X-RAY OBSERVATION OF SN1987A FROM GINGA

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ABSTRACT. An unusual hard X-ray source was discovered in an error box of 0.2° x 0.3° including SN1987A from the X-ray astronomy satellite Ginga. The energy spectrum is quite unusual for any known classes of X-ray source, and apparently consists of two separate components, a soft component and a very hard component. This source is considered to be identified with SN1987A. The X-ray emergence occurred in July, 1987, or possibly even earlier. The soft component is significantly time-variable and also showed a flare-like increase in January, 1988, while the intensity of the hard component has remained relatively unchanged for more than 200 days.

1. OBSERVATION OF SN1987A

We began search for X-rays from the supernova 1987A in the Large Magellanic Cloud (LMC) from the X-ray astronomy satellite Ginga since February 25, 1987, right after the optical discovery (Shelton 1987; Nelson and Jones 1987). Ginga carries a set of proportional counters of a total 4000 cm^2 effective area and a full field of view of 2° x 4° . (For more detail of Ginga, see Makino 1987.) SN1987A is about 0.6° away from LMC X-1. This source is one of the brightest X-ray sources in the LMC with an intensity of approximately 20 mCrab in the 1 - 10 keV range, and is also time variable. In order to observe the SN separated from LMC X-1, two different modes of observation have been employed; (1) slow scans along a path through the SN and LMC X-1, and (2) pointing observations at a position about 1° offset from LMC X-1 on the side of the SN as shown in Fig. 1, which gives an exposure to the SN with approximately half the maximum sensitivity and little contribution from LMC X-1.

2. RESULTS

2.1. Discovery of a Hard Source Near SN1987A

In Fig. 2, we show the result obtained from the scanning observations on September 2 and 3 in the form of histograms of the count rate with time in different energy bands. In the energy range below 10 keV, the

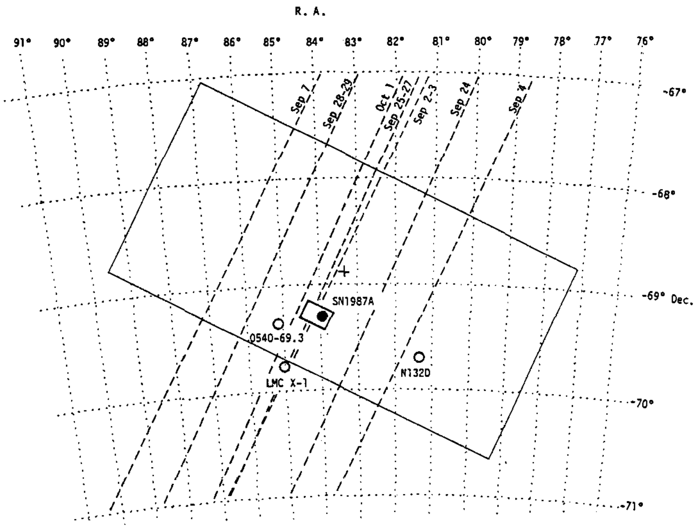

Figure 1: The sky map of the LMC region. The scan paths (dashed lines), the target position (+) for the offset pointing mode and the full field of view (2° x 4°) are indicated. The thick solid rectangle shows the 90% confidence error box of the hard source.

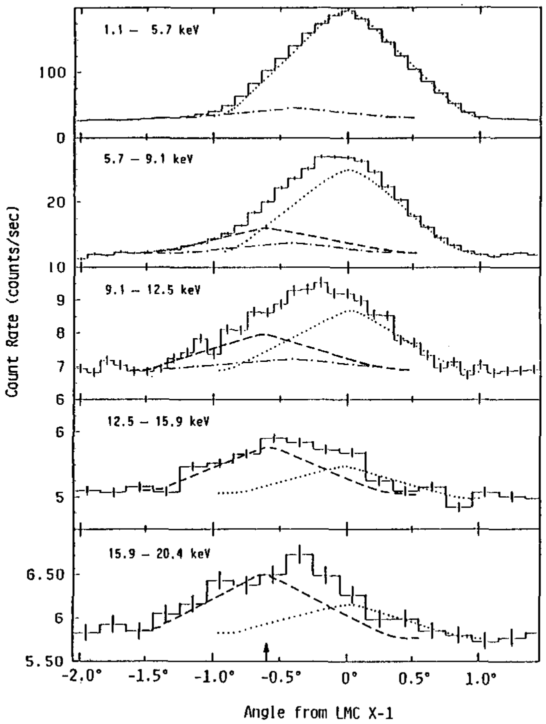

Figure 2: Count rate histograms obtained from the scans on September 2 - 3 are shown in five different energy bands. The dotted lines (LMC X-1), dash-dotted lines (SNR0540-69.3) and dashed lines (the hard source) indicate the fits to the collimator response function. Position angle of SN1987A is marked by an arrow.

