THE ULTRALUMINOUS X-RAY SOURCES NEAR THE CENTER OF M82

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\section{ABSTRACT}

We report the discovery of a recurrent ultraluminous X-ray source (ULX), a background AGN, and a young supernova remnant near the center of the starburst galaxy M82. From a series of \textit{Chandra} observations taken from 1999 to 2005, we found that the ULX first appeared in 1999 October. The source turned off in 2000 January, but later reappeared and has been active since then. The X-ray luminosity of this source varies from below the detection level ($\sim 2.5 \times 10^{38}$ erg s$^{-1}$) to its active state in between $8 \times 10^{39}$ erg s$^{-1}$ and $1.3 \times 10^{40}$ erg s$^{-1}$ (in the 0.5-10 keV energy band) and shows unusual spectral changes. The X-ray spectra are best fitted with an absorbed power-law model with photon index ranging from 1.3 to 1.7. The spectra are similar to those Galactic black hole binary candidates seen in the low/hard state except that a very hard spectrum was seen in one of the observations. By comparing with near infrared images taken with the \textit{Hubble Space Telescope}, the ULX is found to be located within a young star cluster. Radio imaging indicates that it is associated with a H II region. We suggest that the ULX is likely to be a $>100 M_\odot$ intermediate-mass black hole in the low/hard state. In addition to the transient ULX, we also found a highly absorbed hard X-ray source which is likely to be an AGN and an ultraluminous X-ray emitting young supernova remnant which may be related to a 100-year old gamma-ray burst event, within 2 arcsec of the transient ULX.

\textit{Subject headings:} \textit{black hole physics} --- \textit{galaxies: individual (M82)} --- \textit{supernova remnants} --- \textit{X-rays: binaries} --- \textit{X-rays: galaxies}

\section{1. INTRODUCTION}

Ultraluminous X-ray sources (ULXs) are defined as off-nuclear X-ray sources with isotropic luminosities much higher than the Eddington limit for a solar mass black hole ($L_X \sim 1.3 \times 10^{38}$ ergs s$^{-1}$). Typical X-ray luminosities of ULXs are in between $10^{38}$ ergs s$^{-1}$ and $10^{41}$ ergs s$^{-1}$. The physical nature of ULXs has been an enigma because of their high energy output. Many ULXs show strong variability suggesting that they are accreting compact objects. Assuming the emission is isotropic, then some of the ULXs may harbor intermediate-mass black hole (IMBH; Colbert & Mushotzky 1999; Makishima et al. 2000) with masses of $100 - 100000 M_\odot$. Alternatively, ULXs may simply be stellar-mass black holes. It has been suggested that ULXs are stellar-mass black holes with radiation pressure-dominated (Begelman 2002) or slim (Ebisawa et al. 2003) accretion disks that cause super-Eddington luminosities. Furthermore, ULXs may be stellar-mass black holes with anisotropic X-ray emission (King et al. 2001), or micro-blazars which happened to be observed along the direction of their relativistically beamed jet (Körding et al. 2002). In addition, some ULXs may be young X-ray luminous supernova remnants in a high-density medium, or hypernova remnants. Finally, we would also expect that some ULXs are background AGNs (e.g., López-Corredoira & Gutiérrez 2006; Vázquez et al. 2007). Each of these models has difficulties to fully explain the observations, but yet has some supporting pieces of evidence. Currently, we do not have a complete picture about the physical nature of ULXs, primarily because we do not have dynamical mass measurements of the compact objects that power ULXs.

In our current stellar formation and evolution theory, we are only able to constrain two classes of black holes, the supermassive black holes with masses exceeding $10^6 M_\odot$ at the center of galaxies and stellar-mass black holes with masses lower than $20 M_\odot$. If some ULXs host IMBHs, they might provide a clue to fill in the missing link between stellar-mass black holes and supermassive black holes.

In this paper, we report on a recurrent transient ULX in the starburst galaxy M82 by using archival \textit{Chandra} and \textit{Hubble Space Telescope} (\textit{HST}) data. The source is located near the galactic dynamical center and is one of the most luminous X-ray sources within the upper-bubble region of M82 (Matsushita et al. 2005; Matsumoto et al. 2000), close to several super-star clusters. This source is probably the second most luminous source in M82. The most luminous source, M82 X–1, is a prime candidate of IMBH and is about 5 arcsec from the transient (see Kaaret et al. 2006 and references therein). In addition, we also study the physical nature of the two ULXs very close to the ultraluminous transient by using multi-wavelength data.

