REVEALING THE SUPERNOVA REMNANT POPULATION OF M33 WITH CHANDRA

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ABSTRACT

We present results of a search for supernova remnants (SNRs) in archival Chandra images of M33. We have identified X-ray SNRs by comparing the list of Chandra X-ray sources in M33 with tabulations of SNR candidates identified from (1) elevated [S ii]/Hα ratios in the optical and (2) radio spectral indices. In addition, we have searched for optical counterparts to soft sources in the Chandra images and X-ray SNR candidates identified in the XMM-Newton survey of M33. Of the 98 optically known SNRs in M33, 22 have been detected at >3σ level in the soft band (0.35–1.1 keV). At least four of these SNR candidates are spatially extended based on a comparison of the data to simulated images of point sources. Aside from the optically matching SNRs, we have found one soft X-ray source in M33 that exhibits no optical emission and is coincident with a known radio source. The radio spectral index of this source is consistent with particle acceleration in shocks, leading us to suggest that it is a nonradiative SNR. We have also found new optical counterparts to two soft X-ray SNRs in M33. These counterparts exhibit enhanced [S ii]/Hα ratios characteristic of radiative shocks. Pending confirmation from optical spectroscopy, the identification of these two optical counterparts increases the total number of known optically emitting SNRs in M33 to 100. This brings the total number of identified SNRs with X-ray counterparts, including those exclusively detected by the XMM-Newton survey of M33, to 37 SNRs. We find that while there are a similar number of confirmed X-ray SNRs in M33 and the LMC with X-ray luminosities in excess of 10^{35} erg s^{-1}, nearly 40% of the LMC SNRs are brighter than 10^{36} erg s^{-1}, while only 13% of the M33 sample exceed this luminosity. Including X-ray SNR candidates from the XMM-Newton survey (objects lacking optical counterparts) increases the fraction of M33 SNRs brighter than 10^{36} erg s^{-1} to 22%, still only half the LMC fraction. The differences in luminosity distributions cannot be fully explained by uncertainty in spectral model parameters and are not fully accounted for by abundance differences between the galaxies.

Key words: galaxies: individual (M33) — galaxies: ISM — shock waves — supernova remnants

1. INTRODUCTION

M31, M33, and the Milky Way are the dominant galaxies of the Local Group and are the nearest normal galaxies that can be studied in detail. In particular, the proximity of M33 (795 ± 75 kpc; van den Bergh 1991), its low inclination (<55°; Zaritsky et al. 1989), and modest foreground extinction [N_H(Gal) ≤ 6 × 10^{20} cm^{-2}; Stark et al. 1992] have made this stellar system one of the best studied galaxies. Classified as a late-type Sc II–III spiral, M33 is intermediate between the more massive early-type spirals such as the Milky Way and M31 and the dwarf irregular galaxies such as the Magellanic Clouds. M33 exhibits a large number of OB associations, H ii regions, and supershells (Boulesteix et al. 1974; Viallefond et al. 1986), indicating that it is host to a large number of active star-forming regions.

The Local Group galaxies are host to a large number of supernova remnants (SNRs). These objects are fundamental to our understanding of the interstellar medium (ISM) and to changes in the composition of galaxies over time. They are probes of and a major energy input source to the ISM. The distribution of supernovae, and hence SNRs, determines how much of the ISM is hot (T ≈ 10^6 K); therefore, emission from SNRs is intimately connected with the soft X-ray background in nearby galaxies.

Multiwavelength surveys of M33 have been especially useful for understanding the global properties of SNRs in that galaxy. These surveys are highly useful tools for probing the global properties of nearby galaxies, but they are also subject to limitations. Variations in detector resolution and sensitivity across different wavelength bands result in varying degrees of completeness in radio, optical, and X-ray source catalogs. In addition, physical processes such as absorption can affect some wave bands (such as the soft X-ray band) more than others (such as the optical band). This is particularly true of soft X-ray sources such as SNRs, which are easily rendered undetectable even in moderately absorbed regions.

Altogether, the most successful searches for SNRs have been performed in the optical for galaxies such as the LMC and SMC (Mathewson & Clarke 1973; Mathewson et al. 1983, 1984, 1985), M31 (Blair et al. 1982), M33 (Sabbadin 1977, 1979; D’Odorico et al. 1980; Blair & Kirshner 1985; Viallefond et al. 1986; Long et al. 1990; Smith et al. 1993; Gordon et al. 1998, hereafter GKL98), the Sculptor Group galaxies NGC 300 and 7793 (Blair & Long 1997), M83 (Blair & Long 2004), and the nearby spirals NGC 2403, 5204, 5585, 6946, M81, and M101 (Matonick et al. 1997; Matonick & Fesen 1997). The optical identification technique consists of dividing continuum-subtracted, narrowband [S ii] images of galaxies by narrowband Hα images and then searching the ratio image for features with elevated [S ii]/Hα ratios. There is generally a strong separation in [S ii]/Hα ratio between H ii regions ([S ii]/Hα ≲ 0.1) and SNRs ([S ii]/Hα ≳ 0.4) (Mathewson & Clarke 1973). The ratio differences are due to...
the fact that photoionization keeps S ionized beyond S+, resulting in weak [S ii] emission. On the other hand, radiative recombination in SNRs produces a wide range of temperatures and ionization states so that a zone exists behind the shock where a larger fraction of S resides in S+ and [S ii] emission is strong.

M33 has been surveyed by each successive X-ray mission up to the present day. These include surveys by Einstein (Long et al. 1981; Trinchieri et al. 1988), ROSAT (Schulman & Bregman 1995; Long et al. 1996; Haberl & Pietsch 2001), and XMM-Newton (Pietsch et al. 2003, 2004). The Einstein High Resolution Imager (HRI) and Imaging Proportional Counter (IPC) surveys showed that the X-ray appearance of M33 is dominated by a hard nuclear source. The luminosity of this object (M33 X-8) was found to be $10^{39}$ erg s$^{-1}$ (Long et al. 1996), a result later confirmed by Chandra observations (Dubus & Rutledge 2002). This makes M33 X-8 the brightest X-ray source in the Local Group. The 14 other unresolved sources found in the Einstein survey [$L_X(0.1-2.4 \text{ keV}) \gtrsim 10^{37}$ erg s$^{-1}$; Long et al. 1996] were classified as X-ray binaries. Subsequent surveys with the HRI and PSPC on ROSAT revealed faint diffuse emission within 10º of the nucleus and increased the total number of detected X-ray sources to 184. The ROSAT survey depth was $L_X(0.1-2.4 \text{ keV}) \approx 10^{36}$ erg s$^{-1}$ (Long et al. 1996), resulting in the detection of 12 of the 98 optically identified SNRs in M33. The most recent X-ray survey of M33 was performed with XMM-Newton and covered the full $D_{25}$ isophote with uniform sensitivity down to a luminosity $L_X(0.5-10 \text{ keV}) \approx 10^{35}$ ergs s$^{-1}$ (Pietsch et al. 2003, 2004). That survey brought the total number of sources detected in M33 to 408, including 28 sources matching optical SNRs from the catalog of GKL98.

