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HARD X-RAY SPECTRUM OF SUPERNOVA 1987A ON DAY 407

P. UBERTINI AND A. BAZZANO
Istituto di Astrofisica Spaziale, CNR, Frascati, Italy
R. SOOD
University College, University of New South Wales, Canberra, Australia
R. STAUBERT
Astronomisches Institut, University of Tübingen, Germany
T. J. SUMNER
Blackett Laboratory, Imperial College, London
AND
G. FRYE
Case Western Reserve University
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ABSTRACT

We report evidence for a hard X-ray continuum emission from a source in the LMC region centered on the optical position of SN 1987A. The supernova region was observed on day 407 with a hard X-ray and a high-energy (>50 MeV) gamma-ray detector flown together on a balloon payload. The X-ray data show a very hard power-law spectrum with a photon index $\alpha = 1.1$ in the range 17–165 keV, with an intensity of 1.2×10^{-4} photons $\text{cm}^{-2}\ \text{s}^{-1}\ \text{keV}^{-1}$ at 50 keV. If compared with previous observations our data indicate an almost steady, if not increasing, high-energy emission from SN 1987A in the last 9 months. Our data are compared with the predictions expected from theoretical models based on the Comptonization of the ^{56}Co nuclear lines or the presence of an internal continuum power source.

Subject headings: stars: supernovae — X-rays: spectra

I. INTRODUCTION

The explosion of SN 1987A close to the Galaxy has offered a unique opportunity to study the final stage in the evolution of a massive star. Of particular interest is the possible presence of a newborn neutron star, a hypothesis supported by the detection of neutrino burst events just before the optical discovery of the supernova (Aglietta *et al.* 1988; Koshiba 1988; Matthews *et al.* 1988).

After more than 1 yr of continuous monitoring at optical, IR, UV, and X-ray wavelengths, there is little doubt that most of the hard X-ray emission from the supernova is due to the ^{56}Co, the decay product of 0.075 $M_{\odot}$ of ^{56}Ni synthesized during the explosion (Pinto and Woosley 1988*a*). The ^{56}Co decays with a half-life of 78.8 days producing nuclear gamma-ray lines primarily at 847 keV and 1238 keV that are then down–Compton-scattered by the optically thick envelope to produce a continuum spectrum in the hard X-ray range. Nevertheless, the low-energy X-ray variability ($E < 20$ keV; Makino 1988) and the slow increase in the intensity of the hard X-ray continuum ($E > 30$ keV, Sunyaev *et al.* 1987; Sunyaev *et al.* 1988) may be indicative of the presence of an additional source of energy.

Observations of SN 1987A were carried out on day 55 and on day 407 with a balloon-borne payload consisting of a hard X-ray detector and a high-energy gamma-ray spark chamber. During the first balloon flight, neither hard X-ray nor high-energy gamma rays were detected (Sood *et al.* 1988; Ubertini *et al.* 1988*a*). The quick-look data analysis of the second observation led to a positive detection of SN 1987A with the hard X-ray detector (Ubertini *et al.* 1988*b*).

We report here the final analysis of the scientific data collected from the Multiwire Proportional Counter (MWPC) in the range 17–165 keV; the gamma-ray data analysis is still in progress.

II. THE INSTRUMENT

The payload employed to observe SN 1987A, described in detail elsewhere (Sood *et al.* 1988; Ubertini *et al.* 1988*a*), comprised four major subsystems: the spark chamber, the hard X-ray detector, the orientation and pointing system, and the communication and flight systems.

The multiplate optical spark chamber operating in the gamma-ray range and the X-ray detector operating in the hard X-ray range were pointed at the same azimuth. The gamma-ray detector, sensitive in the range 50–500 MeV, had a geometric area of 400 cm^2 on axis and a field of view of 60° FWHM.

The hard X-ray detector, described in the literature (Ubertini *et al.* 1981), consisted of a 2.0 bar xenon-filled MWPC with a geometric area of 500 cm^2 and a spectral resolution of 8% at 130 keV. The nominal time resolution of the two instruments was 10 μs. The field of view of the MWPC was limited by an hexagonal copper collimator with an aperture of 4°.0 FWHM. The MWPC sensitivity was increased with the use of a plastic active shield that reduced the background counting rate to 2.8×10^{-4} counts $\text{cm}^{-2}\ \text{s}^{-1}\ \text{keV}^{-1}$ at 3 mbar. Real-time housekeeping data from the on-board sensors, analyzed on-line during the observation, allowed a real-time aspect check to within 30′. The final post facto flight attitude reconstruction error was ±0°.1.

