# REVEALING THE SUPERNOVA REMNANTS OF M33 WITH *CHANDRA* AND *XMM-NEWTON*

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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]/Halpha ratios in the optical, and (2) radio spectral indices. Of the 98 optically known SNRs in M33, 22 have been detected at $> 3\sigma$ level in the soft band (0.35-1.1 keV). At least four of these SNR candidates are spatially extended. We have also found new optical counterparts to two soft X-ray SNRs in M33, tentatively increasing the total number of known optically emitting SNRs in M33 to 100. The total number of identified SNRs with X-ray counterparts, including those exclusively detected by the XMM-Newton survey of M33, is now 37. 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 $10^{35}$ ergs s$^{-1}$, nearly 40% of the LMC SNRs are brighter than $10^{35}$ ergs s$^{-1}$, while only 13% of the M33 SNRs exceed this luminosity. The differences in luminosity distributions cannot be fully explained by uncertainty in spectral model parameters, and is not fully accounted for by abundance differences between the galaxies.

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

## 1. INTRODUCTION

Due to the low inclination ($<$ 55 degrees) and proximity (795 kpc) of M33, a detailed study of the the X-ray source population of this galaxy is particularly rewarding. Here we present results of a search for supernova remnants (SNRs) in archival *Chandra* and *XMM-Newton* images of this galaxy, utilizing spatial extent and hardness ratios as discriminants. We compare the list of *Chandra* and *XMM-Newton* X-ray sources with narrowband KPNO Mosaic images from the NOAO archive (Massey et al. 2002) to search for new optical SNRs at the positions of soft X-ray sources. Drawing together both SNRs with optical counterparts and SNR candidates lacking optical counterparts, we have generated an X-ray luminosity distribution for the M33 SNRs. Here we present a characterization of the X-ray spectral properties of this distribution and compare it to those of the SMC and LMC. A full description of this work can be found in Ghavamian et al. (2005).

## 2. OBSERVATIONS

The *Chandra* datasets analyzed here were acquired during Cycle 1 (ObsID 786 in ACIS-S imaging mode, ObsID 1730 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, while the Cycle 2 pointing was aimed at NGC 604, the giant starburst H II region along the northern spiral arm. Using CIAO version 3.0.2, we applied the CXC CTI correction to the level 1 event files and screened the data to remove background flare events and restrict the energy range of the resulting images to 0.35−8 keV. The final exposure times for the ObsID 786, 1730 and 2023 datasets were 46.3 ks, 49.4 ks and 88.8 ks, respectively.

### 2.1. X-ray Source Detection

We used the CIAO routine Wavdetect to search for X-ray sources in the *Chandra* data. We optimized our search for spatially extended X-ray emission from SNRs by conducting our Wavdetect runs on spatial scales of $0.''5$, $1''$, $2''$, $4''$, $8''$, $16''$, $32''$ and $64''$. We filtered each events file to create images in each of the following bands: 0.35−1.1 keV (S, or soft), 1.1−2.6 keV (M, or medium), 2.6−8.0 keV (H, or hard) and 0.35−8.0 keV (broad). The number of unique sources detected in the broad band images of ObsIDs 786, 1730 and 2023 was 166 (207) at the $3\sigma$ ($2\sigma$) level. We compared the list of

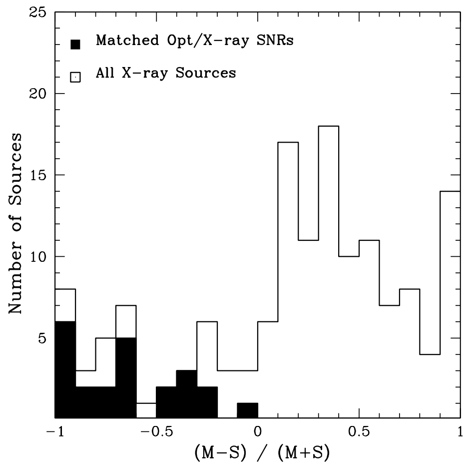


*Figure 1. Hardness ratios for the 166 sources detected in the Chandra observations of M33, where S and M are defined as emission in the 0.35−1.1 keV and 1.1−2.6 keV range, respectively. The hardness ratios of soft Chandra sources matching the 22 Gordon et al. (1998) SNRs are shown for comparison (a 23rd source lacking an optical counterpart but exhibiting soft X-ray emission characteristic of a SNR is also included).*

X-ray sources with the catalogue of M33 SNRs identified optically by Gordon et al. (1998) by their elevated [S II]/H$\alpha$ line ratios ($\geq 0.4$). We performed the cross-correlation in two steps. First, we obtained a culled list of sources in all three bands that matched the coordinates of Gordon et al. (1998) SNRs to within a generous coincidence radius of 20$''$. Next, we looked for secondary signs of a match, such as evidence of extended morphology. 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.

## 3. SUPERNOVA REMNANTS DETECTED WITH *CHANDRA* AND *XMM-NEWTON*

Of the detected X-ray sources in the archival data, we find that 22 match optical SNRs from the optical catalogue at $\geq 3\sigma$ level in the S band (**Fig.** 1). In their *XMM-Newton* survey of M33, Pietsch et al. (2004) found X-ray counterparts to 13 additional optical SNRs not detected in the *Chandra* observations. These remnants are either intrinsically too faint to be detected in the given exposure times, are located too far off the *Chandra* optical axis (rendered undetectable by smearing of the PSF and/or high detector background), or are located outside the *Chandra* field of view. However, the *XMM-Newton* survey also identified 13 additional soft X-ray sources lacking optical counterparts as SNR candidates, based on their hardness ratios. We were able to identify optical counterparts to two of these sources in the KPNO Mosaic images.

Another relationship we can measure from the *Chandra* data is the cumulative luminosity distribution, $N(>L)$, of the M33 SNRs in the X-rays. We utilized the PIMMS online tool of the Chandra X-ray Center for the calculations and assumed a Raymond-Smith model, $kT = 1$ keV and 0.2 solar abundances. We fixed the M33 column to be $N_H$(M33) = $7\times10^{20}$ cm$^{-2}$, the best fit value for the brightest SNR detected in the *Chandra* observations. We used $N_H$(LMC) = $N_H$(SMC) = $2\times10^{20}$ cm$^{-2}$. The Galactic column used for all three galaxies was $N_H$(Gal) = $5\times10^{20}$ cm$^{-2}$. The assumed distances to M33, the LMC and SMC were 795, 50 and 60 kpc, respectively. 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 $10^{35}$ ergs s$^{-1}$, nearly 40% of the LMC SNRs are brighter than $10^{36}$ ergs s$^{-1}$, while only 13% of the M33 sample exceed this luminosity. Including X-ray SNR candidates from the *XMM-Newton* survey increases the fraction of M33 SNRs brighter than $10^{36}$ ergs 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 is not fully accounted for by abundance differences between the galaxies. An explanation for this result is a focus of our ongoing investigation.

## 4. A DEEP *CHANDRA* SURVEY OF M33

The work outlined here is a prelude to a much more detailed investigation of M33 planned for Cycle 7 of *Chandra* . Our group (M. Sasaki, P.I.) has been awarded 1.4 Ms observing time to perform a survey of the entire galaxy with $\leq 1''$ resolution (*Chandra* ACIS-I Survey of M33: ChASeM33) down to a luminosity of $5\times10^{34}$ ergs s$^{-1}$ for point sources and $10^{35}$ ergs s$^{-1}$ for diffuse sources. The rich data set from this survey, together with what promises to be an iconic image, will be part of the legacy of *Chandra* .

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