TWO NEW X-RAY/OPTICAL/RADIO SUPERNOVA REMNANTS IN M31

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ABSTRACT

We compare a deep (37 ks) Chandra ACIS-S image of the M31 bulge to Local Group Survey narrowband optical data and Very Large Array (VLA) radio data of the same region. Our precisely registered images reveal two new optical shells with X-ray counterparts. These shells have sizes, [S II]/Hα flux ratios, and X-ray spectral properties typical of supernova remnants (SNRs) with ages of 9±3 and 17±6 kyr. Analysis of complementary VLA data reveals the radio counterparts, further confirming that they are SNRs. We discuss and compare the properties and morphologies of these SNRs at the different wavelengths.

Subject headings: galaxies: individual (M31) — supernova remnants — techniques: image processing

1. INTRODUCTION

The high spatial resolution of the Chandra X-Ray Observatory is allowing supernova remnants (SNRs) in M31 to be resolved at X-ray wavelengths for the first time (Kong et al. 2002a, 2003). These detections provide the first opportunity to perform resolved multiwavelength studies of SNRs in M31. Studies of these extragalactic SNRs avoid several difficulties that hinder Galactic studies, such as unreliable distances, large angular sizes, and high Galactic absorption. Multiwavelength studies of these SNRs allow reliable comparative size analyses for future determinations of supernova rates and open the door to detailed studies of supernova feedback in M31.

Optical emission-line surveys of M31 date back to Rubin et al. (1972), and X-ray surveys back to van Speybroeck et al. (1979). Without digital imaging to allow the subtraction of continuum emission from the emission-line images and without high spatial resolution X-ray data, reliable determination of counterparts was difficult for these early surveys. While optical surveys continued to catalog hundreds of SNRs in M31 (e.g., Braun & Walterbos 1993; Magnier et al. 1995; Williams et al. 1995), ROSAT studies had little luck in discovering X-ray SNRs in M31 (Magnier et al. 1997).

Very recently, with deep Chandra and XMM-Newton images of M31, finding X-ray counterparts of optical SNRs has become more feasible. Kong et al. (2002a) found a previously known optical SNR that was well resolved in Chandra images. Later, Kong et al. (2003) found two previously unclassified SNRs that were resolved in X-ray, optical, and radio images.

Herein we report the discovery of two more SNRs in M31, found by comparing narrowband images from the Local Group Survey (LGS; Massey et al. 2001) to a precision-aligned, deep Chandra image. One object, CXOM31 J004248.9+412406 (r3-84), R.A. = 00°42′48″.97, decl. = +41°24′06″.97 (J2000.0), coincides with one of the two SNR candidates reported independently by Trudolyubov & Priedhorsky (2004; XMMU J004249.1+412407). The second object, CXOM31 J004224.1+411733 (r2-57), R.A. = 00°42′24″.16, decl. = +41°17′33″.6 (J2000.0), also has the X-ray, optical, and radio properties of an SNR and has not been reported elsewhere. Section 2 describes the data and analysis techniques used. Section 3 discusses the X-ray, optical and radio properties of the SNRs, and § 4 provides a summary of our conclusions.

2. DATA ANALYSIS

2.1. Optical Data

We obtained the [O III], [S II], Hα, and V bands images of the LGS field 5 from the LGS Web site.3 These images have already been properly flat-fielded and the geometric distortions removed so that the coordinates in the images are good to ±0.25′ on the FK5 system and the images at the different bandpasses are registered with one another. We therefore were easily able to subtract the V band continuum from the [O III] image and the R band continuum from the [S II] and Hα images in order to make the line-emitting sources stand out.

We performed a rough calibration of the LGS [O III] image by matching the [O III] fluxes of 10 planetary nebulae (PNs) with published [O III] fluxes (Ciardullo et al. 1989). This calibration provided a conversion factor of 5.5×10−16 ergs cm−2 s−1. We also roughly calibrated the Hα and [S II] images by matching the fluxes of the SNR DDB 1-15 (D’Odorico et al. 1980) to the fluxes measured in the calibrated data set of Williams et al. (1995; Hα = 7.3×10−14 ergs cm−2 s−1; [S II] = 5.5×10−14 ergs cm−2 s−1). This calibration yielded conversion factors of 1.0×10−16 ergs cm−2 s−1 and 1.8×10−16 ergs cm−2 s−1 in Hα and [S II], respectively. Using these [O III], Hα, and [S II] factors, we converted the LGS count rates to units of ergs cm−2 s−1.

