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The $\Sigma - D$ relation for supernova remnants in nearby galaxies*

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Abstract. This paper examines relations between the radio surface brightness Σ and the diameter D (also known as $\Sigma - D$ relations) for a sample of extragalactic supernova remnants (SNRs) as constructed from a combination of published data and data from our own surveys. Our sample of extragalactic SNRs is the largest ever devised for the purpose of analyzing $\Sigma - D$ relations. The main results of this paper may be summarized as follows: (i) the empirical relations for SNRs in 10 of the 11 nearby galaxies studied have the approximately trivial $\Sigma \propto D^{-2}$ form, therefore limiting their interpretation as physically meaningful relations. In addition, these relations are subject to selection effects rendering them even less useful. Further Monte Carlo simulations suggest that the effect of survey sensitivity has the opposite effect of volume selection (e.g. Malmquist bias, a volume selection effect that shapes the Galactic sample) by tending to flatten the slopes toward a trivial relation. In this case, the true slopes may be steeper than the observed slopes; (ii) compact M 82 SNRs appear to follow a uniquely different $\Sigma - D$ relation in comparison to the larger, older SNRs in the other 10 galaxies. Monte Carlo simulations suggest that the probability of this difference arising by chance is ≈1% to 10%, depending on what is assumed regarding the underlying SNR population; (iii) three candidate hypernova remnants were identified in our sample of 11 nearby galaxies.

Key words. ISM: supernova remnants – methods: statistical – radio continuum: galaxies

1. Introduction

1.1. The $\Sigma - D$ relation – a short review

The relation between surface brightness Σ and diameter D for supernova remnants (SNRs) – known as the $\Sigma - D$ relation – presents a possible avenue for investigating the radio brightness evolution of these sources. Shklovsky (1960a) theoretically analyzed the synchrotron radiation for a spherical expanding nebula and finds a $\Sigma - D$ relation of the form

$$\Sigma = AD^{-\beta}. \tag{1}$$

This relation was also analyzed theoretically by Lequeux (1962), Poveda & Woltjer (1968) and Kesteven (1968), and an updated theoretical derivation of this relation for shell-like SNRs is described by Duric & Seaquist (1986, hereafter D&S): the structure of the derivation presented by D&S is similar to the one presented by Shklovsky (1960a). D&S adopted both Bell's (1978a,b) formulation of Fermi's acceleration mechanism and a magnetic field model based on the research of Gull (1973) and Fedorenko (1983). Gull (1973) proposed a model in which the ambient magnetic field, which is assumed to be amplified in the convection zone, provides the environment in which relativistic electrons can radiate efficiently. Fedorenko (1983) formulated a model in which the magnetic field B varies with D according to $B \propto D^{-x}$, where $1.5 \leq x \leq 2$.

1.1.1. The Galactic relation

Early observations supported the existence of a $\Sigma - D$ relation in the form that the Shklovsky theory had predicted. The first empirical $\Sigma - D$ relation was determined by Poveda & Woltjer (1968). Using the $\Sigma - D$ relation, Shklovsky (1960b) presented

* Appendix A is only available in electronic form at
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a way to determine distances to SNRs based on their surface brightnesses. This method of distance determination for SNRs has a significant advantage over other methods in that the surface brightness of a radio SNR does not depend on its distance.

Milne (1970) derived an empirical $\Sigma - D$ relation and calculated distances to all of the observed SNRs in our Galaxy (97 in total). This relation was the subject of many investigations in an attempt to precisely determine a specific set of calibrators to achieve an improved $\Sigma - D$ relation. The basic criterion for the choice of calibrators is a reliable distance to the SNR. Most studies of the $\Sigma - D$ relation that were conducted during the 1970s and the early 1980s are of this type. More sensitive observations enabled more precise calculations of the distances to the calibrators, and thus the number of quality calibrators increased. During this time, Galactic $\Sigma - D$ relations were studied by Downes (1971), Ilovaisky & Lequeux (1972), Woltjer (1972), Berkhuijsen (1973), Clark & Caswell (1976), Sabbadin (1977), Milne (1979), Caswell & Lerche (1979), Göbel et al. (1981), Lozinskaya (1981) and Sakhibov & Smirnov (1982). Critical analysis of this relation began with Allakhverdiyev et al. (1983a,b) and continued with the research of Green (1984), Allakhverdiyev et al. (1986a), and Allakhverdiyev et al. (1986b). Inaccurate calculations of the distances to certain calibrators is the basic deficiency of the relations derived in this manner, i.e. there are not as many SNRs with precisely calculated distances as are needed to derive the proper $\Sigma - D$ relation (Green 1984). Also, the ambient interstellar medium where supernovae explode must be taken into consideration. Allakhverdiyev et al. (1983a, 1983b, 1986a, 1986b) argued that the $\Sigma - D$ relation was only applicable to shell-type SNRs. Other significant works on the relation were conducted by Li & Wheeler (1984), Huang & Thaddeus (1985) and Berkhuijsen (1986).

Initial studies of the $\Sigma - D$ relation yielded significant differences between theoretical models and empirical results. Green (1991) argued that too much scatter exists among the calibrators used for studies of the $\Sigma - D$ relation and therefore no valid relation can be derived. However, this view was challenged by Case & Bhattacharya (1998, hereafter C&B) who presented calculations of distances to 37 calibrators with the help of new Galactic constants. Using these new distances, C&B obtained a much flatter slope for the $\Sigma - D$ relation and emphasized the inconsistency between the empirical and the theoretical $\Sigma - D$ relations. Finally, C&B also updated the Galactic empirical relation and determined distances for all identified shell-type SNRs. After nearly four decades of research, our understanding of the $\Sigma - D$ relation continues to evolve from both theoretical and empirical perspectives.

1.1.2. Extragalactic relations

The construction of extragalactic $\Sigma - D$ relations are both possible and straightforward because all of the calibrators are at approximately the same distance. Therefore, the distance determination problem is reduced once we know the distance to the galaxy. If we identify a radio SNR, we may consider that source to be a calibrator; furthermore, a set of extragalactic radio SNRs does not suffer from Malmquist bias, i.e., distance dependent selection effects. However, sensitivity becomes an issue with increasing distance to target galaxies, and for that reason most extragalactic radio SNRs have been detected in nearby Local Group galaxies, such as the Large Magellanic Cloud (LMC), the Small Magellanic Cloud (SMC), M 31, and M 33. The first empirical extragalactic $\Sigma - D$ relation was constructed by Mathewson & Clarke (1973b) for the LMC with 15 identified SNRs, followed by the work of Milne et al. (1980) with 19 SNRs in the LMC, Mathewson et al. (1983) with 31 SNRs (25 from the LMC and 6 from the SMC), and finally Mills et al. (1984) with 38 SNRs (27 in the LMC and 11 SNRs in the SMC).

The $\Sigma - D$ relations for radio SNRs in the nearby spiral galaxies M 31 and M 33 were investigated by Berkhuijsen (1983). Observations conducted by Braun & Walterbos (1993) detected radio emission from 24 radio SNRs in M 31 using observations made with the Very Large Array (VLA) at an observing frequency of 1465 MHz. Similarly, Duric et al. (1995) identified 53 SNRs in M 33 using the VLA at approximately the same frequency. In general, the $\Sigma - D$ relations for radio SNRs in these two galaxies were found to be flatter than the Galactic $\Sigma - D$ relation.

1.2. Compact SNRs

A growing number of rather compact radio SNRs have been recently detected in several nearby starburst galaxies. An example of such a galaxy is M 82, which is known to harbor a particularly large number of these SNRs (Huang et al. 1994). These compact SNRs are presumably young, so at the opposite evolutionary extreme to the old SNRs, e.g. the Galactic radio loops (Urošević 2002, 2003). Including these young SNRs with the older SNRs in an analysis of the $\Sigma - D$ relation provides an opportunity to explore this relation beyond the parameters normally considered in earlier studies, as well as to seek out unique evolutionary signatures in the data.

