PROBING ELEMENTAL ABUNDANCES IN SNR 1987A USING XMM-NEWTON

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ABSTRACT

We report on the latest (2007 January) observations of supernova remnant (SNR) 1987A from the XMM-Newton mission. Since the 2003 May observations of Haberl et al., 11 emission lines have experienced increases in flux by factors ~3–10, with the 775 eV line of O vii showing the greatest increase; we have observed six lines of Fe xvii and Fe xviii previously unreported by XMM-Newton. A two-shock model representing plasmas in nonequilibrium ionization is fitted to the EPIC pn spectra, yielding temperatures of ~0.4 and ~3 keV, as well as elemental abundances for N, O, Ne, Mg, Si, S, and Fe. We demonstrate that the abundance ratio of N and O can be constrained to less than ~20% accuracy. Normalizing our obtained abundances by the Large Magellanic Cloud (LMC) values of Hughes, Hayashi, & Koyama, we find that O, Ne, Mg, and Fe are underabundant, while Si and S are overabundant, consistent with the findings of Aschenbach. Such a result has implications for both the single-star and binary accretion/merger models for the progenitor of SNR 1987A. In the context of the binary merger scenario proposed by Morris & Podsidiadlovs, material forming the inner, equatorial ring was expelled after the merger, implying that either our derived Fe abundance is inconsistent with typical LMC values or that iron is underabundant at the site of the progenitor star of SNR 1987A.

Subject headings: circumstellar matter — methods: data analysis — plasmas — shock waves — supernovae: individual (SN 1987A) — supernova remnants — X-rays: individual (SN 1987A)

1. INTRODUCTION

SNR 1987A is the Rosetta Stone (Allen 1960) of Type II supernova remnants, resolved and well studied in multiple wave bands, including the infrared (Bouchet et al. 2006; Kjaer et al. 2007), optical/ultraviolet (Groningssson et al. 2008; Heng 2007), and radio (Gaensler et al. 2007). The physical mechanism partially powering optical/ultraviolet emission from the reverse shock is the same as the one at work in Balmer-dominated supernova remnants (Heng & McCray 2007; Heng et al. 2007). The detection of a neutrino burst confirmed the core collapse nature of the progenitor (Kohsaka et al. 1987; Svoboda et al. 1987), although a pulsar has yet to be detected (Manchester 2007). A system of three rings may be the result of a binary merger between two massive stars about 20,000 years prior to the supernova explosion (Morris & Podsidiadlovs 2006, 2007; hereafter MP06 and MP07). Reviews of the multiwavelength studies of SNR 1987A can be found in McCray (1993, 2005, 2007).

Mixing of the stellar envelope and core by Rayleigh-Taylor instabilities within the progenitor star, Sanduleak –69°202, has been invoked to explain the early emergence of the 847 keV γ-ray line from SNR 1987A, which was predicted by Shibazaki & Ebisuzaki (1988) to reach its peak around 1.1 yr after the explosion, if one assumes a mixed mass of about 5 M⊙. (Ebisuzaki & Shibazaki 1988). Instead, Matz et al. (1988) observed the 847 keV line ~6–8 months postexplosion, suggesting even more extensive mixing of 56Co than assumed. A similar explanation (Ebisuzaki & Shibazaki 1988) was given for the early emergence of 16–28 keV X-rays (Sunyaev et al. 1990; Inoue et al. 1991). The γ-rays originate from the radioactive decay of 56Co, while the X-rays are from the Compton degradation of the γ-rays (McCray et al. 1987).}

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Mg, and Fe are underabundant, while Si and S are overabundant, relative to typical values for the Large Magellanic Cloud (LMC; Hughes et al. 1998). Such a result has implications for modeling the progenitor of SNR 1987A, which we discuss.

2. OBSERVATIONS AND DATA REDUCTION

The latest XMM-Newton (Jansen et al. 2001) observations of SNR 1987A were performed from 2007 January 17 18:23 to January 19 01:18 UT. For our spectral analysis, we utilize data from the CCD cameras EPIC pn (Strüder et al. 2001a, 2001b) and EPIC MOS (Turner et al. 2001), and the Reflection Grating Spectrometers (RGS; den Herder et al. 2001). Additional details and net exposure times for the different instruments are summarized in Table 1.

