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ASCA OBSERVATIONS OF THE LARGE MAGELLANIC CLOUD SUPERNOVA REMNANT SAMPLE: TYPING SUPERNOVAE FROM THEIR REMNANTS

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ABSTRACT

We present our first results from a study of the supernova remnants (SNRs) in the Large Magellanic Cloud (LMC) using data from *ASCA*. The three remnants we have analyzed to date, 0509−67.5, 0519−69.0, and N103B, are among the smallest, and presumably also the youngest, in the Cloud. The X-ray spectra of these SNRs show strong Kα emission lines of silicon, sulfur, argon, and calcium with no evidence for corresponding lines of oxygen, neon, or magnesium. The dominant feature in the spectra is a broad blend of emission lines around 1 keV which we attribute to *L*-shell emission lines of iron. Model calculations (Nomoto, Thielemann, & Yokoi 1984) show that the major products of nucleosynthesis in Type Ia supernovae (SNs) are the elements from silicon to iron, as observed here. The calculated nucleosynthetic yields from Type Ib and II SNs are shown to be qualitatively inconsistent with the data. We conclude that the SNs which produced these remnants were of Type Ia. This finding also confirms earlier suggestions that the class of Balmer-dominated remnants arise from Type Ia SN explosions. Based on these early results from the LMC SNR sample, we find that roughly one-half of the SNRs produced in the LMC within the last $\sim$1500 yr came from Type Ia SNs.

Subject headings: galaxies: individual (Large Magellanic Cloud) — nuclear reactions, nucleosynthesis, abundances — supernova remnants — X-rays: ISM

1. INTRODUCTION

A total of 32 supernova remnants (SNRs) have been identified in the Large Magellanic Cloud (LMC) based on observations at optical, radio, and X-ray wavelengths (Mathewson et al. 1983, 1984, 1985). The remnants range in diameter from 2 pc up to about 100 pc and span the range of known evolutionary phases, from young ejecta-dominated remnants, through middle-aged Sedov-type remnants, to old remnants in the radiative or snowplow phase. Twenty-seven of the LMC remnants emit X-rays at a detectable level ($F_X \gtrsim 5 \times 10^{-13}$ ergs s^{-1} cm^{-2} in the 0.15–4.5 keV band), while at least 11 are bright enough ($F_X \gtrsim 1 \times 10^{-11}$ ergs s^{-1} cm^{-2}) for detailed X-ray spectroscopic study with *ASCA*. Most of these bright remnants have been observed already by *ASCA*: three during the performance verification phase and five during the first six months of the guest observer program by our collaboration. One of our goals for the LMC SNR sample is to find and study young, ejecta-dominated remnants. In this presentation we discuss results from preliminary analysis of data from three such remnants, 0509−67.5, 0519−69.0, and N103B.

Optically, N103B consists of several small bright knots which show the usual set of emission lines seen in most supernova remnants: [O III] λ5007, [S II] $\lambda\lambda$6716, 6731, Hα, and so on (Danziger & Leibowitz 1985). The abundances of N103B inferred from optical spectroscopy are quite similar to those from other considerably larger and more evolved LMC remnants such as N63A and N49 (Russell & Dopita 1990). A high-resolution X-ray image of the remnant showed a spatial extent of only 3 pc radius, with a centrally peaked morphology (Mathewson et al. 1983). The X-ray spectrum appears to be thermal in nature (Singh et al. 1987), although detailed analysis was limited by the poor spectral resolution of these proportional counter data. The X-ray luminosity in the 0.15–4.5 keV band is 1.5×10^{37} ergs s^{-1}, assuming a distance to the LMC of 50 kpc which we adopt throughout.

