Session 1: Plasma and Fresh Nucleosynthesis Phenomena

1-2. Supernovae, Supernova Remnants and Galactic Hot Plasma

X-RAYS FROM SUPERNOVA 1993J AND EJECTA INSTABILITIES

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Abstract.

Among the mechanisms of X-ray emissions from supernovae, we focus on the circumstellar interaction. In particular, we relate the new X-ray features of SN1993J to the hydrodynamical instabilities in the ejecta. First, we model the early-time two component spectral feature by invoking instabilities in the dense cooling shell in the ejecta. Second, we model the gradual increase in the X-ray light curve as X-rays emitted from the reverse shocked ejecta; here the model requires a large scale change in the density distribution due to Rayleigh-Taylor instabilities around the core-envelope interface.

1. Introduction

Supernova explosions are important sources of cosmic X-ray and gamma-ray emissions. They produce various heavy elements whose line X-ray emissions provide a unique tool to trace the chemical evolution of galaxies and the intra-cluster medium. Supernova explosions synthesize radioactive elements whose decays are significant sources of line gamma-rays and positrons. Some supernovae undergo circumstellar interactions which cause intense X-ray emissions.

More specifically, X-ray emissions from supernovae are expected from i) the shock breakout when the color temperature exceeds $\sim 10^6$ K, ii) Compton degradation of line γ-rays from the radioactive decays, iii) pulsar emissions, and iv) circumstellar interaction. Among these mechanisms, we focus on circumstellar interaction in SN 1993J.

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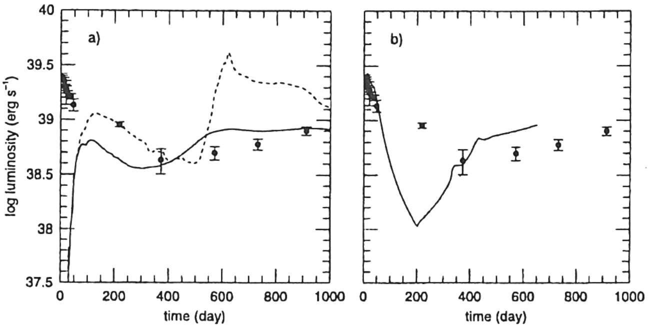

Figure 1. X-ray light curves for various models as compared with the observations of SN 1993J with ROSAT (Zimmermann *et al.* 1996). a) The dashed line shows the X-rays emitted from the reverse shocked ejecta, where the density structure is the same as original 3H11 (solid line in Fig. 2). The solid line shows the X-rays from the reverse shocked ejecta, where the density structure is modified as seen from the dashed line in Figure 2. b) The dotted line shows the X-rays emitted from the CSM which has a large clump in the outer region. The blast wave hits the clump around day 200 causing the X-ray enhancement.

Recent topics on SN 1987A are described in my contribution to the IAU/Joint Discussion 8 (speciall issue of New Astronomy 1998).

2. Early Spectra and Instabilities at the Cooling Shell

SN 1993J has been identified as a Type IIb supernova (SN IIb), whose spectral and light curve features can be well reproduced as the explosion of a red-supergiant whose hydrogen-rich envelope is as small as $\lesssim 1\ M_\odot$ (Nomoto *et al.* 1993; Podsiadlowski *et al.* 1993). The thin-envelope model implies that the progenitor of SN 1993J had lost most of its H-rich envelope and was surrounded with CSM. Then X-ray emissions from the interaction between the ejecta and circumstellar matter are expected, as actually has been observed with ROSAT (Zimmermann *et al.* 1994) and ASCA (Kohmura *et al.* 1994) as seen in Figure 2.

Following Suzuki & Nomoto (1995; see also Fransson *et al.* 1996), we have studied circumstellar interactions using a realistic ejecta model 3H11 (Nomoto *et al.* 1995; Iwamoto *et al.* 1997) and a CSM model with a parameterized density distribution of $\rho_{\rm CSM} = \rho_1(r/r_1)^{-s}$. Here $s = s_{\rm in}$ at $r < r_1 = 4.9 \times 10^{15}$ cm, while $s = s_{\rm out}$ at $r \geq r_1$. The solid line in Figure 2 shows the initial density structure of the ejecta 3H11, where the jump is the interface between the He core and the H-rich envelope.

