EFFECT OF AMBIENT DENSITY ON STATISTICAL PROPERTIES OF SNRs: Σ-D RELATION, N-D RELATION, ENERGY CONTENT

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Abstract: Variations in ambient density can largely account for: slope and extent of the observed Σ-D relations, the slope of about +1 of the cumulative N-D relation, and the increase of E_0 with D as derived from optical line data. E_{min} increases during the evolution; the behaviour of E_X remains uncertain.

Introduction

A sample of 84 SNRs at known distances in the Galaxy, the Magellanic Clouds, M31 and M33 observed at radio wavelengths formed the basis for a comparison of data at 1 GHz with X-ray data and [SII]-line data (Table 1 in Paper I = Berkhuijsen, 1986). A close correlation between the surface brightnesses in radio (Σ_R) and X-rays (Σ_X) was found, and a study was made of various SNR-properties as a function of apparent ambient density n_0 as derived from the X-ray data. A review of significant relationships is given in Table 1, some of which are discussed below. Details may be found in Papers I, II (Berkhuijsen, 1987) and III (Berkhuijsen, 1988).

Σ-D relations

Evolutionary models of X-ray SNRs (Fusco-Femiano and Preite-Martinez, 1984) indicate that during the adiabatic phase Σ_X is fairly constant until it drops sharply at the beginning of the radiative phase. Similarly, since $\Sigma_R \propto \Sigma_X^{0.7}$, radio remnants may evolve at nearly constant Σ_R through the observed strip in the Σ_R-D_R diagram until they reach the maximum observable diameter at the beginning of the radiative phase. This conclusion is confirmed by the increase of the minimum energy in relativistic particles and magnetic fields with radius after correction to $n_0 = 1$ cm^{-3} (Fig. 1, Table 1), i.e. $E_{min}(n_0{=}1) \propto R_R(n_0{=}1)^{2.7\pm0.3}$, which implies $\Sigma_R(n_0{=}1) \propto R_R(n_0{=}1)^{0.5\pm0.5}$.

The slopes of the Σ-D relations observed in radio continuum and X-rays then may not reflect evolutionary tracks. Instead, the slopes of the distributions and part of the variations in Σ and D can be explained by the dependence of Σ and D on apparent ambient density n_0. It is remarkable that data of SNR-candidates in M82 and radio supernovae are consistent with this picture (Paper I).

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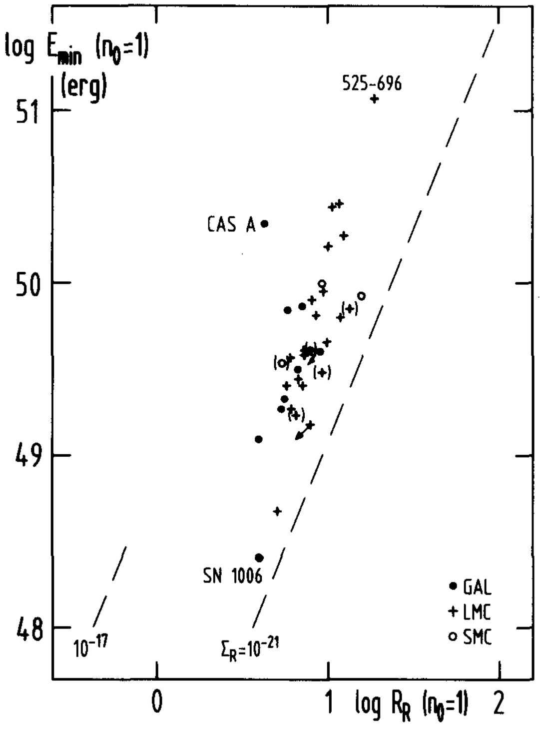

Fig. 1: Dependence of $E_{min}(n_o=1)$ on $R_R(n_o=1)$ for shell-type SNRs. Two lines of constant Σ_R are shown.

Table 1. Review of significant[a] correlations for shell-type SNRs[b] Orthogonal (o) and normal (n) regression lines

Y	X	#pp.	o/n	Slope	Zero point (Y on X)	Correl. coeff.
log Σ_R	log Σ_X	37	o	0.58±0.07	-39.03∓2.49	0.77±0.06
log Σ_R	log n_o	33	o	1.13±0.17	-19.34±0.11	0.75±0.08
log D_R	log n_o	33	o	-0.37±0.04	1.19±0.02	0.84±0.05
log E_{min} -SN1006, 525-696	log n_o	32	o	-0.54±0.12	49.69±0.03	0.62±0.11
log $E_{min}(n_o=1)$	log $R_R(n_o=1)$	33	n	2.72±0.31	47.22±0.28	0.84±0.05
log T_S[c]	log $R_X(n_o=1)$	23	n	-1.57±0.33	1.62∓0.28	0.71±0.11
log E_X[c]	log $R_X(n_o=1)$	23	n	1.31±0.36	49.21∓0.31	0.61±0.13

Units: Σ_R in W Hz^{-1} m^{-2} sr^{-1}, Σ_X in erg s^{-1} pc^{-2}, n_o in cm^{-3}, D_R and $R_R(n_o=1)$ in pc, $E_{min}(n_o=1)$ and E_X in erg, T_S in keV.

a) level of significance P < 0.0027; *b)* without Cas A;
c) for 14 objects with known T_S

