X-RAYS FROM THE EXPLOSION SITE: 15 YEARS OF LIGHT CURVES OF SN 1993J

POONAM CHANDRA1,6, VIKRAM V. DWARKADAS2, ALAK RAY3, STEFAN IMMLER4, AND DAVID POOLEY5

1 Department of Astronomy, University of Virginia, P.O. Box 400325, Charlottesville, VA 22904, USA; pc8s@virginia.edu
2 Department of Astronomy and Astrophysics, University of Chicago, 5640 S Ellis Ave, AAC 010c, Chicago, IL 60637, USA
3 Tata Institute of Fundamental Research, Mumbai 400 005, India
4 NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
5 University of Wisconsin, 4512 Sterling Hall, Madison, WI 53706, USA
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ABSTRACT

We present a comprehensive analysis of the X-ray light curves of supernova (SN) 1993J in a nearby galaxy M81. This is the only SN other than SN 1987A, which is so extensively followed in the X-ray bands. Here, we report on SN 1993J observations with Chandra in the year 2005 and 2008, and Swift observations in 2005, 2006, and 2008. We combined these observations with all available archival data of SN 1993J, which includes ROSAT, ASCA, Chandra, and XMM-Newton observations from 1993 April to 2006 August. In this paper, we report the X-ray light curves of SN 1993J, extending up to 15 years, in the soft (0.3–2.4 keV), hard (2–8 keV), and combined (0.3–8 keV) bands. The hard- and soft-band fluxes decline at different rates initially, but after about 5 years they both undergo a \( t^{-1/2} \) decline. The soft X-rays, which are initially low, start dominating after a few hundred days. We interpret that most of the emission below 8 keV is coming from the reverse shock which is radiative initially for around first 1000–2000 days and then turn into adiabatic shock. Our hydrodynamic simulation also confirms the reverse shock origin of the observed light curves. We also compare the H\( \alpha \) line luminosity of SN 1993J with its X-ray light curve and note that the H\( \alpha \) line luminosity has a fairly high fraction of the X-ray emission, indicating presence of clumps in the emitting plasma.

Key words: radiation mechanisms: thermal – shock waves – supernovae: individual (SN 1993J) – X-rays: stars

Online-only material: color figures

1. INTRODUCTION

The explosion of a massive star as a supernova (SN) can drive powerful shocks into the circumstellar medium (CSM) of the progenitor. The CSM is established by the mass lost from the progenitor prior to explosion. Collision of the ejected material with the CSM leads to a blast wave shock with velocities 10,000–20,000 \( \text{km s}^{-1} \) and a hot shell of \( T \approx 10^6 \text{K} \). The interface of the expanding ejecta where it first meets the CS gas is the contact discontinuity which itself propagates outward with time. As the ejecta expand, the interface region between the blast wave shock and the contact discontinuity sweeps up matter from the expanding ejecta where it first meets the CS gas is the contact discontinuity which itself propagates outward with time. As the ejecta expand, the interface region between the blast wave shock and the contact discontinuity sweeps up matter from the CS gas and decelerates due to the accumulated mass. This in turn gives rise to a shocked shell that propagates back into the cold expanding ejecta. This “reverse” shock propagates inward at \( \approx 10^3 \text{ km s}^{-1} \), significantly slower speed than the fastest expanding stellar ejecta and has a temperature of \( T \approx 10^7 \text{ K} \). The reverse shock is believed to be the site of most of the observable X-ray emission at late times.

In this paper, we describe the long-term light curves of the SN 1993J in various X-ray bands. We briefly describe in Section 2 the current understanding about the unusual nature of SN 1993J and its progenitor star as obtained from multiwavelength observations and theoretical analysis. We discuss the X-ray emission mechanisms and the previous X-ray studies of SN 1993J in Section 3. In Section 4, we discuss the X-ray observations and analysis of SN 1993J over the years made with several X-ray telescopes. Our detailed results and interpretation are mentioned in Section 5. Hydrodynamical simulations are discussed in Section 6, and X-ray versus optical H\( \alpha \) correlation in Section 7. We report our main conclusions in Section 8.

2. A SUPERNOVA THAT UNDERWENT A METAMORPHOSIS OF SPECTRAL TYPES

SN 1993J is one of the best studied SNe in all wavelength regimes, second only to SN 1987A. It was visually discovered on 1993 March 28, 906 UT (Ripero & Garcia 1993), in the nearby galaxy M81 (aka NGC 3031 at \( d = 3.6 \text{ Mpc} \); Freedman et al. 1994). It was the optically brightest SN in the northern hemisphere since SN 1954A, having reached a secondary maximum brightness of \( V = 10.8 \text{ mag} \) on day 21.1.

SN 1993J is a SN that has undergone an “identity crisis.” Its spectrum underwent a transition from a type II spectrum (characterized by strong hydrogen Balmer lines) at early epochs, to a type Ib-like spectrum at \( \approx 300 \text{ days} \) (with its nebular spectra having weak hydrogen but strong He I lines). This SN was classified as Type Ib SN and provided for the first time a link between type II SNe and type Ib SNe (Filippenko et al. 1993; Swartz et al. 2003). Models of SN 1993J based on the early light curve indicated that the progenitor star lost all but a small amount of its hydrogen layers due to mass transfer in a binary system (Nomoto et al. 1993; Ray et al. 1993; Podsiadlowski et al. 1993; Woosley et al. 1994). Thus, the shock-heated photosphere could quickly recede through the small H layer into the deeper He layers during the initial expansion and cooling phase itself. Among core collapse SNe, it is thus possible to have a continuum of hydrogen envelope masses remaining on the progenitor star when it explodes.

At early epochs SN 1993J showed the typical signatures of CS interaction in the radio (Van Dyk et al. 1994), UV (Fransson & Sonneborn 1994), and X-ray (Zimmermann et al. 1994) wavelengths. The UV and optical spectra taken with the Hubble Space Telescope (HST) and Keck telescopes have revealed the signature of a massive star, along with the fading SN 10 years...
after explosion, which is the binary companion of the progenitor that exploded (Maund et al. 2004). The CSM has therefore been modified by the mass loss in a binary system in SN 1993J.

3. X-RAY EMISSION AND EARLY X-RAY STUDIES OF SN 1993J

The X-ray luminosity and its time variation depend, among other things, on the density structure of the stellar ejecta. In core collapse SNe, the explosion dynamics quickly lead to an ejecta outer density profile with a steep power law ($\rho \propto r^{-n}$, where $n$ is a constant) in the radial coordinate, but with a relatively flat inner core density profile (Chevalier and Soker 1989; Matzner & McKee 1999). The ejecta density profile depends on the initial structure of the star and, in particular, is affected by if the progenitor had a radiative or a convective envelope (Matzner & McKee 1999). The shock propagation through the outer profile does not depend upon the behavior of the inner layers and a limiting structure is described by a self-similar solution as the shock front accelerates while propagating through the outer layers with rapidly decreasing density. The self-similar nature of the evolution of the ejecta-dominated SNe (or supernova remnants (SNRs)) applies only for ejecta with steep envelope index $n > 5$, since for such steep $n$, the mass and energy of the ejecta remain finite (Truelove & McKee 1999).

