THE X-RAY PROPERTIES OF SUPERNOVA REMNANTS IN THE LARGE MAGELLANIC CLOUD

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There are at least 25 supernova remnants (SNR) in the Large Magellanic Cloud (LMC) with X-ray luminosities exceeding 2×10^{35} erg s^{-1}. As many as 25 other SNR may be contained in the X-ray survey conducted with the Einstein Observatory of the LMC. The X-ray spectra of the 6 SNR observed with the Solid State Spectrometer (SSS) resemble their galactic counterparts; two SNR, N157B and 0540-69.3, may emit X-rays primarily by synchrotron radiation. The density of the medium in which SNR are expanding inferred from the X-ray data appears to decrease with SNR diameter; the density of the ISM inferred from the Balmer lines of 4 new SNR in the LMC is much lower than that inferred from X-ray observations. The apparent thermal energy content of LMC SNR evolves with diameter, peaking at $\sim 5 \times 10^{50}$ ergs. The ratio of the densities of the X-ray and [SII] emitting plasmas is consistent with their being in pressure equilibrium. The SN rate in the LMC is $\sim$1 per 100-200 years. This is the number of SN expected from other considerations. The number diameter relation of LMC SNR is consistent with free expansion. The X-ray data are difficult to understand in terms of traditional Sedov models on SNR evolution; probably ejecta and multiphase ISM are required to explain the X-ray properties of LMC SNR.

The LMC is morphologically quite different from the Galaxy. An irregular barred galaxy, the LMC is roughly 1/10 as massive as the Galaxy. Nevertheless, because absorption along the line of sight to the LMC is small ($E_{B-V}\sim0.1$) and because all LMC objects are at essentially the same distance ($\sim$55 kpc), it may be better suited to studies of the generic properties of supernova remnants than the Galaxy. Recently, Long, Helfand and Grabelsky (1981) completed a study of the LMC with the imaging instruments on the Einstein Observatory. This survey consisted of more than 100 individual Imaging Proportional Counter (IPC) observations with times which averaged 2000 seconds. Most of the optically prominent portions of the LMC were covered, including the diffuse optical bar, the 30 Doradus nebula and surrounding HI cloud and much of the spiral arms. Sources were detected in all portions of the LMC; $\sim\frac{1}{2}$ of the sources lie superposed on the HI cloud which envelopes 30 Doradus, implying Pop I progenitors for the majority of the LMC

J. Danziger and P. Gorenstein (eds.), Supernova Remnants and their X-Ray Emission, 525–533.

sources. Approximately ¼ of the 97 sources in the survey are expected to be foreground stars or active galaxies; active ground-based observational programs are underway to characterize the objects which were detected.

A substantial number of sources in the survey were immediately identifiable as SNR. Twelve of the 13 SNR which had been recognized by Mathewson and Clarke (1973) on the basis of a non-thermal radio spectrum and a large [SII]/Hα flux ratio were detected as X-ray sources; the radio sources N157B and 0540-69.3 were also detected, apparently confirming their identification as SNR despite the lack (at that time) of optical counterparts. Five other objects were coincident with entries in a list of SNR candidates which had been compiled by Davies, Eliot and Meaburn (1976) solely on the basis of filimentary Hα emission. Thus 17 objects previously suspected or identified as SNR were detected as X-ray sources.

To further characterize the sources detected with the IPC, Long Helfand and Grabelsky carried out High Resolution Imager (HRI) observations of many of the brighter sources. Of the twenty sources which had no firm identification which were detected with the HRI, eight were extended and thus determined to be SNR. In all 25 SNR have been detected as X-ray sources in the LMC; about 15 other sources are known to be point sources including LMC X-1, 2, 3, and 4. If a similar percentage of the remaining sources are SNR, then the total number of SNR in the LMC approaches 50.

A search to identify new SNR in the LMC based on the X-ray observations is being carried out by Mathewson, et. al. (1983); no new SNR have been identified as yet, although optical emission associated with all of the X-ray discovered SNR has been found. Four of these remnants have spectra which are dominated by Balmer line emission similar to Tycho's SNR and SN1006 (Tuohy et al 1982) which explains why they were not recognized as SNR previously; the remainder appear to have typical SNR emission characteristics.

