Energetics and Birth Rates of Supernova Remnants in the Large Magellanic Cloud

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Received 2016 November 11; revised 2017 January 24; accepted 2017 February 13; published 2017 March 1

Abstract

Published X-ray emission properties for a sample of 50 supernova remnants (SNRs) in the Large Magellanic Cloud (LMC) are used as input for SNR evolution modeling calculations. The forward shock emission is modeled to obtain the initial explosion energy, age, and circumstellar medium density for each SNR in the sample. The resulting age distribution yields a SNR birthrate of 1/(500 yr) for the LMC. The explosion energy distribution is well fit by a log-normal distribution, with a most-probable explosion energy of $0.5 \times 10^{51}$ erg, with a $1\sigma$ dispersion by a factor of 3 in energy. The circumstellar medium density distribution is broader than the explosion energy distribution, with a most-probable density of $\sim 0.1 \text{ cm}^{-3}$. The shape of the density distribution can be fit with a log-normal distribution, with incompleteness at high density caused by the shorter evolution times of SNRs.

Key words: ISM: supernova remnants – Magellanic Clouds

1. Introduction

The study of supernova remnants (SNRs) is of great interest in astrophysics. SNRs can provide valuable information relevant to their stellar progenitors and the associated explosion events that end their stellar lives. The hot shocked gas in the interior of a SNR is observed in X-rays, with a temperature of $\sim 1 \text{ keV}$. This temperature is determined by the physics of shocks and the evolutionary history of the interior of the SNR. Models, based on hydrodynamic simulations can be constructed, representing a reasonable approximation of the evolution of a SNR (e.g., Cioffi et al. 1988; Truelove & McKee 1999). Such models, together with the observed X-ray emission, can be used to deduce the explosion energy and the age of the SNR, and the density of its surroundings. A study of a large number of SNRs can yield insights about the physical processes related to SNRs, such as SNR evolution, SN explosion energies, and the properties of the environment in which SNe explode.

Studies of populations of SNRs have previously been carried out. Here a few recent studies are pointed out. The sizes of SNRs in the LMC and SMC are known to follow a linear cumulative distribution (McKee 1999). Badenes et al. (2010) showed this to be most likely caused by SNRs exploding in an ISM that has a conspicuous “constant-efficiencies” model for radio emission did not fit the data. Asvarov (2014) studied the size distribution of SNRs in M33. SNRs were chosen based on their X-ray hardness ratio to get a sample that was as free as possible from selection effects. Monte Carlo methods were used to generate model sets of size distributions to compare to the observed distribution. The main conclusions were that the warm ISM (with a density in the range $0.1–1 \text{ cm}^{-3}$ has a filling factor of $\sim 90\%$, and the birthrate of SNRs in M33 is $\approx 7$ per 1000 yr.

An important input required to carry out SNR modeling is the shock radius. This, in turn, requires knowledge of the SNR’s distance. For this reason, this work considers SNRs located in the Large Magellanic Cloud (LMC). The distance to the LMC is well determined at $49.97 \pm 0.19$ (statistical) $\pm 1.11$ (systematic) kpc (Pietrzyński et al. 2013). LMC SNRs also have been observed extensively in X-rays by XMM-Newton (Maggi et al. 2016). Among the most important results were: identification of SN type (core-collapse or type Ia) for a number of SNRs and measurement of LMC element abundances from SNRs dominated by emission from a shocked interstellar medium.

The current paper further analyzes the sample of LMC SNRs from Maggi et al. (2016) by applying the models from Truelove & McKee (1999) with some additional extensions and calculations. Section 2 describes the data and the models that are used. Section 3 gives the results for the derived explosion energies, ages, and circumstellar medium densities. Section 4 summarizes the results.