The shocked shells (forward or reverse) generated due to ejecta-wind interaction have very high temperatures (Section 1) and can emit X-rays. The forward shock is adiabatic almost all the time and its luminosity follows the time dependence of $L_{\text{rad}} \propto t^{-1}$ (Chevalier & Fransson 2003). However, depending upon the ejecta density profile and the mass-loss rate of the SN progenitor star, the reverse shock can either be adiabatic or radiative, or can be radiative at early phase and then make a transition to adiabatic phase. The expression for free–free emission from adiabatic reverse shock and its luminosity is derived by Chevalier & Fransson (2003) and Fransson et al. (1996):

$$L_{\text{rev}}^{\text{ad}} \approx 3 \times 10^{40} \frac{(n-3)(n-4)^2}{4(n-2)} \left( \frac{M_{\text{ej}}}{u_{w1}} \right)^2 \left( \frac{t}{\text{1 day}} \right)^{-1} \mathrm{erg} \, \text{s}^{-1}.$$  \hspace{1cm} (1)

Here $M_{\text{ej}}$ is progenitor mass-loss rate in units of $10^{-5} M_\odot \, \text{yr}^{-1}$, $u_{w1}$ is the wind velocity in units of $10^3 \, \text{km} \, \text{s}^{-1}$, and $\frac{\bar{g}_{\text{ff}}}{n}$ is the free–free Gaunt factor. This shows that free–free emission from adiabatic reverse shock follows time evolution of $t^{-1}$ for constant mass-loss rate and wind velocity. However, if line emission dominates, the time dependence of X-ray line luminosity is $t^{1.2-2.2m}$ (Chevalier & Fransson 1994), where $m$ is the expansion parameter in $R \propto t^m$.

Fransson et al. (1996) have discussed that in the initial phase, reverse shock with high density gradient is likely to be radiative resulting in formation of a cooled shell between the reverse shock and the forward shock. When the electron temperature is $T_e \leq 2 \times 10^7 \, \text{K}$, the line emission dominates the total X-ray emission. Chevalier & Fransson (2003) have discussed the importance of line emission and its effect on the cooling rate of the gas behind the reverse shock. In case of line emission, a thermal instability develops and the gas cools up to about $10^5 \, \text{K}$ where the temperature is stabilized only by photoelectric heating from the shock balancing the cooling. For an ejecta velocity scale of $V_{ej}$, and a reverse shock moving through an ejecta density gradient $\rho \propto r^{-n}$ with solar composition one obtains a cooling timescale from $t_{\text{cool}} = 3kT_e/n\Lambda$, where $\Lambda$ is the cooling function. The cooling time can be expanded as (Fransson et al. 1996; Chevalier & Fransson 2003)

$$t_{\text{cool}} = \frac{605}{(n-3)(n-4)(n-2)} \left( \frac{V_{ej}}{10^4 \, \text{km} \, \text{s}^{-1}} \right)^{5.34} \times \left( \frac{M_{\text{ej}}}{u_{w1}} \right)^{-1} \left( \frac{t}{\text{1 day}} \right)^2 \text{days.}$$  \hspace{1cm} (2)

Since large exponents of the velocity scale and density gradient index are involved, it is clear that the cooling time is sensitive to them, and also the mass-loss rate of the pre-explosion progenitor star. The most important effect of cooling gas between the reverse shock and the observer is that the cool gas absorbs most of the emission from the reverse shock, and in spite of the higher intrinsic luminosity of the reverse shock, little of it will be directly observable initially. The column density of the cool gas also thins out as the SN ages and expands in scale. In such a situation the total luminosity of the reverse shock may contribute appreciably, or even dominate, to the bolometric luminosity and is defined as

$$L_{\text{rev}}^{\text{rad}} = 1.6 \times 10^{41} \frac{(n-3)(n-4)}{(n-2)^3} \left( \frac{M_{\text{ej}}}{u_{w1}} \right) \times \left( \frac{V_{\text{rev}}}{10^4 \, \text{km} \, \text{s}^{-1}} \right)^3 \, \text{erg} \, \text{s}^{-1}.$$  \hspace{1cm} (3)

Since $V_{\text{rev}} \propto t^{-(n-2)/3}$, the time dependence of luminosity in cooling case is $L_{\text{rev}}^{\text{rad}} \propto t^{-3/(n-2)}$. In Table 3, we tabulate the timescales up to which the reverse shock remains radiative under different conditions. We take the case with density index of 7, 12, and, 20 for three compositions: solar, helium, and oxygen. As one can see from the table, the deeper in the ejecta the reverse shock (where the composition is dominated by heavier elements) is, the longer time do the reverse shocks remain radiative.

It has been argued that SN 1993J-like objects with their high mass-loss rate will have radiative reverse shocks (where cooling is important) even at late epochs (>100 days) whereas SNe with low mass-loss rates such as SN 1999em (a type IIP SN) with long cooling times will develop adiabatic reverse shocks early on (Nynmark et al. 2006). However, in some cases adiabatic and radiative reverse shocks co-exist as has been seen in SN 1987A (Gröningsson et al. 2006). Nynmark et al. (2009) has discussed that if the ejecta or the CSM is clumpy, the adiabatic reverse shock may give rise to slow moving oblique shocks which are radiative in nature.

Soon after its discovery SN 1993J was observed and detected in the X-rays by ROSAT (Zimmermann et al. 1993). Since then, the SN has been observed at various epochs with a number of X-ray telescopes, including ROSAT (Zimmermann et al. 1994; Immel et al. 2001), ASCA (Tanaka 1993; Kohmura et al. 1994; Uno et al. 2002), Chandra (Swartz et al. 2003, and this paper), XMM-Newton (Zimmermann & Aschenbach 2003), and Swift (this paper) satellite missions. The Oriented Scintillation Spectrometer Experiment (OSSE) on the Compton Observatory had detected the SN in 50–150 keV energy band on day 12 and 30 with very high X-ray luminosity ($5 \times 10^{38} \, \text{erg} \, \text{s}^{-1}$) on day 12 (Leising et al. 1994). However, they found that the 50–150 keV emission faded below detection by day 108.