2.2. X-Ray Data

We also obtained a deep Chandra ACIS-S image centered on the M31 nucleus (observation ID [ObsID] 1575). This data set, obtained on 2001 October 5, had an exposure time of 37.7 ks, target R.A. = 00°42′44″.4, target decl. = 41°16′08″.3, and a roll angle of 180°.42. We created exposure maps for this image using the CIAO script merge_all,4 and we found and measured positions for the sources in the image using the
CIAO task \textit{wadetect}.\footnote{Available at http://cxc.harvard.edu/ciao3.0/download/doc/detect\_html\_manual/Manual.html.} This processing identified sources in the image down to a flux limit of $\sim8 \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$, assuming an absorbed power-law spectrum with slope 1.7 and $N_{\text{H}} = 10^{21}$ cm$^{-2}$, or an (unabsorbed) luminosity limit of $\sim7 \times 10^{34}$ ergs s$^{-1}$ in M31, assuming a distance of 780 kpc (Stanek & Garnavich 1998; Williams 2003).

### 2.2.1. X-Ray/Optical Image Alignment

We aligned the coordinate system of the ACIS-S image with the LGS coordinate system by translating and adjusting the plate scale of the ACIS-S coordinate system so that 13 globular cluster sources had the same coordinates as the centroids of the respective globular clusters in the LGS $I$ band image. This transformation, performed using the IRAF\footnote{IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.} task \textit{ccmap}, had rms residuals of $0'016$ in R.A. and $0'015$ in decl.

### 2.2.2. X-Ray Spectra

We extracted energy spectra and the associated responses from the ACIS-S image with the CIAO task \textit{psextract}\footnote{See http://cxc.harvard.edu/ciao/ahelp/psextract.html.} and CALDB version 2.26, which automatically corrects for the degradation in the effective low-energy quantum efficiency of the ACIS-S detectors. The background spectra were extracted with an annulus region. Since we only have 43 counts (37 background-subtracted) for r2-57 and 37 counts (31 background-subtracted) for r3-84, we used two methods to fit the spectra from 0.3 to 5 keV.

We first binned the spectra with $\geq5$ counts per bin and employed $\chi^2$-Gehrels (1986) statistics to find the best fit using the CIAO 3.0/Sherpa fitting package (Freeman et al. 2001). Errors were estimated using the Sherpa command \textit{projection},\footnote{See http://cxc.harvard.edu/ciao/ahelp/projection.html.} which varies each parameter’s value independently along a grid of values to determine the 1 $\sigma$ confidence intervals.

We fitted the spectra with two single-component models with absorption, power-law and Raymond-Smith (RS). The power-law model is commonly a good fit to the continuum of X-ray spectra and has three free parameters: index, absorption column, and normalization. The RS model is often used to describe the spectra of SNRs. We applied this model with the abundance parameter fixed to solar and the redshift fixed to zero, leaving three free parameters: temperature, absorption column, and normalization. Results are discussed in \S~3.1.1 and shown in Figure 1. To verify the results, we then fitted the unbinned spectra (background not subtracted) with Cash statistics (Cash 1979).

We further investigated the nature of the X-ray sources by calculating the hardness ratios of the detected counts. These were calculated from counts extracted in three different energy bins. The soft bin ($S$) contains photons of energies 0.3–1 keV. The medium bin ($M$) contains photons of energies 1–2 keV. The hard bin ($H$) contains photons of energies 2–8 keV. The final background-subtracted hardness ratio equations were $H1 = (M - S) / (H + M + S)$ and $H2 = (H - M) / (H + M + S)$ (Prestwich et al. 2003). These hardness ratios are discussed in \S~3.1.1.

Finally, we checked the results of the \textit{Chandra} energy spectra with \textit{XMM-Newton} archival data, since the effective area of \textit{XMM-Newton} is much larger than that of \textit{Chandra}. There are four \textit{XMM-Newton} observations of the center of M31 with exposure times from \~10 to 60 ks. Unfortunately, one of the SNRs (r2-57; see \S~2.4) lies too close to the center of M31 to be resolved from the diffuse emission at the resolution of \textit{XMM-Newton}; we therefore could not perform a reliable spectral fit for any \textit{XMM-Newton} observation of this SNR.

