A RADIO NEBULA SURROUNDING THE ULTRALUMINOUS X-RAY SOURCE IN NGC 5408

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ABSTRACT

New radio observations of the counterpart of the ultraluminous X-ray source in NGC 5408 show for the first time that the radio emission is resolved with an angular size of 1.5″–2.0″. This corresponds to a physical size of 35–46 pc, and rules out interpretation of the radio emission as beamed emission from a relativistic jet. In addition, the radio spectral index of the counterpart is well determined from three frequencies and found to be $\alpha = -0.8 \pm 0.2$. The radio emission is likely to be optically thin synchrotron emission from a nebula surrounding the X-ray source. The radio luminosity of the counterpart is $3.8 \times 10^{44}$ erg s$^{-1}$ and the minimum energy required to power the nebula is $\sim 1 \times 10^{49}$ erg. These values are 2 orders of magnitude larger than in any Galactic nebula powered by an accreting compact object.

Subject headings: black hole physics — galaxies: individual (NGC 5408) — galaxies: stellar content — X-rays: galaxies

1. INTRODUCTION

Ultraluminous X-ray sources (ULXs) are nonnuclear X-ray sources in external galaxies with apparent luminosities above the Eddington limit for a 20 $M_\odot$ black hole, the maximum mass of any dynamically measured black hole mass in the Galaxy (Remillard & McClintock 2006); for a review, see Fabbiano (2006). ULXs with strong variability are likely accreting objects and may either be “intermediate-mass” black holes (Colbert & Mushotzky 1999; Makishima et al. 2000; Kaaret et al. 2001) or normal (stellar-mass) black holes with beamed or super-Eddington radiation (King et al. 2001; Kording et al. 2002; Begelman 2002). The ULX in the dwarf irregular galaxy NGC 5408 (NGC 5408 X-1) is variable and with strong variability are likely accreting objects and may either be “intermediate-mass” black holes (Colbert & Mushotzky 1999; Makishima et al. 2000; Kaaret et al. 2001) or normal (stellar-mass) black holes with beamed or super-Eddington radiation (King et al. 2001; Kording et al. 2002; Begelman 2002). The ULX in the dwarf irregular galaxy NGC 5408 (NGC 5408 X-1) is variable and is one of the few ULXs with a known radio counterpart (Kaaret et al. 2003). The radio emission could arise directly from a relativistic jet beamed toward our line of sight, in which case a stellar-mass black hole would suffice to produce the radio and X-ray emission, or from a nebula surrounding the compact object. Recent radio observations presented by Soria et al. (2006) suggest that the source has a steep spectrum ($\alpha < -1$), but show no indication of radio flux density variability.

In order to better understand the nature of the radio emission from NGC 5408 X-1, we obtained new joint observations in the radio using the Very Large Array (VLA) of the National Radio Astronomy Observatory1 and in the X-ray using the Chandra X-Ray Observatory. In addition, because the target is a low-mass black hole, the maximum mass of any dynamically measured black hole mass in the Galaxy (Remillard & McClintock 2006); for a review, see Fabbiano (2006). The ULX in the dwarf irregular galaxy NGC 5408 (NGC 5408 X-1) is variable and is one of the few ULXs with a known radio counterpart (Kaaret et al. 2003). The radio emission could arise directly from a relativistic jet beamed toward our line of sight, in which case a stellar-mass black hole would suffice to produce the radio and X-ray emission, or from a nebula surrounding the compact object. Recent radio observations presented by Soria et al. (2006) suggest that the source has a steep spectrum ($\alpha < -1$), but show no indication of radio flux density variability.

1 The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

2. OBSERVATIONS AND ANALYSIS

2.1. VLA Observations

VLA observations of the ULX source in NGC 5408 were made at 4.9 GHz (6 cm) with four different array configurations between 2003 December and 2005 January: A, BnA, B, and CnB (see Table 1). Each observation was approximately 3.5 hr long and corresponds to a joint Chandra X-ray observation. Standard procedures were carried out for flux and phase calibration using the Astronomical Imaging Processing System (AIPS) of the NRAO. We used the flux density calibrator, J1331+305, and the phase calibrator, J1353–441, a source which is located within 3° of the target. For all observations, fast switching between the target source and calibrator was used with a cycle time for the calibrator-source pair of 2.5–3 minutes (with 45 s on the calibrator and 90 to 120 s on the source).