Here we present the results of a search for SNRs in archival Chandra images of M33, using positive coincidence with optically known SNRs and hardness ratios as discriminants. We focus our analysis on the SNR population and do not attempt to characterize the properties of the global distribution of X-ray sources in this galaxy (a broader discussion is provided by Grimm et al. 2005). When we began this work, there were 98 known optical SNRs in M33, of which 78 lay in the field of view of the Chandra archival images. Of these, only 26 were located within a 10º diameter circle in which the Chandra point-spread function (PSF) is characterized by a 50% encircled energy ($E = 1.49 \text{ keV}$; Chandra Proposers’ Guide, ver. 6) of 25º or less. We have found X-ray counterparts to at least 22 optically known SNRs in the archival Chandra images of M33. We have also found two previously unidentified optical SNRs in M33 by comparing Chandra and XMM-Newton source lists with narrowband optical images.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Chandra Images

The Chandra archival data used in our analysis were acquired during Cycle 1 (ObsID 786 in ACIS-S imaging mode, ObsID 1750 in ACIS-I imaging mode) and Cycle 2 (ObsID 2023 in ACIS-I imaging mode). The Cycle 1 observations targeted the bright nuclear source of M33 (aim points at $\alpha_{2000.0} = 01^\text{h}33^\text{m}50^\text{s}8$, $\delta_{2000.0} = 30^\circ39'36''6$), while the Cycle 2 pointing was centered on NGC 604, the giant starburst H ii region along the northern spiral arm (aim point at $\alpha_{2000.0} = 01^\text{h}34^\text{m}32^\text{s}29$, $\delta_{2000.0} = 30^\circ47'40''7$). The Chandra imaging fields are marked on a continuum-subtracted Ho image of M33 in Figure 1. The combined field of view of the Chandra images covers approximately half of the region determined by the $D_{25}$ isophote of M33 (Tully 1988).

Using CIAO version 3.0.2, we applied the Chandra X-ray Center (CXC) charge transfer inefficiency (CTI) correction to the level 1 event files and screened the data to remove time intervals with background rates $>4$ $\sigma$ above the median level and to restrict the energy range of the resulting data sets to 0.35–8 keV. We then applied the CIAO destreaking algorithm to remove the streak pattern from the chip. Finally, we used the CXC aspect offset tool to correct the world coordinate system (WCS) information for each event file. The resulting exposure times for the ObsIDs 786, 1730, and 2023 data sets were 46.3, 49.4, and 88.8 ks, respectively.

2.2. Narrowband Optical Imagery

To search for optical counterparts to the X-ray sources in the Chandra data, we retrieved Kitt Peak National Observatory (KPNO) 4 m Mosaic images of M33 from the NOAO data archive. The optical data include narrowband imagery in H, [S ii], and [O iii] and cover most of the $D_{25}$ isophote from the Local Group Survey of Massey et al. (2002). The images we used from the archive were the final combined frames (stack of five dithered frames) and were overscan- and bias-subtracted, flat-fielded, and corrected for bad pixels.

To remove the continuum emission from the narrowband images, we first subtracted a constant pedestal value from the H, [S ii], and [O iii] frames to bring all the frames to a zero-level background. We then scaled and subtracted the [O iii] band image from the H and [S ii] frames to remove stellar continuum from the narrowband images. Similarly, we used the B-band image to subtract the continuum emission from the [O iii] image. We then divided the continuum-subtracted [S ii] and H$\alpha$ frames to produce a [S ii]/H$\alpha$ ratio image. To ensure the reliability of the [S ii]/H$\alpha$ ratios measured from the NOAO images, we compared values of the ratio at positions of known optical SNRs to the ratios listed in Table 3 of GKL98. Our calculated [S ii]/H$\alpha$ ratios agreed with the tabulated values of GKL98 to within 20%, and all known SNRs were readily distinguishable in the ratio image.

3. X-RAY SOURCE DETECTION

We used the CIAO routine wavdetect, which detects sources by convolving the pixels with “Mexican Hat” wavelet functions for source detection (Freeman et al. 2002). Optical surveys of M33 (Long et al. 1990; GKL98) have shown that the SNRs in this galaxy span a wide range of radii, from $\sim 1''$ ($\sim 4$ pc) up to $\sim 15''$ ($\sim 60$ pc). Accordingly, we optimized our search for spatially extended X-ray emission from SNRs by conducting our wavdetect runs on wavelet scale sizes up to 64’. The wavelet sizes used during our runs were 0’5, 1’, 2’, 4’, 8’, 16’, 32’, and 64’. The largest threshold significance for output source lists was set to $10^{-6}$.

Before searching for sources in the data we used 1 keV exposure maps to correct the count rates of each image. We input the exposure map into each wavdetect run to avoid detection of spurious sources from such features as charge transfer streaks. We filtered each event file to create images in each of the

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4 The Chandra Proposers’ Guide can be found at http://cxc.harvard.edu/proposer/POG/index.html.
following bands: 0.35–1.1 keV (soft), 1.1–2.6 keV (medium), 2.6–8.0 keV (hard), and 0.35–8.0 keV (broad). We performed the source detection on each filtered image separately. Since the imaging fields of the three data sets overlap, we scanned the source detection output for multiply detected sources. If a source appeared in more than one observation with similar signal-to-noise ratio (S/N) in both images, we retained the detection parameters from the observation with the best imaging quality (i.e., the one in which the source was closest to the ACIS aim point). On the other hand, exceptions were made if a multiply detected source exhibited significantly higher S/N in one image than another, in which case we retained detection parameters from the image with the stronger detection. The number of unique sources detected in the broadband images of ObsID 786, 1730, and 2023 was 166 (207) at the 3 \( \sigma \) level.

4. CROSS-CORRELATION OF CHANDRA SOURCES WITH OPTICAL AND RADIO CATALOGS

As is evident from the optical images of M33 (GKL98), many SNRs in this galaxy are expanding into inhomogeneous media, with many exhibiting distorted morphologies. The likely mixture of radiative and nonradiative shocks in these SNRs can produce wide variations in X-ray and optical brightness along their shells. Depending on whether the shocks are radiative, nonradiative, or a combination, portions of the shell may be detected solely in the optical, solely in X-rays, or in both bands. Furthermore, unlike many SNRs studied in galaxies outside the Local Group, the M33 SNRs are often large enough (\( \gtrsim 3'' \), or 12 pc, across) to be spatially resolved in optical and Chandra X-ray images. The net effect is that choosing a fixed matching radius during the cross-correlation can cause real matches to be missed. To avoid this problem, we performed the cross-correlation in two steps. First, we obtained a culled list of sources in all three bands that match the coordinates of GKL98 SNRs to within a generous coincidence radius of 20''.