Theory predicts that the evolution of young SNRs ($\ll$10 pc diameter) is different enough to define a measurably distinct $\Sigma - D$ relation. For example, in the theory of D&S, the youngest SNRs should follow a relation with $\beta = 5$, while the older SNRs should exhibit $\beta = 3.5$. To test this theoretical prediction, we have included 21 of the young radio SNRs within M 82 as identified by Huang et al. (1994) in our analysis. A comparison of these young radio SNRs with other extragalactic and Galactic radio SNRs is presented in Sects. 2 and 3.

1.3. Objectives

This paper examines the $\Sigma - D$ relations of extragalactic SNRs for the purpose of:

(i) investigating the role of selection effects, particularly the effect of sensitivity in the extragalactic samples;
(ii) identifying signatures of evolutionary effects linked to a specific theory that predicts it; and
(iii) identifying hypernova remnant (HNR) candidates in nearby galaxies.

Table 1. General properties of the nearby galaxies with radio SNRs.

Galaxy	Hubble type[†]	Major and minor (arcmin)[†]	Distance (Mpc)	Incl. angle (degrees)[‡]	Number of radio SNRs
LMC	SB(s)m	645 × 550	0.055[a]	35	52
SMC	SB(s)m pec	320 × 185	0.065[a]	61	12
M 31	SA(s)b	190 × 60	0.75[b]	78	30
M 33	SA(s)cd	70.8 × 41.7	0.82[b]	56	53
IC 1613	IB(s)m	16.2 × 14.5	0.69[b]	27	1
NGC 300	SA(s)d	21.9 × 15.5	2.1[c]	46	17
NGC 6946	SAB(rs)cd	11.5 × 9.8	5.1[d]	42	35
NGC 7793	SA(s)d	9.3 × 6.3	3.38[e]	50	7
M 82	I0	11.2 × 4.3	3.9[f]	66	50
NGC 1569	IBm	3.6 × 1.8	2.2[g]	64	3
NGC 2146	SB(s)ab pec	6.0 × 3.4	14.5[h]	36	3

Note: [†]NED Database; [‡]Tully (1988); [a]Filipović (2002); [b]Freedman et al. (2001); [c]Freedman et al. (1992); [d]de Vaucouleurs (1979); [e]Puche & Carignan (1988); [f]Sakai & Madore (1999); [g]Israel (1988); [h]Tarchi et al. (2000).

2. Analysis of $\Sigma - D$ relations in nearby galaxies

2.1. Selection effects

Data sets of Galactic SNRs suffer from a severe Malmquist bias; i.e., intrinsically bright SNRs are favored because they are sampled from a larger spatial volume compared to any given flux limited survey. The result is a bias against low surface-brightness remnants such as highly evolved old SNRs. On the other hand, data sets made up of extragalactic SNRs do not suffer from Malmquist bias because all SNRs are at the same distance and are therefore sampled from the same volume. Though extragalactic data sets are generally better behaved compared to Galactic samples, they do suffer from other selection effects from limitations in sensitivity and resolution, as well as from source confusion. These selection effects cause samples of extragalactic radio SNRs to span a shorter range of both diameters and surface brightness.

2.2. Radio SNRs in nearby galaxies and $\Sigma - D$ relations

To prepare the sample of sources considered in this paper, we performed a detailed literature search for candidate radio SNRs detected in nearby galaxies and added them to our own data. Properties of the 11 galaxies considered in this paper are listed in Table 1 and include Hubble type, major and minor axes (in arcmin), distance (in Mpc), inclination angle (in degrees) and a number of known radio SNRs. For our study, we selected only those SNRs both with a flux density at approximately 1.4 GHz (for M 82 we used 8.4 GHz data). When available, we adopted the given diameters for these SNRs as measured by radio observations; however, in most cases radio diameters were available for only the nearest extra-galactic SNRs (e.g. sources in the LMC and the SMC) or those sources observed at extremely high angular resolution with such instruments as MERLIN (e.g. sources in NGC 1569 and NGC 2146). In other cases where a radio diameter was not available, diameters measured for the optical counterparts to the radio SNRs were adopted. Finally, where available, we adopted published values for the spectral index α ($S_\nu \propto \nu^{-\alpha}$) of these sources; if no spectral index was given, a value of 0.5 was assumed. For almost every radio SNR in our sample, we have calculated a surface brightness at 1 GHz using a published flux density at ~1.4 GHz (8.4 GHz for M 82) and a published (or assumed) spectral index. Below we give some comments about each galaxy in our study and their corresponding set of radio SNRs.

In Table A.1, for each extragalactic radio SNR in our sample we list the name of the source, the host galaxy, the diameter D (in parsecs), the flux density $S_{1.4}$ at 1.4 GHz (in mJy), the spectral index α, and the surface brightness $\Sigma_{1\ \mathrm{GHz}}$ at 1 GHz (in W m^{-2} Hz^{-1} sr^{-1}). In Table 2, we list the resolution and sensitivity data (observing frequency ν, angular resolution, linear resolution, root-mean-square noise, and limiting radio luminosity L_ν) for the radio SNR searches conducted in each galaxy. We have used the least-squares method to derive $\Sigma - D$ relations for samples of radio SNRs in individual galaxies (such as the LMC, the SMC, M 31, M 33 and M 82), as well as for the entire sample of radio SNRs in all of the galaxies. In Table 3 we list the derived values for β for each case; and to quantify the goodness of each fit, we also give the corresponding values for the correlation coefficient between $\log A$ and β (see Relation 1) and for the fit quality based on the value of minimum Chi squared (scatter of residuals relative to the best fit line). All of the calibrators used to define these $\Sigma - D$ relations are assumed to have equal statistical weight. Finally, all errors are formal standard errors as derived by the least-squares method.

2.2.1. LMC and SMC

The LMC and the SMC, the two closest galaxies to the Milky Way, are excellent choices for a survey of a nearby galaxy's candidate radio SNR population. At distances of only 55 kpc and 65 kpc (Filipović 2002), respectively, the SNRs in these galaxies are close enough to be resolved for detailed study at many wavelengths (including radio); yet observations of these SNRs can be made without the observational biases that affect studies of Galactic radio SNRs. The first study of SNRs in the LMC was provided by Westerlund & Mathewson (1966), who

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Table 2. Resolution and sensitivity for searches for radio SNRs in nearby galaxies.

Galaxy	ν (GHz)	Resolution (arcsec)	Resolution (pc)	rms noise (μJy/beam)	Limiting L_ν ($\times 10^{22} \frac{\text{erg}}{\text{s Hz}}$)	Reference
LMC	1.40	912	243	30 000	11	Filipović et al. (1998b)
SMC	1.42	828	261	15 000	7.7	Filipović et al. (1998b)
IC 1613	1.46	5	17	56	3.2	Lozinskaya et al. (1998)
M 31	1.465	5	18	30	2.0	Braun & Walterbos (1993)
M 33	1.42	7	28	50	4.1	Gordon et al. (1999)
NGC 300	1.45	4	39	60	30	Pannuti et al. (2000)
NGC 6946	1.45	2	49	20	63	Lacey et al. (1997)
NGC 7793	1.47	7	115	60	83	Pannuti et al. (2002)
M 82	8.4	0.182	3	360	660	Huang et al. (1994)
NGC 1569	1.412	0.20	2	25	15	Greve et al. (2002)
NGC 2146	1.6	0.17	12	35	890	Tarchi et al. (2000)

Table 3. Fit characteristics of $\Sigma - D$ relations at 1 GHz for SNRs in nearby galaxies.

Galaxy	β (c.c.; f.q.)	No. of SNRs (comments)
M 31	1.67 ± 0.26 (–0.77; 60%)	30
M 33	1.77 ± 0.20 (–0.79; 62%)	51
LMC	2.28 ± 0.40 (–0.77; 59%)	25
SMC	2.28 ± 0.52 (–0.89; 80%)	7
Galactic (C&B)	2.38 ± 0.26 (–0.84; 71%)	36 (excluding Cas A)
M 82	3.41 ± 0.24 (–0.95; 91%)	21
"Master"		
	3.20 ± 0.11 (–0.92; 84%)	148 (complete sample)
	3.30 ± 0.09 (–0.95; 89%)	145 (excluding 3 HNRs)

Note: c.c. and f.q. represent the correlation coefficient and the fit quality, respectively.

used radio and optical observations to identify three SNRs in the LMC – N49, N63A, and N132D. Since that work, numerous additional radio studies of the SNRs in these two galaxies have been conducted (Mathewson & Clarke 1972, 1973a,b; Mathewson et al. 1983, 1984, 1985; Dickel et al. 1993, 1994, 1995; Filipović et al. 1998a,b). For the present work, we have considered 25 of the best-studied radio SNRs in the LMC and 7 in the SMC. Flux densities and spectral indices for these sources have been extracted from the work of Filipović et al. (1998b). We calculated diameters for these sources using our assumed distances to these two galaxies and the optical diameters (in arcseconds) listed by the Magellanic Cloud Emission-Line Survey (MCELS[1]).

