PROPERTIES OF OPTICALLY SELECTED supernova remnant candidates in M33

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ABSTRACT

Narrowband images covering strong emission lines are efficient for surveying supernova remnants (SNRs) in nearby galaxies. Using the narrowband images provided by the Local Group Galaxy Survey, we searched for SNRs in M33. Culling the objects with enhanced $[S\,ii]/H\alpha$ and round morphology in the continuum-subtracted $H\alpha$ and $[S\,ii]$ images, we produced a list of 199 sources. Among them, 79 are previously unknown. Their progenitor and morphology types were classified. A majority of the sample (170 objects) are likely remnants of core-collapse supernovae (SNe), and 29 are remnants of Type Ia SNe. The cumulative size distribution of these objects is found to be similar to that of the M31 remnants derived in a similar way. We obtain a power-law slope, $\alpha = 2.38 \pm 0.05$. Thus, a majority of the sources are considered to be in the Sedov–Taylor phase, consistent with previous findings. The histogram of the emission-line ratio ($[S\,ii]/H\alpha$) of the remnants has two concentrations at $[S\,ii]/H\alpha \sim 0.55$ and $\sim 0.8$, as in M31. Interestingly, $L_X$ (and $L_{20\,cm}$) of the compact center-bright objects are correlated with their optical luminosity. The remnants with X-ray emission have brighter optical surface brightnesses and smaller diameters than those without X-ray emission.

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

Online-only material: color figures, machine-readable table

1. INTRODUCTION

Supernova remnants (SNRs) are a unique resource that enables us to investigate the final stage of the evolution of massive stars or binary stars interacting with the surrounding interstellar medium (ISM). Studies of individual SNRs in the Milky Way (MW) are important for understanding the detailed interaction between SNRs and the ISM. However, determining the global properties of the MW SNRs is difficult because of uncertain distances to individual remnants and high extinction in the Galactic plane where most of the SNRs are found. Extragalactic SNRs do not suffer from these problems, so they are an ideal target for investigating statistically their global properties and evolution as well as their relationship to the ISM. They provide a clue to understanding the star formation history and chemical evolution of galaxies.

Extragalactic SNRs have been identified mostly at three bands: optical, radio, and X-ray wavelengths. A majority of the known SNRs in nearby galaxies were detected by optical surveys (Magnier et al. 1995; Matonick & Fesen 1997; Matonick et al. 1997; Pannuti et al. 2002; Blair & Long 2004; Sonbas et al. 2009; Dopita et al. 2010; Franchetti et al. 2012; Blair et al. 2012; Leonidaki et al. 2013). We have been carrying out a project to detect SNRs in nearby galaxies. We presented a result of the first target, M31 (Lee et al. 2014, henceforth L14). This paper is the second of the series, presenting the results for M33. M33 is an ideal galaxy for SNR surveys, because it is nearby ($\sim 800$ kpc; Lee et al. 2002), relatively face-on ($i = 56^\circ$; Regan & Vogel 1994), and is a late-type spiral (SA(s)cd) galaxy.

Dodorico et al. (1978) first detected three SNRs using optical images in M33. Subsequent optical studies have increased the number of M33 SNRs to 137 (Long et al. 2010, henceforth L10). Long et al. (1990) showed the cumulative size distribution (CSD) of 50 SNRs in M33. It follows a power law, with an index $\alpha = 2.1$. They estimated the supernova (SN) rate to be one per 26–300 yr from the number of SNRs. Gordon et al. (1998, henceforth G98) identified 98 SNRs, of which 53 are previously unknown. They presented a CSD for the 98 SNRs and showed that the Sedov–Taylor (ST) expansion model is a better fit to the distribution than the free expansion model. The ST expansion model is used to derive the SN rate in M33 as one SN every 360 yr. However, they used narrow images obtained under poor seeing, ranging from 2′′ to 2′′4 (which corresponds to 8–10 pc at the distance of M33). They could not measure an accurate size of the SNRs and could not distinguish SNRs on the outskirts of star forming (SF) regions.

L10 presented a list of 137 SNRs derived from two emission-line surveys using Local Group Galaxy Survey (LGGS) data taken at the KPNO 4 m telescope (Massey et al. 2006, 2007) and observational data obtained from the 0.6 m Burrell Schmidt telescope at KPNO. They showed that 82 of 137 SNRs are matched with X-ray objects derived from the ChASeM33 survey using Chandra. However, they missed a significant fraction of SNRs with low optical surface brightness (SB) ($<10^{-16}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$). They mainly discussed X-ray properties of the SNRs in M33. Recently, Asvarov (2014) estimated the SN rate of M33 to be one SN every 140–150 yr using X-ray data of the M33 SNRs and physical models at various conditions of the ambient ISM.

Thus, we carry out a new optical search of SNRs in M33 utilizing the images taken in the LGGS. Using these data, we find new M33 remnants, especially those with low SB, concentrating on their optical properties.

2. DATA REDUCTION

2.1. Identification Method

We utilized the $H\alpha$ and $[S\,ii]$ images in the LGGS to find new M33 remnants. The LGGS covered three 36′ square fields of M33. We subtracted continuum sources from the narrowband images using $R$-band images. We smoothed the images with better seeing to match the point-spread function in the images.
with worse seeing, using the IRAF task *psfmatch*. We then scaled and subtracted the resulting continuum images from narrowband images.