The VLA image resolutions vary between 1.01″ × 0.28″ (A configuration) and 6.01″ × 3.30″ (CnB configuration). Because of the proximity of the bright starburst region in NGC 5408 and the weak radio emission associated with the ULX, obtaining an accurate flux density for this source is difficult. However, with the high resolution of the VLA A, BnA, and B configurations, it is possible to distinguish the radio emission associated with the ULX from the extended emission from the starburst region in most of our images.

In fact, in attempting to determine the accurate flux density and source structure, the extended emission from this starburst region turns out to be a key issue. One way to examine the contribution of the extended emission is to adjust the imaging weighting function. The Briggs’ ROBUST parameter controls the data weights in the $(u, v)$-plane. Positive values of the ROBUST parameter (1–5) bring out the more extended structure by weighting the inner part of the $(u, v)$-plane more heavily (“natural weighting”). Such values will increase the signal to noise on extended features but lower the spatial resolution. Negative values of the...
roughly simultaneous), the ULX X-ray flux in the 0.3–8 keV band in units of Chandra and UT time of the start of the flux from the starburst, a ($u/v$) cutoff range of ($1.2$ and $2.3$ GHz) there is still contamination from the starburst. During imaging, a variety of ROBUST parameters were also used to downweight the extended emission, similar to the procedure in the VLA imaging. In addition, we analyzed archival ATCA observations of NGC 5408 at a range of frequencies, observed during 2000–2004 (listed in Table 2). In the several of the ATCA data sets (e.g., the 6D array 4.9 GHz data [Kaaret et al. 2003], and the 2.3 and 1.4 GHz archival data sets) a ($u/v$) cutoff range of $3k_{\nu}$ was used to remove flux on extended scales larger than $11''$.

### 2.3. X-Ray Observations

NGC 5408 was observed with the Chandra X-Ray Observatory (Weisskopf 1988) five times using the ACIS spectroscopic array (ACIS-S; Bautz et al. 1998) in imaging mode and the High-Resolution Mirror Assembly (HRMA; van Speybroeck et al. 1997). The observations began in 2002 and ended in 2005; see Table 1. Because a high X-ray count rate was expected, only the S3 chip was operated with a 1/4 subarray mode for the first observation and a 1/8 subarray for the other observations. This gave an exposure time of 0.8 s for the first observation and 0.4 s for the others. For each observation, we constructed an image using all valid events on the S3 chip and used the wavdetect tool, which is part of the CIAO data analysis package, to search for X-ray sources. Typically, only the ULX was detected in each observation. The position of the ULX was within $0.23''$ of R.A. = $14^h 03^m 19.63^s \pm 0.01^s$, decl. = $-41^\circ 22.5' 8.65'' \pm 0.2''$ (J2000.0) in all observations.

We fit the X-ray spectrum of the ULX for each observation using the XSPEC (Arnaud 1996) spectral fitting tool which is part of the LHEASOFT X-ray data analysis package, and response matrices calculated using CIAO. As previously reported by Kaaret et al. (2003), we found that absorbed single power-law models did not provide an adequate fits (except for the last observation), while models consisting of either an absorbed broken power law or the absorbed sum of a multicolor disk blackbody plus a power law did provide adequate fits. There were no pronounced changes in spectra shape between the different observations. The fit parameters were similar to those quoted in Kaaret et al. (2003). The flux for each observation calculated using the fitted multicolor disk blackbody plus power-law model are given

### Table 1

| Date/Time       | X-Ray Flux | VLA Configuration |
|-----------------|------------|-------------------|
| 2002 Mar 07 13:45:47......... | 1.42       | C0                |
| 2003 Dec 20 13:06:33......... | 1.49       | B                 |
| 2004 Feb 04 10:29:47......... | 1.58       | CnB               |
| 2004 Dec 30 13:44:33......... | 1.47       | A                 |
| 2005 Jan 29 11:02:49......... | 1.50       | BnA               |

Note.—The Chandra/VLA observations of NGC 5408 including the date and UT time of the start of the Chandra observation (the VLA observations were roughly simultaneous), the ULX X-ray flux in the 0.3–8 keV band in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$ during the observation, and the VLA array configuration.

