OPTICAL STUDIES OF SUPERNOVA REMNANTS IN THE MAGELLANIC CLOUDS

D.S. Mathewson, V.L. Ford, M.A. Dopita and I.R. Tuohy
Mount Stromlo and Siding Spring Observatories

K.S. Long and D.J. Helfand
Columbia University

Optical identifications of 32 X-ray sources in the Magellanic Clouds confirm that they are SNRs. They are separated into four classes: the evolved, the oxygen-rich, the Balmer-dominated and the Crab-like. High velocity HI emission is observed from an extended region near 0525-66.0. It is suggested that this is produced by a possible Type III supernova which occurred out of the plane of the LMC and on the far side of the disk. The cumulative number-diameter relation for the LMC SNRs shows that they have evolved much faster than expected from the Sedov theory. It is suggested that this apparent "free-expansion" up to quite large diameters is due to the gradual conversion of the kinetic energy of the ejecta into thermal energy as they overtake the decelerating blast wave.

1. CONFIRMED SNRs IN THE MAGELLANIC CLOUDS

Optical identifications with SNRs have been made for 26 of the LMC X-ray sources in the catalog of Long et al. (1981) and for 6 of the SMC X-ray sources in the catalogs of Seward and Mitchell (1981) and Tanaka (1983). Mathewson et al. (1983) present the narrow-band images of most of the SNRs obtained using the Anglo-Australian Telescope together with the X-ray isophotes obtained with the Einstein Observatory.

Table 1 lists the SNRs in the LMC. Column 2 gives the X-ray source number from the catalog of Long et al. (1981). Column 3 gives the numbers from the catalogs of Henize (1956) and Davies, Elliott and Meaburn (1976). Column 6 gives the optical diameters except for 0525-66.0 and 0535-66.0 where the X-ray diameters are used due to the highly fragmented nature of their optical emission. Generally the optical and X-ray images are co-extensive.

Table 2 lists the SNRs in the SMC. Column 4 gives the optical diameters except for 0049-73.6 where the field is partly obscured and the radio diameter measured by Mills et al. (1982) is given. For the

J. Danziger and P. Gorenstein (eds.), Supernova Remnants and their X-Ray Emission, 541–549.

https://doi.org/10.1017/S0074180900034410 Published online by Cambridge University Press

TABLE 1

SUPERNOVA REMNANTS IN THE LARGE MAGELLANIC CLOUD

SNR Catalog No.	X-Ray Source No.	Other Catalog No.	Position of Optical Center (1950) R.A. h m s	DEC ° ' "	Mean Diameter pc
0453-68.5	1		04 53 46	-68 34 15	36
0454-66.5		N11L	04 54 42	-66 30 22	15
0455-68.7	2	N86	04 55 53	-68 43 52	53
0500-70.2	7	N186D	05 00 20	-70 12 26	31
0505-67.9	10	DEM71	05 05 49	-67 56 38	20
0506-68.0	11	N23	05 06 03	-68 05 51	11
0509-68.7	13	N103B	05 09 13	-68 47 15	6
0509-67.5	14		05 09 36	-67 34 56	7
0519-69.7	23	N120	05 19 08	-69 42 11	28
0519-69.0	26		05 19 52	-69 05 05	8
0520-69.4	27		05 20 07	-69 28 53	32
0525-66.0	34	N49B	05 25 24	-66 01 46	37
0525-69.6	35	N132D	05 25 27	-69 41 02	29
0525-66.1	36	N49	05 25 57	-66 07 32	17
0527-65.8	39	DEM204	05 27 51	-65 52 13	56
0528-69.2	40		05 28 05	-69 14 29	32
0532-71.0	47	N206	05 32 35	-71 02 15	47
0534-69.9	53		05 34 29	-69 56 56	30
0535-70.5	54	DEM238	05 34 52	-70 35 16	46
0535-66.0	59	N63A	05 35 39	-66 03 52	19
0536-70.6	61	DEM249	05 36 43	-70 40 30	39
0538-69.1	67	N157B	05 38 10	-69 11 56	7
0540-69.3	79		05 40 34	-69 21 24	2
0543-68.9	82	DEM299	05 43 27	-69 00 05	76
0547-69.7	88	N135	05 47 37	-69 43 11	56
0548-70.4	89		05 48 24	-70 25 44	28

TABLE 2

SUPERNOVA REMNANTS IN THE SMALL MAGELLANIC CLOUD

SNR Catalog No.	Position of Optical Center (1950) R.A. h m s	DEC ° ' "	Mean Diameter pc
0045-73.4	00 45 28	-73 24 51	26
0046-73.5	00 46 38	-73 35 37	31
0049-73.6	00 49 30	-73 38 25	39
0101-72.4	01 01 40	-72 25 47	25
0102-72.3	01 02 25	-72 18 00	7
0103-72.6	01 03 38	-72 39 09	57

https://doi.org/10.1017/S0074180900034410 Published online by Cambridge University Press

other SNRs the optical and radio sizes are similar.