III. THE OBSERVATION

The experiment, launched on 1988 April 5, floated from 00.00 UT at a ceiling altitude corresponding to a residual atmospheric pressure between 3.0 and 3.8 mbar for 10 hr. The observation program was carried out while maintaining the azimuth of the gondola always oriented toward the supernova azimuth except when rotated off-source to establish the variation of the background with azimuth and to obtain an in-flight absolute calibration of the magnetometers using Sun sensor data. The spark chamber elevation angle was tilted at a fixed value of 45° to the vertical in order to maximize the exposure during the SN 1987A transit. At the same time, the X-ray MWPC was rocked on-off the source, by the elevation drive on a time scale short enough to avoid possible systematic errors due to variations in background counting rate because of changes in altitude, geographic position, or change of detector gain.

SN 1987A was observed during a period of 8 hr while rocking the collimator off-source every 10 minutes toward a sky area free of known hard X-ray sources to collect background data. The aperture of the passive collimator and the observation strategy were optimized to minimize systematic effects and contamination from known sources close to SN 1987A. The region tracked during the observation contained a few known X-ray sources. These sources had been previously observed with high sensitivity and spatial resolution by the TTM experiment on-board the MIR station in the range 2–30 keV (Skinner *et al.* 1988). The authors reported a very weak X-ray emission from LMC X-4, at a milliCrab level, a flux corresponding to 0.5 milliCrab from PSR 0540−693 (a 50 ms pulsar) and less than 10 milliCrab from LMC X-1. This last source had an exposure factor of about 70% during our observation, taking into account the MWPC collimator field of view, and it could possibly have contaminated our data. A comparison between the LMC X-1 emission reported from the MIR station and the former data obtained by *EXOSAT* and *HEAO 1* implies that the contamination of our SN 1987A observation must be less than 10% in the lower energy channel (17–30 keV). The other three sources in the SN 1987A region (LMC X-2, LMC X-3, and the "transient" source) are less intense than LMC X-1 above 10 keV and in any case are out of, or at the border of, the MWPC collimator's field of view. The region of sky selected for the background measurements was free of any known hard X-ray source.

The first part of the flight was dedicated to a systematic scan of the sky in elevation, maintaining the same azimuth, in order to study the correlation between the background variation and the elevation of the detector. We have found a very weak dependence of the background counting rate on detector elevation. In fact, the background was very stable during the whole flight due to the good shielding of the detector and its roughly spherical active volume. Anyway, as a standard procedure, the whole set of data has been normalized to remove effects due to variations in the altitude and geographic position of the balloon which occurred during the flight.

IV. DATA ANALYSIS

The set of 16 on-source/off-source differences, each obtained from 20 or more minutes of observation, were binned in five energy channels and added together to improve the statistics of the measurement. The statistical excess obtained corresponds to 6.9 σ over the energy range 17–165 keV. The raw excess, as observed from the source, was folded through the matrix simulating the detector with a standard reiterative χ^2 procedure. The detector matrix was determined by taking into account the detector parameter (gas mixture, geometry of the cells, escape effect, etc.), the electronics thresholds, the collimator effect, and the atmospheric absorption and was checked for this particular detector using Crab observations obtained from previous flights. This MWPC has been flown successfully several times after it was finally filled and sealed 5 yr ago. In particular during 1987 August the Crab was scanned during a single observation as an in-flight calibration source. The MWPC and the associated electronics were in the same configuration as for the SN 1987A flight, while the collimator was narrower (Baker *et al.* 1984). The detector gain and resolution were monitored during the flight with an on-board ^{241}Am calibration source. The SN 1987A data, in the range 17–165 keV, were fitted with a power-law spectrum of the form: $dN/dE = K \times (E/E_0)^{-\alpha}$ photons cm^{-2} s^{-1} keV^{-1}, with $E_0 = 50$ keV; K is the source intensity at 50 keV, close to the pivoting point of the spectrum where the interdependence of intensity and spectral index is at a minimum. Figure 1 shows the deconvolved spectra of SN 1987A and of the Crab at the top of the atmosphere; the Crab best-fit spectrum obtained from the *HEAO 1*, A2–A4 experiments is also shown for comparison (Toor and Seward 1974; Carpenter, Coe, and Engel 1976). The data points from SN 1987A correspond to the best-fit spectrum, obtained with $K = (1.2 \pm 0.3) \times 10^{-2}$ photons cm^{-2} s^{-1} keV^{-1} and $\alpha = 1.1 \pm 0.4$ and give a $\chi^2_{\rm d.o.f.} = 0.95$ (for 3 d.o.f.). The errors in the parameters correspond to a confidence level of 68% ($\chi^2_{\rm min} + 2.3$) following Lampton, Margon, and Bowyer (1976).

