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Statistics of Galactic Supernova Remnants *

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Abstract We collected the basic parameters of 231 supernova remnants (SNRs) in our Galaxy, namely, distances (d) from the Sun, linear diameters (D), Galactic heights (Z), estimated ages (t), luminosities (L), surface brightness (Σ) and flux densities (S_1) at 1-GHz frequency and spectral indices (α). We tried to find possible correlations between these parameters. As expected, the linear diameters were found to increase with ages for the shell-type remnants, and also to have a tendency to increase with the Galactic heights. Both the surface brightness and luminosity of SNRs at 1-GHz tend to decrease with the linear diameter and with age. No other relations between the parameters were found.

Key words: methods: statistical — (ISM:) supernova remnants

1 INTRODUCTION

Supernova explosion of a massive star usually leaves a compact celestial object and/or a supernova remnant (SNR). SNRs can be classified into three types: Shell type (S-type), Plerion type (P-type) and Composite type (C-type). Most of known SNRs have a shell. The P-type remnants have a central component with irregular shapes. The C-type remnants have a plerionic component surrounded by an outside shell.

The S-type SNRs usually have four evolution stages: the free expansion phase, the Sedov or adiabatic phase, the radiative or snowplough phase and the dissipation phase. The first stage lasts for a few hundred years, when the linear diameters are less than a few pc. Most of the observed SNRs are in the adiabatic phase, and some in the 3rd, and none in the 4th phases.

Many authors have analyzed the distribution of radio spectral indices, α (the flux density at frequency ν is $S_\nu \propto \nu^\alpha$), of SNRs. From the spectral indices of 93 SNRs, Becker & Kundu (1975, hereafter BK75) claimed that the mean Galactic height z is 175 pc for remnants with radio indices between 0.0 and −0.25, and decreases to 56 pc for remnants with radio indices between −0.46 and −0.65. Clark & Caswell (1976) failed to confirm this trend from a similar analysis of 68 radio shell SNRs. Lerche (1980) showed that the spectral indices of 68 radio shell SNRs have no correlation with the radius, age or galactic height, which is probably an

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indication of a repowering process active throughout most of the life of an SNR (Bell 1978a, b; Lerche 1980). We noticed that some SNRs have different values of spectral indices in the BK75 paper and in Green's SNRs catalog (Green 2004): for example, for SNR G290.1−0.8, $\alpha = -0.62$ in BK75 and −0.4 in the catalog. The distribution of spectral indices is concentrated around $\alpha = -0.5$ in Green's catalog, but this is not the case in BK75, which indicates the bias in the conclusion of BK75.

The relation between the radio surface brightness (Σ) and the diameter (D) of SNRs is well known, and the relation can be used to determine the distance of the SNR (e.g., Poveda & Woltjer 1968; Clark & Caswell 1976; Lozinskaya 1981; Huang & Thaddeus 1985; Duric & Seaquist 1986; Guseinov et al. 2003). Some authors found that SNRs have quite a wide spread of intrinsic properties (Green 1984; Mills et al. 1984; Allakhverdiyev et al. 1985; Berkhuijsen 1986; Arbutina et al. 2004), implying that using the Σ-D relation for distance determination may cause large uncertainties. Huang & Thaddeus (1985) presented a good Σ-D relation for shell-like remnants, using the distance to an SNR from the associated molecular cloud, which led to a substantially smaller scatter than previous determinations and established a good distance scale for shell-like remnants. This means SNRs with similar intrinsic properties or surrounding medium should be selected to derive a nice Σ-D relation. The factors include the kinetic energy of the progenitor outburst, the magnetic field intensity and homogeneity of the ambient medium, etc. We will investigate the Σ-D relation and luminosity L-D relation by considering the types of Galactic SNRs, and discuss the relations between the surface brightness Σ (also luminosity L) and the age (t) of SNRs.

In Sect. 2 we will describe the procedure to obtain all the SNR parameters for our statistics, the basic methods to estimate the age of the SNRs, and also the method to derive the SNR distances. In Sect. 3 we show some statistical results of the SNR parameters and discuss their physical reasons. Our conclusions are presented in Sect. 4.