We selected M33 remnants considering three criteria: emission-line ratio ([S\textsc{ii}]/H\textalpha), the morphological structure, and the absence of blue stars inside the sources, as was done for M31 in L14. Details are described in L14. We detected objects with [S\textsc{ii}]/H\textalpha > 0.4 in emission-line ratio maps, and selected objects with round or shell structures in each narrowband image. As a result, we chose 435 sources.

We estimated an integrated emission-line ratio (i.e., the ratio of integrated [S\textsc{ii}]/H\textalpha fluxes) for individual remnants to select the genuine SNRs among these candidates. We set an approximate circular region to cover the region with [S\textsc{ii}]/H\textalpha > 0.4 in emission-line ratio ([S\textsc{ii}]/H\textalpha) maps, and carried out aperture photometry of these sources. We determined the value of the local background for individual remnants, using a 100 pc × 100 pc box region that shows no emission near the SNR candidate. We selected objects that have integrated [S\textsc{ii}]/H\textalpha > 0.4. In the cases of objects with 0.4 < [S\textsc{ii}]/H\textalpha < 0.6, we examined the existence of blue stars inside the remnants. We excluded the sources with blue stars. Then, we removed objects larger than 100 pc, which are too big to be SNRs. Finally, we considered 199 objects to be probable SNRs, including 79 new ones.

L10 provided a catalog of 137 sources based on optical and X-ray data. We examined these objects according to our identification criteria and considered 17 of these objects to be non-SNRs, such as H\textsc{ii} regions or superbubbles. Of these, seven objects do not appear to have high enough [S\textsc{ii}]/H\textalpha to be cataloged as SNR candidates, and they are likely H\textsc{ii} regions. Nine objects have sizes with D > 100 pc and embed many blue stars inside, so we considered them to be superbubbles. L10 also suggested that these objects are possible superbubbles. One object (L10-35) is an oxygen-dominated SNR with little emission in H\textalpha and [S\textsc{ii}] (L10). Table 1 lists the 17 objects excluded according to our criteria. Consequently, we confirmed that 120 of the 137 known objects satisfy our identification criteria.

Figure 1 compares (a) L(H\textalpha), (b) D, (c) SB(H\textalpha), and (d) [S\textsc{ii}]/H\textalpha of the remnants in this work and L10. The two measurements for each physical quantity of the objects are correlated well. We fit the data with linear least-squares fitting, obtaining (a) log L(H\textalpha)(this work) = 0.94(±0.03) × log L(H\textalpha)(L10) + 2.12(±1.06) erg s\(^{-1}\), (b) D(this work) = 1.05(±0.05) × D(L10) − 3.11(±1.94) pc, (c) log SB(H\textalpha)(this work) = 1.20(±0.10) × log SB (H\textalpha)(L10) − 0.11(±0.07) erg cm\(^{-2}\) s\(^{-1}\) arcsec\(^{-2}\), and (d) [S\textsc{ii}]/H\textalpha (this work) = 1.19(±0.06) × [S\textsc{ii}]/H\textalpha (L10) + 3.07(±0.89).

We estimated the diameters of the circles covering the region with [S\textsc{ii}]/H\textalpha > 0.4 in the emission-line ([S\textsc{ii}]/H\textalpha) images. In the case of objects with partial shells, we determined their sizes on the basis of the visible portion of the shells. The errors in the size measurements are about 0.5 for small objects (D = 10 ~ 50 pc) and about 1" for larger objects (D > 50 pc). L10 determined ellipsoidal regions that best traced optical shells of remnants, and they defined the geometric mean of the major and minor axes of the above ellipses as the sizes of the sources. They expanded the sizes slightly in a few cases to embrace the X-ray emission that is apparently associated with the SNR. Their errors in measuring the diameter are 0.05 for small objects (< 5 for small objects (< 0.10). In Figure 1(b), we compared the diameters of the remnants in this work and L10. They agree well in general. About 10 objects show differences larger than 10 pc. We checked the images of these objects, and confirmed that our measurements are reasonable. The mean difference (D = 10–40 pc) is derived to be 1.7 pc, showing that our measurements are on average slightly larger than L10's.

### Table 1

A List of Previous M33 SNR Candidates Excluded in This Work

| Name   | R.A. (J2000.0)\(^{a}\) | Decl. (J2000.0)\(^{a}\) | log L(H\textalpha)\(^{b}\) (erg s\(^{-1}\)) | log L([S\textsc{ii}]/H\textalpha)\(^{b}\) (erg s\(^{-1}\)) | D\(^{c}\) (pc) | [S\textsc{ii}]/H\textalpha | Class\(^{d}\) |
|--------|------------------------|------------------------|--------------------------------------|--------------------------------------|----------------|----------------|-------------|
| L10-1  | 23.1162779             | 30.462805              | 37.02                                 | 37.01                                 | 136            | 0.98           | S           |
| L10-5  | 23.1772499             | 30.349584              | 36.77                                 | 36.58                                 | 98             | 0.64           | S           |
| L10-12 | 23.2502728             | 30.512455              | 37.49                                 | 37.07                                 | 62             | 0.38           | H           |
| L10-19 | 23.2814598             | 30.714882              | 36.66                                 | 36.21                                 | 74             | 0.35           | H           |
| L10-28 | 23.3278923             | 30.451220              | 37.10                                 | 36.84                                 | 158            | 0.55           | S           |
| L10-35 | 23.3708439             | 30.795719              | 35.52                                 | 34.65                                 | 18             | 0.13           |             |
| L10-43 | 23.3974609             | 30.708994              | 37.28                                 | 36.72                                 | 80             | 0.28           | H           |
| L10-50 | 23.4197102             | 30.709921              | 37.06                                 | 36.84                                 | 100            | 0.60           | S           |
| L10-68 | 23.4672909             | 30.942835              | 36.93                                 | 36.65                                 | 112            | 0.52           | S           |
| L10-70 | 23.4922905             | 30.810335              | 37.14                                 | 36.61                                 | 80             | 0.29           | H           |
| L10-98 | 23.55298697            | 30.586670              | 36.61                                 | 36.10                                 | 62             | 0.31           | H           |
| L10-122| 23.6327095             | 30.944935              | 36.94                                 | 36.87                                 | 126            | 0.85           | S           |
| L10-131| 23.6745396             | 30.626440              | 36.87                                 | 36.52                                 | 156            | 0.45           | S           |
| L10-132| 23.6857471             | 30.710779              | 36.39                                 | 35.86                                 | 50             | 0.29           | H           |
| L10-133| 23.7286701             | 30.688061              | 36.94                                 | 36.48                                 | 72             | 0.35           | H           |
| L10-136| 23.7550793             | 30.638155              | 36.65                                 | 36.27                                 | 124            | 0.42           | S           |
| L10-137| 23.7652504             | 30.619529              | 36.61                                 | 36.53                                 | 124            | 0.83           | S           |

