Publ. Astron. Soc. Japan **43**, 213–223 (1991)

X-Ray Observation of SN 1987A from Ginga

Hajime INOUE, Kiyoshi HAYASHIDA,* Masayuki ITOH, Hideji KONDO,
Kazuhisa MITSUDA, Toshiaki TAKESHIMA, Kenji YOSHIDA, and Yasuo TANAKA

Institute of Space and Astronautical Science,
1-1, Yoshinodai 3-chome, Sagamihara-shi, Kanagawa 229

(Received 1990 June 20; accepted 1991 January 22)

Abstract

An X-ray light curve of SN 1987A was obtained from Ginga over a 1000-day period since its outburst. X-rays from the SN appear to comprise two separate components: a hard and a soft component. Hard X-rays were first detected in July 1987, reached a maximum near the end of 1987, and declined steadily through January 1989. Later, the hard component has been close to or below the detection limit. A remarkable soft X-ray flare conclusively from SN 1987A occurred in January 1988. In addition, soft X-rays were occasionally observed significantly in the region of SN 1987A.

Key words: SN 1987A; Supernova; X-rays.

1. Introduction

SN 1987A, a Type-II supernova in the Large Magellanic Cloud, occurred on February 23, 1987, and has been observed from the X-ray astronomy satellite Ginga since its outburst. X-rays from the supernova (hereafter abbreviated SN) were first detected in July 1987 from Ginga. The first result was published by Dotani et al. (1987), hereafter referred to as Paper I. It was shown in Paper I that X-rays from the SN appeared to comprise two separate components: a hard component which was essentially flat in the range 10–40 keV, and a soft component which rose towards low energies. The observed hard X-ray spectrum is consistent with that expected for down-Comptonized gamma-rays of ^{56}Co origin. The observed intensity of the hard component was in general agreement with the result from an independent observation from the Mir-Kvant by Sunyaev et al. (1987), which measured the spectrum up to about 1 MeV. However, the Kvant observation did not confirm the soft component observed from Ginga.

In the present paper we report on the history of the X-ray intensity of the SN obtained from the Ginga observations over a period of more than 1000 days after

*Present address: Department of Physics, Faculty of Science, Osaka University, 1-1, Machikaneyama-cho, Toyonaka, Osaka 560.

the outburst. The results concerning the X-ray energy spectrum will be reported separately.

2. Observations and Data Analysis

Observations of the SN have been conducted regularly once every two to three weeks. Only recently, since about 900 days after the outburst, the frequency of observation has been reduced to once every month. After the error box was determined, we employed only the pointing mode, since this mode gives much better statistics than does the scanning mode (see Paper I).

In determining the X-ray intensity of the SN, there are three different sources of systematic errors in addition to the statistical errors. These are: (1) the cosmic-ray induced background in the counters, (2) the aspect (pointing direction), and (3) contributions from neighbouring sources in the observing field of view. The last item is discussed in detail in the next section. The results published in Paper I were also re-examined regarding these systematic errors.

A background measurement was performed immediately before or after each SN observation. However, this background count rate could inevitably be different, if slight, from that during the SN observation. Instead of a separate background observation, the background count rate during each SN observation can be reproduced empirically by a method developed by Hayashida et al. (1989), established from an extensive data base of the background. This method also provides an estimate of the systematic error in the background estimation, which corresponds to about 1% of the background count rate. This systematic error is substantially larger than the statistical error, and is incorporated in the present error estimation. The error in the aspect (pointing direction) determination influences not only the derived intensity of the SN, but also corrections for the nearby source contaminations. The error in the pointing direction estimated from a comaprison of gyro data with intermittent star tracker data is found to be at most 1.5 arcmin. Although this error is not quite statistical in nature, we include the effect corresponding to an offset of ± 1.5 arcmin in the error estimation.

3. Corrections for Nearby Sources

The region of the SN is populated with many X-ray sources, as is shown in figure 1. This figure includes sources from the Einstein LMC survey by Long et al. (1981). Among these sources, LMC X-1 and four supernova remnants SNR 0540−69, N132D, N157B and SNR 0519−69 [source No. 26 from the Einstein survey (Long et al. 1981)] are relatively intense, and their contributions are taken into account for a correction. The other sources in the field of view are much fainter and have been estimated to be negligible.