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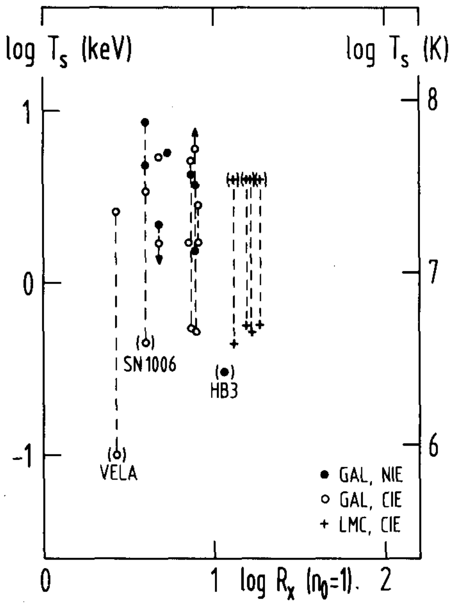

Fig. 2: Dependence of T_S on $R_X(n_o=1)$. T_S has been deduced from X-ray spectra by means of models of collisional ionization in equilibrium (CIE) or not in equilibrium (NIE). References are given in Paper III.

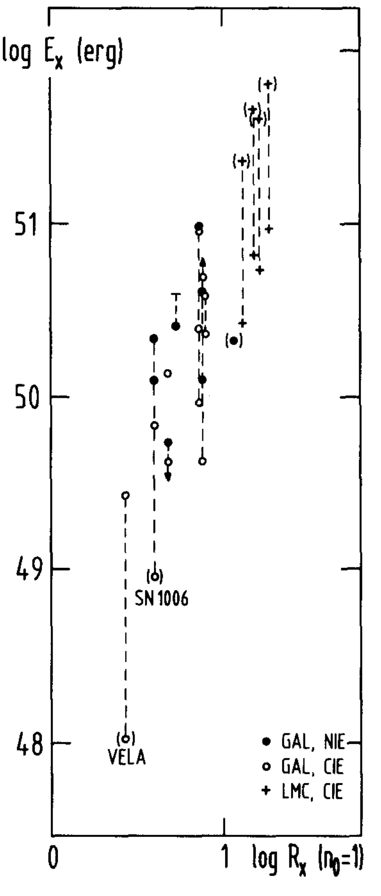

Fig. 3: Dependence of E_X on $R_X(n_o=1)$ for SNRs with known T_S.

N-D relation

The observed exponent of about +1 of the cumulative N-D relations could result from a random distribution of diameters, which may be largely ascribed to variations in n_o. After correction to n_o = 1 cm^{-3} the exponent is considerably larger than +1. For a total sample of 74 radio diameters the exponent of 2.5±0.7 suggests adiabatic expansion of the remnants in the sample. However, the statistical significance does not permit definite conclusions on their average expansion law (Paper II).

Energy content

The total energy in relativistic particles and magnetic fields, $E_{tot}(n_o=1)$, would be higher than $E_{min}(n_o=1)$ if the energy in particles were very different from that in magnetic fields. Indeed, in Kepler's SNR

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(Matsui et al., 1984) the ratio of energy densities in particles and fields is much higher than in the ISM suggesting a decrease of this ratio with $R_R(n_o=1)^{-1.5}$ during the evolution of a remnant. In this case the total energy in particles and fields possibly varies as $E_{tot}(n_o=1) \propto R_R(n_o=1)^{2.0}$.

The thermal energy seen in X-rays was obtained from shock temperatures T_S derived from X-ray spectra by means of adiabatic models. The dependences of T_S and E_X on $R_X(n_o=1)$ are shown in Figs. 2 and 3. Gronenschild and Mewe (1982) have pointed out that the low T_S-values in young remnants and the high T_S-values in old remnants found from CIE models may not apply. Disregarding such CIE points Figs. 2 and 3 yield $T_S \propto R_R(n_o=1)^{-1.6\pm.3}$ and $E_X \propto R_R(n_o=1)^{1.3\pm.4}$ (Table 1), whereas for adiabatic remnants exponents of −3 and 0 are expected, respectively.

The initial kinetic energy E_o as derived from [SII]-line ratios increases with R^3, but is independent of $R(n_o=1)$ in agreement with the assumption of adiabatic expansion. This result may be fortuitous, however, since for adiabatic remnants $N_e(SII) \propto R(n_o=1)^{-3}$ should hold, whereas no dependence of $N_e(SII)$ on $R(n_o=1)$ was found. This disagreement may be caused by the inclusion of values of $N_e(SII)$ for filaments interior to the shell not representative for shell conditions (Preite-Martinez, 1985).

The lack of direct proof for adiabatic expansion casts doubt on the reliability of estimates of E_X and E_o obtained above. An estimate of the mean value of $E_{tot}(n_o=1)$ indicates that a mean value of $E_o \simeq 2\ 10^{51}$ erg might be consistent with the data (Paper III).

References
Berkhuijsen, E.M.: 1986, Astron. Astrophys. **166**, 257 (Paper I)
Berkhuijsen, E.M.: 1987, Astron. Astrophys., in press (Paper II)
Berkhuijsen, E.M.: 1988, Astron. Astrophys., in preparation (Paper III)
Fusco-Femiano, R., Preite-Martinez, A.: 1984, Astrophys. J. **281**, 593
Gronenschild, E.H.B.M., Mewe, R.: 1982, Astron. Astrophys. Suppl. Ser. **48**, 305
Matsui, Y., Long, K.S., Dickel, J.R., Greisen, E.W.: 1984, Astrophys. J. **287**, 295
Preite-Martinez, A.: 1985, Proceedings of Workshop on "Model Nebulae", Meudon, July 1985

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