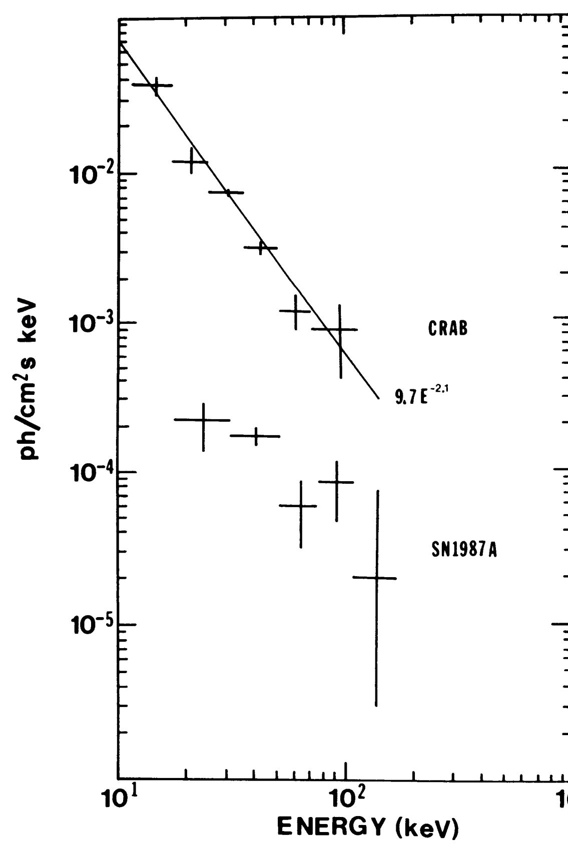

FIG. 1.—Deconvoluted spectra of the Crab and SN 1987A at the top of the atmosphere. The error bars represent ± 1 standard deviation. The solid line is the canonical Crab spectrum (Toor and Seward 1974).

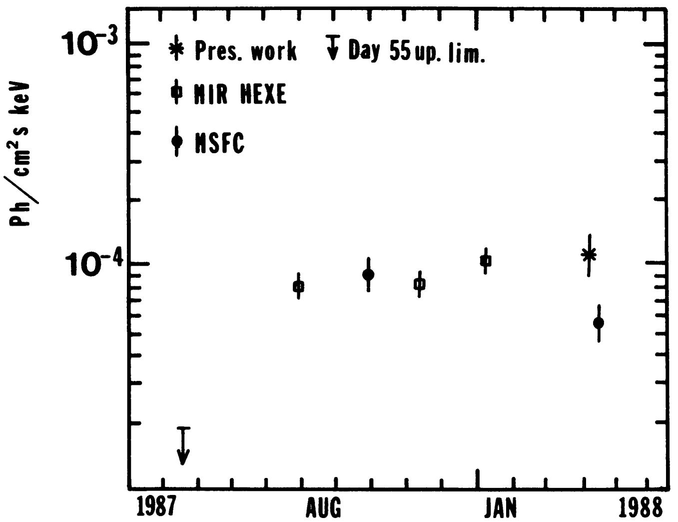

FIG. 2.—Time evolution of SN 1987A flux at 50 keV. Data sources are as follows: day 55 upper limit from Ubertini *et al.* (1988*a*); MIR HEXE from Sunyaev *et al.* (1988) (taken from their Fig. 5); and MSFC from Wilson *et al.* (1988) and Fishman *et al.* (1989).

V. DISCUSSION

Even before the occurrence of SN 1987A, theoretical models had already shown that it was likely that a hard X-ray continuum would emerge due to the Comptonization of high-energy gamma-ray line photons emitted by radioactive material produced in the core of the supernova (see McCray, Shull, and Sutherland 1987; Xu *et al.* 1987; Woosley *et al.* 1987 and references therein). In particular, in the case of the postulated spherical expansion of the ejecta one would expect the Comptonized flux to become detectable with the most sensitive satellite and balloon experiments no earlier than day 250–300. In spite of that prediction, early observations were carried out as soon as 55, 86, and 95–96 days after the SN 1987A explosion (Sood *et al.* 1988; Ubertini *et al.* 1988*a*; Sandie *et al.* 1988; Cook *et al.* 1987; Matz *et al.* 1988) and led to an upper limit which was not stringent enough (flux $< 3 \times 10^{-5}$ photons cm^{-2} s^{-1} keV^{-1} in the hard X-rays) to constrain models with no mixing, such as 5L from Pinto and Woosley (1988*b*), which predicts a very low flux.

The early detection of X-rays by the *Ginga* satellite below 30 keV (Dotani *et al.* 1987) and by the MIR station between 20 and 200 keV (Sunyaev *et al.* 1987) have demonstrated that the expansion of the ejecta cannot be spherically symmetric. The basic consequences drawn from the continuum data are that the X-ray emission below 30 keV, except for the "January flare" (Tanaka 1988; Makino 1988), is generally constant and that there is a slight monotonic increase in the hard X-ray range (Sunyaev *et al.* 1988). Our data are consistent with an increase, as depicted in Figure 2, which shows the temporal evolution of the X-ray flux at 50 keV.