2 PARAMETERS OF SNRS

Most of the parameters of SNRs can be found from the catalog compiled by Green (2004), but a lot of supplementary data on the distances and/or linear diameters can be found in Guseinov et al. (2003). We also collected many data from other literature.

All the SNR data are listed in Table 1 (see *http://www.chjaa.org/2005v5n2*). Column 2 lists the SNR ages estimated by different methods, indicated by different subscripts and explained in Sect. 2.1. Superscript '0' indicates that the SNR age is estimated by other methods, for example, through the decay time of radioactive ^{44}Ti in γ-ray lines such as for SNR G266.2−1.2 (Aschenbach et al. 1999). Many of the radio SNRs have more than one published value for age, distance or diameter. For these, we either chose the most recent estimates or used an average of the available estimates, or the most commonly adopted value.

2.1 Age Estimates

There are mainly five ways to estimate the age of an SNR:

1. If an SNR is associated with a neutron star, one can estimate its age by using the pulsar characteristic age derived from the rotation period of the pulsar (P) and the rate of change of period ($\dot{P}$) according to $t = P/2\dot{P}$. For example, Gotthelf et al. (2000) suggested $t \approx 720\,\mathrm{yr}$ for SNR Kes75 according to the pulsar parameters, $P = 0.3236\,\mathrm{s}$ and $\dot{P} = (7.097 \pm 0.001) \times 10^{-12}\,\mathrm{s\,s^{-1}}$.
2. One can derive the age of an SNR from the total exploding energy (E) of a supernova and the energy loss rate ($\dot{E}$) of the remnant, according to $t = E/\dot{E}$. For example, for SNR

G0.9+0.1, if we suppose the explosion energy is $E \sim 1.3 \times 10^{48}$ erg and the energy rate is $\dot{E} \sim 1.3 \times 10^{37}$ erg s^{-1}, then an age of $t \approx 2700$ yr is estimated (Sidoli et al. 2000).

3. One can estimate the age from the linear diameter (D) or the radius (R) of the SNR and the expanding velocity (υ_s) of the shock wave of the SNR. This dynamical age is $t = CR/\upsilon_s$, with C a constant. For SNR G18.8+0.3 (Dubner et al. 1999), the radius is $R = 4$ pc, and the expanding velocity $\upsilon_s \approx 240$ km s^{-1}, so the estimated age is $t \approx 16\,000$ yr. This method is often used for the S-type remnants. Note the constant C is equal to or less than 1; usually the value 2/5 is taken because the observed S-type SNRs are usually in the adiabatic phase. According to the Sedov relation (Sedov 1959)

$$R = (2.026E/\rho)^{1/5} t^{2/5}. \tag{1}$$

Here E is the supernova explosion energy in the remnant, ρ is the density of the surrounding gas. For a freely expanding remnant, $C = 1$, but for a radiative remnant $C = 2/7$. For SNR W51C a characteristic age of $t = 2R/(5\upsilon_s) \approx 30\,000$ yr was obtained by Koo et al. (1995), with $R \approx 38$ pc and $\upsilon_s \approx 490$ km s^{-1}. Obviously, the coefficient C depends on the expanding velocity of the shock wave (υ_s) of the SNR after the supernova explosion.

4. For SNRs with a known radius (R) and thermal temperature (T) measured from X-ray observation, the age can be obtained by $t = 3.8 \times 10^2 R_{\rm pc} (kT)^{-1/2}_{\rm keV}$ yr, which is derived from Eq. (1) using $kT = (3/16) 0.61 m_{\rm H} \upsilon_s^2$. Here $m_{\rm H}$ is the mass of the hydrogen atom. For example, for CTA1, with $R = 21.6$ pc, $kT = 0.22$ keV, Seward et al. (1995) obtained $t \approx 15\,000$ yr.

5. Some SNRs have their spectrum measured already which shows the usual break at frequency ν_b due to synchrotron losses in a magnetic field B. One can then use the following equation to calculate the age of the SNR: $t \approx 40\,000 B^{-1.5} \nu_{\rm b}^{-0.5}$ yr. For example, for SNRG 21.5−0.9 (Bock et al. 2001), with $B \approx 460\,\mu$G, $\nu_b < 100$ GHz, the estimated age $t \geq 13\,000$ yr.