LMC X-1 is, by far, the brightest among them, and is also time variable. We therefore point the Ginga field of view so as to keep LMC X-1 practically outside. In this way, the exposure to LMC X-1 has always been less than 2%, with only one exception for the observation of 1987 July 4, in which the exposure was about 9%. Since the intensity of LMC X-1 at the time of each observation is unknown,

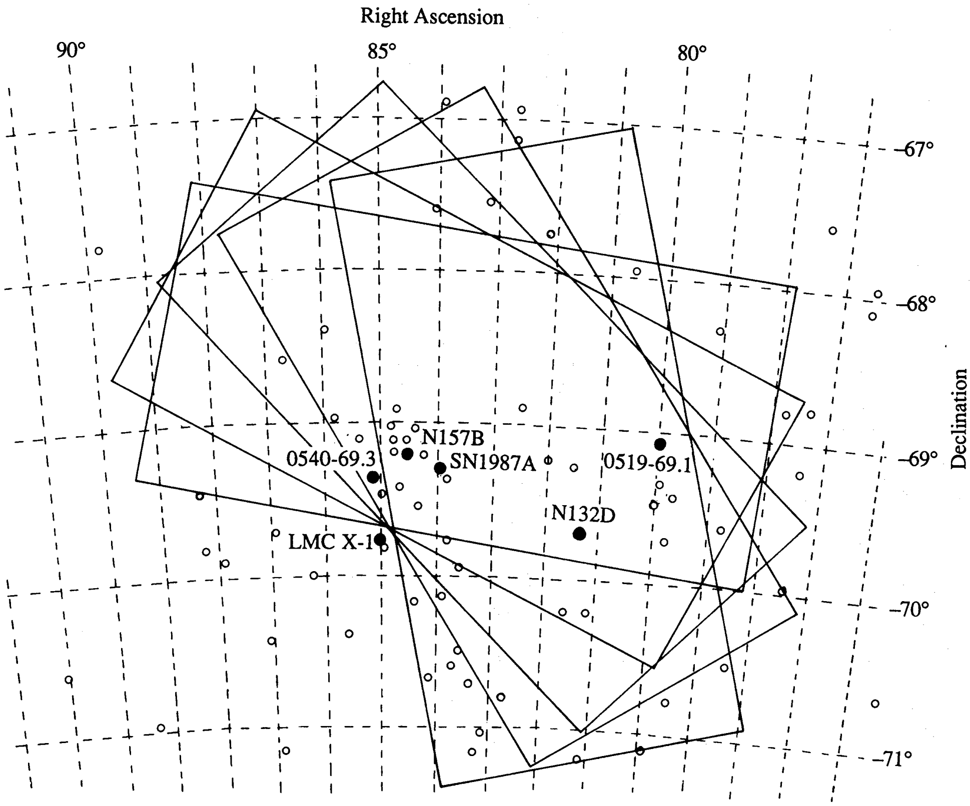

Fig. 1. Sky region of the Large Magellanic Cloud including SN 1987A. X-ray sources detected from the Einstein survey (Long et al. 1981) are indicated, and various orientations of the Ginga field of view employed for the SN observations are also illustrated.

we include an error sufficiently large to cover the maximum range of variation, based on the results from frequent Ginga observations of LMC X-1. The contamination by LMC X-1 through reflection on the collimator walls is absolutely negligible in the range above 6 keV. As a result, the contribution of LMC X-1 is much smaller than that of SNR 0540−69.3, as described below.

Contributions of the supernova remnants (SNR 0540−69.3, N132D, N157B, and SNR 0519−69) were individually estimated for every SN observation. The spectrum of each of these SNRs was measured from separate Ginga observations with various pointings, putting the SN outside of the field of view. However, because these sources are all weak for the Ginga sensitivity, the statistical uncertainties, particularly at high energies, remain fairly large. We therefore determined the acceptable range of intensity for each source, using two different model spectra: a power-law model and a thin thermal model. The power-law model naturally gives higher flux estimates at high energies than does the thin thermal model.

Among these sources, SNR 0540−69.3 requires the largest correction, because this source, located only half a degree away from the SN, is the strongest in the energy range concerned, and is known to possess a hard spectrum (Clark et al. 1982).

This SNR includes a 50-millisec pulsar inside. According to Seward et al. (1984), this SNR is similar to the Crab Nebula in several respects. Its pulsar component is measured during every SN observation from Ginga; thus, an accurate intensity has been obtained. The power-law index determined over the range 1–24 keV was 1.77±0.09, thus in agreement with that obtained in the Einstein energy range, 0.5–4 keV (Seward et al. 1984). In the overlapping energy range, the measured fluxes from Ginga and the Einstein Observatory also agree with each other within statistical errors. The pulsed fraction in the range 1.7–4 keV is 27±4% according to Seward et al. (1984). For obtaining a high estimation of the total flux from SNR 0540−69.3, we assume that the pulsed fraction is constant over the entire energy range of Ginga. However, the pulesd fraction may increase with energy, as in the case of the Crab Nebula. For a low estimation, we assume a thin thermal spectrum with kT=10 keV for the remnant. In this case, the flux in the range 16–28 keV is essentially due to the pulsed component alone.