2. SNR CLASSIFICATION

2.1 The Evolved SNRs

This class contains the majority of the SNRs. Their spectrum which is characterised by a [SII] to Hα ratio greater than 0.7, is recognized as due to shock waves of modest velocities (50 - 200 km s^{-1}). There is no well-defined velocity of expansion of these SNRs and it is thought that the optical emission arises from shocked cloudlets in the interstellar medium.

In general the X-ray images reflect the general characteristics of the optical images although there is not a one to one correlation. It is believed that most of the X-ray emission also arises in shocked cloudlets but in regions of intermediate density which are not so dense as to have cooled too much. The displacement of the X-ray from the optical knots reflects the density structure of the cloudlets.

Figure 1 shows the HRI X-ray isophotes superimposed on the Hα image of 0534-69.9. A well-collimated optical jet runs out from its western edge for about 20pc. It appears to originate near the center of the SNR and is similar to the jet in the Crab Nebula discovered by Gull and Fesen (1982). There is an association with the X-ray structure which shows a central band of emission just south of the jet.

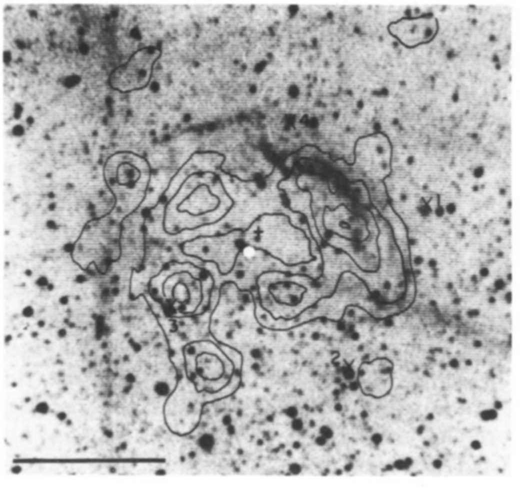

Fig. 1 SNR 0534-69.9 in the light of Hα. N to the top and E to the left. The dot marks the optical center and the bar is one arc min. The contour levels of the superimposed HRI X-ray isophotes are 0.006, 0.012, 0.018 and 0.024 counts s^{-1} arc min^{-2}.

https://doi.org/10.1017/S0074180900034410 Published online by Cambridge University Press

2.2 The Oxygen-rich SNRs

Three examples of young oxygen-rich SNRs have been found in the Magellanic Clouds, N132D (Danziger and Dennefeld, 1976, Lasker, 1980), 0540-69.3 (Mathewson et al. 1980) and 0102-72.3 (Dopita et al. 1981). The oxygen-rich SN ejecta has its origin deep within the chemically processed layers of a star greater than 25 $M_{\odot}$. Their spectra are characterised by high velocity dispersions ranging from 3000 km s^{-1} to 6000 km s^{-1}.

Surrounding 0102-72.3 is a ring of faint emission which exhibits the high excitation line of HeII $\lambda 4686$ and may be produced by the UV flash at the time of the explosion. Between this ring and the [OIII] filaments is a dark region, which may represent the position of the blast wave whose high temperature would suppress the optical emission.

The three SNRs have intrinsic X-ray luminosities much greater than CasA: indeed N132D is 16 times more luminous than CasA. This high X-ray luminosity is a general feature of LMC SNRs as 9 of the 26 are brighter than CasA between 0.15 and 4 keV.

2.3 The Balmer-dominated SNRs

SNRs 0505-67.9, 0509-67.5, 0519-69.0 and 0548-70.4 belong to this class (Tuohy et al. 1983) whose main feature is that their filamentary shells are strong in the Balmer lines of hydrogen but absent or very weak in [OIII] and [SII]. Their Balmer spectra can be understood in terms of a very high velocity non-radiative shock encountering gas which is partially neutral. It is believed that the four SNRs resulted from Type I supernovae because they have similar optical, X-ray and radio properties to the galactic Type I supernovae, Tycho, Kepler and SN 1006.

