CHANDRA’S TRYST WITH SN 1995N

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ABSTRACT

We present the spectroscopic and imaging analysis of Type IIn supernova SN 1995N observed with the Chandra X-Ray Observatory on 2004 March 27. We compare the spectrum obtained from our Chandra observation with that of the previous observation with ASCA in 1998. We find the presence of neon lines in the Chandra spectrum that were not reported in the ASCA observation. We see no evidence of iron in either epoch. The observed absorption column depth indicates an extra component over and above the Galactic absorption component and is possibly due to a cool dense shell between the reverse shock and the contact discontinuity in the ejecta. The ASCA and the ROSAT observations suggested a nonlinear behavior of the X-ray light curve. However, with the higher spatial resolution and sensitivity of Chandra, we separate out many nearby sources in the supernova field of view that had additionally contributed to the supernova flux due to the large point-spread function of ASCA. Taking out the contribution of those nearby sources, we find that the light curves are consistent with a linear decline profile. We consider the light curve in the high-energy band separately. We discuss our results in the context of models of nucleosynthesis and the interaction of the shock waves with the circumstellar medium in core-collapse supernovae.

Subject headings: circumstellar matter — line: identification — nuclear reactions, nucleosynthesis, abundances — supernovae: individual (SN 1995N) — techniques: image processing — X-rays: stars

1. INTRODUCTION

X-rays from a supernova explosion arise from the interaction of the supersonic ejecta with the circumstellar medium (CSM). The CSM typically consists of a slow-moving wind with the density ρ = M⋆/4πr²vw, where M⋆ is the mass-loss rate, r is the distance from the supernova, and vw is the wind velocity. When the ejecta collides with the CSM, it creates two shocks: a high-temperature, low-density forward shock ploughing through the CSM (known as the blast wave shock) and a low-temperature, high-density reverse shock moving into the expanding ejecta. Initially, the X-rays come from the forward-shocked shell dominated by continuum radiation, but later on X-rays arise also from the reverse shock, which can have substantial line emission, thus providing nucleosynthetic fingerprints of the ejecta. The temporal evolution of the X-ray luminosity of a supernova can yield information on the density distribution in the outer parts of the exploding star (ρ ∝ r⁻n; here n can be in the range 7–12; typically n ≈ 10 for a blue supergiant and n ≈ 12 for a red supergiant; see Chevalier & Fransson 2003). These studies therefore are of interest from the stellar structure and evolutionary points of view.

SN 1995N was discovered in MCG −02-38-017 (Arp 261) on 1995 May 5 (Pollas 1995) at a distance of 24 Mpc (see Fransson et al. 2002). Pollas (1995) estimated that the supernova was at least 10 months old upon discovery by comparing with spectroscopic chronometers. We assume the date of explosion to be 1994 July 4 throughout the paper. To date, 22 supernovae have been detected in the X-ray bands,1 and SN 1995N appears to be at the high end of the X-ray luminosity (Fox et al. 2000), which makes it suitable for study in the X-ray wave bands even at late stages. In addition, SN 1995N is one of only six supernovae of Type IIn from which X-ray emission has been observed; the others are SN 1978K (Schlegel et al. 2004), SN 1986J (Schlegel 1995), SN 1988Z (Fabian & Terlevich 1996), SN 1998S (Pooley et al. 2002), and SN 2002hi (Pooley & Lewin 2003).

Nomoto et al. (1996) have suggested a continuum of merged stars in binary systems with different common-envelope masses as possible progenitors of various types of supernovae, in particular Types III, Iib, and IIn. The evolutionary path of a close binary system depends on the initial mass ratio q0 (= m₂/m₁, where m₂ is the less massive secondary star and m₁ is the more massive primary star) and on their initial separation a₀. If the

1 See S. Immler’s X-ray supernova page http://lheawww.gsfc.nasa.gov/users/immler/supernovae-list.html and Immler & Lewin (2003).
initial mass ratio is $q_0 \leq 0.4$, the mass transfer is highly non-conservative and leads to the formation of a common envelope and the subsequent spiral-in of the secondary toward the core of the primary. The structure of the CSM from the spiral-in may be asymmetric, where the ejected mass may form a bipolar jet or a disklke structure. When the stellar core collapses and explodes, the supernova lights up the slow-moving gas into narrow emission lines, leading to the Type II supernova classification (“n” for narrow emission line). Type IIn supernovae show unusual optical characteristics and are known to span a very broad range of photometric properties such as decline rates at late times (Filippenko 1997). It is likely that these differences are related to their progenitor’s structure, mass, and composition, as well as the composition and the density profile of the CSM (Li et al. 2002). These supernovae show the presence of strong, narrow Balmer line emission on top of the broader emission lines in their early spectra. It is believed that the narrow emission lines originate in the dense and ionized circumstellar (CS) gas (Henry & Branch 1987; Filippenko 1991). The presence of strong Hα emission lines, the high bolometric luminosity, and the broad Hα emission base powered by the interaction of the supernova shock with the CSM all point toward a very dense CS environment (Chugai & Danziger 2003). This interaction of the supernova shock with the dense CS gas is indicated by strong radio and X-ray emission detected from several Type IIn supernovae and, in particular, from SN 1995N. Optical and ultraviolet observations of SN 1995N (Fransson et al. 2002) up to about 1800 days after the explosion revealed three distinct velocity components. Narrow lines from the CS gas show both low and high ionization states and are caused by photoionization of the CS by X-rays from the shock. The intermediate component has a velocity of 2500–5000 km s$^{-1}$ and is dominated by the newly processed oxygen that is conjectured by Fransson et al. (2002) to be a part of the unshocked (by the reverse shock) ejecta. The broad component whose extended wings reach $\sim$10,000 km s$^{-1}$ is dominated by lines of H i, He i, Mg ii, and Fe ii.

Apart from the narrow lines of Hα mentioned above, SN 1995N showed narrow lines of several other elements in multiple charge states. In particular, the intensity ratios of narrow oxygen lines suggested a high electron density, $n_e \geq 10^6$ cm$^{-3}$ (Garnavich et al. 1995). SN 1995N has turned out to be relatively bright in all the wave bands. It has been detected in radio wave bands with the Very Large Array (Van Dyk et al. 1996) and the Giant Metrewave Radio Telescope (P. Chandra & A. Ray 2005, in preparation). In the X-ray wave band, it was detected by ROSAT in 1996 August and 1997 August and later by ASCA in 1998 January (Fox et al. 2000). The ROSAT observations showed a 30% decline in the X-ray flux from 1996 August to 1997 August, whereas the ASCA observations showed a rise by a factor of 2 between 1997 August and 1998 January (see Table 1). To address the question of nonsteady decline of the luminosity unequivocally, however, it is important to spatially resolve the field of view (FOV) around SN 1995N to an accuracy substantially larger than the ASCA angular resolution. If this trend is indeed real, it could have very interesting implications for the supernova. It could imply that the X-ray emission may be coming from the clumpy clouds crushed by the forward shock, or it could show the inhomogeneity in the reverse shock itself. Figure 1 illustrates two different scenarios of the X-ray emission: one due to the emission from the reverse-shock heated smooth ejecta, which predicts linear decline in the luminosity light curve, and the other due to slow shocks in the CSM clumps, predicting bumps in the light curve.

