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Optical Observations of SNRs in the Magellanic Clouds

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Abstract

A review is presented of optical observations of SNRs in the Magellanic Clouds. A model for these SNRs, based on cloudlet shocks, is shown to agree well with the observations.

Introduction

For many years the standard picture of SNR evolution has been divided into a number of evolutionary phases (Spitzer 1968):

(i) A free expansion phase; this phase terminates when the swept-up interstellar matter equals the mass of the ejecta.

(ii) An adiabatic blast wave phase; in this phase radiative losses are small compared with the initial energy E_0 of explosion, which may be described by similarity solutions (Taylor 1950; Sedov 1959).

(iii) A radiative phase (Cox 1972*a*); this phase starts when the cooling time behind the shock becomes shorter than the hydrodynamic time and it terminates when a substantial fraction of E_0 has been radiated. Since optical radiations ([OI], [OII], [OIII], [NI], [NII], [SII], [NeIII] etc.) are emitted appreciably for plasma temperatures $T_e \leqslant 10^5$ K, all SNRs that show optical filaments were presumed to have entered the radiative phase.

(iv) A momentum conserving stage (Oort 1946); this phase terminates when the expansion velocity becomes comparable with the random turbulent or thermal motions in the interstellar medium.

The last four years have seen a very rapid expansion in the observational field of thermal X rays from SNRs, much of which has been covered in excellent reviews by Gorenstein and Tucker (1976) and Culhane (1977). There is a large measure of agreement that the results for galactic SNRs of diameter 10–40 pc (Cygnus Loop, Vela X, IC 443 and Pup A) are consistent with an adiabatic blast wave interpretation. From an optical viewpoint this is disconcerting, as the optical observations point towards phase (iii) rather than phase (ii). The difference is reflected in estimates of shock velocities, e.g. in IC 443 the X-ray data point toward a velocity of about 800 km s^{-1} (Malina *et al.* 1976).

Measured optical velocity dispersions would only suggest a velocity in the range 65–100 km s^{-1} (Lozinskaya 1969; Al-Sabti 1970). Similar velocities are also indicated for other galactic SNRs, using diagnostics derived from emission line intensity ratios in the radiating shock waves (Dopita 1977*a*, Paper II; Dopita *et al.* 1977, Paper III).

