The Radial Distribution of SNRs in Nearby Galaxies

Manami Sasaki,[1] Dieter Breitschwerdt[2]
(1) Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
(2) Max-Planck-Institut für extraterrestrische Physik, Giessenbachstraße, Postfach 1312, 85741 Garching, Germany

Abstract

Since supernova remnants (SNRs) are believed to be the primary energy sources of the interstellar medium in general and of Galactic cosmic rays (CRs) in particular, their distribution in galaxies is an important basis for modelling the distribution of the CRs and their γ-ray spectrum. We analyzed the radial surface density of X-ray and radio selected SNRs in the Large Magellanic Cloud (LMC), M 33, M 31, and NGC 6946. In each of the galaxies, the surface densities of the X-ray and radio SNRs are in excellent agreement, showing an exponential decay in radius. The radial scale length of the distribution is $\frac{1}{4} - \frac{1}{3}$ of the radius of the galaxies, fully consistent with values derived for the Milky Way. Therefore, not only the radio SNRs, but also the X-ray detected SNR sample can be interpreted to be representative for the CR sources within a star forming galaxy.

1. Introduction

Diffusive shock acceleration in SNRs is thought to be the key process in generating Galactic CRs below $\sim 10^{15}$ eV. Therefore, the distribution of SNRs in the Galaxy is a crucial basis for the understanding of the CR distribution. Based on data of Galactic SNRs, [12] showed that the surface density can be described as $f(x) = C\, x^{\alpha} \exp(-\beta x)$ (x: radial distance) with a maximum at a distance of several kpc from the Galactic centre. [4] used the function $f(x) = C\, sin(\pi x + \theta) \exp(-\beta x)$, noticing that the distribution seems to be larger than zero at $x = 0$. However, since the sample of Galactic SNRs is flux limited, older and distant remnants are missed systematically. The analysis of *supernovae* (SNe) in different galaxies by [6] showed that the average distribution can be written as $f(x) = C \exp(-\beta x)$. While observing SNRs reveals us the population in a time interval of more than 1000 years, the sample of SNe is limited to only a few decades. In addition, Galactic SNR samples are plagued with distance uncertainties. Thus with present day X-ray and radio telescopes and their instrumentation, the observation of SNRs in *external face-on galaxies* in these wavelengths is by far

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Table 1. Fit results for $f(x) = C \exp(-x/R)$. D_{25} and R denote the optical diameter and the exponential radial scale length in kpc, respectively.

Data		C	$R = 1/\beta$	Red. χ^2
LMC (Radio)	[7] a.r.t.	3.74±1.59	0.29±0.06	1.16
LMC (X-rays)	[11] a.r.t.	3.25±1.17	0.27±0.05	1.03
M 33 (Radio)	[8]	2.84±0.71	0.28±0.03	1.06
M 33 (X-rays)	[9]	1.52±0.84	0.23±0.06	1.23
M 31 (Radio)	[2] a.r.t.	0.10±0.05	0.37±0.08	1.65
M 31 (X-rays)	[15]	0.12±0.07	0.33±0.09	1.82
NGC 6946 (Radio)	[10]	1.32±0.50	0.24±0.04	1.42

Note: a.r.t.: and references therein.

the best method to study their radial distribution. We therefore analyzed X-ray and radio selected SNRs of the Large Magellanic Cloud (LMC) – a dwarf galaxy with spiral arms and bar-like structure. In order to compare the results with the Milky Way, we also selected the grand-design spiral M 31 and the face-on spiral M 33 as well as the spiral starburst galaxy NGC 6946.

2. Radial SNR surface density distribution

After the SNR positions were corrected for projection and the radial distances to the centre of the galaxies were normalized to $D_{25}/2$, the surface density of the SNRs was calculated for equidistant radial binning. In Fig. 1, the SNR surface densities are plotted against the normalized radial distance together with model distributions. The best fit parameters for the exponential distributions are listed in Table 1.

The radial dependencies of the SNR surface densities of the X-ray selected and radio selected SNRs in the LMC are comparable with a scale length for an exponential distribution of $\sim 0.3 \times D_{25}/2 \approx 1.4$ kpc. In M 33, the surface density distribution of H I is known to peak at $\sim 10' = 0.3 \times D_{25}/2 \approx 1.9$ kpc. Also in the SNR distribution, there is a maximum at the corresponding distance within the statistical errors, suggesting that the star formation rate correlates with the H I surface density. As for M 31, the radio and X-ray selected SNRs have similar surface densities with a maximum again at $\sim 0.3 \times D_{25}/2 \approx 5.8$ kpc distance from the centre of the galaxy. This distribution is in perfect agreement with the SNR distribution in the Milky Way. The SNR surface density in NGC 6946 increases steeply towards the centre, probably due to the starburst activities in the central part. In total, the radial surface density distribution of the radio selected SNRs in NGC 6946 has an exponential scale length of $0.24 \times D_{25}/2 \approx 2.2$ kpc.