The other SNR (r3-84; see \S~2.4) is in the gap between CCD chips in two of the four \textit{XMM-Newton} observations. We performed spectral analyses on the other two observations, taken on 2001 June 29 (ObsID = 0109270101, target R.A. = 00$^\text{h}$42$^\text{m}$43$^\text{s}$, target decl. = 41$^\circ$15$'$46$''$, P.A. = 76$^\circ$.5, medium filter, and exposure $=30.6$ ks) and 2002 January 6 (ObsID =0112570101, target R.A. = 00$^\text{h}$42$^\text{m}$43$^\text{s}$, target decl. = 41$^\circ$15$'$46$''$, P.A. = 249$^\circ$.84, thin filter, and exposure $=56.5$ ks). We extracted the 0.3–5 keV spectra with the \textit{XMM-Newton} SAS package version 5.4.1; only EPIC pn CCD spectra were considered because of the higher sensitivity.

The spectra were binned to have at least 15 counts per spectral bin in order to allow the use of $\chi^2$ statistics. Background spectra were extracted from source free regions. The source contained 150 counts (84 background-subtracted) in the 27 ks observation and 314 counts (205 background-subtracted) in the 51 ks observation. Results are discussed in \S~3.1.1 and shown in Figure 2.
As both of the newly discovered SNRs are several arcminutes off-axis in the Chandra data, there is a possibility that the larger off-axis point spread function (PSF) of Chandra could be misinterpreted as an extended source in the X-ray image. To test this possibility, we used the SNRs’ spectral fits to simulate their Chandra PSF at their location on the ACIS-S detector. The simulation was performed with the Web-based PSF simulator ChaRT.

PSF simulations containing about the same number of counts as the detections are shown next to the X-ray SNR detections in Figures 3 and 4. We also produced PSF simulations with ~10^5 counts. Azimuthally averaged profiles of these simulations and of the SNR detections were measured in 15' annuli. The χ^2 tests of the detected SNRs’ profiles against the simulated PSFs (normalized to the surface brightness of the central 3' of the SNR detection) were calculated to assess whether the SNRs were resolved (results in § 3.1.3). The number of counts in each annulus ranged from 1 to 21 in the SNR detections. Profile errors were determined by Gehrels statistics (Gehrels 1986) in annuli with ≤10 counts and by standard Poisson statistics in annuli containing >10 counts. Results are discussed in § 3.1.3.

2.3. Radio Data

The radio data were collected from a 20 cm Very Large Array (VLA) survey source list presented by Braun (1990) complemented by a recent 6 cm VLA B array observation (L. O. Sjouwerman et al., in preparation). We also retrieved 20 cm archive VLA C array and 6 cm archive VLA D array data from the NRAO archive. These data sets, albeit pointed to the center of M31 instead of directly at the SNRs, were the most sensitive data sets to search for arcsecond extended radio counterparts.

L. O. Sjouwerman et al. (in preparation) observed a field of view of about 8' using the VLA at 6 cm for 22 hr on three days in June 2002, obtaining an angular resolution of 1'2 and the ability to detect angular structures up to about 35'. The 20 cm archive VLA data with a field of view of about 30' in diameter were taken during 20 hr on three days in August 1993, has an angular resolution of 13'', and is sensitive to angular structures up to about 15''. The 6 cm archive VLA data with a field of view of about 8' in diameter were taken during 19 hr on four days in July 1992, has an angular resolution of 14'', and is sensitive to angular structures up to about 5''. The data were all calibrated and imaged in NRAO’s AIPS package using the new VLARUN pipeline procedure with additional self-calibration for the 20 cm archive data as outlined in the AIPS Cookbook. The resulting rms noise in the images is 60 μJy for the 20 cm archive data, 15 μJy for the 6 cm archive data, and 6 μJy for the 6 cm Sjouwerman et al. (in preparation) data.