SSS spectra of 6 SNR in the LMC were obtained by Clark et al. (1982). Four of the remnants, N132D, N49, N49B and N63A, have emission-line dominated spectra similar to most galactic remnants; two, N157B and 0540-69.3, have spectra which can be fit to a power law. These two remnants, in addition to N103B, have centrally peaked X-ray morphologies and may be examples of Crab-like SNR in the LMC.

The relationship between X-ray luminosity and SNR diameter for the LMC remnants is shown plotted in figure 1. The diameters used here and elsewhere are derived from a consideration of the X-ray and optical morphologies documented by Mathewson, et al (1983). The SNR with optical spectra dominated by the Balmer lines of hydrogen (▲) and the SNR with centrally-condensed X-ray morphologies (■) are plotted separately. Numerical models of SNR (such as those discussed by White and Long, 1983) evolve from low to high luminosity as more IS material is shock heated,

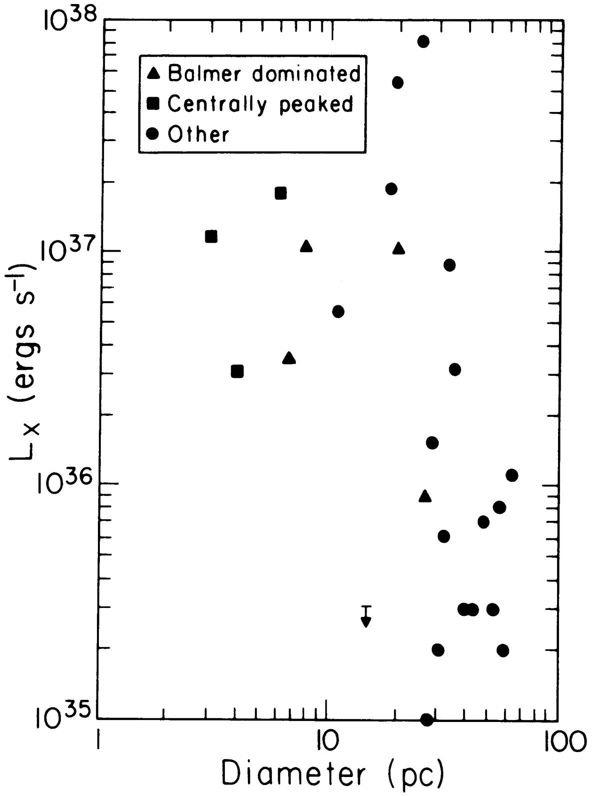

Figure 1.

and subsequently fade as the temperature of the material falls below that required to generate X-rays. The LMC SNR appear with considerable scatter to follow such an evolutionary track.

In principle, the luminosity L_x and diameter D of a SNR permit a determination of the density of the ISM into which a SNR is expanding if its X-ray emission is dominated by shocked gas from the ISM. Specifically, the ISM density

$$n = \left(\frac{6}{\pi}\right)^{\frac{1}{2}} \epsilon^{-\frac{1}{2}} f^{\frac{1}{2}} L_x^{\frac{1}{2}} D^{-3/2}$$

where ϵ is the specific emissivity and $f(=\langle n_e^2\rangle/\langle n_e\rangle^2)$ is the fraction of the SNR volume filled with X-ray emitting material. If f and ϵ do not change greatly with diameter, the inferred ISM densities evolve strongly with diameter as shown in figure 2. Here f was taken to be ¼ and ϵ to be 3×10^{-23} erg cm^{-3} s^{-1}, appropriate for a strong shock and a collisionally-equilibrated plasma having cosmic abundance ratios and a temperature of 5×10^6 K (Raymond and Smith 1977). Possible explanations for this trend include the following: (1) Cloudlet evaporation.