The uncertainty of estimated SNR ages are very large, even up to an order of magnitude. There are few SNRs with associated pulsars, so only for a very limited number of SNRs we can obtain an estimated age using the first method. For some SNRs, observationally determined R and υ_s values are available, then the estimated ages have a good accuracy. When such information is not available, rough reasoning from the progenitor outburst energy, or kT, or even spectral break, would give us some plausible indications or limits on the age.

2.2 SNR Distances

Distances to SNRs can be determined by observations of extinction, X-ray, SN magnitude, background star, SNR kinematics and HI absorption, etc. (Strom 1988).

The absorption line of neutral hydrogen (21-cm wavelength) observed in the direction of an SNR is a useful tool for the determination of its distance (Sato 1977). One can make interferometric observations of the line against many continuum sources including SNRs, checking the absorption will give the dynamic distance of the SNR. For example, Reynoso & Goss (1999) reported a new determination of the distance of the remnant of Kepler's supernova (SN1604, 3C358), by using Very Large Array HI observations of the remnant carried out with an angular resolution of approximately 15″ and velocity resolution of 1.3 km s^{-1}. Based on a weak HI absorption feature at <21.3 km s^{-1} seen in the new data, a lower limit of 4.8±1.4 kpc can be derived. When the remnant has not been influenced by the circumstellar medium, it seems to have a negligible effect on the expansion process. At a velocity of +21.3 km s^{-1}, emission from an HI cloud to the east of the SNR is detected, which may be physically associated with the remnant based on morphological considerations. An upper limit of 6.4 kpc to the distance can be derived based on the lack of HI absorption at velocities >50 km s^{-1}, where extended

HI emission is detected. Therefore, Reynoso & Goss (1999) concluded that the distance of the Kepler SNR is about 5.6±0.8 kpc.

2.3 The Radio Spectral Index of SNRs

The spectral index of radio emission from SNRs can only be derived from observations at several bands. It is a basic physical parameter for SNRs, but relatively difficult to be acquired. Radio spectrum of SNRs in general follows a power-law. Evidently the radio emission of SNRs is produced by synchrotron radiation.

The data of spectral indices of 231 SNRs in Green (2004) are compiled from the literature, derived from observations by different authors using different radio telescopes with various resolutions at different frequencies. We directly adopt the spectral index values from the catalog of Green (2004) for our statistical work. The average spectral index is $\alpha = -0.5 \pm 0.25$, which means that the energy spectral index of emission electrons is $\mu = 2 \pm 0.5$.

Due to the reacceleration process by shocks as discussed by Bell (1978a), the SNR spectral index is correlated with no other SNR parameters than the shock velocity.

3 STATISTICAL RESULTS AND DISCUSSION

3.1 Age-Diameter Relationship for S-Type SNRs

From the Sedov solution, Eq. (1), for S-type SNRs in the adiabatic phase we can find

$$\log_{10}\left(\frac{D}{\mathrm{pc}}\right) = a_0 + \frac{2}{5}\log_{10}\left(\frac{t}{\mathrm{yr}}\right), \tag{2}$$

where D is the diameter of the SNR, t is the age since the explosion, and a_0 is a constant. So in the $\log_{10}D$-$\log_{10}t$ diagram one should find a straight-line with a slope of 2/5 for adiabatic SNRs.

For radiative SNRs, McKee & Ostriker (1977) and Blinnikov et al. (1982) obtained the diameter evolution with a slope of 2/7, in the form of

$$\left(\frac{D}{\mathrm{pc}}\right) = 1.42\left(\frac{E}{n_0}\right)^{5/21}\left(\frac{t}{\mathrm{yr}}\right)^{2/7}, \tag{3}$$

where n_0 is the original number density of uniform interstellar medium (ISM).