### Table 2

| Date/Time       | Array | Frequency (GHz) | Reference          |
|-----------------|-------|-----------------|--------------------|
| 2000 Apr 01 02:09......... | 6D    | 4.8, 8.6        | Kaaret et al. (2003) |
| 2003 Mar 03 05:31......... | 6A    | 4.8, 8.6        | Archival 1         |
| 2003 May 20 22:05......... | 1.5C  | 1.4             | Archival 2         |
| 2003 Jul 27 17:45......... | 6D    | 1.4             | Archival 3         |
| 2003 Dec 07 10:05......... | 6A    | 2.3, 4.8        | This paper         |
| 2003 Dec 08 11:30......... | 6A    | 2.3, 4.8        | This paper         |
| 2003 Dec 09 11:02......... | 6A    | 2.3, 6.1        | This paper         |
| 2004 Dec 09 to Dec 11...... | 6D    | 1.4, 2.3        | Soria et al. (2006) |
| 2004 Dec 09 to Dec 11...... | 6D    | 4.8, 6.1        | Soria et al. (2006) |

Note.—The ATCA observations of NGC 5408 including the observation date, the frequency or frequencies of observation, and the measured flux density.
in Table 1. We also did not observe any significant changes in the X-ray flux level between observations.

2.4. HST Observations

Two WFPC2 observations of NGC 5408 are present in the Hubble Space Telescope (HST) archive. The observations were obtained as part of a snapshot survey of nearby dwarf galaxy candidates (GO-8601; PI: P. Seitzer) and consist of 600 s WFPC2 exposures with the F606W and F814W filters obtained on 2000 July 4. After extracting the data from the HST archive, we used IRAF to mosaic and clean the images. We corrected the absolute astrometry of the HST image using stars from the 2MASS catalog (Skrutskie et al. 2006) using the Graphical Astronomy and Image Analysis Tool (GAIA). We used only 2MASS sources on the WF3 chips where the ULX is located in order to preclude issues regarding the relative positioning of the WFPC2 chips. We estimate that the astrometric uncertainty is 0.2″. We used the HSTphot stellar photometry package to obtain photometry (Dolphin 2000). We removed bad pixels, cosmic rays, and hot pixels and then obtained simultaneous photometry for the F606W and F814W images.

3. RESULTS

3.1. Radio Counterpart

The flux density of the radio emission associated with the ULX in the VLA and ATCA images was measured by fitting a twodimensional (2D) Gaussian point source to the peak radio emission in each of the various images. In all cases, the source appears to be pointlike with slightly extended emission, but nothing which we can confidently resolve. The radio source position from our VLA B configuration image is R.A. = 14h03m19.6s ± 0.1s, decl. = -41°22'58.7″ ± 0.2″ (J2000.0), which is within 0.1″ of the ULX position calculated from the Chandra observations (Kaaret et al. 2003). This is well within the Chandra error circle. Using the ATCA 4.8 GHz and 6.1 GHz data, the position of the radio source is R.A. = 14h03m19.61s ± 0.02s, decl. = 41°22'58.5″ ± 0.2″ (J2000.0).

3.1.1. 4.9 GHz Emission

Table 3 lists the measured 4.9 GHz flux density and corresponding ROBUST weighting, array configuration, geometrical beam size ([θmajθmin]^{1/2}), and an indication of any (u, v) cutoff used in the imaging. Radio emission was detected above 3σ in 20 of the 21 images made at 4.9 GHz from the VLA and ATCA data. The source was not detected in the highest resolution 4.9 GHz

| Telescope Configuration | Robust Weight | Flux Density (mJy) | Geometric Beam Size (u, v) cutoff |
|-------------------------|---------------|--------------------|-------------------------------|
| VLA A........................ | -1            | <0.10 ± 0.03       | 0.53                          |
| VLA A........................ | 1             | 0.13 ± 0.02        | 0.75                          |
| VLA A........................ | 3             | 0.14 ± 0.02        | 0.83                          |
| VLA BnA...................... | -1            | 0.15 ± 0.03        | 1.17                          |
| VLA BnA...................... | 1             | 0.20 ± 0.02        | 1.53                          |
| VLA B........................ | -1            | 0.21 ± 0.03        | 1.70                          |
| VLA B........................ | 0             | 0.23 ± 0.03        | 1.93                          |
| VLA B........................ | -5            | 0.20 ± 0.03        | 1.62                          |
| VLA B........................ | 5             | 0.23 ± 0.02        | 2.66                          |
| ATCA 6A........................ | -5            | 0.21 ± 0.03        | 1.57                          |
| ATCA 6A........................ | 5             | 0.20 ± 0.03        | 1.89                          |
| ATCA 6A........................ | 2             | 0.19 ± 0.02        | 3.25                          |
| ATCA 6A........................ | 5             | 0.19 ± 0.02        | 3.24                          |
| ATCA 6D........................ | -5            | 0.25 ± 0.06        | 1.59                          |
| ATCA 6D........................ | 5             | 0.18 ± 0.04        | 3.18                          |
| VLA CnB........................ | 0             | 0.51 ± 0.03        | 4.45                          |
| VLA CnB........................ | -5            | 0.46 ± 0.04        | 3.77                          |
| VLA CnB........................ | -5            | 0.32 ± 0.04        | 3.71                          |
| VLA CnB........................ | -1            | 0.47 ± 0.03        | 4.08                          |
| ATCA 6D........................ | 5             | 0.43 ± 0.04        | 3.46                          |

