MONITORING X-RAY EMISSION FROM SN1986J

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Abstract

SN1986J ranks as one of the most luminous, X-ray bright supernovae ever observed. The X-ray emission is attributed to circumstellar interaction with the dense wind from its progenitor star. I present results from recent *Chandra* observations of SN1986J which, combined with data from *ROSAT*, *ASCA*, and *XMM-Newton*, yield an X-ray light curve spanning much of the first 20 years of the supernova's evolution. Together with observations in other wave bands, these data provide strong constraints on models for this type IIn supernova. I show that the 0.5–2.5 keV X-ray emission is declining $\propto t^{-1.7\pm0.25}$, and suggest that the enhanced abundance of silicon and sulfur in the X-ray spectrum argues against a shocked wind-cloud origin for the X-ray and narrow optical line emission.

1 Introduction

Powerful X-ray emission from a young supernova can arise when high-velocity supernova ejecta are decelerated by interaction with a dense circumstellar medium (Chevalier & Fransson, 1994). The supernova explosion drives a strong shock into the circumstellar medium with an initial forward shock velocity of $\sim 10^4$ km s^{-1}. At the same time, a reverse shock moves upstream into the supernova ejecta at $\sim$ 1000 km s^{-1} relative to the ejecta. In the standard picture (e.g., Chevalier & Fransson 1994), a self-similar solution describes the evolution of the shocked interaction shell when both the ejecta and the circumstellar medium have power-law density profiles. Within the shocked shell, a contact discontinuity marks the boundary between the shocked ejecta and the shocked circumstellar medium. At the contact discontinuity, turbulence develops rapidly due to the growth of Rayleigh-Taylor instabilities. This turbulent region is the source of powerful synchrotron radio emission. Although considerable X-ray emission is expected from the reverse-shocked ejecta, much of it is likely to be absorbed in a cool, dense shell of material which accumulates near the contact discontinuity (Chevalier & Fransson, 1994). Photoionized material near the reverse shock is expected to produce significant optical and UV line emission (Chevalier & Fransson, 1994).

X-ray and radio emission from SN1986J in NGC891 seems consistent with an unusually energetic circumstellar interaction (Pérez-Torres et al., 2002; Bietenholz, Bartel & Rupen, 2002; Houck et al., 1998). SN1986J was discovered as a bright radio source by Rupen et al. several years after the outburst. By extrapolating Very Long Baseline Interferometer (VLBI) angular size measurements backward in time, Bietenholz, Bartel & Rupen (2002) infer an explosion date of 1983.2. Because of the large radio luminosity from the supernova ($\sim 10^{38}$ erg s^{-1}), its progenitor star is thought to have had an unusually dense wind corresponding to $\dot{M} \gtrsim 2\times10^{-4}$ $M_\odot$ yr^{-1} (Weiler, Panagia & Sramek, 1990). Chevalier (1987) predicted that the source should be luminous in soft X-rays. Later *ROSAT* PSPC observation confirmed this prediction, revealing that SN1986J is one of the brightest and most X-ray luminous supernovae ever observed (Bregman & Pildis, 1992). The PSPC X-ray spectrum is consistent with thermal emission with T_X = 1.0–3.9 keV and an absorbing column of (5–14)$\times10^{21}$ cm^{-2}, with a luminosity of L_X (0.1–2.5 keV) = (1.6–7)$\times10^{40}$ erg s^{-1}. A second PSPC observation, in 1993, revealed that the soft X-ray flux was dimming approximately as t^{-2} where t is the time since explosion (Houck et al., 1998). The time dependence of the X-ray emission provides an important model diagnostic, which, along with the temperature, depends on the density structure in the envelope of the progenitor star and in the circumstellar medium.