SNR 0519−69.0 belongs to a class of SNRs which show only hydrogen emission lines in their optical spectra with virtually no emission from collisionally excited forbidden lines. The prototypical Balmer-dominated SNR is the remnant of SN 1572 observed by Tycho Brahe, which is believed to be a Type Ia SN based on its historical light curve. The interpretation of the optical spectrum from the remnant in the context of a model in which a high-velocity nonradiative shock overtakes neutral interstellar gas (Chevalier, Kirshner, & Raymond 1980) allows for the independent determination of the SN shock velocity. For remnants in the LMC, this provides crucial information for constraining the age of the SNR. Analysis of the Balmer-dominated optical spectrum of 0519−69.0 indicates a shock velocity of 1000–1900 km s^{-1}, which, when combined with a radial size of 3.6 pc, makes the remnant 750–1500 years old (Smith et al. 1991). The high-resolution X-ray image of this remnant shows a nearly circular shell of emission that correlates very well with the Hα emission (Mathewson et al. 1983). Except for its broadband luminosity (8.9×10^{36} ergs s^{-1}), no other information concerning its X-ray spectrum was available before *ASCA*.

The third remnant in our sample, 0509−67.5, is also Balmer-dominated. Smith et al. (1991) obtained only a lower limit to the shock velocity of 2000 km s^{-1}; when combined

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with the remnant's radius (3.3 pc), this sets an upper limit to the age of 1000 yr. The soft X-ray luminosity is 2.8×10^{36} ergs s^{-1}.

The Balmer-dominated remnants (0509−67.5 and 0519−69.0) are particularly important because Tuohy et al. (1982) have suggested that they arise from the explosions of Type Ia SNs. As we show below, our *ASCA* data confirm this suggestion by observing directly the expected products of nucleosynthesis from such SNs.

2. DATA ANALYSIS

SNRs 0509−67.5, 0519−69.0, and N103B were observed on 1993 November 10, 8, and 9, respectively, by the X-ray astronomy satellite *ASCA* (Tanaka, Inoue, & Holt 1994). The data discussed here are from the two CCD detectors (Solid-state Imaging Spectrometer SIS0 and SIS1) and were obtained in the "1-CCD faint" mode of operation. We used the FTOOLS software package developed by the *ASCA* Guest Observer Facility for the following reduction procedures. The data were converted from faint to bright mode, hot pixels in the CCD were identified and removed using the CLEANSIS algorithm and the source light curves were searched for count rate excesses or flares (none were found). Events with grades 0, 2, 3, 4 were extracted from a circular region with radius $\sim 4'$ centered on the target.

The broad point-spread-function of the *ASCA* X-ray telescope makes determining an appropriate background spectrum extremely difficult, since the source flux from an unresolved object, such as we have here, extends over most of the CCD chip. In this analysis, background was estimated from areas of the detector away from the source, but from within the same chip. At about 1 keV, roughly 5% of the target flux was included in the background spectrum and this fraction increased to ~20% at 4 keV. Although this effect does not compromise our results here, it does cause a reduction in the intensity of the higher energy emission relative to that at lower energy. This should be kept in mind when assessing the significance of line features in our spectra.

The net effective exposure times were 3.3×10^4 s, 2.3×10^4 s, and 1.9×10^4 s, and the average background-subtracted count rates per SIS were 0.18 s^{-1}, 0.59 s^{-1}, and 0.92 s^{-1}, for SNRs 0509−67.5, 0519−69.0, and N103B, respectively. Figure 1 shows the *ASCA* spectra for the three remnants where, for presentation purposes only, the data from SIS0 and SIS1 have been summed.

There are several notable aspects of our *ASCA* spectra. First is the general similarity among the spectral features present. The dominant feature is a broad smooth blend of emission peaking between 0.7 and 1 keV which we identify as the unresolved complex of iron *L*-shell lines. Over roughly the same energy range, *K*-shell line emission from highly ionized ions of oxygen, neon, and magnesium is conspicuously absent, while at higher energies we clearly see prominent Kα emission from He-like ions of silicon, sulfur, argon, and (excepting SNR 0509−67.5) calcium. If we merely use the relative intensities of the observed lines as an indicator of the relative elemental abundances, our data suggest that the abundances of silicon, sulfur, argon, calcium, and iron are considerably enhanced relative to those of oxygen, neon, and magnesium. Additional quantitative support for this argument is presented in § 3 below.