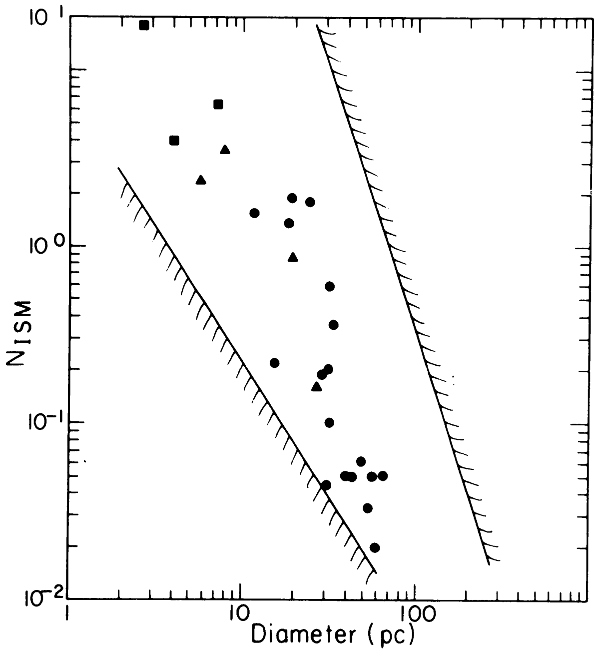

Figure 2.

The correlation of apparent density with SNR diameter was first noticed in a small sample of galactic SNR by McKee and Ostriker (1977). They used this correlation to support a multiphase model of the ISM in which a pervasive tenuous gas is studded with dense cloudlets. After the passage of a SNR shock which is carried by the tenuous medium, the cloudlets are heated by either conduction or more slowly moving secondary shocks to X-ray temperatures. Because the disruption of cloudlets is more rapid while the shock velocity is high, the apparent density inferred using a single phase model of the ISM evolves with SNR diameter. (2) Emission from SN ejecta. Substantial amounts of material are ejected from the star in a SN explosion; if shock heated, either by interaction with circumstellar material or the surrounding ISM, the ejecta should emit at X-ray temperatures. Because this debris represents a smaller and smaller portion of the total shocked gas as the SNR grows, the apparent density, when ejecta are neglected, would appear to evolve. Long, Dopita and Tuohy (1982) argue that if the ejecta is metal rich, the density diameter relation can be understood. Analyses of SSS spectra of young SNRs show deviations from cosmic abundance ratios of heavy metals even when non-equilibrium effects are taken into account (Becker, et al 1980 a,b). However, the SSS is insensitive to the ratio of metals to H and He. SN ejecta are known to be important in some remnants. Reverse shocks are observed in Cas A (Fabian, et al 1980), Tycho's SNR (Seward, Gorenstein and Tucker 1982) and possibly N132D. In Balmer-dominated SNR the density of the neutral ISM can be inferred from the optical line intensities; for the LMC remnants, the neutral ISM density

https://doi.org/10.1017/S0074180900034392 Published online by Cambridge University Press

is much lower than total density obtained from the X-ray data (Tuohy, et al 1982). (3) Selection effects. Finally, the X-ray survey of the LMC is luminosity limited. Until the post shock temperature falls below 10^6K, the X-ray luminosity scales as n^2D^3. For a SNR to have been detected, the ISM density must exceed $0.2(D/10pc)^{-3/2}$. Furthermore, a SNR in a dense medium cools below 10^6K at a smaller diameter than does a SNR encountering more tenuous material. If the explosion energies of LMC SNR do not exceed 10^{51} ergs, observable SNR must be located in regions in which $n \lesssim 330\ (D/10pc)^{-3}$. The excluded regions are shown shaded in Figure 2. Possibly all these effects contribute the apparent diameter density relation of the LMC SNR.

The thermal energy content of the LMC SNR can be inferred from the size, density and temperature of the X-ray emitting material. If we assume (in contrast to Gronenschild and Mewe 1982) that a line temperature of 5 x 10^6K derived from the SSS spectra under equilibrium assumptions is appropriate, then the thermal energy content evolves from 8 x 10^{48} ergs to 5 x 10^{50} ergs, as illustrated in figure 3. Blair, Kirshner and Chevalier have attempted to derive the thermal energy content of galactic and extragalactic SNR using the pressure inferred