2. LMC SNR Data and SNR Evolution Models

Maggi et al. (2016) present the results of extensive XMM-Newton observations of LMC SNRs. They present X-ray images and spectral analysis results for 51 SNRs. From this list we analyze all but SN1987A, for which our models do not apply, leaving a sample of 50 SNRs. The primary data inputs for our analysis come from their Tables C1, E1, and E2. In particular, the quantities of interest here are the outer shock radius, the temperature, and the emission measure. The XMM-Newton temperatures and emission measures are generally the best available values for these LMC SNRs. In several cases Chandra images are available with higher spatial resolution. For those cases we use the shock radius from the Chandra images.

For modeling this sample, some simplifying assumptions are made. Spherically symmetric SNR evolution is assumed, which allows for the use of analytic approximations to SNR evolution models. This assumption can be relaxed if carrying out multi-dimensional hydrodynamic models, but that is beyond the
scope of the current work. As discussed in Truelove & McKee (1999), prior to the onset of radiative cooling, spherically symmetric SNR evolution can be described by unified solutions. These are more complex than self-similar solutions, but are analytic in nature. They describe the SNR evolution (forward and reverse shock evolution) throughout the ejecta-dominated and Sedov–Taylor phases, as well as the transition between the two phases. For the transition from the Sedov–Taylor phase to the radiative phase, the models of Ciofi et al. (1988) are used. For the circumstellar medium, a uniform density is assumed. The ejecta density profiles are taken as a power-law in radius, with index $n$. Truelove & McKee (1999) present models for $n = 0$ up to $n = 14$ ($n = 5$), $n = 7$ is expected for a Type Ia explosion (Colgate & McKee 1969) and $n > 5$ is expected for core-collapse supernovae (Chevalier & Fransson 1994).

The model emission measures for material heated by the forward shock, EM, are calculated using the interior SNR structure (density, temperature, and pressure profiles): $EM = \int n_ne_m dV$. Dimensionless EM is defined by $dEM = EM/(R^2 n_{sh} n_{H_{sh}})$, with post-shock electron density $n_{e_{sh}} = 4n_e$ and post-shock H density $n_{H_{sh}} = 4n_H$. $n_e$ and $n_H$ are the pre-shock (ISM) values, with $n_e$ calculated as if the gas were ionized to the same state as the post-shock gas. $\mu_e$ and $\mu_H$ are the mean molecular weights (or mean masses) per H atom and per electron of the post-shock gas. From the definition of mean molecular weights in terms of mass density $\rho$, $\rho = \mu_e n_e + \mu_H n_H$, one obtains $n_e = \frac{\rho_0}{2\mu_H}$. With this definition, $dEM$ is independent of $R$ and $n_{H_{sh}}$ and depends only on the shape of the interior density distribution. $dEM$ is a constant for the self-similar phases of the evolution during which the shape of the density does not change. For the Sedov–Taylor phase, the interior structure and $dEM$ for the self-similar solution are calculated using the equations given in White & Long (1991) with the cloud evaporation source term set to zero. For the ejecta-dominated phase, $dEM$ is calculated using the self-similar interior solutions given in Chevalier (1982) for the $n = 7$ and $n = 12$ cases. Only part of the self-similar solution exterior to the contact discontinuity is used to obtain $dEM$ of the forward-shocked material. For the transition phase from the ejecta self-similar phase to the Sedov–Taylor self-similar phase, $dEM$ is calculated for the $n = 7$ and $12$ cases as follows. The ejecta self-similar phase ends at time $t_{core}$ and the Sedov–Taylor self-similar phase starts at time $t_{ST}$. $t_{core}$ and $t_{ST}$ are defined and values for different $n$ are given in Truelove & McKee (1999). Between $t_{core}$ and $t_{ST}$, $dEM$ is interpolated between the ejecta phase value for $n = 7$ or $n = 12$ and the Sedov–Taylor value. Models have been tested for different $n$ on a few SNRs in our sample and it was found that results differ by much less (typically less than a few parts in 1000) than the differences caused by the uncertainties in the input parameters. Thus, the presented models are given for the $n = 7$ case. Tests were made using models with different values of ejected mass between 0.5 and 10 $M_\odot$. Again, the results differed by much less than the differences caused by the uncertainties in the input parameters. Thus, the presented models are given for an ejected mass of 1.4$M_\odot$.