**Notes.**

\(^{a}\) Measured in the H\textalpha image.

\(^{b}\) Derived using \(L = 4\pi d^2 \times \text{flux adopting } d = 800 \text{ kpc}.\)

\(^{c}\) Size derived using \(1" = 3.88 \text{ pc}.\)

\(^{d}\) H\textsc{ii} regions with [S\textsc{ii}]/H\textalpha < 0.4, and blue stars inside; S: superbubbles (larger than \(D = 100 \text{ pc}\) and a number of blue stars inside).

An oxygen-dominated SNR with little emission in H\textalpha and [S\textsc{ii}] (L10).

(This table is also available in a machine-readable form in the online journal.)
samples in M33 show resolved morphological structure at the resolution of the Hα images we use. Even in relatively confused regions on the outskirts of H II regions and SF regions, the objects are resolved well. Thus, we classified 199 sources in M33 according to their shape as well as environments. Table 2 summarizes our criteria used for the classification. Figure 2 displays some examples of the remnants for individual morphological categories. The majority of A2-class remnants have brighter SB than other types, as shown in Figures 3(a) and (b). The majority of B2-class remnants are embedded in SF regions. Their SB is brighter compared with the other B-class objects, as displayed in Figures 3(c) and (d).

3. RESULTS

3.1. A List of M33 Remnants

By applying the SNR search method described in the previous section, we detected a total of 199 sources. Among these, there are 79 new objects detected in this work and 120 known ones in the catalogs of previous studies (G98 and L10). Table 3 presents a list of the 199 sources. In the table, the columns give the ID number, the coordinates in right ascension and declination (J2000.0), L, D, [SII]/Hα, morphological types, N(OB), and progenitor types. The last column in Table 3 gives the identification matched with the catalog of L10.

Of the sample, 170 objects are more likely to be from CC SNe, with the remainder more likely to be from Type Ia SNe. M33 has flocculent spiral arms, so a significant fraction of its disk is occupied by SF regions. Therefore, the Type Ia remnants located in the disk are likely to be classified as CC remnants, according to our classification criteria, and the 170 sources classified as CC would be an overestimate. If the number density of Type Ia remnants is uniform, about 10% of the CC remnants may be Type Ia remnants. There are a few results for the relative ratio of two categories of remnants (Chu & Kennicutt 1988; Franchetti et al. 2012; L14). According to the study of 32 objects in the LMC by Chu & Kennicutt (1988), more than 60% of them are CC remnants. Franchetti et al. (2012) and L14 also inspected the stellar population around remnants in M101 and M31, respectively. They showed that ∼25% (9 of 34) and ∼27% (42 of 156) are more likely to be Type Ia remnants, respectively. A fraction (∼17%) of the Type Ia SNR remnants for M33 in this work are smaller than those for M101 and M31.

The majority of A-class and B-class objects are CC SNRs (∼85% for each). In the cases of the A3-class (∼31%) and B3-class (∼39%) objects, the Type Ia proportions are high compared with those of objects of different morphological categories. L14 showed that ∼85% of M31 remnants are classified as shell remnants and ∼15% are center-bright remnants. The majority (∼90%) of the M33 remnants are also shell remnants. It is noted that the proportions of the shell remnants and center-bright remnants in the MW at radio wavelengths are 78% and 4%, with the rest being composite-type remnants (Green 2009).

3.2. Spatial Distribution

Massive stars (which explode as CC SNe) tend to be found near SF regions such as H II regions, molecular clouds, and spiral arms, while evolved, lower mass stars (which explode as Type Ia SNe) are expected to be distributed in a more random manner across the plane of a galaxy’s disk. Below, we examined the distributions of remnants relative to spiral arms, as well as the radial distributions of their number density. The positions of the M33 remnants are displayed in Figure 4. The background
Figure 2. Samples of M33 remnants with different morphological categories. Sizes of the objects are marked by circles. An individual image covers 64′′ × 64′′ (251 pc × 251 pc). North is up, and east to the left.

(A color version of this figure is available in the online journal.)