Suzuki et al. (1993) did a detailed analysis of the early X-ray emission from the SN. They carried out hydrodynamical modeling of the collision between the ejecta and a CSM created by steady winds ($\rho_{\text{CSM}} \propto r^{-2}$), and claimed that the observed
| Date of Observation | Mission          | Instrument | Observation ID | Exposure (ks) |
|---------------------|------------------|------------|---------------|--------------|
| 1993 Apr 03.41      | ROSAT            | PSPC       | RP180015N00   | ...          |
| 1993 Apr 05.25–Apr 06.04 | ASCA       | ...       | 15000120      | 27.4         |
| 1993 Apr 07.25–Apr 07.94 | ASCA   | ...       | 15000130      | 28.3         |
| 1993 Apr 08.34–Apr 09.35 | ROSAT     | PSPC       | RP180015N00   | ...          |
| 1993 Apr 12.23–Apr 13.01 | ROSAT   | PSPC       | RP180015N00   | ...          |
| 1993 Apr 16.83      | ROSAT            | PSPC       | RP180015N00   | 5.1          |
| 1993 Apr 16.94–Apr 18.73 | ASCA   | ...       | 15000030      | 66.4         |
| 1993 Apr 22.05–Apr 24.0 | ROSAT     | PSPC       | RP180015N00   | ...          |
| 1993 Apr 25.76      | ASCA            | ...       | 15000020      | 11.1         |
| 1993 Apr 25.76      | ROSAT            | PSPC       | RP180015N00   | 5.1          |
| 1993 Apr 25.85–May 02.59 | ASCA   | ...       | 15000040      | 21.6         |
| 1993 Apr 04.30–May 06.30 | ROSAT     | PSPC       | RP180015A01   | ...          |
| 1993 Apr 12.85–May 13.48 | ASCA   | HRI       | RH00247A01    | ...          |
| 1993 Apr 18.87–May 19.86 | ASCA   | ...       | 10018000      | 39.6         |
| 1993 May 01.93–May 02.59 | ASCA   | ...       | 15000040      | 39.6         |
| 1993 May 04.30–May 06.30 | ASCA   | ...       | 15000040      | 39.6         |
| 1993 May 12.85–May 13.48 | ASCA   | ...       | 10018000      | 39.6         |
| 1993 May 18.87–May 19.86 | ASCA   | ...       | 15000040      | 39.6         |
| 1993 May 12.85–May 13.48 | ASCA   | ...       | 10018000      | 39.6         |
| 1993 May 18.87–May 19.86 | ASCA   | ...       | 15000040      | 39.6         |
| 1993 May 12.85–May 13.48 | ASCA   | ...       | 10018000      | 39.6         |
| 1993 May 18.87–May 19.86 | ASCA   | ...       | 15000040      | 39.6         |
| 1993 May 12.85–May 13.48 | ASCA   | ...       | 10018000      | 39.6         |
| 1993 May 18.87–May 19.86 | ASCA   | ...       | 15000040      | 39.6         |
| 1993 May 12.85–May 13.48 | ASCA   | ...       | 10018000      | 39.6         |
| 1993 May 18.87–May 19.86 | ASCA   | ...       | 15000040      | 39.6         |
| 1993 May 12.85–May 13.48 | ASCA   | ...       | 10018000      | 39.6         |
| 1993 May 18.87–May 19.86 | ASCA   | ...       | 15000040      | 39.6         |
| 1993 May 12.85–May 13.48 | ASCA   | ...       | 10018000      | 39.6         |
| 1993 May 18.87–May 19.86 | ASCA   | ...       | 15000040      | 39.6         |
| 1993 May 12.85–May 13.48 | ASCA   | ...       | 10018000      | 39.6         |
| 1993 May 18.87–May 19.86 | ASCA   | ...       | 15000040      | 39.6         |
| 1993 May 12.85–May 13.48 | ASCA   | ...       | 10018000      | 39.6         |
| 1993 May 18.87–May 19.86 | ASCA   | ...       | 15000040      | 39.6         |
| 1993 May 12.85–May 13.48 | ASCA   | ...       | 10018000      | 39.6         |
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| 1993 May 12.85–May 13.48 | ASCA   | ...       | 10018000      | 39.6         |
| 1993 May 18.87–May 19.86 | ASCA   | ...       | 15000040      | 39.6         |
| 1993 May 12.85–May 13.48 | ASCA   | ...       | 10018000      | 39.6         |
| 1993 May 18.87–May 19.86 | ASCA   | ...       | 15000040      | 39.6         |
features of X-ray emission can be accounted for with thermal free–free emission from the shock-heated ejecta. They also predicted that the expansion velocities of the ejecta must be high and the density gradient of the ejecta shallow. Later they extended their analysis to X-ray observations of first 600 days in Suzuki & Nomoto (1995). In this paper, they assumed a more
realistic ejecta model, a steep density gradient in the outermost layer followed by a much shallower density gradient in the inner H-rich envelope. The density profile suddenly increases and becomes steeper again at the interface of H-rich envelope and He layer. The density profile going as \( r^{-1} \) after explosion were reported by Immler et al. (2001), with a thermal-plasma model with a single temperature (vmekal model). The earlier discrepancy in \( \rho_{\text{CSM}} \propto r^{-2} \) profile. The earlier discrepancy in radio band was claimed to be due to neglecting the synchrotron-self absorption process which plays an important role in the radio absorption for SN 1993J. However, Mioduszewski et al. (2001) included both synchrotron self-absorption and free–free absorption in their analysis and claimed that the radio emission could not be fitted with a CSM declining as \( r^{-2} \), but that a density profile going as \( r^{-1.7} \) provided a much better fit. In this paper, we use the CSM profile to \( \rho_{\text{CSM}} \propto r^{-2} \), though we explore the possibility of different profiles in Section 6.

4. OBSERVATIONS AND ANALYSIS

As mentioned in Section 3, SN 1993J has been observed at various epochs with multiple X-ray telescopes since its discovery. Below, we describe these observations in detail. We analyzed the 2005 and 2008 Chandra data and the Swift data at several epochs between 2006–2008. We also reanalyzed the 2001 XMM-Newton and 2000 Chandra data sets and extracted unabsorbed fluxes in 0.3–2.4 keV, 2–8 keV, and 0.3–8 keV bands. For ROSAT and ASCA, we extracted unabsorbed fluxes in the above bands using best-fit parameters mentioned in various references (see below). In our fits, the column density is a measure of the absorbing cool shell in the SN plus the galactic absorption shell. The column density was set to zero to extract the absorption corrected luminosities. Below we describe the various SN 1993J X-ray observations in detail. The details of all observations used in this paper are summarized in Table 1.

4.1. ROSAT Observations

X-ray observations of SN 1993J by ROSAT between days 6 and 1181 after explosion were reported by Immler et al. (2001), in which both PSPC and HRI observations were included. HRI data were binned in observation blocks of length 5–20 ks exposure time whereas the PSPC observation blocks had integration times ranging 2–18 ks long. They had assumed a constant absorption column density and extracted the fluxes. Zimmermann & Aschenbach (2003) reanalyzed all the ROSAT data and reported the observations up to day 1800. They fitted all the spectra assuming column density as a free parameter and with a thermal-plasma model with a single temperature (vmekal in XSPEC) fixing the element abundances to that obtained from, e.g., XMM-Newton EPIC-PN spectrum. They found that due to the high temperatures in the early ROSAT observations there is almost no difference between fitting either with solar or with the XMM-Newton elemental abundances. We use the best-fit
parameters quoted in Table 3 of Zimmermann & Aschenbach (2003) to extract the ROSAT fluxes of the SN at various epochs. Table 2 shows the unabsorbed luminosities for the ROSAT-HRI and ROSAT-PSPC observations in the energy range of 0.3–2.4 keV.

4.2. ASCA Observations

ASCA flux points were extracted from Kohmura et al. (1994), Uno et al. (2002), and Swartz et al. (2003). The large field of view (FoV) of ASCA showed the presence of the SN host galaxy and a bright X-ray binary source at respectively 3′ and 1′ away from the SN. Since ASCA point-spread function has a resolution of 3′, the bright X-ray binary was strongly contaminating the SN flux. To avoid this contamination Kohmura et al. (1994) and Uno et al. (2002) isolated SN 1993J flux through a one-dimensional image fitting, by using 1′ × 2′ rectangular boxes containing the SN and the X-ray binary separately, and by modeling the one-dimensional intensity profile. They claimed to get rid of almost all the contamination from the M81 and the X-ray binary source, by this method.