In § 2 we describe the \textit{Chandra} and \textit{HST} observations. We present the data analysis and results in § 3. A discussion of the three ULXs is given in § 4.

\section{2. OBSERVATIONS}

\subsection{2.1. \textit{Chandra}}

M82 (NGC 3034) is a nearby starburst galaxy. We adopt a distance of 3.6 Mpc to M82 and is based on the Cepheid distance of $3.63 \pm 0.34$ Mpc to its close neighbor galaxy M81 (Freedman et al. 1994). M82 was observed ten times between the year of 1999 and 2005 with \textit{Chandra}. The details of the observations are given in Table 1. Among these ten observations, only one observation (ObsID 1411) was using the High Resolution Camera (HRC-I). The rest were using the Advanced CCD Imaging Spectrometer array (ACIS-I or ACIS-S). We used CIAO, HEAsoft, and XSPEC packages to perform data reduction and analysis.
For ObsIDs 1411 and 380, there are two separate observations within the same event list. Therefore, we used a time-filter to split the observations and analyzed the data separately. Four of the observations (ObsIDs 378, 379, 380, and 6097) are off-axis to reduce pile-up of M82 X–1 due to its high luminosity. In particular, during ObsIDs 6097, 5644, and 6361, the detector was employed a 1/8 subarray mode with a frame time of 0.441 s to reduce pile-up.

### Table 1

| Date       | ObsId | Exposure | Instrument | Remark       |
|------------|-------|----------|------------|--------------|
| 1999−09−20 | 361   | 33.7 ks  | ACIS-I     |              |
| 1999−09−20 | 1302  | 15.7 ks  | ACIS-I     |              |
| 1999−10−28 | 1411−1| 36.3 ks  | HRC-I      |              |
| 1999−12−30 | 378   | 4.2 ks   | ACIS-I     | off-axis     |
| 2000−01−20 | 1411−2| 17.8 ks  | HRC-I      |              |
| 2000−03−11 | 379   | 9.1 ks   | ACIS-I     | off-axis     |
| 2000−05−07 | 380−1 | 3.9 ks   | ACIS-I     | off-axis     |
| 2000−06−12 | 380−2 | 1.2 ks   | ACIS-I     | off-axis     |
| 2002−06−18 | 2933  | 18.3 ks  | ACIS-S     |              |
| 2005−02−04 | 6097  | 58.2 ks  | ACIS-S     | off-axis, 1/8 subarray |
| 2005−08−17 | 5644  | 75.1 ks  | ACIS-S     | 1/8 subarray |
| 2005−08−18 | 6361  | 19.2 ks  | ACIS-S     | 1/8 subarray |

NOTE.— ObsIDs 1411 and 380 have two observations merged in one event list. We used a time filter to separate the two observations.

#### 3. DATA ANALYSIS AND RESULTS

##### 3.1. X-ray Imaging

The brightest source in the field of M82 is M82 X–1 (CXOU J095550.2+694047; see Fig. 1). We note that the X-ray coordinate is based on an astrometric corrected image (see § 3.5). About 5 arcsec southeast of M82 X–1, there is a complex of three bright X-ray sources. By examining the Chandra images, the brightest one, CXOU J095551.0+694045 (J095551.0 hereafter), was clearly below the detection limit in two observations indicating that it is a highly variable source. Note that previous studies have mentioned the transient behavior of this source (Matsumoto et al. 2001; Kaaret et al. 2006). In addition to J095550.2, there are several additional transients as shown in Figure 1; the discussion of these transients is out of the scope of this paper. There are two fainter X-ray sources, CXOU J095551.2+694044 (J095551.2 hereafter) and CXOU J095550.6+694044 (J095550.6 hereafter) located at about 2 arcsec to the south of J095551.0 forming a triangle (Fig. 1). In contrast to J095551.0, these two sources are always active.

#### 3.2. X-ray Spectroscopy

We performed spectral analysis for all Chandra ACIS data by using XSPEC v11.3. We also used CIAO’s Sherpa for independent check. In three of the observations, the X-ray sources are located near the aim point and we can use a circular extraction region with radii of 0.8–1.3 arcsec depending on the contamination of nearby sources. The relatively small extraction radii were used because the three X-ray sources that we are interested in are close to each other. For the remaining four observations, our targets were off-axis and therefore we used an elliptical region to extract the spectra. For the background, we used a nearby source free region. We rebin the 0.3–7 keV spectra with at least 20 counts per spectral bin, and used $\chi^2$ statistics to find the best-fitting parameters. Corresponding response files were generated using CIAO.