2.4 The Crab-like SNRs

Danziger et al. (1981) and Clark et al. (1982) suggest that N157B is a Crab-like SNR because of its centrally condensed radio structure, flat radio spectral index and nonthermal X-ray spectrum. The HRI X-ray isophotes presented in Figure 2 are also centrally peaked which supports their suggestion. The optical remnant appears to be the shell about 7 pc in diameter visible in the [OIII] image in Figure 2; the dot marks the center of the shell and the cross marks the [SII] patch found by Danziger et al. (1981). The X-ray source is smaller than this and lies on the western edge of the shell near the position of the radio source. This region has HI surface densities of 4×10^{21} atoms cm^{-2} and some of the X-ray structure may be obscured. N157B is probably a combination of shell and filled-in center SNR similar to Vela XYZ and MSH 15-52 in our Galaxy (Weiler 1983).

Clark et al. (1982) suggest that 0540-69.3, an oxygen-rich SNR, may also be a Crab-like remnant as it has a smooth power law X-ray

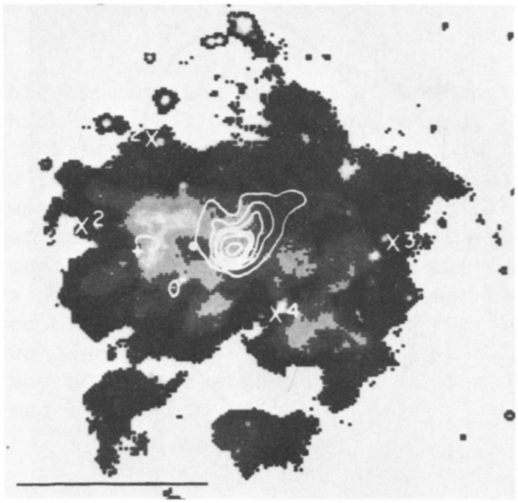

Fig. 2 SNR 0538-69.1 (N157B) in the light of [OIII]. N to the top and E to the left. This is a black and white print of a false color photograph to show clearly the shell of the SNR, the center of which is marked by a dot. The bar is one arc min. The cross marks the region strong in [SII]. The contour levels of the superimposed HRI isophotes are 0.01, 0.03, 0.05, 0.08 and 0.15 counts s^{-1} arc min^{-2}.

spectrum consistent with a synchrotron origin. Although they point out that a hot plasma of temperature 4 x 10^7K composed principally of oxygen with absorption at low energies could mimic the observed spectrum. The centrally peaked X-ray isophotes (Mathewson et al. 1983) are probably due to the source being unresolved by the HRI. This and the fact that the radio spectral index is normal argue against 0540-69.3 being a Crab-like SNR.

3. A POSSIBLE TYPE III SNR

Mathewson and Clarke (1973) found that the nebulosity between N49 and 0525-66.0 and surrounding 0525-66.0 (see Figure 3) is collisionally excited. During the course of an HI survey using the Parkes 64-m radio telescope, high velocity emission was discovered from a region containing 0525-66.0 and N49 and 270 pc by 160 pc in extent (Figure 3). Figure 4 shows the HI profile recorded at the center of this region. The high velocity peak is at a velocity 70 km s^{-1} greater than the main HI peak which is representative of this area in the LMC. The mass of the high velocity gas is calculated to be 17,000 $M_{\odot}$ and its kinetic energy is 8 x 10^{50} ergs.

https://doi.org/10.1017/S0074180900034410 Published online by Cambridge University Press

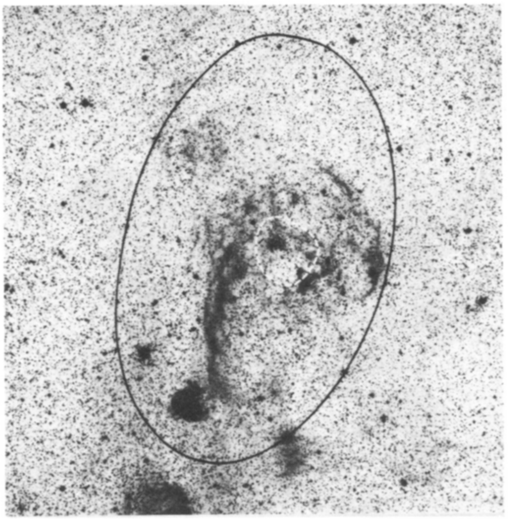

Fig. 3 A red photograph of the field of N49 and 0525-66.0. The dashed contour is the outer HRI X-ray isophote of 0525-66.0. The ellipse (17' x 10') encloses the region from which high velocity HI emission is observed.