Finally, we retrieved 20 cm high-resolution (1''; A array) VLA data from the NRAO archive to detect any compact components of these SNR candidates. These data consist of 11 pointings in the center and southern half of M31. The data were also calibrated and imaged with the VLARUN pipeline procedure. Images with an rms noise of ~0.2 mJy were produced.

2.4. SNR Search

We visually searched the aligned [O III] image for shell structures with X-ray counterparts by placing 2'' radius circles onto the [O III] image centered on the locations of all X-ray sources detected in the ACIS-S images. This search yielded five counterpart candidates, three of which have been cataloged as X-ray SNRs and were previously discussed in Kong et al. (2002a, 2003). The X-ray images were then inspected at the locations of the two new SNRs. Figures 3 and 4 show the Chandra, Hα, [O III], [S II], and VLA (low-resolution 20 cm) images of each new SNR. These two new matches showed previously cataloged X-ray counterparts: CXOM31 J004224.1+411733 (r2-57) and CXOM31 J004248.9+412406 (r3-84; Kong et al. 2002b).

Once the two new matches in optical and X-ray were found, radio counterparts were sought for in the list of Braun (1990). Indeed, r3-84 is listed as an extended source (source number 97). Source r2-57 is located near an area of diffuse emission and, although not listed in Braun (1990), is marginally visible in his Figure 3. We therefore also checked our recent 6 cm VLA data (Sjouwerman et al., in preparation). The 6 cm data have only a limited field of view, with a FWHM of 500'', meaning that r3-84 is too far away from the field center (8') to be visible. However we found a ~10'' extended 2 σ patch at the position of r2-57. This triggered a search in the VLA archive for more sensitive data, for which we chose the sets discussed in § 2.3. The archive data do confirm a radio detection of r2-57 at 20 cm and at 6 cm, and yield an additional independent radio detection of r3-84 at 20 cm. No other radio matches were found in the literature.

3. RESULTS

3.1. X-Ray Properties

3.1.1. Spectral Properties

We were able to constrain the physical properties of both SNRs with their spectra from Chandra and XMM-Newton. Plots of the best fits using the RS model are provided in Figures 1 and 2.

For r2-57, the binned spectrum is well fitted by a power-law model with α = 5.3^{+0.6}_{-0.8}, N_H = 2.8^{+0.5}_{-0.4} \times 10^{21} \text{ cm}^{-2} (5.4^{+0.6}_{-0.8} \text{ cm}^{-2} for 5 degrees of freedom [dof]) and 0.3–7 keV luminosity of 3.4^{+0.5}_{-0.4} \times 10^{37} \text{ ergs s}^{-1}. The spectrum is also fitted well by an RS model with kT = 0.17^{+0.34}_{-0.06} \text{ keV and N_H} = (8.9 \pm 3.2) \times 10^{21} \text{ cm}^{-2} (5.4^{+0.6}_{-0.8} \text{ cm}^{-2} for 5 degrees of freedom [dof]) and an absorption-corrected 0.3–7 keV luminosity of 4.3^{+0.5}_{-0.4} \times 10^{37} \text{ ergs s}^{-1}. Fits of the unbinned spectrum give similar results.
In the case of r3-84, a power-law model does not fit the binned spectrum with reasonable parameters; the photon index is >10, suggesting a soft X-ray source. On the other hand, the spectrum is well fitted by an RS model with $kT = 0.30_{-0.03}^{+0.05}$ keV, $N_H = 4.17_{-1.6}^{+2.3} \times 10^{21}$ cm$^{-2}$ ($\chi^2_r = 0.4$ for 4 dof) and an absorption-corrected 0.3–7 keV luminosity of $2.3_{-1.0}^{+1.5} \times 10^{36}$ ergs s$^{-1}$.