We then generated a final list of X-ray counterparts to the GKL98 SNRs by visually inspecting each matching object. We blinked between aligned X-ray and H\( \alpha \) images of each source to confirm that the X-ray source lies within the optically measured diameter of the SNR. We also looked for secondary signs of a match, such as evidence of extended morphology. However, this feature is not a strong discriminant, since the interaction of SNRs with compact ISM clouds can produce localized regions of enhanced X-ray emission unresolved by Chandra. Although we have taken advantage of overlaps between the three Chandra observations wherever possible to select SNR candidates with the best imaging quality and highest count levels, the final group of candidates are invariably affected by strong variations in the size of the Chandra PSF between data sets and within each individual observation. This is the most significant complicating factor in distinguishing point sources from extended sources.
In the majority of cases the X-ray emission from SNRs is dominated by thermal emission (lines + bremsstrahlung continuum) from shocks in ISM and ejecta material. The thermal emission is typically soft, peaking below 1 keV. Therefore, we concentrated our search for SNRs on the soft-band images (0.35–1.1 keV) of M33.

5. SUPERNOVA REMNANTS DETECTED WITH CHANDRA

5.1. Optical Matches

Of the detected sources in ObsID data sets 786, 1730, and 2023, we find that 22 match SNRs from the optical catalog, all at $\geq 3 \sigma$ in the $S$ band (Table 1). Images of the matching sources are shown in Figures 2–5.

Before we attempted to interpret the results of our matches, we first calculated the expected number of random coincidences between the two source lists. As shown in Figure 1, the Chandra observations of M33 do not cover the entire spiral. Although the Chandra images cover a smaller fraction of the M33 spiral than the earlier ROSAT images (Long et al. 1996; Haberl & Pietsch 2001), the higher sensitivity and better spatial resolution of Chandra have resulted in a greater number of X-ray detections of optically identified SNRs. Of the 98 SNRs cataloged by GKL98, 78 lie within the total field of view of the three Chandra observations. Since M33 fills the entire X-ray field of view, we can expect to find both background objects (active galactic nuclei [AGNs]) and M33 sources on each ACIS chip. Assuming these objects are distributed randomly across the field, the number of chance coincidences between the 166 X-ray sources and the 78 optical SNRs in the Chandra field is $< 3$ for a matching radius of 15".

This may be an underestimate, given that X-ray sources intrinsic to M33 are not randomly distributed. However, the culling of individual matching sources by spectral hardness (and visual inspection as a secondary indicator) reduces the likelihood that chance coincidences are retained in the final list of matches.

SNRs are extended objects. To check whether spatial extent could provide an additional criterion for selecting SNRs from the X-ray sample, we visually compared each SNR candidate with a simulated X-ray image of a point source containing the same number of counts and located at the same off-axis angle as the SNR candidate. We performed these simulations at 1.5 keV using the CXC applications ChaRT and MARX 4.0.8. SNR candidates that clearly appeared to be larger than their corresponding simulated sources were labeled as extended (Table 1). Since our simulated point-source images did not include background emission, they were of limited usefulness in identifying extended SNRs that were faint and/or located far from the imaging axis.

The inability to separate background fluctuations from real extended emission made 10 of the SNR candidates unsuitable for direct visual comparison with point-source images. However, four sources showed clear extended morphology, while three others showed marginal evidence of extended emission, and five showed morphologies consistent with unresolved (point source) emission. Note that since the X-ray emission from some sources may originate in localized regions smaller than the Chandra imaging resolution, a test for spatial extent can only confirm the SNR nature of a source, not disprove it.
Aside from extended morphology, SNRs are also expected to show temporally steady fluxes. We searched for time variability in our SNR candidates by converting XMM-Newton count rates of optically matching candidates to expected Chandra count rates, then comparing these rates with the Chandra values from Table 2. We performed the conversion using the best-fit parameters for each source from Table 3 (see discussion below).

Of the 16 SNR candidates detected by both XMM-Newton and Chandra, all but two exhibit fluxes consistent to within 20%. The 0.35–10 keV Chandra count rates predicted for GKL98 SNRs 28 and 29 by the XMM-Newton data are nearly twice the values obtained in Table 2. The reason for the discrepancy is unclear but may arise from the inclusion of nearby soft diffuse emission in the XMM-Newton spectral extraction regions of Pietsch et al. (2004). On the other hand, it is also possible that the match between these two X-ray sources and their optical counterparts is the result of a random coincidence. In the case of SNR 28, at least, this possibility is lessened by the marginally extended morphology of its X-ray counterpart. However, we have no such assurance for the SNR 29 counterpart, which shows no obvious extent. Therefore, we proceed with the remaining analysis of our paper with the caveat that two of the most luminous soft X-ray sources in our sample may not be SNRs.

5.2. Properties of X-Ray Sources Matching Optical SNRs

During the extraction of X-ray spectra from SNR candidates we were confronted with the problem of choosing aperture regions large enough to accommodate both the extended morphologies of the sources and significant variations in the size of the Chandra PSF across each field. A lower limit on the aperture...
size for a given source is obtained by assuming it is pointlike and simply setting the aperture radius equal to the size of the Chandra PSF at that location. An upper limit can be obtained by using both the PSF size and the (admittedly rough) optically measured sizes for the known optical SNR. Empirically we found that a source extraction radius $R_{\text{extr}} = R_{\text{PSF}} + 1.5R_{\text{opt}}$ was large enough to include all the S-band emission from the SNR candidates. We set $R_{\text{PSF}}$ to the value enclosing 95% of the counts at 1.5 keV ($R_{\text{PSF}}$ is a function of off-axis angle; see Figure 4.12 in the Chandra Proposers’ Guide, ver. 6). The extraction regions used in our SNR analysis are marked on Figures 2–5 and range from approximately 4″ to 21″ in radius. We estimated the local X-ray background of each object using an annulus centered on the source, with inner radius set to 2$R_{\text{extr}}$ and outer radius to 3$R_{\text{extr}}$. Known X-ray sources lying within a given annulus were excluded from the background spectral extraction, as were chip edges and diffuse emission from NGC 604. For all the remaining sources in the Chandra observations we set the size of the extraction apertures to $R_{\text{PSF}}$.

Source counts were extracted in soft ($S$), medium ($M$), and hard ($H$) bands defined above and used to compute the hardness ratios $HR_1 \equiv (M-S)/(M+S)$ and $HR_2 \equiv (H-M)/(H+M)$ (Table 2). In many cases the raw object and/or background spectra exhibited low count levels ($N \lesssim 20$), requiring the usage of Poisson statistics in defining the errors (rather than the commonly used Gaussian statistics). In cases in which $N < 10$, we used the Gehrels (1986) approximation to compute the 1 σ errors on the count levels. This results in an asymmetric distribution with the error bars on the upper limit larger than on the lower limit. In these cases we set the lower error bar equal to the upper error bar before computing HR1 and HR2 and propagating the errors.