To estimate more reliable ASCA fluxes of SN 1993J, we attempted to utilize the late Chandra observations. Due to its high angular resolution, Chandra is able to easily separate the SN, and the nearby X-ray binary and M81 nucleus. Our aim was to extract the uncontaminated flux of the X-ray binary and then subtract it from all the ASCA observations. However, for this technique to work, we needed to make sure that the X-ray binary is not a time variable source. To determine this, we analyzed two Chandra data sets, one of 2000 May 7 and another on 2005 Jun 01 and extracted the flux of the X-ray binary from both the data, respectively. Our analysis shows that the X-ray binary is a highly variable source, especially in the hard X-rays. The 0.3–8.0 keV flux decreases by a factor of 2 in 5 years, from 2.79 × 10^{12} erg cm^{-2} s^{-1} in 2000 May to 1.40 × 10^{12} erg cm^{-2} s^{-1} in 2005 June. The change in the SN flux at 2–8 keV is by more than a factor of 3 in the two observations (2.26 × 10^{12} erg cm^{-2} s^{-1} in 2000 May to 6.9 × 10^{11} erg cm^{-2} s^{-1} in 2005 June). Thus, in view of high variability of the X-ray binary source, it is not advisable to reanalyze all the ASCA data sets to remove the contribution of the X-ray binary on the basis of Chandra flux of the binary. We use the spectral fit parameters of Kohmura et al. (1994) and Uno et al. (2002) to convert the count rates into unabsorbed fluxes in bands 0.3–2.4, 2–8 and 0.3–8 keV fluxes (Table 2).

4.3. Chandra Observations

Chandra first observed SN 1993J on 2000 March 21 and 2000 May 07 under ObsIDs 390 and 735 with ACIS-S by Swartz et al. (2003). They showed that SN 1993J faded since its discovery and its spectrum softened. At this time SN 1993J was ∼2600 days old and displayed a complex thermal spectrum from a reverse shock rich in Fe L and highly ionized Mg, Si, and S but lacking oxygen. The unabsorbed luminosity reported in Table 2 are extracted from Swartz et al. (2003).

Chandra ACIS-S observed the SN starting from 2005 May 26 to 2005 July 6, on 15 different occasions (Obs IDs: 5935-5949; PI: Pooley). Each observation was around 11–12 ks. We analyzed this data using CIAO analysis threads and XSPEC. Event 2 files (pipeline processed files) were used for the data analysis. Standard methods were used to analyze the data (Chandra et al. 2005). We combined the whole data set in two groups to increase the signal-to-noise ratio and extracted the unabsorbed fluxes at various epochs in 0.3–2.4 and 2.0–8.0 keV ranges. We also did spectral analysis of ∼180 ks Chandra ACIS-S data in 2005 given its large exposure. We get an excellent fit to the data using a two-component thermal-plasma model (reduced χ^2 of 1.09) with absorption column density of (6.0 ± 1.5) × 10^{20} cm^{-2}. This is close to the Galactic absorption in the direction of M81, which is expected at such late epochs when the cool shell absorption may have become insignificant. The two temperatures obtained from the best fit are 0.73 ± 0.04 keV and 2.21 ± 0.24 keV. Other models do not fit the data well. The non-equilibrium ionization (NEI) model gives reduced χ^2 = 1.88 for 104 degrees of freedom and power-law model gives reduced χ^2 = 3.48 for 105 degrees of freedom. The two-temperature bremsstrahlung model yields a reduced χ^2 = 1.90 for 103 degrees of freedom. Hence, the two-component thermal-plasma model is the most plausible one. We could not fit the various lines to the data given its sparseness. We plot the spectral fit to this data in Figure 1.

We also extracted the archival data observed with Chandra ACIS-S in HETG mode on 15 occasions from 2005 February 24 to 2006 August 12 (Obs IDs: 6174, 6346-47, 5600-01, 6892-6901; PI: Canizares) and analyzed it. These observations were taken for M81, the host galaxy of SN 1993J which is 3′ away from the SN. SN 1993J flux was a byproduct of these observations. Half of the observations were centered on ACIS chip S2 and the rest of the half on S3. We combined all the data sets in these two major sets and extracted the flux using best-fit models. In this case, we fixed the column density to be 0.06 × 10^{22} cm^{-1}, the one obtained from the 2005 Chandra observations (see above).

Latest observations of SN 1993J with Chandra was taken on 2008 February 1 (PI: Immler). The observations were taken in ACIS-S mode without any grating. The total exposure time was 14.80 ks, out of which we could extract 10 ks of good data. The count rate in this observation was (2.22 ± 0.15) × 10^{-2} counts in full ACIS band. We converted these count rate into flux using N_H = 0.06 × 10^{22} cm^{-1} and temperature of 0.7 keV.

4.4. XMM-Newton Observations

XMM-Newton observed SN 1993J on 2001 April 22 around 8 years after the explosion for about 132 ks duration, under obsID 0111800301 (Zimmermann & Aschenbach 2003). Data
Figure 2. X-ray light curves of SN 1993J in the 0.3–8 keV (upper left panel), 2–8 keV (upper right panel), and 0.3–2.4 keV (lower left panel) bands observed with multiple telescopes. For around first 1000 days, 0.3–2.4 keV light curves declines slowly (t\(^{-0.25}\)) whereas the 2–8 keV light curves decline as t\(^{-1}\). The overall 0.3–8 keV light curve declines as t\(^{-0.65}\) indicating radiative nature of the reverse shock. After around day 1000, the shocks seem to become adiabatic. The lower right panel shows the comparison between the 0.3–2.4 keV and 2–8 keV components and demonstrates that the soft component takes over around day 200 and dominates at late epochs.

(A color version of this figure is available in the online journal.)

from the EPIC PN camera, run in small window mode, and the MOS2 camera in imaging mode were obtained. Zimmermann & Aschenbach (2003) did the detailed analysis of the data and fit the X-ray spectrum with two-component thermal-plasma model. They claimed emissions from highly ionized Mg, Si, S, Ar, Ca, and complex Fe. We used their best fit parameters to extract the unabsorbed luminosity in 0.3–2.4 keV, 2–8 keV and 0.3–8 keV bands.

4.5. Swift Observations

The X-Ray Telescope (XRT; Burrows et al. 2005) on board the Swift Observatory (Gehrels et al. 2004) observed SN 1993J on 2005 April 21, 2005 August 25, 2006 June 24, 2006 November 18–20, and on 2008 January 09–15. We combine the data closely spaced in time, i.e., 2005 April 21–August 25, 2006 June 24–November 18, and 2008 January 09–15, to increase the sensitivity of the data.

The HEASOFT\(^7\) (version 6.2) and Swift software (version 2.6.1, build 20) tools and latest calibration products were used to reanalyze the data. X-ray counts were extracted from a circular region with a 10 pixel (24") radius centered on the optical position of the SN. The background was extracted locally from a source-free region of 30" radius and corrected for the 100% encircled energy radius, to account for the detector and the sky background, and for residual diffuse emission from the host galaxy. SN 1993J is detected in X-rays in the 21 ks XRT observation from 2006 November 18 to 20 at a 7.0\(\sigma\) significance of source detection and a net count rate of (4.1 \(\pm\) 0.6) \(\times\) 10\(^{-3}\) counts s\(^{-1}\) (0.2–10 keV). Table 2 gives details of these observations.