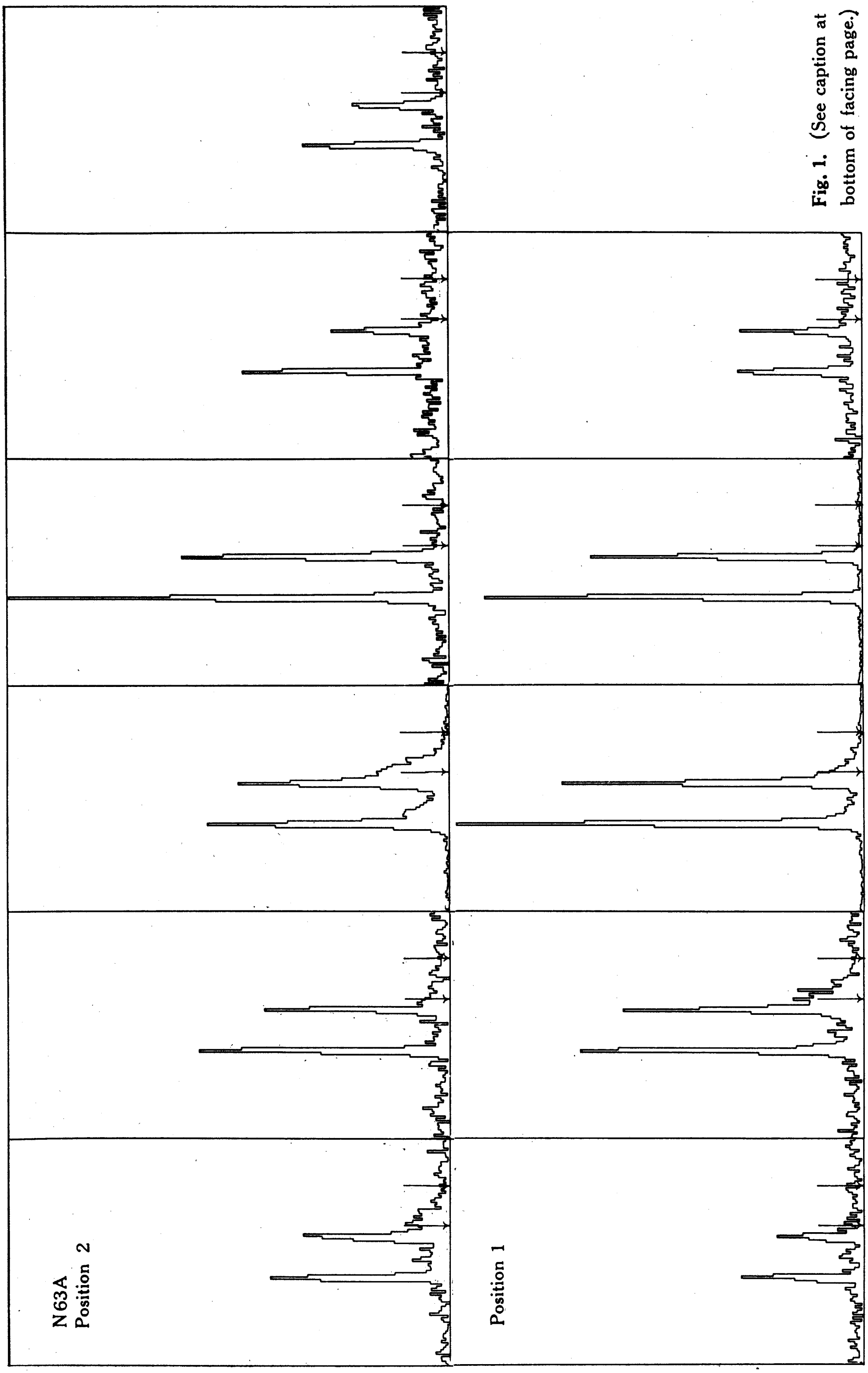

Fig. 1. (See caption at bottom of facing page.)

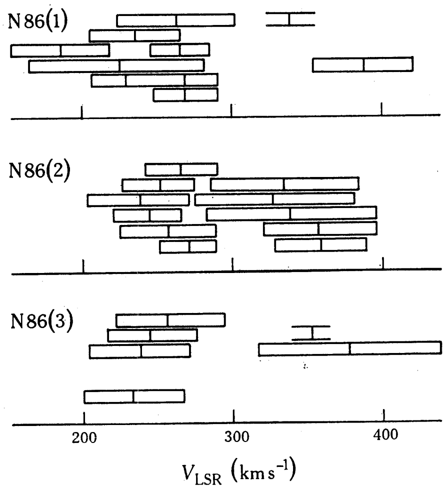

Fig. 2. Profile widths and maxima seen in N86.

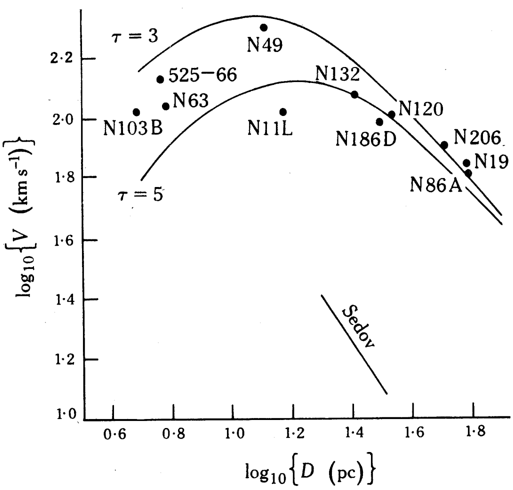

Fig. 3. Plot of velocity V against diameter D for Magellanic Cloud SNRs, showing the dispersion observed. The expected slope according to Sedov's (1959) theory is indicated. (For the significance of the curves marked $\tau = 3$ and 5, see text.)

Fig. 1. Profiles of the [OII] doublet in N63 obtained with the IPCS on the Royal Greenwich Observatory spectrograph of the Anglo-Australian telescope. Each profile corresponds to a portion of the slit at each position. Note the faint high velocity feature (top left) corresponding to a faint nebulous arc outside the previously recognized SNR. The horizontal axis is in wavelength, and the arrows designate the rest wavelengths of the doublet.

The best explanation for these very large discrepancies seems to be that the interstellar medium is cloudy. The physics of the interaction of dense clouds with the blast wave has been discussed and developed by Bychkov and Pikel'ner (1975), McKee and Cowie (1975), Sgro (1975), Woodward (1976), McKee and Ostriker (1977) and McKee *et al.* (1978).

Some caution as to the applicability of similarity solutions to the interpretation of the X-ray data is required, however, following the demonstrations by Lerche and Vasyliunas (1976) and Isenberg (1977) that the isothermal and adiabatic similarity solutions respectively are unstable to radial perturbations over a wide range of assumed conditions. However, the recent discoveries by Woodgate *et al.* (1974) of the coronal line of [FeXIV] (which was predicted by Shklovsky 1967) and by Gorenstein *et al.* (1971) and Stevens *et al.* (1973) of the [OVII] and [OVIII] X-ray lines have placed a further constraint on derived physical parameters. No substantial disagreement between these line data and the continuum data has been found.

In the case of the Magellanic Cloud supernovae we are presented with a number of optical remnants at least equal to or greater than the total number known optically in our own Galaxy. These are at a wide range of evolutionary development and are all at a common, and (perhaps more importantly) known, distance. They therefore represent a largely unexploited testing ground both for evolutionary scenarios and, in the optical wavelengths at least, for theories of enrichment of heavy elements.

