The X-ray lightcurve of SN 1987A

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Received; accepted

Abstract. X-ray observations of SN 1987A in the Magellanic Clouds have been performed throughout the ROSAT mission, using the PSPC and the HRI detectors. We present the X-ray light curve based on all observations in the years 1991–1995. For the first time a significant increase of the X-ray flux from SN 1987A can be seen, corresponding to X–ray luminosities (0.5-2 keV) of 0.8–2.2 × 10\(^{34}\) erg/s about 4 – 8 years after the explosion. SN 1987A is surrounded by a ringlike nebula, which is thought to form the interface between the blue–supergiant wind and the denser red–supergiant wind of the progenitor. The X-ray data can constrain the density of the matter inside the ring to about 30\(^{\text{amu cm}^{-3}}\) and the date at which the blast wave will reach the ring to about AD 2003, when a dramatic brightening is expected to occur. Nevertheless, other interpretations of the X-ray emission are possible.

Key words: supernovae: individual (SN 1987A) – X-rays: stars – supernova remnants

1. Introduction

The explosion of SN 1987A (Shelton 1987) was one of the exciting historical astronomical events. The neutrino flux detected at the time of the explosion (Koshiba et al. 1987), and the observations of X- and soft γ-rays (Sunyaev et al. 1987, Dotani et al. 1987) constitute some of the “first observations” of such phenomena from supernovae confirming the general correctness of our theoretical understanding. In addition SN 1987A is classified as type II, therefore a neutron star is expected at the center of this remnant.

Hard X-rays have been detected from SN 1987A with the Kvant module on the Russian MIR station and with the Japanese Ginga satellite (Sunyaev et al. 1987; Dotani et al. 1987). The high-energy X-rays originate from the decay of \(^{56}\)Co, where the γ-ray lines undergo multiple Compton scatterings and are degraded into X-rays which, however, are absorbed through the tenuous cocoon of the stellar ejecta which is thick enough to block out soft X-rays from the compact object for quite a long time.

The “soft” X-ray component originally observed with Ginga below \(\sim\) 10 keV could not be confirmed by MIR-TTM and MPE rocket observations (Aschenbach et al. 1987), nor by the ROSAT first-light observations (Trümper et al., 1991). Since 1991, however, the supernova is detected as a faint soft X-ray source (Beuermann et al., 1994; Gorenstein et al., 1994). In this Letter we present data from continuous monitoring of SN 1987A with ROSAT.

Table 1. Observation Summary

| Date          | Day\(^1\) | Instr. | Time [s] | Count Rate\(^2\) [10\(^{-3}\) c/s] |
|---------------|-----------|--------|----------|-------------------------------|
| 16.06.90-28.06.90 | 1215      | PSPC   | 6400     | < 2.7\(^3\)                   |
| 11.02.91-13.02.91 | 1448      | HRI    | 23465    | 0.8 ± 1.0                     |
| 21.04.91-07.10.91 | 1645      | PSPC   | 24908    | 1.8 ± 0.5                     |
| 03.02.92-14.05.92 | 1872      | PSPC   | 27288    | 2.2 ± 0.5                     |
| 04.12.92-05.07.93 | 2258      | PSPC   | 23404    | 3.2 ± 0.6                     |
| 28.09.93-30.09.93 | 2408      | PSPC   | 9426     | 3.8 ± 0.8                     |
| 23.12.93-04.10.94 | 2715      | HRI    | 21182    | 3.9 ± 1.3                     |
| 01.01.95-11.10.95 | 3013      | HRI    | 62420    | 4.8 ± 0.7                     |

\(^1\) mean day after explosion
\(^2\) PSPC channel 52–201, HRI channel 2–8 multiplied with 2.65
\(^3\) from Trümper et al., 1991

2. Observations and Results

SN 1987A was the target of the ROSAT first light observation, and was scanned during the ROSAT All-Sky Survey. In both cases only upper limits could be derived (Trümper et al., 1991). Since then SN 1987A has been monitored regularly with both the PSPC and the HRI detectors aboard ROSAT. Table 1 gives an overview of the observations.