counts from LMC X-1 dominate. On the other hand, as the energy increases, the peak position shifts towards the line position near the SN. The contributions of LMC X-1 and SNR0540-69.3 are minor in the range above 10 keV and quickly diminish with increasing energy. The histograms clearly indicate the presence of a new source having a very hard spectrum separated from LMC X-1. We are certain that this source did not exist in the March - April period. By fitting the collimator response function to the observed count-rate histograms, we determined the contribution of the variable source LMC X-1 and the intensity as well as the line position of the hard X-ray source separately. The contribution of the nearby supernova remnant 0540-69.3 is also taken into account using the result of a separate Ginga observation of this remnant. The result of the fit is shown by the dashed lines in Fig. 2. The line position of the hard source thus determined is in agreement with that of the SN within ±0.1° (90% confidence limit). The discovery of this hard source was announced on an IAU Circular (Makino et al. 1987).

In order to determine the error box of the hard source, we conducted separate scans on September 4 - 7 and September 24 - October 1 along several different paths which were parallel to each other with separations of 0.3° to 05° . These scan paths are shown in Fig. 1. From the comparison of the peak count rate observed on each scan path, we determined the 90% confidence error box of the hard source of the size 0.2° x 0.3° as shown in Fig. 1. This error box includes the SN. Furthermore, as shown later, the spectrum of the new source is quite unusual for any of the known classes of X-ray source. Also, this source was not present until April, 1987, and emerged some time between May and July, 1987. From these facts, we consider it most plausible to identify the new source with SN1987A. Once the position was known, pointng observations give the source flux and energy spectrum with much better statistics than scanning observations. We therefore employed the pointing mode only, for later observations.

2.2 X-Ray Light Curve

The light curves of the source so far obtained from pointing observations are shown for two different energy bands, 6 - 16 keV and 16 - 28 keV, in Fig. 3. We shall hereafter call these two energy bands the soft X-ray band and the hard X-ray band, respectively. The count rates are given after subtraction of the contributions from nearby sources, and the aspect correction. In addition to the contributions from LMC X-1 and SNR0540-69.3, minor contributions from N132D, N157B and two other Einstein sources (source No's. 26 and 83 from the Einstein survey by Long, Helfand and Grabelsky (1981)) were also corrected for. The spectrum of each of these sources was determined from separate Ginga observations. The other sources in the field of view are much fainter and estimated to be negligible. The contributions from the nearby sources never exceeded 40%, except for the data on July 4, of the total counts in the soft X-ray band and 10% in the hard X-ray band. Therefore, it is beyond doubt that significant flux is coming from SN1987A not only in the hard X-ray band but also in the soft X-ray band.

In addition, the background subtraction is a source of systematic error. A background measurement is performed immediately before or after each SN observation. The systematic errors in the process of background subtraction was estimated to be about 1 % and is incorporated in the error estimation of the SN flux.

One notices in Fig. 3 that time variations in the two energy bands are qualitatively different. The first positive detection in the soft X-ray band was on July 20, 1987. The intensity in the soft X-ray band (6 - 16 keV) is found to vary significantly by a factor of two to three in 1987. The intensity on December 26 was the lowest so far