Table 2

| Type | Number a | \(L(\text{H}\alpha)\)  | \(L([\text{S}II])\)  | \(D\)  | \([\text{S}II]/\text{H}\alpha\)  | Environment  | Description  |
|------|----------|------------------------|------------------------|-------|------------------------|---------------|--------------|
| A1   | 41(5)    | Moderate  | Moderate   | Moderate | High  | Isolated  | Complete shells  |
| A2   | 19(0)    | High      | High       | Small    | High  | Isolated  | Center-bright remnants  |
| A3   | 29(9)    | Low       | Low        | Small    | Low   | Isolated  | Diffuse and extended shells  |
| B1   | 36(3)    | Moderate  | Moderate   | Moderate | High  | Isolated  | Partial shells  |
| B2   | 24(0)    | High      | High       | Moderate | Low   | Confused  | Bright partial shells  |
| B3   | 28(11)   | Low       | Moderate   | Large    | High  | Isolated  | Diffuse partial shells  |
| C b  | 21(1)    | …         | …          | …        | …     | …         | …  |

Notes.

a Values in parentheses represent numbers of Type Ia remnants.
b Ambiguous objects, excluding A-class and B-class remnants.

The radial number density profile for the M33 remnants is seen in Figure 5. We derived the deprojected galactocentric distance (\(R\)) adopting a position angle 22.5° (Paturel et al. 2003) and an inclination angle 56° (Regan & Vogel 1994). The radial image (Spitzer 24 μm) exhibits the SF regions along the arms. The CC remnants are mainly distributed along the spiral arms. In contrast, the majority of the Type Ia remnants are located in the outer part of M33.
number density profile of all the objects decreases slightly outward with an abrupt break near $R = 4$ kpc. Discernible concentrations are seen at $R \sim 2$ kpc and $\sim 3.5$ kpc, and a much weaker concentration is seen at $R \sim 5$ kpc. The histogram of the A-class remnants shows discernible concentrations at the $R \sim 2$ kpc and $\sim 3.5$ kpc, and the number density decreases slightly outward. On the other hand, the distribution of the B-class remnants decreases more smoothly.

We investigated the radial variation in physical properties of all the remnants in Figure 6: (a) $L(\text{H}$α$)$, (b) $L(\text{[S} ii\text{]})$, (c) $D$, (d) SB(\text{H}$α$)$, and (e) SB(\text{[S} ii\text{]}). The $L(\text{H}$α$)$ and $L(\text{[S} ii\text{]})$ of the objects change little at $R < 3.5$ kpc. In the outer region ($R > 3.5$ kpc), $L(\text{H}$α$)$ and $L(\text{[S} ii\text{]})$ of the objects decrease slightly outward. In the same range of $R$, $D$ increases from 40 pc to 50 pc. Thus, the radial gradients of SB(\text{H}$α$) and SB(\text{[S} ii\text{]}) are seen in Figures 6(d) and (e). This might be caused by the selection bias in our SNR survey. We could find the remnants with larger $D$ and lower SB easily in the outer region of a galaxy.

### 3.3. Size Distribution

The evolution of SNRs has been the subject of many theoretical studies (Woltjer 1972; Blondin et al. 1998; Truelove & McKee 1999). Some previous studies tried to explain observational data in theoretical aspects (Mathewson et al. 1983; Green 1984; Badenes et al. 2010, henceforth B10; Dopita et al. 2010). Their evolution is described in terms of age. However, it is hard to determine observationally the age of the SNRs. Thus, their sizes are used as a proxy for age. The differential size distributions of the M33 remnants are shown in Figure 7(a). Their

![Histograms of SB(H$α$) (left panel) and SB([S ii]) (right panel) of M33 remnants with different morphological categories.](image)

(A color version of this figure is available in the online journal.)

### Table 3

| ID | R.A. (J2000.0)$^a$ | Decl. (J2000.0)$^a$ | log $L(\text{H}$α$)$/$L(\text{[S} ii\text{]})$ | $D$ (pc) | [$\text{[S} ii\text{]}$/H$\alpha$] | Morphology Type | N(\text{OB})$^d$ | Progenitor Type | Comments |
|----|------------------|------------------|-----------------|---------|-----------------|-----------------|-------------|-------------|----------|
| 1  | 23.1074047       | 30.501122        | 36.16           | 81      | 0.74            | B3             | 4           | CC          |          |
| 2  | 23.1160583       | 30.59718         | 36.05           | 72      | 0.98            | B3             | 6           | CC          |          |
| 3  | 23.1306095       | 30.592470        | 36.02           | 28      | 0.59            | C              | 18          | CC          | L10-2    |
| 4  | 23.1473484       | 30.588837        | 36.36           | 85      | 0.50            | A3             | 2           | CC          |          |
| 5  | 23.1548519       | 30.298412        | 36.15           | 85      | 0.60            | B3             | 0           | Ia          |          |
| 6  | 23.1657581       | 30.465267        | 35.36           | 36      | 0.93            | B3             | 3           | CC          |          |
| 7  | 23.1676331       | 30.272575        | 35.65           | 44      | 0.52            | A3             | 1           | Ia          |          |
| 8  | 23.1694889       | 30.275404        | 35.36           | 42      | 0.79            | A3             | 1           | Ia          |          |
| 9  | 23.1705875       | 30.530849        | 36.36           | 86      | 0.51            | A3             | 1           | Ia          |          |
| 10 | 23.1779709       | 30.605574        | 36.07           | 58      | 0.49            | B              | 17          | CC          |          |

Notes:

$^a$ Measured in the H$\alpha$ image.