Identification of SNRs

The technique of optical identification of SNRs in the Magellanic Clouds (Mathewson and Clarke 1972, 1973*a*, 1973*b*, 1973*c*) consists in identifying a non-thermal radio source with an optical nebulosity, and comparing narrow band $H\alpha$ and [SII] photographs. A nebulosity in which $H\alpha$ and [SII] have similar intensities is liable to be an SNR. This method has been successfully applied to discover three SNRs in M33 by D'Odorico *et al.* (1978).

Application of the technique of optical identification to large diameter SNRs becomes difficult for several reasons. Firstly, simply due to the faintness of the radio emission, it may be difficult to measure a spectral index. Secondly, since the radio flux density is a rapidly decreasing function of radius, whereas the $H\alpha$ surface brightness changes but slowly, the ratio of these may mimic that of a thermal plasma at large SNR radii. Thirdly, a problem arises if shell sources centred on OB stars or associations such as the Henize objects N57, N70 and N185 are the result of super-giant mass loss (Castor *et al.* 1975). Since we see optically the cooling–recombination zone of a shock, we have no way of distinguishing the driving processes. Of course, photo-ionization by the central stars may have some effect on the optical spectrum, but this is only a further complicating factor. From the point of view of energy, cluster mass loss over a period of 10^5–10^6 years could deposit as much energy in the interstellar medium as a single supernova explosion. Many of the shell sources listed as possible SNRs by Davies *et al.* (1976) appear to be associated with OB clusters, so that it is not clear which of these are mass-loss bubbles or SNRs.

Physical Conditions in SNR Shocks

It is perhaps surprising that, up to the present, no systematic study has been made of the expansion velocity of an SNR as a function of its diameter. Mathewson and

Clarke (1973*c*) measured the velocity ellipsoid of N49, and gave an expansion velocity of about 200 km s^{-1}. Danziger and Dennefeld (1976*a*, 1976*b*) measured N132D, and found radial velocities in the [OIII] line over a range of some 4400 km s^{-1}. In order to rectify this deficiency, the author, as part of a more extended optical study of SNRs in the Magellanic Clouds, used the Image Photon Counting System (IPCS) on the Anglo–Australian telescope at high resolution ($\sim$25 km s^{-1}) in the [OII] doublet $\lambda 3726 \cdot 1$ and $\lambda 3728 \cdot 8$ Å (Dopita 1978*b*). The slit length of 108″ arc was divided into six sections. In very few cases could the motions be described as an organized expansion (see Figs 1 and 2); they appear to vary randomly, with very little correlation from point to point along the slit.

In Fig. 3 we plot half the mean velocity dispersion as a function of diameter. This shows remarkable features. Firstly, the smallest SNRs appear to have lower velocity dispersions than N49, for example, whereas the falloff in velocity is only a slow function of size for the larger SNRs. For SNRs with diameters greater than 10 pc, the regression fit is

$$V = 570\, D^{-0 \cdot 5 \pm 0 \cdot 1}, \tag{1}$$

with V in km s^{-1} and D in pc. To see what this implies, consider the generalized similarity solution for a medium whose density varies as $\rho(r) = Ar^{-\omega}$ (Isenberg 1977). If t is the age of the remnant then the blast wave radius r_s is given by

$$r_s = (E_0/A)^{1/(5-\omega)}\, t^{2/(5-\omega)} \tag{2}$$

and the blast wave velocity V_s is given by

$$V_s = 2(5-\omega)^{-1}\, (E_0/A)^{1/(5-\omega)}\, t^{-(3-\omega)/(5-\omega)}. \tag{3}$$

Equations (2) and (3) imply

$$t = 2r_s/(5-\omega)V_s, \qquad E_0 = Ar_s^{(5-\omega)}\, t^{-2}, \qquad V_s = cr_s^{-(3-\omega)/2}, \tag{4}$$

where c is a constant involving A, E_0 and ω. The equations (1) and (4) suggest a medium whose density varies with an index $\omega = 2$.

Fortunately, since the [OII] doublet was observed, we have a direct measure of the preshock density. Since the [OII] emission comes from a fairly cool zone near the recombination zone of the shock front, the density in this zone reflects the preshock density multiplied by the compression factor f of the gas, which is roughly given by $f \approx 4T_s/T_{[\mathrm{OII}]}$, where T_s is the shock temperature and $T_{[\mathrm{OII}]}$ is the temperature of the [OII] zone. This arises because the shock is strong and the subsequent cooling almost isobaric. From detailed shock models, Dopita (1977*a*, 1978*a*; Papers II and IV) has shown that the density $n_{[\mathrm{OII}]}$ measured from the [OII] ratio for a temperature of 10^4 K provides us with the preshock density n_0 through the relation

$$n_{[\mathrm{OII}]} = 31\, n_0\, (V_s/100)^2, \tag{5}$$

where the densities are given in cm^{-3} and V_s is given in km s^{-1}. A similar expression holds for the analogous [SII] density-sensitive ratio $\lambda 6731/\lambda 6717$,