By this definition, soft sources such as SNRs and active stars tend to exhibit negative hardness ratios, while hard sources such as AGNs and X-ray binaries tend to exhibit positive hardness ratios. This is generally a good discriminant for separating thermal sources (soft) from nonthermal sources (hard). However, among the X-ray sources lacking known optical counterparts we

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**Fig. 3.—** Same as Fig. 2. The thumbnail for SNR 60 from the GKL98 catalog is 1.00 on a side, while the remaining thumbnails are each 1.50 on a side.
there are also a number of objects exhibiting mixed hardness ratios. Determining the physical origin of these sources is more difficult, since they may exhibit a mixture of thermal and non-thermal emission but are too faint for conclusive X-ray spectral fitting.

From Figure 6 and Table 2 it is clear that the background-subtracted spectra of the SNR candidates exhibit hardness ratios consistent with soft emission \((HR_1 < 0, HR_2 < 0)\). To within the errors this is consistent with thermal emission from shocked plasma. The spectra of many SNR candidates exhibit negative counts in the \(H\) band after background subtraction, consistent with zero net counts. In these cases we report \(HR_2 = 0\). Some candidates, such as the counterparts to optical SNRs 37, 54, 62, and 85, even exhibit zero net counts in the \(M\) band, giving \(HR_1 = 0\).

As shown in Figure 1, there appears to be a cluster of X-ray SNRs detected in the southern spiral arm of M33, just south of the nucleus. This may be a selection effect due to the coverage of the spiral arm and nucleus by the ACIS S3 chip in the ACIS-S imaging data set (ObsID 786). Although the same region is covered in an ACIS-I imaging observation (ObsID 1730) with nearly the same integration time, the factor of 2 higher sensitivity of the S3 chip results in a larger number of SNR detections (19 optically known SNRs covered by the S3 chip, 7 detected).

Guided by the spectral softness of the SNR candidates, we calculated luminosities for the sources under the assumption that their spectra are dominated by thermal emission attenuated by M33 and Galactic absorption. Aside from remnants 28, 29, 31, 35, and 55, the remaining objects exhibit <100 counts in their broadband (0.35–8.0 keV) spectra (Table 2). In these fainter sources it is not possible to detect and/or resolve any of the emission-line structure one expects from a thermal plasma. Therefore, the only quantities we can meaningfully constrain in these sources are those that influence the overall shape of the thermal spectrum such as the plasma temperature \((kT)\), the local absorbing column \((N_H)\), and spectral normalization.

Given the above constraints, we adopted the following approach for estimating the luminosities of the SNR candidates.
Fig. 5.—Same as Fig. 2. SNR 94 is located inside the starburst H II region NGC 604. All thumbnails measure 1/5 on a side.

TABLE 2

Chandra X-Ray Counterparts of Optical SNRs in M33

| IDa | α12000.0b | δ12000.0b | Count Rate (10⁻³ counts s⁻¹)c | (M–S)/(M+S)d | (H–M)/(H+M)e,f |
|-----|------------|------------|-----------------------------|--------------|-----------------|
| 9... | 01 32 57.1 | 30 39 24.8 | 0.60 ± 0.19                 | −0.93 ± 0.40 | −1              |
| 27... | 01 33 28.0 | 30 31 34.9 | 0.38 ± 0.16                 | −0.96 ± 0.43 | −1              |
| 28... | 01 33 29.0 | 30 42 17.1 | 5.24 ± 0.34                 | −0.70 ± 0.50 | −0.97 ± 0.24    |
| 29... | 01 33 29.4 | 30 49 11.9 | 2.35 ± 0.26                 | −0.85 ± 0.39 | −0.50 ± 0.99    |
| 31... | 01 33 31.2 | 30 33 33.6 | 6.10 ± 0.37                 | −0.35 ± 0.66 | −0.86 ± 0.38    |
| 35... | 01 33 35.9 | 30 36 28.0 | 2.10 ± 0.22                 | −0.46 ± 0.63 | −1              |
| 37... | 01 33 37.7 | 30 40 10.2 | 0.31 ± 0.18                 | −1           | +1              |
| 45... | 01 33 43.5 | 30 41 04.0 | 0.49 ± 0.14                 | −0.04 ± 0.73 | −1              |
| 47... | 01 33 48.3 | 30 33 05.2 | 0.96 ± 0.18                 | −0.48 ± 0.63 | −1              |
| 53... | 01 33 54.3 | 30 33 50.5 | 0.69 ± 0.25                 | −0.81 ± 0.54 | −0.49 ± 2.95    |
| 54... | 01 33 54.6 | 30 45 18.9 | 0.32 ± 0.10                 | −1           |                 |
| 55... | 01 33 54.9 | 30 33 10.9 | 10.5 ± 0.50                 | −0.78 ± 0.44 | −0.93 ± 0.33    |
| 60... | 01 33 58.5 | 30 36 24.6 | 0.34 ± 0.12                 | −0.70 ± 0.62 | −1              |
| 62... | 01 33 58.5 | 30 33 33.7 | 0.90 ± 0.26                 | −1           | −1              |
| 64... | 01 34 00.3 | 30 42 18.6 | 1.34 ± 0.20                 | −0.70 ± 0.52 | −0.54 ± 0.84    |
| 66... | 01 34 01.5 | 30 35 19.3 | 1.44 ± 0.28                 | −0.33 ± 0.70 | −0.09 ± 0.78    |
| 73... | 01 34 10.7 | 30 42 23.8 | 1.71 ± 0.19                 | −0.70 ± 0.51 | −1              |
| 78... | 01 34 14.3 | 30 53 54.1 | 0.47 ± 0.11                 | −0.28 ± 0.71 | −0.54 ± 0.84    |
| 83... | 01 34 16.5 | 30 51 54.5 | 0.44 ± 0.09                 | −0.76 ± 0.49 | −1              |
| 85... | 01 34 17.5 | 30 41 23.2 | 0.27 ± 0.10                 | −1           | +1              |
| 94... | 01 34 33.0 | 30 46 38.3 | 0.41 ± 0.07                 | −0.25 ± 0.70 | −1              |
| 97... | 01 34 41.0 | 30 43 28.0 | 0.73 ± 0.10                 | −0.65 ± 0.55 | −0.63 ± 0.75    |
| 270... | 01 34 23.3 | 30 54 24.0 | 0.29 ± 0.08                 | −0.36 ± 0.49 | −0.13 ± 0.74    |

Note. — Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

a IDs from the optical SNR catalog of GKL98.
b Coordinates measured from the computed centroid of the source from the soft-band image.
c Count rate in the broadband spectrum, 0.35–8.0 keV.
d S = 0.35–1.1 keV (soft band), M = 1.1–2.6 keV (medium band), H = 2.6–8 keV (hard band).
e Hardness ratios are set to −1 when there are zero counts in the harder band of the ratio and +1 when there are zero counts in the softer band of the ratio.
f This is a new optical identification for an X-ray source designated as CXOM33 J013441.0+3043280 (see §7 for details) and matching source 270 from the XMM-Newton catalog of Pietsch et al. (2004).
and spectrum normalization as free parameters. Spectra of the remaining remnants in the table were computed using $N_{\text{H}}(\text{Gal}) = 5.4 \times 10^{20} \text{ cm}^{-2}$ (frozen), $N_{\text{H}}(\text{M33}) = 7 \times 10^{20} \text{ cm}^{-2}$ (best-fit value from SNR 55; now frozen), and with $kT$ and spectrum normalization as free parameters.