We checked our Chandra spectral results using the two XMM-Newton spectra of r3-84. These spectra were fit with several single-component models (with absorption) including power-law, RS, nonequilibrium ionization (NEI), and bremsstrahlung models. The NEI and bremsstrahlung models give acceptable fits. The (solar abundance) NEI model has $\chi^2_r = 1.11$ for 19 dof with $N_H = 3.4_{-1.7}^{+2.0} \times 10^{21}$ cm$^{-2}$, $kT = 0.45_{-0.06}^{+0.08}$ keV, and ionization age $\tau = (1.2 \pm 0.2) \times 10^{10}$ s cm$^{-3}$; the modeled unabsorbed 0.3–7 keV luminosity is $(9 \pm 1) \times 10^{36}$ ergs s$^{-1}$. The best-fitting single-component model is bremsstrahlung; it has $\chi^2_r = 0.97$ for 20 dof with $N_H = (2.9 \pm 2.4) \times 10^{21}$ cm$^{-2}$ and $kT_{brem} = 0.2 \pm 0.1$ keV; the modeled unabsorbed 0.3–7 keV luminosity is $(9.4 \pm 2.5) \times 10^{36}$ ergs s$^{-1}$.

The overall best-fitting model for the XMM-Newton spectra is an RS plus power-law\textsuperscript{10} (see Fig. 2). It provides a good fit ($\chi^2_r = 0.86$ for 18 dof) with $N_H = 7_{-2}^{+5} \times 10^{20}$ cm$^{-2}$, $kT_{RS} = 0.25 \pm 0.03$ keV, and modeled unabsorbed 0.3–7 keV luminosity $(7 \pm 3) \times 10^{35}$ ergs s$^{-1}$, but it had a poor $\chi^2_r (1.44$ for 20 dof).

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\textsuperscript{10} The single component RS model had $N_H < 1.3 \times 10^{21}$, $kT_{RS} = 0.25 \pm 0.03$ keV, and modeled unabsorbed 0.3–7 keV luminosity $(7 \pm 3) \times 10^{35}$ ergs s$^{-1}$, but it had a poor $\chi^2_r (1.44$ for 20 dof).

Fig. 3.—New SNR r2-57 shown at five wavelengths: X-ray (upper left), [O iii] (middle left), [S ii] (middle right), H$\alpha$ (lower left), and low-resolution radio (20 cm; lower right). The circles (90 $^\circ$ diameter, $\sim$34 pc) show the approximate size of the SNR. The X-ray PSF has FWHM = 14 in this image, showing that r2-57 is clearly resolved in X-rays. For comparison, a simulation of the Chandra PSF at this location in the focal plane is shown (upper right). The radio image is from the low-resolution 20 cm archive VLA data. The image has too low a resolution ($\sim$13$^\circ$) to allow a detailed comparison with the optical and X-ray morphologies. The deconvolved size is given in the text.
$kT_{RS} = 0.25^{+0.04}_{-0.06}$, and power-law slope $\alpha = 3.3^{+1.4}_{-1.0}$, the modeled unabsorbed 0.3–7 keV luminosity is $1.7^{+0.3}_{-0.7} \times 10^{35} \text{ ergs s}^{-1}$. These results are consistent with the Chandra results as well as the temperature and luminosity ranges determined from fits to the XMM-Newton data by Trudolyubov & Priedhorsky (2004), but the temperature and luminosity are both significantly lower than those given by the NEI model fit. We use the Chandra temperature results, which are consistent with all of the XMM-Newton fits, to calculate age and density estimates in § 3.4.

While these spectral fits do not allow detailed modeling of the sources, they show that the X-ray spectra and luminosities are typical of X-ray SNRs. The softness of the spectra is confirmed by the hardness ratios. For r2-57, $H_1 = -0.5 \pm 0.2$ and $H_2 = -0.4 \pm 0.1$. For r3-84, $H_1 = -0.6 \pm 0.2$ and $H_2 = -0.2 \pm 0.1$; these ratios are typical of SNRs (Prestwich et al. 2003). Neither of these sources contain counts with energies higher than 2 keV, also consistent with typical X-ray SNRs.

### 3.1.2. Variability

The variability of these X-ray sources has been investigated by Kong et al. (2002b), who found r2-57 to have constant flux. On the other hand, r3-84 was classified as a variable source in their survey, inconsistent with our finding that this source is an

![Fig. 4.—New SNR r3-84 shown at five wavelengths: X-ray (upper left), [O iii] (middle left), [S ii] (middle right), H\(\alpha\) (lower left), and low-resolution radio (20 cm; lower right). The circles (8’ diameter, ~30 pc) show the approximate size of the SNR. The X-ray PSF has FWHM = 4’1 in this image, showing that r3-84 is only marginally resolved in X-rays. For comparison, a simulation of the Chandra PSF at this location in the focal plane is shown (upper right). The radio image is from the low-resolution 20 cm archive VLA data. The image has too low a resolution (~13’) to allow a detailed comparison with the optical and X-ray morphologies. The deconvolved size is given in the text.](image)
SNR. We checked the variability of this source, and it is variable according to their criteria because of a low count rate in one detection. Further inspection of the detection with the low count rate shows that r3-84 is on the edge of the chip, so that some of the source flux could have missed the detector, calling into question the classification of this source as variable.

