THE MAGELLANIC CLOUD SUPERNOVA REMNANTS

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1. SURVEYS FOR SNR IN THE MAGELLANIC CLOUDS

It was some twenty years ago, at the previous IAU symposium devoted to the Magellanic Clouds, that Mathewson and Healey (1964) announced the discovery of the first supernova remnant (SNR) in the LMC. The method used was to identify a non-thermal radio source with a filamentary optical emission object and this confirmed N49 in the catalogue of Henize (1956) as an SNR and suggested N63 and N132 D as likely candidates.

Westerlund and Mathewson (1966) and Mathewson and Clarke (1972, 1973a,b,c) developed and exploited a technique whereby collisionally ionised gas could be distinguished from photoionised gas. This relies on the fact that the [S II] lines are much stronger with respect to Hα in plasma excited by collisions. Thus nebulosities that appear equally bright on [S II] and Hα plates are likely to be SNRs, those that are much brighter at Hα are H II regions and objects that are about equally bright at V, Hα and [S II] are probably stars or distant galaxies. By searching in the vicinity of known non-thermal radio sources, they identified twelve SNR in the LMC and two in the SMC. (see also Lasker 1976).

Such a selection procedure, although very successful, can now be recognized with the benefit of hindsight to carry with it a bias towards the detection of only evolved SNR. Young oxygen-rich SNR, although strong sources of non-thermal radio emission, must be found in the [O III] lines (Mathewson et al. 1980). Furthermore, several SNR have been discovered to be of the collisionless-shock type, showing only Balmer lines in their spectra (Tuohy et al. 1982) and relatively weak non-thermal radio emission. We thus now have as optical selection criteria for SNR (a) strong [S II] lines c.f. Hα (b) Hα and Hβ emission only and (c) strong [O III]; Hα, Hβ absent!

The launching of the Einstein Observatory led to the most recent SNR discoveries in the Clouds. In the LMC, Long, Helfand and Grabelsky

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(1981) listed a total of twenty-six SNR of which five were optical nebulosities in the catalog of Davies, Elliot and Meaburn (1976) and six were found to be extended in follow-up HRI observations. In the SMC, Seward and Mitchell (1981) concluded that one source was an SNR; confirmed by Dopita, Tuohy and Mathewson (1981), and that four others were probably SNRs. A complete catalogue of optical identifications and X-ray maps is given by Mathewson et al. (1983a).

In the SMC, the X-ray survey of Tanaka (1983), by going deeper than the Seward and Mitchell (1981) survey, resulted in several tentative SNR identifications (Mills et al. 1982). This survey together with the deep radio survey of Mills et al. (1983) in both the SMC and LMC has allowed the additional optical identification of five SNR in the SMC and two in the LMC (Mathewson et al. 1983b).

Detailed study of these SNR has proven to be very rewarding in its Astrophysical yield. The chemical abundances in both the Interstellar Medium (ISM) and the supernova ejecta can be studied, information on the mass of precursor stars can be derived in some cases and a great deal can be inferred about the physical structure of the ISM. These aspects will be the subject of the remainder of this review, with an emphasis on the younger SNR.

2. THE OXYGEN-RICH SNR

For many years only the fast moving knots of Cas-A were known to display the characteristic spectrum of this type of remnant, namely very strong forbidden lines of oxygen and a few heavier elemental species, but a total absence of hydrogen and helium recombination lines. (Chevalier and Kirshner 1979). Since then one other SNR of this type has been discovered in each of our Galaxy (Goss et al. 1979) and NGC 4449 (Balick and Heckman 1978). However, as many examples again are now known in the Magellanic Clouds; two in the LMC (Danziger and Dennefeld 1976; Mathewson et al. 1980) and one in the SMC (Dopita, Tuohy and Mathewson 1981).

Astrophysically, the Cas-A type SNRs are very exciting, since their peculiar spectra strongly suggest that we see directly matter ejected from deep within the core of a massive progenitor star from which vital clues about the nucleosynthesis processes and processes of ejection during the supernova event may be gathered.