SN 1995N has declined very slowly in the optical band (see Li et al. 2002 and references therein), with only a 2.5 mag change in the $V$ band over 2500 days after explosion. This is consistent with the slow spectral evolution reported in Fransson et al. (2002). Ground-based optical and Hubble Space Telescope observations of the late-time spectral evolution of SN 1995N were used by Fransson et al. (2002) to argue that the late-time evolution is most likely powered by the X-rays from the interaction of the ejecta and the CSM of the progenitor. They in turn proposed that the progenitors of Type IIn supernovae are similar to red supergiants in their superwind phases, when most of their hydrogen-rich gas is expelled in the last 10$^4$ yr before explosion.

We observed SN 1995N under the Cycle 5 Chandra Guest Observation program for 55.74 ks of exposure time on 2004 March 27 with ACIS-S3. In this paper we present the analysis and interpretation of the data and their implications. Section 2 deals with the observation and data analysis. In § 3 we present the results of spectroscopic and imaging analysis. Section 4 gives a discussion of the results, and § 5 presents a summary.

2. OBSERVATIONS AND DATA ANALYSIS

We observed SN 1995N from 2004 March 27 UT 17:55 to 2004 March 28 UT 10:00 with the Advanced CCD Imaging Spectrometer (ACIS-S) instrument of the Chandra X-Ray Observatory as a part of GO observations (ObsID 5191). The CCDs S2, S3, I2, and I3 were switched on for the observations with the aim point on the back-illuminated chip S3. The back-illuminated chip has the advantage of relatively flat spectral resolution over the front-illuminated chips. The observation was taken in very faint mode. The total exposure on the source was 55.74 ks. A summary of the Chandra observations, along

### Table 1: Summary of All X-Ray Observations of SN 1995N

| Date       | Mission and Instrument | Exposure (ks) | Counts | $kT$ (keV) | $N_H$ ($10^{21}$ cm$^{-2}$) | Unabsorbed Flux (10$^{-11}$ ergs cm$^{-2}$ s$^{-1}$) | $L_X$ (10$^{40}$ ergs s$^{-1}$) |
|------------|------------------------|---------------|--------|------------|----------------------------|------------------------------------------------------|-------------------------------|
| 1996 Jul–Aug| ROSAT HRI             | 18.30         | 172    | 9.1$^{+2.7}_{-1.5}$ | $1.1 \pm 0.4^c$ | 6.5–8.7 | 9.0–12.0 | 12 |
| 1997 Aug 17 | ROSAT HRI             | 18.80         | 126    | 9.1$^{+2.7}_{-1.5}$ | $1.1 \pm 0.4^c$ | 4.5–6.3 | 6.4–8.4 | 8  |
| 1998 Jan 20 | ASCA SIS              | 91.13         | 1960   | 9.1$^{+2.7}_{-1.5}$ | $1.1 \pm 0.4$   | 7.5–10.5 | 12.2–13.2 | 14 |
| 2004 Mar 27 | Chandra               | 55.74         | 750    | 9.1$^{+2.7}_{-1.5}$ | $1.1 \pm 0.4$   | 8.6–11.5 | 14.0–15.2 | 15 |

Note.—Reference for ROSAT and ASCA measurements is Fox et al. (2000).

* Unabsorbed luminosities are in the energy range 0.1–10.0 keV band; $d$ = 24 Mpc.

* Obtained from spectral fits of ASCA data since ROSAT HRI does not have spectral response.
with all previous X-ray observations of SN 1995N, is provided in Table 1.

The data were analyzed using CIAO analysis threads and XSPEC (Arnaud 1996). Event 2 files (pipeline processed files) were used for the data analysis. In order to check for any X-ray flaring events, we selected a background region of size 87" × 87" centered at SN 1995N’s position. The total count for the source events was 758, and the observed count rate was 0.0138 ± 0.0026 counts s⁻¹. We also extracted an annulus of inner radius 7" and outer radius 22" centered at the supernova position to obtain the background counts. We then generated the “pulse invariant” spectra for the source and the background events using dmextract. The response matrices were constructed at the position of SN 1995N. We corrected the response matrix in order to take into account the contamination due to the ACIS quantum efficiency degradation at low energies. To generate the response matrices (RMF and ARF), we used the CIAO threads acis_fef_lookup, mkrmf, asphist, and mkarf.

### 2.1. Data Analysis: Spectral Lines

We binned the data in 20 counts per channel for the spectral analysis using the HEASARC tool GRPPHA. We used the XSPEC software for the spectral fitting of the data. We ignored the counts below 0.3 and above 7.5 keV. This is because there was almost no flux in this energy range and the Chandra response is quite poor at these energies. We modeled the background with a best-fit broken power law model with a break at an energy of 2.7 keV and remove its contribution from the source spectrum. Table 2 gives the best-fit parameters for the background model.

### 2.2. Imaging Analysis

We imaged the FOV of SN 1995N. We used only the S3 chip for imaging, the aim point for SN 1995N. We did not apply the CTI (charge transfer inefficiency) correction to the data because the S3 back-illuminated chip is not significantly affected by this effect. Also, we did not have enough counts to be able to see this tiny correction factor. We built the relevant instrument map for the data using mkinstmap and then generated the spectrally weighted exposure map using mkexpmap. This file was generated using the CIAO script spectrum.sl. The event 2 image divided by the exposure map gives the corrected image. We also ran wavdetect to detect the faint sources in the FOV.