$^b$ Derived using $L = 4\pi d^2 \times \text{flux adopting } d = 800$ kpc.

$^c$ Size derived using $1'' = 3.88$ pc.

$^d$ Numbers of OB stars within 100 pc from the center of individual remnants.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Figure 4. Positions of Type Ia and CC remnants in M33 plotted over the grayscale map of the Spitzer MIPS 24 μm image. Dashed line ellipses represent 2, 4, and 6 kpc from the center. (A color version of this figure is available in the online journal.)

Figure 5. Number density vs. galactocentric distance of all, A-class, and B-class remnants in M33. (A color version of this figure is available in the online journal.)

diameters range from 10 pc to 100 pc. The histogram shows a noticeable concentration at $D \sim 45$ pc, with a broad wing toward larger sizes. A discernible concentration at the same value is seen in the histogram of the CC remnants. On the other hand, no distinguishable concentration is shown in the histogram of the Type Ia remnants. The majority of the objects smaller than $D = 30$ pc are CC remnants. The mean diameter of Type Ia remnants is larger than that of the CC remnants. This means that a majority of the CC remnants may lie on denser ambient ISM than the Type Ia remnants.

The CSD of SNRs in a galaxy is useful for studying their evolutionary phases. Their evolution is generally described by a three-phase model: the free expansion phase, the ST phase, and the radiative phase (Woltjer 1972; McKee & Ostriker 1977; Dopita & Sutherland 2003; Draine 2011). We consider that the shapes of the CSD are different, depending on the evolution phase. If the SN rate in a galaxy is constant, the CSD of SNRs becomes steeper as SNRs evolve. During the free expansion phase, it will increase linearly, $N(<D) \propto D$. The power-law index will be 2 for the ST phase and 3.5 for the radiative phase. Thus, a study of the CSD of SNRs in a galaxy is important to understand the evolution of SNRs. The transition sizes between these three phases are supposed to depend on several parameters, including the density of surrounding ISM, mass of ejected material, and energy released by SNe (Blondin et al. 1998; Truelove & McKee 1999). The transition radius from the free expansion phase to the ST phase ranges from 1 to 10 pc, and that from ST to the radiative phase is about 25 pc.

The CSD of the M33 remnants is seen in Figure 7(b). It follows a power-law form ($N(<D) \propto D^{\alpha}$). The power-law index is $\alpha = 2.38 \pm 0.05$ ($D = 17-50$ pc). The majority of the remnants are considered to be in the ST phase. Their number decreases abruptly at $D = 17$ pc as the size of the objects decreases. There are only a few sources that have sizes of $D = 10-17$ pc. The slope of the CSD of SNRs at $D > 50$ pc is flatter compared with that of smaller SNRs. This indicates two possibilities. First, the flatter slope may be due to incompleteness. We might have missed a significant number of SNRs that have large $D$ and low SB in the inner regions of the galaxy. Second, this may correspond to the transition stage from the ST phase to the radiative phase. B10 suggested that the majority of the objects are in the ST phase, and that they rapidly fade away below the detection limit once they transition to the radiative phase. The slope for the CC remnants.
is \( \alpha = 2.27 \pm 0.05 \) (\( D = 17–50 \) pc), but that for the Type Ia remnants is \( \alpha = 3.26 \pm 0.12 \) (\( D = 40–60 \) pc).

In Figures 8(a) and (b), we plot the size histograms of the objects with different morphological categories. The histogram of the A-class remnants shows two concentrations at \( D \sim 40 \) pc and \( \sim 60 \) pc, whereas that of the B-class remnants shows a broad concentration at \( D \sim 50 \) pc. The diameter of the A-class remnants is, on average, \( D \sim 45 \) pc, which is smaller than that of the B-class remnants, \( D \sim 54 \) pc. In Figure 8(b), the CSDs of the A-class and B-class remnants have close slopes up to 50 pc. The slopes for the A-class and B-class remnants are \( \alpha = 2.44 \pm 0.07 \) (\( D = 17–50 \) pc) and \( \alpha = 2.61 \pm 0.08 \) for the same range, respectively. This means that the size evolution of SNRs may not depend on their morphological category.

3.4. \([\text{SII}]/\text{H\alpha}\) Distribution

We derived the emission-line ratio (\([\text{SII}]/\text{H\alpha}\)) to identify SNR candidates. Objects with \([\text{SII}]/\text{H\alpha} > 0.4\) were considered SNRs in our survey. The histograms of the emission-line ratio (\([\text{SII}]/\text{H\alpha}\)) for the sources with different progenitor categories are shown in Figure 9(a). All the objects have \([\text{SII}]/\text{H\alpha}\) of 0.4–1.2, and their distribution is bimodal, with concentrations at \([\text{SII}]/\text{H\alpha} \sim 0.55\) and \( \sim 0.8\). The histograms for different morphological categories in Figures 9(b) and (c) are roughly divided into two sets at the boundary of \([\text{SII}]/\text{H\alpha} \sim 0.7\). Most of the A1-class, A2-class, B1-class, and B3-class remnants have elevated \([\text{SII}]/\text{H\alpha}\), whereas most of the A3-class and B2-class remnants have low \([\text{SII}]/\text{H\alpha}\). The A3-class remnants have low SB and smooth shapes. One may suggest that they should be
diffuse ionized gas with large \( D \) and low SB. Because their mean diameter is \( D \sim 50 \) pc, we consider the objects to be bona fide SNRs. The B2-class remnants with high \( L(\text{H}\alpha) \) and low \([\text{S}\ II]/\text{H}\alpha \) are located in SF regions.