From the collected data of 80 S-type SNRs (see Fig. 1), we obtained :

$$\left(\frac{D}{\mathrm{pc}}\right) = (1.03 \pm 0.02)\left(\frac{t}{\mathrm{yr}}\right)^{0.34\pm0.02}, \tag{4}$$

which shows that the linear diameter (D) of an S-type remnant increases with the age (t), as expected. The slope 0.34 is an intermediate value between that for the adiabatic phase ($2/5 = 0.4$) and that for the radiative phase ($2/7 \sim 0.3$). Probably the SNRs in our sample are a mixture of adiabatic and radiative SNRs. From Eq. (4) we can find the correlation between the velocity and age to be

$$v = \frac{1}{2}\frac{dD}{dt} = (1.7 \times 10^5)\left(\frac{t}{\mathrm{yr}}\right)^{-0.66} \mathrm{km\,s^{-1}}. \tag{5}$$

Clearly, the expanding velocity decreases with age.

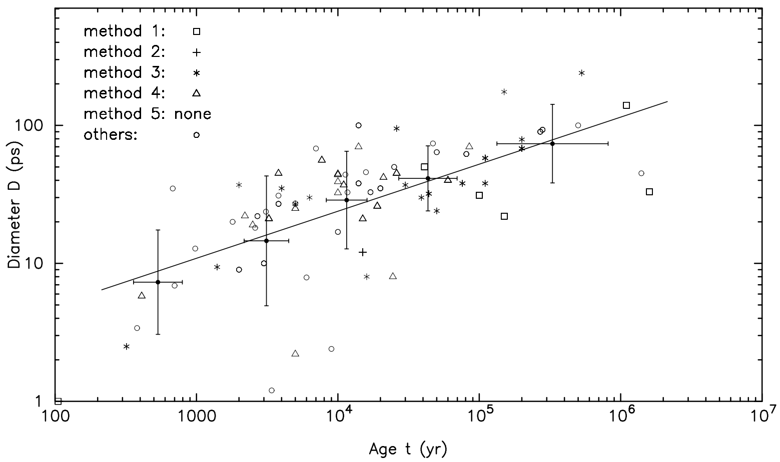

Fig. 1 Linear diameter (D) of 80 radio S-type SNRs plotted against the age (t). The solid-line is the best fit to the average values in 5 bins, given by Equation (4) with a slope of 0.341.

3.2 SNR Diameter versus Galactic Height

We plot the linear diameters (D) of 190 all-type supernova remnants against their Galactic heights (z) in Fig. 2, and find that SNRs at lower Galactic heights (small z-values) tend to have smaller diameters. The straight-line in the plot with a slop of 0.133 is the best fit to the average values in 5 bins:

$$\left(\frac{D}{\mathrm{pc}}\right) \simeq (16.2 \pm 0.13) \left(\frac{z}{\mathrm{pc}}\right) . \tag{6}$$

This relation is understandable. In general, the distribution of interstellar medium (ISM) in our Galaxy is not homogeneous: it has a much higher density near the Galactic plane, and the density exponentially decreases upwards. Undoubtedly SNRs can expand more rapidly in a low density than in a high density environment. Therefore, averaged over all ages, SNRs at large Galactic heights can have larger linear diameters.

3.3 SNR Σ-D and L-D relations

As supernova remnants evolve, their sizes should increase with time, but their brightnesses fade away. Naturally, surface brightnesses (Σ) should anti-correlate with SNR linear sizes (diameter, D). Shklovsky (1960) proposed this relation, and suggested to use it to estimate SNR distance because Σ can be obtained directly from observations, independent from distance.

Many authors have tried to find the experiential relation for these two parameters, in the form of $\Sigma = A\ D^{\beta}$, with a value for the power-law index β from -2.2 to -3.8 for different data-sets of earlier sample, or subsample of SNRs, or at different frequencies (e.g. Clark & Caswell 1976). Apparently, both surface brightness and expansion rate of a SNR should depend on local electron density and magnetic fields in the interstellar medium. Therefore, Milne (1979) and Caswell & Lerche (1979) suggested that the Σ-D relation should be z-dependent. Though Green (1984, 2004) argued otherwise, the tendency for the Σ-D relation for SNRs with very reliable distances clearly shown in Fig.2 and Fig.3 of Green (1984) and Fig.11 of Green (2004). Similar relation was also found for SNRs in LMC and SMC by Mills et al. (1984) and M82 by