From a dynamical viewpoint there is little doubt that the matter which is at present radiating in the visible has undergone little or no decelleration since ejection. In Cas-A, for example Kamper and van den Bergh (1976) show that the knots have a space velocity which is directly proportional to their distance from the center of expansion and that no decelleration of individual knots can be detected. If the knots are excited at the time they run into the reverse shock generated by interaction of the ejecta with the ISM, then they must map the dynamics of a particular zone in the ejecta. What evidence there is

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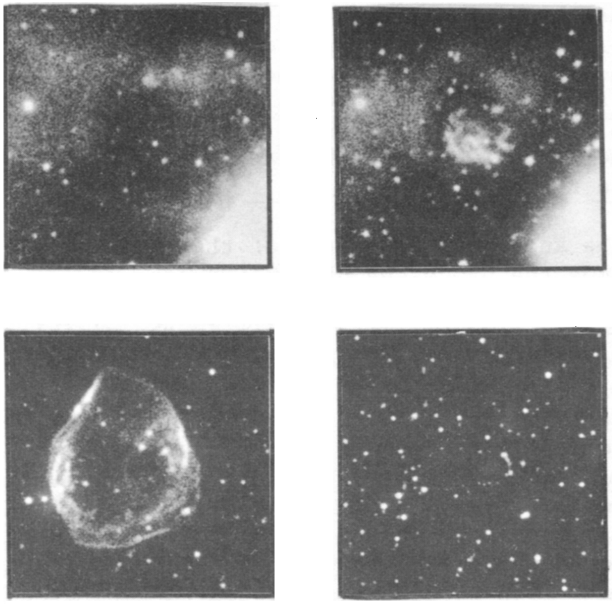

Fig. 1. Two SNR in the Magellanic Clouds, left Hβ right [O III]. The top remnant, 1E0102-7219, is a young SNR in the SMC with oxygen-rich filaments and diffuse highly ionised halo. The lower object is DEM 71, in the LMC and is an example of the non-radiative shock SNR.

suggests that this zone is not spherical. Lasker (1978) showed that, rather, the high-velocity material is N132 D maps into an annular feature apparently expanding at 2250 km s^{-1} in a plane inclined at 45° to the line of sight. The existence of similar high velocity rings of ejecta has since been inferred in Cas-A from X-ray dynamical evidence (Winkler et al. 1982), and in the Galactic SNR G292.0+1.8, from high-resolution X-ray mapping (Tuohy, Clark and Burton 1982). However, perhaps the most curious ring is seen in the SMC remnant 1E0102.2-7219 (see Fig. 1). The dynamics of this remnant (Tuohy and Dopita 1983) show a perturbation in the polar direction which oscillates as cos 3θ in azimuthal angle and with an amplitude that varies with azimuthal angle. Even with such a complex structure, the underlying expanding ring motion appears to be preserved. Such a complex structure argues strongly for a global instability of the ejecta either caused by plasma instability during the ejection or else during the collapse phase.

The fact that ring ejection appears to be a common feature of oxygen-rich (Type II) supernova events is an important clue in the physics of the collapse phase. At the present time only the model of Bodenheimer and Woosley (1982) appear to generate such a feature naturally. This model (for a 25 $M_{\odot}$ precursor star) generates a thick

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shocked disk during collapse in which explosive nuclear burning coupled with a rotational bounce near the core drives out high velocity equatorial ejection. Such a model is capable of producing a large degree of core overturn and mixing and this may be observable by spectrophotometric studies of the knots. If temperatures rise high enough, explosive burning of neon may occur. The 'ashes' of this are very sensitive to temperature (Woosley and Weaver 1980) and traces of this process may also be found in the ejecta.