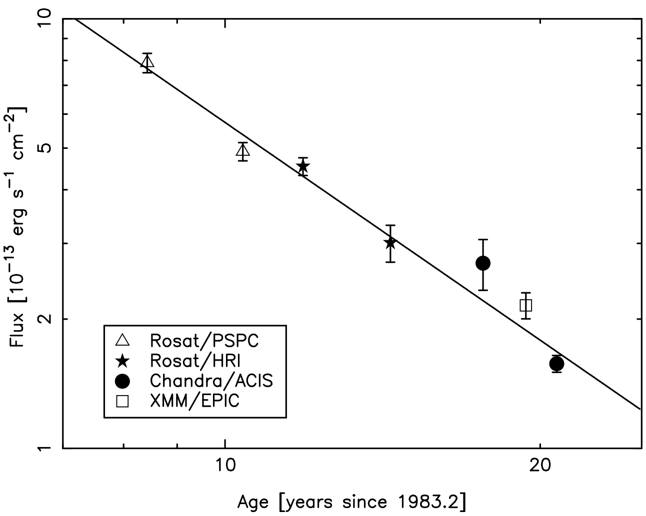

Figure 1: Unabsorbed X-ray flux (0.5–2.5 keV).

Instrument	Date	MJD	Exposure ks	Ref.
ROSAT PSPC	1991 Aug 18	48486.10	23.87	1,2
ROSAT PSPC	1993 Aug 08	49206.45	30.51	1,2
ASCA	1994 Jan 21	49373.33	47.13	2
ROSAT HRI	1995 Jan 26	49743.96	97.17	2
ASCA	1996 Jan 30	50112.00	54.44	2
ROSAT HRI	1997 Aug 03	50663.09	41.52	
Chandra ACIS-S3	2000 Nov 01	51849.80	52.39	
XMM EPIC-PN	2002 Aug 22	52508.29	12.67	
XMM EPIC-MOS1	2002 Aug 22	52508.29	18.04	
XMM EPIC-MOS2	2002 Aug 22	52508.29	18.06	
Chandra ACIS-S3	2003 Dec 10	52983.37	120.62	

Table 1: X-ray observations of SN1986J. References: 1) Bregman & Pildis 1992 2) Houck et al. 1998

2 X-ray spectrum

Motivated by the unusually narrow Balmer emission lines observed by Leibundgut et al. (1991), Chugai (1993) suggested an alternative model for the origin of the soft X-ray emission. The Balmer lines are usually identified with the outer part of the exploded star which, for SN1986J, was initially expanding at > 7000 km s^{-1} (Bartel, Shapiro & Rupen, 1989). However, the optical Balmer lines, and some metal lines, had a full-width-half-max of < 600 km s^{-1} (Leibundgut et al., 1991). Chugai (1993) proposed that the progenitor wind was clumpy and that the narrow emission lines originate in the wind clumps; these clumps or clouds also produce the soft X-ray emission (Leibundgut et al., 1991).

In Chugai's model, the reverse shock is too weak to produce observable soft X-rays. Rather, it is the pressure in the strongly shocked wind which crushes the embedded clouds, driving weaker shocks into them. These weaker shocks then generate the soft X-rays, and eventually, the Balmer emission. The inertia of the clouds is so great that they are not accelerated outward, so the full-width-half-max of the optical emission lines reflects only the speed of the shock driven into the clouds. The existence of a nonuniform circumstellar medium associated with SN1986J was also suggested by Weiler, Panagia & Sramek (1990). From examination of the radio light curve shape, they argued that the data were best described by a non-uniform medium consisting of mixed thermal absorbers and emitters.

In this paper, I present results from recent X-ray observations of SN1986J. I concentrate on results from the *Chandra* observation of 2003 Dec 10 which yielded the best X-ray spectrum of the supernova to date. *Chandra*'s high angular resolution clearly resolved the supernova, yielding a spectrum relatively uncontaminated by emission from bright nearby point sources and diffuse emission associated with the host galaxy. I also discuss the time evolution of the X-ray emission, presenting previously unpublished observations by *Chandra*, *XMM-Newton* and *ROSAT*.

3 X-ray observations

Table 1 lists all available X-ray observations of SN1986J. The *ROSAT* HRI observation of 3 Aug 1997 and the *Chandra* and *XMM-Newton* observations are discussed here for the first time. For a detailed discussion of data analysis procedures, see Houck (2005, in prep).