3.1.3. X-Ray Sizes

In addition to the spectrophotometric properties of the SNRs, the Chandra data allow estimates of the SNRs’ sizes. The X-ray detection of r3-84 appears as a very faint shell structure 6″ across. Although the structure appears to be this size in the detection, the Chandra PSF 8″ off axis (where this detection of r3-84 is located) has a FWHM of 4″1 according to our ChaRT simulation (see § 2.2.3). A χ² comparison of the azimuthally averaged profile of our detection of r3-84 against the azimuthally averaged simulated PSF at the same location in the Chandra focal plane yields a χ²/ν of 9.2/4, leaving only a 5.6% chance that this object is a point source. The X-ray simulation, X-ray image, optical images, and radio image of the source are shown on the same scale, with circles of 8″ diameter in Figure 4. The X-ray size is very similar to that of the optical (and the low-resolution radio) counterpart.

The X-ray detection of r2-57 also appears as a very faint shell structure, but at ~8″5 across and 4″ off-axis (where the ACIS-S point spread function is 1″4 according to our ChaRT simulation), this source is clearly resolved. The PSF simulation (see § 2.2.3) shows no similarity to the shell-like source detection; a χ² comparison of the azimuthally averaged profile of our detection of r2-57 against the azimuthally averaged simulated PSF at the same location in the Chandra focal plane yields a χ²/ν of 28.1/4, leaving a probability of 10⁻⁵ that this object is a point source. The X-ray simulation, X-ray image, optical images, and radio image of the source are shown on the same scale, with circles of 9″ diameter in Figure 3.

3.2. Optical Properties

The narrowband LGS images provided estimates of the Hα, [S ii], and [O iii] luminosities of these SNRs, as well as the SNR sizes. The relative strength of these emission lines is a well-known diagnostic for distinguishing shock-heated SNRs from photoionized H II regions and planetary nebulae (e.g., Levenson et al. 1995). In addition, the SNR sizes and structures help to constrain their ages (e.g., Kong et al. 2002a).

We measured the counts in the narrowband images using an aperture of 4″ radius centered on r3-84 and an aperture of 5″ radius centered on r2-57. The measured Hα, [S ii], and [O iii] fluxes, in units of 10⁻¹⁴ ergs cm⁻² s⁻¹, were 1.0, 0.9, and 1.5 for r2-57, and 1.1, 0.9, and 1.7 for r3-84, respectively. These [S ii]/Hα ratios of ~0.9 are strong indications that these objects are SNRs. Typically, SNRs have [S ii]/Hα > 0.4, while the ratios of H II regions are lower (Levenson et al. 1995).

The [O iii]/Hα ratio must be corrected for absorption because of the large difference in wavelength. We used the N_H values from the X-ray spectral fits (see § 3.1.1) to estimate the reddening values of the SNRs (Predehl & Schmitt 1995). These values were A_V ~ A_[O iii] ~ 5.0 for r2-57 and A_V ~ A_[O iii] ~ 2.2 for r3-84. Assuming a standard reddening law, A_K ~ A_Hα ~ 3.7 for r2-57 and A_K ~ A_Hα ~ 1.6 for r3-84, so that the absorption-corrected [O iii]/Hα ratios are factors of 3.2 and 1.7 higher than the measured ratios, for r2-57 and r3-84, respectively. The [O iii]/Hα ratios are therefore ~5 and ~3 for r2-57 and r3-84, respectively. Such ratios are slightly high, but not unprecedented for SNRs containing a variety of shock velocities ≥100 km s⁻¹ (e.g., Vancura et al. 1992; Fesen et al. 1997; Mavromatakis et al. 2000).