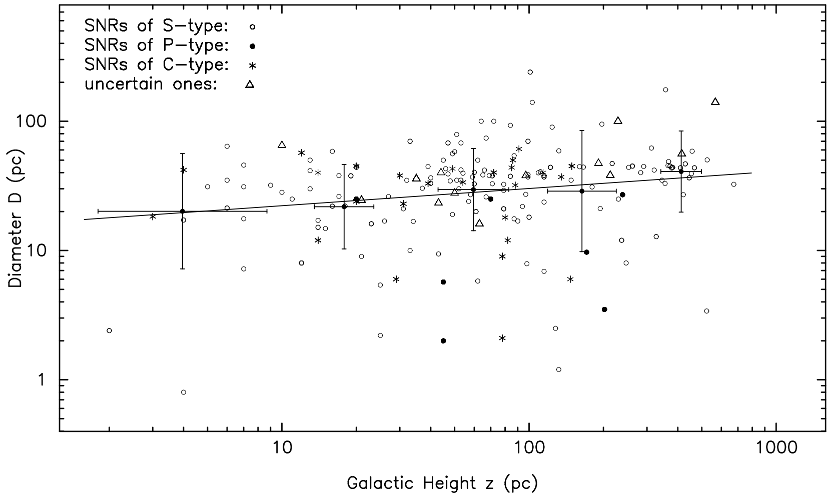

Fig. 2 Correlation between the linear diameter (D) of 190 radio all-type SNRs and their Galactic height (z). The line with a slope of 0.133 is the best fit to the averages. The tendency is clear that SNRs at lower Galactic heights have smaller diameters.

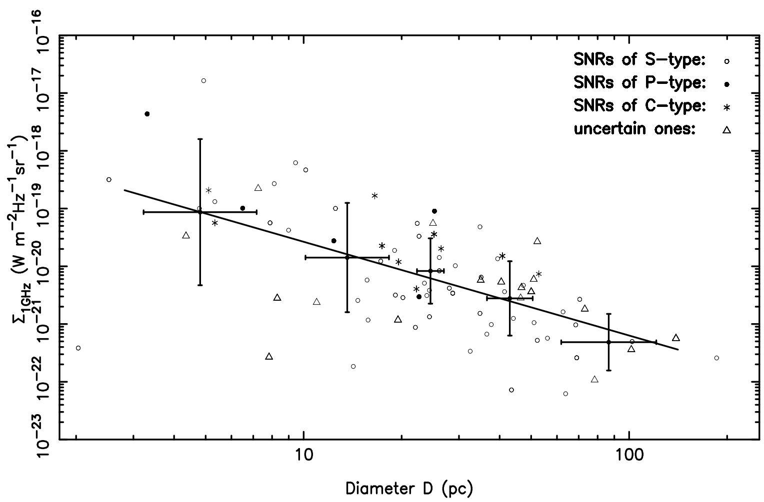

Fig. 3 Surface brightness of 85 SNRs against their linear diameter (D). A fit to the five averages gives a slope $\beta = -1.6 \pm 0.3$.

Arbutina et al. (2004). If one selects SNRs with similar environment, e.g. in cloudy medium (Arbutina et al. 2004) or just shell SNRs (Allakhverdiyev et al. 1983), a much better correlation with less scatter between Σ and D can be obtained (see Huang & Thaddeus 1985). Theoretical explanations for the Σ-D relation can be found in Duric & Seaquist (1986).

In Fig.3, we plotted Σ against D of 85 SNRs, for which distances were not estimated from Σ-D relation but other approaches (Table 1 on web page). We also noticed that their luminosities, L, are almost independent on D as shown in Fig.4 with large scatter. Green (2004) is right that the Σ-D relation is dominated by the D, rather than luminosity, because $\Sigma \sim L/D^2$. The fit we got in Fig. 3 gives a power-law slope of -1.6 ± 0.3, very close to -2. The figure