4 Light curve

The X-ray observations listed in Table 1 were used to derive the 0.5–2.5 keV light curve of SN1986J spanning the twelve year period from 1991 Aug to 2003 Dec (Fig. 1). *ASCA* observations were excluded because their low angular resolution introduced significant contamination from other X-ray sources in the field of view. Based on the remaining datasets, the absorbing column is consistent with fixed absorbing column of $N_H \approx 5\times10^{21}$ cm^{-2}, corresponding to line-of-sight absorption in our Galaxy and in NGC891 (Houck et al., 1998). Using this absorbing column to derive the unabsorbed flux, I find that the unabsorbed 0.5–2.5 keV light curve (Fig. 1) is well described by a power-law decline of the form $F \propto t^{-\alpha}$ where t is the elapsed time since the outburst (1983.2 – see Bietenholz, Bar-

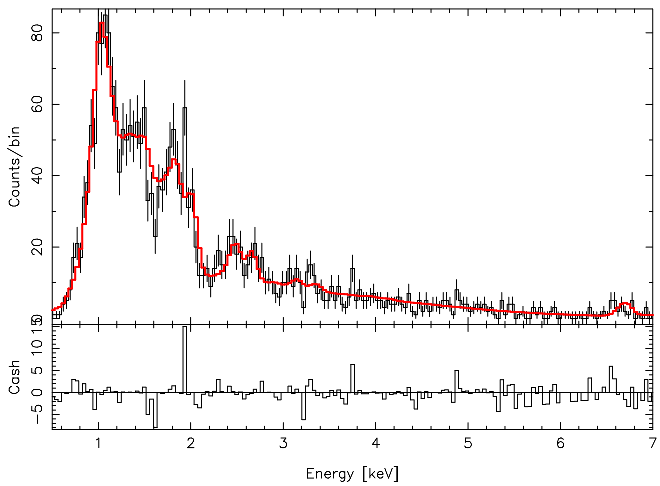

Figure 2: *Chandra* ACIS-S spectrum of SN1986J from 2003 Dec (age = 20.7 yr). The red curve is the absorbed, two-temperature VMEKAL model described in Table 2. The data were grouped by a factor of 4 to preserve energy resolution for display. The lower panel shows Cash-statistic residuals from the model fit.

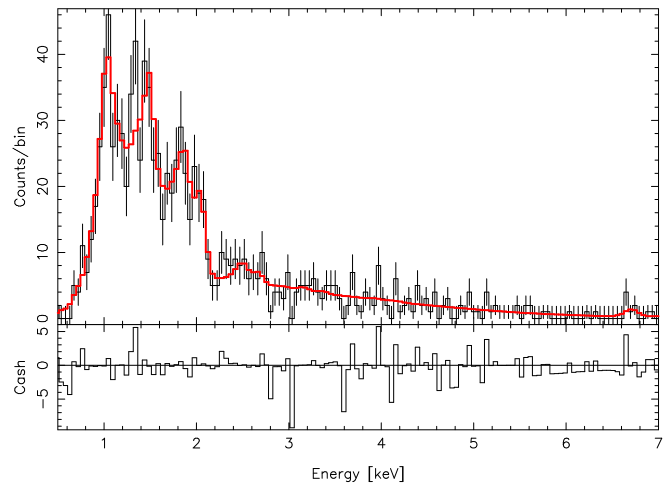

Figure 3: *Chandra* ACIS-S spectrum of SN1986J from 2000 Nov (age = 17.6 yr). The red curve is an absorbed, two-temperature VMEKAL model similar to that described in Table 2. The lower panel shows Cash-statistic residuals from the model fit.

tel & Rupen 2002). The best-fit power-law exponent is α = 1.7±0.25 (90% confidence), indicating that the decline is somewhat slower than previously suggested (Houck et al., 1998).