3.5. \( L–D \) Relation and \( SB–D \) Relation

We examined the relations among \( L, D, \) and SB of all, Type Ia, and CC remnants in M33. We inspected the relation between \( L \) and \( D \) of the remnants in Figures 10(a) and (b). Weak correlations between \( D \) and \( L(\text{H}\alpha) \) (and \( L([\text{S}\ II]) \)) of all the objects are found. On the other hand, there are better correlations for the Type Ia remnants. From the fitting, we derived \( L \propto D^{-1.78 \pm 0.29} \) and \( L \propto D^{1.83 \pm 0.33} \) in \( \text{H}\alpha \) and \([\text{S}\ II] \), respectively.

The relation between SB and \( D \) for the Type Ia and CC remnants in M33 is seen in Figures 10(c) and (d). Weak correlations are found between SB(\( \text{H}\alpha \)) (and SB([\text{S}\ II])) and \( D \) of all the objects. The Type Ia remnants show better correlations between two parameters than the CC remnants. For the Type Ia remnants, the slopes for the SB and \( D \) relation in \( \text{H}\alpha \) and \([\text{S}\ II] \) are \( \beta = -1.62 \pm 0.39 \) and \( \beta = -1.81 \pm 0.53 \), respectively.

4. DISCUSSION

4.1. Comparison with Previous Studies of SNR Candidates in M33

There are several previous studies of M33 SNRs using optical images (Dodorico et al. 1978; Long et al. 1990; G98; L10). The number of known M33 SNRs detected in these studies is 137. In this work, we added 79 new ones, which have mostly low SB. We excluded 17 among the 137 known objects, as mentioned in Section 2.1. These excluded objects are probably \( \text{H}\ II \) regions or superbubbles. In Figure 11, we display the positions of the 79 new objects and the 120 known objects in M33. Previously known sources are mainly concentrated in the inner part of M33, whereas the majority of the new ones are located in the outer part. A majority of the new objects are considered to be relatively evolved sources with low SB at optical wavelengths, so they are probably too faint to be detected in the previous X-ray surveys.

Figure 12 displays the histograms of \( L(\text{H}\alpha), \ L([\text{S}\ II]), \ SB(\text{H}\alpha), \ SB([\text{S}\ II]), \ D, \) and \([\text{S}\ II]/\text{H}\alpha \) for the known SNR candidates and new ones in M33. The new objects have, on average, fainter \( L \), lower SB, and larger \( D \) than the known ones. The known objects have \([\text{S}\ II]/\text{H}\alpha \) values ranging from 0.4 to 1.2, with two concentrations at \([\text{S}\ II]/\text{H}\alpha \sim 0.55 \) and \sim 0.85. The new ones have close \([\text{S}\ II]/\text{H}\alpha \) values, but with a noticeable concentration at \([\text{S}\ II]/\text{H}\alpha \sim 0.5 \). The ratio of the number of known objects to that of the new ones is lower for low \([\text{S}\ II]/\text{H}\alpha \) than for elevated \([\text{S}\ II]/\text{H}\alpha \) (> 0.7). A small number of the new objects with large \( D \) are likely diffuse ionized gas. However, it is hard to distinguish bona fide SNRs from diffuse ionized gas using only narrowband images.

Figure 13 compares the CSD of the M33 remnants in this work with those in the previous studies (G98 and L10). G98 presented the CSD of 98 remnants and showed that it follows a power law with \( \alpha \sim 2.5 \). They suggested that the majority of the objects are considered to be in the ST phase. In Figure 13(a), the slope of the CSD obtained from the G98 sample is \( \alpha = 2.72 \pm 0.14 \) (\( D = 13–33 \) pc). The CSD obtained from the L10 sample is shown in Figure 13(b). It follows a double power law with indices \( \alpha = 2.82 \pm 0.04 \) (\( D = 9–21 \) pc) and \( \alpha = 1.60 \pm 0.03 \) (\( D = 21–50 \) pc). Figure 13(c) displays the CSD of the remnants in this work. It follows a power law, and the power index is \( \alpha = 2.38 \pm 0.05 \) (\( D = 17–50 \) pc). If we adopt the same diameter ranges, \( D = 19–36 \) pc, for comparison, we obtain \( \alpha = 2.23 \pm 0.08 \) for this work, \( \alpha = 2.24 \pm 0.13 \) for the G98 sample, and \( \alpha = 1.62 \pm 0.07 \) for the L10 sample. Thus, the value of the power index for our sample is very close to that of G98, but is much larger than that of L10. The reason for the discrepancy in slope between this work and L10’s is considered to be due to the difference in the size measurement. Our measurement is on average slightly larger than L10’s, as described in Section 2.1. In conclusion, the majority of the M33 remnants are considered to be in the ST phase, consistent with previous studies (Long et al. 1990; G98).
4.2. Comparison of SNR Candidates in M33 and M31

The two spiral members of the Local Group galaxies M31 and M33 have been the target of many observational studies to investigate the physical properties of these neighboring systems. M31 and M33 are the nearest early-type (Sb) and late-type (Scd) spiral galaxies, respectively. Therefore, they may experience different star formation activities and have different ISM conditions. One might expect that there is a difference in the distributions of physical properties of SNRs in two galaxies.