The temperature of the X-ray spectrum of the outer shock component of an SNR is the emission-weighted temperature. In the models considered, the temperature increases as radius decreases inside the shock front. Thus the emission-weighted temperature is higher than the temperature at the shock front. At the shock, electrons and ions are heated to different temperatures. The initial heating per particle for a strong shock, with an adiabatic index $\gamma = 5/3$ is $\frac{\mu_e}{4\pi} \frac{3}{2} n_0 V_0^2$. Here $\mu_e$ is the mean molecular weight for the plasma $1/\mu = 1/\mu_{ion} + 1/\mu_e$, with $\mu_{ion}$ and $\mu_e$ being the mean molecular weights for the ions and for the electrons, respectively. Mean molecular weights corresponding to LMC abundances are used. These affect the relation between the mass density, number density, pressure, and temperature. Thus abundances affect the shock jump conditions, SNR evolution, and emission measures. Details on the SNR models, including the effects of abundances, are given in Leathy & Williams (2017).

As the plasma ages the electrons and ions slowly equilibrate in temperature. Ghavamian et al. (2013) gives a detailed discussion of electron–ion equilibration. Collisionless shocks are complex, governed by interactions in the plasma that depend on collective processes, and electron heating is not yet well understood. For our main calculations, the calculation of electron heating given in Cox & Anderson (1982; hereafter CA82) is followed, which uses the results of Itoh (1978). For simplicity, the standard composition $n_{H_{sh}} = 0.1n_{H}$ used in CA82, is used for the calculation of electron–ion equilibration. Observations of electron-to-proton temperature ratios in SNRs are relatively recent. Thus an alternate calculation of electron heating is done here using the phenomenological $1/V_0^2$ model (Equation (5) in Ghavamian et al. 2013). The minimum $T_e/T_{ion}$ is set to 0.1 to agree with the observations, which typically have large factors (of 2–5) errors (Figure 2 in Ghavamian et al. 2013). The results from the two methods (CA82 and 1/V02 models) are compared.

For the CA82 calculation, electron–ion temperature equilibration is due to Coulomb collisions. The equilibration timescale is: $t_{eq} = 5000E_3^{1/4}n_0^{4/7}$ yr, with $E_3$ being the explosion energy in units of 1051 erg and $n_0$ being the density in cm–3. The electron-to-ion temperature ratio $\alpha = T_e/T_{ion}$ is given to a good approximation by $\alpha = 1 - 0.97 \exp(-5/3)(1 + 0.3(5/3)^{1/2})$. Here $f = \frac{\ln(A)}{81 \frac{n_0}{T_{ion}^{1/2}} (T_e - T_0)$, with the Coulomb logarithm given by $\ln(A) = (1.2 \times 10^7 T_0^{1/2} T_e (4n_0)^{-1/2})$. $T_0$ is the time at which a parcel of gas was shocked and the post-shock density is $4n_0$. The factor of 0.97 in the expression for $\alpha$ has been included to give reasonable agreement with the measured electron-to-proton temperature ratios for young SNRs (Figure 2 in Ghavamian et al. 2013). For typical SNR parameters (explosion energy 1051 erg, ejected mass of 1.4$M_\odot$, density of 1 cm–3) our calculations give $\alpha = 0.055$ for an age of 100 yr, increasing rapidly to 0.31 at an age of 1000 yr, then more slowly, reaching 0.97 at 5000 yr. To get realistic X-ray (i.e., electron) temperatures from the models, the inclusion of progressive equilibration of electron and ion temperatures is essential.

The ionization states of the ions are generally out of equilibrium with the electron temperature for many SNRs. However, this is already taken into account in modeling the X-ray spectra, so the electron temperatures derived from the X-ray spectrum are corrected for this effect.