$$n_{[\mathrm{SII}]} = 45\, n_0\, (V_s/100)^2. \tag{6}$$

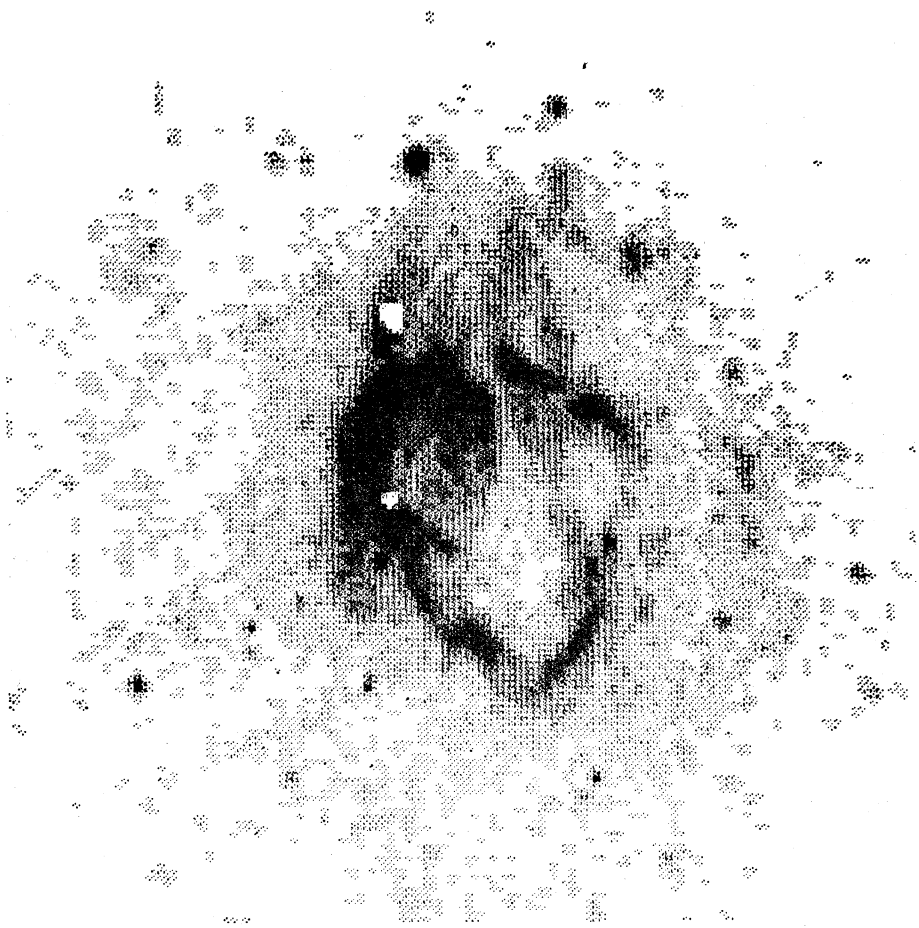

Fig. 4. A typical reduced SEC vidicon frame, showing N86 in Hα. The filter was sufficiently narrow in its bandpass (16 Å) to exclude [NII] emission.

Furthermore, an estimate of n_0 can also be obtained from the absolute surface flux brightness. The present brightness measurements were made with the 1 m telescope of the Siding Spring Observatory, using an interference filter centred at Hα and excluding [NII]. A focal reducing camera and SEC (secondary electron collection) vidicon detector were used (see Fig. 4). Utilizing the computations of Raymond (1976, 1978) in preference to my own, since his treatment of the recombination zone is more sophisticated, we find for a single plane-parallel shock observed at normal incidence that the Hα flux density $S_{H\alpha}$ is given by

$$S_{H\alpha} = 1\cdot 63\times 10^{-6} n_0 (V_s/100)^p, \tag{7}$$

where the index p is given by

$$p \approx 1\cdot 7 \quad \text{for} \quad V_s \leqslant 150 \quad \mathrm{km\,s^{-1}},$$

$$p \approx 2\cdot 1 \qquad\qquad V_s > 150 \quad \mathrm{km\,s^{-1}}.$$

The run of n_0 derived by these three methods (equations 5–7) against diameter is given in Fig. 5. The [SII] densities were derived from observations by Dopita *et al.* (1977).

Fig. 3 implies $\omega = 2$, but Fig. 5 asserts that there is no significant variation in the preshock density, which is high (with logarithmic and arithmetic means of 12 and 24 cm^{-3} respectively). It is clear, therefore, that *no homogenous or smoothly varying preshock density is consistent with the observations.*

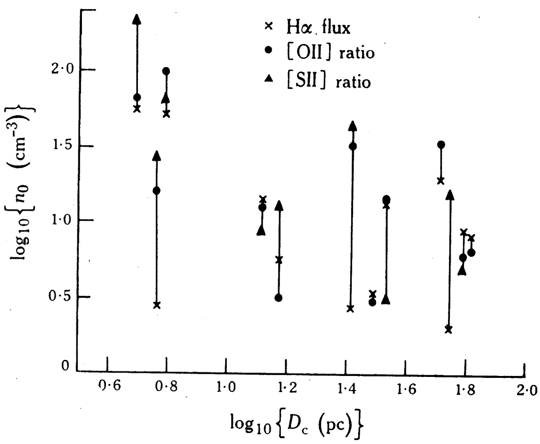

Fig. 5. Relationship between the preshock density n_0 and the diameter D_c for Magellanic Cloud supernovae.