[1] See `http://www.ctio.noao.edu/mcels/snrs/snrcat.html` The MCELS is funded in part through the support of the McLaughlin Fellowship, a bequest from the family of Dr. Dean B. McLaughlin in memory of his lasting impact on astronomy. Funding is also provided through the NSF.

The $\Sigma - D$ relations for the 25 LMC and 7 SMC SNRs are:

$$\Sigma_{1\text{GHz}} = 3.76^{+11.55}_{-2.84} \times 10^{-17} D^{-2.28\pm0.40} \quad (2)$$

and

$$\Sigma_{1\text{GHz}} = 2.52^{+13.87}_{-2.13} \times 10^{-17} D^{-2.28\pm0.52}, \quad (3)$$

respectively and their slopes are remarkably similar.

2.2.2. M 31

The radio SNR population in M 31, the nearest major galaxy at a distance of 0.75 Mpc (Freedman et al. 2001), has been the subject of several studies, but its very steep inclination angle and its large angular size have made a thorough analysis of this SNR population very difficult. A total of 221 SNRs have been identified in this galaxy by optical surveys (D'Odorico et al. 1980; Braun & Walterbos 1993; Magnier et al. 1995); of these optically-identified SNRs, 30 have radio counterparts (Dickel et al. 1982; Dickel & D'Odorico 1984; Braun & Walterbos 1993) and fifteen have X-ray counterparts (Supper et al. 2001). In our sample, we calculated the diameters for the radio SNRs using the optical axes for each SNR as given by Braun & Walterbos (1993). Flux densities were extracted from the list presented by Braun & Walterbos (1993; measured at 1.465 GHz) with two exceptions. In the case of the optically-identified SNR K527A, the flux density given by Braun & Walterbos (1993) does not correspond to a 3σ detection, so it was excluded. In the case of the optically-identified SNR DDB-7, we used the flux density given by Dickel & D'Odorico (1984) instead of the value given by Braun & Walterbos (1993). We took the names for the SNRs from both the lists of D'Odorico et al. (1980) and Braun & Walterbos (1993), with an emphasis on the former work.

For the 30 selected radio SNRs in M 31, we obtained the relation

$$\Sigma_{1\text{GHz}} = 1.99^{+2.94}_{-1.19} \times 10^{-18} D^{-1.67\pm0.26}. \quad (4)$$

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2.2.3. M 33

Like M 31, M 33 has been the subject of many SNR studies given its proximity (0.82 Mpc – Freedman et al. 2001), but unlike M 31 the face-on orientation of M 33 is far more conducive to detailed studies of these sources at multiple wavelengths: e.g., Duric et al. (1995) and Gordon et al. (1999) at radio (6 and 20 cm), Long et al. (1996) at X-ray, and Gordon et al. (1998) at optical wavelengths. Based on radio observations, a total of 53 radio SNRs in M 33 have now been identified, and 51 are included here. For diameters of the sources, we adopted the values listed by Gordon et al. (1999), who assumed a slightly greater distance (to M 33 of 0.84 Mpc) than the present work. We recalculated the diameters accordingly to find, in all cases, a very slightly difference. Spectral indices and flux densities at 1.4 GHz for the radio SNRs were also taken from Gordon et al. (1999). Two radio SNRs from that survey (namely their sources 44 and 83) are not included in our analysis because confusing emission from adjacent HII regions prevented accurate measurement of flux densities for those two radio SNRs.

We derived a $\Sigma - D$ relation for the 51 radio SNRs, adopting $\alpha = 0.5$ for the 9 SNRs that had no spectral index information. The corresponding relation has the form

$$\Sigma_{1\mathrm{GHz}} = 3.50^{+3.53}_{-1.76} \times 10^{-18} D^{-1.77\pm0.20}. \quad (5)$$

Note that the slopes for the $\Sigma - D$ relations of radio SNRs in M 31 and M 33 are similar within the error bounds. Both relations are flatter than the $\Sigma - D$ relations derived for radio SNRs in the LMC and the SMC.

2.2.4. IC 1613

The radio SNR in IC 1613 was first cataloged as an HII region ("S8") by Sandage (1971) and identified as an SNR by D'Odorico et al. (1980). Additional radio and optical observations and analysis of this source were presented by Dickel et al. (1985) and Peimbert et al. (1988). A thorough multiwavelength study (X-ray, optical and radio) of this SNR was described by Lozinskaya et al. (1998), who measured a flux density of 1.9 ± 0.1 mJy at 1.4 GHz and a spectral index of $\alpha = 0.57 \pm 0.054$, which we used to calculate the surface brightness for this SNR at 1 GHz. Lozinskaya et al. (1998) also measured a diameter of 3 arcsec $\times$ 2 arcsec for this source using both radio and optical data; assuming a distance to IC 1613 of 0.69 Mpc (Freedman et al. 2001), this corresponds to a linear diameter of 8.4 pc.

2.2.5. NGC 300 and NGC 7793

NGC 300 and NGC 7793 are nearby, nearly face-on Sd galaxies located in the Sculptor Group (Puche & Carignan 1988). An optical search for SNRs by Blair & Long (1997) identified a total of 56 SNRs in these two galaxies. Subsequently, Pannuti et al. (2000) and Pannuti et al. (2002) detected radio counterparts to five of these SNRs – N300-S10, N300-S11, N300-S26, N7793-S11 and N7793-S26 – and provided both flux densities at 1.4 GHz and spectral indices for these sources. We adopted the optical diameters for these sources as given by Blair & Long (1997) who assumed distances of 2.1 Mpc for NGC 300 and 3.38 Mpc for NGC 7793 (Freedman et al. 1992; Puche & Carignan 1988). Radio properties for these SNRs were taken from the works of Pannuti et al. (2000, 2002). Note that N7793-S26 has a peculiar morphology; in both optical and radio images, this source appears to be more filamentary (about 450 pc long) than circular (Blair & Long 1997; Pannuti et al. 2002). This source is considered to be a candidate HNR; in Sects. 2.3.2 and 3.3, we will discuss other candidate HNRs in our sample in more detail.

2.2.6. NGC 6946

This galaxy has been the subject of both optical and radio searches for SNRs (Matonick & Fesen 1997; Lacey et al. 1997). Though both searches detected a large number of sources (27 and 35, respectively), only two were in common (Lacey & Duric 2001): MF9 and MF16, using the notation from Matonick & Fesen (1997). MF16 is known to be an extremely luminous X-ray source with luminosity of approximately 10^{39} erg per second: the true nature of this X-ray emission is still not known (Dunne et al. 2000; Schlegel et al. 2000). We adopted the optical diameters for these sources as listed by Matonick & Fesen (1997), assuming a distance to the galaxy of 5.5 Mpc (Tully 1988). We also adopted the spectral indices and flux densities at 1.4 GHz for these two sources as given by Lacey & Duric (2001).

2.2.7. M 82

Starburst galaxies are expected to be excellent targets when searching for SNRs, given the extensive amount of star formation activity throughout their galactic disks. As mentioned previously, the starburst galaxy M 82 is known to have a large population of young radio SNRs. Huang et al. (1994) detected 50 radio SNRs in this galaxy, all of which were less than six parsecs in diameter. These authors also constructed a $\Sigma - D$ relation for these remnants at 8.4 GHz, obtaining a fit with a slope of $\beta = 3 \pm 0.3$, and used 39 SNRs with precisely determined angular diameters and flux densities. Another relation for 28 calibrators with angular diameters less than or equal to the beam size was derived, yielding a slope of $\beta = 3.6 \pm 0.4$. For the 21 SNRs with both reliable diameters and calculated spectral indices from the parsec-scale study by McDonald et al. (2002) – which measured the spectral indices of compact radio sources in this galaxy – we obtained the relation

$$\Sigma_{1\mathrm{GHz}} = 2.54^{+0.51}_{-0.43} \times 10^{-15} D^{-3.41\pm0.24}, \quad (6)$$

with 91% fit quality. The $\Sigma - D$ diagram for M 82 is shown in Fig. 1.