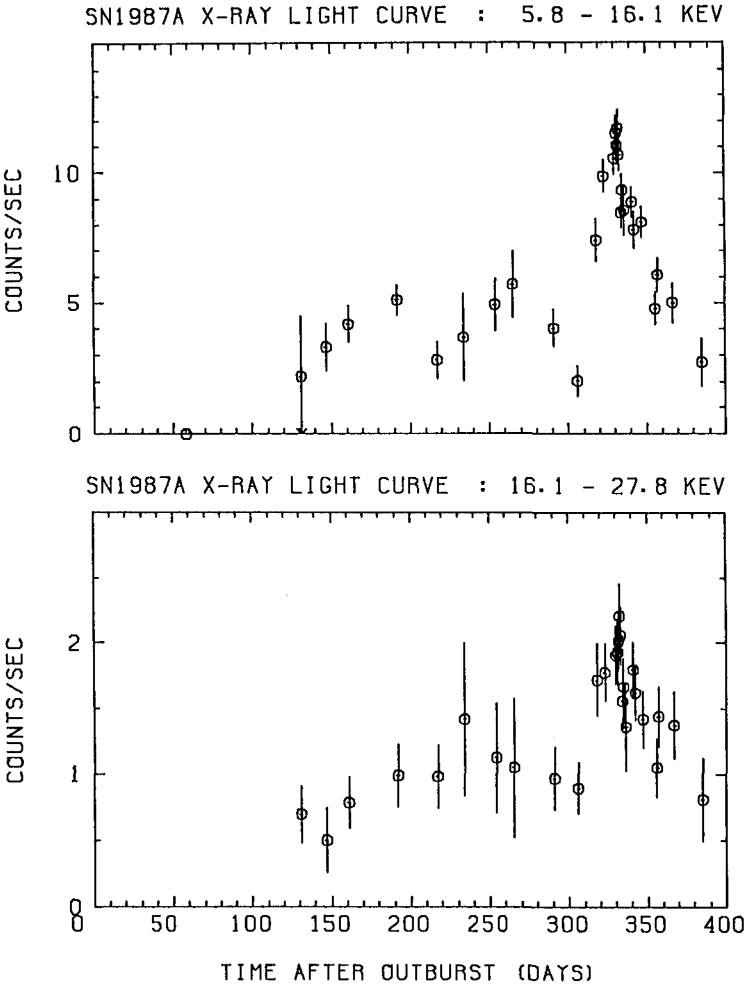

Figure 3: X-ray light curves in two energy bands.

observed. After twelve days, on January 7, 1988, the sourcee showed a dramatic intensity increase by nearly a factor of four. The intensity increased further and stayed at the maximum level until January 22, which was about a factor of six of that on December 26. Then, on January 23, it dropped by 30 %, which is statistically significant. Since then, it decreased slightly through February 5. About 10 days later, on February 14, the intensity was found to have returned to the general level of 1987. We shall hereafter call this event the "Januray flare".

On the other hand, the X-ray intensity in the hard X-ray band (16 - 28 keV) exhibits much less change than those in the soft X-ray band. The first positive detection was on July 4, 1987. It should be mentioned, however, that the epoch when the hard X-ray intensity exceeded the Ginga detection threshold remains somewhat uncertain. This is because the observing condition was unfavorable in May and June, 1987. Since the detection, the intensity in the hard X-ray band has remained almost constant within the statistical uncertainties through December, 1987. In the January flare, the hard X-ray intensity increased simultaneously by a factor of two, which was however much smaller than the factor of increase in the soft X-ray band.

2.3. Energy Spectrum

The energy spectrum of SN1987A has a unique shape, suggesting the presence of two separate components (Dotani et al. 1987). Fig. 4 shows the average spectra for three different intensity levels. This averaging is justified because the spectra observed on different days but at the same intensity level are consistent to be the same within statistical uncertainties. The spectrum A shows the average of September 28 and December 26 for the lowest intensity group, and the spectrum B that of August 3, September 3 and November 4. The spectrum C is the average from January 19 through 22 when the intensity was highest during the January flare. These spectra are corrected for the energy-dependent detection efficiency.

The shape of the spectra A and B would hardly be explicable in terms of a single component. In addition, while these two spectra are significantly different from each other below 15 keV, they are essentially the same above 15 keV. These facts suggest that there are two separate components, a soft component and a hard component, of which the hard component remains essentially constant independent of the soft component. This explains the little intensity change observed in the hard X-ray band. Besides, a flux minimum in the 10 - 15 keV range in the spectrum A suggests that the hard component is cut off below 20 keV.

We attempt to determine the spectral shape of the hard component by assuming the form $E^{-1} \times \exp(-\sigma N_h)$. However, the assumed power-law form is not critical for the present energy range limited below 40 keV. The power-law E^{-1} was simply chosen for a qualitative representation of the result of the Kvant observations in the higher energy range (Sunyaev et al. 1987) and also the numerical results of the Compton degradation model (e.g., Itoh et al. 1987, and references therein). The soft component is assumed to be expressed by the bremsstrahlung spectrum.

In order to determine the absorption column N_h, the above model was fitted to the average spectra. As the result, the spectra A and B gave N_h-values both approximately equal to 10^{25} H atoms/cm^2 for the cosmic abundances of element. The spectrum C is insensitive to determine the N_h-value uniquely. However, we assume the same form of the hard component also during the January flare, because the hard component is likely to be independent of the soft component. We therefore fixed the N_h at 10^{25} H atoms/cm^2, and performed fitting to the spectrum C. The intensity of the hard component was dealt with as a free parameter.