N157B is an SNR whose spectrum is hard, similar to that of SNR 0540−69.3; its intensity is about a quarter of SNR 0540−69 in the Einstein energy range (Clark et al. 1982). For N157B, we assume the same spectral shape as that of SNR 0540−69 with one quarter in intensity over the entire energy range of Ginga.

N132D is a bright, oxygen-rich SNR similar to Cas A. According to the result of the Einstein observation by Clark et al. (1982), the energy spectrum comprises a soft ($kT = 0.57$ keV)component dominating the low-energy range, and a hard ($kT = 4.0$ keV) component. However, an extrapolation of their best-fit model results in a much smaller flux than that actually measured from Ginga, although the Ginga field of view includes another weaker source, SNR 0519−69. Since the Einstein spectrum of N132D (Clark et al. 1982) is very steep, a straightforward extrapolation of this spectrum from the Einstein range to the Ginga range is subject to large ambiguity. We estimated the intensities of these two SNRs from our own Ginga observations by assuming the same spectral shape for both SNRs and employing an intensity ratio of eight to one obtained from the Einstein observation (Long et al. 1981). A high estimation is obtained from the best-fit power law of an index of 2.2; a low estimation is given by an acceptable thin thermal spectrum with $kT = 10$ keV.

The thus-obtained high and low estimates of the source intensities are tabulated in table 1. The relative contributions from these sources to the observed counts quickly diminish towards higher energies. The diffuse background intensity above 6 keV in the SN region was determined for the field directly north of the SN, which excluded all of the major sources listed above.

4. X-Ray Light Curves of the SN

The X-ray light curves are presented in two energy bands: a soft X-ray band at 6–16 keV and a hard X-ray band at 16–28 keV. These two energy bands are so chosen that the separation of the hard and soft components is optimum, since the observed energy spectrum indicates that the hard X-ray component is cut off below about 20 keV.

The light curves of the SN so far obtained are shown in figure 2a for the 6–16 keV band and in figure 2b for the 16–28 keV band. Two different flux values (open circles

Table 1. Estimated fluxes of the nearby sources.

Source Name	6–16 keV (counts/s)		16–28 keV (counts/s)	
	High Estimate	Low Estimate	High Estimate	Low Estimate
LMC X-1	20.30 ± 12.2		0.65 ± 0.48	
N132D	1.27	0.54	0.06	0.005
SNR 0540−63	5.40	4.30	0.45	0.10
SNR 0519−69	0.16	0.07	0.008	0.00
N157B	1.24	0.99	0.10	0.00
Diffuse Bkgd.	0.16		0.02	

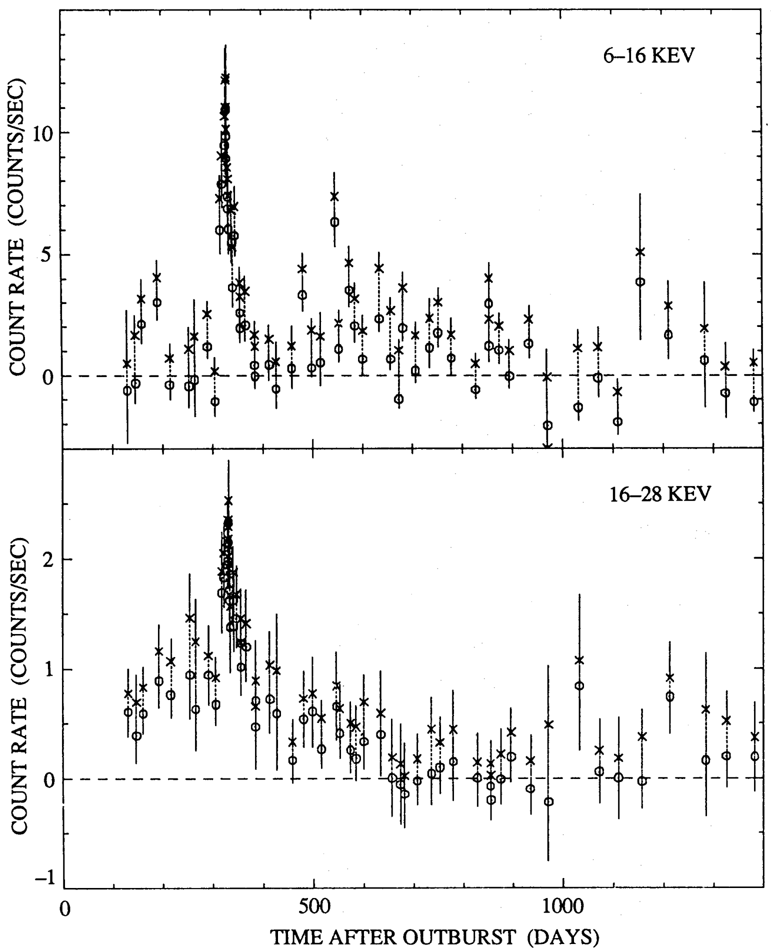

Fig. 2. X-ray light curves of SN 1987A in two energy ranges: (a) the soft X-ray band in 6–16 keV, and (b) the hard X-ray band in 16–28 keV. Open circles and crosses correspond to the cases in which the high estimates and the low estimates of the nearby source intensities are employed for the corrections, respectively. The error bars drawn on only one side include all systematic errors.