5. RESULTS AND INTERPRETATION

We tabulate the details of all the above observations described in Section 4 in Table 1. We report the unabsorbed luminosities in 0.3–2.4, 2–8 and 0.3–8 keV bands in Table 2. We plot the light curves constructed in these bands from the above observations in Figure 2. The light curve in 0.3–8 keV shows linear decline with power-law index of \(-0.65\) for first few hundred days. At late epochs, from day 2500 onward, the light curve declines at \(t^{-1}\). Due to the lack of observations between day 500 to 2500, it is not possible to predict its evolution in this time range. However, the flux seems to have increased in this gap of \(\sim\)2000 days, contrary to the expected decline. The light curve in 2–8 keV seems to have declined much faster with a power-law index of \(-1\) throughout all the observations. In this band too, there seems to be a possible increase in the luminosity in the gap of 500–2500 days. Fortunately, ROSAT-PSPC observations have covered this gap with many data points in the softer band. The light curve in 0.3–2.4 keV shows an overall decline in the light curve with a power-law index of \(-0.25\) for until about 1500 days. Thereafter, the light curve is consistent with \(t^{-1}\) decline. However, after day \(\sim\)200–300 the light curve reveals a sudden drop in the luminosity which rises back slowly and

\(^7\) http://heasarc.gsfc.nasa.gov/docs/software/lheasoft/
reaches back to the $-0.25$ index profile by day 800. There is another possible small dip around day 1000–1500.

As discussed in Section 3, the X-rays may originate either from the forward shock or from the reverse shock. Since the density and temperature conditions of the two shocks are widely different, this information can help us identify the X-ray emission regions in a given energy band. The CS temperature can be written as

$$T_{\text{CS}} = 1.36 \times 10^9 \left( \frac{n - 3}{n - 2} \right)^2 \left( \frac{V_{ej}}{10^4 \text{ km s}^{-1}} \right)^2 \text{ K}.$$  

Radio VLBI of SN 1993J suggests an expansion velocity of the order of 7000–8000 km s$^{-1}$ at current epoch (Bartel et al. 2007; Bartel et al. 2002). Her observations suggest that the ejecta velocity has to be at least 7500 km s$^{-1}$. Fransson et al. (1996) have argued that the value of density-power-law index $n$ is 8–12. Putting these values in the above equation implies that CS temperature should be at least $T_{\text{CS}} \gtrsim 50$ keV. At such a high temperature of the CS shock, there will be very little emission which will come out in the 0.3–8 keV band. At early epochs the velocities would be much higher resulting in high $T_{\text{CS}}$, of the order of at least few tens of keV and thus will have little flux in the energies below 8 keV. Fransson et al. (1996) have also indicated that all the flux below 10 keV is mostly arising from the reverse shock on the basis of early X-ray observations of the SN. The above discussion indicates that the 0.3–2.4 keV and 2–8 keV bands are at much lower temperatures to account for the emission from the forward shock, and most probably the X-rays in these bands are arising mostly from the reverse shock. Our claim is further strengthened by the hydrodynamic simulation (see Section 6), which also seems to suggest the reverse shock origin.

X-ray light curve behavior can give information about the nature of the reverse shock from which majority of X-rays is coming. The adiabatic shock luminosity declines with a power-law index of $-1$, whereas the radiative reverse shock declines much more slowly. The slow decline of 0.3–8 keV light curve at early epoch is consistent with the radiative nature of the reverse shock at these epochs. The late-time $-1$ decline is consistent with an adiabatic reverse shock. Due to the lack of data it is not possible to pin point the transition from radiative shock to adiabatic shock. However, the soft band light curve without this gap of 2000 days clearly indicates that the shock made the transition from a radiative reverse shock to an adiabatic on around day 1500–2000. Initially hard band emission is much higher than the soft band emission but the latter dominates from day 200 onward. Since SN 1993J emission is becoming softer with time, this kind of luminosity evolution is expected. The fast decline of luminosity in 2–8 keV band also indicates that very little of this radiation is being absorbed by the cool shell in this band and most of it is coming out as adiabatic shock. The overall light curve evolution is consistent with an early radiative reverse shock turning into an adiabatic shock after around 1000 days. This kind of behavior has been predicted by Nynmark et al. (2006) for such SNe. The sudden decline and gradual rise of the X-ray flux between day 200–800 and a possible dip around day 1200–1500 may be due to the density fluctuations in the ejecta. Suzuki & Nomoto (1995) had predicted a possibility of a jump in the SN 1993J light curve. They claim that while moving backward into the ejecta, the reverse shock encounters a density jump at the interface of the hydrogen envelope and the helium core. This density jump at the interface of the two regions will show up as luminosity jump in the light curve. Mioduszewski et al. (2001) clearly show the effect of this density jump on the radio emission. Suzuki & Nomoto (1995) have calculated the possible time for this jump to be around 500–1000 days, although Mioduszewski et al. (2001) found it to be slightly later. It is probable that we are seeing this effect in the light curves of SN 1993J. However, the Suzuki & Nomoto (1995) model is one-dimensional and the strong density gradients are likely to be smoothed by instabilities.

We use the cooling time expression in Equation (2) to derive a timescale for which a reverse shock may remain radiative for the relevant parameters for SN 1993J mentioned in previous sections. A rapid cooling of the gas ahead of the shock is required such that at any stage the cooling timescale is less than the elapsing timescale so that a layer of cool and dense absorbing gas forms, i.e., $t_{\text{cool}}/t < 1$. This condition along with Equation (2) gives

$$t \leq \frac{(n - 3)(n - 4)(n - 2)^{3.34}}{605} \left( \frac{M_{\odot}}{u_w t} \right)^{-5.34} \left( \frac{V_{ej}}{10^4 \text{ km s}^{-1}} \right)^{-3.34} \text{ days.} \quad (4)$$

For $n = 12$, this equation gives $t \leq 260(M_{\odot}/u_w t)(V_{ej}/10^4 \text{ km s}^{-1})^{-5.34}$ days. We tabulate radiative timescales for various values of $V_{ej}$ and $M_{\odot}$ in Table 3. This indicates that it is possible for reverse shock to remain radiative at late epochs, as indicated by our light curves.

6. HYDRODYNAMIC SIMULATION AND COMPUTED X-RAY LIGHT CURVES

The analytic calculations in this paper assume a CS density profile that varies as $r^{-2}$. However, in numerical simulations, we do not constrain ourselves with $r^{-2}$ and explore a larger parameter space. We have carried out several analytic simulations to find the best possible CSM density structure that provides an adequate fit to the observed X-ray data. We chose to reproduce the data in the hard X-ray band, because this band is likely to behave adiabatically (as evident from our 2–8 keV light curve) and hence have no complicated line emission due to the cooling effects. Our simulations are based on Mioduszewski et al. (2001) for a spherically symmetric system using high-resolution V1–3 dimensional finite difference code. Mioduszewski et al. (2001) produced simulated radio light curves using a detailed radiative transfer calculation and fit the radio light curve of SN 1993J. These hydrodynamic results were updated in Bartel et al. (2007) to match updated VLBI data from 1993J. Herein, we use an updated version of this hydrodynamic calculation to simulate the observed X-ray light curves of SN 1993J reported in this paper. The code computes the interaction of the ejecta with a CSM whose density profile leads to the calculation of X-ray flux density of the SN at each epoch. The calculations were carried out in one-dimensional Lagrangian coordinates and remapped on to an Eulerian grid. The shocked interaction region between the forward and reverse shocks was adequately resolved, which is important, as most of the X-rays are emitted in this region.