2.2.8. NGC 1569 and NGC 2146

NGC 1569 and NGC 2146 are two other starburst galaxies like M 82, which are located at distances of 2.2 Mpc (Israel 1988) and 14.5 Mpc (Tarchi et al. 2000), respectively. Searches for

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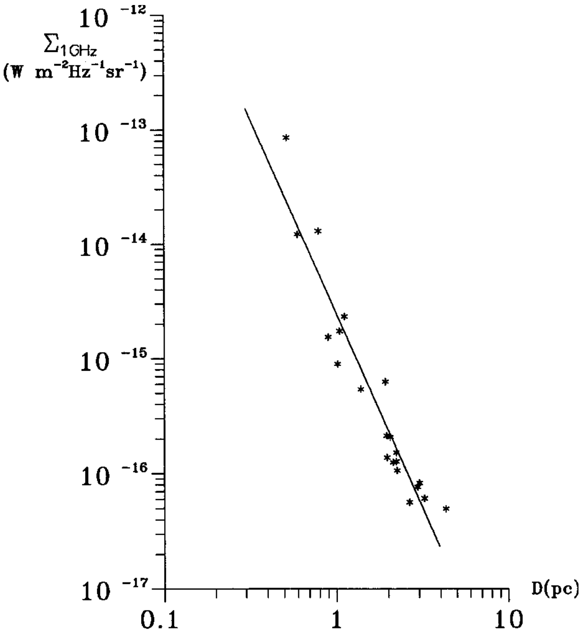

Fig. 1. The $\Sigma - D$ diagram at a frequency of 1 GHz for 21 M 82 calibrators.

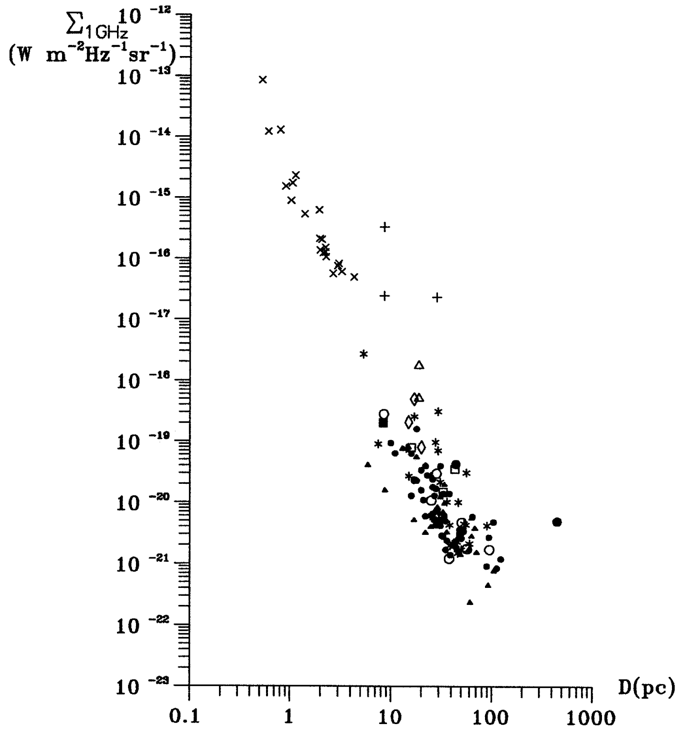

Fig. 2. The $\Sigma - D$ diagram at a frequency of 1 GHz. The SNRs are represented by: asterisks (LMC), open circles (SMC), filled triangles (M 31), filled dots (M 33), open box (IC 1613), open squares (NGC 300), filled circles (NGC 7793), open triangles (NGC 6946), "x"'s (M 82), crosses (NGC 2146) and open diamonds (NGC 1569).

radio supernovae and radio SNRs in these galaxies using observations made with MERLIN and the VLA are presented by Greve et al. (2002) and Tarchi et al. (2000), respectively. Greve et al. (2002) identified three radio SNRs in NGC 1569 (denoted in their work as VLA-8, VLA-16 and M-6), while the search presented by Tarchi et al. (2000) detected three radio SNRs in NGC 2146 (denoted in their work as 37.6+24.2, 38.9+22.5 and 41.4+15.0). Both papers gave radio diameters and spectral indices for the SNRs, while Tarchi et al. (2000) gave flux densities at 1.6 GHz for their sources, and Greve et al. (2002) gave flux densities for all three SNRs at 1.4 GHz. We incorporated all of these values into our analysis.

2.3. The "master" relation

We now consider properties of the data for all of the radio SNRs in the 11 galaxies discussed so far. This ensemble contains a total of 148 SNRs, and the $\Sigma - D$ relation for the ensemble may be expressed as

$$\Sigma_{1\rm GHz} = 8.84^{+3.96}_{-2.74} \times 10^{-16} D^{-3.20\pm0.11}, \quad (7)$$

with a 84% fit quality.

2.4. Effects of extreme points on the derived $\Sigma - D$ relation

Three of the radio SNRs in our sample – N7793-S26 in the galaxy NGC 7793, as well as the SNRs 37.6+24.2 and 38.9+42.5 in the galaxy NGC 2146 – place in the right part of the $\Sigma - D$ diagram (Fig. 2), indicating that these SNRs are more radio-luminous than expected for sources with their diameters. All three are considered HNRs based on their extreme radio luminosities. To test their effects on our derived fits, we re-derived a $\Sigma - D$ relation for the SNRs in our master ensemble after excluding the three HNRs. As shown in Table 3, the slope for this sample of 145 SNRs did not change within the statistical errors ($\beta = 3.30 \pm 0.09$). To further test the effects of extreme points, we again re-derived the relation after excluding the three HNRs once again along with ten other radio SNRs located toward the middle of the Σ vs. D plot. These ten particular SNRs are located in galaxies which lie outside of the Local Group (that is, located in the galaxies NGC 300, NGC 1569, NGC 2146, NGC 6946 and NGC 7793, with M 82 excluded). The corresponding $\Sigma - D$ relation is $\Sigma_{1\rm GHz} \propto D^{-3.30\pm0.09}$ (for the sample of 135 remaining SNRs). This relation is very similar to the one derived for the whole sample if the 3 HNRs are excluded. We therefore argue that including the "outlier" sources in our sample – either HNRs or other extreme SNRs – does not dramatically affect our relations.

3. Discussion

3.1. Monte Carlo simulations of the M 82 relation

In order to check whether the apparently anomalous M 82 could arise by chance, we performed a series of Monte Carlo simulations with the null hypothesis of no relation between Σ and D. We generated random SNR populations (10 000 SNRs) according to various functional forms of $N(\Sigma)$. Then for each measured value of $\log D$ we randomly selected one of the artificially generated Σ values. If the pair fell within the sensitivity cutoffs, we kept it; otherwise we randomly selected another Σ value until the pair did fall within the sensitivity cutoffs. This

Table 4. Parameters from the Monte Carlo simulation for the M 82 slope.

Apparent slope	Probability if power law (power = –3)	Probability if half-Gaussian
3.1*	96/1000 = 9.6%	42/1000 = 4.2%
3.4	43/1000 = 4.3%	11/1000 = 1.1%

Note: * This is the slope obtained after removing the highest $\log\Sigma$ point from the M 82 Σ – *D* diagram.

procedure was repeated until we matched up all the measured values of $\log D$ with artificially generated $\log\Sigma$'s. Then we fit a line through the points and measured the slope. The process was repeated 1000 times, leading to a histogram of 1000 slopes. A total of 7 different distributions were used, leading to 7 such histograms. The results from two representative distributions (a power law distribution with slope of –3 and a Gaussian) are shown in Table 4.

Inspection of Table 4 shows that the probability of obtaining a slope equal to the measured slope, or greater, is the range of 1% to 9.6% depending on the assumed SNR population and the uncertainties in the measured slope. It therefore seems likely that the M 82 relation is statistically different from the other 10 galaxies, at a confidence level of ≈90–99%.