Although the knots and filaments of these remnants offer the potential to study the processes of nucleosynthesis in massive stars, this potential has not been realised for two reasons; the lack of an adequate number of diagnostic line ratios in the visible, and failing this, the lack of a believable model for the excitation of the knots.

It has generally been assumed that the optical emission in the fast-moving material is the result of a radiative shock passing through it (Peimbert and van den Bergh 1971, Lasker 1978, Chevalier and Kirshner 1978, 79, Goss et al. 1979, Murdin and Clarke 1979, Kirshner and Blair 1980, Blair, Kirshner and Winkler 1983). This would naturally result from the interaction between cloudy ejecta and a hot reverse-shocked intercloud medium. The cloudy ejecta could be generated by operation of a Rayleigh-Taylor instability at the core envelope interface in the star (Falk and Arnett 1973, Chevalier 1975, 76) or at the ejecta/ISM interface (Gull 1973) or else by early thermal instability in the oxygen-rich ejecta (Dopita, Binette and Tuohy 1983).

Shock-wave models for the filaments have been developed by Itoh (1981a,b) for the pure-oxygen case and by Dopita, Binette and Tuohy (1983) for a reasonable mix of elements. The models display some extraordinary properties resulting from the very efficient cooling of oxygen which include a large separation between ion and electron temperatures, a 'freezing' of states of high ionisation to very low temperature, and a very extensive region of pre-ionisation. Entertaining as these effects may be, the computed spectra bear little resemblance to those observed (Lasker 1978; Dopita and Tuohy 1983), and Dopita, Binette and Tuohy (1983) conclude that the shock excitation theory is no longer tenable. If not shocks, then what? Three possible mechanisms were suggested, photoionisation by X-rays, electron conduction and direct heating by suprathermal ions (which will occur when the cloud is smaller than the stopping distance for these ions).

Whatever the mechanism of excitation, it is common to all SNR of this class. From the spectra of Table 1, it is clear that although there are obvious differences resulting from different chemical compositions (e.g. presence or absence of lines of neon, calcium and sulphur) the physical conditions are very similar. For example, the electrom temperature given by the [O III] λ4363/λ5007 Å ratio is very little different from $T_e \sim 2000$°K and the degree of excitation given by [O I]: [O II]: [O III] line ratios varies within very narrow limits. We can therefore confidently expect that a successful model will yield abundances that

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can be believed.

TABLE 1. Spectrophotometry of Young SNR (Dopita + Tuohy 1983)

Ion	λ (Å)	G292	0540	N132 D*	1E0102
[Ne V]	3426	-	-	-	3.5
[O II]	3726, 9	79	54	165	130
[Ne III]	3869	7	-	9	14
	3967	2	-	3	5
[S II]	4068, 76	-	4	-	-
[O III]	4363	3	3	5	4
	4959	32	30	31	34
	5007	100	100	100	100
[O I]	6300	5	3	11	3
	6363	-	1	4	1
Ca I]	6573	-	17	-	-
[S II]	6717, 31	-	63	-	-
[O II]	7319, 30	-	(2)	10	-

* Below 5007, global spectrum; above 5007 single filament spectrum.

Spectral similarities apart, each of the Magellanic Cloud oxygen-rich remnants have individual peculiarities. N132 D has, apart from the oxygen-rich ring, a few very bright knots of more normal composition which were discovered by Mathewson and Clarke (1973b) and a 26 pc diameter halo first described by Lasker (1978). This halo appears to be normal shock excited gas and is visible in X-rays over the same or slightly greater diameter (Mathewson et al. 1983a). Given the very rapid expansion of the oxygen-rich ring (Lasker 1980), it is difficult to avoid the conclusion that N132 D is a double SNR event resulting possible from the closely sequential explosion of the components of a binary. The other LMC remnant, SNR 0540-69.3 (in N158 A) shows broad [S II] lines and, probably, a Ca I] line in its spectrum. These have very similar velocity dispersion to the [O III] lines. (Dopita and Tuohy 1983). There is some evidence that these other elements are confined in a smaller annular ring than the [O III] emission (Mathewson et al. 1980), this may be caused by the limited bandpass of the filter used to image the remnant, but would be consistent with their zone of nucleosynthesis in the parent star.