The hydrodynamic runs use the 4H47 ejecta density distribution model of Shigeyama and Nomoto (courtesy of K. Nomoto 1999, private communication). This model had an ejecta mass of 3.12 $M_{\odot}$, the pre-SN progenitor star radius of 350 $R_{\odot}$, and an envelope mass of 0.47 $M_{\odot}$. The mass fraction of helium in the envelope was about 0.79. The explosion kinetic energy was 10$^{51}$ erg. The surrounding density profile has a slope that varies over time, from $r^{-1.4}$ in the very early stages, to $r^{-2.1}$ up to 10$^{17}$ cm,
and then a steeper drop to \( r^{-2.6} \) at late epochs. This CSM density profile was used to adequately fit the VLBI data in Bartel et al. (2007), and produced radii and velocities comparable to the radio and optical (H\(_\alpha\)) observations. The computation of radiative emission from the hydrodynamic model further requires the electron temperature, whereas the hydrodynamics gives the post shock temperature, which is the temperature of the ions \( T_{\text{ion}} \). We have found that an electron temperature about 15\% of the ion temperature provides an adequate fit to the emission. This is a somewhat simplistic assumption. We calculated the X-ray emission between 1–6 Å (2–10 keV). The observational analysis show that the absorption by the cool shell is less significant for the hard X-ray emission, thus we ignore it. Line emission may also be ignored in this hard band. We used abundances that are appropriate for the ambient medium and SN ejecta in SN 1987A, as outlined by Lundqvist (1999). Nynmark et al. (2009) also found the SN 1987A abundances to be a reasonable set of abundances for the SN 1993J. The ionization of various species was computed by a model due to Shull & van Steenberg (1982). Differences between various ionization models are small and do not alter the hard X-ray flux significantly, or the fundamental result that the X-ray flux arises from reverse shocked ejecta.

Given the density and temperature in every zone, the hydrodynamic model calculates the free–free and bound-free luminosity from that zone using the CHIANTI code (Dere et al. 1997). This is being done for 10,000 zones, over each time step. The contribution from each zone is added up to give the total luminosity. Having the contribution from each zone also allows us to determine exactly the part of the density profile that is contributing most to the X-ray emission. The computed X-ray luminosity in the hard band is shown in Figure 3. Looking at the simplicity of our run, the match between the simulated light curve and actual luminosity is encouraging. Between 10 and about 400 days the luminosity decreases only slowly. Some of the later peaks are due to the reverse shock running into ejecta structures which compresses them. After 1000 days, the slope becomes steeper \((L \propto t^{-1})\), in accordance with the data. We find that the hard X-ray band is shown in Figure 3. Looking at the simplicity of our run, the match between the simulated light curve and actual luminosity is encouraging. Between 10 and about 400 days the luminosity decreases only slowly. Some of the later peaks are due to the reverse shock running into ejecta structures which compresses them. After 1000 days, the slope becomes steeper \((L \propto t^{-1})\), in accordance with the data. We find that the hard X-ray emission process at early phase), however seems to reproduce the observed early luminosity evolution for first 10–15 days (probably due to complicated X-hard band observed luminosities in 2–8 keV band. The model does not trace the evolution starting from a Nomoto and Shigeyama 4H47 model. We plot this model with the hardness ratio, which is the ratio of 2–8 keV luminosities vs. 0.3–2.4 keV luminosities at various epochs. The hardness ratio decreases with time and roughly follows a power-law dependence with a time index of \(-0.55\).

X-rays arise from just behind the reverse shock. The region of hard X-ray production expands inward in the ejecta over the next decade or so till they begin to arise from most of the shocked ejecta, between the reverse shock and the contact discontinuity. After about 50 years, the forward shock starts to dominate the emission. This confirms our prediction that almost all the X-rays below 8 keV over the observed time period are coming from the reverse shock.

Our hydrodynamic simulation models are carried out in spherical symmetry. It is encouraging that even using these simple hydrodynamic models it is possible to qualitatively understand the evolution of the SN, and explore several basic features, such as the fact that the hard X-ray emission is coming predominantly from the reverse shock.

7. DISCUSSION

7.1. Column Depth and the Cool Shell

Immler et al. (2001) had analyzed \textit{ROSAT} data fixing the column depth to be \(4 \times 10^{20} \text{ cm}^{-2}\), same as the Galactic absorption column density. However, the reanalysis of the same data by Zimmermann & Aschenbach (2003) and letting column density to be a free parameter revealed that column densities are much higher than the Galactic column density. Uno et al. (2002) fitted the \textit{ASCA} data with the two-component thermal-plasma model and found that the low-temperature component has much higher column density than the high-temperature component. These high column densities in excess to the Galactic absorption can be attributed to the absorption by an additional cool shell. Since most of the X-ray emission below 8 keV is coming from the reverse shock, this indicates that both the \textit{ROSAT} and the \textit{ASCA} data have revealed the presence of a cool shell between the forward and a reverse shock, thus presence of a radiative reverse shock. However, the column density seems to reduce with time and after around 2000 days, the best-fit column densities are consistent with that of the Galactic absorption. This indicates that the reverse shock has most likely become adiabatic by this epoch.

7.2. Hardness Ratio and Electron Temperature

In Figure 4, we plot the ratio of SN 1993J luminosity in the 2–8 keV versus 0.3–2.4 keV bands. The figure clearly shows that...
the hard X-ray emission dominates for first ~100–200 days. After ~200 days, soft X-ray emission starts to take over and continues to dominate. At current epoch, i.e., 15 years after the explosion, the soft X-ray is dominant by around an order of magnitude.

Since most of the flux below 8 keV is coming from the reverse shock, the ratio of the reverse shock free–free luminosity in 2–8 keV band to 0.3–2.4 keV band can be written as (Fransson et al. 1996):

\[ H \equiv \frac{L_{2.0-8.0 \text{ keV}}}{L_{0.3-2.4 \text{ keV}}} = \frac{0.8 \text{ keV}}{2.0 \text{ keV}} \left( \frac{E}{kT} \right)^{-0.4} \exp \left( -\frac{kT}{T} \right) dE. \]  

Here \( (E/kT)^{-0.4} \) is the Gaunt factor in the given energy regime. This equation puts some interesting constraint on the temperature of the reverse shock. The current hardness ratio of 0.14 corresponds to the electron temperature of 1.05 keV. This equation also shows that electron temperature was ~1.5 keV around day 500 and it has evolved very slowly since then to reach the current value of 1 keV. Since free–free emission dominates above temperature 2 keV (Fransson et al. 1996), our derived temperature of 1 keV at current epoch will contribute mostly to the free–free continuum emission, as well as possibly to the line emission.