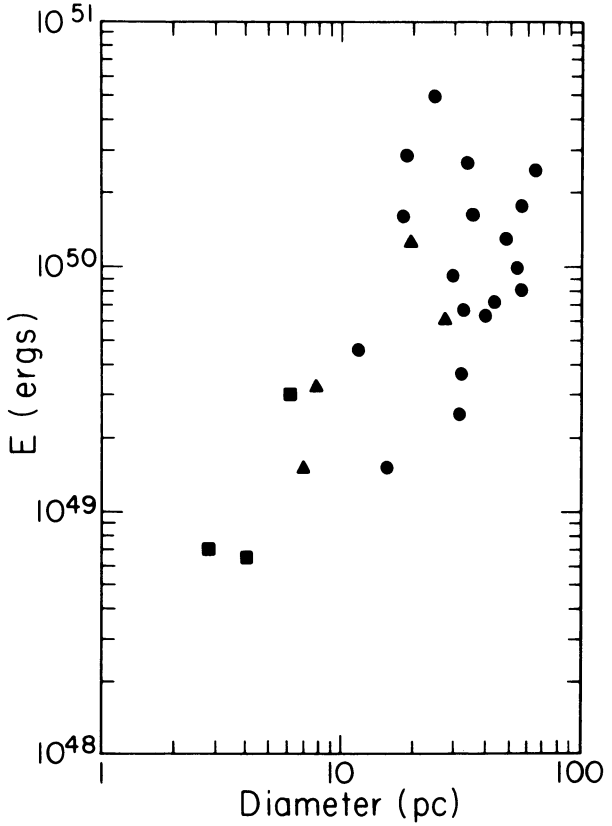

Figure 3

from [SII] line ratios, assuming that pressure in the clouds where SII is formed is identical to that outside the clouds; Blair, Kirshner and Chevalier (1981) also find that the thermal energy content in SNR increases with radius. (See figure 5 of their paper.) The simplest interpretation of these results is that energy of the initial explosion is evolving into thermal energy and that this evolution is not complete until SNR are quite large, at least 30pc in diameter. Blair, Kirshner and Chevalier (1981) suggest this energy is stored in magnetic fields, but alternatively it may be stored in the kinetic energy of the ejecta. Such an interpretation is probably inconsistent with single phase models of the ISM where the evolution in expected to be much more rapid. In order for the kinetic energy of the ejecta to remain high, it is necessary that the medium which is slowing the ejecta be quite tenuous.

The densities derived from the X-ray observations and the densities of the [SII] emitting regions as measured by Dopita† (1979) are correlated, as shown in figure 4. The ratio between densities of the shocked cloudlets emitting in [SII] to the X-ray plasma is ~ 500 if the X-ray filling factor is ¼. With this filling factor and a temperature of ~5 x 10^6K, there is approximate pressure equilibrium between the shocked [SII] cloudlets which have a temperature of 10^4K and the post shock X-ray plasma.

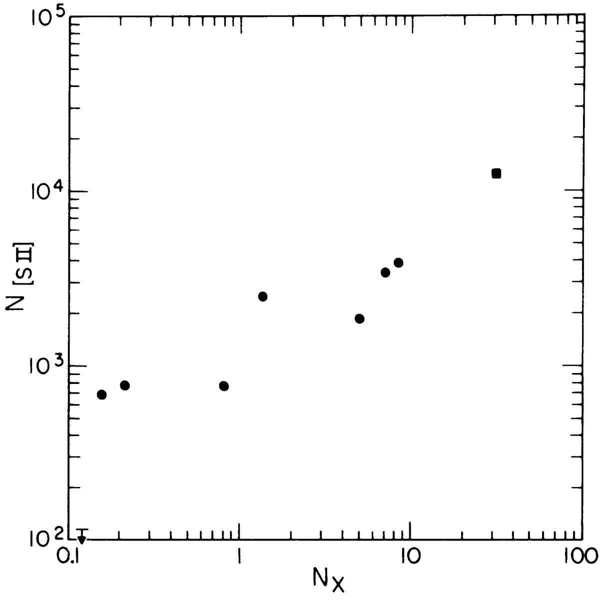

Figure 4.

†Although the post-shock densities are not given explicitly by Dopita, they can be obtained using equation 8 of his paper.