and crosses) are plotted for each SN observation. The open circles and the crosses correspond, respectively, to cases in which the low and high estimates of the nearby source intensities are employed for corrections. (See table 1.) The 1σ errors (including all systematic errors) are indicated on only one side of the individual data points. In the soft X-ray band, the difference between the open circles and the crosses is due mostly to that between the high and low intensity values of SNR 0540-69.3 and/or N132D employed for the nearby source corrections, depending on the orientataion of the field of view. On the other hand, in the hard X-ray band, the difference is due almost completely to that between the high and low estimates for the intensity of SNR 0540-69.3 adopted. For an approximate conversion to an energy flux of the SN in units of 10^{-12} ergs cm^{-2} s^{-1} , the count rate (counts s^{-1}) should be multiplied by 4.6 for the soft X-ray band and by 32 for the hard X-ray band.

Hard X-rays from the SN were detected positively for the first time on 1987 July 4 (131 d after outburst). The observed light curve indicates that the intensity in the hard X-ray band increased gradually by roughly a factor of two from July through December, 1987. In 1988 January, the hard X-ray intensity increased by a factor of two, which was, however, much less pronounced than the increase in the soft X-ray band. From a study of the energy spectrum, this increase in the hard X-ray band can be explained as being due to a spill over from the soft X-ray band. Excluding this period, the maximum of the hard X-ray intensity appears to have occurred near the end of 1987. Since then, the intensity in the hard X-ray band has been gradually decreasing. The observed light curve is consistent with a smooth decay. If one assumes an exponential decline, the decay constant lies in the range between 200 and 350 days. The flux approached the detection limit around 1989 January. Later, the average hard X-ray flux over the last seven hundred days (650–1400 d) has been close to or lower than the detection limit, which is consistent with a further steady decline.

The X-ray light curve in the soft X-ray band appears to be qualitatively different from that in the hard X-ray band. The first positive detection in the soft X-ray band was on 1987 August 3. The observed soft X-ray intensity is highly variable, in contrast to a rather smooth excursion of the hard X-ray intensity. In particular, a spectacular flare-like increase was recorded in 1988 January. Expanded light curves for this event in the two energy bands are shown in figure 3, together with the hardness ratio of the flaring component. On 1988 January 7 (318 d), a sudden increase of soft X-rays was detected. The intensity increased further and reached a maximum level on January 19 (330 d). The intensity then decreased rapidly for the first several days and, subsequently, more gradually through March 14 (384 d), coming back to the "pre-flare" level. We shall hereafter call this event the "January flare." Regarding this flare, we were able to determine the line position of the source by means of an aspect switching method. The 99% confidence error box includes the SN, as is shown in figure 4. In addition, the energy spectrum during the flare is found to be very hard. The lowest panel of figure 3 shows the hardness ratio of the flare component, the ratio of the excess counts above the pre-flare level in the range 16–28 keV to those in the range 6–16 keV, as a function of time. If we assume a power-law spectrum modified by photoelectric absorption in cool matter, the observed hardness ratio corresponds to a photon index of 1.3–1.4 for the column density of an absorber, $N_{\rm H}$, smaller than 10^{23} H atoms cm^{-2}. This spectrum is much harder than that of any known class of