Consider now the possibility that what we see in the [OII], [SII] and Hα emissions are slow shocks being driven by surface pressure into cloudlets. This proposal is along the lines suggested by McKee and his collaborators (McKee and Cowie 1975; McKee and Ostriker 1977; McKee *et al.* 1978), a view supported by the high value (12–24 cm^{-3}) derived for the preshock density (cf. 6 cm^{-3} for the Cygnus Loop obtained by Cox 1972*b*).

If a blast wave velocity V_s moving into a medium of density ρ_0 and ratio of specific heats γ overruns a dense cloud of density ρ_c and ratio of specific heats γ_c then a shock is propagated into the cloud at a velocity V_c given by McKee and Cowie (1975) through

$$\rho_c V_c^2 = \beta\{(\gamma_c+1)/(\gamma+1)\}F\rho_0 V_s^2, \tag{8}$$

where

$$F = 3\cdot 15 - 4\cdot 78x + 2\cdot 63x^2, \qquad \text{with} \qquad x = (\gamma+1)V_c/(\gamma_c+1)V_s. \tag{9a, b}$$

Here β is a factor describing the falloff in pressure behind the blast wave (so that $\beta = 1$ at blast shock) and F is a factor describing the extent to which the surface pressure upon the cloud is enhanced over the intercloud value, and so can reach a value of $3\cdot 15$ for a large contrast between the cloud and intercloud densities. Sgro (1975) found that for extended clouds F has a value as high as 6.

The behaviour of the pressure behind the blast wave can be investigated using the similarity solutions. For a medium with $\rho_0(r) = Ar^{-\omega}$, the appropriate similarity variable is

$$\lambda = (A/E_0 t^2)^{1/(5-\omega)} r, \tag{10}$$

and the self-similar transformed pressure is

$$P(r,t) = \rho_0(r)\, V_s^2\, P_0(\lambda). \tag{11}$$

Isenberg (1977) showed that near the shock we have

$$P_0(\lambda) = \frac{2}{\gamma+1}\left\{1+\frac{1}{\gamma-1}\left(\frac{2\gamma^2+7\gamma-3}{\gamma+1}-\omega\right)(\lambda-1)\right\}. \tag{12}$$

If we regard equation (12) as an expansion of the function $P_0(\lambda) = c\lambda^n$ to first order then we obtain

$$n = \frac{1}{\gamma-1}\left(\frac{2\gamma^2+7\gamma-3}{\gamma+1}-\omega\right).$$

Using $\gamma = 5/3$ we obtain $\omega = 0$ for $n = 8$ and $\omega = 2$ for $n = 5$. From equations (2), (3), (4), (10) and (11) we find that if r_c is the distance of the cloud from the explosion centre then

$$P(r,t) \propto r_s^{-11}\, r_c^8 \qquad \text{for} \qquad \omega = 0, \tag{13a}$$

$$\propto r_s^{-6}\, r_c^3 \qquad\qquad \omega = 2. \tag{13b}$$

Since the cloud shock velocity V_c varies as the square root of the pressure (provided F does not change rapidly), the velocity of the cloud shock at the moment of its formation is predicted to vary as $r_s^{-3/2}$ for $\omega = 0$ and 2. (In fact, this is true for any $\omega < 3$.) This is inconsistent with Fig. 3, and so we conclude that *cloudlet shocks, if they exist, cannot be young* (in terms of the supernova expansion time scale).

Another possibility is that we see a variety of shocks at all possible radii. This is equivalent to the assumption that the cloudlet shocks take a time greater than the expansion time scale to propagate through the cloudlets. This problem can be solved exactly for a critical value of ω, namely $\omega_* = (7-\gamma)/(\gamma+1)$; for $\gamma = 5/3$ we have $\omega_* = 2$. The self-similar solution is then particularly simple:

$$P_0(\lambda) = \{2/(\gamma+1)\}\, \lambda^{2(\gamma+5)/(\gamma+1)}, \tag{14}$$

so that for this case the relations (13) are valid right to the origin. However, with a constant space density of cloudlets, the space weighted mean of the cloudlet shock velocity still varies as $r_s^{-3/2}$. For other ω values the variation will not be exactly as $r_s^{-3/2}$, but it will not be very far removed from this.

There remains one possibility, that we see cloudlets only for a finite time, after which (presumably) the shock has passed through the cloud and the cloud undergoes steady acceleration towards the intercloud velocity without further appreciable optical emission. Since the blast wave moves at a much higher velocity than the cloudlet shock, this implies that the diameter of the SNR observed in the optical filaments in, say, [SII] or [OII] is somewhat smaller than the blast wave diameter.