Note.—The 4.9 GHz flux densities for the radio counterpart of the ULX in NGC 5408. All fits are for an unresolved source. (200 times the rms level of 20 μJy beam^{-1}).
VLA image (1.01″ × 0.28″; A configuration, ROBUST = −1) with an upper limit of 0.1 mJy. The largest angular size detectable with the VLA in its A configuration is 10″. The radio source is detected in the other two VLA A configuration images, but with modest detections (≲ 0.07 in both cases). Figure 1 shows the BnA configuration image of NGC 5408 (ROBUST = 1). The resolution of this image is 1.94″ × 1.20″, and the source is clearly detected at the 10σ level.

Figure 2 shows the highest resolution 4.9 GHz ATCA image, which has a beam size very similar to the VLA BnA configuration image shown in Figure 1. In the majority of the VLA and ATCA images, the radio emission associated with NGC 5408 X-1 is obvious and clearly separated from the extended emission associated with the NGC 5408 starburst. However, in cases such as the VLA B configuration naturally weighted image, where the resolution is lower and favors the extended structures, a significant amount of extended emission is present (see Fig. 3, left). Removing the shortest (u, v) baselines (< 5 kλ) for these lower resolution images produces an image, shown in Fig. 3 (right), where the radio emission associated with NGC 5408 X-1 is clearly separated from the extended emission associated with the starburst.

Figure 4 shows the flux density and associated errors versus the geometric beam size for measurements from 16 images of VLA (diamonds) and ATCA (square; new and archival) data taken from Table 3. The filled symbols indicate that a (u, v) cutoff was applied to the data in order to remove extended emission which may contaminate the flux density. However, not all measurements were included in Figure 4. Images made with the VLA CnB configuration at all robust weightings and with the ATCA 6D configuration have low enough resolution that it is difficult to separate the background emission from NGC 5408 from the radio emission at the position of the ULX. In fact, the flux densities for the VLA CnB configuration and ATCA 6D array measurements are in the range 0.32–0.51 mJy, up to twice as high as measurements made with more extended arrays, indicating that the background contributes significantly to the measurement. For this reason, only the measurements from images where we were confident we were separating out the radio emission associated with NGC 5408 X-1 were used to make Figure 4.

3.1.2. Source Size and Structure

Previously, Soria et al. (2006) had made some of the highest resolution observations of the ULX in NGC 5408 using the ATCA. They measured the flux density in images with beam sizes of 1.5″–3.5″ and found an essentially flat distribution of flux density with beam size. However, their observations do not resolve the source and therefore are only consistent with emission from a point source (Soria et al. 2006). The VLA data presented here for the first time probe even higher angular resolutions (0.5″–1.5″). Figure 4 shows that the VLA data are crucial in studying the flux density versus geometric beam size for scales < 1.5″. There is a clear trend of...
images where the shortest (servations of Soria et al. (2006). Filled symbols represent measurements from beam size of 1.5\,000 decreasing flux density at smaller beam sizes below a geometric beam size of 1.5\,arcsec. The linear rise of flux density with beam size shown in Figure 4 indicates that there is extended emission associated with this source on beam size scales between \sim 0.5\,arcsec and \sim 1.5\,arcsec. For beam sizes greater than \sim 1.5\,arcsec, the flux density measurements are relatively constant (within the errors), suggesting the source has an angular extent in the range 1.5\,arcsec–2.0\,arcsec.

3.1.3. Variability

Because the radio source associated with the ULX is likely to be somewhat extended, different configurations of the VLA radio telescope will be sensitive to emission on differing angular size scales. Therefore, it is not possible to look for flux variability in our high-resolution VLA observations (where the configuration ranges from A configuration to CnB configuration). However, ATCA observations over a number of epochs (e.g., Kaaret et al. 2003; Soria et al. 2006; this paper) have shown that the flux density at 4.9 GHz does not appear to vary significantly and has an average, overall value near 0.20\,mJy.