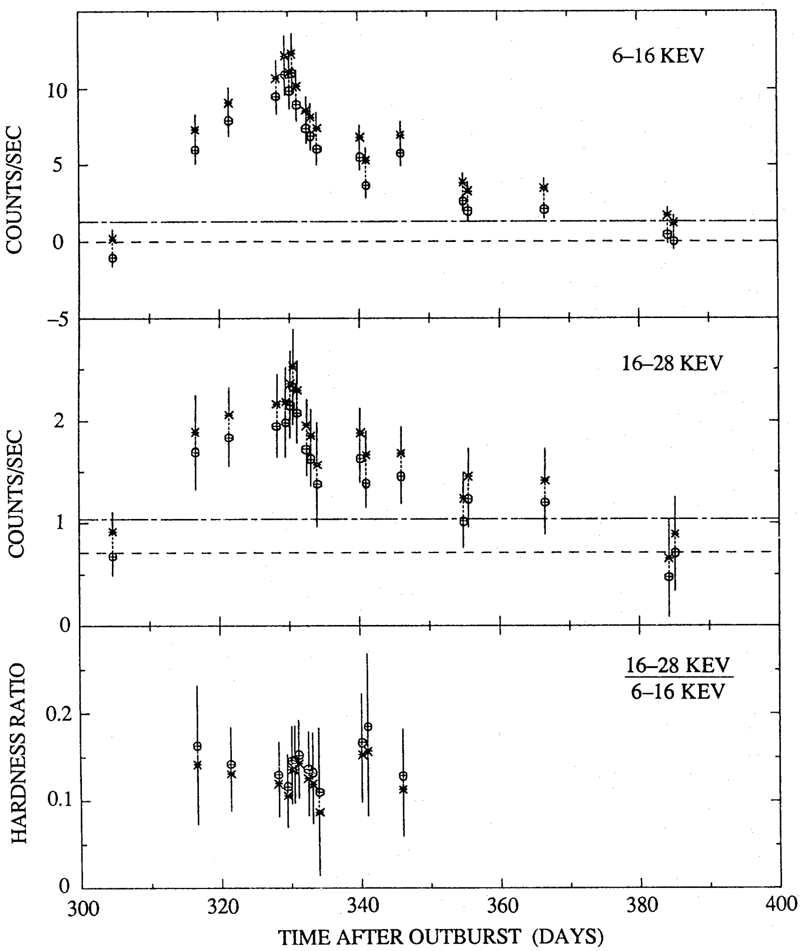

Fig. 3. X-ray light curves during the January flare in the 6–16 keV band (top panel) and the 16–28 keV band (middle panel), together with the hardness ratio of the flare component (bottom panel), the ratio of the excess counts above the pre-flare levels in the two energy bands. The estimated pre-flare levels are indicated by the broken and dash-dotted lines in the upper two panels, respectively, corresponding to high and low estimates of the nearby source contributions. (See the caption of figure 2.)

galactic sources, unless the $N_{\rm H}$ Value is significantly larger than 10^{23} H atoms $\rm cm^{-2}$. These results support the idea that the source of the flare is SN 1987A. Besides the January flare, a significant soft X-ray flux has been observed occasionally, as shown in figure 2a. For the open circles, in which high estimations of the nearby source intensities are used, about two thirds of the points are consistent to be null. On the other hand, there are several points for which the observed soft X-rays are quite intense. The presence of a variable soft X-ray source in the region of SN 1987A is beyond doubt. The soft X-ray intensity is highly variable on a time scale of the order of one day.

However, the position of this soft X-ray source has not yet been accurately determined. In order to obtain the source position, we are currently performing aspect

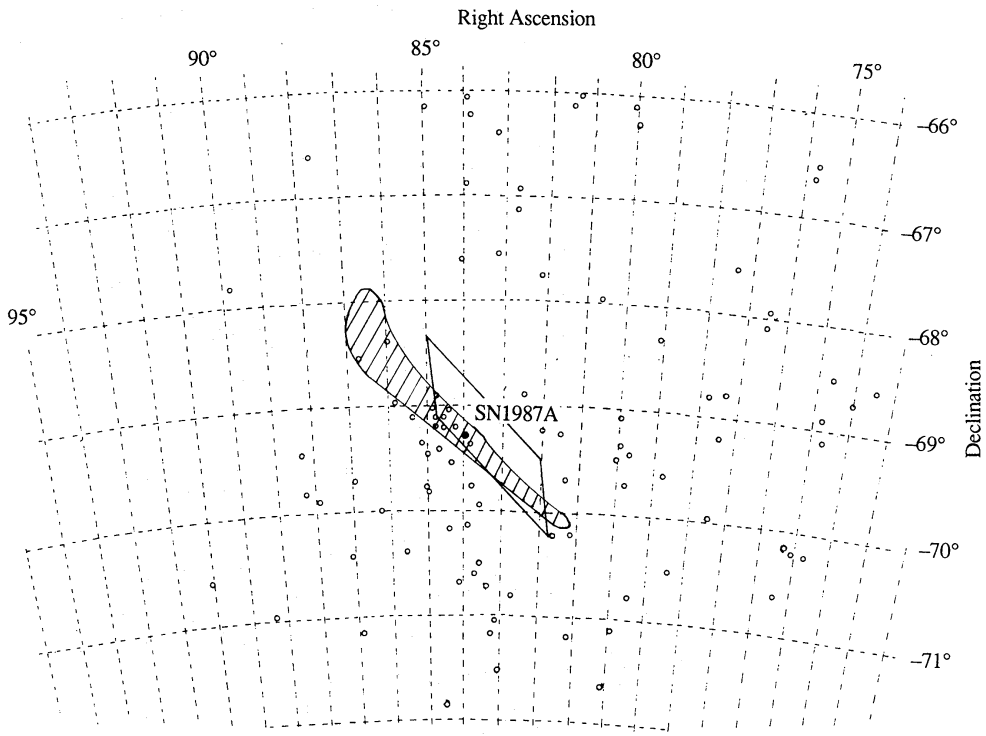

Fig. 4. The error box (99% confidence limit) of the January flare (hatched), and that (90% confidence limit) of the source of variable soft X-rays (see figure 2a).