The SMC remnant 1E0102.2-7219 shows a remarkable halo of high excitation which largely surrounds it. This appears to be excited by the remnant itself and has very strong He II lines in its spectrum (Dopita, Tuohy and Mathewson 1981, Tuohy and Dopita 1983). It is separated from the remnant by a dark annulus which in its outer bound-

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ary appears to delineate the position of the blast-wave (see Fig. 1). This spatial separation between oxygen-rich filaments and blast-wave is expected in the reverse-shock hypothesis.

3. THE NON-RADIATIVE SHOCK SNR

Amongst the SNR identified by Long, Helfand and Grabelsky (1981) purely on their X-ray properties, four were found to emit in the visible only in the Balmer lines (Tuohy et al. 1982) (see Fig. 2). Three of these were not previously known to have an associated optical nebulosity. A further example of transitional class was later found in the SMC (Mathewson et al. 1983b). These discoveries more than doubled the SNR of this type, since only Tycho (Kirshner and Chevalier 1978) and the remnant of SN 1006 (Schweizer and Lasker 1978) are similar; although both the Cygnus Loop (Raymond et al. 1980) and IC 443 (Lozinskaya 1979) show some regions with similar properties.

The theory of such spectra has been developed by Chevalier and Raymond (1978), Chevalier, Kirshner and Raymond (1980) and Raymond et al. (1983) as due to a high-velocity non radiative shock passing through a partially ionised ISM. In this case the neutral hydrogen is collisionally excited by the high temperature electrons before it is finally ionised and joins the high-velocity post-shock plasma. Since the neutral gas is not initially coupled to the bright velocity stream by Coulomb interactions, the Balmer lines emitted by it are very narrow. However, a broad component to these lines may arise by resonant charge-ex change with the ionised stream. Where this is seen, as in SNR 0519-69.0 this can be used to estimate the current blast-wave velocity directly.

All the non-radiative shock SNR are young (or youthful) and there is fairly strong circumstantial evident to comment them with Type I supernova events. For SNR 0519-69.0, the following parameters are derived for the mass and energy of the supernova event, respectively:

$$1.8 \times 10^{51} < E_\circ < 2.2 \times 10^{51} \text{ ergs}$$

$$1.2 < M < 4.0 \ M_\odot$$

These figures are similar to those derived by Chevalier, Kírshner and Raymond (1980) for Tycho's SN except that the mass range was brighter, 0.9 - 2.8 $M_\odot$. This event was certainly of Type I from its high curve (Clark and Stephenson 1977). Furthermore, Wu et al. (1983) recently observed an OB star projected against SNR 1006 in the UV and found strong absorption lines of iron with a velocity dispersion of about 5000 km s^{-1}. This would be expected from the theory of Type I supernova events which are thought to result from carbon detonation or deflagration of a white dwarf or the degenerate core of a moderate mass star (up to 9 $M_\odot$) (Wheeler 1982), with consequent ejection of iron-peak elements.

Although there is little remarkable about the X-ray properties of

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these remnants, both the Magellanic Cloud and Galactic examples of this class of SNR appear to be underluminous at radio frequencies by factors of order ten (Tuohy et al. 1982). This implies that either different physical conditions or different physical processes moderate the radio emission from these remnants.

4. THE EVOLVED (RADIATIVE) SNR

As McKee (1983) points out, SNRs are thought to generate a hot intercloud component of the interstellar medium (ISM) and thus govern the inhomogeneity of the ISM to a significant extent. In turn, the cloudy structure of the ISM strongly influences the evolution and appearance of the SNRs, and evolved remnants may therefore be used to probe this structure.