For maximum electron temperature of ~30 keV (Fransson et al. 1996), the hardness ratio is 1.45. In fact, Equation (5) above reaches asymptotic upper limit of ~1.5 which is around day 100, irrespective of temperature. However, this demonstrates that in the initial X-ray observations, where hardness ratio is larger than 1.5, the contribution between 2–8 keV is not solely because of the reverse shock but may have some contribution from the CS shock too. After day ~100, all the X-ray flux below 8 keV comes from the reverse shock (see Figure 4).

### 7.3. \( H \alpha \) and the X-ray Luminosity Evolution

\( H \alpha \) emission in SNe arises initially by radioactivity and later by reprocessing of X-rays produced due to ejecta-wind interaction. In the case of adiabatic shocks, the \( H \alpha \) emission may come from the unshocked material heated by the X-rays coming from the adiabatic shock waves. If the reverse shock is radiative, then the dense cool shell between the reverse and the forward shocks may also give rise to significant \( H \alpha \) emission.

There have been extensive \( H \alpha \) observations of SN 1993J. Matheson et al. (2000a, 2000b) describe the detailed optical spectra of SN 1993J up to 2500 days. In Matheson et al. (2000b), they also measure the line widths of boxy \( H \alpha \) spectra of SN 1993J up to 2500 days. After 250 days, continued presence of strong broad lines of \( H \alpha \) in SN 1993J have been explained as a result of photoionization by X-rays and UV emission from the radiative reverse shock propagating into the SN ejecta (Fransson et al. 2005). Patat et al. (1995) show that late-time \( H \alpha \) emission from SN 1993J can be described by a shell of hydrogen between 7500 and 11,400 km s\(^{-1}\). Similar velocity range for emitting gas shells for broad, box-shaped UV lines are seen in the \( HST \) spectra of SN 1993J (Fransson et al. 2005) apparently coming from an ejecta and a cool dense shell.

We tabulate these \( H \alpha \) luminosities after day 170 in Table 4. We also plot the \( H \alpha \) luminosities with soft and hard band X-ray luminosities in Figure 5. The figure shows that the \( H \alpha \) luminosity seems to follow the hard X-ray band luminosity evolution after a few hundred days, but with significant efficiency. However, it fails to trace the soft band X-rays completely. The significant rate of conversion of the kinetic luminosity of the ejecta wind interaction into broad \( H \alpha \) emission by the reprocessing of the X-ray luminosity of the reverse shock wave was also noted by Patat et al. (1995). It should be noted that Patat et al. (1995) have cautioned that possibly up to 30% of the emission at \( H \alpha \) wavelengths in SN 1993J may originate from an unidentified

| Days Since Explosion | Luminosity (erg s\(^{-1}\)) | Observatory | Reference |
|----------------------|-----------------------------|-------------|-----------|
| 171                  | 14.98 × 10\(^{38}\)         | Asiago     | Patat et al. (1995) |
| 205                  | 8.67 × 10\(^{38}\)         | Asiago     | Patat et al. (1995) |
| 236                  | 4.96 × 10\(^{38}\)         | Asiago     | Patat et al. (1995) |
| 255                  | 4.11 × 10\(^{38}\)         | Asiago     | Patat et al. (1995) |
| 299                  | 2.29 × 10\(^{38}\)         | Asiago     | Patat et al. (1995) |
| 367                  | 1.28 × 10\(^{38}\)         | Asiago     | Patat et al. (1995) |
| 553                  | 2.50 × 10\(^{38}\)         | Lick       | Matheson et al. (2000b) |
| 670                  | 3.00 × 10\(^{38}\)         | Keck       | Matheson et al. (2000b) |
| 687                  | 2.88 × 10\(^{38}\)         | NAOC       | Zhang et al. (2004) |
| 700                  | 2.75 × 10\(^{38}\)         | NAOC       | Zhang et al. (2004) |
| 881                  | 2.50 × 10\(^{38}\)         | Lick       | Matheson et al. (2000b) |
| 976                  | 4.80 × 10\(^{38}\)         | Keck       | Matheson et al. (2000a) |
| 986                  | 2.19 × 10\(^{38}\)         | NAOC       | Zhang et al. (2004) |
| 998                  | 1.95 × 10\(^{38}\)         | NAOC       | Zhang et al. (2004) |
| 1034                 | 1.99 × 10\(^{38}\)         | NAOC       | Zhang et al. (2004) |
| 1280                 | 1.74 × 10\(^{38}\)         | NAOC       | Zhang et al. (2004) |
| 1318                 | 1.29 × 10\(^{38}\)         | NAOC       | Zhang et al. (2004) |
| 1395                 | 1.38 × 10\(^{38}\)         | NAOC       | Zhang et al. (2004) |
| 1729                 | 1.10 × 10\(^{38}\)         | NAOC       | Zhang et al. (2004) |
| 1766                 | 0.86 × 10\(^{38}\)         | Keck       | Matheson et al. (2000b) |
| 2066                 | 0.65 × 10\(^{38}\)         | NAOC       | Zhang et al. (2004) |
| 2454                 | 0.37 × 10\(^{38}\)         | Keck       | Matheson et al. (2000b) |
| 3149                 | 0.50 × 10\(^{38}\)         | NAOC       | Zhang et al. (2004) |
| 3401                 | 0.43 × 10\(^{38}\)         | NAOC       | Zhang et al. (2004) |
| 3503                 | 0.43 × 10\(^{38}\)         | NAOC       | Zhang et al. (2004) |
| 3610                 | 0.28 × 10\(^{38}\)         | Keck       | Filippenko & Matheson (2005) |

Figure 5. Plot of \( H \alpha \) luminosity light curve (taken from Table 4). We also plot the 2–8 keV X-ray light curve. The \( H \alpha \) roughly traces the 2–8 keV band light curve after day ~300 indicating that \( H \alpha \) arises due to the CS interaction. The \( H \alpha \) luminosities are high fractions (30%–50%) of X-ray luminosities, which probably indicate toward the presence of clumps in the ejecta.

(A color version of this figure is available in the online journal.)
band of emission around 6600 Å which is hypothesized due to a broad blend of emission lines extending between 6050 and 6800 Å as seen to be present in type Ib/Ic SNe.

The Hα seems to trace the hard band evolution but the efficiencies are 30%–50% of the X-ray production in this band, whereas the expected efficiency is typically no more than 1%–5% of the X-ray luminosity. This indicates that there could be another component which is contributing significantly to Hα flux. The clumps in the ejecta can be one such candidate which can give rise to Hα with high efficiency. The non-smooth Hα evolution also probably indicates toward the possibility of significant Hα origin from the clumps. Patat et al. (1995) also invoked an earlier suggestion by Chugai (1993) where the clumpiness of the wind material and possibly the clumpy structure of the dense and Rayleigh–Taylor unstable region in the ejecta helped attain a more efficient transformation of kinetic energy into radiation. Chugai & Danziger (1994) proposed a model for SN 1988Z, in which a radiative shock wave is driven into the dense cloud by thermal and dynamical pressures behind the main (blast wave shock and reverse shock) shock waves or by the dynamical pressures of the expanding unshocked ejecta. The shock in the cloud is significantly slower due to the higher density in the cloud and the shocked gas cools by soft X-ray or UV emission which then pumps the optical emission from the cool dense material behind the radiative shock wave in the cloud.