The data were processed with the XMM-Newton Science Analysis Software (SAS) version 7.1.0. Using ds9, we extracted source and background EPIC spectra of SNR 1987A from circular regions placed on the source and a proximate, point source–free area (Fig. 2). For the EPIC pn spectra, single-pixel (PATTERN 0) events were selected; for EPIC MOS all valid event patterns (PATTERN 0 to 12) were used. RGS spectra were produced using rgsproc. The spectra were binned to contain a minimum of 20 and 30 counts per bin for EPIC and RGS, respectively.

3. RESULTS

3.1. Spectral Fitting

Spectral fitting was done using XSPEC (Arnaud 1996) version 11.3.2. We fit the reduced spectra using models with two components: a low ($T_{\text{low}}$) and a high ($T_{\text{high}}$) temperature component. Two models are considered in XSPEC: VNEI+VRAYMOND and VPSHOCK+VPSHOCK. In H06, the former (Model A) is seen to give an excellent fit (reduced $\chi^2$ of $\chi^2_r \approx 1.1$) to the EPIC pn data. However, the VRAYMOND component of the model, which describes a plasma in ionization equilibrium, is at odds with the belief that both plasmas are in nonequilibrium ionization (NEI; Z06); we note that Park et al. (2004, 2006) found the low-temperature plasma component to be in a highly advanced ionization state (with ionization ages $\approx 10^{12} - 10^{13}$ cm$^{-3}$ s).
be described by a thermal plasma in collisional ionization equilibrium. The VNEI model is a somewhat unsatisfactory representation of the physical situation in the postshock plasma of SNR 1987A because it considers only one value of the ionization age/time, $\tau$, for the entire plasma. The VPSHOCK model generalizes the VNEI one, as it integrates over portions of the plasma with different ionization ages. Borkowski et al. (2001) showed that NEI models with a single value of $\tau$ are poor descriptions of the so-called Sedov models (Hamilton et al. 1983) designed to model thermal X-ray emission from SNRs. Instead, plane-parallel models with multiple temperatures and $\tau$ are good fits to the Sedov models, further justifying the preference for the VPSHOCK model. We have utilized version 2.0 of the NEI models in XSPEC, as used by Z06; the files, with updated “inner shell processes” (Z06), were kindly provided to us by the author of the models, K. Borkowski (2007, private communication).

The data and model fits are plotted in Figures 3 and 4. Details of the fits to the EPIC pn data as well as the derived parameters are given in Table 2. For the VPSHOCK+VPSHOCK model, the range of ionization ages, $\tau \equiv n_{\text{e,ion}}$, is bounded by $0 \leq \tau \leq \tau_{\text{e}}$. Consistent with previous studies of SNR 1987A in the X-ray, the upper limit to the ionization age, $\tau_{\text{e}}$, is higher for the lower temperature component. The computed abundances are given relative to their solar values (Anders & Grevesse 1989, hereafter AG89; Wilms et al. 2000, hereafter W00; see §4), as defined in XSPEC. Galactic foreground absorption is fixed at $6 \times 10^{20}$ cm$^{-2}$, following H06. To account for absorption by the LMC, we take the elemental abundances to be 0.5 relative to their solar values, with the exception of helium, which is kept at its solar value. To get a handle on the systematic errors, we consider both the AG89 and W00 tables. For meaningful comparisons, output abundance values must be normalized to values relative to hydrogen using the respective abundance table used. In the said version of XSPEC, we note that the help file for the VPSHOCK function erroneously lists it as being hardwired to the AG89 tables, even though it is superseded by the abund command (K. Arnaud 2007, private communication).

The errors are computed using the error function for $\Delta \chi^2 = 2.706$. In general, the dependence of the confidence level on $\Delta \chi^2$ is a nontrivial function (Wall & Jenkins 2003). Avni (1976)
finds that it depends on the number of parameters that are estimated simultaneously, i.e., "interesting parameters," and not on the total number of parameters in the fitting function. For one interesting parameter, the 90% confidence interval corresponds to $\Delta \chi^2 = 2.71$; if more interesting parameters are considered, the required value of $\Delta \chi^2$ increases. The $\Delta \chi^2 = 2.706$ level is often quoted as the 90% confidence interval in XSPEC analyses of SNR 1987A; we wish to point out that this should be regarded with some care. Following Z06 and H06, the abundances of He, C, Ar, Ca, and Ni are held fixed; He and C values are taken from Lundqvist & Fransson (1996), while Ar, Ca, and Ni are from Russell & Dopita (1992).