Model fits were performed to gain some insight into the average thermodynamic state of the X-ray emitting gas in these SNRs. A parametric model consisting of a thermal bremsstrahlung continuum, Gaussian lines, and interstellar X-ray absorption was used. Figure 1 shows the best-fit models superposed on the data. The fitted continuum temperatures were quite

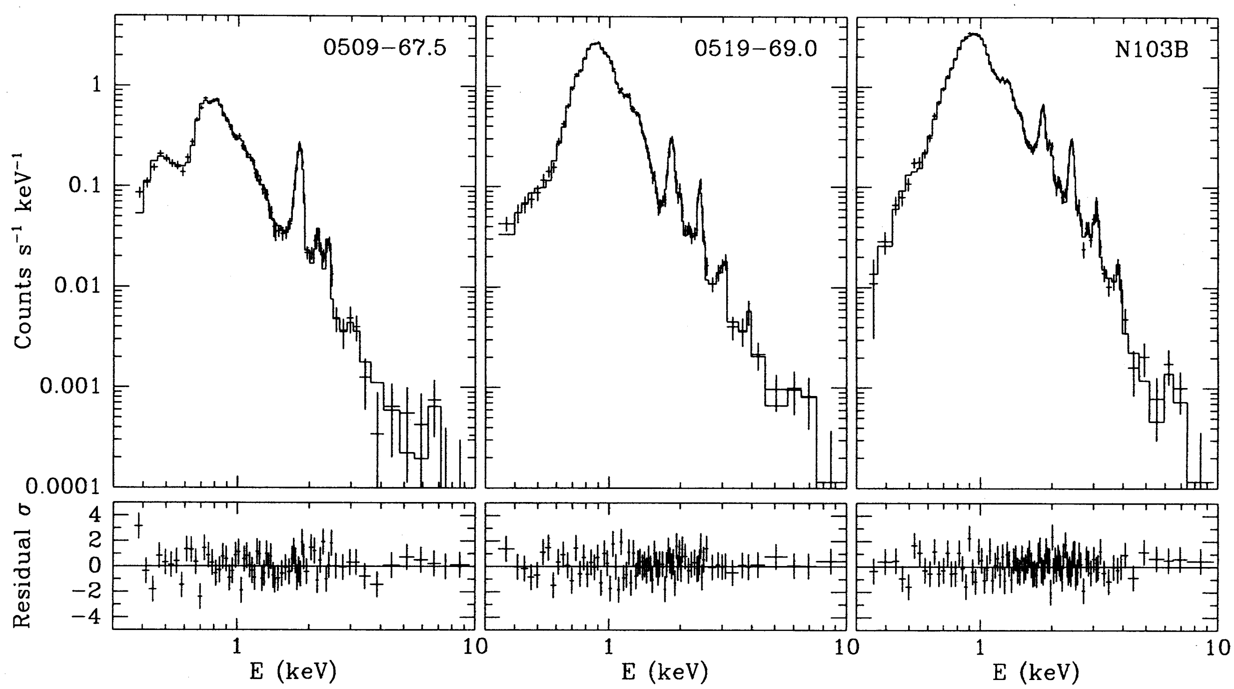

FIG. 1.—*ASCA* X-ray spectra of three LMC SNRs: 0509−67.5, 0519−69.0, and N103B. The data have been background subtracted and the spectra from both sensors have been added. Note that the background dominates the source spectrum at energies greater than about 5 keV. Energy channels were grouped so that each bin contained at least 25 counts in the raw spectrum. The best-fit parametric model for each source is shown as the histogram. The small panels at the bottom indicate the difference between the data and model in terms of the statistical error in each channel. Although we have included a narrow emission line in the fits around 6.5 keV, the interpretation of this as Fe Kα line emission from the SNRs is highly uncertain due to the presence of strong instrumental background fluorescence lines of Fe and Ni in this energy band.