### 3. RESULTS: X-RAY SPECTRA AND HIGH-RESOLUTION IMAGE

#### 3.1. Spectral Fits to the Data: Line Emission

While fitting the source data models in our Chandra spectrum, we initially fixed the background to the values derived in § 2.1 (Table 2), and later, while doing the final iteration, we allowed these parameters to vary to get the real estimates on the errors of the source model parameters. First we fit the continuum thermal bremsstrahlung model, including the Galactic absorption. This fit is certainly not a good fit. The spectral shape suggests the possibility of a line around 1 keV. We then add a Gaussian component at 1 keV and refit the data. The fit improves with the total χ² changing by 18, so the line parameters have a confidence level of 99.9%. The best-fit line energy is 1.02 keV. We fit the Gaussian with its line width fixed at zero. When allowed to vary, the line width remains close to zero within the errors because the ACIS resolution is insufficient to resolve the line. We further note the possibility of another line around 0.9 keV. Since both of the lines are very closely spaced
in energy, it is difficult to fit both the lines together. Therefore, fixing the parameters of the Gaussian already fit at 1.02 keV, we add another Gaussian at 0.9 keV, again with the line width of the Gaussian fixed to zero. The $\chi^2$ improves by 5, significant at the 90% level for two parameters of interest (line position, normalization). The best-fit line energy is 0.85 keV. Although this is not a very robust detection, we suggest the possible identification of this line as Ne ix. Alternatively, it could be a signature of the Ne i K edge. In Table 3 we report the best-fit values for the various models. In Table 3 the best fit $\chi^2$ is obtained for the reported parameters of the bremsstrahlung model ($kT = 2.35$ keV, $N_{HI} = 1.51 \times 10^{21}$ cm$^{-2}$) with only two Gaussian components. The data and our model are shown in Figure 2. The corresponding confidence contours of the line at 1.02 identified as the Ne x Kα line are shown in Figure 3, and this line is very well constrained in the line centroid and normalization. Figure 4 shows the confidence contours for the line at 0.85 keV, demonstrating that the line is reasonably constrained at the 90% confidence level in the centroid and normalization. We also plot the confidence contours of Galactic absorption versus the bremsstrahlung temperature. Both of the parameters are well constrained (see Fig. 5).

We tried to fit other lines as well, but we obtained only the upper limits and our fits did not improve significantly via a change in $\chi^2$. Table 4 gives the upper limits on the O, Mg, Si, S, and Fe lines. Only the Si line at 2 keV shows little significance; however, when we plot the confidence contours for the Si line, the lower bound of the line is completely unrestricted even at the 90% level. Figure 6 shows the confidence contours for the Si line, which clearly rules out the possibility of the presence of the Si feature at 2 keV.

We also applied the VMEKAL model to the spectrum. VMEKAL is a model in XSPEC for an optically thin thermal plasma model developed using the codes of Kaastra (1992), Mewe et al. (1985, 1986), and Liedahl et al. (1995). The L in MEKAL refers to the iron L shell corrections to the codes from Liedahl et al. (1995). We fit a model to the spectrum with a fixed hydrogen density of $2 \times 10^6$ cm$^{-3}$, with a solar abundance. We find that the VMEKAL model fits are least sensitive to the hydrogen density. Here the abundances of C, N, Na, Al, Ar, Ca, and Ni were fixed to the solar abundance. We separately let the abundances of O, Mg, Ne, Si, S, and Fe vary. Only the abundance of Ne and Si are significant with respect to solar (see Tables 3 and 4). The enhanced Ne is consistent with the results obtained from the bremsstrahlung plus Gaussian fit, so we

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**TABLE 3**

| Model               | $\chi^2$/dof | $N_{HI}$ | Parameter 1  | Parameter 2  | Equivalent Width | Normalization |
|---------------------|--------------|----------|--------------|--------------|------------------|---------------|
| Bremsstrahlung ......| 1.61         | 35       | $kT = 2.20 \pm 0.41$ | ...         | ...              | 3.64 ± 1.09   |
| Bremsstrahlung ......| 1.09         | 33       | $kT = 2.35^{+0.51}_{-0.72}$ | ...         | ...              | 3.50 ± 1.70   |
| +Gaussian*          | ...          | ...      | $E_{line} = 1.02^{+0.04}_{-0.02}$ | $N^b = 0.34 \pm 0.19$ | 129$^{+53}_{-20}$ eV | ...          |
| +Gaussian*          | ...          | ...      | $E_{line} = 0.85^{+0.04}_{-0.08}$ | $N^b = 0.27 \pm 0.41$ | <200 eV        | ...          |
| VMEKAL              | 1.51         | 33       | $kT = 3.03^{+0.39}_{-0.34}$ | ...         | ...              | 5.21 ± 0.97   |
| +Ne                  | ...          | ...      | ...          | ...          | ...              | ...          |
| +Si                  | ...          | ...      | ...          | ...          | ...              | ...          |
| Bremsstrahlung ......| 1.20         | 34       | $kT = 3.17 \pm 0.60$ | ...         | ...              | 2.62 ± 0.71   |
| +Gaussian*          | ...          | ...      | $E_{line} = 1.02 \pm 0.02$ | $N^b = 0.29 \pm 0.16$ | 124$^{+30}_{-30}$ eV | ...          |
| +Gaussian*          | ...          | ...      | $E_{line} = 0.86 \pm 0.06$ | $N^b = 0.13 \pm 0.22$ | <135 eV        | ...          |

**Notes.**—All errors listed are 90%. Units are $10^{21}$ cm$^{-2}$ for $N_{HI}$, keV for $kT$, keV for line energy, and $10^{-5}$ for normalization.

a Gaussian widths were fixed to zero.
b Normalization of the Gaussian component in units of $10^{-5}$.
c Abundances are with respect to solar abundances: $X/X_\odot$.
d Galactic absorption $N_{HI}$ was fixed at $6.1 \times 10^{20}$ cm$^{-2}$. Obtained from the Galactic extinction calculation.
identify the 1.02 keV emission as Ne x. The presence of the Si line is ruled out from the confidence contour plot, as discussed above. Table 4 shows the upper limits on the abundances of various lines. The best-fit column density and temperature in the VMEKAL fit are \( N_H = (3.71 \pm 2.79) \times 10^{20} \) cm\(^{-2}\) and \( kT = 3.03 \) keV.

Based on \( \chi^2 \) arguments, the bremsstrahlung plus two Gaussians model provides a better fit to the data than the VMEKAL model fit. Table 3 provides the best-fit parameters for the VMEKAL. Fluxes predicted by various models extrapolated to the ROSAT (0.1–2.4 keV) and ASCA (0.5–7.0 keV) bands are given in Table 5. The fluxes quoted here are absorbed fluxes. It is noticeable that in both the models, the fluxes predicted are quite similar to each other.

The value of best-fit absorption column density in the bremsstrahlung model is \( N_H = 1.51 \times 10^{21} \) cm\(^{-2}\). From the Galactic extinction maps, we get \( E_{B-V} = 0.1158 \) for the SN 1995N coordinates, which gives Galactic absorption of \( N_H = 5.3 \times 10^{21} E_{B-V} \) using the relation of Predel & Schmitt (1995), to \( 6.1 \times 10^{20} \) cm\(^{-2}\). The latter is about \( 21/2 \) times smaller than the value we obtain from the model fits. We tried to fit the above models again by fixing the Galactic absorption at \( 6.1 \times 10^{20} \) cm\(^{-2}\). Our results were much worse than the previous fits. Table 3 gives best-fit parameters for the model fit when \( N_H \) is fixed to \( 6.1 \times 10^{20} \) cm\(^{-2}\). Here we mention that the \( N_H \) determined from radio measurements of the Galactic 21 cm line (Dickey & Lockman 1990) is \( 7.8 \times 10^{20} \) cm\(^{-2}\), which is consistent with the \( N_H \) determined from optical extinction (see \( N_H \) from HEASARC page). We considered the possibility that the

\[ M_{rev} = N_{cool} 4\pi R_s^2 m_p (X_O / X_O^{sh}) = 2 \times 10^{-3} M_\odot, \]

since it is the oxygen abundance of the gas (\( X_O / X_O^{sh} = 100 \)) that mainly contributes to the X-ray absorption near 1 keV. If the cool shell is well into the helium-rich layers, then the implied mass in the absorption shell is considerably larger (~0.8 \( M_\odot \)).