3.2. Selection effects

The "master" relation does not appear useful for defining unique evolutionary tracks but does combine one potentially useful relation (M 82) and a number of non-useful relations (for SNRs from the other 10 nearby galaxies).

The Galactic relation (C&B) probably also has the trivial $\Sigma \propto D^{-2}$ form and therefore does not represent a physically meaningful relation. We concluded that the previously reported Galactic relations were subject to severe selection effects, the impact of which (e.g. volume dependent selection) is to make the slope of the relation appear steeper than it really is. These results suggest that even the modestly steep relation of C&B may be too steep, possibly a result of Malmquist bias and favor the interpretation of Green (1991).

It is apparent that the Σ – *D* relations within individual galaxies have the trivial form (except for M 82). Selection effects may explain the slight systematic differences between the Magellanic clouds on the one hand, and M 31 and M 33 on the other. The surveys of M 31 and M 33 were performed at better linear resolution and with greater sensitivity than those of the LMC and the SMC (see Table 2). These differences may give rise to different levels of confusion and to a systematic shaping of the relations. In any case, the effect is not great and relations among the four galaxies are generally consistent with each other.

Beyond the Local Group galaxies, we still do not have a very large sample of radio SNRs with well-defined diameters, spectral indices and flux densities. The greater distances to these galaxies, combined with selection effects (related to

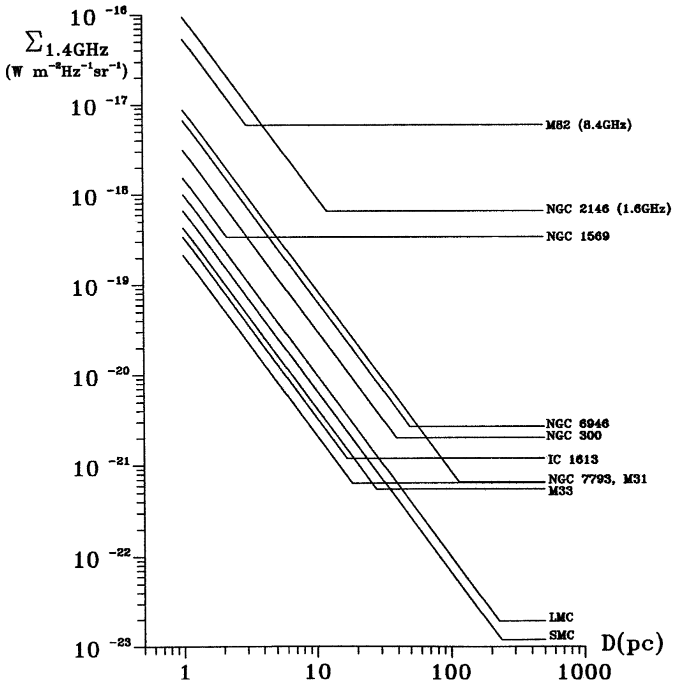

Fig. 3. Sensitivity lines in the Σ – *D* plane for radio surveys of 11 nearby galaxies at 1.4 GHz. The sensitivity lines for M 82 and NGC 2146 are at 8.4 GHz and 1.6 GHz, respectively.

sensitivity, resolution and source confusion), are the major difficulties in detecting radio SNRs in these galaxies. Thus, only the most luminous radio SNRs were detected in the more distant galaxies in our sample. The detection limitations for the nearby galaxies in terms of sensitivity and resolution are presented in Table 2. In Fig. 3, we present a plot in the Σ – *D* plane that illustrates limits in both Σ and *D* for the surveys considered in this paper. Notice that only SNRs located above and to the right of each line would be detected by the radio searches.

3.2.1. Monte Carlo simulation of selection effects related to survey sensitivity

To test the significance of our statistical results we performed a new Monte Carlo simulation as described below.

For a particular galaxy, we measured the standard deviation in $\log\Sigma$ of the real data from the best fit line, assuming that $\log D$ is the independent variable. We then selected an interval in $\log D$ 5 times as long as that of the real data. We sprinkled this interval randomly with points with the same density in $\log D$ as the real data. Then we projected these points that lie on the $\log D$ axis onto a series of lines of different slopes (1 to 5), each passing through the extreme upper left hand end of the best fit line to the real data. Then we added Gaussian noise in $\log\Sigma$. The noise is related to the scatter of the real data by a parameter called "scatter". A scatter of "1" corresponds to the same standard deviation as that of the real data. We applied the appropriate sensitivity cutoff to the simulated datapoints and generated a least squares best fit line from the selected points. We did this 100 times and calculated the mean and standard deviation of the best fit slopes.

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Table 5. Parameters from the second Monte Carlo simulation for LMC.

For a scatter of 1		
Slope before selection	Mean slope after selection	Standard deviation of slope after selection
5.0000	3.7876	1.0019
4.5000	3.3537	0.8958
4.0000	3.1155	0.4671
3.5000	2.8753	0.3201
3.0000	2.6225	0.1920
2.5000	2.3306	0.1533
2.0000	1.8482	0.1170
1.5000	1.3903	0.0778
1.0000	0.9298	0.0350
For a scatter of 2		
5.0000	3.1890	1.1770
4.5000	2.9444	0.8250
4.0000	2.8324	0.9241
3.5000	2.5965	0.4056
3.0000	2.3976	0.3581
2.5000	2.0796	0.2426
2.0000	1.6452	0.2002
1.5000	1.2089	0.1235
1.0000	0.8007	0.0690

Table 6. Parameters from the second Monte Carlo simulation for M 33.

For a scatter of 1		
Slope before selection	Mean slope after selection	Standard deviation of slope after selection
5.0000	4.2440	0.6589
4.5000	3.8234	0.4301
4.0000	3.4694	0.4543
3.5000	3.0667	0.3484
3.0000	2.6211	0.2723
2.5000	2.1759	0.1887
2.0000	1.7322	0.1404
1.5000	1.3125	0.1033
1.0000	0.8649	0.0437
For a scatter of 2		
5.0000	3.4422	0.9152
4.5000	3.1051	0.7685
4.0000	2.8787	0.6503
3.5000	2.3977	0.4810
3.0000	2.0118	0.3661
2.5000	1.6886	0.2916
2.0000	1.3388	0.2287
1.5000	0.9781	0.1431
1.0000	0.6772	0.0770

Table 7. Parameters from the second Monte Carlo simulation for M 82.

For a scatter of 1		
Slope before selection	Mean slope after selection	Standard deviation of slope after selection
5.0000	4.8057	0.3728
4.5000	4.3656	0.2875
4.0000	3.9091	0.2469
3.5000	3.3846	0.1900
3.0000	2.8901	0.1530
2.5000	2.4197	0.1023
2.0000	1.9249	0.0693
1.5000	1.4611	0.0513
1.0000	1.0035	0.0438
For a scatter of 2		
5.0000	4.2431	0.6543
4.5000	4.0003	0.5339
4.0000	3.5063	0.5152
3.5000	3.1518	0.4270
3.0000	2.7152	0.3060
2.5000	2.2278	0.2299
2.0000	1.7648	0.1269
1.5000	1.3359	0.1016
1.0000	0.8910	0.0531

The results for LMC, M 33, and the M 82 are summarized in Tables 5–7, and reveal the following trends:

(i) comparing the closest values of the mean apparent (simulated) slopes to those of the measured slopes in a scatter one scenario, suggests that true (simulated) and measured slopes (Table 3) are the same to within the slope uncertainties. The difference between the true slope and the measured slope can be characterized as Galaxy(true, measured) = LMC(2.5, 2.3 ± 0.4), M 33(2, 1.8 ± 0.2), M 82(3.5, 3.4 ± 0.2). On the surface, it would appear that the apparent slopes are statistically the same as the true slopes;

(ii) further inspection of the tables shows that, if one takes the uncertainties of the fit into consideration, that a range of steeper true slopes is possible for each measured slope; e.g., for LMC a measured slope of 2.3 ± 0.4 is actually consistent with a range of true slopes 2.5–3.5, i.e. LMC(2.5 to 3.5, 2.3), M 33(2.0 to 2.5, 1.8), and M 82(3.5 to 4.0, 3.4) if one assumes a scatter of one. The systematic trend is to flatten the measured slope relative to the true slope. Despite this effect however, the relation for M 82 appears to remain statistically separate from the other two;

(iii) if one assumes that the true scatter in the date is twice that observed (as described above), the situation becomes less clear. In this case Galaxy(true slope, measured slope) = LMC(2.5 to 5.0, 2.3), M 33(2.0 to 3.0, 1.8), and M 82(3.5 to 5.0, 3.4). The measured slope acts as a lower limit to the steepness of the relation, clearly a selection

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effect arising from the limited sensitivity of the surveys and the intrinsically large scatter in the $\Sigma - D$ plane.