We compared the physical properties of the M33 remnants in this work with those of the M31 remnants studied using similar methods by L14. In Figures 14(a) and (b), we compare the histograms of $L(\text{H}\alpha)$ and $L(\text{[S} \text{II})$, respectively. The SNR detection limits for both M31 and M33 are found to be close. The histograms of $\text{SB(}[\text{S} \text{II})$ and $\text{SB(}[\text{S} \text{II})/\text{H}\alpha$ have similar ranges, as plotted in Figures 14(c) and (d). Figure 14(e) compare the differential size distributions of the remnants in two galaxies. The histogram of the objects in M33 has a concentration at $D \sim 45$ pc, close to that of the sources in M31. Figure 14(f) plots the histogram of the emission-line ratio (S II)/Hα of the remnants in M33 and M31. The histogram of the sources in M33 is bimodal, with two concentrations at [S II]/Hα $\sim 0.55$ and $\sim 0.8$, and that of objects in M31 is nearly bimodal, having two concentrations at [S II]/Hα $\sim 0.4$ and $\sim 0.9$. In conclusion, there is little difference in the distributions of physical properties between the M31 and M33 SNR candidates.
Figure 14. Comparisons of histograms of (a) $L(\text{H}\alpha)$, (b) $L(\text{SII})$, (c) SB(\text{H}\alpha), (d) SB(\text{SII}), (e) $D$, and (f) $\text{[SII]}/\text{H}\alpha$ of M33 remnants with those of M31 remnants (L14). (A color version of this figure is available in the online journal.)

4.3. Comparison of CSDs of the SNRs

The CSDs of SNRs can be often described by a power law (Mathewson et al. 1983; Mills et al. 1984; Green 1984; Hughes & Helfand 1984; Long et al. 1990; Dopita et al. 2010). The CSDs of both the MW SNRs and SNRs in the Magellanic Clouds (MCs) were represented well by a power-law index $\alpha \sim 1$ (Mathewson et al. 1983; Mills et al. 1984; Hughes & Helfand 1984), while the M33 remnants follow a power law, having an index $\alpha \sim 2.5$ (G98). L14 presented the CSD of M31 remnants. It follows a power law, with an index $\alpha \sim 2.5$. The CSD is taken as evidence that the majority of the remnants in the MW and the MCs are likely to be in the free expansion phase, while the majority of the objects in M31 and M33 are considered to be in the ST phase.

In Figure 15, the CSD of the M33 remnants is compared with those for the MCs, the MW, and M31. The CSDs for individual galaxies follow a power law. Table 4 presented the different power-law indices among galaxies. Figure 15(a) displays the CSD of the M33 remnants. The power-law index is $\alpha = 2.38 \pm 0.05$ ($D = 17–50$ pc). In Figure 15(b), we display the CSD of the remnants in the MCs. We derived the power-law slopes using the B10 sample. The value for the LMC SNRs is $\alpha = 1.34 \pm 0.04$ ($D = 15–55$ pc), and that for the SMC SNRs is $\alpha = 1.18 \pm 0.03$ ($D = 25–50$ pc). These results mean that most of the MC SNRs are probably in the free expansion phase. However, it is noted that the shapes of the CSDs of SNRs depend also on the selection effect (Mills et al. 1984) and the density distribution of the ISM (B10).

Figure 15(c) plots the CSD derived from the catalog of 274 MW SNRs (Pavlović et al. 2013). They estimated the sizes of most SNRs using the relation between radio SB and $D$ derived from SNRs with known distances. Thus, the size estimates of these SNRs have large uncertainties. The majority of the MW SNRs have diameters with $D = 15–30$ pc. The slope of the size distribution is $\alpha = 3.60 \pm 0.06$ ($D = 15–30$ pc). This is much steeper than the value for M33, indicating that most of the MW SNRs are likely to be in the radiative phase. The CSD of the objects in M31 obtained from L14 is seen in Figure 15(d). They present the diameters of the 156 sources in M31 detected in the LGGS data. The slope of the CSD of these SNRs is derived to be $\alpha = 2.53 \pm 0.04$ ($D = 17–50$ pc). This value is very close to that for the objects in M33.

4.4. Multiwavelength Properties of Remnants

Inspecting the properties of SNRs in multiwavelength images is useful for understanding their nature and evolution. Some previous studies of extragalactic SNRs showed weak or little correlations among X-ray, radio, and optical properties of SNRs (Pannuti et al. 2007; L10; Leonidaki et al. 2013). On the other hand, a good correlation between $L_X$ and $L(\text{H}\alpha)$ for the center-bright remnants in M31 was found by L14. Here, we discuss any correlations between X-ray (radio) and optical properties of the M33 remnants.

First, the optical properties of the M33 remnants are compared with their properties at X-ray wavelengths. L10 detected 82 X-ray bright sources among the 137 optically selected samples.
using \textit{Chandra} data from the ChASeM33 survey. Of 199 sources detected in this work, 78 are matched with the L10 catalog. Much larger proportions of the remnants with complete shells (\(~51\%\) and \(~95\%\) for A1-class and A2-class remnants, respectively) are found at the X-ray wavelengths. In Figures 16(a) and (b), \(L(H\alpha)\) and \(L([S\text{II}])\) of the matched sources are compared with \(L_X\), respectively. All the matched sources, with one exception, are brighter at optical wavelengths than at X-ray wavelengths. Weak correlations between the optical luminosity (\(L_{\text{opt}}\)) and \(L_X\) are found for all the matched objects. The correlation difference between the A-class remnants and the B-class remnants is considered to be related to the distribution of the ambient ISM. Pannuti et al. (2007) pointed out, based on simple emissivity models, that \(L_{\text{opt}}\) and \(L_X\) of SNRs might increase with increasing density of the ambient ISM. They expected a good correlation between \(L_{\text{opt}}\) and \(L_X\) of SNRs, if the ambient ISM is uniform. The correlation between \(L_{\text{opt}}\) and \(L_X\) of the A-class remnants is stronger than that of the B-class remnants in M33. This means that the ISM around the A-class remnants is more uniform than that around the B-class remnants.