A 120 kilosecond observation with the *Chandra* X-ray Observatory in 2003 Dec yielded the best available X-ray spectrum of SN1986J (Fig. 2). The source was observed using ACIS-S in timed exposure mode. These data were filtered using standard criteria. The source spectrum was extracted from a 2″ radius circle centered on the supernova. The background during the observation was fairly constant at a low level. A local background spectrum was extracted from a nearby 100″ square region free of obvious point sources; because of the very low background level, the background contribution to the source spectrum was negligible. The data were analyzed using ISIS (Houck & Denicola, 2000). The instrumental effective area curve included the effects of absorption due to accumulated contamination on the ACIS optical blocking filter. Table 2 gives the results of spectral fits to the 2003 *Chandra* ACIS-S spectrum for the 0.5–7 keV band.

Fitting the data with a single-temperature collisional ionization equilibrium model (VMEKAL) yielded a fit with $\chi^2/\mathrm{d.o.f} \sim 2$. The resulting best-fit parameters are shown in the first column (1T) of Table 2. The abundances are unusual, with neon enhanced by more than an order of magnitude, but with oxygen and magnesium consistent with solar abundance. The fit was significantly improved ($\chi^2/\mathrm{d.o.f} \sim 1.4$) by adding a second collisional equilibrium component and by constraining the two components to have the same abundances. The resulting best-fit parameters are shown in the second column (2T) of Table 2. In this model, iron L-shell emission from the low-temperature component accounts for the bulk of the emission near 1 keV and is consistent with about a solar abundance of iron. With the strong peak at 1 keV dominated by iron L-shell emission, this model sets upper limits on the abundances of oxygen, neon and magnesium. In both models, the abundances of silicon and sulfur appear enhanced relative to solar by a factor of 2–4.

I also examined a planar shock model (VPSHOCK) with similar electron temperature and abundances and with a maximum ionization parameter of τ_u = 1.6×10^{12} s cm^{-3} (see Table 2). Using the chronological age of ∼ 20.7 yr, this maximum ionization parameter is consistent with an electron density of the same order of magnitude as that derived from the spectrum normalization (see below). Nevertheless, the data do not require non-equilibrium ionization.

Comparing the *Chandra* ACIS-S spectra from 2000 Nov (Fig. 3) and 2003 Dec (Fig. 2), the source shows little evidence for spectral evolution. Fitting each data set with a two-temperature collisional equilibrium model, the fit parameters agree within their 90% confidence limits, apart from the change in normalization

Parameter	1T VMEKAL	2T VMEKAL	VPSHOCK
χ^2/d.o.f.	127/61	79/58	99/60
N_H	$0.43^{+0.01}_{-0.06}$	$0.55^{+0.1}_{-0.1}$	$0.48^{+0.05}_{-0.04}$
kT_1	$3.8^{+0.6}_{-0.2}$	$5.5^{+0.9}_{-0.8}$	$5^{+0.9}_{-0.7}$
kT_2	-	$1.1^{+0.1}_{-0.1}$	-
$\tau_u \times 10^{-12}$	-	-	$1.6^{+0.4}_{-0.2}$
$K_1 \times 10^4$	$1.2^{+0.13}_{-0.03}$	$1.2^{+0.1}_{-0.1}$	$1.2^{+0.06}_{-0.05}$
$K_2 \times 10^4$	-	$0.34^{+0.1}_{-0.1}$	-
O	1	< 1.2	< 0.52
Ne	$13^{+3.3}_{-1.3}$	< 2.1	$2^{+1.0}_{-0.6}$
Mg	1	< 2.6	$0.85^{+0.5}_{-0.6}$
Si	$1.9^{+0.9}_{-0.9}$	$1.9^{+2}_{-0.4}$	$1.7^{+0.5}_{-0.3}$
S	3.3^{+2}_{-1}	$4.3^{+1.4}_{-1.2}$	$3.1^{+1}_{-0.7}$
Fe	$0.95^{+0.3}_{-0.2}$	$1.3^{+0.4}_{-0.3}$	$1.2^{+0.2}_{-0.1}$

Table 2: Model fit results for the 2003 Dec *Chandra* ACIS spectrum. Single-parameter 90% confidence limits are shown

due to the overall decline in luminosity. At lower confidence, however, there may have been a decline in the Mg/Si ratio between 2000 Nov and 2003 Dec.