Figure 3 shows the SN 1987A photon intensities compared with those found by the MSFC observation (Fishman *et al.* 1989) performed 3 days later and with the emission expected on day 400 according to the theoretical models 5L (no mixing) and 10HM (mixed) given by Pinto and Woosley (1988*b*). The statistics are not good enough to discriminate between the two ^{56}Co decay models, but we believe the model 10HM to be the most realistic, taking into account the high-energy time evolution of SN 1987A (Gehrels, Leventhal, and MacCallum 1988). We have also compared our data with the prediction of the model 10HMM (Pinto and Woosley 1988*a*), which implies more mixing, and with the "plerion emission" model from Bandiera, Pacini, and Salvati (1989), and they are in agreement within the statistics with both of them.

The source of the low-energy X-ray flux from the supernova has been a problem since the very beginning from a theoretcial point of view. One of the mechanisms which could explain this emission and the "January flare" was proposed by Bandiera, Pacini, and Salvati (1989). The authors assume a "plerion emission" in the center of the supernova irradiating synchrotron photons that reach the outer envelope through optically thin "holes" in the already fragmented ejecta. This model can

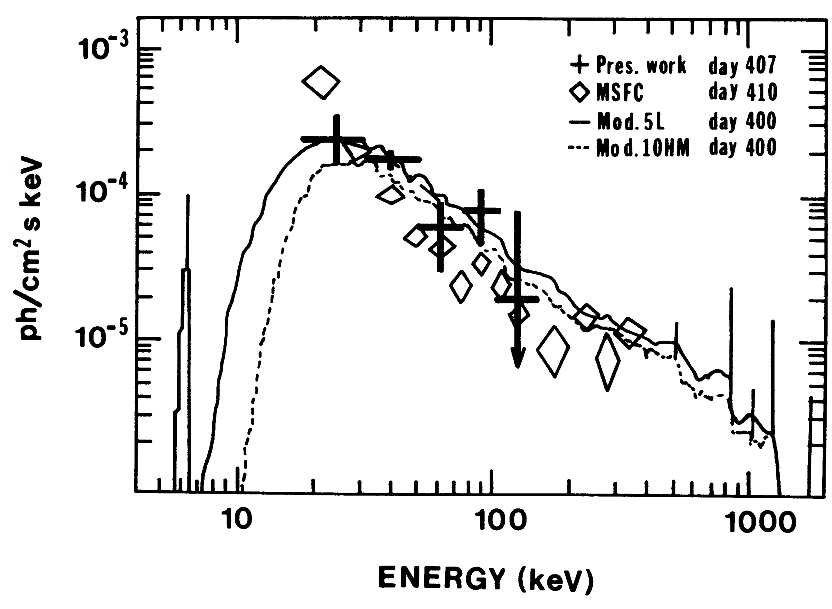

FIG. 3.—SN 1987A photon intensities compared with the MSFC data (Fishman *et al.* 1989) and with the predicted emission from theoretical models 5L and 10 HM (Pinto and Woosley 1988*b*).

very well provide an explanation for data obtained at both high and lower energies.

VI. CONCLUSIONS

The flux measured from SN 1987A on day 407, if compared with the other available observations, indicates a possible increase of the emission in the hard X-ray range. A comparison between data collected with different experiments is not straightforward and may be affected by uncertainty in the absolute efficiency of the various detectors. Nevertheless in Figure 2 we have reported all the available data at 50 keV, as far as we know, as a function of time (Ubertini *et al.* 1988*a*; Sunyaev *et al.* 1988 [taken from their Fig. 5]; Wilson *et al.* 1988; Fishman *et al.* 1989). As can be seen they are compatible with a steady emission, or a slight increase.

The presence of soft X-ray emission and the slight increase in the Comptonized flux may conflict with the pure ^{56}Co decay model and is perhaps an indication of the emergence of a low power pulsar or of some other process which is very efficient at generating X-rays with energy less than 20 keV. Further observations are fundamental to the development of a better understanding of SN 1987A.

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A. BAZZANO and P. UBERTINI: Istituto di Astrofisica Spaziale, C.P. 67-00044 Frascati, Italy

G. FRYE: Case Western Reserve University, University Circle, Cleveland, OH 44106

R. SOOD: University College, University of New South Wales, Northcott Drive, Campbel ACT, Australia 2600

R. STAUBERT: Astronomisches Institut der Universitat Tübingen, Waldhauser Strasse 64, D-7400 Tübingen, Federal Republic of Germany

T. J. SUMNER: Blackett Laboratory, Imperial College, Prince Consort Road, London SW7, United Kingdom