The VPSHOCK+VPSHOCK model is marginally superior to the VNEI+VRAYMOND one for fitting the EPIC pn data; the reduced $\chi^2$ is $\chi^2 = 1.21$ versus 1.31. For reference, we note that the calibration spectra for XMM-Newton are typically fitted with a "goodness" of $\chi^2 \approx 1.5$. To check for consistency between the different XMM-Newton instruments, we have taken the VPSHOCK+VPSHOCK fit to the EPIC pn data, folded it with the corresponding detector response and compared it with the EPIC MOS and RGS spectra. All of the fit parameters are held fixed in the comparison, but the normalization is allowed to vary via a constant factor. This yields $\chi^2 = 1.52$ (MOS1), 1.41 (MOS2), and 1.56 (RGS); for the VNEI+VRAYMOND model, we get $\chi^2 = 1.45, 1.46,$ and 1.54 instead. Full-fledged and independent fits—such as those for the EPIC pn spectra—to the EPIC MOS data and their corresponding $\chi^2$ values are displayed in Figure 4. We note that making more parameters free did not necessarily improve the fits, implying good cross calibration between the EPIC pn and EPIC MOS cameras.

The better counting statistics of the EPIC pn data—and its wider energy coverage compared to the RGS—motivate us to use it as a template for obtaining the temperatures of the two plasma components. Moreover, the higher-temperature component lies beyond the energy range of the RGS. From performing the VPSHOCK+VPSHOCK fit to the EPIC pn data, we obtain $kT_{\text{low}} = 0.4$ keV and $kT_{\text{high}} = 3.0$ keV, consistent with the values of $\sim 0.5$ and $\sim 3$ keV by Z06 (2004 August through September), who also used a two-shock, NEI model. By contrast, the VNEI+VRAYMOND fit to the EPIC pn data gives $kT_{\text{low}} = 0.3$ keV and $kT_{\text{high}} = 2.4$ keV. An NEI plasma is at a higher temperature than is reflected by the ionization stages of its elements; therefore, modeling it as a plasma in collisional ionization equilibrium underestimates its temperature. We do not expect the temperatures of the plasmas to be substantially lower relative to earlier epochs, as the hot spots on the equatorial ring continue to brighten. A worthwhile future endeavor will be to obtain $kT_{\text{low}}$ and $kT_{\text{high}}$ for all of the existing Chandra, XMM-Newton, and Suzaku observations of SNR 1987A, analyzed self-consistently using the same VPSHOCK+VPSHOCK model with both AG89 and W00 abundance tables.

3.2. Integrated Flux

By integrating the X-ray spectra, one can obtain fluxes in different subbands. Park et al. (2004) trisected the spectral range into the 0.3–0.8 keV subband to represent the O line features (O band), the 0.8–1.2 keV subband for the Ne line features (Ne band), and the 1.2–8 keV subband for the Mg/Si lines plus any hard-tail emission features (H band). The soft X-ray band is commonly regarded to be in the 0.5–2 keV range (P05; H06), a historical convention from the era of ROSAT (Hasinger et al. 1996). The “hard band” is taken to be 3–10 keV by P05. We integrate the uncorrected X-ray spectra for various subbands and tabulate them (for 1σ confidence intervals) in Table 3. To correct for Galactic and LMC absorption, one sets the column densities to zero and then recomputes the fluxes. Due to the different abundance tables used and column densities inferred, the absorption-corrected luminosities are model dependent. Assuming a distance...
to the SNR 1987A of $d \approx 50$ kpc, we obtain for $L_{0.5-2keV}$: 1.95 x 10^{36} erg s^{-1} (VPShock+VPShock, W00 table), 2.32 x 10^{36} erg s^{-1} (VPShock+VPShock, AG89 table), and 2.28 x 10^{36} erg s^{-1} (VNEI+VRaymond, W00 table). For $L_{0.5-10keV}$, we get 2.17 x 10^{36} erg s^{-1} (VPShock+VPShock, W00 table), 2.54 x 10^{36} erg s^{-1} (VPShock+VPShock, AG89 table), and 2.49 x 10^{36} erg s^{-1} (VNEI+VRaymond, W00 table). For the 2007 January observation of Park et al. 2007, $L_{0.5-10keV} \approx 2.35 \times 10^{36}$ erg s^{-1}.