3.3. Evolutionary tracks in the $\Sigma - D$ plane

Investigation of Fig. 3 shows that for all galaxies, except M 82 and NGC 2146, the D^{-2} sensitivity lines are bunched in a relatively narrow band in the $\Sigma - D$ plane. Consequently any fits made to the collective data are affected by this observational selection effect. This explains, in part, the slope of the master relation, which is consistent with 2[2] when M 82 is excluded, although NGC 2146 does not play a significant role statistically because there are only three data points associated with it. Addition of M 82 steepens the slope because its sensitivity line is shifted significantly to the right in Fig. 3, partly explaining the steeper value obtained when all data are used in the fit. In the case of M 82 by itself, the only major observational effect is its own D^{-2} sensitivity line, which by itself cannot account for the steep slope of 3.4 obtained when only the M 82 data are fit, as shown in Sects. 3.1 and 3.2.

The two sets of Monte Carlo simulations, the first relating to the probability of a particular slope arising by chance and the second investigating the effect of selection effects, both suggest that the $\Sigma - D$ relation for M 82 is anomalously steep relative to the relations of the other galaxies in our sample. At the same time, the SNR diameters are uniquely small compared to the other SNRs in the master sample. The measured slope for the M 82 SNRs is $\beta = 3.4 \pm 0.2$, while that of the remaining SNRs in the master relation is $\beta = 1.9 \pm 0.15$. The latter slope does not have a physical origin, but is consistent with the luminosity-diameter scattering artifact (see Arbutina et al. 2004). According to theory, the surface brightness of the SNR is a function of the density of the gas of the medium the SNR is interacting with. One particular model (e.g. Bell 1978a,b) predicts the surface brightness to have form

$$\Sigma \propto B^{1+\alpha} n_{\rm e} D^{-2}, \tag{8}$$

where B is the magnetic field strength and $n_{\rm e}$ the number density of pre-shock thermal gas. If the values for $n_{\rm e}$ vary greatly among the environments of the SNRs in our sample, the evolutionary track predicted by D&S ($\beta = 5$ and 3.5 for compact SNRs and larger SNRs, respectively) would be dominated in a statistical sample by this effect, as implied by Eq. (8). Given the results of the Monte Carlo simulations, if such environmentally-induced scatter does exist, then the theoretically predicted value of the steeper slope may indeed be consistent with the measured slope of the steeper relation.

According to the D&S theory, only coefficient A in Eq. (1) depends on $n_{\rm e}$, also obvious from Eq. (8). From the same theory, coefficient β explicitly does not depend on $n_{\rm e}$. Therefore the slopes of potential shallower (or steeper) components are the same for all SNRs, and evolutionary tracks are parallel. The breaks exist and, for all evolutionary tracks are located at different points in the $\Sigma - D$ plane. We probably identified one steep evolutionary track for SNRs in M 82 at higher density, without the corresponding shallower part that is probably hidden by the selection effects. Nevertheless, for other (generally closer) galaxies we did not identify a unique shallower track; we just proposed possible shallower tracks for the SNRs that probably evolve in more dilute media without the corresponding very young SNR tracks. These galaxies are non-starburst, so we do not expect to see enough very young SNRs to define the steeper track.

Despite the apparent effect of environmental differences, the M 82 result supports previous observations that the SNRs in M 82 are younger and follow a different evolutionary track in the $\Sigma - D$ plane. Furthermore, the steep slope of the M 82 relation is not caused by selection effects, because the difference in slopes is greater (by a factor of over two) than the difference that can be replicated by known selection effects in the Galaxy or in the data-sets for radio SNRs in M 31 and M 33 (Urošević 2003).

To investigate the break in the relation further, we examined the locations of the SNRs in the $\Sigma - D$ plane from other starburst galaxies. In the case of NGC 2146, the result was as expected. However, in the case of NGC 1569, the SNRs were found to belong to the shallower sample. This result suggests that the SNRs in that galaxy are possibly more evolved, consistent with the hypothesis that NGC 1569 is currently in a post starburst stage of evolution (Greve et al. 2002). Also, it indicates that the location on a $\Sigma - D$ plot for a candidate radio SNR in a starburst galaxy (that is, in the shallower or steeper part of the plot) may originate from purely a "physical" evolutionary effect predicted by D&S.

In the absence of knowledge about true scatter in the $\Sigma - D$ plane, we tentatively conclude:

(i) given the measured slope of the master relation and that of all individual galaxies (except M 82), it is evident that the selection effects described above tend to flatten the intrinsic (true) relations toward a trivial slope of 2. This effect runs opposite to the effect of volume selection in the Galactic sample of SNRs;

(ii) despite these selection effects, the relation for M 82 does appear to be distinct from the rest as suggested by the Monte Carlo simulations described in Sect. 3.1. In Scenario 1 (scatter = 1) of the simulation of selection effects (described in Sect. 3.2.1), the difference in slopes is not masked by the intrinsic spread of values in the $\Sigma - D$ plane. In Scenario 2 of the same simulation a suggestion remains that M 82 is different simply because its relation has not been flattened to the neighborhood of $\beta = 2$. Nevertheless, the effect of scatter on the relation weakens the case for an evolutionary difference between M 82 and the other galaxies and strengthens the case for $\Sigma - D$ relations being dominated by intrinsic scatter in evolutionary paths as might occur when SNR evolve in widely differing media;

(iii) these results also suggest that the true slope of the M 82 relation may be steep enough to resolve any discrepancy between theory and observation.

[2] For the 114 radio SNRs in the Local Group galaxies – LMC, SMC, M 31, M 33, and IC 1613 – the collective relation at 1 GHz is: $[\Sigma_{\rm 1GHz} = 6.65^{+4.58}_{-2.71} \times 10^{-18} D^{-1.93\pm0.15}$.

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3.4. Candidate HNRs in our $\Sigma - D$ sample

We briefly comment on properties of the three candidate HNRs included in our sample of extragalactic SNRs. In a separate study, we calculated the minimum energies required to power these sources through synchrotron radiation: we found that the minimum energies for all three SNRs exceeded 10^{51} ergs (Pannuti et al. 2005, in preparation). This result suggests that these three sources may have indeed been produced by extremely luminous supernova explosions known as hypernovae (e.g., Wang 1999), though the true nature of these sources is still the subject of intense debate (Snowden et al. 2001; Chen et al. 2002). It is interesting to note that both of the host galaxies for these three SNRs exhibit characteristics of starburst activity; NGC 2146 has a disturbed morphology and extensive star formation throughout its disk (Hutchings et al. 1990), while NGC 7793 – though more regular in appearance than NGC 2146 – still shows extensive massive star formation activity, as evidenced by large amounts of photo-ionized gas permeating the disk of this galaxy (Blair & Long 1997). Lastly, we note that Chevalier & Fransson (2001) discussed the high radio luminosity of SNRs located in starburst galaxies and argued that these elevated radio luminosities are correlated with the higher average molecular cloud densities with which these radio SNRs are interacting in these galaxies. Additional radio observations of more galaxies (both normal and starburst) are necessary in order to learn more about these very luminous radio SNRs, their environments, and their host galaxies.

