et al. 2006). Nebulae formed by the combined action of supernova remnants and stellar winds are not supposed to have He ii emission unless it contains very massive stars. Thus, detection of a non-spherical He ii nebula at the position of the ULX will support the beaming model of the ULX in NGC 5953/5954.

Based on the X-ray morphology of CXOU J153434.9+151149, we have seen above that the beaming could enhance the intrinsic X-ray intensity, at the most, by a factor of 3. This clearly suggests that the mass of the accretor of this ULX system has to be more than $50 M_\odot$, assuming that it is accreting at the Eddington rate. However, the X-ray colors and spectral results indicate that this ULX has a hard/flat power-law tail ($\alpha_x = 0.5$, Table 1 and Section 2.1), which indicates that it is a sub-Eddington system. If we assume that $\lambda_{\text{Edd}}/L_{\text{X}} \sim 0.1$, then the mass of the accretor will be more than $500 M_\odot$. This type of IMBH system can be hosted in a young star cluster, which is most likely present within the error circle at the position of the ULX (shown in Figure 3). In addition, the IMBH system will photoionize its local environment, which can be detected from the optical spectra. Future observations, which we have planned to carry out, will reveal the true nature of this system.

In conclusion, we have detected a bright ULX in NGC 5953/5954. Its Chandra image is elongated. Most likely, its optical companion is either an O-type supergiant star or a young star cluster. This ULX is associated with an extended nebular He ii and [N ii] (16584 Å) emissions with a [N ii]/He ii line-ratio of about unity. This nebula is moving at the characteristic velocities of the galaxy NGC 5954. A nearby, faint radio source is located at $5''$ from the Chandra position of the ULX. All these results are best explained in the framework of a model, which consists of mildly beamed binary with a black hole more massive than $50 M_\odot$. Follow-up radio, optical and X-ray observations are highly wanted to clearly establish the nature of this ULX.

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