The simplest demonstration that the ISM is not homogeneous comes from a cumulative number/diameter relationship. This was first plotted for the LMC remnants by Mathewson and Clark (1973b) and has been updated several times since (Dopita 1982, Mills 1983, Mathewson et al. 1983) and we present in Figure 2 the latest version of this diagram (which excludes the non-radiative SNR and so refers to Type II supernovae). According to Sedov theory for blast waves in a uniform medium, this should have a slope of 5/2. In fact, it is nowhere near as steep as this and can be best fitted by a linear relationship N(D) = 0.4 D pc. This implies that, even out to diameters of 50 or 60 parsecs, the LMC remnants appear to be expanding with a uniform velocity.

For a uniform ISM, the free expansion phase is terminated when the mass of ISM swept up about equals the mass ejected. A reverse shock then heats the ejecta and the remnant enters the Sedov phase in which the majority of the energy is thermal. The LMC cumulative number/diameter relationship therefore either implies free expansion <u>or</u> the storage of an appreciable fraction of energy in the kinetic form until quite late in the evolution. This was suggested by Clarke (1976), and was confirmed observationally by Dopita (1979) who measured directly the pressure in the optical filaments in a number of LMC remants. Since this is very nearly constant, a thermal energy content increasingly almost as fast as R^3 is inferred. For constant driving pressure, the blast-wave would, of course, move at constant velocity; which would explain the cumulative numbers/diameter relationship.

The inescapable conclusion of these observations is that <u>both</u> the interstellar medium <u>and</u> the ejecta are cloudy. The theory of this geometry has been developed by McKee (1983). In this type of model, the optically radiative shocks are moving into dense pre-existing interstellar clouds which are pressurised by the external hot gas. The position of the blast-wave will be delineated by non- radiative shocks (as in the case of IC 443 and Cygnus mentioned in the previous section), by coronal emission of species such as [Fe XIV] and by the outer boundary of X-ray shell. A relatively smooth [Fe XIV] has been mapped for the brightest of the LMC remnants, N49, by Dopita and

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Mathewson (1979). This did indeed lie for most of its length outside the brightest of the optical filaments. Little has so far been said about X-ray observations.