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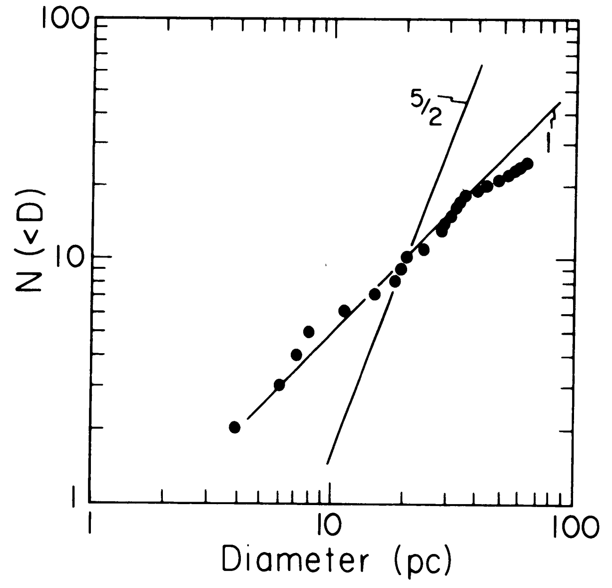

Figure 5.

If most of the LMC are expanding into a uniform density ISM and have swept up enough IS material so that their time evolution resembles that of a Sedov explosion, the number of SNR with diameters less than D should increase as $D^{5/2}$. This is not the case, as is evident from figure 5. Instead, the number-diameter relation is consistent with a power law index of 1. It is as if the SNR which we observe have not been decelerated at all by the ISM. This result is not new; Mathewson and Clarke in their original discussion noted that the number-diameter relation was much flatter than that expected from the Sedov relations. The result was discounted, however, because galactic SNR seem to obey a $N^{5/2}$ law, a result Mills (1983) has now shown to be due to the Σ -D relation assumed for galactic remnants. If SNR are still freely expanding at diameters of 30pc, high velocity material should exist within them; N132D is the only large diameter remnant in which material moving at velocities ($>$ 1000 km s^{-1}) has been discovered (Lasker 1977). If SNR are freely expanding with a velocity which averages 5000 km s^{-1}, then the SN rate in the LMC lies between 1 per 200 (100) years assuming 25(50) SNR with diameters less than 50pc. The SN rate is not very dependent on the assumption of free expansion; Long, Helfand, and Grabelsky derived rates of 1 per 110 to 340 years from a Sedov analysis of SNR expansion. The SN rate in the LMC, for almost any reasonable set of assumptions, is consistent with the SN rate per unit mass in the Galaxy.

Although the importance of selection effects should not be underestimated, the data on SNR in the LMC seem to present fundamental problems for the traditional view that most SNR which we observe can be understood in terms of the Sedov solutions to a point explosion in a uniform density medium. The observations do not currently resolve whether most of the emission arises from SN ejecta or from cloudlets in a multiphase ISM. It appears likely that the apparent density evolution, the Balmer-line inferred densities, free expansion, multiple-temperature SSS spectra, and thermal energy evolution can be accomodated within either context. Probably both are partially correct.

Acknowledgements: Much of this work was carried out in the context of a collaboration on the LMC with DJ Helfand, IR Tuohy, MA Dopita and DS Mathewson. Financial support was provided at Columbia and Johns Hopkins by NASA contracts NAS 8-30753 and NAS 5-27000. Travel support by the IAU is gratefully acknowledged.

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DISCUSSION

CHEVALIER: The suggestion (by Blair, Kirshner and Chevalier) of dominant magnetic pressure will not work for a high temperature X-ray emitting gas.

FABIAN: Another way of explaining the possible inverse-correlation of density with radius and evidence for free expansion is through stellar winds. The remnant should expand relatively freely to the edge of the bubble which could be 20-40pc from the explosion.

MCKEE: Ejecta expanding into a multiphase medium in which much of the volume is at very low density can expand to fairly large diameters (20-40pc) before thermalizing. Out to what radii are you confident that the uniform expansion model applies?

LONG: There appears to be a break in the slope of the number diameter relation between 30 and 40pc. However, it is very difficult to determine to what diameter the sample is complete.