5 Discussion

The observed steep decline of the X-ray luminosity is difficult to explain within the framework of the self-similar model for circumstellar interaction. Chevalier & Fransson (1994) examine self-similar models in which the outer layers of the progenitor star have $\rho_{\rm sn} \propto r^{-n}$ and which have a circumstellar medium with density profile $\rho_{\rm w} \propto r^{-2}$. Fransson, Lundqvist & Chevalier (1996) extend this analysis to consider cases in which the circumstellar medium has $\rho_{\rm w} \propto r^{-s}$. The general conclusion is that, for a wide range of the parameters n and s, the X-ray luminosity is expected to decline more slowly than $L_X \propto t^{-1}$. The observed steep decline in X-ray luminosity, $L_X \propto t^{-1.7}$, occurs only in self-similar models for which the circumstellar density profile is much steeper than $\rho_{\rm w} \propto r^{-2}$. Such a steep circumstellar density profile is inconsistent with a steady wind, but might be produced by variations in either the mass-loss rate or the wind velocity or both during the last few thousand years before the supernova outburst. Variations in the mass-loss rate are expected because red supergiant progenitors are known to be pulsationally unstable (Freyer, Hensler & Yorke, 2003; Heger et al., 1997; Garcia-Segura, Mac Low & Langer, 1996). However it is not clear that such instabilities would naturally lead to a steep density radial profile in the circumstellar medium. One possibility is that a steep density profile might be created by the onset of a "superwind" phase (Heger et al., 1997; Garcia-Segura, Mac Low & Langer, 1996).

The model normalization derived from fitting the X-ray spectrum is proportional to the emission measure and is defined to be $K = 10^{-14} \int n_e n_H dV/(4\pi D^2)$, where D is the angular diameter distance, n_e is the electron density, n_H is the proton density and where the integral extends over the emitting volume. To derive a lower limit on the density of the X-ray emitting material, I consider a uniform density medium filling a fraction, f, of a spherical volume of radius θD. The emission measure then implies a density

$$n_{\rm rms} \gtrsim 6.9 \times 10^3 f^{-1/2} \times \left(\frac{D}{9.6{\rm Mpc}}\right)^{-1/2} \left(\frac{\theta}{5.7{\rm mas}}\right)^{-3/2} {\rm cm}^{-3} \quad (1)$$

where $n_{\rm rms} \equiv (n_e n_H)^{1/2}$. In this expression I have used an angular size of $\theta = 6.1$ mas corresponding to free expansion since the most recent VLBI radius measurement (Pérez-Torres et al., 2002; Bietenholz, Bartel & Rupen, 2002). Because the VLBI data suggest that the ejecta have decelerated slightly (Pérez-Torres et al., 2002) the assumption of free expansion leads to a slight overestimate of the radius, consistent with obtaining a lower limit on the density. The corresponding mass of X-ray emitting material is $M_X \approx 16 f^{1/2}\ M_\odot$.

Recently published VLBI observations by Pérez-Torres et al. (2002) show that, at an age of 15.9 yr (Feb 1999), the average expansion velocity has slowed from $\sim$ 7400 km s^{-1} in 1988.74 down to about 6300 km s^{-1} in 1999.14. This slow decrease in the VLBI expansion rate suggests that the progenitor hydrogen envelope mass was $\gtrsim 12\ M_\odot$ (Pérez-Torres et al., 2002). Significant asymmetries in the radio brightness distribution and marked evolution in morphology indicate that the evolution is not self-similar.

If the X-ray emission arises from shocked clouds, one can infer the cloud density contrast required to match the post-shock plasma temperature. Both the VPSHOCK and VMEKAL models are consistent with an electron temperature of about 5 keV. If I assume the electron temperature and ion temperature are equal, the post-shock electron temperature

$$T_e = \frac{3}{16}\frac{\bar{m}}{k} v_{\rm sh}^2 \quad (2)$$

yields a shock velocity of about $v_{\rm sh} \approx 2000\ \mu^{-1/2}$ km s^{-1} where μ is the mean particle mass in atomic mass units. If the VLBI expansion rate corresponds to the velocity of the forward shock which in turn produces the X-ray emission by driving shocks into dense clouds, I can infer a cloud density contrast of order

$$\delta \approx \left(\frac{v_{\rm VLBI}}{v_{\rm sh}}\right)^2 \sim 10. \qquad (3)$$

With a cloud volume filling factor $f < 0.1$, the total mass of X-ray emitting material associated with the clouds is $M_X \lesssim 5\ M_\odot$.