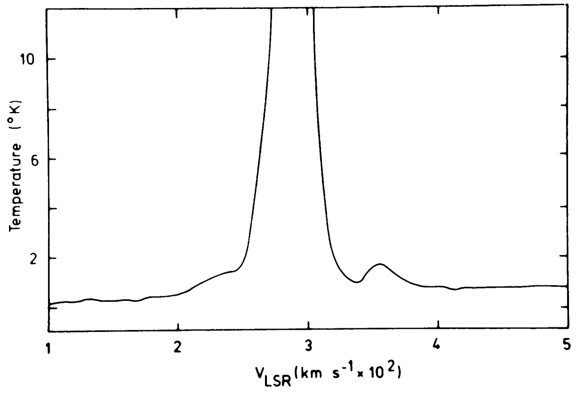

Fig. 4 The HI profile measured at the position of 0525-66.0 using the 64-m radio telescope at Parkes. The high velocity emission peak is at V_{LSR} = 356 km s^{-1}.

It is tempting to suggest that the widespread nebulosity and high velocity HI was produced by 0525-66.0. However the age of 0525-66.0 would certainly be less than 10,000 years and mean velocities in excess of 10^4 km s^{-1} would be necessary to produce such a phenomenon. This

https://doi.org/10.1017/S0074180900034410 Published online by Cambridge University Press

seems unlikely particularly as the observed velocity of the associated HI is only 70 km s^{-1}.

A more plausible explanation is that it was an independent, much earlier SN event which occurred out of the plane of the LMC and on the far side. The bubble developed more rapidly in the tenuous outer disk region and now the swept-up material has recombined and is moving out of the plane away from the observer. The visible nebulosity was excited by the blast wave travelling transverse to the line of sight in the outer disk medium. The total energy in the explosion would have been in excess of 10^{52} ergs and therefore may have been a Type III SN. The shock waves of this fossil SNR possibly triggered off the formation of the two massive stars which produced N49 and 0525-66.0 whose blast waves may be now reheating the cavities in the interstellar medium formed by the old remnant.

4. THE EVOLUTION OF SNRs

The evolution of SNRs has conventionally been divided into three phases. The first is a free-expansion phase, terminated when the mass of interstellar matter that is swept up equals the mass of the ejecta. Most observed SNRs are presumed to have entered the second phase, the adiabatic blast wave phase, which is described by the Sedov similarity solution. This states that

$$D \propto \left(\frac{E_o}{\rho_o} \right)^{1/5} t^{2/5}$$

where D is the diameter of the SNR, E_o is the energy in the initial explosion (assumed constant), ρ_o is the density of the interstellar medium and t is the age of the remnant.

The cumulative number, N(< D), - diameter, D, relationship is traditionally used to investigate SNR evolution. Figure 5 shows that this relation for LMC SNRs up to a diameter of 40 pc is $N(< D) = 0.48\ D_{pc}^{1.0\pm0.2}$. It is clear that SNRs do not evolve according to the Sedov solution for which the corresponding relation is $N(< D) \propto D^{5/2}$. Rather they appear to be in the free-expansion phase which is difficult to explain up to a diameter of 40 pc even assuming the three phase model of the interstellar medium of McKee and Ostriker (1977).

An explanation of this apparent free-expansion of SNRs may be as follows. When the mass of the swept-up material approaches that of the mass of the supernova material in the high velocity blast wave, the SNR will decelerate. However the ejecta travelling ballistically outward at velocities proportional to their distance from the center will overtake the decelerating blast wave and a reverse shock will be driven into the stellar ejecta. The kinetic energy of the ejecta will be transformed into thermal energy of the SNR which will prevent its

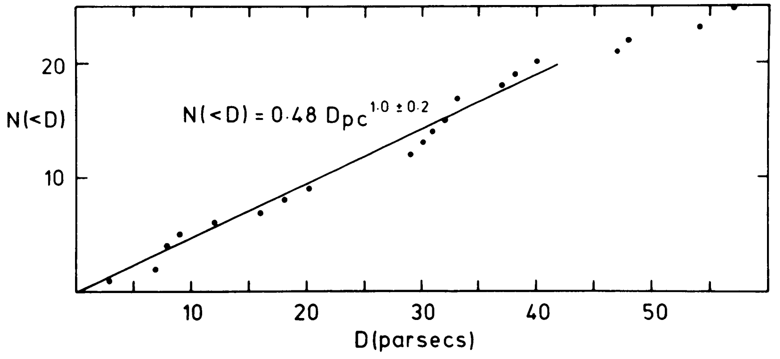

Fig. 5 The cumulative number (N < D) - diameter (D) relation for the SNRs in the LMC.

deceleration until the kinetic energy of the ejecta is exhausted. Thus the "free-expansion" phase will be maintained to quite large diameters. The clumps of reverse-shocked ejecta will be sites of high X-ray and optical emission because of their high density and chemical enrichment. Observational evidence which supports this model is the X-ray structure of Tycho and CasA which Gorenstein et al. (1983) interpret as due to an outer blast wave closely followed by the reverse shocked ejecta.