For the transient (J095551.0), the X-ray spectra can be adequately fitted with an absorbed power-law model. The spectral parameters are listed in Table 2. In general, the photon index varies between 0.9 and 1.7 while the $N_H$ is about $3 \times 10^{22}$ cm$^{-2}$, consistent with the extinction measured with near IR observations (Alonso-Herrero et al. 2003). It is worth noting that during one observation (ObsId 2933), the source suffers mild pile-up. In this case, we included a pile-up model in spectral fit yielding a pile-up fraction of $\sim 15\%$. Since four of the observations (ObsId 378, 379, 380, and 6097) are off-axis, the spectra of the transient are contaminated by J095551.2 and J095550.6. The contamination is particularly serious in ObsId 378, 379, and 380 and may result the relatively hard spectra of these observations. To verify the contamination, we extracted combined spectra of all three sources using ObsId 5644 and 6361 for which the sources are well resolved. While the X-ray flux is dominated by the transient, the X-ray spectra become significantly harder with a photon index of $\sim 1$. This indicates that the hard spectra of the three contaminated observations are likely due to nearby sources. The best fitting power-law spectrum of ObsId 5644 is shown in Figure 2.

J095551.2 is the next brightest source near the transient. We first fitted the spectra with an absorbed power-law model and the spectral parameters are shown in Table 2. Three of the fits are acceptable and the spectra turn over at about 4 keV suggesting very high absorption. The best fitted $N_H$ is about $(1−2) \times 10^{23}$ cm$^{-2}$ which is an order of magnitude greater than the other two nearby sources. In addition, all spectra are very hard with $\Gamma \lesssim 1$ except for ObsId 361. For ObsId 5644, a soft excess is clearly seen in the spectrum (Fig. 2) and the fit is much poorer than the others. Indeed, soft excess is seen in all spec-
Fig. 1.—*Chandra* 0.3–7 keV images of the central 45′′ × 45′′ region of M82 as seen on 1999 September 20 (Left; ObsID 361) and 2002 June 18 (Right; ObsId 2933). Both figures have the same spatial scale. The locations of the three ULXs discussed in this paper are marked. We also indicate the position of M82 X–1. The images has been slightly smoothed with a 0.5′′ σ Gaussian function.

tra but with larger uncertainties due to shorter exposure time or smaller collecting area of ACIS-I below 2 keV. Soft excess is a common feature of AGN with an ionized absorber. We then refitted the spectrum (ObsID 5644) with an additional ionized absorber (*absor* model in *XSPEC*; Zdziarski et al. 1995). The fit is acceptable with a reduced $\chi^2$ of 1.06, and the best-fit photon index steepens to 2 with a large absorbing column of $N_H = 9 \times 10^{23} \text{ cm}^{-2}$ (see Fig. 3); the absorbed 0.5–10 keV flux is $10^{-12} \text{ ergs cm}^{-2} \text{s}^{-1}$.

Apart from ObsID 5644, the X-ray spectra of J095550.6 can be fitted with an absorbed power-law with $N_H \sim 3 \times 10^{22} \text{ cm}^{-2}$ and a photon index of $\Gamma > 2.7$. ObsID 5644 has the longest exposure time and the X-ray spectrum of J095550.6 is clearly more complicated. It cannot be fitted with any single component model. Instead, a combination of Raymond-Smith model and power-law model is required. In addition, emission lines are clearly seen in the X-ray spectrum (Fig. 4). The X-ray spectrum indicates that J095550.6 is either a nearby foreground star or a supernova remnant in M82. We will show in §4.3 that J095550.6 is indeed a young supernova remnant in M82.