similar: 1.24 ± 0.20, 1.48 ± 0.13, and 1.13 ± 0.06 keV for 0509−67.5, 0519−69.0, and N103B, respectively. This quantity was constrained mainly by the shape of the continuum above ~ 1.4 keV. We derived an ionization state indicator by taking the ratio of intensities of the silicon hydrogen-like to helium-like Kα lines. The ratios obtained, $\lesssim 0.02$, 0.22, and 0.37, correspond to ionization timescales, $n_e t$, of $\lesssim 10^{10.4}$, $10^{11.2}$, and $10^{11.4}$ cm^{-3} s (assuming the best-fit continuum temperatures derived above), when the nonequilibrium ionization (NEI) model of Hughes & Singh (1994) is employed. This sequence of increasing level of ionization from 0509−67.5 to N103B, is qualitatively consistent with the observed increase in the mean energy of the iron *L*-shell blend along the same sequence. We note that the lowest ionization timescale we measure is close to the value known for the 400 yr old remnant of Tycho's SN (Hughes 1991). The larger values for the other remnants are still far from equilibrium ionization ($n_e t \sim 10^{12.5}$ cm^{-3} s).

3. DISCUSSION

Simulations using the NEI plasma emission model were performed to interpret the observed line ratios. We assumed the mean temperature ($kT = 1.28$ keV) and ionization timescale ($n_e t = 10^{11}$ cm^{-3} s) from the parametric fits. However, our conclusions are not sensitive to this choice and any single set of values derived above would yield essentially the same results. A column density of 2×10^{21} atoms cm^{-2}, appropriate for sources in the LMC, was assumed. Detailed NEI fits and parameter estimation are underway, but, at the present time, results are limited by uncertainties in the background subtraction, instrumental calibrations, and the atomic physics required to model the X-ray emission. Figure 2 presents simulated *ASCA* SIS spectra for three cases which we discuss below.

The leftmost panel of Figure 2 shows the *ASCA* SIS spectrum expected from a plasma with mean LMC abundances (roughly 0.3 times cosmic). Strong iron *L*-shell emission around 1 keV is apparent in the model spectrum. However, the prominent Kα emission lines of oxygen, neon, and magnesium, on the one hand, and the relatively weak Kα emission lines from the higher atomic number elements on the other, are inconsistent with our data and argue strongly against a swept-up ISM interpretation of our X-ray spectra.

The middle panel of Figure 2 assumes a plasma with abundances corresponding to the ejecta from a 25 $M_\odot$ core-collapse SN (Type II SN). During the normal course of their evolution, massive stars produce large amounts of O-group elements which are ejected during the SN explosion. Numerical models for the nucleosynthetic yield as a function of progenitor mass have been calculated by Thielemann, Nomoto, & Hashimoto (1994), Woosley (1991), and others. In general, these models predict that the ejecta of Type II SNs should contain an overabundance of the O-group elements relative to Si and the elements beyond. Recent analysis of archival X-ray spectral data for the oxygen-rich SNR G292.0+1.8 (Hughes & Singh 1994) has confirmed these general abundance patterns for at least one massive-star core-collapse SN. The *ASCA* X-ray spectrum of the young oxygen-rich SNR 0102.2−72.2 in the Small Magellanic Cloud (Hayashi et al. 1994) has revealed strong line emission from O, Ne, and Mg and thus is qualitatively consistent with having arisen from a core-collapse SN. Because the *ASCA* spectral data from the three remnants presented here show no emission from O-group elements, it is clear that they did not originate as Type II SNs.

The origin of Type Ib SNs remains somewhat controversial. Two models are currently popular: off-center detonations in accreting white dwarfs or core collapse in massive Wolf-Rayet stars which have lost their hydrogen envelopes. Optical observations of these SNs at late times show strong oxygen line emission and consequently both classes of progenitor model have been developed in order to produce ejecta containing large amounts of oxygen (Woosley, Taam, & Weaver 1986; Ensman & Woosley 1988), which makes them inconsistent with our X-ray data.