switching observations. In this mode, we switch the pointing direction back and forth by 0.°2 during an observation. When a significant soft X-ray flux is present, the line position of the source can be determined from the amount of change in the count rate against a given change in aspect. A two-dimensional error box will be obtained from the crossing of the line positions determined at different orientations of the rectangular field of view. At present, a thus-localized source region is shown in figure 4, which includes the SN. The error box is still fairly large, and we cannot yet firmly exclude the possibility that some other highly variable source exists near the SN. It should be mentioned that this soft X-ray source was not seen during the time of the Einstein survey of this region by Long et al. (1981).

Searches for a pulsation with a high time resolution mode were also conducted during every SN observation. The result so far is negative. The present upper limit for the pulsed component is 2×10^{36} erg s^{-1} in the range 1–16 keV. It is to be noted, however, that, if the pulsation period were shorter than 2 milliseconds, it would not be possible for Ginga to detect the pulsar, because of the limitation of its time resolution.

5. Discussion

We have so far performed observations of the SN from Ginga more than sixty times during a period of over 1000 days. The complete time history of the X-ray intensity of the SN is given in figure 2. As can be noticed in the figure, the X-ray light curves in two energy bands appear to be qualitatively different. As a matter of fact, the observed energy spectra of the SN strongly suggest the presence of two separate components: a hard component which varies only gradually and a soft component which varies both rapidly and irregularly.

The light curve of the hard component is in general agreement with that obtained from less frequent Mir-Kvant observations (Sunyaev et al. 1990). As shown in Paper I, the spectral shape of the hard component is consistent with that expected from the model of the down-Comptonized gamma-ray line from ^{56}Co (McCray et al. 1987; Chan and Lingenfelter 1987; Gehrels et al. 1987; Grebenev and Sunyaev 1987; Xu et al. 1988; Ebisuzaki and Shibazaki 1988a). However, the observed behavior of X-rays was distinct in a much earlier emergence and a much longer persistence than was originally expected. The earlier emergence has led to extensive studies of possible large-scale mixing of the radio-active interior into the outer layers (Itoh, M. et al. 1987; Kumagai et al. 1988a, b; Pinto and Woosley 1988a, b; Ebisuzaki and Shibazaki 1988b; Shibazaki and Ebisuzaki 1988; Sutherland et al. 1988; Arnett 1988; Grebenev and Sunyaev 1988; Leising 1988; Yamada et al. 1989; Fu and Arnett 1989; Bussard et al. 1989). On the other hand, the observed slow decay on a time scale of the order of 300 days might imply that photoelectric absorption in the ejecta is effectively reduced as a result of the formation of clumps in which heavy elements are confined (Kumagai et al. 1989; Nomoto et al. 1990). Alternative possibilities are a substantial contribution of ^{57}Co in the later stage of the decline (Pinto et al. 1988; Kumagai et al. 1989; Woosley et al. 1989), and/or an increasing contribution of the powering by the suspected but yet unrevealed neutron star.

The presence of an intense soft component was quite unexpected. The most spectacular event was a flare-like increase which occurred in January 1988 (January flare). As mentioned in the preceding section, the line position as well as an unusually hard spectrum of the flare suggest that the flare occurred in the SN. On the other hand, the High Energy X-ray Experiment (HEXE) on board Mir-Kvant, which observed the SN sometimes during the flare, did not detect any significant increase in the energy range above 15 keV in which HEXE is sensitive (Sunyaev et al. 1990). [The Coded Mask Imaging Spectrometer (TTM) which had sensitivity in lower energy range was not in operation at that time.] The detection efficiency of HEXE as a function of the energy is largely different from that of the Ginga detector. From a quantitative comparison which takes this into account, we consider that the non-detection of the flare with HEXE is not in definite contradiction of the observed result from Ginga. In addition to the January flare, a significant soft X-ray flux was occasionally observed from the region of the SN which varied on a time scale of the order of one day, as can be seen in figure 2. While a firm source identification is still required, it should be mentioned that TTM in the Mir-Kvant module did not detect any soft X-rays from the SN region (Sunyaev et al. 1987; Sunyaev et al. 1988). We believe that this is not a discrepancy for the following reasons: (i) Since the observations were not simultaneous, the source intensity could have been different. (ii) The soft X-ray sensitivity of Ginga is substantially higher than that of TTM. For example, the incident flux averaged over two observations on August 3 (day 161) and September 3 (day 192) was $(6–8)\times10^{-5}$ photons cm^{-2} s^{-1} keV^{-1} in the range 6–16 keV. This flux was found later to be close to, or below, the detection limit of TTM, $(1–2)\times10^{-4}$ photons cm^{-2} s^{-1} keV^{-1}, after re-examination of the background noise level of TTM (Sunyaev et al. 1989). Incidentally, the preliminary result shown in figure 4 in Paper I gives an overestimate by a factor of about two for the range below 10 keV due to an insufficient correction for the nearby source contributions.

