X-ray and radio bright type Ic SN 2002ap – a hypernova without an associated GRB

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Abstract. Combined X-ray (0.3 -10 keV) and Radio (0.61 and 1.42 GHz) observations of the type Ic SN 2002ap are used here, to determine the origins of the prompt X-ray and Radio emission from this source. Our analysis of the XMM-Newton observations suggests that the prompt X-ray emission originates from inverse Compton scattering of photospheric thermal emission by energetic electrons. In addition, we use the reported multifrequency VLA observations of this supernova. We compare the early radiospheric properties of SN 2002ap with those of SN 1998bw (type Ic) and SN 1993J (type IIb), to contrast the prompt emission from a GRB associated SN and other supernovae without such counterparts.

1 Introduction

The nature and origins of X-ray and radio emission from supernovae is a subject of much interest. This is mainly because early (few days to years) emission in these bands occurs from a shocked, dense CSM around the progenitor, and this can be used to infer the mass loss rate and the nature of the progenitor. Further, early synchrotron radio emission can also occur from relativistic electrons in amplified magnetic fields within the ejecta itself and its detection constrains theoretical models on emission and reabsorption mechanisms in shocked matter.

SN 2002ap is an energetic ($E_{\text{explosion}} \sim 4 - 10 \times 10^{51}$ ergs [8]), one of the closest (in M 74, distance $d = 7.3$ Mpc [12]), type Ic SN which exploded on Jan. 28±0.5, 2002 [8]. It was also one of the earliest detections in multiple bands, as in SN 1987A and SN 1993J. Interest in highly energetic ("hypernova") type Ib/Ic SNe has been intense after the temporal and positional near-coincidence of GRB 980425 with the type Ic SN 1998bw implied a possible GRB-SNe connection for the long duration GRBs.

We report our findings from the combined, near-simultaneous observations of SN 2002ap with XMM-Newton, GMRT [14] and VLA [1]. For a detailed analysis of the X-ray data and early 610 and 1420 MHz observations of SN 2002ap with GMRT (Giant Meterwave Radio Telescope), we refer the reader to [14].

2 XMM-Newton and GMRT Observations and Analysis

SN 2002ap was detected by XMM-Newton EPIC CCDs between 5.025 to 5.42 days after explosion [10] (See also [13], [14]), with an effective exposure time
of ∼ 25.5 ks. After subtracting the contribution from the nearby "contaminating" X-ray source CXU J013623.4+154459 in the 50′′ spectral extraction region on the EPIC-PN CCD, we estimate the 0.3-10 keV flux from SN 2002ap as 1.07^{+0.63}_{-0.31} \times 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1}. Because the source is very faint, both thermal bremsstrahlung model \((N_H = 0.49 \times 10^{22} \text{ cm}^{-2}, kT = 0.8 \text{ eV})\) and a simple powerlaw \((N_H = 0.42 \times 10^{22} \text{ cm}^{-2}, \text{ spectral index } \alpha = 2.5)\) fit the sparse spectra well, with \(\chi^2/d.o.f. = 1.2/20.\) Simultaneous XMM-Newton Optical Monitor (OM) observations of M74 in the UVW1 band yield a flux of 7.667(±0.002) \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \, \mu \text{A}^{-1}.

SN 2002ap was observed with the Giant Meterwave Radio Telescope (GMRT) at 0.61 GHz 8.56 days after explosion, and at 1.42 GHz 42 days after explosion. The exposure time for each observation was 4 hours. We did not detect the SNe in either observation and the upper limits on the flux have been tabulated in table 1.

3 Results and Discussion

The earliest radio detection of SN 2002ap was ∼ 4.5 days after the explosion, in the 8.46 MHz band, and the frequency of the peak radio flux declined gradually from 8.46 GHz to 1.43 GHz over a period of 10 days from the explosion epoch (VLA observation, [1]) – a clear indication of the presence of relativistic e−. This wavelength dependence of the radio turn-on can be due to either free-free absorption (FFA) in the thermally excited, homologously expanding matter overlying the interaction region, or synchrotron self-absorption (SSA) by the relativistic e− responsible for radio emission, accelerated in regions close to the expanding interaction region [3]. In the case of SN 2002ap, the combined GMRT upper limits [14] and VLA observations [1] are best fit by the SSA model (fig. [3]) in the optically thin, spherically symmetric limit, consistent with the early optical observations. The corresponding values of spectral index \(\alpha\), magnetic field \(B\), and the radius of the radiosphere \(R_r\) are tabulated in Tab. 2.