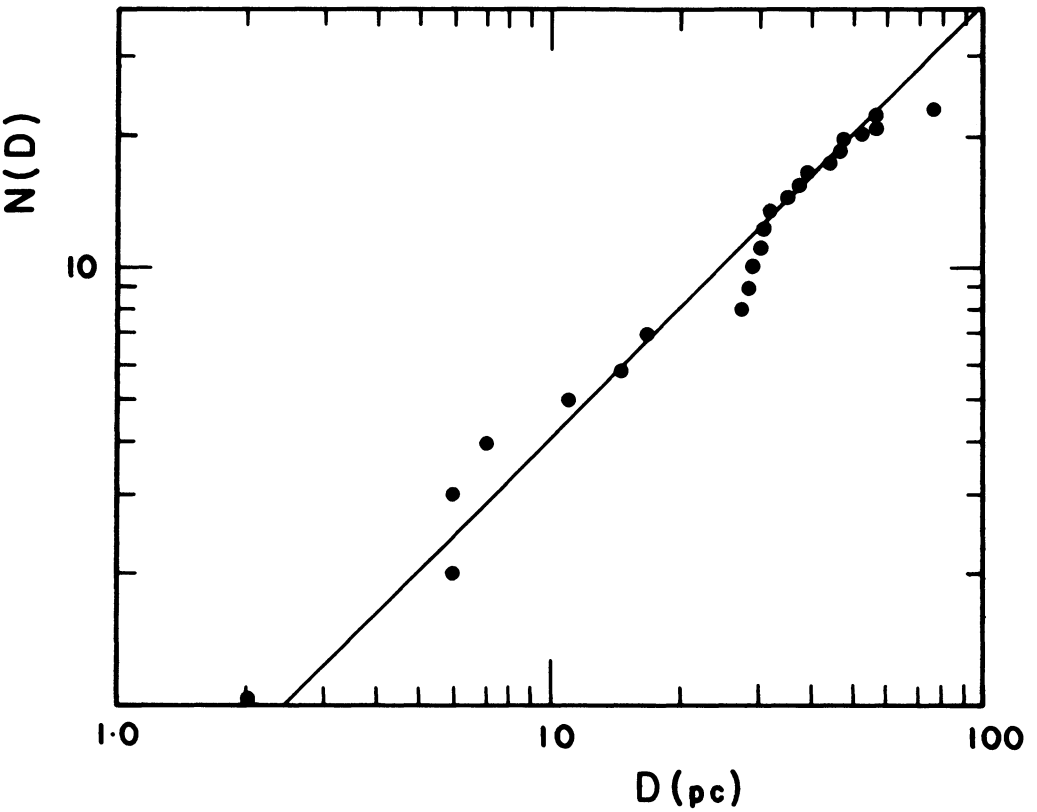

Fig. 2. The cumulative number, N(D), diameter relationship for the Type II SNR in the LMC.

The X-ray surface brightness declines rapidly with radius for the LMC remnants, as first shown by Long and Helfand (1979). The X-ray surface brightness between 0.15 and 45 KeV, L_X, can be fitted best by the relationship $L_X = 1.1\ Dpc^{-3.3}$ (erg cm s^{-2} s^{-1} sr^{-1}). In this respect it has similar behaviour to the radio surface brightness at 408 MHz, L_R, which is fitted by $L_R = 1.5 \times 10^{-16}\ Dpc^{-2.6}$ (W.M.$^{-2}$ Hz^{-1} sr^{-1}) (Mathewson et al. 1983a). A variety of different effects can determine this relationship. Density variations in the ejecta and ISM will lead to large pressure variations which in turn strongly influence the X-ray morphology. In particular, McKee (1983) points out the the impact of a blob of ejecta on an interstellar cloud will result in rapid thermalisation of the kinetic energy and the production of a secondary blast-wave and X-ray hot spot. This process may be responsible for the scolloped appearance of some SNR. Another effect that cannot be

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ignored is the high abundances of important X-ray coolants in the ejecta which will enhance the emissivity of this material in the early phases of the evolution (Long, Dopita and Tuohy 1982). A third effect is the production of an X-ray synchrotron continuum by a pulsar. The SSS of the Einstein Observatory was used to measure the spectra of six bright SNR in the LMC. Four of these showed a normal thermal spectrum, but two young remnants N157 B and 0540-69.3 had featureless continuum a consistent with a power law (Clark et al. 1982).

In conclusion, much observational data now exist to produce a self consistent model of the ISM in the Magellanic Clouds and the evolution of the SNR in this medium using data from the optical, X-ray and radio domains. It is clear that this will involve a multiphase ISM (e.g. McKee and Ostriker 1977) but must also properly account for the structure and abundances in the ejecta. Further work on the young SNRs is required both observationally and theoretically to provide this data and to examine the physics of the supernova event in its own right.

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DISCUSSION

Dufour: Do you observe any evidence of slow-moving pre-SN ejected material enriched with nitrogen (or other) within, or in front of, the O-rich material in young oxygen-rich Cloud SNRs?
Dopita: Only in the case of N132D are dense shocked cloudlets seen.
Dufour: So the young O-rich SNRs in the Clouds are not like Cas A with substantial pre-SN mass loss?
Dopita: No, there is probably nothing corresponding to the quasi-stationary flocculi of Cas A.
Lasker: The detection of [ArIII] λ7132 in the young O-rich SNRs still appears marginal. Please elaborate on this and on the other trace elements that are suggested by the stellar interior models.
Dopita: I agree that the fainter lines are indeed very faint. The spectra I have shown are the summation of many spatial pixels shifted to zero velocity. This has extended the sensitivity limit to very faint lines by a factor of order five. It appears that, except for N158A, very faint lines of other species are almost entirely absent.

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