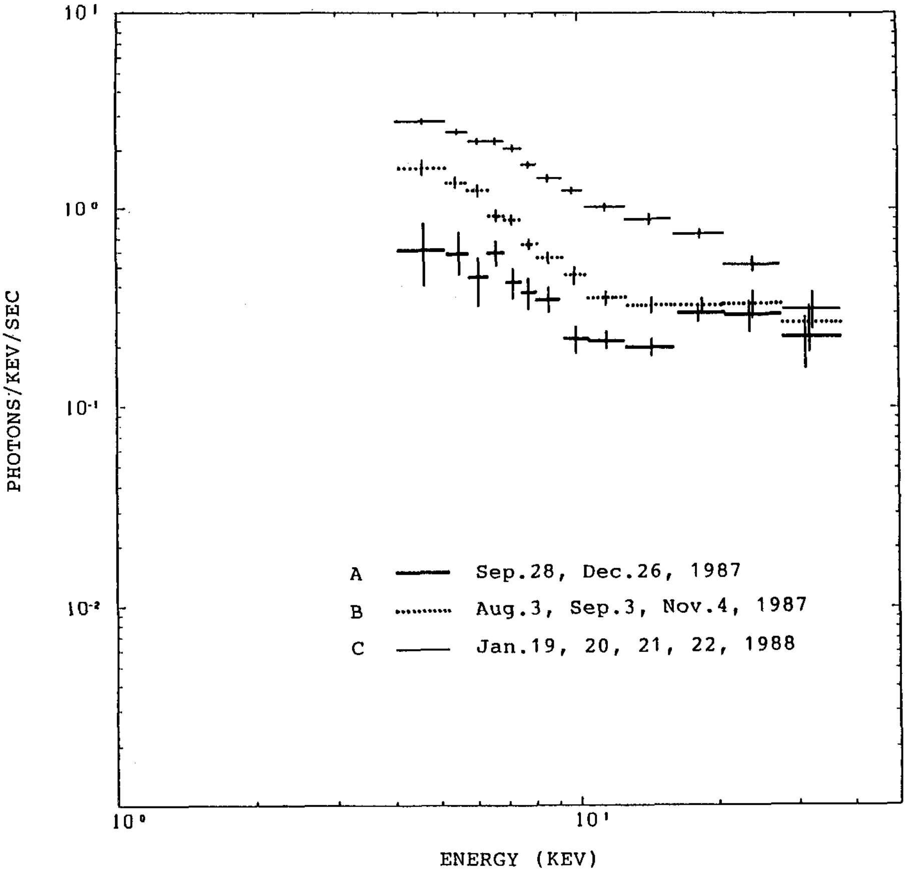

Figure 4: Average spectra for three different intensity levels

Satisfactory fit was obtained for all cases. As the result, the intensity of the hard component turned out to be the same for all three spectra within the errors. This implies that the hard component remained essentially constant for more than 200 days. The temperature kT of the soft component is found to be about 10 keV for the spectra A and B but is higher than 50 keV for the spectrum C. The count rate increase in the hard X-ray band (16 - 28 keV) during the January flare (see Fig. 3) is thus interpreted as due to an enhanced contribution of the hardened soft component. The luminosity of the soft component reached 10^{38} ergs/sec at the flare peak, for the assumed distance of 50 kpc.

The absorption column of the soft component, N_s, is generally found to be about 10^{23} H atoms/cm^2 or less. The lower bound of N_s is difficult to estimate because of the increasing systematic errors in the corrections for the nearby sources towards lower energies. For the same reason, whether or not N_s changes with time remains uncertain.

An emission line of iron is significantly visible in the spectrum of the soft component when statistics is sufficiently good. This may be a supportive evidence for the thermal origin of the soft component. In particular, the iron line is clearly seen during the January flare. The energy of the iron line observed during the flare is determined to be 6.8 ± 0.2 keV with an equivalent width of about 200 eV. Therefore, the line is emitted most likely from helium-like or hydrogen-like iron ions.

What are the origings of X-rays from SN1987A? The spectral shape of the hard component is in general agreement with that expected from the model of the down-Comptonized ^{56}Co gamma-ray lines. However, if it is the case, much earlier emergence of X-rays than expected and the essential constancy of the hard component for more than 200 days remain to be explained (see Itoh et al. 1987). Besides, the presence of an intense soft component was quite unexpected. A possible scenario is that the expanding ejecta interacts with fairly dense circumstellar matter and the shock-heated plasma emits thermal radiation (Masai et al. 1987). Very high luminosity, temperature close to 10^9 K and a rapid change in intensity observed during the January flare might require rather exceptional conditions for this model. Search for regular pulsations is obviously very important. Thus far, no pulsation has been detected.

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