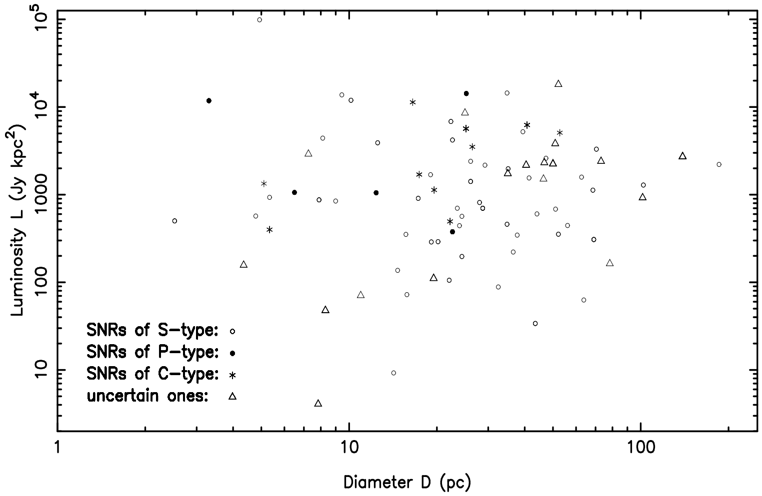

Fig. 4 Radio luminosities of 85 SNRs show no relation to their linear diameter.

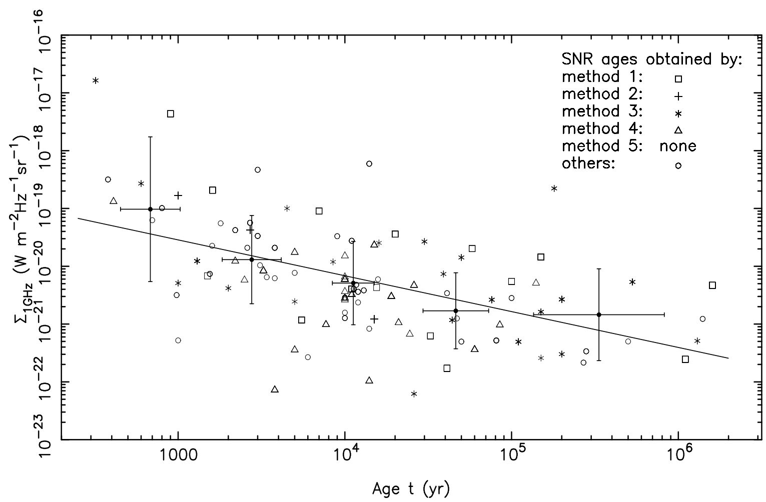

Fig. 5 Surface brightness (D) of 108 SNRs decrease with age (t).

shows no broken line as that by Clark & Caswell (1976); Allakhverdiyev et al. (1983; 1985); Duric & Seaquist (1986); Guseinov et al. (2003), etc. but a single straight line similar to the statistical results by some others. The Σ-D relation could be interpreted as two following main bases. At first the remnant diameter becomes larger as the shock waves expanding, and then flux intensity in per unit area observed will decrease. For another reason, the electron energy would gradually diminish until that paiticle acceleration practically ceases since the physical procedure of emission loss with time, leading to the remnant flux intensity fades away. Therefore surface brightnesses (Σ) appear anti-correlate with SNR linear sizes. The power-law slope value in Fig. 3 is somewhat smaller than the former outcome by others. Because our statistics have contained all-sort-type of SNRs with very different properties, e.g., different outburst kinetic energy E of progenitor, different environment such as magnetic fields and ambient gas density, etc. If a "good" sample was selected in advance, then there would be to some extent less scatter on the plot, and also the obtained line may be a little steeper.

3.4 SNR Σ-t and L-t Relations

Figures 5 and 6 show the relation between surface brightness Σ or luminosity L and age of SNRs. The straight lines in two figures are the best fits,

$$\Sigma = (2.09 \pm 0.12) \times 10^{-18} t^{-0.62\pm0.01}\ \mathrm{W\ m^{-2}\ Hz^{-1}\ sr^{-1}}, \tag{7}$$

and

$$L = (3.79 \pm 0.12) \times 10^{3} t^{-0.13\pm0.01}\ \mathrm{erg\ s^{-1}\ Hz^{-1}}. \tag{8}$$

Here age t is in yr. Younger SNRs tend to be brighter than older SNRs. Naturally, the relativistic electrons accelerated in the shock wave of the SNRs to produce synchrotron radiation are more energetic in the early stage than in the later stage. As the SNR evolves, the relativistic electrons are likely to lose some of their energies, and the power of the SNR's shock wave is likely to get weaker. Therefore, as an SNR expands and its size increases, its luminosity cannot remain constant. Figures 5 and 6 show the evolution, though with much scatter.