In contrast, there is little correlation between \(L_{\text{opt}}\) and \(L_X\) of the B-class SNRs. The correlation difference between the A-class remnants and the B-class remnants is considered to be related to the distribution of the ambient ISM. Pannuti et al. (2007) pointed out, based on simple emissivity models, that \(L_{\text{opt}}\) and \(L_X\) of SNRs might increase with increasing density of the ambient ISM. They expected a good correlation between \(L_{\text{opt}}\) and \(L_X\) of SNRs, if the ambient ISM is uniform. The correlation between \(L_{\text{opt}}\) and \(L_X\) of the A-class remnants is stronger than that of the B-class remnants in M33. This means that the ISM around the A-class remnants is more uniform than that around the B-class remnants.

Figures 16(c) and (d) show \(L_X\) versus SB(\(H\alpha\)) and SB([S\text{II}]), respectively, of the matched sources. There are tight correlations between SB of only the A2-class remnants and \(L_X\). Correlation
coefficients are derived to be 0.63 (and 0.69) in Hα (and [SII]). Thus, the two samples are considered to be strongly correlated.

Second, we inspected the correlation between optical and radio properties of the M33 remnants. Gordon et al. (1999) presented a catalog of 186 radio sources obtained from Very Large Array-WRST observations. We found that 43 of the 199 optically selected samples in this work are matched with the Gordon et al. (1999) catalog. Higher fractions of the A2-class (~63%) and B2-class (~42%) remnants are detected than other categories at radio wavelengths as well as at optical wavelengths.

Figures 17(a) and (b) show comparisons of $L_{\text{Hz}}$ and $L_{\text{Hα}}$ of the matched sources with $L_{20\text{cm}}$, respectively. Weak correlations between $L_{\text{opt}}$ and $L_{20\text{cm}}$ for all the matched objects are found, but strong correlations are found for the A2-class remnants. In Figures 17(c) and (d), we plot $L_{20\text{cm}}$ versus $SB(H\alpha)$ and $SB([S\text{II}])$, respectively, of the matched sources. We found that there are also good correlations between $SB(H\alpha)$ and $L_{20\text{cm}}$.

The histograms of $SB(H\alpha)$ and $SB([S\text{II}])$ for the objects with X-ray emission, those without X-ray emission, and all the M33 remnants are seen in Figure 18. The majority of the objects with large $SB(H\alpha)$ (and $SB([S\text{II}])$) have X-ray counterparts. The distributions in $H\alpha$ and [SII] of the objects with X-ray emission show concentrations at $10^{-15.7}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$ and $10^{-15.9}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$, respectively. The majority of objects with low SB have no X-ray counterparts. The objects with X-ray emission have a nearly flat distribution for $D = 15–60$ pc, as shown in Figure 19(a). The objects with X-ray emission have a median $D$ of 38 pc, smaller than the value of 50 pc for those without X-ray emission. Figure 19(b) shows that the slope of the objects with X-ray emission is $\alpha = 2.26 \pm 0.2$ ($D = 19–30$ pc), while that for those without X-ray emission is $\alpha = 2.21 \pm 0.05$. However, the slopes of the CSD of the remnants for $30 < D < 46$ pc are different. The slopes for objects with X-ray emission are $\alpha = 1.52 \pm 0.02$, much flatter than those without X-ray emission, $\alpha = 4.11 \pm 0.11$.

5. SUMMARY

We presented a survey of SNR candidates in M33 using the [SII]/$H\alpha$ technique on the optical narrowband images. We expanded the remnant list to 199 objects, of which 79 are new findings. We utilized this catalog to study their optical and X-ray properties, and found that the majority of them are remnants of CC SNe. The Type Ia proportion (~15%) for M33 is lower than that for M31 (~27%; L14). The radial number density profile of the remnants shows two significant concentrations at $R \sim 2$ kpc and ~3.5 kpc. For $R > 3.5$ kpc, the sizes of the objects increase,
on average, slightly outward. In contrast, the mean value of their SB(Hα) (and SB([S ii])) decreases. A noticeable concentration is seen at D ∼ 45 pc in the differential size distribution of the CC remnants. Power-law fitting to the CSD of the remnants yielded a value of α = 2.38 ± 0.05 (for the range D = 17–50 pc). This value is close to the value from that for the M31 remnants, α = 2.53 ± 0.04 (L14). Thus, the majority of the objects in both M33 and M31 are the ST phase. The histogram of the emission-line ratio ([S ii]/Hα) of the remnants has two concentrations, at [S ii]/Hα ∼ 0.55 and ∼ 0.8. Tight correlations between D and L(Hα) (and L([S ii])) for the Type Ia remnants are found. A significant proportion of the remnants are detected in X-rays for the A1-class and A2-class (∼ 51% and ∼ 95%, respectively). These sources have mostly large SB, small D, and complete shapes at optical wavelengths. Strong correlations between L_X (and L_{20 cm}) and optical properties are found for the A2-class remnants.

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