3.3. X-ray Variability

With the spectral fits, we can estimate the X-ray fluxes of the three sources and study the long-term variability. We limit our analysis with *Chandra* data because the three sources as well as M82 X–1 are not resolved with *Einstein*, ROSAT, and XMM-Newton. The luminous X-ray source, J095551.0, displays strong variability on the timescales of months (see Fig. 5). In particular, the source was not detected in 1999 September and reappeared in 1999 October. It was below the detection limit again in 2000 January and then turned back on in 2000 March. Figure 5 shows the long-term X-ray lightcurve of J095551.0 from 1999 September to 2005 August. For the HRC-I observations, we estimated the X-ray flux by assuming an absorbed power-law model with $N_H = 3 \times 10^{22} \text{ cm}^{-2}$ and a photon index of 1.5. When the source is active, the X-ray luminosity shows very little variability at $(8-13) \times 10^{39} \text{ ergs s}^{-1}$.

J095551.2 has a soft spectrum ($\Gamma = 2$) during the first observation and it becomes much harder ($\Gamma < 1$) in subsequent observations. Because of the high $N_H$, the flux is very sensitive to the photon index. For instance, if we fit the spectra with an ionized absorber plus power-law model fixing the spectral parameters except for the normalization as in ObsID 5644, the luminosities will become $\sim 10^{40} \text{ ergs s}^{-1}$. Hence, the source does not show significant variability.

For J095550.6, the apparent softening during the last observation is likely an artifact because of the low count rate. We used the same Raymond-Smith plus power-law model as in ObsID 5644 and the spectrum can be fitted equally well. The resulting luminosity is about $2.4 \times 10^{39} \text{ ergs s}^{-1}$, consistent with other observations. Therefore, J095550.6 is consistent with a constant X-ray source.

We also study the short-term variability of our targets. We extracted the source and background lightcurves from the 0.3–7 keV event files except that there is no energy filter for HRC-I data. We applied similar procedure as discussed in §3.2 to define the source and background regions of our targets. All three sources do not show significant variability on timescale of hours. We show the short-term lightcurves of the transient in Figure 6.

3.4. Radial Profile

We investigated the spatial extent of the ULXs using ObsID 5644 for which the sources have the highest number of counts and are well resolved. Soft (0.3–3 keV) and hard (3–7 keV) band counts were extracted from energy filtered images. We also generated images of the point spread functions (PSF) of each source using *Chandra* Ray Tracer (ChaRT) and compared
with a count rate of 9 assuming a Raymond-Smith model with $\mu = 7$.

Counts from these images were compared with the real sources. Counts from these images were compared with the PSF models; we do not find significant difference based on the Kolmogorov-Smirnov (K-S) test. The deviation of the source profile from PSF is generally larger in soft band due to the soft diffuse emission around these sources.

3.5. Near IR Imaging

In order to compare the Chandra and HST NICMOS images, we first aligned the two images. For the X-ray image, we used the HRC-I observation taken on 1999 October 28 (ObsID 1411) as the reference frame because it has a wide field-of-view and moderate exposure. Furthermore, all three targets were active during this observation. We used CIAO tool wave detect to detect X-ray sources in the HRC-I image. We compared the X-ray source list with the 2MASS catalog, and looked for coincidence of bright and isolated stellar objects. We found one star (2MASS J09551494+6936143) that is < 1" from the X-ray position. From the ACIS-I observation (ObsID 2933), the X-ray colors of the X-ray emitting star indicate that it has a very soft X-ray spectrum (84% of the source counts come from < 1 keV with no counts above 2 keV), consistent with a very soft X-ray source (Di Stefano & Kong 2004). The X-ray radiation is therefore likely due to the coronal emission from a foreground star. The star has a $R$ magnitude of 10.1 (Monet et al. 2003). We calculated the X-ray to optical flux ratio as $\log(f_x/f_r) = \log f_x + 5.67 + 0.4R$ (Hornschemeier et al. 2001). With a count rate of $9.4 \times 10^{-4}$ c/s in the ACIS-I detector and assuming a Raymond-Smith model with $kT_H = 0.3$ keV and $N_H = 4 \times 10^{20}$ cm$^{-2}$ (the Galactic value toward the direction of M82), the $0.3-10$ keV flux is $10^{−6}$ ergs cm$^{-2}$ s$^{-1}$ and the corresponding $f_x/f_r$ is $5.1 \times 10^{-5}$, consistent with a foreground star.