Fig. 3 contains isochrones for $\tau = 3$ and 5 in the case of $\omega = 2$, where τ is the time taken for the shock radius to increase in size by 1 pc from an initial value of 10 pc. It is evident that a good fit to the observed $\log_{10} V$, $\log_{10} D$ relationship is obtained, including the decrease of V_c for very small diameters. No allowance is made for any possible variation in the factor F.

A similar, though not exact, analysis for the case $\omega = 0$ within the limits of validity of the relations (13) produced a fit of lower quality, since the decrease in $\log_{10} V$ is much too great for small values of $\log_{10} D$ while, at high $\log_{10} D$, the isochrones fall much closer to the $\tau = 0$ curve with slope $-3/2$.

The fact that an index $\omega \approx 2$ seems to apply for the intercloud medium is explicable in terms of thermal evaporation from the cloud component produced by the initial radiation pulse. McKee *et al.* (1978) predicted an index $\omega = 5/3$ on the basis of this mechanism, though presumably at large distance the ω will have to tend towards zero. An index of about 2 could also be generated by pre-supernova mass ejection; but this hypothesis is unlikely, since the cloud component would tend to come into pressure equilibrium with the intercloud component, giving an index of 2 for the clouds as well, and momentum transfer from the outflowing medium of the clouds would give an outward-directed velocity to the cloud component. Neither of these effects are observed.

To conclude, a model of shocks moving into dense clouds embedded in a medium of lower density whose initial density varies as $\sim r^{-2}$ seems to be the only reasonably simple model that can explain the Large Magellanic Cloud SNR observations. This model can be taken further. Firstly, according to the model, the derived initial cloudlet shock velocities reduced to a standard SNR diameter of 10 pc are very similar ($2\cdot84 > \log_{10} V > 2\cdot50$ for $\tau = 5$ and $2\cdot63 > \log_{10} V > 2\cdot27$ for $\tau = 3$, where V is in km s^{-1}). Since the cloud densities are similar, this implies a similar pressure and hence a similar explosive energy.

An estimate of the explosive energy can be made from estimates of the dimensions of the cloudlets. Lasker's (1976, 1977) photographs in some cases show what appear to be cloudlets on a scale of 2–4″ arc (0·5–1·0 pc). Taking this to be a characteristic cloudlet size we derive the following values for mean parameters: $V_s(10) = 1100$–2600 km s^{-1}, $F = 1\cdot85$–$2\cdot53$, $\rho_c = 12$ cm^{-3}, $\rho_0(10) = 0\cdot1$–$0\cdot7$ cm^{-3}, $A = (1\cdot5$–$11\cdot0) \times 10^{14}$ g cm^{-1}, $t(10) = 2600$–6100 yr, $E_0 = (6\cdot6$–$8\cdot5) \times 10^{50}$ erg, where 10 in parentheses refers to the value at a radius of 10 pc. Let us now compare these values with the mean of those obtained from X-ray measurements of the Cygnus Loop, Vela X, IC 443 and Pup A (Gorenstein *et al.* 1974; Rappaport *et al.* 1974; Malina *et al.* 1976; Zarnecki *et al.* 1978). The mean preshock density obtained for the galactic SNRs is $0\cdot32$ cm^{-3} and the initial energy is $E_0 = 4 \times 10^{50}$ erg. The parameters derived above for Large Magellanic Cloud SNRs are similar, showing that there is no appreciable difference in the physical processes involved.

The present model predicts that the blast wave radius lies beyond the characteristic cloudlet radius. The difference between the two is shown in Fig. 6 for the case $\omega = 2$, with $\tau = 3$ and 5. Evidence that this occurs in the case of the Cygnus Loop comes from the X-ray data of Rappaport *et al.* (1974), who measured a diameter of $2^\circ\cdot75$ compared with an optical filament diameter of $2^\circ\cdot65$. Recently, Woodgate *et al.* (1977) measured the [FeXIV] coronal emission to lie about $0^\circ\cdot08$ beyond the optical edge. Taking the diameter to be 40 pc, the difference in the logarithmic diameters is about 0·02, or 50% of the effect predicted. In the case of the LMC remnants themselves, some better data are available from Lasker's (1977) photographs. In N86, N186D and N206 he found a difference between the diameters measured in [OIII] and [SII], and a much less irregular appearance in [OIII]. Since the fast blast-wave shock will be much more efficient in radiating [OIII] than the slow cloudlet shocks (which are strong in [SII] and [OII]), it may be possible to identify the [OIII] shell with the blast wave. If this is so then, for N206, the logarithmic difference in diameter is 0·03–0·05 (theory) and 0·05 (observed).