*ID's from the optical SNR catalog of GKL98.

Notes.—All fits are computed assuming a Raymond-Smith model and a distance of 795 kpc to M33. The luminosity of SNR 55 was computed with $N_{\text{H}}(\text{Gal}) = 5.4 \times 10^{20} \text{ cm}^{-2}$ (frozen), abundances 0.4 solar (frozen), and with $N_{\text{H}}(\text{M33}), kT,$ and spectrum normalization as free parameters. Spectra of the remaining remnants in the table were computed using $N_{\text{H}}(\text{Gal}) = 5.4 \times 10^{20} \text{ cm}^{-2}$ (frozen), $N_{\text{H}}(\text{M33}) = 7 \times 10^{20} \text{ cm}^{-2}$ (best-fit value from SNR 55; now frozen), and with $kT$ and spectrum normalization as free parameters.

First, we generated ancillary response files (ARFs) and redistribution matrix files (RMFs) for each object. This accounted for the spatial and energy dependences of the High Resolution Mirror Assembly (HRMA) and ACIS responses at the position of each source. Then we fit the Chandra spectrum of the brightest SNR candidate in our sample (number 55, 480 integrated counts) with a Raymond-Smith model in XSPEC 11.3.1. Quantities held fixed during the fit were the Galactic absorbing column [$N_{\text{H}}(\text{Gal}) = 5.4 \times 10^{20} \text{ cm}^{-2}$; Stark et al. 1992] and the abundances of the emitting plasma. We set the latter quantity to 0.4 solar, the average value obtained by Blair & Kirshner (1985) from optical spectroscopy of 12 SNRs in M33. The local M33 absorbing column $N_{\text{H}}(\text{M33})$, plasma temperature $kT$, and spectrum normalization were left free. After fitting the spectrum of remnant SNR 55 (Fig. 7), we fit the spectra of the remaining sources by fixing $N_{\text{H}}(\text{M33})$ to the best value obtained for SNR 55 [$N_{\text{H}}(\text{M33}) = 5 \times 10^{21} \text{ cm}^{-2}$] and using the $kT$ and normalization for SNR 55 as starting values for the fits. The M33 column density obtained by the spectral fit of SNR 55 lies comfortably in the range of values measured in $H$ observations of that galaxy [$5 \times 10^{20} \leq N_{\text{H}}(\text{M33}) \leq 5 \times 10^{21}$; Newton 1980], giving confidence that the columns used in our fits are reasonable [we assume solar metallicity for the M33 absorbing column; a metallicity of 0.4 solar would raise $N_{\text{H}}(\text{M33})$ to $1.3 \times 10^{22} \text{ cm}^{-2}$]. Finally, we converted the resulting intrinsic fluxes to luminosities assuming a distance of 795 kpc for M33. The best-fit temperatures and calculated luminosities are shown in Table 3. The faintest optically matched SNR in the Chandra field of view is associated with SNR 37 from the GKL98 catalog and exhibits a 0.35–8.0 keV luminosity of $7 \times 10^{34} \text{ ergs s}^{-1}$ ($S_X \approx 9 \times 10^{-16} \text{ ergs cm}^{-2} \text{ s}^{-1}$). This is comparable to the depth achieved for older surveys of SNRs in much nearer galaxies such as the LMC (Long et al. 1981) and demonstrates that close to the optical axis ($\leq 4\arcmin$) a pointed ACIS-S imaging observation of M33 is capable of detecting some of the faintest M33 remnants in a 50 ks integration.

5.3. Comparison with the XMM-Newton Source Catalog

An X-ray survey of M33 has recently been completed with XMM-Newton (Pietsch et al. 2003, 2004). The survey covered the $D_{25}$ isophote of the galaxy [nearly twice the area observed by Chandra] and to a relatively uniform depth $L(0.2–4.5 \text{ keV}) = 10^{35} \text{ ergs s}^{-1}$. In their analysis of the XMM-Newton data Pietsch et al. (2004) identified 408 sources in M33, with 28 of the sources...
matching known optical SNRs from GKL98 (Table 3 of Pietsch et al. 2004) and exhibiting the soft spectral characteristics of shock-heated gas. Pietsch et al. (2004) found counterparts to 13 SNRs from the GKL98 catalog not detected in our Chandra analysis: SNRs 11, 12+13 (blended), 15, 18, 20, 21, 25, 36, 57, 59, and 86+87 (blended). These remnants are not detected by Chandra, because they are intrinsically too faint, located too far off the optical axis (rendered undetectable by such effects as smearing of the PSF and/or high detector background), or are located outside the Chandra field of view.

Although the portion of M33 covered by the Chandra observations lies completely within the larger field covered by XMM-Newton, the Chandra observations were still able to detect X-ray counterparts to six optical SNRs not revealed by the XMM-Newton survey (Table 1). This may be due to the location of some of these SNRs within regions of extended diffuse emission. If the source is faint enough, the larger PSF of XMM-Newton can cause SNR emission to merge with the surrounding diffuse background, resulting in a nondetection. An excellent example is the case of SNR 94 from the GKL98 catalog (Fig. 5). This remnant is embedded within the starburst H II region NGC 604 (D’Odorico et al. 1980; GKL98) and is surrounded by diffuse X-ray emission. The source is well detected in the Chandra data (S/N ≈ 4) but is absent from the XMM-Newton source catalog. This is a clear illustration of the advantages of Chandra over XMM-Newton in locating X-ray sources in confused regions. Most of the optical SNRs with X-ray counterparts are also known radio sources (Gordon et al. 1999). As shown in Table 1, most of these objects exhibit negative radio spectral indices.

6. NONRADIATIVE SNR CANDIDATES

Apart from the 22 SNRs detected in our sample, there are 84 soft sources in the Chandra data that do not match any optically identified SNRs, known foreground stars, X-ray binaries (XRBs), or supersoft sources. While some of these objects may be background AGNs, we can also expect that some will be young, nonradiative SNRs expanding in low-density environments. The spectra of these soft sources contain too few counts (<100) for meaningful X-ray fits, making the task of uniquely identifying them from the Chandra data alone impossible.

Despite the above limitations, we can at least identify potential nonradiative SNR candidates in M33 by searching for radio counterparts to the soft X-ray sources. The radio continuum emission from active stars, supersoft sources, and XRBs is intrinsically faint (see Ogley et al. [2002] for radio observations of Galactic supersoft sources and Fender et al. [1998] for a radio survey of transient sources in the Magellanic Clouds), while synchrotron radiation from particle acceleration can produce radio fluxes of up to a few mJy at the distance of M33 (Gordon et al. 1999). Note that the method of selecting SNR candidates is limited by the differing sensitivities of the X-ray and radio data, since an unknown number of nonradiative SNRs may be intrinsically faint in the radio and remain undetected in the Gordon et al. (1999) observations.