The abundance distribution for the ejecta of a Type Ia SN has been determined by Nomoto et al. (1984) assuming that these events arise from the carbon deflagration of a C+O

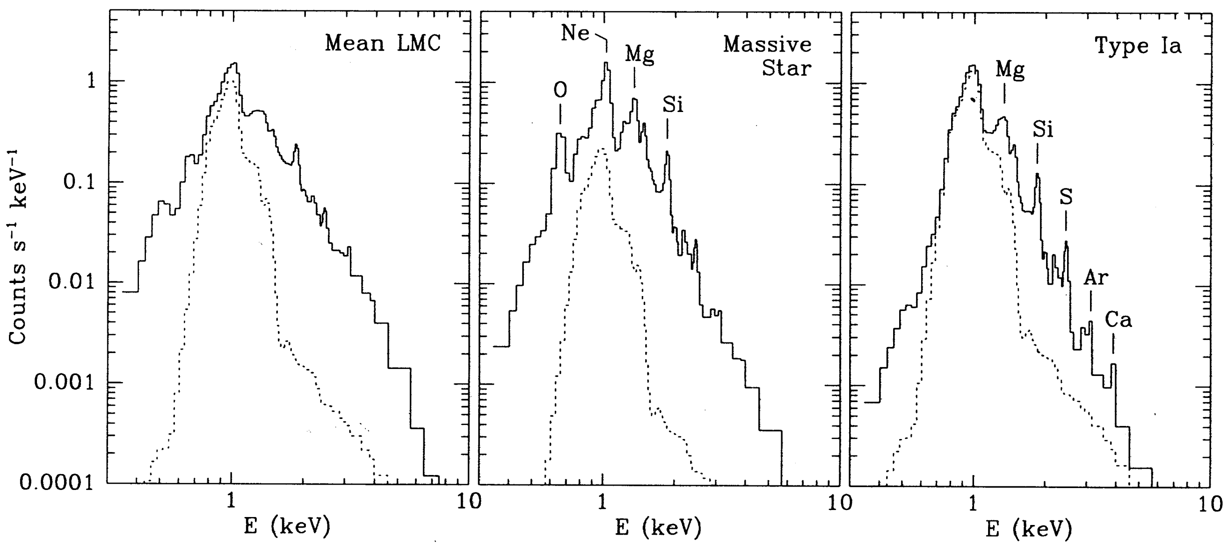

FIG. 2.—NEI spectral models for three possible sets of elemental abundances. The left panel shows a model spectrum assuming a plasma with the mean abundances of the LMC (0.3 times cosmic), the middle panel assumes a plasma with abundances corresponding to the ejecta from a massive-star core-collapse SN (the 25 $M_\odot$ case from Thielemann et al. 1994), and the right panel assumes the abundance distribution in the ejecta of a Type Ia SN (the "W7" model of Nomoto et al. 1984). All cases employ a single-temperature, single-ionization-timescale NEI model with $kT = 1.28$ keV and $n_e t = 10^{11}$ cm^{-3} s. The emission from Fe is shown separately as the dotted curve. Prominent Kα emission lines from the various elemental species are indicated.

TABLE 1

THE SMALLEST SUPERNOVA REMNANTS IN THE LARGE MAGELLANIC CLOUD

SNR Name	Age or Radius	SN Type
SN 1987A	8 yr	II
0540−69.3......	1.5 pc	II
N157B	1.8 pc	(II)?
N103B	3.0 pc	Ia
0509−67.5......	3.3 pc	Ia
0519−69.0......	3.6 pc	Ia

white dwarf. The dominant ejecta products according to these calculations are Si, S, Ar, Ca, and Fe. The simulated SIS spectrum based on this model (rightmost panel of Fig. 2) clearly shows emission line features from these species with an absence of strong O and Ne emission. Our observed spectra bear a remarkable resemblance to this model spectrum. Thus we conclude, based on the *ASCA* spectral data, that the three remnants under study here arose from Type Ia SN explosions.