3. Results and Discussion

For each SNR in the LMC with an observed radius, $R$, emission measure, EM, and X-ray temperature, $kT$, an initial explosion energy, $E_0$, age, and circumstellar medium density, $n_0$, were used to calculate a model. The process was iterated until convergence of the output $R$, EM, and $kT$ to the observed
values. The procedure is similar to that described in Leaky & Ranasinghe (2016). The resulting $E_\text{exp}$ and $n_0$ for each of the 50 SNRs is listed in Table 1. The input $R$ is also given. The inputs EM and $\delta T$ and their uncertainties are identical to those listed in Maggi et al. (2016) and thus are not repeated here. The results from model fitting using the alternate prescription for electron heating show the following differences. Derived density, $n_0$, is identical. Age, on average, was smaller by a factor of 0.88 (standard deviation 0.19) and energy was larger by a factor of 1.22 (standard deviation 0.52). For SNRs with an X-ray temperature $<0.27$ keV (13 SNRs) there is no significant difference ($<1\%$ and typically $<0.1\%$) in age or explosion energy. For an X-ray temperature $>0.27$ keV (37 SNRs), the age is usually smaller, and the explosion energy is usually

Table 1

| MCSNR | $R$(pc) | $E_\text{d}(10^{31}\text{erg})$ | $E_\text{d}$ Error | Age (yr) | Age Error | $n_0$(cm$^{-3}$) | $n_0$ Error |
|-------|---------|-------------------------------|-------------------|--------|-----------|---------------|----------|

Note.

$^a$ All models have SN ejecta masses of $1.4M_\odot$. $R$ is the outer shock radius, $E_\text{d}$ is the explosion energy, and $n_0$ is the pre-shock density.
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larger. The mean log(age) is 4.12 (1.3 $\times 10^4$ yr) for the CA82 $T_e/T_{\text{ion}}$ method and 4.05 (1.1 $\times 10^4$ yr) for the $1/V_i^2 \, T_e/T_{\text{ion}}$ method. The mean log(E51) is $-0.293 \, (5.1 \times 10^{50}$ erg) for the CA82 $T_e/T_{\text{ion}}$ method and $-0.144 \, (7.2 \times 10^{50}$ erg) for the $1/V_i^2 \, T_e/T_{\text{ion}}$ method.

To obtain uncertainties in $E_0$, $n_0$, and age, the models were rerun with EM and $kT$ set to the four different combinations of upper and lower limits. Then the extreme values of $E_0$, age, and $n_0$ from this set of fits were used as the upper and lower limits. Generally, asymmetric errors on the parameters were obtained, as shown in Table 1. The errors in Table 1 are derived from the errors of the input parameters. An additional systematic error for $E_0$ and age exists because of the uncertainty in $T_e/T_{\text{ion}}$ calculation. A measure of that uncertainty is the standard deviation of difference in results from the two $T_e/T_{\text{ion}}$ calculation methods, which are 19% for age and 52% for $E_0$.

There are wide ranges for the deduced values of $E_0$, age, and $n_0$. The supernova (SN) explosion energies range from $0.037 \times 10^{51}$ erg (J0453-6829) to $11 \times 10^{51}$ erg (J0449-6920), i.e., by a factor of 300. Such a wide range should not be surprising: the range in observed SN energies is similarly wide (for Type II SN energies see Rubin et al. 2016). The deduced ages range from 1300 yr (J0537-6910) to 60,000 yr (J0517-6759). This is in rough agreement with what is expected because SNRs are expected to become too faint to observe after several $10^4$ yr. The deduced circumstellar densities range from 0.0007 cm$^{-3}$ (J0505-6753) to 5.5 cm$^{-3}$ (J0453-6655). This spans 4 orders of magnitude and is similar to what is expected for Milky Way SNRs exploding in different environments, ranging from the hot ionized medium, with densities $\approx 0.001$ cm$^{-3}$, to the diffuse warm and cool H I, with densities $\approx 0.1 \text{--} 1$ cm$^{-3}$, to the molecular medium with densities $\geq 1$ cm$^{-3}$ (Cox 2005).