3.1.4. Multifrequency Data and Spectral Index

Multifrequency observations at 1.4, 2.3, 4.9, and 6.1 GHz were made as part of the new ATCA data presented here. At each frequency, all existing ATCA data were combined (see Table 2), and a point source was fit to the radio emission associated with the ULX. We find flux densities of 0.62 ± 0.10\,mJy at 1.4 GHz [geometric beam size of 6.7\,arcsec; ROBUST = −5; (u, v) cutoff < 5\,k\,arcsec], 0.37 ± 0.08\,mJy at 2.4 GHz [geometric beam size of 3.3\,arcsec; ROBUST = −5], 0.20 ± 0.03\,mJy at 4.9 GHz [geometric beam size = 1.5\,arcsec, ROBUST = −5], and 0.17 ± 0.03\,mJy at 6.1 GHz. At 1.4 GHz, the contribution from the extended background may be present even though we used uniform weighting and limited the shortest (u, v) data; the beam size is large. At 2.3 GHz, the image is made with uniform weighting and the contribution from the extended starburst region is not apparent. Therefore, we determine the spectral index based on the 2.4, 4.9, and 6.1 GHz measurements only and obtain \alpha = −0.8 ± 0.2, where S_{\nu} \propto \nu^\alpha. Figure 5 shows the flux density versus frequency and includes the 1.4 GHz measurement as well as the 8.5 GHz ATCA upper limit from Kaaret et al. (2003). Although not included in the fit, the 1.4 and 8.5 GHz measurements are consistent with the fitted spectral index.

3.2. Optical Counterpart

Figure 6 shows the HST WFPC2 image in the F606W filter for the area near the ULX. The circle drawn on the figure is centered at the VLA source position quoted above and has a radius of 0.28\,arcsec, which represents the relative position uncertainty including both the radio position uncertain and the optical astrometry uncertainty. Only one object lies within the error circle. It is located at a position of R.A. = 14\,03\,19.62\,decl. = 41\,22\,58.54 (J2000.0) which is 0.17\,arcsec from the radio position and well inside the error circle. The next closest HST source is 0.43\,arcsec from the VLA position and is outside the error circle. We identify the HST source within the error circle as the likely optical counterpart of the ULX.

The optical counterpart has magnitudes, in the WFPC2 flight photometric system, of 22.387 ± 0.021 in the F606W filter and 22.396 ± 0.043 in the F814W filter (Dolphin 2000). The equivalent Johnson-Cousins magnitudes are V = 22.4 and
I = 22.4. We corrected for reddening using an extinction $E(B - V) = 0.068$ based on the dust maps of Schlegel et al. (1998) and using an $R_V = 3.1$ extinction curve. The dereddened magnitudes are $V_0 = 22.2$ and $I_0 = 22.3$ and the color is $V_0 - I_0 = -0.1 \pm 0.1$.

4. DISCUSSION

The radio counterpart size of 1.5''–2.0'' corresponds to a physical diameter of 35–46 pc at the distance of 4.8 Mpc to NGC 5408, as determined by from the tip of the red giant branch Karachentsev et al. (2002). Therefore, we can rule out the interpretation of the radio emission associated with the NGC 5408 ULX as a relativistically beamed jet (Kaaret et al. 2003).

The radio surface brightness of NGC 5408 at 4.9 GHz is $-4 \times 10^{-20}$ W m$^{-2}$ Hz$^{-1}$ sr$^{-1}$, assuming a source size of 1.5''. Taking a spectral index of $-0.8$, we can calculate the surface brightness at 1.4 GHz in order to compare to values for known supernova remnants of similar sizes (Green 2004). The value of $-1 \times 10^{-19}$ W m$^{-2}$ Hz$^{-1}$ sr$^{-1}$ is significantly higher than that of known supernova remnants of similar size. It is therefore more likely that the radio emission associated with NGC 5408 X-1 arises instead from an extended radio lobe. The radio spectrum ($\alpha = -0.8$) of this source is consistent with optically thin synchrotron emission.