We also performed a cross-correlation between our broadband source lists and Gordon et al. (1999) radio sources not matching any known optical SNRs. We found no matching radio sources to within 15″ of any broadband object. However, a similar comparison with our soft X-ray source lists revealed one matching source in ObsIDs 786 and 1730, with the former observation showing the stronger detection (S/N = 10). The broadband, background-subtracted count rate of the source from ObsID 786 is 2.7 × 10^{-3} counts s^{-1}. The source is located at α_{2000.0} = 01^h33^m50^s5, δ_{2000.0} = 30°38′21″5 and lies within 0″7 of radio source 100 from the Gordon et al. (1999) catalog. Following the CXC naming convention, we call this source CXOM33 J013350.5+3038215. This source lies approximately 75″ south of the X-ray nuclear source (X-8), at the base of the inner spiral arm. There is little nebular emission visible within 20″ of the X-ray source. The 6–20 cm spectral index of CXOM33 J013350.5+3038215 is consistent with synchrotron emission from shocks (α_{6–20} = −0.6 ± 0.1) but appears to exhibit a somewhat harder spectrum than remnants with optical counterparts (from our Chandra analysis HR1 = −0.06 ± 0.3, HR2 = −0.33 ± 0.35). With only 126 counts in the spectrum, we are unable to establish whether the emission is produced by a combination of thermal and nonthermal components or whether the hardness ratio is attributable to line emission from metal-rich ejecta. The radio spectral index is also consistent with emission from a background radio galaxy, though no obvious optical emission is seen at the position of the X-ray source in the R-band image of M33. Despite the strong detection of this object in the Chandra observation (S/N ~ 10), it is not detected in the XMM-Newton data because of its proximity to the bright source M33 X-8. We examined the light curve of the source using data from ObsIDs 786 and 1730 and found that it exhibited no obvious variability within the errors. CXOM33 J013350.5+3038215 does not show clear evidence of an extended morphology. It is clearly a candidate for a nonradiative SNR and a prime example of an object that would benefit from deeper follow-up X-ray observations of M33.

7. SEARCH FOR OPTICAL SNR EMISSION FROM SOFT X-RAY SOURCES

7.1. Optical Emission from Chandra Sources

Given the richness of the Chandra data sets, it is tempting to use the X-ray source lists as a guide to finding SNRs in optical narrowband images of M33. Our approach was to overlay the positions of soft-band X-ray sources lacking counterparts from the GKL98 catalog onto the NOAO Mosaic H α, [S ii], and [O iii] images of M33. We visually examined each field in which X-ray sources were located, searching for telltale signs of SNR emission such as filaments and shell-like structures. We also generated [S ii] / Hα ratio images from the Mosaic data to search for enhancements in the ratio expected from radiative shocks.

Our comparison of the optical and X-ray images of M33 revealed one new optical counterpart: an emission knot exhibiting an elevated [S ii] / Hα ratio (0.7–0.8; fully consistent with radiative shock excitation) and matching a soft source located 6′8 north of the starburst H II region NGC 604 (Fig. 8). The X-ray source is detected in ObsID 2023 and exhibits hardness ratios consistent with thermal emission: HR1 = −0.36 ± 0.5, HR2 = −0.13 ± 0.74. It matches the position of XMM-Newton source 270, one of 16 X-ray sources detected by XMM-Newton and classified as a SNR by Pietsch et al. (2004) on the basis of hardness ratios. This source is located at α_{2000.0} = 01^h34^m23^s3, δ_{2000.0} = 30°54′24″70 in the soft-band image of M33, agreeing with the XMM-Newton position to well within the positional uncertainty of both observations (~15″–20″). This source, which we designate CXOM33 J013441.0+3043280, exhibits only 30 counts in ObsID 2023 and lies well off the imaging axis of Chandra, so we are unable to determine whether it is extended. In addition, there is no radio counterpart to CXOM33 J013441.0+3043280 from the catalog of Gordon et al. (1999). Assuming a Raymond-Smith plasma with model fitting parameters from Table 3, we obtain a temperature of 0.3 keV and a 0.35–8 keV luminosity L_X = 2.5 × 10^{35} ergs s^{-1}. Although the portion of M33 containing
CXOM33 J013441.0+3043280 was covered by GKL98, identification of the optical counterpart was not included in that survey.

7.2. Optical Emission from XMM-Newton Sources

Of the 16 XMM-Newton sources categorized as SNRs by Pietsch et al. (2004), only three were detected at the 3σ level in the soft-band Chandra images (one of these objects is source 270 described above). The remaining 13 XMM-Newton SNR candidates either fell below the detection threshold of Chandra or lay outside the field of view of the Chandra images. However, we can at least search for optical counterparts to these candidates in the KPNO Mosaic images.

Overlaying the positions of the 13 XMM-Newton SNRs onto the continuum-subtracted Hα, [S ii], and [O iii] images, we found a good match between XMM-Newton source 68 and an optical shell 9′ (35 pc) across, located near the end of the southern spiral arm at αJ2000.0 = 01h32m46.s5, δJ2000.0 = 30°34′39″0. The eastern side of the shell is particularly bright (Fig. 9) and exhibits a [S ii]/Hα varying from 0.6 to 0.8, confirming that the emission is shock-excited. The shell is also detected in [O iii], in which its emission is more evenly distributed along the rim. The XMM-Newton hardness ratios for source 68 are (M – S)/(M + S) = 0.14 ± 0.16 and (H – M)/(H + M) = −0.79 ± 0.18, where S is (0.2–0.5) keV, M is (0.5–1.0) keV, and H is (1.0–2.0) keV.

Like XMM-Newton source 270, source 68 escaped identification in the optical survey of GKL98 and exhibits no radio counterpart in the Gordon et al. (1999) catalog. This object lies in the field of Chandra ObsID 1730, approximately 14′ off-axis on the S3 chip. The faintness of this source [Fν(0.1–4.5 keV) ≈ 10−15 ergs cm−2 s−1] in the XMM-Newton data; Pietsch et al. 2004] along with the strongly broadened Chandra PSF at its off-axis position are likely responsible for the lack of detection of this source in the Chandra data.

Since the Hα filter used in the M33 imagery also transmits [N ii] line emission, we have likely underestimated the [S ii]/Hα ratios of CXOM33 J013441.0+3043280 and XMM-Newton source 68. Optical spectroscopy will be required to obtain a more accurate measurement and to better characterize the physical properties of this SNR. The discovery of optical emission from CXOM33 J013441.0+3043280 and XMM-Newton source 68 brings the total number of confirmed SNRs in M33 to 100. The total number of unique remnants with optical counterparts in both the Chandra and XMM-Newton observations is 37, nearly 1/3 of the total identified in the optical.