Based on the 2MASS counterpart, the boresight correction that needs to be applied to the X-ray source positions is $0.87 \pm 0.56$ arcsec in R.A. and $0.73 \pm 0.27$ arcsec in decl.; the uncertainties are a quadratic sum of the positional errors of the X-ray and 2MASS source. To study the IR environment of X-ray sources, we plot the refined X-ray error circles, which are the quadratic sum of the positional uncertainty for the X-ray source, the uncertainty in the optical astrometry (2MASS to ACS astrometry and ACS to NICMOS astrometry), and the uncertainty in the X-ray boresight correction, of the three X-ray sources on the HST NICMOS image (see Fig. 8). In the figure, we also plot the locations of several known super-star clusters and M82 X–1. As expected, this area has many star formation activities with the presence of super-star clusters. The three luminous X-ray sources as well as M82 X–1 are located near star clusters. In particular, a star cluster is at the center of the error circle of J09551.0, suggesting that the X-ray source is associated with the cluster. J09551.2, however, does not seem to have any counterpart. While there is no obvious counterpart within the X-ray error circle of J09550.6, some unresolved IR emission is seen. Furthermore, a super-star cluster, MGG–8, is just outside the 1σ X-ray error circle locating 1 arcsec from the source. It is also worth noting that M82 X–1 is located just outside the super-star cluster, MGG–11.

4. DISCUSSION

4.1. J09551.0: An Ultraluminous X-ray Transient

The most intriguing behavior of J09551.0 is the X-ray variability. The source varies from below the detection limit, $\sim 2.5 \times 10^{38}$ ergs s$^{-1}$ in the 0.5–10 keV band, to $\sim 10^{40}$ ergs s$^{-1}$ on timescales between observations of ~ 2 months. Furthermore, the source shows recurrent outbursts. Recurrent ultraluminous transients are not common in nearby galaxies. By comparing ROSAT and XMM-Newton observations, Winter et al. (2006) found that most of the ULXs are persistent sources with less than a factor of 3 in flux variation over the timescale from ROSAT to XMM-Newton. Nevertheless, ultraluminous X-ray transients are recently found in NGC 3628 (Strickland et al. 2001), M74 (Soria & Kong 2002), NGC 300 (Kong & Di Stefano 2003), NGC 253 (Bauer & Pietsch 2005), and M101 (Kong et al. 2004; Kong & Di Stefano 2005). Two of these sources (NGC 300 and M101) are ultraluminous super-soft sources with $kT \lesssim 0.1$ keV. The ones in NGC 3628 and M74 are typical power-law sources with $\Gamma \sim 2$ while the ULX in NGC 253 can be described with a bremsstrahlung model with $kT = 2.2$ keV. J09551.0, however, has a much harder spectrum. These sources also show diverse luminosity range. The sources

| Date       | J095551.0 | J095551.2 | J095550.6 |
|------------|-----------|-----------|-----------|
| Date       | $N_p$     | $\chi^2/\text{dof}$ | $N_p$     | $\chi^2/\text{dof}$ | $N_p$     | $\chi^2/\text{dof}$ |
| 1999-09-20 | 21.75 ± 0.8 | 17 ± 0.7 | 1.081 |
| 1999-12-30 | 2.67 ± 0.35 | 7.4 ± 0.4 | 0.8/16 |
| 2000-03-11 | 2.88 ± 0.37 | 8.5 ± 0.3 | 0.9/47 |
| 2000-05-07 | 3.34 ± 0.47 | 8.3 ± 0.4 | 1.3/24 |
| 2002-06-18 | 3.63 ± 0.49 | 7.8 ± 0.2 | 0.8/69 |
| 2005-02-04 | 3.19 ± 0.31 | 12 ± 0.1 | 0.02/93 |
| 2005-08-17 | 3.56 ± 0.29 | 13 ± 0.1 | 1.1/331 |
| 2005-08-18 | 3.34 ± 0.34 | 11 ± 0.2 | 0.9/126 |

NOTE.— All quoted uncertainties are 90% except for the luminosities which are 1σ.

The spectrum of J09551.0 taken on 2002 June 18 suffered pile-up and a pile-up model was applied during spectral fit.

a in units of 10$^{-2}$ cm$^{-2}$

b 0.5–10 keV unabsorbed luminosity in units of 10$^{39}$ ergs s$^{-1}$ (assuming d = 3.6 Mpc).
in NGC 253, M74, and NGC 300 only reach $L_X \gtrsim 10^{39}$ ergs s$^{-1}$ suggesting that an IMBH is not necessary. On the other hand, the sources in NGC 3628 and M101 can have 0.3–8 keV luminosities of $\sim 5 \times 10^{40}$ ergs s$^{-1}$ with bolometric luminosities approaching $10^{41}$ ergs s$^{-1}$. While we cannot totally rule out a stellar-mass black hole model, a black hole of intermediate mass is certainly an attractive scenario.