4. Summary and conclusions

The three major results of this paper may be summarized as follows:

(i) Monte Carlo simulations to gauge the effects of chance and selection effects in shaping the observed properties of the SNRs in our sample of galaxies suggest that the $\Sigma - D$ relation for M 82 is really steeper than relations for the other galaxies in our sample. The measured slope for the smaller SNRs is $\beta = 3.4 \pm 0.2$ while that of the remaining SNRs in the master relation is $\beta = 1.9 \pm 0.15$. The latter slope does not have a physical origin. It is the luminosity-diameter scattering artifact which produces the trivial $\Sigma \propto D^{-2}$ form. The possible change in slope for smaller diameter SNRs is consistent with predictions made by the theoretical $\Sigma - D$ relation of D&S. In any case, the M 82 result supports the previous observations that the SNRs in M 82 are younger than the larger, older SNRs in the other 10 galaxies and follow a distinct relation in the $\Sigma - D$ plane. Monte Carlo simulations showed, that the probability of this difference arising by chance is $\approx$1% to 10% and that the slope of the $\Sigma - D$ relation for M 82 is not strongly affected by selection effects connected with sensitivity, thereby reinforcing the conclusion that the M 82 relation is significantly different from those of the other galaxies.

(ii) The empirical relations for SNRs in the 10 other nearby galaxies (except M 82) have approximately trivial $\Sigma \propto D^{-2}$ form, consistent with a random distribution of evolutionary tracks for the SNRs in the sample, and therefore useful relations do not exist. Even if SNRs follow well-defined evolutionary tracks individually, they do so in widely differing environments with density probably the most important parameter in driving the variations. In addition, these relations are not useful because they are subject to selection effects. Our Monte Carlo simulations suggest that the effect of survey sensitivity is opposite to the volume selection effects (e.g. Malmquist bias, which is a volume selection effect that shapes the Galactic sample). In this case, the true slopes may, in fact, be steeper than the observed slopes.

(iii) We identified three candidates for hypernova remnants in our $\Sigma - D$ sample of radio SNRs in 11 nearby galaxies.

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Appendix A: "Master" table

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Table A.1. The basic quantities for 148 SNRs in nearby galaxies used in this paper for deriving of the updated Σ − *D* relations.

Galaxy	Name	D (pc)	$S_{1.4}$ (mJy)	α	Σ_{1GHz} $(\frac{W}{m^2 Hz\, sr})$
		Normal galaxies			
LMC	B0450-709	89	758	0.36	4.2E-21
LMC	B0453-685	36	299	0.38	1.0E-20
LMC	B0454-665	15	133	0.49	2.7E-20
LMC	B0455-687	53	283	0.45	4.6E-21
LMC	B0500-702	31	407	0.73	2.2E-20
LMC	B0506-680	14	320[a]	0.58	7.7E-20
LMC	B0513-692	55	289[a]	0.45	4.3E-21
LMC	B0519-697	28	1692	0.35	9.7E-20
LMC	B0519-690	7.5	110[D]	0.47	9.1E-20
LMC	B0520-694	32	120[a]	0.32	5.0E-21
LMC	B0524-664	46	73[a]	0.33	1.5E-21
LMC	B0525-660	29	1265	0.60	7.1E-20
LMC	B0525-696	29	5600[D]	0.58	3.1E-19
LMC	B0525-661	17	1595	0.51	2.6E-19
LMC	B0527-658	60	176	0.32	2.1E-21
LMC	B0528-692	38	138[a]	0.44	4.3E-21
LMC	B0532-710	47	505[a]	0.31	1.0E-20
LMC	B0534-699	30	107[a]	0.48	5.6E-21
LMC	B0534-705	45	103[a]	0.44	2.3E-21
LMC	BO535-660	5.3	1613	0.57	2.7E-18
LMC	B0536-676	50	201[a]	0.38	3.6E-21
LMC	B0536-706	39	62[a]	0.61	2.0E-21
LMC	B0547-697	56	1987	0.61	3.1E-20
LMC	B0548-704	27	73[a]	0.55	4.6E-21
LMC	B0528-672	50	81[a]	0.79	1.7E-21
SMC	B0045-734	28	423[a]	0.15	3.0E-20
SMC	B0047-735	38	24[a]	0.79	1.2E-21
SMC	B0050-728	95	245[a]	0.40	1.7E-21
SMC	B0058-718	50	189[a]	0.42	4.7E-21
SMC	B0101-724	25	106[a]	0.50	1.1E-20
SMC	B0102-722	8.5	285[a]	0.73	2.8E-19
SMC	B0103-726	57	88[a]	0.47	1.8E-21
M 31	DDB-7	18	2.3	0.36	5.7E-20
M 31	DDB-11	29	0.83 ± 0.13	0.5[b]	8.6E-21
M 31	DDB-13	22	0.18 ± 0.05	0.5[b]	3.3E-21
M 31	DDB-15	36	0.51 ± 0.07	0.5[b]	3.3E-21
M 31	DDB-16	22	2.29 ± 0.08	0.41	4.2E-20
M 31	DDB-17	29	0.47 ± 0.07	0.5[b]	4.8E-21
M 31	DDB-18	31	1.35 ± 0.05	0.5[b]	1.3E-20
M 31	DDB-19	34	2.60 ± 0.10	0.22	2.1E-20
M 31	K53	68	2.00 ± 0.20	0.5[b]	3.9E-21
M 31	K86	92	0.45 ± 0.05	0.5[b]	4.6E-22
M 31	K180	27	0.50 ± 0.10	0.5[b]	5.7E-21
M 31	K230A	49	0.85 ± 0.15	0.5[b]	3.1E-21
M 31	K268	8.7	0.14 ± 0.03	0.5[b]	1.6E-20
M 31	K310	61	0.10 ± 0.03	0.5[b]	2.4E-22
M 31	K327	13	1.55 ± 0.10	0.5[b]	7.8E-20
M 31	K490A	63	2.60 ± 0.30	0.5[b]	5.6E-21
M 31	K506A	34	1.30 ± 0.10	0.5[b]	9.9E-21
M 31	K548	33	0.65 ± 0.05	0.5[b]	7.1E-21
M 31	K566	5.9	0.16 ± 0.03	0.5[b]	4.2E-20
M 31	K567	63	1.30 ± 0.10	0.5[b]	2.9E-21
M 31	K574	26	0.36 ± 0.02	0.5[b]	5.7E-21
M 31	K583	31	0.73 ± 0.10	0.5[b]	6.7E-21
M 31	K594	25	2.00 ± 0.05	0.5[b]	2.9E-20

Table A.1. continued.