Plots of the various SNR parameters were made to check that the models gave reasonable results. Figure 1 shows $n_0$ versus age. The SNRs are scattered across the plot except for a clear deficit in the upper right corner (high density and high age). This absence is expected because the onset of radiative losses occurs earlier for SNRs in higher density ISM. The expected transition time to the PDS phase is $t_{\text{PDS}} = 13300(E51)^{3/14}n_0^{-4/7} \, \zeta_{\text{m}}^{-5/14}$ (CMB88), with $\zeta_{\text{m}}$ being the metallicity correction to the cooling function. This is plotted in Figure 1 as the dashed and dotted lines for explosion energies of $10^{50}$ and $10^{51}$ erg. SNRs become much fainter as they approach the PDS phase, so the upper limits on the derived ages are consistent with expectations. A plot of explosion energy versus age shows no correlation. However, there is an empty region in the plot at large age and low explosion energy, which is likely because old SNRs with low explosion energies are too faint to be in the sample. The plot of radius versus age is similar to the plot of radius versus number because the birthrate of SNRs in the LMC is consistent with a constant value (see below). The reason for the nearly linear trend was discussed in detail by Badenes et al. (2010): it can be explained by the spread of ISM densities in which SNRs explode.

Figure 2 shows the distribution of SN explosion energies, $E_0$, derived here for the LMC SNRs. $E_0$, for each SNR, is plotted as a function of the cumulative number of SNRs with energy less than or equal to the energy of a given SNR, and the vertical axis is the energy of that SNR. The solid curve is a fit for the probability distribution expressed as a log-normal distribution (parameters are given in the text).
Figure 3. Cumulative distribution of ages (histogram with error bars) for the LMC supernova remnant sample. The solid curve is a linear fit equivalent to a constant birthrate of 1 per 503 yr. The fit is done for the 40 youngest SNRs in the sample.

distribution:

\[
\frac{dN}{dE} = \frac{N_T}{\sqrt{2\pi\sigma_{\log E}^2}} e^{-\frac{(\log(E)-\log(E_0))^2}{2\sigma_{\log E}^2}},
\]

where \( N_T \) is the total number in the sample, \( E_0 \) is the peak in number versus energy and \( \sigma_{\log E} \) is the dispersion in \( \log(E) \). The solid line in Figure 1 is the best-fit cumulative distribution, with parameters \( E_0 = 0.48 \times 10^{51} \) erg and \( \sigma_{\log E} = 0.47 \). The latter corresponds to a 1σ dispersion of a factor 2.94 in energy. The process was repeated for the explosion energies derived using the the 1/\( V_e^2 T_e / T_{ion} \) method. The plot looks nearly the same as the one in Figure 2. Those energies are also well fit by a log-normal distribution, but with parameters \( E_0 = 0.54 \times 10^{51} \) erg and \( \sigma_{\log E} = 0.50 \). The latter corresponds to a 1σ dispersion of a factor 3.16 in energy.

The distribution of SN ages for the LMC SNRs is shown in Figure 3. Age is plotted for each SNR versus the cumulative number of SNRs with ages less than or equal to that of the given SNR. In this case, for ages \( \leq 20,000 \) yr, the distribution is uniformly distributed in age, and is well fit by a straight line. The slope of the line is the birthrate of SNRs in our sample, which corresponds to observable X-ray SNRs in the LMC. The derived birthrate is 1/(503 yr), where the fit is done only for SNRs with ages \( \leq 20,000 \) yr. The fits were repeated for the ages derived using the 1/\( V_e^2 T_e / T_{ion} \) method. The plot looks nearly the same as the one in Figure 3. The derived birthrate is 1/(507 yr), where again the fit is done only for SNRs with ages \( \leq 20,000 \) yr.