The collision between the ejecta and circumstellar matter creates a reverse shock which is radiative to form a cooling dense shell in the ejecta. X-rays emitted from the reverse shock are mostly absorbed by this shell at early times (Fig. 2a). Instead, early hard X-rays up to ~ day 50 are well

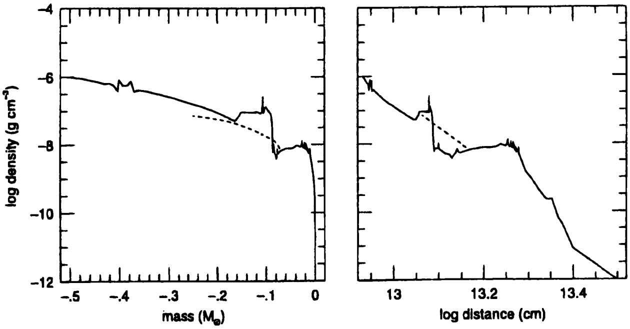

Figure 2. The density profile of the outer ejecta of 3H11 (solid). The dashed line is the profile adopted to account for the gradual increase in the X-ray observations.

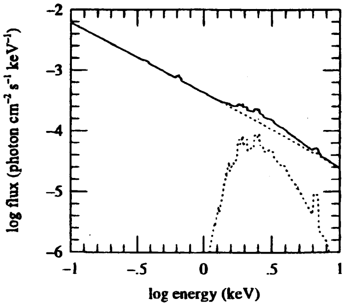

Figure 3. The calculated spectrum at day 20. The upper dashed line is the X-ray from the shocked circumstellar matter, and the lower one is the X-ray leaked through the cooling dense shell. The total emission is shown by the solid line.

modeled as thermal emissions from the shocked CSM (Fig. 2b).

Re-analysis of the ASCA observations has shown that the X-ray spectrum at day 20 consists of two components: (1) a high-temperature component with low absorption and (2) a low-temperature component with high absorption (Uno *et al.* 1997b). These two components are likely originate from (1) the forward shocked CSM and (2) the reverse shocked ejecta, respectively. However, the hydrodynamical model shows that the column-density of the cooling shell at day 20 is too high for X-rays from the reverse shocked layer to be observed.

We resolve this problem as follows: the cooling dense shell is Rayleigh-Taylor unstable, thus being clumpy. Its column density must be less than in the spherical model, so that X-rays from the ejecta can be leaked out through the cooling shell. We calculate the same hydrodynamical model but with the column density of the cooling shell reduced by a factor of 4, and obtain the spectrum in Figure 3. The upper dashed line is the X-rays from the shocked CSM and the lower one is the X-rays leaked through the cooling shell, which well reproduces the observed feature.

3. X-Ray Light Curve and Instabilities at the Core Edge

After day ~ 400, the ROSAT X-ray light curve shows a gradual increase (Figure 2; Zimmermann *et al.* 1996), as also reported by ASCA observations (Uno *et al.* 1997a). Here we explore several models for the light curve.

1. The dashed line in Figure 2a shows the X-rays emerged from the reverse shocked ejecta of original 3H11. The CSM has $s_{\rm in} = 1.7$ and $s_{\rm out} = 2.0$. The X-ray flare has been predicted to occur around day 500 when the reverse shock hits the density jump at the H/He interface.
2. The solid line in Figure 2 also shows the X-rays from the reverse shocked ejecta, where the density profile is modified as shown by the dashed line in Figure 2. The CSM has $s_{\rm in} = 1.7$ and $s_{\rm out} = 2.5$. The X-ray luminosity increases more gradually because the reverse shock arrives at the interface as early as day 300 - 400 and propagates against the power-law density profile rather than the jump.
3. The solid line in Figure 2b shows alternative possibility that a collision between the blast wave and a large clump in the CSM (around day 200) enhances the X-ray emission from the CSM.

To reproduce the gradual increase in the X-ray luminosity, we assume that the Rayleigh-Taylor instabilities have made the density distribution at the core-envelope shallower, from the sharp jump to the power-law (r^{-10}) as shown by the dashed line in Figure 2. The instabilities in the H-rich envelope should be more extensive than our original model 3H11. An asymmetric structure due to the spiral-in of the companion star into the envelope (Nomoto *et al.* 1995) would cause more extensive mixing.

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