3.1.1. Density and Ionization State of the Radiating Plasma

An important question in studying the radiative properties of an ionized plasma is the mechanism of ionization, which we

**TABLE 4**

| ELEMENT | LINE ENERGY (keV) | NORMALIZATION | ABUNDANCE WITH RESPECT TO SOLAR |
|---------|------------------|----------------|------------------|
|         |                  | Central Value  | Error Range      | Central Value  | Error Range      |
| O.............. | 0.65             | 7.73 \times 10^{-10} | 0–5.70 \times 10^{-6} | 0.01 | 0–0.44 |
| Mg............. | 1.36             | 2.16 \times 10^{-10} | 0–5.67 \times 10^{-7} | 0.5 | 0–2.8 |
| Si.............. | 1.86             | 2.45 \times 10^{-9}  | 0–1.42 \times 10^{-5} | 4.0 | 2.4–5.6 |
| S.............. | 2.4              | 3.15 \times 10^{-8}  | 0–8.47 \times 10^{-5} | 2.2 | 0–4.8 |
| Fe.............. | 6.7              | 8.16 \times 10^{-9}  | 0–1.85 \times 10^{-4} | 0.05 | 0–0.30 |
shall discuss elsewhere. The strengths of the Ne x line reported in § 3.1 (see Table 3) allow us to deduce whether the plasma is in a local ionization equilibrium state. The relaxation time for a particular ion, \( \tau_{\text{rel}} \), is the minimum of the ionization time \( \tau_{\text{ion}} = [C(T_e)n_e]^{-1} \) (Mewe 1999) and recombination time \( \tau_{\text{rec}} = [\alpha(T_e)n_e^{-1}] \), where \( C(T_e) \) and \( \alpha(T_e) \) are the collisional ionization and recombination coefficients, and \( T_e \) is the electron temperature. The reionization parameter is given by (Verner & Ferland 1996)

\[
\alpha(T_e) = a \left( \frac{T_e}{T_0} \right)^{1/2} \left[ 1 + \left( \frac{T_e}{T_0} \right)^{1/2} \right]^{1-b} \left[ 1 + \left( \frac{T_e}{T_1} \right)^{1/2} \right]^{-1},
\]

where \( a, b, T_0, \) and \( T_1 \) are best-fit parameters, obtained from Verner & Ferland (1996) for Ne xi, and leads to a recombination parameter \( \alpha(T_e) = 2.8 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1} \). Hence \( n_e \tau_{\text{rel}} = \text{min}[1/C(T_e), 1/\alpha(T_e)] = 1.32 \times 10^{12} \text{ cm}^{-3} \text{ s}^{-1} \).

For a steady state ionization to hold, the relaxation time for ionization should be shorter than the local cooling and the expansion times. The cooling timescale \( \tau_{\text{cool}} \) given by \( n_e \tau_{\text{cool}} = 3kT/\Lambda \), where \( \Lambda \) is cooling function, can be obtained from McCray (1987):

\[
\Lambda = 1.99 \times 10^{-23} T_e^{0.7} + 7.27 \times 10^{-25} T_e^{1/2} \text{ ergs cm}^2 \text{ s}^{-1},
\]

where \( T_e \) is the temperature in \( 10^7 \text{ K} \). Hence we get \( \Lambda = 1.03 \times 10^{-23} \text{ ergs cm}^2 \text{ s}^{-1} \). Therefore \( n_e \tau_{\text{cool}} = 1.1 \times 10^{15} \text{ cm}^{-3} \text{ s} \), approximately the same as the corresponding hydrodynamic timescale parameter and much larger than the relaxation time. Hence the plasma is in ionization equilibrium, which is expected for a high-density young supernova. We note that the above analytical expression for cooling does not hold for a nonsolar composition. However, T. Nymark et al. (2005, private communication) have shown that the equilibrium is nevertheless expected, except for the low-temperature shocks and shocks in medium highly enriched in heavy elements (e.g., oxygen), and that equilibrium does not hold good for lines with \( \hbar \nu \leq 0.1 \text{ keV} \).

3.1.2. Line Luminosity, Neon Mass, and the Location of the Emitting Gas

The line luminosity for a given line can be given as the volume integral of its emissivity. For the Ne x line,

\[
L_{\text{Ne x}} = \eta \int \int j_{\text{Ne x}} d\Omega \, dV,
\]

where \( \eta \) is a cascade factor that denotes the fraction of recombinations that leads to emission of the Ly\( \alpha \) line in neon; \( \eta \) is at least 0.13 (the number of direct recombinations to the \( n = 2 \) \( 2P \) excited state is typically 13% of the total, see Osterbrock 1989, Table 2.1) and ranges up to about \( \sim 50\% \) for all final states except the ground state (we assume \( \eta = 0.4 \)). From Table 3, the line strength of Ne x \( (3.4 \times 10^{-6} \text{ photons cm}^{-2} \text{ s}^{-1} = 5.6 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1}) \) leads to \( L_{\text{Ne x}} = 3.9 \times 10^{38} \text{ ergs s}^{-1} \) at the distance of SN 1995N (24 Mpc). The emissivity for Ne x can be given as

\[
j_{\text{Ne x}} = n_e n_{\text{Ne x}} \alpha_{\text{eff}} \frac{\hbar \nu_{\text{Ne x}}}{4\pi}.
\]

Let us assume that \( n_{\text{Ne x}} \) is a fraction \( f \) of total \( n_{\text{Ne}} \); i.e., \( n_{\text{Ne x}} = f n_{\text{Ne}} \). If most of the Ne is in the helium zone close to the C+O core boundary (see § 4), then with \( n_{\text{Ne}} = 6.65 \times 10^{-4} n_{\text{He}} \) (see Woosley et al. 2002, Fig. 9, for a 15 \( M_\odot \) star) and \( n_e = 2n_{\text{He}} \), the emissivity of Ne x (see the above two equations) gives

\[
\eta \int n_e^2 dV = \frac{4\pi R^3}{3} n_e^2 = 6.41 \times 10^{63} f \text{ cm}^{-3}.
\]