For the purpose of this paper all ROSAT data of SN 1987A obtained since the beginning of 1991 have...
been analysed using the MPE interactive analysis system EXSAS (Zimmermann et al., 1994). For the PSPC data all good time intervals selected by the ROSAT standard analysis (SASS; Voges et al. 1992) have been analysed, yielding a net observing time of 85026 seconds. HRI events have been selected using a custom made procedure after having joined the SASS accepted and rejected event files. This resulted in a net observing time of 107066 seconds, a gain of \( \sim 5\% \) compared to the SASS products. Figure 1 shows the X-ray images centered on SN 1987A. The PSPC image has been accumulated in the energy range \( \sim 0.5-2 \) keV (pulse height channels 52-201). The HRI image was restricted to the pulse height interval 2–8, accepting a minimal loss (\( \sim 6\% \)) of X-rays but at the same time significantly reducing the intrinsic and particle-induced HRI background (see David et al., 1995). The supernova shows up as a weak point source embedded in a rather complex region of diffuse X-ray emission. The average HRI position \( R.A.(2000) = 5^h35^m28.5^s, DEC(2000) = -69^\circ16^\prime11.5^\prime\) is within 2 arcsec from the catalogued position; no evidence is seen of a possible second, nearby X-ray source suggested by Gorenstein et al. (1994).

Table 2. Spectral Analysis

| Model          | \( \chi^2_{red} \) | dof | \( \Gamma/kT \) | Flux / EM |
|----------------|-------------------|-----|---------------|-----------|
| power law      | 0.65              | 5   | 3.3 ± 0.4     | 5.38 ± 0.81 |
| thermal brems  | 0.96              | 5   | 0.44 ± 0.11   | 5.36 ± 0.84 |
| blackbody      | 1.74              | 5   | 0.17 ± 0.02   | 7.88 ± 2.0  |
| RS (z=1)       | 3.61              | 5   | 1.00 ± 0.16   | (5.0 ± 1.5) \( \cdot \) 10^{56} |
| RS (z=0.3)     | 3.00              | 5   | 0.99 ± 0.17   | (1.4 ± 0.4) \( \cdot \) 10^{57} |
| RS (z=3)       | 3.87              | 5   | 1.00 ± 0.17   | (1.8 ± 0.6) \( \cdot \) 10^{56} |
| 2T-RS (z=1)    | 1.22              | 3   | 0.14          | 1.8 \( \cdot \) 10^{57} |
|                |                   |     | 1.28          | 6.5 \( \cdot \) 10^{56} |

1 \( N_H \) fixed to \( 1.1 \cdot 10^{21} \) cm\(^{-2}\)

2 Flux in \( 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\) (PL, TB and BB)

3 Emission measure in cm\(^{-3}\) (RS models)

Fig. 2. PSPC pulse height spectrum of SN 1987A. The solid line shows the model for a 0.44 keV thermal bremsstrahlung spectrum and a neutral hydrogen column density fixed to \( 1.1 \cdot 10^{21} \) cm\(^{-2}\).

For the spectral analysis care has been taken of the complex diffuse emission in the vicinity of the supernova. PSPC source photons were accumulated in a circle around SN 1987A with radius 36", while background photons were taken from an annulus with inner radius 36" and outer radius 82". The pulse height distribution in the range 11-250
channels has been binned to a signal to noise ratio of 4, yielding 318 net counts. Various spectral models have been fit to the data, assuming a fixed line-of-sight absorption column density of $N_H = 10^{21} \text{ cm}^{-2}$ (Gorenstein et al., 1994). The PSPC response matrix is known to change as a function of time (Prieto et al., 1996), a fact which is taken care of by EXSAS using different instrument matrices for the beginning and the end of the PSPC lifetime. Since the PSPC data covers a long period of time (1991 Apr - 1993 Sep) the fits were performed with both response matrices in order to test for systematic errors, however no significant differences were found. Table 2 gives an overview of the spectral fits. Continuum spectra like a simple power law with photon index $\Gamma = 3.3$ or thermal bremsstrahlung with $kT = 0.44 \text{ keV}$ fit the data well. Figure 2 shows the PSPC pulse height spectrum with the corresponding thermal bremsstrahlung model. The average 0.5-2 keV luminosity derived for the power law or bremsstrahlung fit is $(1.6 \pm 0.2) \cdot 10^{34} \text{ erg s}^{-1}$, assuming a distance of 51 kpc to the LMC. A single-temperature Raymond-Smith thermal plasma model (RS), which is dominated by few emission lines, is rejected at a probability greater than 99%, even if the abundance is varied. This may indicate a more complicated ionization or temperature distribution. A two-temperature Raymond-Smith model is given for completeness, however, the errors are too large to draw firm conclusions.