### 3.3. Line Fitting

For the RGS observations, we consider only data points between 0.45 and 1.1 keV, the range over which 11 emission lines were previously listed by H06 (see their Table 5 and Z06). We note that 38 lines were considered by H06, but only 11 were listed so as to facilitate comparison with the Chandra studies. We rebin the spectra such that each bin has a minimum of 30 photon counts; we find that if the minimum count is 40, some of the lines are covered by only 2 to 3 bins. The RGS spectra are modeled using a thermal bremsstrahlung component for the continuum and a set of Gaussian profiles for the lines. We first fit only to the 11 lines of N vii, O vii, O viii, Ne vi, and Ne x (Fig. 5). We see that several lines are not fitted by such a model; we propose that six additional lines are now observed: the 725, 727, 739, 741, 831, and possibly the 873 eV line (See Table 1 of Behar et al. [2001] and Figure 2 of Rasmussen et al. [2001] for details on the expected lines in SNR spectra within the RGS energy range.) The detection of the iron lines lends support to our derived Fe abundance and its implications (see § 4).

Following H06, we force the widths of all of the lines to be the same. The more energetic lines are probably powered by the faster shocks, and should therefore have larger widths. A more realistic approach is therefore to model the widths as some increasing function of the ionization potential of each line. However, the rather narrow energy range considered here does not warrant such an approach. The redshift inferred from the fits is $(1.88 \pm 0.26) \times 10^{-3}$. The Gaussian width of the lines is $\sigma_{ll} = 0.87 \pm 0.11$ eV; the full width at half-maximum (FWHM) value is $2.05 \pm 0.26$ eV, which is narrower than the $5.3 \pm 1.0$ eV value of H06. The measured Gaussian width is indicative of the velocities of the shocks responsible for the X-ray emission; the velocities inferred are $v_{\text{sh}} \sim 0.87c/\varepsilon_{\text{ox}}$, where $\varepsilon_{\text{ox}}$ is the energy of a given line in electron volts. For a 1 keV line, we have $v_{\text{sh}} \sim 300$ km s^{-1}, consistent with the Chandra studies of Z06, who find that the X-ray emission originate from shocks with $300 \leq v_{\text{sh}} \lesssim 1700$ km s^{-1}.

### Table 3

**Absorption-uncorrected EPIC pn Fluxes in Various Subbands**

| Subband   | photons cm^{-2} s^{-1} | erg cm^{-2} s^{-1} |
|-----------|-------------------------|-------------------|
| 0.2–0.8 keV | (1.16 ± 0.01) \times 10^{-3} | (1.14 ± 0.01) \times 10^{-12} |
| 0.8–1.2 keV | (1.01 ± 0.01) \times 10^{-3} | (1.54 ± 0.01) \times 10^{-12} |
| 1.2–2 keV | (4.93 ± 0.01) \times 10^{-4} | (1.53 ± 0.04) \times 10^{-12} |
| 0.5–2 keV | (2.28 ± 0.02) \times 10^{-3} | (3.34 ± 0.04) \times 10^{-12} |
| 3–10 keV | (5.31 ± 0.01) \times 10^{-3} | (3.83 ± 0.012) \times 10^{-11} |
| 0.5–10 keV | (4.42 ± 0.01) \times 10^{-3} | (4.05 ± 0.07) \times 10^{-12} |
| 0.2–10 keV | (2.67 ± 0.01) \times 10^{-3} | (4.24 ± 0.015) \times 10^{-12} |

Notes.—1 $\sigma$ (68%) confidence intervals; $A_b$ is shorthand notation for $A \times 10^b$. 