Galaxy	Name	D (pc)	$S_{1.4}$ (mJy)	α	Σ_{1GHz} $(\frac{W}{m^2 Hz\, sr})$
M 31	K638	49	0.35 ± 0.05	0.5[b]	1.5E-21
M 31	K640A	59	0.62 ± 0.03	0.5[b]	1.7E-21
M 31	K774	17	0.17 ± 0.03	0.5[b]	5.3E-21
M 31	K782	15	2.26 ± 0.08	0.5[b]	8.3E-20
M 31	K817	25	0.30 ± 0.03	0.5[b]	4.1E-21
M 31	K891	105	1.00 ± 0.20	0.5[b]	7.9E-22
M 31	K947	71	0.90 ± 0.30	0.5[b]	1.6E-21
M 33	GDK2	104	5.0 ± 0.7	0.5 ± 0.1	4.8E-021
M 33	GDK3	32	0.3 ± 0.1	0.4 ± 0.5	2.9E-021
M 33	GDK5	94	2.3 ± 0.6	0.5 ± 0.2	2.7E-021
M 33	GDK8	53	0.9 ± 0.2	0.5[b]	3.4E-021
M 33	GDK9	112	1.0 ± 0.2	0.6 ± 0.2	8.5E-022
M 33	GDK11	18	0.7 ± 0.2	0.5 ± 0.3	2.3E-020
M 33	GDK13	17	0.6 ± 0.2	0.5[b]	2.4E-020
M 33	GDK17	26	1.1 ± 0.2	0.8 ± 0.3	1.8E-020
M 33	GDK20	47	0.6 ± 0.1	0.3 ± 0.3	2.6E-021
M 33	GDK24	64	2.3 ± 0.2	0.5 ± 0.1	5.9E-021
M 33	GDK25	10	0.8 ± 0.2	0.7 ± 0.3	9.4E-020
M 33	GDK28	89	0.7 ± 0.3	0.5 ± 0.5	9.2E-022
M 33	GDK29	27	0.9 ± 0.2	0.7 ± 0.3	1.3E-020
M 33	GDK35	36	0.3 ± 0.1	0.5[b]	2.4E-021
M 33	GDK39	22	1.8 ± 0.2	0.5 ± 0.1	4.0E-020
M 33	GDK42	26	1.4 ± 0.2	0.9 ± 0.2	2.4E-020
M 33	GDK46	48	0.7 ± 0.2	0.5[b]	3.2E-021
M 33	GDK47	23	1.2 ± 0.1	0.8 ± 0.2	2.8E-020
M 33	GDK50	11	0.8 ± 0.2	0.2 ± 0.2	6.4E-020
M 33	GDK52	20	0.5 ± 0.1	0.9 ± 0.5	1.6E-020
M 33	GDK54	28	0.4 ± 0.2	0.5 ± 0.5	5.2E-021
M 33	GDK57	38	1.8 ± 0.1	0.8 ± 0.1	1.4E-020
M 33	GDK64	31	3.5 ± 0.2	0.7 ± 0.1	4.0E-020
M 33	GDK74	50	0.5 ± 0.1	1.1 ± 0.7	2.6E-021
M 33	GDK75	28	0.5 ± 0.1	0.8 ± 0.4	7.2E-021
M 33	GDK77	33	1.3 ± 0.3	0.8 ± 0.3	1.4E-020
M 33	GDK81	20	1.2 ± 0.1	0.6 ± 0.2	3.4E-020
M 33	GDK90	35	0.2 ± 0.1	0.5[b]	1.7E-021
M 33	GDK92	22	0.3 ± 0.1	0.2 ± 0.2	6.0E-021
M 33	GDK99	29	0.6 ± 0.2	0.7 ± 0.5	7.8E-021
M 33	GDK103	41	0.4 ± 0.1	0.0 ± 0.3	2.0E-021
M 33	GDK105	48	0.7 ± 0.1	0.8 ± 0.3	3.6E-021
M 33	GDK110	39	0.2 ± 0.1	0.5[b]	1.4E-021
M 33	GDK111	16	1.3 ± 0.1	0.9 ± 0.1	6.4E-020
M 33	GDK112	18	4.4 ± 0.2	0.7 ± 0.1	1.6E-019
M 33	GDK114	21	0.4 ± 0.1	0.9 ± 0.7	1.1E-020
M 33	GDK116	28	1.1 ± 0.1	1.0 ± 0.2	1.7E-020
M 33	GDK121	16	0.3 ± 0.1	0.5[b]	1.3E-020
M 33	GDK122	33	0.3 ± 0.1	0.5[b]	2.8E-021
M 33	GDK125	28	0.4 ± 0.1	0.0 ± 0.3	4.3E-021
M 33	GDK130	26	0.5 ± 0.1	0.2 ± 0.2	6.6E-021
M 33	GDK138	48	0.6 ± 0.2	0.8 ± 0.5	3.0E-021
M 33	GDK139	35	0.6 ± 0.1	0.5[b]	5.0E-021
M 33	GDK140	31	0.4 ± 0.1	0.5 ± 0.3	4.2E-021
M 33	GDK148	17	0.5 ± 0.1	1.1 ± 0.4	2.3E-020
M 33	GDK154	25	0.4 ± 0.1	0.4 ± 0.3	6.2E-021
M 33	GDK158	123	1.8 ± 0.2	0.4 ± 0.1	1.2E-021
M 33	GDK160	43	0.4 ± 0.1	0.5 ± 0.3	2.3E-021
M 33	GDK168	50	0.8 ± 0.1	0.4 ± 0.2	3.2E-021
M 33	GDK170	45	0.3 ± 0.1	0.9 ± 0.4	1.8E-021
M 33	GDK181	34	0.8 ± 0.1	0.1 ± 0.2	6.1E-021

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Table A.1. continued.

Galaxy	Name	D (pc)	$S_{1.4}$ (mJy)	α	Σ_{1GHz} ($\frac{W}{m^2 Hz\, sr}$)
IC 1613	S8	8.4	1.9 ± 0.1	0.57 ± 0.05	2.0E-19
NGC 300	S10	16	0.29 ± 0.07	0.6 ± 0.3	8.0E-20
NGC 300	S11	43	0.89 ± 0.15	0.7 ± 0.2	3.5E-20
NGC 300	S26	33	0.22 ± 0.07	>0.7	1.5E-20
NGC 6946	S9	19	0.41 ± 0.08	0.8 ± 0.2	5.36E-19
NGC 6946	S16	19	1.59 ± 0.05	0.5 ± 0.1	1.85E-18
NGC 7793	S11	44	0.45 ± 0.15	0.6 ± 0.5	4.25E-20
NGC 7793	S26	450	4.88 ± 0.47	0.9 ± 0.2	4.96E-21
Starburst galaxies					
M 82	39.1+57.4	0.90	7.0	0.50^c	1.6E-15
M 82	39.4+56.1	3.23	3.5	0.58^c	6.1E-17
M 82	39.6+53.4	2.65	2.3	0.45^c	5.7E-17
M 82	40.6+56.1	3.02	3.9	0.72^c	8.3E-17
M 82	40.7+55.1	1.93	12.8	0.58^c	6.3E-16
M 82	41.3+59.6	1.02	5.2	0.52^c	9.0E-16
M 82	42.7+55.7	4.30	4.8	0.71^c	5.0E-17
M 82	42.8+61.3	1.97	2.9	0.63^c	1.4E-16
M 82	43.2+58.4	1.05	10.1	0.66^c	1.7E-15
M 82	43.3+59.2	0.60	23.5	0.68^c	1.2E-14
M 82	44.3+59.3	1.96	4.4	0.64^c	2.1E-16
M 82	44.5+58.2	2.25	3.0	0.50^c	1.1E-16
M 82	45.2+61.3	1.12	15.6	0.67^c	2.3E-15
M 82	45.3+65.2	2.05	4.4	0.82^c	2.1E-16
M 82	45.4+67.4	2.23	4.0	0.67^c	1.5E-16
M 82	45.8+65.3	2.13	3.2	0.46^c	1.3E-16
M 82	45.9+63.9	2.22	3.7	0.41^c	1.3E-16
M 82	46.5+63.9	1.39	5.4	0.74^c	5.4E-16
M 82	46.7+67.0	2.95	3.4	0.76^c	7.7E-17
M 82	41.9+58.0	0.52	120.4	0.75^c	8.6E-14
M 82	44.0+59.6	0.79	46.7	0.48^c	1.3E-14
NGC 1569	VLA-8	20	0.479 ± 0.032	0.24 ± 0.10	8.1E-20
NGC 1569	VLA-16	15	0.681 ± 0.046	0.27 ± 0.14	2.1E-19
NGC 1569	M-6	17	1.89 ± 0.03	0.55 ± 0.02	5.0E-19
NGC 2146	37.6+24.2	8.6	6.1^e	1.1	3.35E-16
NGC 2146	38.9+42.5	28	4.7^e	1.1	2.35E-17
NGC 2146	41.4+15.0	8.6	0.5^e	0.6	2.45E-17

Note:
[a] S_{20} has been extrapolated from the values listed for α and S_{36} by Filipović et al. (1998b).
[b] No spectral index data available; a value of $\alpha = 0.5$ is assumed.
[c] S_{20} has been extrapolated from the values listed for α by McDonald et al. (2002) and $S_{3.6}$ by Huang et al. (1994).
[D] The flux densities are from the paper by Dickel & Milne (1995).
[e] S_{20} has been extrapolated from the values listed for α and S_{18} by Tarchi et al. (2000).

Radio observations: LMC & SMC – at 1400 and 1420 MHz, respectively (Filipović et al. 1998b); M 31 – at 1465 MHz (Braun & Walterbos 1993); M 33 – 1420 MHz (Gordon et al. 1999); IC 1613 – at 1460 MHz (Lozinskaya et al. 1998); NGC 300 – at 1450 MHz (Pannuti et al. 2000); NGC 6946 – at 1450 MHz (Lacey et al. 1997); NGC 7793 – at 1470 MHz (Pannuti et al. 2002); M 82 – at 8400 MHz (Huang et al. 1994); NGC 1569 – at 1400 MHz (Greve et al. 2002); NGC 2146 – at 1600 MHz (Tarchi et al. 2000).

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