In Table 1 we list the six SNRs in the LMC with X-ray diameters less than 10 pc (Mathewson et al. 1983). Four of these have good age estimates: SN 1987A, of course, is 8 yr old, 0540−593 is between 700 and 1100 yr old (Reynolds 1985; Kirshner et al. 1989), and 0509−67.5 and 0519−69.0 are both less than 1500 yr old (Smith et al. 1991). We assume, based on their small sizes, that N157B and N103B are also younger than 1500 yr. These six remnants indicate a SN rate in the LMC of 1.4 SN per century per 10^{10} $L_{\odot}$ (assuming L_B for the LMC is 2.8×10^9 $L_{\odot}$).

We have argued above that three of the remnants in Table 1 are products of Type Ia SNs. The three remaining young remnants are almost certainly the product of massive star explosions: for N157B and 0540−693, the dominant X-ray and radio emission have the characteristics of pulsar-driven, Crab-like remnants, and in the latter, we see the pulsar itself (as well as oxygen-rich ejecta); the progenitor of the third, SN 1987A was directly observed to be a massive star. These results indicate that the ratio of Type Ia to Type II (+Ib) SNs in the LMC is approximately 1:1 based on the sample of remnants younger than 1500 yr.[8]

In their review of SN rates, van den Bergh & Tammann (1991) find this ratio to be 1:10 for galaxies of Hubble type Sdm–Im, although this value is based on a very small number of observed events, and assumes a galaxy inclination correction for Type II events only which more recent work has cast into doubt (van den Bergh 1994); assuming that no factor is required to correct for events missed in edge-on galaxies, the adopted ratio would fall to 1:5. van den Bergh & Tammann (1991) also discuss explicitly the expected rates of different SN types in the LMC. The massive star-formation rate and the expected SN rate from extragalactic patrols converge on a Type II value of 2×10^{-3} per year. The Type Ia rate is discussed both in terms of the extragalactic observations, and the ratio of nova rate to SN Ia rate; the expected value for the LMC in both cases is $\sim 5 \times 10^{-4}$ per year.

The results presented here favor an even higher rate of Type Ia events relative to massive star explosions (we reject a ratio of 1:4 or smaller at 90% confidence, assuming Poisson statistics). It is possible that observational selection effects have militated against the discovery of some young SNRs from Type II SNs, those which, for example, might have exploded in heavily absorbed regions or in low-density superbubbles. However, this is unlikely to be the complete explanation since the Type II (+Ib) SN rate based on the remnants in Table 1 is fully consistent with the expected rate. It is the absolute Type Ia rate which appears too high: observing at least three events in 1500 years when the mean rate is 1 per 2000 years has a Poisson probability of only 4%.

4. CONCLUSIONS

In this article we have presented new *ASCA* X-ray spectral data for three small SNRs in the LMC. We find that the X-ray spectra are dominated by emission from the astrophysically abundant elements from silicon to iron. Emission from oxygen, neon, and magnesium is relatively much weaker. This leads us to conclude, based on comparison to model predictions of the nucleosynthesis expected from the various types of SNs, that all three remnants are the products of Type Ia SNs. Since two of the remnants are classified as having Balmer-dominated optical spectra, our results confirm earlier suggestions (Tuohy et al. 1982) that such remnants arise from Type Ia SNs.

When examined in the context of the LMC SNR sample in general, we are led to the conclusion that the ratio of rates of Type I to Type II (+Ib) SNs is nearly 1:1. Furthermore we find that it is the absolute rate of Type Ia SN which appears higher than expected based on statistical samples of SNs in late-type galaxies. These observations have interesting implications for the nature of the progenitors of Type Ia SNs as well as for the chemical evolution of the LMC.

[8] Some slight correction to this ratio may be required to account for known LMC remnants which are larger than 10 pc in diameter, but may be younger than 1500 yr (N132D is one possible example, see Hughes 1987).

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