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THE Σ-D RELATION FOR SHELL-LIKE SUPERNOVA REMNANTS

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ABSTRACT

A large fraction of Galactic supernova remnants, including a dozen shell-like remnants, can be associated with large molecular clouds or cloud complexes with well-determined distances. The Σ-D relation for these shell-like remnants, derived using distances to the associated molecular clouds, shows substantially smaller scatter than previous relations and establishes a good distance scale for shell-like remnants from Type II events.

Subject headings: interstellar: molecules — nebulae: supernova remnants

In 1960, Shklovskii derived an empirical relation between the distance-independent surface brightness (Σ) of SNRs at radio frequency and their linear diameters (D) of the form $\Sigma = AD^{\beta}$. In previous investigations (e.g., Clark and Caswell 1976; Milne 1979; Lozinskaya 1981; Allakhverdiyev *et al.* 1983*b*; Sakhibov and Smirnov 1982) based on samples of different SNR calibrators with varying distance estimates, the fitted values of $\log A$ and β deviated from -16.6 to -12.9 and from -4.7 to -2.3, respectively. The uncertainty in estimating the distance to individual SNRs from these Σ-D relations is never better than a factor of roughly 2. Introducing other parameters of SNRs to explain the large uncertainties of Σ-D distances, Caswell and Lerche (1979) and Milne (1979), using different approaches, claimed a dependency of Σ on the displacements ($|z|$-distances) of SNRs from the Galactic plane, which appears to account for the influence of density and of the magnetic field strength of the surrounding medium on the evolution of surface brightness. The reasoning of both approaches, however, is questioned in recent studies (see discussion below) by Allakhverdiyev *et al.* (1983*b*) and Green (1984).

Most attempts to estimate the distances of SNR calibrators have been based on the kinematic method, either measurements of H I absorption or from the Hα velocities of optical filaments (Green 1984). Both Green and Allakhverdiyev *et al.* (1983*a*) separately studied the reliability of distances to previously used calibrators, and both concluded that most estimates of distance to these calibrators are quite unreliable. The considerable scatter in previous Σ-D relations may simply be a result of large uncertainties in estimating the distances to the calibrators in our Galaxy. However, the SNRs in the Large or Small Magellanic Cloud (all at essentially the same distances) remain scattered in the Σ-D plot (Mills 1983; Green 1984), suggesting that no single Σ-D relation can be constructed that will be applicable to all SNRs, perhaps because the intrinsic properties and external environments of SN progenitors differ widely.

But it may be possible to construct effective Σ-D relations by using different sets of calibrators for specific subgroups of SNRs. Such subgroups can be selected straightforwardly according to the radio morphologies of SNRs: shell-like, Crab-like, and combination (e.g., Weiler 1983). In this work we limited our study of the Σ-D relation to shell-like remnants, because the filled-center emission, presumably powered by central pulsars or SS 433–like objects, may contribute substantially to the surface brightness of Crab-like or combination remnants.

Reliable calibrators are necessary to obtain a better distance scale for SNRs from the Σ-D relation. Although direct estimates of distances to Galactic SNRs are generally unavailable, the known distances of accompanying objects may provide a good indicator. Large molecular clouds or cloud complexes (with a mass $\geq 10^5$ $M_{\odot}$), where most massive progenitors of Type II supernovae come from, may be the best objects with which to search for a connection with galactic Type II remnants because the trace molecule CO can be easily detected to great distances.

The detection of a cloud accompanying an SNR may provide a good calibrator if the distance to the cloud can be estimated reliably. In many cases, we can obtain the distance to a cloud with an uncertainty of roughly $\pm 20\%$ from the spectrophotometric distance of an accompanying OB association or an H II region. If no spectrophotometric distance to the cloud is available, the kinematic distance, estimated by adopting a flat rotation curve ($V_{\odot} = 250$ km s^{-1} and $R_{\odot} = 10$ kpc) for the outer Galaxy and Burton's (1971) curve for the inner Galaxy, can be used. The kinematic method usually has a greater uncertainty than the spectrophotometric method because of the possible large noncircular motions (e.g., those detected in $l = 100°$–$140°$ and $l \approx 160°$; Rickard 1968; Georgelin, Georgelin, and Roux 1973).