The enhanced abundances of silicon and sulfur in the X-ray emitting material suggest that this material is enriched in nucleosynthesis products from the oxygen core of the progenitor star. This argues against the cloud crushing model of Chugai (1997) because it is unlikely that the wind material could be so enriched in silicon and sulfur. Although Wolf-Rayet stars and O stars are known to show surface enhancements in nitrogen, carbon and oxygen (Cox, 2000), I know of no examples of massive stars with strong surface enhancements in silicon and sulfur. Unless the progenitor star formed from material enhanced in silicon and sulfur, nucleosynthesis in the core of the progenitor is presumably the primary source for this enriched material. It is unclear whether or not a mechanism exists which could transport this material from the core of the progenitor to the wind *before* the supernova outburst occurs. However, because the oxygen burning stage in massive stars is extremely short-lived ($\lesssim 100$ yr; Arnett 1996), it seems unlikely that such a mechanism could effectively enrich the stellar wind out to a radius consistent with the current VLBI angular size (assuming that the X-ray emission arises from a region of comparable size).

Interpreting the X-ray emitting material as shocked ejecta, the abundances of oxygen, neon and magnitude pose a different problem. The presence of silicon and sulfur suggests that significant macroscopic mixing has taken place. The limits on the abundances of oxygen, neon and magnesium are somewhat surprising because Type II supernova progenitors with main sequence masses $\gtrsim 20\ M_\odot$ are expected to synthesize several solar masses of oxygen (Nomoto et al., 1997). Although the oxygen mass is the most sensitive indicator, the synthesized masses of neon and magnesium are also quite sensitive to the progenitor mass; core collapse models by Nomoto et al. (1997) show that the neon mass increases by a factor of 30 as the progenitor mass increases from 13 to 40 solar masses. The magnesium mass shows a similar dependence. An onion-skin nucleosynthesis model predicts that silicon and sulfur shells would lie interior to the oxygen-rich material (Arnett, 1996). It is surprising then, that the X-ray emitting material, which apparently consists of macroscopically mixed nucleosynthesis products, shows enhanced silicon and sulfur abundances but no obvious enrichment of oxygen, neon and magnesium.

The only other X-ray bright Type IIn SN with a reasonably good quality X-ray spectrum, SN1998S, also appears to have a low oxygen abundance in its X-ray spectrum. Pooley et al. (2002) analyzed *Chandra* observations of SN1998S and found that a single-temperature VMEKAL model fit to the sum of 4 *Chandra* observations yielded a best-fit oxygen abundance of about 0.7, with a 90% confidence upper limit of 2.9. They argued that the observed abundances favored a low-mass progenitor in the range 15–20 $M_\odot$. Unfortunately, the count statistics in their observations were insufficient to place tight constraints on most of the other elemental abundances.

Chugai (1997) has suggested that Type IIn supernovae like SN1986J might be produced by low mass progenitors with main-sequence masses $M \sim$ 8–10 $M_\odot$. Asymptotic giant branch (AGB) stars just below this mass interval are known to have superwinds which have the required mass-loss rates and are also pulsationally unstable (Heger et al., 1997), suggesting a mechanism for generating clumping in the stellar wind. Core evolution models by Nomoto (1984) suggest that such stars might explode through an unusual mechanism, via electron-capture driven collapse of an O-Ne-Mg core. During this collapse, most of the core would burn to nuclear statistical equilibrium. Because these low-mass progenitors do not form an oxygen mantle, the ejecta are expected to be poor in oxygen. The neon and magnesium abundances may be similarly affected. On the other hand, the low progenitor mass is somewhat inconsistent with the VLBI results which show that the dynamics imply a massive progenitor (Pérez-Torres et al., 2002).

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