A possible scenario for the soft X-ray emission from the SN is that the expanding ejecta hits fairly dense circumstellar matter which was formed by the mass loss of the progenitor (Itoh, H. et al. 1987; Masai et al. 1987). According to this scenario, the January flare is interpreted as being due to a collision of the ejecta with a dense cloud (Masai et al. 1988). This model also suggests a strong absorption of low-energy X-rays by the intervening ejecta, which is consistent with the non-detection during the rocket experiments by Burrows et al. (1989). However, a question remains how such a dense structure was formed in the close vicinity of the progenitor.

As an entirely different possibility, the neutron star at the center could be the power source of the observed X-rays. Bandiera et al. (1988) proposed that a synchrotron nebula around a young pulsar might be visible through gaps of a fragmented ejecta. Apart from this picture, a possibility that the central neutron star is in a close binary system and is accreting mass, which would produce thermal emission and account for the observed soft X-rays (Fabian and Rees 1988). In this connection, it is interesting to note that the maximum luminosity during the January flare was approximately equal to the Eddington limit for a $\sim 1 M_{\odot}$ neutron star.

The authors are indebted to all Ginga Team members for the entire support to the SN observations. They are grateful to Dr. K. Nomoto for careful reading of the manuscript and useful suggestions.

References

Arnett, W. D. 1988, in *Supernova 1987A in the Large Magellanic Cloud*, ed. M. Kafatos and A. Michalitsianos (Cambridge University Press, Cambridge), p. 301.

Bandiera, R., Pacini, F., and Salvati, M. 1988, *Nature*, **332**, 418.

Burrows, D. N., Nousek, J. A., Berthiaume, G. D., and Garmire, G. P. 1989, *Astrophys. J.*, **347**, 1114.

Bussard, R. W., Burrows, A., and The, L. S. 1989, *Astrophys. J.*, **341**, 401.

Chan, K. W., and Lingenfelter, R. E. 1987, *Astrophys. J. Letters*, **318**, L51.

Clark, D. H., Tuohy, I. R., Long, K. S., Szymkowiak, A. E., Dopita, M. A., Mathewson, D. S., and Culhane, J. L. 1982, *Astrophys. J.*, **255**, 440.

Dotani, T., Hayashida, K., Inoue, H., Itoh, M., Koyama, K., Makino, F., Mitsuda, K., Murakami, T., Oda, M., Ogawara, Y., Takano, S., Tanaka, Y., Yoshida, A., Makihsima, K., Ohashi, T., Kawai, N., Matsuoka, M., Hoshi, R., Hayakawa, S., Kii, T., Kunieda, H., Nagase, F., Tawara, Y., Hatsukade, I., Kitamoto, S., Miyamoto, S., Tsunemi, H., Yamashita, K., Nakagawa, M., Yamauchi, M., Turner, M. J. L., Pounds, K. A., Thomas, H. D., Stewart, G. C., Cruise, A. M., Patchett, B. E., and Reading, D. H. 1987, *Nature*, **330**, 230 (Paper I).

Ebisuzaki, T., and Shibazaki, N. 1988a, *Astrophys. J.*, **328**, 699.

Ebisuzaki, T., and Shibazaki, N. 1988b, *Astrophys. J. Letters*, **327**, L5.

Fabian, A. C., and Rees, M. J. 1988, *Nature*, **335**, 50.

Fu, A., and Arnett, W. D. 1989, *Astrophys. J.*, **340**, 414.