Finally, we measured the sizes of r2-57 and r3-84 using the ruler option in the image viewing program ds9. The sizes were measured in all three bandpasses. The Hα sizes were 8″8 and 6″6 respectively. The [S ii] sizes were 8″4 and 6″4 respectively, and the [O iii] sizes were 8″8 and 6″2, respectively. Combining these measurements yields optical sizes of 8″7 ± 0″2 (33 ± 1 pc) and 6″4 ± 0″2 (24 ± 1 pc), respectively. These sizes were used to calculate our age and density estimates in § 3.4.

3.3. Radio Properties

Unfortunately the most sensitive radio data available has insufficient resolution and/or sensitivity to obtain more detailed morphologies than the deconvolved sizes. The deconvolved size of r2-57 at 20 cm is 4″3 ± 2″8, and ~10″9 at 6 cm. Because r2-57 has been detected at two different wavelengths (20 and 6 cm) with similar (u, v)-coverage, a radio spectral index could be obtained from the integrated flux densities, about 0.25 ± 0.09 and 0.24 ± 0.22 mJy at 20 and 6 cm, respectively. Unfortunately, a spectral index taken from such measurements would be unreliable, considering the large errors. These large errors are attributable to the weakness of the signals as well as the (unreliable) correction factor for r2-57 at 6 cm due to loss of sensitivity near the half-power point of the antennas. Nevertheless, we conclude that the radio spectral index for r2-57 is not inconsistent with average spectral indices of SNRs.

In the 20 cm VLA archive data we measured an integrated flux density of 1.2 ± 0.2 mJy and a deconvolved size of 8″6 ± 1″5 for r3-84. In the 20 cm high-resolution archival data, a point source of 0.8 mJy is seen coincident with the brightest region in the lower-resolution data. Because r3-84 is too far away from the phase center in the 6 cm data sets to be detected, we are unable to comment on a spectral index for this source.

3.4. Comparing X-Ray/Optical/Radio Morphologies

The similar size measurements for these SNRs at X-ray, optical, and radio wavelengths suggests that at first these SNRs have similar morphologies at all wavelengths. However, in the case of r2-57, the brightest region in all three optical wavelengths is the eastern rim, while the brightest regions in the radio and X-ray images are the north-northeast and northwest parts of the SNR, respectively. Even with this low-count X-ray detection, we can begin to learn about the multiwavelength structure of this SNR.

Although the low spatial resolution of the deep radio data limit detailed morphological comparison with the shorter wavelengths, the deconvolved sizes of the SNRs provide some interesting comparisons. The sizes are all consistent within the errors, but the size of r2-57 at 20 cm may be about half the size at 6 cm. If there is a real size difference, we attribute it as likely due to strong 20 cm radiation originating in different areas of the SNR than the 6 cm radiation. The small-scale 20 cm structure seen in r3-84 (see Fig. 5) hints that this hypothesis is reasonable by showing how these SNRs can have some complex structures at radio wavelengths.

The morphology of r3-84 appears to be more consistent across all wavelengths. While r3-84 is too far off axis and has too few counts to say anything detailed about its X-ray morphology, there is a hint that the northwest portion of the SNR is the brightest region in X-rays. This hint is consistent with the optical SNR, which is brightest in the northwest portion in all three narrowband images. In addition, our high-resolution
solution as done in Kong et al. (2002a). We assume the SNRs are in the adiabatic expansion phase.

We adopt radii of $17 \pm 1$ pc (r2-57) and $12 \pm 1$ pc (r3-84) and shock temperatures of $T_s = 0.17^{+0.54}_{-0.06}$ keV (r2-57) and $T_s = 0.3^{+0.7}_{-0.2}$ keV (r3-84). We assume an initial explosion energy of $E_{51} = 3.3^{+0.4}_{-0.1}$ (in units of $10^{51}$ ergs s$^{-1}$) for both SNRs. This value of $E_{51}$ is the average value from a sample of M31 SNRs surveyed by spectroscopic observations, bracketed by the range of measured $E_{51}$ values, ignoring the highest and lowest values (Blair et al. 1981). From equations (1) and (2) of Kong et al. (2002a), we obtain an age estimate of $17^{+6}_{-9}$ kyr and a density estimate of $n_0 = 0.2^{+0.7}_{-0.2}$ cm$^{-3}$ for r2-57. Applying the same calculations to r3-84 yields an age estimate of $9^{+3}_{-2}$ kyr and a density estimate of $n_0 = 0.3^{+1.5}_{-0.5}$ cm$^{-3}$.