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**Fig. 2.** — Power-law spectral fits of J095551.0 (top), J095551.2 (middle), and J095550.6 (bottom). Spectra are from ObsID 5644. See Table 2 for spectral parameters.

**Fig. 3.** — Chandra spectrum of J095551.2 with an ionized absorber plus power-law model ($N_H = 9 \times 10^{23}$ cm$^{-2}$, $\Gamma = 2$, ionization parameter $\xi = 882$, $\chi^2$/dof = 1.06/69). We fixed the absorber temperature and Fe abundance at $10^5$ K and solar values, respectively as the fit was not sensitive to these parameters.

**Fig. 4.** — Chandra spectrum of J095550.6 with an absorbed Raymond-Smith plus power-law model ($N_H = 2.9 \times 10^{22}$ cm$^{-2}$, $kT_{RS} = 0.9$ keV, $\Gamma = 2.01$, $\chi^2$/dof = 1.1/56).

**Fig. 5.** — Long-term X-ray lightcurve of the ultraluminous X-ray transient, J095551.0. The luminosities are determined by spectral fits (see Table 2). For the HRC-I observation, we assume an absorbed power-law spectral model with $N_H = 3 \times 10^{22}$ cm$^{-2}$ and $\Gamma = 1.5$. For non-detections, a 90% upper limits are shown.
FIG. 6.—*Chandra* short-term lightcurves of the transient J095551.0, when it is active. The time resolution of each plot is 500 s. We do not show ObsID 380-2 due to its short exposure time (1.2 ks). We note that the apparent difference in the count rate is due to different detectors and off-axis angle of the source.
A factor of > 50 in flux variation indicates that J095551.0 is a compact source while recurrent outbursts and hard X-ray spectra can rule out the possibility that the source is a young supernova remnant. It is also unlikely to be a background AGN since AGN normally varies by a factor of < 10 on timescales of days to months. However, transient AGNs are not unusual (e.g., Komossa et al. 2004; Grupe et al. 2004) and they belong to a class of AGNs called narrow-line Seyfert 1 galaxies. These galaxies have X-ray spectra much softer (\( \Gamma > 2.5 \); e.g., Boller et al. 1996; Grupe et al. 2004) than J095551.0. The more likely scenario is that J095551.0 is a binary system with a black hole accretor. The high X-ray luminosity (\( L_X \approx 10^{40} \text{ ergs s}^{-1} \)) when it is active indicates that it may be an ULX with an IMBH. Assuming the emission is isotropic, the X-ray luminosity implies that the compact object is a \( \sim 100 M_\odot \) black hole. Many ULXs have a thermal component with a temperature of \( \approx 0.1 \) keV which is interpreted as evidence of IMBHs with masses of \( \sim 1000 M_\odot \) (Miller et al. 2004). J095551.0, however, does not have any soft excess and the X-ray spectra are well fitted with an absorbed power-law model with photon index \( \Gamma = 1.3 - 1.7 \). This resembles to the low/hard state of Galactic black hole X-ray binaries (McClintock & Remillard 2006). It is therefore possible that the source can be explained in the framework of the advection-dominated accretion flow (ADAF) model.

More recently, Yuan et al. (2007) apply an ADAF model to describe the X-ray emission of M82 X–1 and argue that the accreting compact object is an IMBH. During the low/hard state, the ADAF model predicts that the X-ray luminosity is about < 1% – 10% of the Eddington luminosity. If J095551.0 is accreting at a rate similar to the hard-state of Galactic black hole X-ray binaries, this implies a black hole mass of \( \sim 1000 - 10^4 M_\odot \).