Model calculations of cooling shocks by Dopita (1979) show that the pressure just behind the shock in the interstellar clouds can be connected to the observed density using the density sensitive red [SII] line ratios. Assuming dynamic pressure equilibrium between blast wave and the shocked cloud, an estimate of E_o can be made. This was plotted as a function of diameter for SNRs in the Galaxy, M31, M33 and the LMC (Dopita, 1979 and Blair et al. 1981). It was found that $E_o \propto D^{2.3}$ up to diameters of 30 to 40 pc where it levelled off to a constant value of about 10^{51} ergs. In the context of the present model, this increase in E_o is due to the gradual conversion of the kinetic energy of the SN ejecta into thermal energy of the gas in the blast wave. If this observed dependence of E_o on diameter is substituted in the Sedov formula, it is found that $t \propto D^{1.2}$ and therefore $N(< D) \propto D^{1.2}$. This is close to that found for the LMC SNRs. The conclusion is that no longer can the Sedov solution alone be used to describe the evolution of SNRs because the value of E_o is not constant throughout the lifetime of each remnant.

REFERENCES

Blair, W.P., Kirshner, R.P. and Chevalier, R.A.: 1981, Astrophys. J., 247, 879.

Clark, D.H., Tuohy, I.R., Long, K.S., Szymkowiak, A.E., Dopita, M.A., Mathewson, D.S., and Culhane, J.H.: 1982, Astrophys. J., 255, 440.
Danziger, I.J. and Dennefeld, M.: 1976, Astrophys. J., 207, 394.
Danziger, I.J., Goss, W.M., Murdin, P., Clark, D.H., and Boksenberg, A.: 1981, Monthly Notices Roy. Astron. Soc., 195, 33P.
Davies, R.D., Elliott, K.H., and Meaburn, J.: 1976, Memoirs of the Roy. Astron. Soc., 81, 89.
Dopita, M.A.: 1979, Astrophys. J. Suppl., 40, 455.
Dopita, M.A., Tuohy, I.R., and Mathewson, D.S.: 1981, Astrophys. J. (Letters), 248, L105.
Gorenstein, P., Seward, F., and Tucker, W.: 1983, this volume, p. 1.
Gull, T.R. and Fesen, R.A.: 1982, Astrophys. J. (Letters), 260, L75.
Henize, K.G.: 1956, Astrophys. J. Suppl., 2, 315.
Lasker, B.M.: 1980, Astrophys. J., 237, 765.
Long, K.S., Helfand, D.J., and Grabelsky, D.A.: 1981, Astrophys. J., 248, 925.
McKee, C.F. and Ostriker, J.P.: 1977, Astrophys. J., 218, 148.
Mathewson, D.S. and Clarke, J.N.: 1973, Astrophys. J., 179, 89.
Mathewson, D.S., Dopita, M.A., Tuohy, I.R., and Ford, V.L.: 1980, Astrophys. J. (Letters), 242, L73.
Mathewson, D.S., Ford, V.L., Dopita, M.A., Tuohy, I.R., Long, K.S., and Helfand, D.J.: 1983, Astrophys. J. Suppl., in press.
Mills, B.Y., Little, A.G., Durdin, J.M., and Kesteven, M.J.: 1982, Monthly Notices Roy. Astron. Soc., 200, 1007.
Seward, F.D. and Mitchell, M.: 1981, Astrophys. J., 243, 736.
Tanaka, Y.: 1983, these proceedings.
Tuohy, I.R., Dopita, M.A., Mathewson, D.S., Long, K.S., and Helfand, D.J.: 1983, this volume, p. 571.
Weiler, K.W.: 1983, this volume, p. 299.

DISCUSSION

FÜRST: Recently Dr. Berkhuijsen inspected the optical SNR data for M31 and M33. The slope of N(< D) - D turned out to be also of the order one with a flattening at a diameter of 50 pc.

BLAIR: The N(< D) - D relation in M31 is virtually useless at the present time because of incompleteness. The smallest optical SNR identified in M31 has a diameter of roughly 20 pc.

I would like to suggest [OI] imagery to discriminate SNRs from HII regions in M31 and M33. While this line is problematical because of interference from the night sky emission, a test exposure of a field in M31 showed all five of the known SNRs in that field (unfortunately no new ones). This technique would not only find normal SNRs but would also find oxygen-rich SNRs as well.