The first equality assumes that the gas is uniformly distributed. Since the velocity at the oxygen layer is 5000 km s\(^{-1}\), the velocity of the neon has to be greater than this if the neon is in the helium layers. Hence for the present epoch, we assume \( R = vt = 1.57 \times 10^{17} (v/5000 \text{ km s}^{-1})(t/10 \text{ yr}) \). Therefore

\[
n_e = \frac{6.77 \times 10^5}{\sqrt{f}} \text{ cm}^{-3}.
\]

### Table 5

| MODEL          | Fluxes 3.0–7.5 keV | Fluxes 0.3–2.4 keV | Fluxes 0.5–7.0 keV |
|----------------|--------------------|--------------------|--------------------|
|                | 10\(^{-5}\) cm\(^{-2}\) s\(^{-1}\) | 10\(^{-13}\) ergs cm\(^{-2}\) s\(^{-1}\) | 10\(^{-5}\) cm\(^{-2}\) s\(^{-1}\) | 10\(^{-13}\) ergs cm\(^{-2}\) s\(^{-1}\) | 10\(^{-5}\) cm\(^{-2}\) s\(^{-1}\) | 10\(^{-13}\) ergs cm\(^{-2}\) s\(^{-1}\) |
| Bremsstrahlung | 2.97 ± 0.71        | 0.76 ± 0.18        | 2.46 ± 0.58        | 0.47 ± 0.11        | 2.47 ± 0.59        | 0.75 ± 0.18        |
| VMEKAL         | 3.62 ± 0.87        | 0.90 ± 0.20        | 2.99 ± 0.72        | 0.50 ± 0.12        | 3.14 ± 0.75        | 0.85 ± 0.19        |
The ionization potentials of all ionized neon species up to Ne $\text{viii}$ are less than 240 eV, whereas those of Ne $\text{ix}$ and Ne $\text{x}$ are above 1195 eV. Hence at such high temperatures as found by our Chandra observations, the predominant species of neon are expected to be Ne $\text{x}$ and Ne $\text{xi}$. This is also indicated by the clear detection of spectral lines of Ne $\text{x}$ and a possible detection of Ne $\text{ix}$. Thus we expect that the fraction of Ne $\text{xi}$ will be significant, i.e., $f = n_{\text{Ne~xi}} / n_{\text{Ne}} \geq 0.1$. For $f = 0.1$, $n_e = 2.1 \times 10^6$ cm$^{-3}$ and $n_{\text{He}} = n_e / 2 = 1.0 \times 10^6$ cm$^{-3}$, which gives $n_{\text{Ne}} = 687$ cm$^{-3}$. The corresponding mass of Ne, measured from the above Ne density, is $0.16 (f/0.1)^{-1/2} M_\odot$. Note that the implied number density of the electron is not so sensitive a function of the ionization fraction of Ne $\text{xi}$.

Table 6 gives theoretical estimates by Woosley et al. (2002) of elements synthesized in inner zones of massive stars, which can be compared with our estimate of the neon mass detected in SN 1995N. However, the neon mass estimated in the previous paragraph is an overestimate due to two reasons: first, the neon is confined mainly in a thin layer, with a shell of thickness $\delta r$, and not in the entire total volume inside the reverse shock; second, we have assumed a constant density in the shell, whereas the density is a function of radius (velocity) as $\rho \propto (1/r^3)n^{-n}$ ($n \leq 8$ for adiabatic shock). The neon layer lies between oxygen (velocity $\sim 5000$ km s$^{-1}$) and the hydrogen helium zone (velocity $\sim 10,000$ km s$^{-1}$), i.e., in a mass shell of $3.05 - 4.1 M_\odot$ for a $15 M_\odot$ star (see Table 6). Hence, the neon mass depends on the velocity at which it occurs as

$$\int \rho dV \propto \int (1/r^3)v^{-n}4\pi r^2 dr = K \int v^{-n+2}dv.$$ 

This velocity-dependent factor reduces by $\approx 30$ from the oxygen layer to the hydrogen-helium layer boundary for $n = 8$. Hence the actual mass of neon is likely to be at least an order of magnitude lower than the $0.16 M_\odot$ estimated above, or about $5 \times 10^{-3}$ to $1 \times 10^{-2} M_\odot$. This is consistent with neon being in the helium layer for a $15 M_\odot$ star (see third row of Table 6). We find that for other stellar masses and other composition zones, the required neon mass is much larger than observed. Therefore, neon in the helium core of the $15 M_\odot$ star is the probable site where it was cosynthesized with C, N, and He.

### 3.2. Imaging the SN 1995N Field of View

Figure 7 (inset) shows part of the SN 1995N FOV with optical contours overlaid. The positions of SN 1995N and the galactic center of MCG $-03-38-017$ are also shown in Figure 7. The nearest detected source from the supernova at R.A. = $14^h 49^m 29^s 09$, decl. = $-10^\circ 10' 37'' 38$ (J2000.0) at a distance of $26''$ is 20 times less bright (count rate of 0.0007 counts s$^{-1}$) than the supernova. Thus, the resolution and sensitivity achievable by Chandra are crucial for the proper measurement of the SN 1995N flux in this complex field.

We note that in the ASCA observations, the supernova counts were extracted from a circle of radius 4$''$ centered on the supernova position (Fox et al. 2000), excluding the counts in a circle of radius 1.5$''$ centered on source A (shown as the noncircled source at the extreme right edge in Fig. 7). Figure 7 shows the Chandra ACIS S3 image with a circle of radius 4$''$ centered on SN 1995N. It is evident from the figure that even after excluding source A, there are many other sources within the 4$''$ circle that must have contributed toward the supernova flux, including the parent galaxy MCG $-02-38-017$. ROSAT HRI had sufficient resolution to detect these sources. But due to its high instrumental background, it could detect only two sources apart from the supernova in the 4$''$ circle, as opposed to 10 sources in Chandra.
The sources detected by ROSAT HRI were the galactic center (0.0009 counts s\(^{-1}\)) and source A (0.0025 counts s\(^{-1}\)). The corresponding supernova counts in the 1996 August ROSAT observation were 0.009 counts s\(^{-1}\). Using Chandra observations, we extracted the counts from all the sources in a half-power diameter (HPD) of 40\(^{\circ}\) and fit the bremsstrahlung and power-law models to the summed spectrum assuming all the sources in the 40\(^{\circ}\) radius as a single source (excluding source A). Since the power-law model fits give a better \(\chi^2\) (model parameters: \(\gamma = 2.14^{+0.10}_{-0.15}, N_H = 6.97^{+2.4}_{-1.3} \times 10^{20}\) ergs cm\(^{-2}\) s\(^{-1}\)), we adopt the power-law model. The observed count of the combined sources is 2328, whereas the total count for SN 1995N is 758. This means that if we had included all these sources, we would have overpredicted the supernova flux by a factor of 3 at the Chandra epoch.