The case for a dynamical separation between the [OIII] and [SII] emitting zones is particularly strong for the SNR N132D. Danziger and Dennefeld (1976*a*, 1976*b*) found [OIII] emission over a velocity range of 4400 $\mathrm{km\,s^{-1}}$, and this is spatially separated from the [SII] emission which occurs only at low velocity. No such result can arise from a single shock. Furthermore, the range of velocities in the [OIII] is similar to the blast wave velocity predicted above for an SNR of similar diameter to N132D (26 pc from the Hα data).

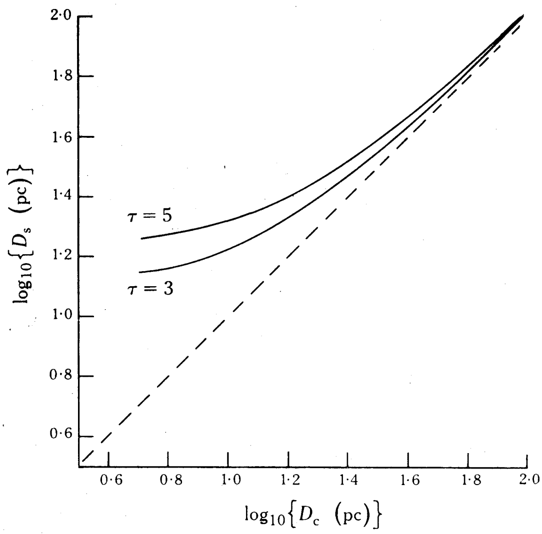

Fig. 6. Relationship between the optically measured D_s and true D_c (blast wave) diameter according to the present theory.

The preliminary data presented at this conference by Professor B. Y. Mills are very promising for the model since, if I interpret the data correctly, they do indeed show the radio sizes to be larger than the optical. It is interesting to note that if the model is correct, then the number of supernovae remaining to be found is much smaller than the prediction by Mathewson and Clarke (1973*b*) (about 350 detectable by the Molonglo cross array) obtained from the $N-D$ relationship. The problem has been re-examined by Clarke (1976) on the basis of a statistical analysis of the Molonglo source catalogue, and he found no evidence for the large number. The discrepancy arises because the $N-D$ relationship for the Large Magellanic Cloud seems to be

$$N(D) = 0{\cdot}24\,D^{1\cdot0}, \tag{15}$$

with D in parsecs. On the other hand, Sedov's (1959) theory would predict an exponent of 2·5. Clark and Caswell (1976) found that an exponent of 2·5 is adhered to very closely. However, in a nonuniform intercloud medium of index ω, the exponent in the $N-D$ relationship (equation 15) is only $\frac{1}{2}(5-\omega)$, or 3/2 for $\omega = 2$, which is the value suggested by Professor Mills's data. The lower value results because high expansion velocities are maintained to a greater diameter than was used in Sedov's theory. If the estimated index of $\omega = 2$ is correct then there should be only 17 unidentified SNRs with diameters in the range 25–60 pc and a further 27 in the range 60–100 pc, with a large probable error in these numbers. On the other hand, the rate of supernovae is not appreciably different from the 1 per 500 years previously predicted. According to the present model, the period is estimated to lie between limits of 400 and 1000 yr.

Abundances in Magellanic Cloud SNRs

Until about two years ago, the problem of abundances within the Magellanic Cloud SNRs was essentially untouched, due to the absence of efficient photon counting systems in the southern hemisphere and the lack of shock models of sufficient sophistication to interpret the data. However, some qualitative results were obtained by Danziger and Dennefeld (1976*a*, 1976*b*). Perhaps their most obvious result was the variation in the strength of the [NII], [SII] and [OIII] lines relative to each other and to Hα. They noted in particular that the [NII] lines appeared to be particularly weak in the Small Magellanic Cloud SNRs, a result which they suggested might be a genuine abundance effect. The observations of Osterbrock and Dufour (1973) showed an anomaly in the [NII] line strengths in N49 compared with predictions by Cox's (1972*a*) shock wave model, although this was not remarked upon.

Nitrogen is a particularly suitable element to use in searching for abundance differences, since it is a secondary nucleosynthesis element, i.e. one which is produced by subsequent processing of primary heavy elements in the star. In the case of ^{14}N, these elements are ^{12}C and (at higher temperature) ^{16}O. Talbot and Arnett (1973) showed that, for time-independent production processes, the abundance of such an element is proportional to the square of the abundance of its precursor primary element.

Recently, D'Odorico and Sabbadin (1976*a*) and Daltabuit *et al.* (1976) established that, for galactic SNRs, the Hα/[NII] emission line ratio was a function of the evolutionary state of the SNR as measured by its diameter. Dopita (1977*b*) discussed this relationship and showed that it was consistent with the hypothesis that the nitrogen is mainly locked up in the form of volatile ices which are sublimed by the radiation pulse during the supernova explosion. Of course, in some cases (the Crab filaments, the quasi-stationary knob in Cas A and the Puppis SNR) it seems likely that we see enriched material thrown out by the supernova or its precursor object, and not shocked interstellar material.