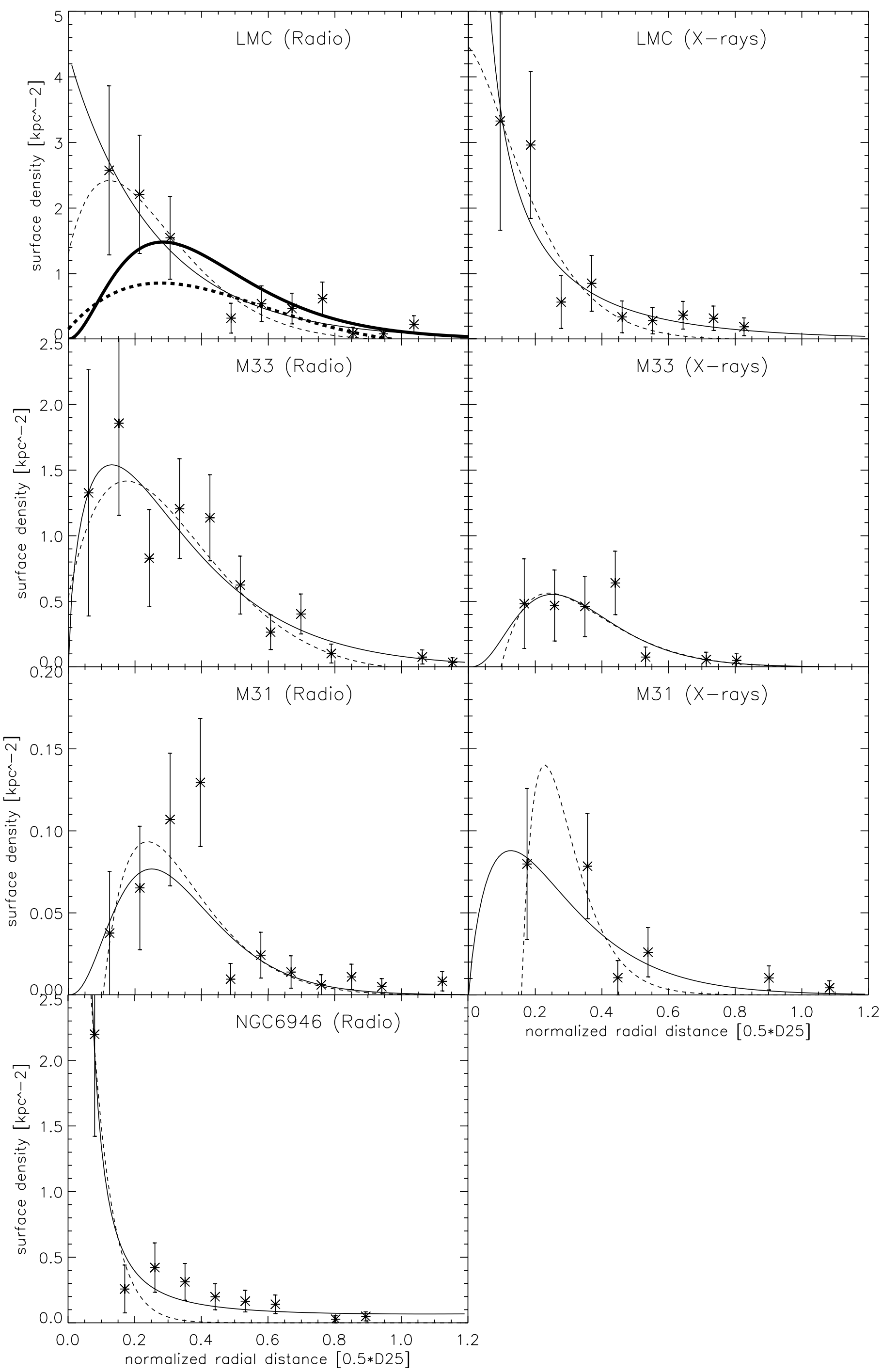

Fig. 1. Surface densities and fit curves for radio and X-ray selected SNRs. Solid lines are used for the model function $f(x) = C\, x^{\alpha} \exp(-\beta x)$ and dashed lines for $f(x) = C\, sin(\pi x + \theta) \exp(-\beta x)$. The models used for the Galactic SNRs by [4] are plotted in the first diagram with thick lines.

3. Discussion

A rather flat radial distribution of the diffuse Galactic γ-ray emission has been observed by COS-B ([13]) and EGRET ([5, 14]). For more than 10 years there has been an ongoing effort to reproduce this weak radial gradient of the γ-ray emissivity in our Galaxy by theoretical models with a strongly peaked CR source distribution similar to the SNR distribution: e.g. [1] presented a model, in which diffusion is the dominant process of the transport; a huge diffusion halo is needed for flattening, but is inconsistent with CR secondary measurements. A model considering dynamical coupling of the CR particles and the thermal plasma was developed by [3], showing that flattening of the γ-ray gradient was a consequence of CR advection, and therefore escape, being proportional to the SNR surface density. Our analysis has shown that the radio and X-ray selected SNRs in M 31 and M 33 have distributions similar to the Galactic SNRs, with a scale length of $\sim 0.25 - 0.35 \times D_{25}/2$ and a maximum at $(0.2 - 0.4) \times D_{25}/2$, thus reiterating that also the Galactic SNR distribution is strongly peaked. The perfect correlation between radio and X-ray selected SNRs indicates that both types are good candidates for CR sources, as it is expected, since both are related to Population I objects. Although the SNR surface densities of the LMC (active star formation) and NGC 6946 (starburst nucleus) differ significantly from that of the Milky Way, M 31, and M 33, the scale lengths of the exponential fit are comparable for all of these galaxies. This suggests that it is the *radial dependence of the gravitational potential*, which controls the global radial SNR distribution, rather than the absolute value of the gas density and thus star formation rate.

4. References

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