Although many Type II remnants are expected to occur near large molecular clouds, without accurate distances to SNRs proximity in space between an SNR and a cloud is difficult to prove in our Galaxy. Fortunately, most SNRs ($l = 70°$–$210°$) that satisfy the following criteria for a spatial coincidence appear, using a statistical model, to be associated with a corresponding cloud (Huang and Thaddeus 1985):

1. The distances of the SNR and the cloud (or the cloud complex) should, within uncertainties, agree. When no other, more reliable method is available to estimate the distance of the SNR, the Σ-D relation of Milne (1979), uncorrected for

the $|z|$-distance and with a presumed uncertainty of a factor of ~ 2 (see Milne's Fig. 1*b*), serves.

2. The location of the SNR on the plane of the sky should lie within a circle that just encloses most CO-emitting portions of the cloud (or the cloud complex).

3. To avoid ambiguity, when more than one large cloud appears in the line of sight to the remnant, these criteria can be satisfied only by a single cloud; absorption-line observations toward the SNR can sometimes help to resolve this ambiguity.

In order to obtain a large number of SNR calibrators, our previous study ($l = 70°–210°$; Huang and Thaddeus 1985) was extended (but not without bias, owing to the incompleteness or unavailability of the Goddard-Columbia in-plane southern CO surveys) to the rest of the Galaxy. The SNR catalog used was compiled by van den Bergh (1983); the data on large clouds were from the Goddard-Columbia northern and southern CO surveys. Table 1 summarizes the parameters of 14 shell-like calibrators with the distance taken from the distance of the corresponding large molecular cloud. We noted that based only on these criteria a few (~ 2) "false" calibrators may have been included simply by chance superposition in the plane of the sky.

The calibrators found allowed us to recalibrate a distance scale for SNRs from the Σ-D relation. The least-squares fit of equal weight for a linear relation between $\log \Sigma$ and $\log D$ to 12 calibrators (all SNRs in Table 1 except HB 9 and G192.8−1.1, which deviate widely from other data points; see Fig. 1) yields

$$\log \Sigma(1\ \mathrm{GHz}) = (-15.44 \pm 0.50) + (-3.21 \pm 0.32) \log D,$$

where Σ is in units of W m^{-2} Hz^{-1} sr^{-1} and D in pc. The calculated linear-correlation coefficient of -0.95 justifies our fit to a straight line. The ratio of the predicted diameter (D) from the Σ-D relation to the corresponding "true" diameter (D_0) (adopted in Table 1) ranges from 0.66 to 1.52, with a standard deviation of 28%; this relatively small scatter justifies the association between the calibrators and their neighboring large molecular cloud complexes. Although excluding data that do not fit a desired conclusion is unusual, because the 12 calibrators used show such a strong correlation and because we expect some "false" calibrators to be included in our selection, we judged that the coincidences between the two remnants (HB 9 and G192.8−1.1) and the corresponding clouds may be due to chance. The inclusion of HB 9 and G192.8−1.1 in our fitting, which changes the values of $\log A$ and β to -16.46 and -2.48, respectively, increases the standard deviation to 61%.

Our Σ-D relation supports neither the break of the Σ-D relation near $D \approx 32$ pc suggested by Clark and Caswell (1976) nor the claimed $|z|$-effect. Using different approaches, both Milne (1979) and Caswell and Lerche (1979) expressed the $|z|$-effect quantitatively: Milne checked the variation of D/D_0 ratios against the variation of $|z|$-distances; Caswell and Lerche studied the $|z|$-variation of Σ across individual