### Table 2

**Comparison of the VNEI+VRaymond and the VPShock+VPShock Models**

| Parameter | VNEI+VRaymond | VPShock+VPShock AG89 | VPShock+VPShock W00 |
|-----------|---------------|-----------------------|---------------------|
| $\chi^2$ | 820.2032 | 805.6812 | 755.9608 |
| $N_{\text{tot}}$ | 624 | 623 | 623 |
| $kT_{\text{low}}$ (keV) | 1.314428 | 1.293228 | 1.213420 |
| $kT_{\text{high}}$ (keV) | 2.42 - 0.176 | 2.88 - 0.15 | 2.99 - 0.22 |
| Galactic $N_H$ (10^{21} cm^{-2}) | 0.6 | 0.6 | 0.6 |
| LMC $N_H$ (10^{21} cm^{-2}) | 3.13 ± 0.14 | 2.37 ± 0.10 | 2.56 ± 0.07 |
| $\tau_{\text{low}}$ ($10^{23}$ cm^{-2} s) | ... | 8.63 ± 0.6 | 8.33 ± 0.2 |
| $\tau_{\text{high}}$ ($10^{23}$ cm^{-2} s) | 1.19 - 0.24 | 2.46 ± 0.71 | 2.21 ± 0.75 |
| $C_{\text{e}}$ | 0.09 | 0.09 | 0.09 |
| $N$ | 0.116 ± 0.10 | 0.30 ± 0.06 | 0.53 ± 0.01 |
| $O$ | 0.0228 ± 0.0074 | 0.0475 ± 0.0045 | 0.0503 ± 0.0018 |
| $Ne$ | 0.157 ± 0.011 | 0.156 ± 0.002 | 0.204 ± 0.014 |
| $Mg$ | 0.208 ± 0.021 | 0.115 ± 0.007 | 0.168 ± 0.011 |
| $Si$ | 0.743 ± 0.019 | 0.262 ± 0.009 | 0.479 ± 0.015 |
| $S$ | 0.689 ± 0.011 | 0.45 ± 0.009 | 0.58 ± 0.009 |
| $Ar^+$ | 0.54 | 0.54 | 0.54 |
| $Ca^+$ | 0.34 | 0.34 | 0.34 |
| $Fe$ | 0.0397 ± 0.0013 | 0.0630 ± 0.0018 | 0.089 ± 0.0017 |
| $N_{\text{Fe}}$ | 0.62 | 0.62 | 0.62 |

Note.—Abundances of elements are listed relative to solar. 

* Abundance table in XSPEC from W00. 

* Abundance table in XSPEC from AG89. 

* Number of degrees of freedom in fit. 

* Parameter is held fixed (see text). 

* VNEI model considers only one value of $\tau = \tau_{\text{high}}$. 

* Fits, respectively.
The fluxes we obtain from fitting to these lines are given in Table 4. In Figure 6, we show the relative increases in flux of the lines (or line complexes) measured in our study versus those of H06. Since 2003 May, the line fluxes have increased by factors of 3—10; the 775 eV line of O viii shows the strongest increase. On average, the lines show an increase of 6.0 ± 0.6 over ~4 yr. The 2003 May soft X-ray flux was measured by H06 to be $F_{0.5-2\text{keV}} = (8.10 \pm 0.09) \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. Our 2007 January value is $F_{0.5-2\text{keV}} = (3.34 \pm 0.04) \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, corresponding to an increase of 4.1 ± 0.1 in the soft X-ray flux. Generally, the same shocks that are responsible for the brightening of the optical and soft X-ray hot spots are also powering the lines. The differences in the flux increases may be an indication that the equivalent widths of the lines are changing, which is evidence for the evolution of the elemental abundances. Such an investigation is deferred to future studies, when one can obtain smaller error bars for the relative increases of the line fluxes (Fig. 6).

4. DISCUSSION

4.1. Individual Abundances and their Ratios

We compare the derived elemental abundances to those of Z06 and H06 and list them relative to hydrogen in Table 5; uncertainties in the AG89 and W00 abundance tables are not propagated. We emphasize that care must be taken to specify the abundance table used, as this may lead to widely differing values of the derived abundances (relative to hydrogen). In modeling the LMC absorption, Z06 used the elemental abundance table of AG89, while H06 chose the table of W00 because the lower oxygen abundance fitted the K absorption edge in the EPIC data better.

Fransson et al. (1989) found N/O = 1.6 ± 0.8, about 12 times higher than the AG89 solar value, which they interpret as evidence of substantial CNO processing. Lundqvist & Fransson (1996) found N/O = 1.1 ± 0.4, while Sonneborn et al. (1997) found N/O = 1.7 ± 0.5. All three of these values were derived from optical/ultraviolet data. Next, we turn our attention to the N/O ratio derived from X-ray studies. Linearly propagating the errors listed by Z06, we find that their results yield N/O = 1.10±0.47 to 0.45.