For comparison, the radio nebula W50 surrounds the relativistic jet source SS 433 (Margon 1984) and is thought to be powered by the relativistic outflow. SS 433 has been suggested as a possible Galactic analog to the ULXs (Fabrika & Mescheryakov 2001; Begelman et al. 2006). Radio nebula in W50 is interesting because the nebular radio emission is unlikely to be beamed. The physical size of W50 is roughly 50 pc and is similar to what we estimate for the radio nebula surrounding NGC 5408 X-1. The radio spectral indexes of the various components of W50 range from $-0.5$ to $-0.8$, also consistent with the spectral index of the radio emission in NGC 5408 X-1 ($\alpha \approx -0.8$). A comparison of the radio brightness can be made for the two sources. W50 has an integrated flux density at 1.4 GHz of $\sim 70$ Jy and a distance of $5$ kpc (Dubner et al. 1998). Assuming a spectral index of $-0.5$, that translates to a 4.9 GHz flux density of 40 Jy, and if it were at the distance of NGC 5408 (4.8 Mpc), its flux density would be $\sim 40$ $\mu$Jy. The integrated flux density of NGC 5408 X-1 at 4.9 GHz is $\sim 200$ $\mu$Jy, so its radio brightness is more than a factor of 5 greater than that of W50.

We investigate the energetics of the radio lobe assuming radiation via synchrotron emission, equipartition between particles and fields, and equal energy in electrons and baryons. We use a spectral index $\alpha = -0.8$ (see § 3.1.4), a lower frequency cutoff of 1.3 GHz, and an upper frequency cutoff of 6.2 GHz. The total radio luminosity of the source is $3.8 \times 10^{34}$ erg s$^{-1}$. For a source diameter of 46 pc and a filling factor of unity, we find that the total energy required is $3.6 \times 10^{49}$ erg, the magnetic field is $16 \mu$G, and the synchrotron lifetime is $\sim 20$ Myr. For contrast, for a diameter of 35 pc and a filling factor of 0.1, the total energy required is $9 \times 10^{48}$ erg, the magnetic field is $39 \mu$G, and the life-time is $\sim 5$ Myr. We note that the estimates of Soria et al. (2006) for the energy content of a synchrotron nebula surrounding NGC 5408 X-1 are about an order of magnitude larger. This is primarily because they assume an electron energy distribution that extends down to a Lorentz factor of 1, while we, conservatively, assume that the electron energy distribution extends only over the range needed to produce the observed radio emission (1.3–6.2 GHz).

The total energy content in relativistic electrons in W50 is in the range $(0.5–7) \times 10^{48}$ erg (Dubner et al. 1998). The total energy content in relativistic electrons in the radio nebula surrounding NGC 5408 X-1 is at least 2 orders of magnitude larger. Therefore, if two nebula are similar, then the jet powering the nebula surrounding NGC 5408 X-1 must be at least 2 orders of magnitude more powerful than that from SS 433 powering W50. The radio lobes powered by the persistent accreting stellar-mass black hole GR5 1758–258 have a radio luminosity of $3 \times 10^{30}$ erg s$^{-1}$, require an energy content of $2 \times 10^{45}$ erg (Rodríguez et al. 1992), and are even less powerful than W50. We note that the ULX Holmberg II X-1 has an associated radio nebula with a total energy similar to that of the NGC 5408 X-1 nebula (Miller et al. 2005).

At the distance to NGC 5408, the absolute magnitude of the optical counterpart would be $M_V = -6.2$. If the light arises only from the stellar companion, then the magnitude and color exclude main sequence and giant stars and require a supergiant star. The absolute magnitude and color are consistent with classification as a B or early A supergiant. The luminosity of such a star would be in the range of $1–5 \times 10^{38}$ erg s$^{-1}$. However, the stellar classification is suspect since light may arise from reprocessing of X-rays from the compact object and since the X-ray luminosity ($\sim 10^{40}$ erg s$^{-1}$ if the emission is isotropic) exceeds the expected stellar luminosity by a factor of at least 20 and may strongly affect the physical state of the star.

The X-ray to optical flux ratio, defined following van Paradijs & McClintock (1995) as $\xi = B_0 + 2.5 \log F_X$, where $F_X$ is the X-ray flux density at 2 keV in $\mu$Jy, and we approximate $B_0 = V_0$ due to lack of a $B$-band image, is $\xi = 20.0$. If we use the flux density at 1 keV, this rises to $\xi = 21.1$. These values are higher than those of any high-mass X-ray binary (HMXB), other than LMC X-3, and are in the range typically found for low-mass X-ray binaries (LMXBs). Thus, it is possible that the companion star contributes little to the observed optical emission, e.g., it is not supergiant, and that most of the optical light arises from reprocessing of X-rays, as occurs in LMXBs (Kaaret 2005).

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