8. PROPERTIES OF OPTICAL SNRs DETECTED WITH CHANDRA AND XMM-NEWTON

Although there are insufficient counts in the spectra of the SNR candidates to obtain detailed information on these sources, we can at least explore correlations between the X-ray and optical observations and identify systematic trends that may reveal properties of the global SNR population in M33. As a first test, we searched for selection effects between the brightnesses of optically identified SNRs and the number of such remnants detected in the X-rays. Assuming that each SNR is of uniform optical surface brightness (an admittedly rough assumption), we calculated Hα fluxes for each object using the Hα surface...
brightnesses and physical sizes of SNRs listed in the GKL98 catalog. In Figure 10 we present a histogram showing the number of optical SNRs $N(S_{\text{H} \alpha})$ per $H\alpha$ flux interval $S_{\text{H} \alpha}$ (98 SNRs from GKL98), with the 22 GKL98 SNRs exhibiting X-ray emission marked separately for comparison. For completeness we have also marked the $H\alpha$ fluxes of optical SNRs detected by XMM-Newton.

It is clear from Figure 10 that the brightest optical SNRs in M33 are not preferentially detected in the Chandra observations. Rather, the greatest number of X-ray–detected SNRs are found where the greatest number of optical SNRs are found: at the optically faint end of the $N(S_{\text{H} \alpha})$ versus $S_{\text{H} \alpha}$ relation. This is markedly different from what is observed in SNR studies of other spirals such as M83 (Blair & Long 2004). Although M83 was observed with Chandra for a similar exposure time as M33 (50 ks), the greater distance of that galaxy resulted in an X-ray survey depth of $L_X(0.3–8.0 \text{ keV}) \geq 10^{36} \text{ ergs s}^{-1}$ (Soria & Wu 2003), nearly an order of magnitude shallower than the M33 observations. Blair & Long (2004) noted that this sensitivity-induced selection effect likely resulted in the detection of only the brightest X-ray SNRs in M83. Interestingly, Blair & Long (2004) stated that the systematic detection of the brightest optical SNRs as X-ray sources in M83 may also be due to the expansion of these remnants into denser than average regions. In that case, the lack of such a strong trend in M33 (say, for remnants with $S_{\text{H} \alpha} \geq 5 \times 10^{14} \text{ ergs cm}^{-2} \text{ s}^{-1}$, for which only 10 out of 32 optical remnants are detected in X-rays by Chandra and XMM-Newton) may be partially caused by expansion of the SNRs into regions of lower than average density.

Another relationship we can measure from the Chandra data is the cumulative luminosity distribution, $N(>L)$, of the M33 SNRs. Comparing this distribution with that of other extragalactic SNR populations observed in X-rays such as the LMC and SMC provides a comparative “snapshot” of each SNR sample. Since the derived luminosity depends upon the assumed spectral model, we have attempted to reduce the systematic differences in the tabulated luminosities of extragalactic SNR surveys by applying the same spectral model when converting from instrument-specific count rates to fluxes. Using both Chandra count rates from our M33 SNRs (Table 2) and count rates for the optically matched SNRs detected exclusively in the XMM-Newton observations of M33 (Pietsch et al. 2004), along with count rates for the LMC SNRs (46 sources from the ROSAT catalog of Sasaki et al. 2000) and count rates for the SMC SNRs (13 sources from the XMM-Newton survey of van der Heyden et al. 2004), we obtained luminosities in the range 0.35–8.0 keV for each SNR distribution. We used the PIMMS online tool of CXC for the calculations and assumed a Raymond-Smith model, $kT = 1 \text{ keV}$ and 0.2 solar abundances. We fixed the M33 column to the best-fit value for SNR 55 [$N_{\text{H}}(M33) = 7 \times 10^{20} \text{ cm}^{-2}$, as found in § 5.2] and used $N_{\text{H}}(\text{LMC}) = 2 \times 10^{20} \text{ cm}^{-2}$ (Heiles & Cleary 1979).

A comparison of the luminosity relations of the three SNR samples in Figure 11 reveals several interesting features. First, the 0.35–8.0 keV luminosity of the brightest GKL98 remnant detected by XMM-Newton, SNR 21, is quite high: $\sim 3 \times 10^{37} \text{ ergs s}^{-1}$ (in good agreement with the 0.1–2.4 keV value measured from ROSAT PSPC observations by Long et al. 1996). By comparison, the two young ejecta-dominated remnants E0102–72.3 in the SMC and N132D in the LMC exhibit luminosities $\sim 2 \times 10^{37}$ and $\sim 4 \times 10^{37} \text{ ergs s}^{-1}$, respectively. SNR 21 exhibits a large optical diameter (28 pc; GKL98) and features an optical spectrum dominated by emission from shocked interstellar gas (Smith et al. 1993). It is undoubtedly older and more evolved than the two brightest Magellanic Cloud remnants.

Another noticeable feature of Figure 11 is the clear luminosity separation between the M33, SMC, and LMC distributions. There appear to be fewer SNRs at the high-luminosity end of the M33 distribution ($>10^{36} \text{ ergs s}^{-1}$) than in the LMC: while there are a similar number of confirmed X-ray SNRs in M33 and the LMC with X-ray luminosities exceeding $10^{35} \text{ ergs s}^{-1}$, nearly 40% of the LMC SNRs are brighter than $10^{36} \text{ ergs s}^{-1}$, while only 13% of the M33 sample exceed this luminosity. The opposite trend is seen between M33 and the SMC, although the relatively smaller sample size of the SMC SNRs makes the comparison of its luminosity function to those of the LMC and M33 more uncertain. The offset in brightness between the M33 and Magellanic Cloud SNRs was also noted by Haberl & Pietsch (2001) in their ROSAT analysis of M33, although the larger sample of remnants in our comparison (35 remnants rather than 13) has filled in more of the low-luminosity population, reducing the contrast between the M33 and LMC distributions. However, the question remains: are the luminosity offsets between the three distributions real? The remnant-to-remnant luminosity differences are small enough ($\sim 2–5$) to be accounted for by uncertainties in temperature and column density; varying the temperatures from 0.5 to 3 keV causes a factor of 2 variation in the calculated luminosities, while varying the column densities over the full range allowed for each galaxy produces a factor of 3 variation in calculated luminosities. Allowing the abundances to range from 0.2 to 0.5 solar yields a 10% variation in luminosity. However, it is unlikely that variations in these three parameters would combine in just the right
proportion to systematically lower the luminosities of the brightest M33 SNRs to values below those of the brightest LMC SNRs. Likewise, it is also unlikely that the variations in emission parameters would systematically raise the M33 luminosity distribution above that of the SMC. 