TABLE 1

CALIBRATORS OF SHELL-LIKE SUPERNOVA REMNANTS

Galactic Number Designation	Other Name	Angular Diameter (arc min)	Spectral Index	Surface Brightness ⟨1 GHz⟩ (W m^{-2} Hz^{-1} sr^{-1})	Surface Brightness ⟨408 MHz⟩ (W m^{-2} Hz^{-1} sr^{-1})	References	Adopted Distance (kpc)	Linear Diameter (pc)	z-Distance (pc)	Associated Population I Object[a]
G34.6−0.5[b]	W44	27.2	−0.30	0.47E-19	0.62E-19	1	3.1	24.6	−27.1	CO(35, 44)
G78.2+2.1[c]	γ Cygni	62.0	−0.7	0.13E-19	0.25E-19	2	1.2	21.6	44.0	Cyg OB9
G84.2−0.8	...	18.0	−0.50	0.46E-20	0.72E-20	3	7.2	37.7	−100.5	CO(85, −38)
G89.0+4.7	HB 21	100.0	−0.40	0.39E-20	0.56E-20	4	0.8	23.3	65.6	Cyg OB7
G109.2−1.0	CTB 109	29.4	−0.50	0.35E-20	0.55E-20	5	3.5	29.9	−61.1	Cep OB1
G111.7−2.1	Cas A	4.2	−0.76	0.29E-16	0.57E-16	1, 6	2.6	3.2	−95.3	Cas OB2
G132.7+1.3	HB 3	90.0	−0.52	0.20E-20	0.32E-20	6, 7	2.2	57.6	49.9	Cas OB6
G160.4+2.8	HB 9	130.0	−0.58	0.11E-20	0.18E-20	8, 9	5.6	211.8	273.7	S217, S219
G166.3+2.5	OA 184	76.0	(−0.59)	0.26E-21	0.44E-21	10, 11	5.0	110.5	218.2	CO(167, −22)
G189.0+3.0	IC 443	40.0	−0.36	0.15E-19	0.21E-19	1, 12	1.5	17.5	78.5	Gem OB1
G192.8−1.1	...	78.0	(−0.55)	0.48E-21	0.79E-21	13	1.5	34.0	−28.8	Gem OB1
G260.4−3.4[d]	Puppis A	47.0	−0.48	0.92E-20	0.13E-19	1	1.8	24.6	−106.8	Vel OB1
G309.8+0.0[e]	...	24.0	−0.51	0.44E-20	0.69E-20	14	3.6	28.6	0.0	RCW 80
G315.4−2.3[f]	MSH 14-63	39.0	−0.62	0.47E-20	0.82E-20	1	2.5	28.4	−100.4	RCW 86

[a] When no optical object is available, the associated large cloud is given as CO(l, v).

[b] The kinematic distance of a CO cloud that appears in the direction of the SNR at a velocity of 44 km s^{-1} (Dame 1983) agrees with that of the SNR inferred from the H I absorption measurements (Caswell *et al.* 1975).

[c] This SNR is probably associated with the Cyg OB9 cloud complex at 1.2 kpc (Cong 1977; Landecker, Roger, and Higgs 1980).

[d] The kinematic distance of 2.3 kpc, which corresponds to $V(\mathrm{H}\alpha) = 15 \pm 10$ km s^{-1} of the optical filaments of the SNR (Baade and Minkowski 1954), agrees, within uncertainties, with the spectrophotometric distance of Vel OB1 at 1.8 kpc (Humphreys 1978).

[e] The Σ-D distance of 4.8 kpc (Milne 1979; Caswell *et al.* 1980) to the SNR is consistent with the spectrophotometric distance of 3.6 kpc (Humphreys 1978) to the OB association RCW 80 which is accompanied by a large CO cloud at about -50 km s^{-1} (Bronfman 1984).

[f] The Σ-D distance of 3.0 kpc (Milne 1979) to the SNR agrees with the spectrophotometric distance of 2.5 kpc to the OB association discovered by Westerlund (1969); the relatively high latitudes of the two objects make an association between them likely.

REFERENCES.—(1) Milne 1979. (2) Higgs, Landecker, and Roger 1977. (3) Matthews *et al.* 1977. (4) Willis 1973. (5) Hughes *et al.* 1984. (6) Clark and Caswell 1976. (7) Braunsfurth 1983. (8) Dwarakanath, Shevgaonkar, and Sastry 1982. (9) Reich 1983. (10) Caswell and Lerche 1979. (11) Dickel and DeNoyer 1975. (12) Erickson and Mahoney 1984. (13) Caswell 1984. (14) Caswell *et al.* 1980.