### 3.3. X-Ray Light Curve of SN 1995N

Since the supernova was observed with ROSAT in 1996 and 1997 and with ASCA in 1998, we construct the light curves over an interval of 8 yr. Figure 8 shows the light curves for the unabsorbed fluxes at soft (ROSAT) energies (0.1–2.4 keV) and at hard (ASCA) energies (0.5–7.0 keV). The ROSAT HRI fluxes were determined by Fox et al. (2000) using the ASCA spectrum. We redetermined the ROSAT fluxes and their uncertainties (ranges) from the ASCA spectrum (see Table 1). Although the fluxes remain identical, the uncertainties increased by a small amount, particularly for the high-energy bands. To calculate the unabsorbed flux, we fixed the Galactic absorption to zero and calculated the fluxes in the above two bands. The light curves show that the ASCA flux is well above all the other flux measurements. Without the ASCA point and only with the ROSAT and Chandra data points, a consistently declining trend in the flux is apparent. If the trend is truly linear, then the expected flux at the ASCA epoch should be \(\sim 6 \times 10^{-13}\) ergs cm\(^{-2}\) s\(^{-1}\) in the 0.1–2.4 keV band and \(\sim 8 \times 10^{-13}\) ergs cm\(^{-2}\) s\(^{-1}\) in the 0.5–7.0 keV band, approximately a factor of 1.6 below the observed ASCA data points (Fig. 8). However, in §3.2 we have shown that due to the large HPD of the ASCA mirror system, the measured flux of SN 1995N in 1998 January was subject to contamination from the other luminous X-ray sources contained within the angular footprint of ASCA. Since our Chandra image identified and measured the fluxes from these sources, we can evaluate this apparent nonlinear behavior of the light curve.

We find from §3.2 that if we assume that the X-ray flux of the combined sources remained constant with time, then this extra contribution explains most of the ASCA flux excess over the predicted flux of SN 1995N from the linear extrapolation.
between the ROSAT and Chandra points shown in Figure 8. The unabsorbed flux from the Chandra spectrum in the 0.1–2.4 keV band in a circle of HPD 4’ (excluding source A) is (2.94 ± 0.34) × 10^{-13} ergs cm^{-2} s^{-1}. Since we know that the contribution of the supernova flux is (0.85 ± 0.20) × 10^{-13} ergs cm^{-2} s^{-1} in this band, the excess flux due to the rest of the sources at present is 2.09 ± 0.39 × 10^{-13} ergs cm^{-2} s^{-1}. Similarly, in the 0.5–7.0 keV energy range, the unabsorbed flux in the 4’ radius is (3.15 ± 0.36) × 10^{-13} ergs cm^{-2} s^{-1}. Excluding the supernova contribution in this higher energy band, i.e., (1.05 ± 0.25) × 10^{-13} ergs cm^{-2} s^{-1}, the flux of the rest of the sources is (2.11 ± 0.44) × 10^{-13} ergs cm^{-2} s^{-1} at present. If we assume that the flux of all these sources remained constant from the ASCA epoch to the present Chandra epoch, then we can subtract this contribution from that of the ASCA measurement of the supernova to estimate the actual contribution due to the supernova only. By this method the supernova flux at the ASCA epoch in the 0.1–2.4 keV band is (6.9 ± 1.6) × 10^{-13} ergs cm^{-2} s^{-1}, and in the 0.5–7.0 keV band it is (10.5 ± 0.7) × 10^{-13} ergs cm^{-2} s^{-1}. Figure 8 shows that in the 0.1–2.4 keV band, the ASCA corrected flux falls on the light curve with the error bars, but the discrepancy is larger at 0.5–7.0 keV. Thus the soft-band light curve appears consistent with a linear decline, including the ASCA 1988 January measurement. However, there appears to be a possibility that there was an extra flux in the hard X-ray band.

We also plot the dereddened V-band optical light curve (Li et al. 2002) and Hα light curve (Fransson et al. 2002), along with the X-ray decline rate (see Fig. 8). Here 

\[ A_V = 3E_{B-V} = 0.3474. \]

The Hα light curve dominates over the V-band light curve until \( \approx 1200 \) days since explosion. Both the V-band and Hα fluxes are much lower than the X-ray fluxes.

3.4. Hard X-Ray Excess in the ASCA Era?

There could be a few possible scenarios to explain this excess of the hard X-ray flux.

1. It is possible that the supernova flux had really increased at the ASCA epoch and that the increase was essentially in the hard X-rays. In that case, it is a physically interesting feature and could be due to the dense clumps from the ejecta being hit by the reverse shock. Alternatively, it could be due to an inhomogeneous CSM being hit by the blast wave shock.

2. Another possible explanation could be that our assumption about the sources within the 4’ FOV of the supernova being constant in time is incorrect. It is quite possible that one or more of these sources are time-variable sources, such as X-ray binaries, and that most of their flux falls in the hard X-ray band. We estimate that to explain the excess flux of \( \sim 2 \times 10^{-13} \) ergs cm^{-2} s^{-1} in the 2.4–7.0 keV band (as described in last section) in the 1998 January ASCA observation over a linear decline between 1996 and 2004, a typical X-ray binary contributing roughly 1000 counts is required. This corresponds to a count rate increase of \( \sim 0.02 \) counts s^{-1} in the bremsstrahlung model with \( kT = 3.32 \pm 0.36 \) and \( N_\text{H} = (8.42 \pm 1.40) \times 10^{20} \) cm^{-2}. Hence, such variability in one X-ray binary can explain the excess ASCA hard-band flux. A detailed analysis of the sources in the Chandra FOV other than SN 1995N is in progress and will be reported elsewhere (F. K. Sutaria et al. 2005, in preparation).

3. In this scenario, we note that for the ASCA analysis of the supernova spectra, the circle of 4’ HPD was chosen for the supernova counts and then the contribution of source A was corrected by excluding the counts from the circle of the 1.5 HPD. We estimate that in view of ASCA’s large PSF, a 1.5 HPD circle around source A would have included only 40% of hard photons coming from source A. The remaining \( \sim 60\% \) of the hard photons would have appeared in the 4’ extraction circle and would have contributed toward the supernova flux in 2–6 keV band. Since source A was very bright, the scattered counts could cause the high flux of the supernova in the harder energy band and hence could explain the discrepancy of the corrected ASCA flux not falling on the linear light curve in the harder X-ray bands. We estimated that the flux for source A in the Chandra observation in the 0.5–7.0 keV band in the bremsstrahlung model was 1.8 × 10^{-13} ergs cm^{-2} s^{-1}, and 60% of this was 1.1 × 10^{-13} ergs cm^{-2} s^{-1}, which accounted for a large fraction of the discrepancy. However, we cannot accurately measure the flux of source A in our Chandra observations because it is on the edge of the chip and so our estimate of the flux of source A and consequently the correction on the ASCA measurement would be an underestimate of the actual flux. We found that source A had \( \sim 700 \) counts in the Chandra data, with most of the photons in the hard X-ray band; the hardness ratio of the source was about \( +0.25 \) [using \( H-S/(H+S) \), where \( H \) were the counts in the 1.0–7.0 keV band and \( S \) the counts in the 0.5–1.0 keV band].