Does the above result carry over to the case of the Magellanic Cloud SNRs? D'Odorico and Sabbadin (1976*b*) pointed out that, at least in the case of N49 and N63, the weakness of the [NII] lines indicated that nitrogen is probably less abundant than in galactic SNRs by a factor of about four. Dopita (1976, Paper I) found a similar result by application of a detailed shock model to N49. Dopita *et al.* (1977) studied red spectra for an almost complete sample of the Magellanic Cloud SNRs, and were able to derive rough abundances for all these objects (their results are listed in Table 1).

A comparison of the results in Table 1 for SNRs in the Galaxy and the Large and Small Magellanic Clouds reveals a correlation between the O and N abundances of the form given above. Appreciable scatter was found from object to object in the Large Magellanic Cloud, however, and although much of this may be due to the method of analysis and the rather restricted spectral range covered by the data, some of the scatter may be caused by evolutionary effects associated with the sublimation of volatiles, as mentioned above.

Fig. 7 is a compilation of all available Hα/[NII] ratios obtained by D'Odorico and Sabbadin (1976*a*, 1976*b*) and Dopita *et al.* (1977), supplemented by various additional (unpublished) data gathered since then. SNRs in the Galaxy and in the Large and Small Magellanic Clouds are denoted by circles, triangles and a square respectively,

Table 1. O, S and N abundances in SNRs

System	Z(O) (10^{-6})	Z(S) (10^{-6})	Z(N) (10^{-6})
SMC	40	0·7	2
LMC	220	2·5	12
Galaxy	380	3·8	52

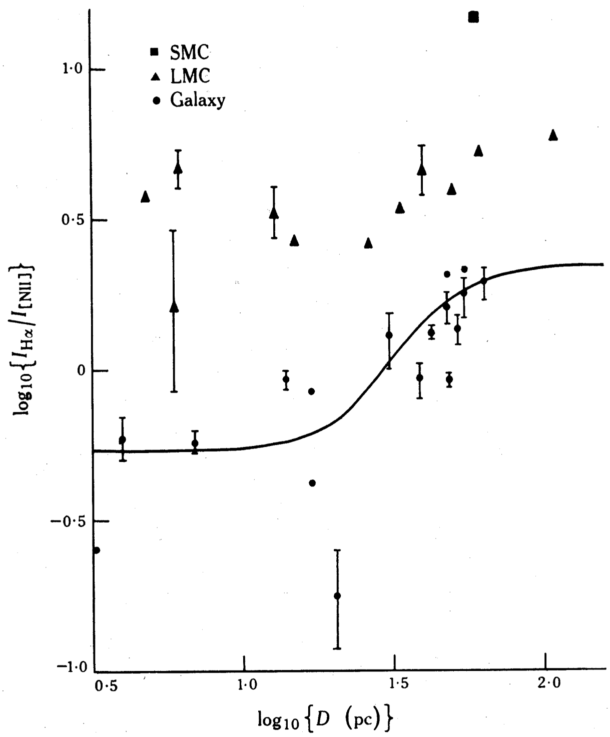

Fig. 7. Hα/[NII] ratio as a function of the diameter D for SNRs in the Magellanic Clouds and Galaxy as indicated. The bars indicate the range of values observed for the object.

the latter being for N19. Clearly, all of the Magellanic Cloud objects are less nitrogen abundant than those in the Galaxy, with the possible exception of 0525−66. Fig. 7 emphasizes the highly anomalous behaviour of Pup A (indicated by the isolated galactic point at $\log_{10} D = 1\cdot31$). Observation of the filaments in Pup A shows strong abundance anomalies in N (and possibly other elements) out to and including the outermost filaments. The photograph by Elliott *et al.* (1976) shows that in Pup A the filaments are unique in lying well outside both the X-ray and radio contours. These filaments may represent shocks pushing high velocity cloudlets formed by thermal instability in the ejecta, assisted by large heavy element overabundance (McCray *et al.* 1975) or by Rayleigh–Taylor instability (Gurzadyan 1953, 1969). (For a review of these instabilities see Chevalier (1977).) It is possible that 0525−66 may be a similar sort of object, and further study of both these objects is proceeding.

A further point of importance arising from a study of Fig. 7 is that the evolutionary behaviour of the Hα/[NII] ratio appears to be far less important in the Large Magellanic Cloud. If the hypothesis that this evolution is due to a volatile sublimation process is correct then this behaviour implies that less nitrogen is locked up on grains in the Large Magellanic Cloud. Fig. 7 implies that the true nitrogen abundance is 4·7 times less than galactic values, but that only about half of the nitrogen has condensed from the gaseous phase onto grains, as opposed to about three-quarters in the galactic interstellar medium.

The general question of how grain formation and growth affects gaseous phase abundances is an unresolved problem of great importance for galactic chemical evolution theory. Since in other spiral systems only the HII region abundances can be measured, some estimate of how far these can be trusted is urgently required. To this end, a program of identification of SNRs in M33 and the Sculptor Group galaxies has been undertaken. Comparison of abundances in these and adjacent HII regions will hopefully resolve this problem.

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