3 The AG89 and W00 values for solar nitrogen-to-oxygen abundance are N/O = 0.132 and 0.110 by number, respectively.
they remark that their derived C, N, and O abundance, C + N + O ≈ 1.98 × 10^{-4}, is lower by about a factor of 2 compared to the 3.72 × 10^{-4} value of Lundqvist & Fransson (1996). Model A (VWEI+VRAYMOND) in H06 yields C + N + O ≈ 1.67 × 10^{-4} and a rather wide range in the nitrogen-to-oxygen ratio, N/O ≈ 133 ± 1.47. Our VPShock+VPShock fit to the EPIC pn data yields C + N + O ≈ 1.29 × 10^{-4} and N/O = 117 ± 0.37 (using the W00 table); we call this combination of N and O the best-fit point. Note that the C abundance is held fixed at 0.09 relative to solar (~3 × 10^{-2} relative to hydrogen) for the C+N+O values derived from the X-ray studies.

We next perform a more careful analysis of the N/O ratio. We first generate a χ^2 map quantifying the interdependence of the fits to the N and O abundance. Contour lines in the χ^2 map form “error ellipses,” which are shown for different Δχ^2 values from the best-fit point (Fig. 7). At the Δχ^2 = 2.706 level, N/O = 1.17 ± 0.20 for the EPIC pn data. In linearly propagating the errors in the individual abundances, one is in essence adopting the largest possible range of ratios, which can be visualized as the edges of a rectangle in the contour map. Our error analysis improves the uncertainties because it considers only values of the abundance ratio within the specified contour. Within the same confidence interval considered, the corresponding C+N+O value is from ~1.1 to 1.4 × 10^{-4}. We see that the errors in the N/O ratio and the individual N and O abundances can be constrained at the ~20% level. We thus confirm the C+N+O underabundance noted by the Chandra studies of Z06, who suggest a couple of physical reasons for such a result: the sub-LMC abundance of C+N+O within the progenitor star, Sanduleak −69°202, and/or an extra source of possibly nonthermal, X-ray continuum.

We perform the same analysis for N/S (Fig. 8). Again using the W00 table, linear propagation of the errors in the abundances obtained from the VPShock+VPShock fit yields N/S = 4.59 ± 0.51, while the error ellipse analysis gives N/S = 4.59 ± 0.15. The iron, nitrogen, and oxygen lines are predominantly from the lower energy part (≤ 1 keV) of the spectrum, while the sulfur lines are situated between ~2.2 and 3.1 keV. (The silicon lines are located between ~1.8 and 2.2 keV.) Abundance ratios based on lines of widely differing energies lead to rounder error ellipses, i.e., “error circles.” In such cases, a more thorough error analysis will not constrain the abundance ratio better, as in the case of N/S. This is partially an instrumental effect; when the energy resolution is comparable to the spacing of the lines, the line complexes overlap and are only partially resolved. There is also the issue of choosing a coordinate system in which the fitting parameters are “orthogonal.” Hydrogen and helium have no X-ray lines; their abundances are derived from the strength of the X-ray continuum. When the pair of elements considered are situated close to each other in energy, the hydrogen abundance has to first order a linear dependence on the continuum strength. Thus, the ratio of the considered abundances is tightly constrained as the individual abundances track each other closely. By contrast, when the pair of abundances considered are located far apart in energy, this linear dependence of hydrogen abundance on the continuum is broken as the dominant uncertainties are in temperature rather than in flux. Orthogonality is now absent. To attain orthogonality for such pairs of lines, one has to construct models that directly