Gehrels, N., MacCallum, C. J., and Leventhal, M. 1987, *Astrophys. J. Letters*, **320**, L19.
Grebenev, S. A., and Sunyaev, R. A. 1987, *Soviet Astron. Letters*, **13**, 397 (945).
Grebenev, S. A., and Sunyaev, R. A. 1988, *Soviet Astron. Letters*, **14**, 288 (675).
Hayashida, K., Inoue, H., Koyama, K., Awaki, H., Takano, S., Tawara, Y., Williams, O. R., Denby, M., Stewart, G. C., Turner, M. J. L., Makishima, K., and Ohashi, T. 1989, *Publ. Astron. Soc. Japan*, **41**, 373.
Itoh, H., Hayakawa, S., Masai, K., and Nomoto, K. 1987, *Publ. Astron. Soc. Japan*, **39**, 529.
Itoh, M., Kumagai, S., Shigeyama, T., Nomoto, K., and Nishimura, J. 1987, *Nature*, **330**, 233.
Kumagai, S., Itoh, M., Shigeyama, T., Nomoto, K., and Nishimura, J. 1988a, in *Supernova 1987A in the Large Magellanic Cloud*, ed. M. Kafatos and A. Michalitsianos (Cambridge University Press, Cambridge), p. 413.
Kumagai, S., Itoh, M., Shigeyama, T., Nomoto, K., and Nishimura, J. 1988b, *Astron. Astrophys.*, **197**, L7.
Kumagai, S., Shigeyama, T., Nomoto, K., Itoh, M., Nishimura, J., and Tsuruta, S. 1989, *Astrophys. J.*, **345**, 412.
Leising, M. D., 1988, *Nature*, **332**, 516.
Long, K. S., Helfand, D. J., and Grabelsky, D. A. 1981, *Astrophys. J.*, **248**, 925.
Masai, K., Hayakawa, S., Inoue, H., Itoh, H., and Nomoto, K. 1988, *Nature*, **335**, 804.
Masai, K., Hayakawa, S., Itoh, H., and Nomoto, K. 1987, *Nature*, **330**, 235.
McCray, R., Shull, J. M., and Sutherland, P. 1987, *Astrophys. J. Letters*, **317**, L73.
Nomoto, K., Shigeyama, T., Kumagai, S., and Yamaoka, H. 1990, in *Supernovae*, ed. S. E. Woosley (Springer-Verlag, Berlin), in press.
Pinto, P. A., and Woosley, S. E. 1988a, *Astrophys. J.*, **329**, 820.
Pinto, P. A., and Woosley, S. E. 1988b, *Nature*, **333**, 534.
Pinto, P. A., Woosley, S. E., and Ensman, L. M. 1988, *Astrophys. J. Letters*, **331**, L101.
Seward, F. D., Harnden, F. R., Jr., and Helfand, D. J. 1984, *Astrophys. J. Letters*, **287**, L19.
Shibazaki, N., and Ebisuzaki, T. 1988, *Astrophys. J. Letters*, **327**, L9.
Sunyaev, R., Churazov, E., Gilfanov, M. R., Loznikov, V., Yamburenko, N., Skinner, G. K., Patterson, T. G., Willmore, A. P., Emam, O., Brinkman, A. C., Heise, J., In't Zand, J. J. M., and Jager, R. 1989, in *Proc. 23rd ESLAB Symposium on Two Topics in X-ray Astronomy*, ed. N. E. White (ESA SP-296), p. 633.
Sunyaev, R. A., Gil'fanov, M. R., Churazov, E. M., Yamburenko, N. S., Brinkman, A. C., Heise, J., In't Zand, J. J. M., Jager, R., Skinner, G. K., Al-Emam, O., Patterson, T. G., and Willmore, A. P. 1988, *Soviet Astron. Letters*, **14**, 252(591).
Sunyaev, R., Kaniovsky, A., Efremov, V., Gilfanov, M., Churazov, E., Grebenev, S., Kuznetsov, A., Melioranskiy, A., Yamburenko, N., Yunin, S., Stepanov, D., Chulkov, I., Pappe, N., Boyarskiy, M., Gavrilova, E., Loznikov, V., Prudkoglyad, A., Rodin, V., Reppin, C., Pietsch, W., Engelhauser, J., Trumper, J., Voges, W., Kendziorra, E., Bezler, M., Staubert, R., Brinkman, A. C., Heise, J., Mels, W. A., Jager, R., Skinner, G. K., Al-Emam, O., Patterson, T. G., and Willmore, A. P. 1987, *Nature*, **330**, 227.
Sunyaev, R., Kaniovsky, A., Efremov, V., Grebenev, S., Kuznetsov, A., Englhauser, J., Doebereiner, S., Pietsch, W., Reppin, C., Truemper, J., Kendziorra, E., Maisack, M., Mony, B., and Staubert, R. 1990, *Soviet Astron. Letters*, **16**, 403.
Sutherland, P., Xu, Y., McCray, R., and Ross, R. 1988, in *Atmospheric Diagnostics of Stellar Evolution, IAU Colloq. No. 108, Lecture Notes in Physics, 305*, ed. K. Nomoto (Springer-Verlag, Berlin), p. 394.
Woosley, S. E., Pinto, P. A., and Hartmann, D. 1989, *Astrophys. J.*, **346**, 395.
Xu, Y., Sutherland, P., McCray, R., and Ross, R. 1988, *Astrophys. J.*, **327**, 197.
Yamada, Y., Kasahara, K., and Nakamura, T. 1989, *Prog. Theor. Phys.*, **81**, 93.