Aside from intrinsic physical causes, another factor influencing the luminosity distributions is the relatively lower completeness of the M33 SNR sample compared with remnants in the SMC and LMC. Thus far we have discussed only the M33 SNRs with known optical counterparts, while the SMC and LMC samples include pure nonradiative SNRs. Clearly some of the optically invisible, soft X-ray sources detected in the Chandra observations of M33 may be nonradiative SNRs. If these remnants are merely unidentified, they could, in principle, be bright enough to fill in the high end of the M33 luminosity distribution. To test the potential influence of nonradiative SNRs on the M33 luminosity function, we note that of the 16 soft sources classified as SNRs by XMM-Newton purely from hardness ratios, two objects (sources 68 and 270) have been shown in this paper to exhibit optical emission. The remaining 14 objects are candidates for nonradiative SNRs, so in Figure 11 we have included a second histogram for M33 showing the luminosity distribution with these sources added in (a total of 51 SNRs and SNR candidates). Here we have computed the luminosities of the 14 X-ray SNR candidates using the same Raymond-Smith model parameters as the optically confirmed SNRs.

Comparing the luminosity functions of the optically confirmed SNRs (Fig. 11, solid red histogram) with those of the combined sample (dotted red histogram), it is clear that, aside from shifting the M33 distribution upward in $\log N(>L)$, the added X-ray SNR candidates do fill in some of the M33 distribution at high luminosities as expected, slightly reducing the slope of the distribution above $10^{36}$ ergs s$^{-1}$. (Now the fraction of M33 SNRs brighter than $10^{36}$ ergs s$^{-1}$ has increased from 13% to 22%.) However, there is still a conspicuous gap between the M33 and LMC distributions. We note that some of the XMM-Newton SNR candidates may be supersoft sources with spectra hardened enough by local absorption to mimic SNR emission. However, given the small number of supersoft sources detected in the XMM-Newton survey (5 objects out of a total of 408; Pietsch et al. 2004) it seems unlikely that the sample of XMM-Newton SNR candidates is significantly contaminated with heavily absorbed supersoft sources. Nevertheless, the danger remains that, in principle, some of the XMM-Newton candidates may be misclassified objects.

There is another selection effect introduced by the Chandra observations that further reduces the completeness of the M33 luminosity distribution. In our analysis we have not taken into account the effects of the decreasing sensitivity of Chandra with off-axis...
angle. As noted earlier, the broadening of the Chandra PSF away from the aim point raises the detection threshold for X-ray sources, resulting in a progressively incomplete luminosity distribution at farther off-axis angles (Kim & Fabbiano 2003). While this clearly reduces the number of SNRs at the faint end of the M33 distribution, it cannot account for the clear separation between the M33 and the LMC SNRs at high (\(\geq 10^{36}\) ergs s\(^{-1}\)) luminosities. The overall conclusion of our analysis is that, even allowing for uncertainties in spectral parameters and the incompleteness of the M33 supernova remnant sample, a real difference likely exists between the luminosity distributions of M33, the SMC, and the LMC.

The separations between the three distributions may reflect real physical differences. Haberl & Pietsch (2001) attributed the high luminosities of the LMC SNRs to the particularly high metallicity of the ISM in the LMC. By that line of reasoning, the progressively fainter luminosity distributions of M33 and the SMC may be caused by progressively lower metallicities in those galaxies. Previous measurements of interstellar abundances in the three galaxies are consistent with this interpretation: the 0.4 solar abundances estimated from spectra of the optical SNRs in M33 (Blair & Kirshner 1985) lie between the 0.2 and 0.5 solar abundances measured by Russell & Dopita (1992) for the SMC and LMC, respectively. However, as mentioned earlier, abundance changes in the context of our assumed model are not sufficient to explain the luminosity offsets seen in Figure 11. Other factors such as differences in average ISM density and explosion energy may also play a role in separating the three luminosity distributions, but a full exploration of these effects is beyond the scope of this paper.

9. SUMMARY

We have performed the first systematic search for Chandra X-ray counterparts to optically identified SNRs in M33. Aside from matching X-ray sources with known optical SNRs, we have also attempted to use soft sources detected by Chandra to find optical counterparts missed by earlier narrowband imagery of M33. Our search was performed using Chandra archival images of M33 and narrowband H \(\alpha\) and [S ii] KPNO Mosaic images from the NOAO archive. Our results are as follows:

1. We have found 22 X-ray counterparts to known optical SNRs from the GKL98 catalog. These X-ray sources exhibit soft spectra characteristic of thermal emission from shock-excited gas. Comparing the Chandra images of the SNR candidates with simulated images of point sources, we have concluded that at least four of the SNR candidates exhibit an extended morphology.

2. One soft X-ray source in the Chandra data exhibits no optical emission but matches a radio source with a steep spectral index suggestive of particle acceleration in shocks. We propose that this source may be a young nonradiative SNR, similar to SN 1006 in the Milky Way.

3. Compared to the optical/X-ray survey of the more distant galaxy M83 (5 Mpc), we find no evidence that the brightest optical SNRs are preferentially detected in X-rays. This is likely due to a combination of higher completeness of the M33 survey caused by the close proximity of that galaxy and a lower average ISM density in M33.

4. We have searched the KPNO Mosaic images for optical counterparts to both soft Chandra sources and objects identified by Pietsch et al. (2004) as potential SNRs on the basis of XMM-Newton hardness ratios. In the Chandra data we find a positional coincidence between one soft source (matching object 270 from the XMM-Newton catalog of Pietsch et al. 2004) and a knot of optical emission. The knot exhibits a [S ii]/H\(\alpha\) ratio of 0.7–0.8, strongly suggesting that the emission from this object is produced in radiative shocks. In addition, we find a positional coincidence between one XMM-Newton SNR candidate (object 68 from the XMM-Newton catalog) and a prominent optical shell approximately 9\(^{\prime}\) across. The [S ii]/H\(\alpha\) ratio of this shell varies from 0.6 to 0.8, indicating that, like source 270, the emission from this object is produced in radiative shocks. Follow-up optical spectroscopy will be required to confirm the high [S ii]/H\(\alpha\) ratios of the two newly confirmed SNRs. However, we are fairly confident that the number of optically emitting SNRs in M33 is now 100. The total number of soft X-ray sources matching optically known SNRs, including those found in the XMM-Newton survey of M33 (Pietsch et al. 2003, 2004), is 37 objects. Nearly 1/3 of the optical SNRs in M33 are now known to have X-ray counterparts.

5. We find that there are fewer confirmed, bright SNRs (\(\geq 10^{36}\) ergs s\(^{-1}\)) in M33 than in the LMC. The opposite trend is seen when comparing the M33 and SMC distributions. This feature may partly reflect differences in interstellar abundances between the three galaxies. However, abundance differences do not fully account for the luminosity separation between M33 and the LMC. While adding X-ray SNR candidates (i.e., objects lacking obvious optical counterparts) from the XMM-Newton survey to the M33 luminosity distribution increases the total number of SNRs at all luminosities and reduces the slope of the M33 distribution at the highest luminosities, the significant separation between the M33 and LMC luminosity functions persists. A full explanation of this trend awaits future investigation.

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