Indeed, pure power-law spectral model for ULXs is not uncommon; Chandra and XMM-Newton observations have revealed hard-state ULXs in several nearby galaxies (see e.g., Roberts et al. 2004; Winter et al. 2006). Hard-state ULXs may be good candidates of IMBHs. If the accreting object is instead a stellar-mass black hole in the hard state, the X-ray emission must be anisotropic in order to produce such a high X-ray luminosity. However, the inner accretion disk of hard-state Galactic black hole X-ray binaries are truncated at large distances from the black hole and this may be a problem for the thick-disk plus central funnels anisotropic radiation model (King et al. 2001). Furthermore, the lack of short time variability of J095551.0 argues against the relativistic beaming model since this would require a very stable jet. It is worth noting that the observed photon index of J095551.0 is sometime harder than the typical hard-state value of 1.5 < \( \Gamma < 2.1 \) for Galactic X-ray binaries (McClintock & Remillard 2006). It is therefore not clear if we can directly compare with Galactic black hole X-ray binaries in the hard state. Alternatively, it may be a unique state that the ULX is a stellar-mass black hole accreting at very high rate.

\[ \text{Fig. 7.-- The soft (0.3–3 keV; solid points) and hard (3–7 keV; triangles) band radial profile of J095551.0 (top), J095551.2 (middle), and J095550.6 (bottom), compared to Chandra PSF model (solid curve), using ObsID 5644.} \]

In addition to the long-term timing variability, the X-ray spectra also vary. Excluding those observations taken with off-axis pointings, the photon index is consistent with 1.5–1.7 except for the last observation (see Table 2). In the last observation, the photon index becomes much harder with \( \Gamma = 1.27 \pm 0.18 \). Moreover, the spectral change is quite dramatic. The observation taken one day earlier has a photon index of \( 1.52 \pm 0.10 \) while the X-ray luminosity does not change signif-


FIG. 8.—HST/NICMOS F160W image of the region around the X-ray sources that we are interested. The 1σ Chandra error circles (0.66 arcsec) are shown. We also label the locations of known super-star clusters and M82 X–1.

4.2. J095551.2: A Highly Absorbed X-ray Source

The X-ray spectrum of J095551.2 is very different comparing to other nearby sources. The source has an unusually high $N_H$ ($\gtrsim 10^{23}$ cm$^{-2}$) while the two nearby sources as well as M82 X–1 (Kaaret et al. 2006) have a $N_H$ of $\sim 3 \times 10^{22}$ cm$^{-2}$, consistent with the extinction measured by IR observations. Furthermore, J095551.2 has a very flat spectrum ($\Gamma \lesssim 1$) with soft excess below 2 keV. The high absorption column density may indicate that the source is a background AGN. AGN normally has a power-law spectral model with $\Gamma \sim 1.7$–2 (e.g., Page et al. 2006) while the spectrum of J095551.2 is much harder. A hard spectral index of AGN may be due to the presence of a reflection component and/or a complex absorber (Cappi et al. 2006).

Near IR and radio observations may provide additional clues about the nature of J095551.0. From the NICMOS image (Fig 8), a star cluster is at the center of the X-ray error circle of J095551.0, suggesting that the source is associated with the cluster. Indeed, young star clusters are ideal places to produce IMBHs via the collapse of very massive stars through runaway stellar collisions (Portegies Zwart et al. 2004). The coincidence of J095551.0 and a star cluster strongly suggests that the ULX is produced in the cluster and is consistent with a black hole of intermediate mass. Radio emission is also detected within the X-ray error circle (Körding et al. 2005; Kaaret et al. 2006). The radio source, known as 42.21+59.0, has been detected several times (e.g., McDonald et al. 2002). The flat spectrum (between 5 and 15 GHz) and extended size (4.9 pc) suggest that it is a giant H II region with 94 O5 stars (McDonald et al. 2002).
that is consistent with the extinction of nearby region of M82, minimosity above 10

SN 1978K is also the first known supernovae with X-ray lu-

emission lines are also seen in some luminous X-ray emitting

shell lines at 1.8 keV, and S K shell lines at 2.5 keV. Strong

dominated by broad emission of Mg XII lines at 1.4 keV, Si K

nant. In particular, it is evident that the spectrum (Fig. 4) is

ing possibility is that it is an X-ray luminous supernova rem-

nant. In particular, it is evident that the spectrum (see Fig. 4).

Given the high $N_H$ that is consistent with the extinction of near-by region of M82.

J095550.6 is unlikely to be a foreground star. The X-ray spec-

trum is not typical for X-ray binaries. We can also rule out a

background AGN due to its unusual spectrum. The remaining

possibility is that it is an X-ray luminous supernova remnant.