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### Table 5

**Elemental Abundances from Different Studies (relative to Hydrogen)**

| Element | Z06^a | H06^b | This Study^a | This Study^b |
|---------|-------|-------|--------------|--------------|
|         | VPShock+VPShock | VWEI+VRAYMOND | VPShock+VPShock | VPShock+VPShock |
| N       | 8.64 ± 2.58^a | 7.49 ± 2.57^b | 3.40 ± 0.67 | 5.00 ± 1.03 |
| O       | 7.83 ± 1.46^a | 5.62 ± 1.11^b | 4.04 ± 0.37 | 4.27 ± 0.30 |
| Ne      | 3.57 ± 0.45^a | 2.95 ± 0.40^b | 1.92 ± 0.10 | 2.51 ± 0.15 |
| Mg      | 9.12 ± 1.52^a | 1.05 ± 0.15^b | 4.41 ± 0.23 | 6.54 ± 0.41 |
| Si      | 9.93 ± 1.12^a | 2.34 ± 0.43^b | 9.30 ± 0.60 | 1.70 ± 0.18 |
| S       | 7.30 ± 1.11^a | 5.96 ± 0.82^b | 7.33 ± 1.25 | 1.09 ± 0.14 |
| Fe      | 7.48 ± 0.94^a | 1.33 ± 0.20 | 2.95 ± 0.08 | 2.83 ± 0.19 |

**Note.**—^a is shorthand notation for A × 10^6.  
^b Abundance table in XSPEC from AG89.  
^c Abundance table in XSPEC from W00.

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Fig. 7.—Contour map of N and O for various Δχ^2 values from the best-fit point, marked by the large plus sign. Values of N and O residing along the dotted line have the same N/O value as that for the best-fit point.

Fig. 8.—Same as Fig. 7, but for N/S.
fit to the abundance ratio considered, an approach that is not explored in this paper.

The error in the abundance ratios increases as one moves a given $\Delta \chi^2$ away from the minimum point. In Figure 9, we compute the mean error sustained by the various ratios as a function of $\Delta \chi^2$. According to Avni (1976), if three interesting parameters are considered (see § 3.1), the 90% confidence interval is situated at $\Delta \chi^2 = 6.25$. In this case, the N/O abundance ratio suffers from errors $\sim 25\%$.

4.2. The Progenitor of SNR 1987A: Single-Star or Binary Model?

A more revealing approach to analyze the elemental abundances is to normalize the results listed in Table 5 by the “canonical” values of the LMC abundances (Hughes et al. 1998). These were derived using a sample of seven middle-aged SNRs in the LMC (N23, N49, N63A, DEM 71, N132D, 0453-68.5, and N49B). This approach was first explored by A07, who showed that the normalized abundances appear to cluster in two groups: N, O, Ne, Mg, and Fe are slightly more than half their LMC values, while Si, S, and Ni exceed their LMC values.

We generalize the A07 approach by considering both sets of abundances derived from using the AG89 and W00 tables. The normalized abundance, relative to its respective LMC value, is $R_{\text{LMC}}^{\text{W00}}$; it is plotted as a function of the elemental mass number in Figure 10. The error bars for $R_{\text{AG89/WMC}}$ are computed by linearly propagating the errors listed in Table 5 and in Hughes et al. (1998). We caution that additional systematic errors may be present that are not taken into account. For example, the derived abundance for Fe is a sensitive function of temperature and may vary substantially when small changes are made to $T_{\text{cool}}$.4

We see that the elements O, Ne, Mg, and Fe are underabundant, while Si and S are overabundant, consistent with the findings of A07. With the exception of Fe, there is a tendency for $R_{\text{AG89/WMC}}$ to increase with larger elemental mass number, a trend that is independent of the AG89 or W00 tables, although we note that it is more pronounced with the latter. The Fe abundance derived is essentially independent of the AG89 or W00 tables, and is underabundant by about 70% relative to the LMC.5 The underabundance of Fe and O was previously noted by Hasinger et al. (2006), who argued for the existence of iron-oxygen “rust grains.” The reduced abundance of Fe alone suggests that the iron is locked up in dust grains. However, Dwek & Arendt (2007) showed from an analysis of the infrared-to-X-ray flux ratio—$R_{\text{IRX}} < 1$ versus the theoretically expected value of $\sim 10$—that the dust in SNR 1987A is severely depleted compared to standard dust-to-gas mass ratios in the LMC, suggesting low dust condensation efficiency or dust destruction in the hot X-ray gas. In fact, $R_{\text{IRX}}$ was shown to decrease with time, which is direct evidence for dust destruction. Our derived plasma temperatures are consistent with this scenario; even if dust could form, it would be destroyed at these temperatures.