| Date of Obs. | \(\nu\) (GHz) | Resolution (arcsec) | 2\(\sigma\) RMS of Flux (mJy) | \(\sigma\) RMS (mJy/beam) |
|-------------|-------------|-------------------|------------------|------------------|
| 5 Feb’02   | 610         | 9.5 x 6           | < 0.34           | 0.17             |
| 8 Apr’02   | 1420        | 8 x 3             | < 0.18           | 0.09             |

| \(\alpha\) | \(\nu_p\) GHz | \(F_p\) \(\mu\) Jy | \(R_r\) cm. | \(B\) G |
|------------|-------------|----------------|--------|-----|
| 0.8        | 2.45        | 397            | 3.5 \times 10^{15} | 0.29 |

The early Radio and X-ray turn-ons imply that the mass-loss rate of the progenitor was relatively low, at \(\dot{M} \leq 6 \times 10^{-5} \, M_\odot \, \text{yr}^{-1}\) ([14], using VLA detection by [1]), and the SSA models for X-ray absorption by [2]).
3.1 Origins of X-ray emission

Using the optical observations of SN 2002ap on the same epoch as the XMM-Newton observation, we find that the radius of the optical photosphere $R_{\text{opt.}} = 3.4 \times 10^{14}$ cm. We note that the radiosphere in the SN (table 2) was well outside this optical photosphere at a similar epoch. However, Compton optical depth considerations suggest that X-ray production region is closer to the optical photosphere.

Free-free emission mechanisms are likely to be dominated by Compton cooling. The high ejecta velocity ($v \geq 20, 500$ km s$^{-1}$ on day 3.5), coupled with high implied temperature of the shocked circumstellar medium ($T \sim 10^9$ K) and a limited cool absorbing shell suggests that the high energy photons would have a flat tail, up to 100 keV. By contrast, the X-ray spectra is quite soft, with thermal bremsstrahlung $T_B = 0.8$ keV. Hence, free-free absorption is unlikely to explain the observed X-ray spectra. However, Compton cooling is the dominant radiative mechanism when the optical photospheric temperature is $T_{\text{eff}} \geq 10^4$ K.

Using the Monte Carlo simulations of Compton scattered spectra for the shocked CSM, we find that the observed flux by XMM can be accounted for both in terms of energetics and spectrum if the electron plasma has $T_e \sim$ few times of $10^9$ K (See [14]). Table 3 gives the properties of Comptonised plasma for two likely progenitor systems ([7], [5]) for this event.

| Scenario | $M_{-5}$ | $u_{w1}$ | $\tau_e$ | $T_e$ | $\theta_{eq}$ | $U_{eq}$ | $B_0$ | $R_0$ |
|----------|----------|----------|----------|-------|-------------|---------|-------|-------|
| Woff-     | 1.5      | 58       | 4        | 2     | 2           | 2.45    | 0.48  | 39.0  |
| Rayet     | 10       | 58       | 25       | 1.5   | 10          | 5.5     | 50.4  | 112.4 |

Finally, we compare the rarely observed early radio spectra of SN 2002ap with that of SN 1993J (type IIb) and SN 1998bw (type Ic, GRB-association), 11 days after explosion. In Fig. 3 we fitted the SSA model to the data, and in table 4, we estimate the energy $U_{eq}$ in the radiating plasma and the magnetic field $B_0$, from equipartition arguments, and determine corresponding the angular radius $\theta_{eq}$ of the radio-sphere. Comparing $\theta_{eq}$ for the 3 SNe, the hydrodynamic shock in SN 1998bw, causes more rapid expansion leading to larger radio-sphere, while SN 2002ap is similar to SN 1993J across type classification, irrespective of presence or absence of H- and He-envelope in the progenitor.

We thank the XMM-Newton helpdesk and the staff of GMRT, especially S. Bhatnagar, for many useful communications during data processing.
Fig. 1. Best fit synchrotron self-absorption spectrum (solid line) for SN 2002ap radio emission on day 8.96 with energy spectral index = -0.8. Also shown is the free-free absorption model (dashed line) with parameters used taken from [1]. The VLA data is marked with a “×”, while the GMRT upper limit at 610 MHz is marked by a “○”.

Fig. 2. Comparison of spectra of three SNe (SN 1993J [3], SN 1998bw [6] and SN 2002ap [1]) near day 11 after explosion. Solid lines show the best fit synchrotron self absorption model and dashed lines show the corresponding free free absorption model.

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