3.5. Comparison with ASCA Spectrum: Continuum and Line Fluxes

SN 1995N was observed in 1998 with ASCA (Fox et al. 2000), although that paper did not include any spectral fits containing line emission. We compared the Chandra bremsstrahlung model with a fit to the ASCA SIS-0 spectrum (SIS-0 provides the best spectral resolution) with the results shown in the top panel of Figure 9 and discussed below. We used the screened event list available from the HEASARC database and extracted the spectrum as described in Fox et al. (2000). We applied the best-fit Chandra (pure bremsstrahlung) spectrum to the ASCA data, and the difference was visible in that the ASCA spectrum was slightly harder and had a line feature at 1.0 and \( \sim 1.3 \) keV, as well as a larger flux (Fig. 9). This Chandra model yields a very poor fit to the ASCA data. We then fit the ASCA spectrum with the bremsstrahlung model with \( N_\text{H} = (3.11 \pm 0.23) \times 10^{21} \text{ cm}^{-2} \) and a temperature \( kT = 2.53 \pm 0.63 \) keV, plus the two lines at 1.02 and 1.32 keV, which yields a drop in \( \chi^2/\nu \) of 19.6, significant at more than 99.99% for the 2 extra degrees of freedom (Fig. 9, bottom). Furthermore, the 0.85 keV line is consistent with being absent at 90% with an upper limit on the equivalent width of \( \sim 40 \) eV. We also detect a line at 1.36 keV at about 1 \( \sigma \) level with an equivalent width of 140 eV (90% upper limit of 190 eV) that is not detected in the Chandra spectrum (90% upper limit of 29 eV). [The ASCA lines mentioned here had norms \( 5 \times 10^{-13}(1.36 \text{ keV}) \) and \( 2.6 \times 10^{-14}(1.02 \text{ keV}) \).] We can interpret these results as an indication of the degree of difference between the ASCA and Chandra spectra (the Chandra ACIS spectrum is displayed in Fig. 2). However, since the ASCA spectrum has contributions from sources other than SN 1995N (see, e.g., § 3.2 above), the small difference between the ASCA and Chandra spectra may not be due to the supernova itself.

The 1.02 keV line is detected in the ASCA data with an equivalent width of \( \sim 250 \pm 115 \) eV (compared to the \( \sim 129 \pm 20 \) eV for the Chandra spectrum). If we attribute the 1.02 keV line to Ne x and the 0.85 keV line to Ne xv, then the change in line strengths may imply a decrease in the ionization conditions in the ejecta. However, as pointed out above, within the errors the values are identical (the error bars are just barely separated at 90%), or the line emission from X-ray binaries within the ASCA PSF contaminates the ASCA spectrum.
4. DISCUSSION

4.1. Spectrum, Light Curve, and the Site of X-Ray Line Emission

The Chandra spectrum differs from that of ASCA in that the ASCA spectrum has a slightly harder X-ray band, a larger flux, and a line at ~1.3 keV not seen in the Chandra spectrum. The presence of at least one line or very likely two lines of Ne in the spectrum indicates that the emitting gas has become optically thin by now. We have a robust detection of one line at 1.02 keV and probable detection of another line at 0.85 keV. At 1.02 keV, it could be Ne x or some of the higher ionized states of iron. The 0.82 keV region contains lines of Fe xvii to Fe xx (Liedahl et al. 1992) that are expected to be strong at high temperatures and low densities. Detailed line calculations and spectra with higher resolution are required to understand the exact range of possibilities. However, the strongest Fe xvii feature in 0.82 keV does not show up in our spectrum, nor is there any evidence of Fe lines around 6.7 keV (see Table 4). Absence of the very strong Fe xvii line feature at 0.82 keV indicates iron is most likely absent in the spectrum (i.e., unmixd with lighter elements in the ejecta) or in a cold state. Therefore, most likely we are seeing the Ne x (1.02 keV) and Ne ix (0.9 keV) lines. But along with the Ne lines, one would have expected to see the oxygen lines as well around 0.6–0.7 keV. However, we do not see this in the Chandra spectrum. This could be due either to the high Galactic absorption in the low-energy bands and/or the lower sensitivity of the ACIS detector below 0.7 keV.

We note that due to low counting statistics, we are unable to resolve the line widths of the Ne lines and thus cannot say whether this gas is indeed at a high (~10,000 km s\(^{-1}\)) or intermediate velocity (2500–5000 km s\(^{-1}\)). If the Ne arises in the O-Ne-Mg core or partially burned C shell and is shocked by the reverse shock, then the high temperature needed for the high ionization state for X-ray emission, as well as the broad emission-line widths seen in the optical–UV spectra (Fransson et al. 2002), are possible. Alternatively, it could be coming from a shell of partially burned helium in a shell burning that is photoionized by the shock. Although SN 1995N is believed to have lost most of its hydrogen-rich envelope before the explosion, and hence the relatively high velocity (~5000 km s\(^{-1}\)) of the oxygen core component in an “untamped” explosion, the UV optical spectrum does reveal a high-velocity (v ~ 10,000 km s\(^{-1}\)) and high-density (n ~ 10\(^5\) cm\(^{-3}\)) hydrogen-helium dominated gas at low ionization.

In our best fits to the spectrum, we find that the absorption column density is at least 2.5 times more than that calculated from the Galactic extinction maps. The best-fit models toward other sources do not show this extra absorption component. This suggests that the moderate, extra absorption is likely to be due to the formation of a thin cool ejecta shell after the reverse shock.

The light curves of SN 1995N suggested a nonlinear profile due to high ASCA flux. If the contributing factor for this jump (or shoulder) is the supernova itself, it could have interesting implications for the CSM. We therefore reanalyzed the ASCA results in view of the high-resolution imaging data obtained by Chandra. We find that due to ASCA’s large PSF, at least 10 more sources were contributing to what was taken to be the supernova flux. The analysis discussed in §3 3.3 and 3.4 indicates that the luminosity light curve is consistent with linear decline within error bars in both hard and soft energy bands.