In order to obtain a light curve of SN 1987A, separate images were produced for all time intervals in table 1. Source counts were extracted from a ring around the supernova with radius 24" for the HRI and 40" for the PSPC, respectively, containing roughly 90% of the HRI photons (Hasinger et al., 1992), respectively. Background counts were extracted from an annulus around the source ring, having an outer radius of 82". Net source count rates were corrected for deadtime and the point-spread-function losses. In order to compare the HRI and PSPC count rates we computed the ratio of the count-to-flux conversion factors for both instruments, taking into account the selected pulse height channel range (channel 52-201 for the PSPC and channel 2-8 for the HRI). Assuming the first three spectral models in table 2, the predicted count rate ratio factor varies between 2.46 and 2.89. We therefore assumed a PSPC/HRI conversion factor of 2.65. The final equivalent PSPC count rates are given in table 1. These count rates can be converted to 0.5-2 keV fluxes assuming a factor of $6.95 \cdot 10^{10}$ PSPC counts per erg cm$^{-2}$ s$^{-1}$. Figure 3 shows the X-ray light curve of SN 1987A, clearly indicating a continuous flux increase during the interval 1500-3000 days after the explosion. We fitted the count rates with a power law model as a function of time and derive an exponent of $1.67 \pm 0.35$ (1$\sigma$). A linear increase starting on day $\sim 900$ can fit the data as well.

### 3. Discussion

Using the FOC aboard the Hubble Space Telescope a faint circumstellar nebula has been observed around SN 1987A which has the shape of a thin ring with a radius of 0.2 pc and a thickness of only 0.02 pc (Jakobsen et al. 1991). The authors estimate a density of $n_e \sim 2 \cdot 10^4 \text{ cm}^{-3}$ and a total mass of $M \sim 0.2M_\odot$ for the ring, which is thought to originate from a shock front in the progenitor wind at the interface between a slow, tenuous red supergiant wind (RSW) and a fast asymmetrical low-density blue supergiant wind (BSW). In the meantime high quality images of the Hubble Space Telescope show two fainter rings above and below the original ring nebula which probably mark the hour-glass shaped transition region between the BSG and the RSG winds, where a substantial density enhancement is expected to occur. The ring nebula is also observed to expand very slowly, presumably somewhat faster than the RSG wind speed (Plait et al., 1995).

Several investigators have discussed the X-ray emission of supernovae, in particular that of SN 1987, in terms of thermal radiation of a reverse shock wave originating from the interaction between the supernova ejecta and the previously existing circumstellar material (e.g. Chevalier 1982). The supernova blast wave is expected to interact with the wind, first with the BSG and later with the RSG wind, causing a shock wave to heat up the circumstellar material to X-ray temperatures.
The X-ray luminosity of the shock wave and its temporal behaviour depend on the density and gradient of the ambient medium. In the case of a freely expanding BSG wind with a density $\rho \sim r^{-2}$ a decline of the X-ray luminosity as a function of time according to $L_X \sim t^{-0.87}$ is expected (Beuermann et al., 1994; Gorenstein et al., 1994). Beuermann et al. have already remarked that the measured X-ray luminosity is too high for the simple free wind model. Our current X-ray light curve is clearly inconsistent with the free wind model.