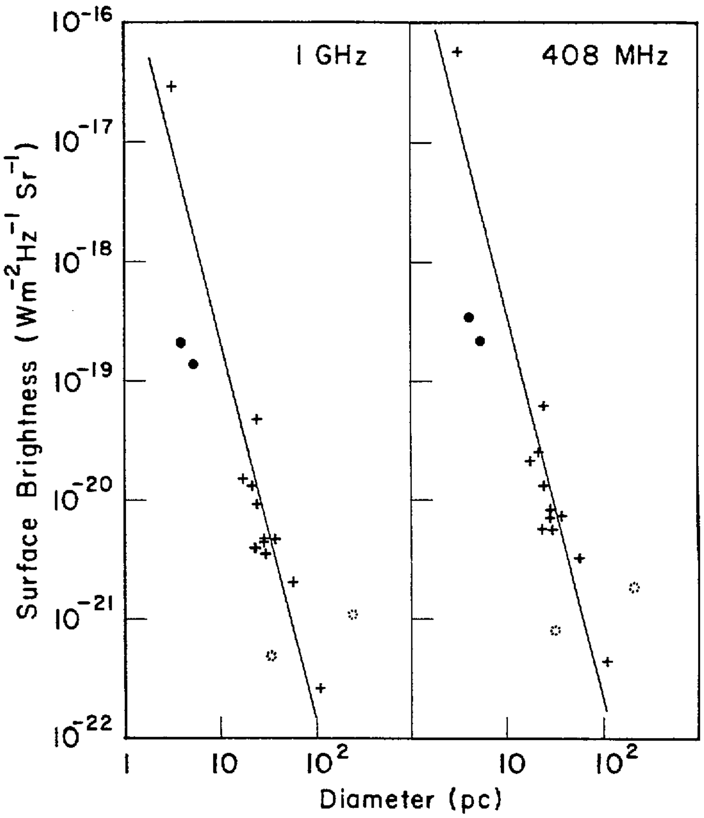

FIG. 1.—Radio surface brightness vs. linear diameter of shell-like SNRs (denoted by +) accompanied by large clouds. The straight lines of least-squares fits of these SNRs are shown at 1 GHz and 408 MHz, respectively. For comparison, Tycho's SN and Kepler's SN (see Huang and Thaddeus 1985 and Sakhibov and Smirnov 1983) unaccompanied by large molecular clouds are shown in the plots by dots and the two remnants (HB 9 and G192.8−1.1) discussed in the text by dotted circles.

SNRs. Both approaches were questioned by Allakhverdiyev *et al.* (1983*b*) and Green (1984): Milne's approach depends almost entirely on two young SNRs (the Crab Nebula and SN 1006); the method of Caswell and Lerche lacks sufficient statistical significance (of the 13 SNRs that show significant asymmetry of Σ on the side closer to the Galactic plane relative to that away from the plane, only eight are brighter toward the plane). When we plotted D/D_0 against $|z|$-distance (Fig. 2), our Σ-D relation did not show any of the exponential dependence of D/D_0 on $|z|$, such as Milne (1979) suggested, and so did not support the existence of the $|z|$-effect. The disappearance of the $|z|$-effect is not surprising, because all of our calibrators are located near large molecular clouds (in which most molecular gas is concentrated; Dame *et al.* 1985) whose distribution, and therefore the distribution of ambient density or magnetic field strength, cannot be expressed as a simple function of $|z|$.