Fransson et al. (1996) have shown that when the ejecta gradient is moderately flat (n < 8), both shocks (CS and reverse) are adiabatic and most flux below 10 keV comes from the reverse shock. Luminosity from the reverse shock can be expressed as (Chevalier & Fransson 2003)

\[
L_{\text{rev}} = 2\pi R_s^2 \rho v^3 \nu_{\text{rev}}.
\]

Since the reverse-shock velocity \( V_{\text{rev}} \propto t^{-1/3} \), this means that the total luminosity of the reverse shock decreases linearly with time:

\[
L_{\text{rev}} \propto t^{-2/3} \propto 1/t.
\]

Therefore, the observed linear decline suggests that the lower temperature ejecta gas struck by the reverse shock can account for the soft X-ray emission seen from young supernovae (see Fig. 1, top), where the velocity scale (and line width) of ~10,000 km s\(^{-1}\) is set by the expanding stellar ejecta (Chevalier & Fransson 2003). The alternate model of Chugai (1997), in which the soft X-rays can emerge from the radiative cooling of shocked, dense clumps embedded in the CS wind overtaken by the blast wave shock and crushed by the shocked wind (Fig. 1, bottom), would require a time dependent turn-on of the shocked clouds. In view of the steady decline seen in SN 1995N, this model is less likely to be valid unless the sampling of the light curve has been infrequent enough to miss out small bumpy features due to a large number of small clouds.

4.2. Neon Ejecta and Implications for Stellar Models

It is well known that the major source of the Galactic supply of \(^{12}\)C and \(^{16}\)O stars is the red giant stars burning He to produce these major ashes. Fortuitous circumstances of the energy level parameters of these \(\alpha\)-particle nuclei are important for the observed abundance of oxygen and carbon (see, e.g., Rolfs & Rodney 1988), where \(^{16}\)O producing neon via \(^{12}\)C(\(\alpha\),\(\gamma\))\(^{16}\)O is not wholly burned away by \(^{16}\)O(\(\alpha\),\(\gamma\))\(^{20}\)Ne. This is, however, not a universal constraint, as higher core temperatures expected in supergiant stars can broaden the Gamow peak window so that more channels in the final \(^{20}\)Ne nucleus open up, so that in turn the overall astrophysical reaction rates are substantially increased over those prevalent in red giants. As a result, the final nucleosynthetic output from, say, a 25 \(M_\odot\) supernova may even yield dominant production factors of neon with respect to solar neon isotopes compared to those of oxygen. In Table 6 we provide a summary of the dominant elements in certain interior mass ranges obtained from the final composition by mass fraction of two presupernova stars of main-sequence masses 15 and 25 \(M_\odot\), as provided in Figure 9 of Woosley et al. (2002). The inner mass ranges reported in this table have O, Ne, and Mg cores, and these elements are products of core C burning or of partially consumed C-shell burning. The outermost layers reported in this table have O, Ne, and Mg cores, and these elements are products of incomplete He shell burning. It is plausible that the Ne lines seen in the Chandra data originate in these shells. Other elements in these shells, such as C, N, or He, do not have X-ray lines in an energy range where ACIS-S has substantial sensitivity. Since the He- and H-rich layers form part of the high-velocity gas seen in the broad spectral components of the optical and UV spectra of SN 1995N, if the Ne that we observe is mixed in with the helium layers, then most likely the Ne x–ray lines are also arising among the same broad-line component. Alternatively, if the Ne arises together with O and Mg in an O-Ne-Mg core as a result of core C burning, one would normally also expect lines of O and Mg to be present in the Chandra X-ray spectrum. However, we note that due to the poor counting statistics, we are already near the threshold of detection of the strongest line, that of Ne, and the absence of O or Mg lines could be due to the lower sensitivity of the ACIS...
at these energies. The possibility that neon emission arises from the O-Ne-Mg core is, however, unlikely, as Table 6 shows that successively higher amounts of neon are overproduced in the inner zones, compared to the outer layers.

Among the isotopes of neon, $^{20}$Ne and $^{21}$Ne are primarily products of carbon burning, as also are $^{24,25,26}$Mg (see Woosley et al. 2002, Table 3), whereas $^{22}$Ne (together with $^{16}$O and $^{18}$O) are products of He burning in nucleosynthesis resulting from massive stars with $11-40 M_{\odot}$, and various metallicities. In fact, the dominant Ne isotope for a solar metallicity star of $25 M_{\odot}$ at the end of the He burning is $^{22}$Ne. The ACIS spectrum is unable to distinguish between different isotopes of the same element. Therefore, a fraction of the neon seen from the SN 1995N spectrum could be due to $^{22}$Ne, especially if the supernova arose from a more massive progenitor. $^{22}$Ne is made from $^{16}$O at high temperatures in reactions $^{16}$O($\alpha$, $\gamma$)$^{20}$Ne during the He burning. The more recent measurements of the $^{16}$O($\alpha$, $\gamma$)$^{20}$Ne reaction (Gies et al. 1993) indicate that this reaction rate may be much higher than that of Caughlan & Fowler (1988), in which case most of the $^{18}$O will end up in $^{22}$Ne. The neutron-rich seed nucleus $^{18}$O is in turn made in massive stars in the sequence in the reaction $^{14}$N($\alpha$, $\gamma$)$^{18}$F($e^-$, $\nu$)$^{18}$O. Thus $^{22}$Ne comes effectively from two $\alpha$-captures on the $^{14}$N left over from the CNO cycle (during the hydrogen-burning phase) and the amount of $^{22}$Ne scales linearly with the initial metallicity of the star (Woosley et al. 2002). $^{22}$Ne itself would be destroyed due to $^{22}$Ne($\alpha$, $n$)$^{25}$Mg reactions in the high-temperature $s$-process occurring late in the helium-burning stage. The fact that the Chandra spectrum reveals Ne lines indicates that either the progenitor of SN 1995N was not sufficiently massive to destroy $^{22}$Ne in this manner, or the initial metallicity of the star was not negligible, or the $^{22}$Ne($\alpha$, $n$)$^{25}$Mg rate may have been overstimated.

5. CONCLUSIONS

Here we summarize the main conclusions of this paper.

1. The Chandra spectrum of SN 1995N is different from the spectrum of the same region observed by ASCA in 1998 that we have reanalyzed here, especially in the soft energy bands. We detect a Ne x line in both observations, and while we detect a Ne ii line in the Chandra observation this was absent in the ASCA observation. At the same time we detect a 1.3 keV line in the ASCA observation that is absent in the Chandra spectrum of SN 1995N. No Fe line was detected in either spectrum. Fe, if present, is in a cool state, without having undergone significant mixing with outer layers.

2. After taking out the contribution from the contaminating sources in the ASCA PSF, the light curve appears to be consistent with a linear decline. This indicates that the X-ray emission is due to the reverse shock going through a shallow ejecta profile.

3. The observed absorbed column depth seems to indicate an extra component over and above that due to the Galactic column absorption. This is likely to be due to a thin cool shell between reverse shock and the contact discontinuity, as discussed in the previous sections.

4. About 0.01 $M_{\odot}$ of Ne in SN 1995N is estimated from the Chandra line detection, which most likely arises in the partially burned He core at velocities greater than 5000 km s$^{-1}$.

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