However, there are reasons to believe that a simple $r^{-2}$ density dependence is not the correct description for the BSG wind of SN 1987A. As the existence of the ring nebula and the terminating discontinuity prove, the BSG wind must catch up and interact with the RSG wind and is therefore no longer freely expanding. Several authors recently assumed the BSG wind matter to be homogeneously distributed within the radius of the ring nebula (Suzuki et al., 1993; Masai and Nomoto; 1994; Luo et al., 1994). In this case a steadily increasing X-ray luminosity is predicted in the BSG wind interaction phase, with a time dependence proportional to $t^{2.04}$, which is consistent with our findings (see fig. 3). Chevalier & Dwarkadas (1995) propose that the supernova shock is now interacting with an $H_{II}$ region created by the BSG star in the swept-up RSG wind. They predict a slow rise of the X-ray flux, which, however should start only around day $\sim 1000$. Our supernova X-ray light curve is consistent with this model, too.

Masai & Nomoto (1994) present detailed hydrodynamical calculations and predict a dramatic increase in X-ray luminosity around the time when the stellar ejecta hit the dense ring nebula. Because the SN B wind is slowed down by the shock interaction, the impact time depends on the density of the ambient medium according to $t_{\text{ring}} \sim \rho^{1/6}$. Different authors assume substantially different values for this density, ranging from $\rho \approx 2 \text{ amu cm}^{-3}$ (Luo et al., 1994; Masai & Nomoto, 1994) to $\rho \approx 100 \text{ amu cm}^{-3}$ in the equatorial plane (Chevalier & Dwarkadas, 1995). Correspondingly, the range of predicted impact dates is still considerable (roughly 1996 – 2008). The new ROSAT determination of the X-ray lightcurve of SN 1987A now allows to put further constraints on the density in the circumstellar material. The total X-ray flux measured on day 3000 (see fig. 3 and tab. 1) corresponds to a 0.5-2 keV luminosity of $L_{X(0.5-2)} = 2.0 \times 10^{34} \text{ erg s}^{-1}$. Depending on the assumed spectral model, the energy band correction factor is quite uncertain. Assuming a correction factor of 3 for a thermal bremsstrahlung spectrum we estimate a total X-ray luminosity of $L_X = 6 \times 10^{34} \text{ erg s}^{-1}$. If we interpret this as coming from the SN B wind in the context of the Masai & Nomoto (1994) model, we can estimate the density of the BSG wind to $\rho_{\text{BSW}} \approx 30 \text{ amu cm}^{-3}$ from their equation (7). Correspondingly, the impact time of the SN B wind at the location of the ring nebula would be $t_{\text{ring}} \approx 15.7 \text{ yr}$ after the explosion, i.e. in the year AD 2003. We have to caution, however, that we find significantly lower temperatures than predicted by Masai & Nomoto. A factor of $\sim 3$ higher density and, correspondingly, a later impact time has been proposed by Chevalier and Dwarkadas (1995). In view of the rather complicated situation these predictions are still quite uncertain.

There could be other contributions to the observed X-ray emission of SN 1987A, in particular radiation from the surface or the magnetosphere of a putative neutron star. Actually, the currently observed X-ray luminosity and temperature are comparable to the values expected from the thermal surface radiation of a young neutron star. However, the circumstellar cocoon of matter is expected to block out all but the highest energy X-rays of the neutron star for a long time. Under relatively optimistic assumptions, Kumagai et al. (1993) predict a possible pulsar to be seen after $\sim 8 \text{ yr}$ only at energies above 6 keV. Nevertheless, relatively little is known about the clumpiness of the absorber and thus the observed increase of X-ray flux could still be associated to radiation from a compact object. The long-term X-ray lightcurve of SN 1987A can likely discriminate between the different possibilities. Continuing X-ray observations of SN 1987A are therefore highly desirable, in particular since at any rate a major brightening is expected in the coming years.

Acknowledgements. We would like to thank K. Beuermann, R. McCray, K. Masai, K. Nomoto and H. Ogelman for important communications. We thank an anonymous referee for helpful comments. The ROSAT project is supported by the Bundesministerium für Bildung, Wissenschaft und Forschung (BMBF) and by the Deutsche Agentur für Luft und Raumfahrt (DARA).

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