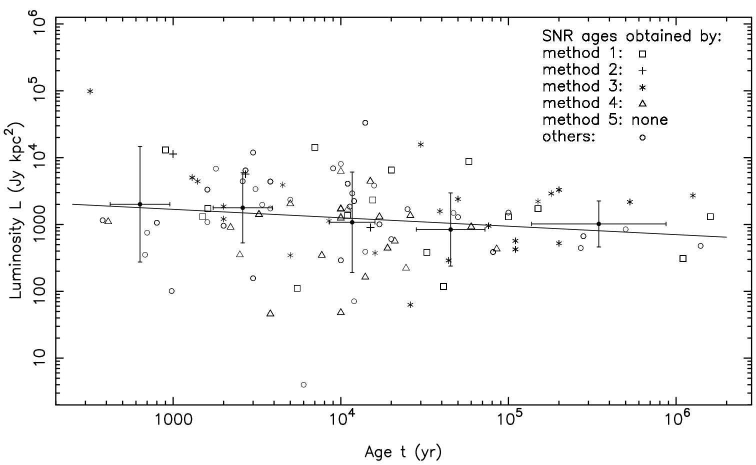

Fig. 6 Luminosity (L) of 107 SNRs tends to decrease with age (t).

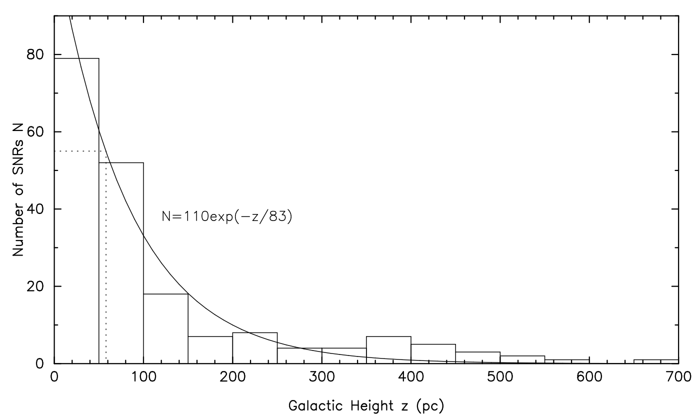

Fig. 7 Spatial distribution of 191 radio all-type SNRs in Galaxy along with their distances from the Galactic plane. It shows that the number of SNRs decreases exponentially with the height. The best fit is $N = 110\, e^{-z/83\mathrm{pc}}$, with half-peak width approximately 58 pc.

3.5 The Galactic Height Distribution of SNRs

Figure 7 shows that the number distribution of SNRs with the Galactic height decreases exponentially. The best fit is $N = 110\, e^{-z/83\mathrm{pc}}$, with a half-peak width approximately 58pc. Thus, the SNRs in the Milky Way are principally distributed in or near the Galactic plane. The greater the distance from the plane, the fewer the SNRs. This distribution is consistent with the position distribution of their progenitors, mainly O or B type massive stars, which are located near the Galactic plane. After a supernova explosion, the remnant remains without any shift in position.

4 CONCLUSIONS

We made a statistical analysis on the parameters of 231 galactic supernova remnants, and obtained following results:

1. The SNR linear size increases with age, as expected;
2. The SNR linear size tends to increase with the Galactic height;
3. Both the SNR surface brightness and luminosity at 1-GHz frequency decrease with the linear diameter.
4. Both the SNR surface brightness and luminosity at 1-GHz frequency decrease with age.
5. SNRs are very much concentrated on the Galactic plane.

We also checked possible relationship among these parameters but no other physically significant correlations were found. For example, there is no firm relation between the spectral index and the galactic height (α-z), nor a relation between the spectral index and age (α-t), etc.

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