4. CONCLUSIONS

By comparing Chandra ACIS-S images with Local Group Survey [O iii] images, we have discovered two new X-ray/optical/radio SNRs in M31. Both of these objects are previously cataloged X-ray sources. One is a previously cataloged radio source, and the other is a newly discovered radio counterpart found in our study. One SNR (r2-57) is well resolved in the X-ray images; the other is marginally resolved. These SNRs have emission-line ratios, X-ray spectra, and sizes typical of other SNRs in M31. The temperatures and sizes of the SNRs provide age estimates of $17^{+6}_{-9}$ kyr (r2-57) and $9^{+3}_{-2}$ kyr (r3-84).

While these relatively weak X-ray detections have been crucial for the discovery of resolved X-ray SNRs in M31, they have only begun to allow studies of the multiwavelength structure of these objects. With a total of five such SNRs resolved by Chandra in X-rays so far, it seems clear that, as deeper X-ray data become available, more of these objects are likely to be discovered and more detailed multiwavelength morphological and spectral studies can be performed.

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REFERENCES

Blair, W. P., Kirshner, R. P., & Chevalier, R. A. 1981, ApJ, 247, 879
Braun, R. 1990, ApJS, 72, 761
Braun, R., & Walterbos, R. A. M. 1993, A&AS, 98, 327
Cash, W. 1979, ApJ, 228, 939
Ciardullo, R., Jacoby, G. H., Ford, H. C., & Neill, J. D. 1989, ApJ, 339, 53
D’Odorico, S., Dopita, M. A., & Benvenuti, P. 1980, A&AS, 40, 67
Fesen, R. A., Winkler, F., Rathore, Y., Downes, R. A., & Wallace, D. 1997, AJ, 113, 767
Freeman, P., Doe, S., & Siemiginowska, A. 2001, Proc. SPIE, 4477, 76
Gehrels, N. 1986, ApJ, 303, 336
Kong, A. K. H., Garcia, M. R., Primini, F. A., & Murray, S. S. 2002a, ApJ, 580, L125
Kong, A. K. H., Garcia, M. R., Primini, F. A., Murray, S. S., Di Stefano, R., & McClintock, J. E. 2002b, ApJ, 577, 738
Kong, A. K. H., Spilker, L. O., Williams, B. F., Garcia, M. R., & Dickel, J. R. 2003, ApJ, 590, L21
Levenson, N. A., Kirshner, R. P., Blair, W. P., & Winkler, P. F. 1995, AJ, 110, 739
Magnier, E. A., Primini, F. A., Prins, S., van Paradis, J., & Lewin, W. H. G. 1997, ApJ, 490, 649
Maguire, E. A., Prins, S., van Paradis, J., Lewin, W. H. G., Supper, R., Hasinger, G., Pietsch, W., & Truemper, J. 1995, A&AS, 114, 215
Massey, P., Hodge, P. W., Holmes, S., Jacoby, G., King, N. L., Olsen, K., Saha, A., & Smith, C. 2001, BAAS, 33, 1496
Mavromatakis, F., Papamastorakis, J., Paleologou, E. V., & Ventura, J. 2000, A&A, 353, 371
Predehl, P., & Schmitt, J. H. M. M. 1995, A&A, 293, 889
Prestwich, A. H., Irwin, J. A., Kilgard, R. E., Krauss, M. L., Zezas, A., Primini, F., Kaaret, P., & Boroson, B. 2003, ApJ, 595, 719
Rubin, V. C., Krishna Kumar, C., & Ford, W. K. J. 1972, ApJ, 177, 31
Stanek, K. Z., & Garnavich, P. M. 1998, ApJ, 503, L131
Trudolyubov, S., & Priedhorsky, W. 2004, in X-ray and Radio Connections, ed. L. O. Spilker & K. K. Dyer, in press (astro-ph/0404586)
Van Noster, L., Ip, M. K., & Hynes, R. I. 2006, MNRAS, 367, 1081