In particular, it is evident that the spectrum (Fig. 4) is
dominated by broad emission of Mg XII lines at 1.4 keV, Si K
shell lines at 1.8 keV, and S K shell lines at 2.5 keV. Strong
emission lines are also seen in some luminous X-ray emitting
supernova such as SN 1978K (Schlegel et al. 2004). Indeed,
SN 1978K is also the first known supernovae with X-ray lumino-
sity above $10^{39}$ erg s$^{-1}$. For direct comparison with SN
1978K, we refit the spectrum of J095550.6 with an absorbed
MEKAL + power-law model. The spectral parameters are not
sensitive to the model, with a best-fit temperature of 0.9 keV.
This is slightly hotter than SN 1978K ($\sim 0.7$ keV; Schlegel et al.
2004). The $0.5$–10 keV luminosity of J095550.6 is $2.2 \times 10^{39}$

ergs s$^{-1}$. Within the X-ray error circle, there is a strong ra-
dio source known as 41.95+575 (McDonald et al. 2001, 2002;
Körding et al. 2005). 41.95+575 is the brightest and most
compact radio source in M82 and has been detected since 1965
(Muxlow et al. 2005). High resolution (3 mas) VLBI imaging
shows that the source has a double-lobed structure (McDonald
et al. 2001). The separation of the two brightest components
is 22.4 mas in 2001 (Muxlow et al. 2005). Furthermore,
multiple-

epoch VLBI observations show that the separation is increasing
at a rate of 0.24 mas yr$^{-1}$. The radio flux also varies over the
last 30 years. It has decreased in flux density at $\sim 8.8$% per
year and an age of around 100 years is estimated (Muxlow et
al. 2005). The simplest explanation of the nature of J095550.6
is that it is a supernova event taking place within a high den-
sity molecular cloud (McDonald et al. 2001). We can also
estimate the age of the remnant using the X-ray spectral fit.
Following Kong et al. (2002), assuming J095550.6 is in the
adiabatic expansion phase, the shock temperature can be writ-
ten as $T_s = (0.18 \text{ keV}) (R/t_3)^2$, where $R$ and $t_3$ are the radius
(in units of parsecs) and age (in units of 1000 yr), respectively.
Adopting a radius of 11 mas ($= 0.19$ pc), and $T_s = 0.9$ keV, we
obtain $t = 85$ yr which is consistent with radio observations.
It is worth noting that long-term radio observations have sug-
gested that 41.95+575 may be a radio afterglow of a 100 year
old gamma-ray burst event (Muxlow et al. 2005).

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5. CONCLUSIONS

We have used archival Chandra and HST/NICMOS data to
study the physical nature of three ULXs near the center of M82.
We found a recurrent transient ULX, J095551.0 from the Chandra
data. During its active state, the X-ray luminosity is about
$8 \times 10^{39} - 1.3 \times 10^{40}$ ergs s$^{-1}$ and it was turned off twice in 1999
and 2000 indicating a factor of $>50$ variability. This also rules
out the possibility that it is a supernova remnant. The X-ray
spectra can be fitted with a power-law model with photon in-
dex $\Gamma = 1.3 - 1.7$ which is similar to Galactic black hole X-ray
binaries in the low/hard state. We suggest that the X-ray emis-
sion might be explained in the framework of the ADAF model
implying a black hole mass of $\sim 100 - 10^4 M_\odot$. However,
we cannot totally rule out that the source is a stellar-mass black
hole system in a unique spectral/luminosity state. In particular,
spectral hardening was seen in one of the observations. We also
examined near IR images taken with HST/NICMOS. We found
a star cluster at the center of the X-ray error circle suggesting
that the source is associated with the cluster.

With an unusually high column density $N_H > 10^{23}$ cm$^{-2}$ and
a rather flat X-ray spectrum ($\Gamma \lesssim 1$) with an ionized absorber,
it is suggested that the source J095551.2 is likely to be a back-
ground AGN. The source also shows spectral change similar to
some narrow-line Seyfert 1 galaxies. In addition, there is a H II
region known as 42.56+580 associated with J095550.6.

The source J095550.6 shows an unusual spectrum that can-
not be fitted with a simple power-law model. Instead, the spec-
trum can be fitted with a Raymond-Smith model, accompany-
ning with broad emissions of Mg, Si, and S, indicating that it is
a supernovae remnant with an age of 85 years. Furthermore,
a radio source known as 41.95+575 is found associated with
J095550.6 within the X-ray error circle. The long-term radio
observations reveal that 41.95+575 may be a radio afterglow of
a 100-year old gamma-ray burst event.

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