Most of our calibrators, presumably remnants of Type II supernovae, are located near the boundaries, not the centers, of the corresponding clouds or OB associations. SN events that detonate within a large molecular cloud will expand only to a diameter of few parsecs after a lifetime of $\sim 10^5$ yr because of the high density within the cloud (Kafatos *et al.* 1980); given this size, the remnants can easily escape detection by radio surveys. Supernovae that explode near the center of an OB association, where the scouring action of strong stellar winds from early-type stars produces a bubble of low ambient gas density, leave no radio remnants (Tomisaka, Habe, and Ikeuchi 1980), because the relativistic electrons ejected by the explosions can freely expand within the bubble without encountering enough gas to form a shock. The tendency of our calibrators to be located near the boundaries of large clouds or OB associations may result from the discontinuity of ambient gas density that allows the radio remnants to evolve in a favorable environment (with an ambient density neither as high as in a molecular cloud nor as low as in a bubble).

While that analysis is based mainly on the radio data at 1 GHz, another parallel analysis has been done at 408 MHz; the near agreement of the two sets of Σ-D relations, which predict distances to SNRs within $\pm 5\%$ at both frequencies, allows our discussion to stand. In contrast, the distances derived from the commonly used relations of Clark and Caswell (1976) at 408 MHz and Milne (1979) at 1 GHz show a considerable discrepancy that may result from the use of different sets of calibrators in each relation.

Most shell-like calibrators included in our study which are associated with star-forming cloud complexes are probably the result of Type II supernovae (see Huang 1985), although the two putative Type I events (Tycho's SN and Kepler's SN), neither of which is accompanied by a large cloud, are also shell-like. Both Type I and Type II supernovae, therefore, may produce shell-like SNRs. The surface brightness of each of these Type I remnants is less than that of a Type II remnant with the same diameter (Fig. 1). The difference between Types I and II in the $\log \Sigma$–$\log D$ evolutionary tracks may result from evolution in different environments, Type II being near

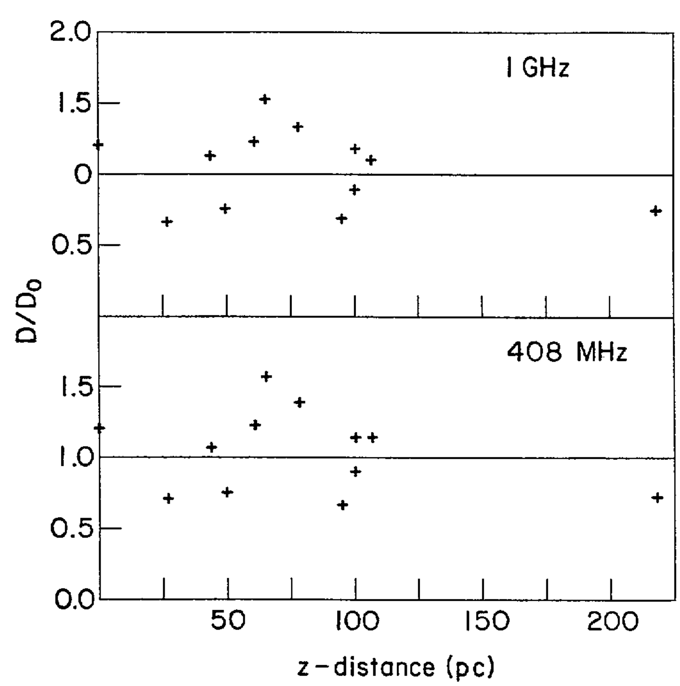

FIG. 2.—Plots of the D/D_0 ratio vs. $|z|$-distance of the calibrators at 1 GHz and 408 MHz, respectively, where D is the diameter estimated from the Σ-D relation and D_0 is the "true" diameter adopted in Table 1.

large molecular clouds and Type I not. This difference is consistent with the study of SNRs in the Magellanic Clouds, where the Balmer-dominated SNRs (presumably the result of Type I supernovae) appear to be less luminous than other SNRs (Mathewson *et al.* 1983).

In summary, the Σ-D relation calibrated using shell-like SNRs associated with large molecular clouds shows less scatter than previous relations and establishes a good distance scale for Type II, shell-like SNRs. A refinement of our Σ-D relation can be made by extending our search for calibrators without bias to all Galactic SNRs (to increase the number of calibrators) and by searching for SNR–cloud interaction (to increase the accuracy of the estimated distance to the SNR, if the cloud's distance is well determined).

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