The excess of ages for rank \( >40 \) can be attributed to incompleteness, i.e., because the SNRs with ages \( \geq 20,000 \) yr are becoming faint, the X-ray surveys are seeing only a fraction of the population. If all of the age \( \geq 20,000 \) yr SNRs (say up to \( 6 \times 10^4 \) yr) were observed, then the rank numbers would be larger, flattening the slope. The incompleteness is estimated by fitting a slope to the set with age ranks between 40 and 50. This gives a birthrate of 1/(4200 yr), suggesting an incompleteness of a factor of \( \geq 8 \) for SNRs with ages between 20,000 and 60,000 yr compared to those with age \( \leq 20,000 \) yr. Including SN1987A in the sample has the following effect: the birthrate remains at 1/(503 yr) but the y-intercept of the line becomes 1060 yr instead of 1560 yr. This suggests that \( \sim 2 \) other young SNRs are missing in the sample, possibly because of confusion due to their small sizes. If the assumption is made that every observable SN produces an observable SNR (for age \( \leq 20,000 \) yr), then the SN rate for the LMC is 1/(500 yr), which is about 1/10 that of the SN rate for the Milky Way. This is roughly consistent with the stellar luminosity of the LMC, which is about 1/10 that of the Milky Way. The uncertainties in the SN rate of the Milky Way and the stellar luminosities of the LMC and Milky Way are large enough that a more detailed comparison is not possible.

As a separate test of the derived birthrate, the derived ages were replaced with available estimates from the literature, as summarized in Maggi et al. (2016). Previous estimates were available for 25 LMC SNRs. It was not assessed for each case whether the previous age estimates are more reliable or less reliable than the currently derived ages; in fact many of them are consistent with the same value. A detailed comparison for individual SNRs will be done in future work. The resulting cumulative age distribution looks much the same as that shown in Figure 2, but the fitted slope is lower, corresponding to a birthrate of 1/(607 yr). The difference is taken as a measure of the uncertainty in the LMC SNR birthrate, i.e., \( \sim 1/(500 \) yr to \( \sim 1/(600 \) yr). Future assessment of the methods of obtaining ages should reduce this uncertainty.

Figure 4 shows the distribution of SNR circumstellar densities, \( n_0 \). The densities are clearly not uniformly distributed. Here the \( n_0 \)
distribution is fit with a log-normal probability function:

\[
\frac{dN}{dn_0} = \frac{N_T}{\sqrt{2\pi \sigma^2_{\log(n_0)}}} \cdot e^{-\frac{\log(n_0) - \log(n_0,av)^2}{2\sigma^2_{\log(n_0)}}},
\]

where \(n_0,av\) is the peak in number versus density and \(\sigma_{\log(n_0)}\) is the dispersion in \(\log(n_0)\). The fit with a single log-normal distribution is poor but separate fits to the lower and upper sets of densities are good. The solid blue line is the best fit to the 30 lowest densities, with parameters \(n_0,av = 0.079\, \text{cm}^{-3}\) and \(\sigma_{\log(n_0)} = 0.51\). The dashed red line is the best fit to the 30 highest densities, with parameters \(n_0,av = 0.091\, \text{cm}^{-3}\) and \(\sigma_{\log(n_0)} = 0.91\). The \(\sigma\)'s correspond to 1\(\sigma\) dispersions of factors of 3.2 and 8.2 in density. Because the peak densities for both fits are so close to the same value, this suggests that there are not two physically distinct distributions of density. One possibility is that the density distribution is not well-described by a log-normal distribution.

This may not be surprising considering the complexity of processes that govern the densities in the ISM (e.g., see Cox 2005). Another possibility is that the high-density end of the distribution is undersampled. SNRs occurring in a high-density medium evolve faster and become radiative at earlier times. Thus they would be under-represented in the sample compared to longer-lived SNRs occurring in lower-density environments. In this case, the poor fit above densities of \(\sim 0.2\, \text{cm}^{-3}\) could be explained by incompleteness. The mean age for the 30 SNRs with the lowest densities is 21,000 yr, whereas the mean age of the 20 SNRs with the highest densities is 12,000 yr. This supports the suggestion that the high-density end of the sample is affected by incompleteness.