In light of Figure 10, the central question to ask is whether the progenitor of SNR 1987A arose from a single star or a binary system. Sanduleak $-69^\circ 202$ was known to be a blue supergiant (BSG) at the time of the supernova explosion, contrary to the expectation that massive stars end their lives as red supergiants (RSGs). Observations of low-velocity, nitrogen-rich circumstellar material are interpreted as the progenitor star being a RSG until about $20,000$ yr before its death (Fransson et al. 1989). Such a timescale has in turn been interpreted as the Kelvin-Helmholtz time of the helium core (Woosley et al. 1997). This BSG-RSG-BSG evolution remains one of the greatest challenges for the single-star model (Woosley et al. 1997, 2002), as is the observed system of three rings produced $\sim 20,000$ yr before the explosion. The favored single-star models require a combination of reduced metallicity and “restricted convection” (Woosley 1988), the former of which is supported by our derived abundance ratios. An additional challenge for the single-star model is to reproduce the overabundance of Si and S (Fig. 10), which may require the invoking of some nonstandard mixing process (H.-T. Janka 2007, private communication).

Binary solutions to Sanduleak $-69^\circ 202$ are subdivided into accretion and merger models (see Woosley et al. 2002, and references therein). The binary accretion models allow helium- and nitrogen-rich material to be added to the progenitor star and require the disappearance of the mass donor in an earlier supernova event. In the binary merger scenario proposed by MP06 and MP07, two stars with masses $<5$ and $\sim 15 M_\odot$ are initially orbiting each other with a period $\sim 10$ yr. The more massive companion transfers mass to the less massive star only after the former has completed helium burning in the core. A common envelope (Paczynski 1976) is formed, during which core material from the primary star

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4 The Fe abundance obtained from the VPSHDCK+VPSHDCK fit (W00 table) varies by $\sim 16\%$ when $T_{\text{cool}}$ is changed by $\sim 10\%$.

5 The O abundance relative to H for the AG89 and W00 tables are the same.
is dredged up to the surface. The merger process takes a few hundred years, culminating in an initially oversized RSG, which loses its excess thermal energy over a few thousand years to become a BSG. The spin-up, rapidly rotating BSG produces a fast stellar wind, sweeping up ejecta associated with the merger, producing the triple ring nebula we now see in projection. The nearly axisymmetric but highly nonspherical nature of the rings suggests that rotation played a role in their formation and is consistent with the proposed scenario. The beauty of the model lies in the fact that it requires no physically ad hoc assumptions—apart from a small kick of \( \approx 2 \) km s\(^{-1} \) given to the ejecta to displace the center of the outer rings from their symmetry axis—and makes a number of predictions. In their favored model, MP06 and MP07 assert that the outer rings are ejected before the stellar core material is dredged up, while the inner, equatorial ring—the site of the observed X-ray emission—is ejected afterward.\(^6\) A relevant consequence of this model is that the dredged-up heavy elements will manifest themselves in the form of X-ray emission lines. This may explain the trend we see in Figure 10; the challenge for binary merger models is to reproduce the derived \( R_{\text{SN 1987A}/\text{LMC}} \) values.

Stellar nucleosynthesis can add and \textit{not} subtract iron; in the context of the MP06 and MP07 binary merger model, we expect \( R_{\text{SN 1987A}/\text{LMC}}(\text{Fe}) \geq 1 \). We are again led to the question: where is the iron? If the Fe abundance derived is an upper limit on the iron used to form Sanduleak \(-69^\circ\) 202, then it is clearly inconsistent with “standard” Fe abundances in the LMC. An alternative interpretation is that there is a strong spatial variation in the Fe abundance throughout the LMC, such that the iron is sub-LMC at the site of SN 1987A and equal to its LMC abundance elsewhere. The \( \text{C+N+O} \) underabundance suggested in § 4.1 supports such a conclusion. An improvement over using the Hughes et al. (1998) \textit{ASCA} abundance values is to reanalyze and expand on their SNR sample using \textit{Chandra} and \textit{XMM-Newton}. Existing studies (e.g., Hughes et al. 2006) tend to pick out regions of interest that may include ejecta enrichment; instead, X-ray emission should be extracted from the entire blast wave, from which average abundances can be inferred. Future studies will be invaluable toward resolving these issues.

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\(^6\) As noted by MP06 and MP07, this hypothesis is verifiable/refutable, as the inner ring should exhibit helium enhancement and more CNO processing relative to the outer rings.

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