8. CONCLUSIONS

In this paper, we have presented the complete X-ray light curves of SN 1993J in 0.3–2.4 keV, 2–8 keV, and 0.3–8 keV bands. We demonstrate that most of the emission below 8 keV comes from the reverse shock, except for the very early soft band emission when the cool shell absorbed all the soft flux from the reverse shock. The light curves reveal that the reverse shock is radiative for around initial 1000 days and then it becomes adiabatic at later epochs, as expected for such SNe (Nynmark et al. 2006). The evolution of column density too seems to indicate this. The column density was higher than the Galactic column density during the ROSAT, ASCA, and early Chandra and XMM-Newton observations, and later became comparable to the Galactic absorption, indicating the presence of a cool shell during the first 1000 days. We demonstrate that for SN 1993J parameters, it is possible for the shock to be radiative at such late epochs.

We have carried out numerical hydrodynamic computations, and calculated the hard X-ray flux from the same, which agree reasonably well with the observed data. Our simulations clearly show that all the emission below 8 keV is indeed coming from the reverse shock, strengthening our claim.

The large fraction of Hα flux in comparison to the X-ray emission indicates possibility of clumps in the ejecta. One of the important questions is how these young SNe evolve toward a SNR. Since young SNe and older SNRs are both products of explosive events a natural question is whether the former evolve continuously into the latter with time, whether similar emission mechanisms differing only in length-scales and timescales operate or if the SNe fade away only to switch on later as SNRs with a different mechanism of radiation. One of the very well studied SNR in our galaxy, Cassiopeia A was thought to be of the Type IIb or Inl (Chevalier & Oishi 2003). However, it has recently been conclusively classified as a Type IIb SN, the same type as that of SN 1993J (Krause et al. 2008). Late-time observations of SN 1993J may provide an important link between young SNe and SNRs. SN 1993J had a large X-ray flux, which, coupled with it being a nearby SN, made it easily observable for a long time with a well sampled light curve. This has made SN 1993J one of the best studied extragalactic SNe, and provided a wealth of information on SN evolution and their CS interaction. Further observations of this SN for a long time is sure to provide much valuable information on these questions.

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REFERENCES

Bartel, N., Bietenholz, M. F., Rupen, M. P., & Dwarkadas, V. V. 2007, ApJ, 668, 924
Bartel, N., et al. 2002, ApJ, 581, 404
Burrows, D. N., et al. 2005, Space Sci. Rev., 120, 165
Chandra, P., Ray, A., Schlegel, E. M., Sutaria, F. K., & Pietsch, W. 2005, ApJ, 629, 933
Chevalier, R. A., & Fransson, C. 1994, ApJ, 420, 268
Chevalier, R., & Fransson, C. 2003, in Lecture Notes in Physics 598, Supernovae and Gamma-Ray Bursters, ed. K. Weiler (Berlin: Springer-Verlag), 171
Chevalier, R., & Oishi, J. 2003, ApJ, 593, L23
Chevalier, R., & Soker, N. 1989, ApJ, 341, 867
Chugai, N. 1993, ApJ, 414, L101
Chugai, N., & Danziger, J. 1994, MNRAS, 268, 173
Dere, K. P., Landi, E., Mason, H. E., Monsignori Fossi, B. C., & Young, P. R. 1997, A&A, 125, 149
Filippenko, A. V., & Matheson, T. 2005, in IAU Coll. 192, Cosmic Explosions, On the 10th Anniversary of SN1993J, ed. J. M. Marcaide & K. W. Weiler (Berlin: Springer), 37
Filippenko, A. V., Matheson, T., & Woosley, S. E. 1993, IAU Circ., 5787, 1
Fransson, C., & Bjorssön, C. I. 1998, ApJ, 509, 861
Fransson, C., Lundqvist, P., & Chevalier, R. A. 1996, ApJ, 461, 993
Fransson, C., & Sonneborn, G. 1994, in Frontiers of Space and Ground Based Astronomy, Astrophysics an Space Science Library 187, ed. W. Wamsteker et al., 249
Gröningsson, P., Fransson, C., Lundqvist, P., Nynmark, T., Lundqvist, N., Chevalier, R., Leibundgut, B., & Spytromili, J. 2006, A&A, 456, 581
Houck, J. C., & Fransson, C. 1996, ApJ, 456, 811
Krause, O., Birkmann, S. M., Usuda, T., Hattori, T., Goto, M., Rieke, G. H., & Misselt, K. A. 2008, Science, 320, 1195
Leising, M. D., et al. 1994, *ApJ*, 431, L95
Lundqvist, P. 1999, *ApJ*, 511, 389
Matheson, T., et al. 2000, *AJ*, 120, 1487
Matheson, T., et al. 2000, *AJ*, 120, 1499
Matzner, C. D., & McKee, C. F. 1999, *ApJ*, 510, 379
Maund, J., et al. 2004, *Nature*, 427, 129
Mioduszewski, A. J., Dwarkadas, V. V., & Ball, L. 2001, *ApJ*, 562, 869
Nomoto, K., & Suzuki, T. 1998, *The Hot Universe*, 188, 27
Nomoto, K., et al. 1993, *Nature*, 364, 507
Nynmark, T. K., Chandra, P., & Fransson, C. 2009, *A&A*, 494, 179
Nynmark, T. K., Fransson, C., & Kozma, C. 2006, *A&A*, 449, 171
Patat, F., Chugai, N., & Mazzali, P. A. 1995, *Astron. Astrophys.*, 299, 715
Podsiadlowski, P., Hsu, J. J. L., Joss, P. C., & Ross, R. R. 1993, *Nature*, 364, 509
Ray, A., Singh, K. P., & Sutaria, F. K. 1993, *J. Astrophys. Astron.*, 14, 53
Ripero, J., & Garcia, F. 1993, *IAU Circ.*, 5731, 1
Shull, J. M., & van Steenberg. M. 1982, *ApJS*, 48, 95
Suzuki, T., Kumagai, S., Shigeyama, T., Nomoto, K., Yamaoka, H., & Saio, H. 1993, *ApJ*, 419, L73
Suzuki, T., & Nomoto, K. 1995, *ApJ*, 455, 658
Swartz, D. A., et al. 2003, *ApJS*, 144, 213
Tanaka, Y. 1993, *IAU Circ.*, 5753, 1
Truelove, J. K., & McKee, C. F. 1999, *ApJS*, 120, 299
Uno, S., et al. 2002, *ApJ*, 565, 419
Van Dyk, S. D., et al. 1994, *ApJ*, 432, L115
Woosley, S. E., Eastman, R. G., Weaver, T. A., & Pinto, P. A. 1994, *ApJ*, 429, 300
Zhang, T., Wang, X., Zhou, X., Li, W., Ma, J., Jiang, Z., & Li, Z. 2004, *AJ*, 128, 1857
Zimmermann, H.-U., & Aschenbach, B. 2003, *A&A*, 406, 969
Zimmermann, H. U., et al. 1993, *IAU Circ.*, 5748, 1
Zimmermann, H.-U., et al. 1994, *Nature*, 367, 621