The density distribution at the sites of SNRs in the LMC has been discussed previously. Badenes et al. (2010) and Bandiera & Petruk (2010) studied the size distributions of SNRs in the LMC, SMC, and M33. There is a nearly linear size distribution over a fairly wide range in radius (up to 60 pc). Both studies considered SNRs that evolve in a distribution of densities and used this to explain the linear size distribution. The upper cutoff in the size distribution was explained by a minimum in the density distribution (Badenes et al. 2010). Our finding an approximately log-normal distribution for density is consistent with the linear size distribution of LMC SNRs, because it was derived from nearly the same sample of LMC SNRs as that used by Badenes et al. (2010). The density distribution derived here (Figure 3) has been fitted by a \(n^{-1}\) distribution (the green line in Figure 3); however, the log-normal distribution gives a significantly better fit. The reasons that the density distribution here is different from that in Badenes et al. (2010) are: they assumed a power-law density distribution and individual SNRs were modeled here with explosion energy, age, and density as parameters for each SNR.

For the current work, the X-ray emission of the forward shock was analyzed. It was noted that the results are very insensitive to the amount of ejected mass, \(M_{ej}\), and to the index \(n\) for the power-law density distribution of the ejecta. However, the behavior of the reverse shock is sensitive to both parameters. The SNR evolution model is currently being improved to be able to model the reverse-shocked ejecta for values of \(n\) between 0 and 14. When the reverse shock model is completed, the X-ray emission from the reverse shock, which is seen in a number of the LMC SNRs, can be modeled. That modeling can yield \(M_{ej}\) and \(n\) values for a sample of SNRs and will enable us to learn about the properties of the SN progenitors.

4. Summary

X-ray emission properties from the forward shock for a set of 50 SNRs in the LMC were recently determined by Maggi et al. (2016). Here, SNR evolution and interior structure calculations have been carried out in order to match the observed radius, emission measure, and electron temperature for each of the 50 SNRs. The results for explosion energy, age, and circumstellar medium density, and their uncertainties, are given in Table 1. \(T_e/T_{\text{ion}}\) was calculated using the Cox & Anderson (1982) prescription and an additional set of models was calculated using the \(1/V^2\) prescription (Ghavamian et al. 2013). The latter gave identical densities, and different ages and explosion energies. However, the analysis of the distributions of ages and explosion energies gave the same results using both methods.

This is the first time that the energy distribution of SNRs, the birthrate of SNRs, and the density distribution for SNRs have been measured for any large sample. The distribution of parameters is summarized in Figures 2–4. For explosion energy and density, the distributions were fit by log-normal distributions. A most-probable explosion energy of \(0.5 \times 10^{51}\) erg was found, with a \(1\sigma\) dispersion by a factor of 3 in energy. For density, two log-normal fits are better than one, which may be caused by complexity in the distribution of the interstellar medium in the LMC or by incompleteness in the sample. In either case, the mean density is \(\sim 0.1\, \text{cm}^{-3}\), with a \(1\sigma\) dispersion by a factor of \(\sim 3–8\) in density. For age, incompleteness is clearly a factor for the older part of the sample (age >20,000 yr). For ages ≤20,000 yr, the ages are well fit by a constant birthrate of 1/(500 yr).

It would be highly desirable to carry out a similar study for Galactic SNRs. One of the main factors limiting such a study is a lack of reliable distances to SNRs in the Galaxy. However, once a sample of Galactic SNRs with distances and X-ray observations is obtained, similar modeling can be carried out. Then the properties of Galactic and LMC SNRs can be compared.

D.L. acknowledges the assistance of undergraduate student J.E. Williams, who compiled the LMC data used as input for this study, and also verified some of the model calculations. This work was supported by a grant from the Natural Sciences and Engineering Research Council of Canada.

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