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DETECTION OF X-RAYS FROM SN 1987A WITH *ROSAT*

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ABSTRACT

Soft X-rays (0.5–2 keV) were detected with the *ROSAT* PSPC from the direction of SN 1987A, which falls within an association in the LMC that is rich in B stars. The emission is consistent with two point sources in the LMC with total luminosity of $\sim 10^{34}$ ergs s^{-1}. The brighter source is identified with SN 1987A on the basis of its positional agreement. We interpret the emission as arising from the interaction of supernova ejecta with the pre-existing blue giant wind. The second source may be an unidentified Be/X-ray binary. Another possibility is that the second source is an X-ray echo from the supernova outburst. The X-ray echo interpretation requires that the supernova emitted $\sim 10^{47}$ ergs in a burst of soft X-rays.

Subject headings: supernovae: individual: (SN 1987A) — X-rays: stars — supernova remnants

1. INTRODUCTION

On 1987 February 23 SN 1987A, the nearest visible supernova in 400 years, was detected in the Large Magellanic Cloud. One hundred thirty-one days later the first positive detection of X-rays was made by *Ginga* (Dotani et al. 1987) and by detectors on the MIR Space Station (Sunyaev et al. 1987) which were sensitive in the hard X-ray band. *Ginga* detected X-ray emission for ~ 1000 days after the explosion (cf. Inoue et al. 1992).

The *ROSAT* PSPC observed the SN 1987A region for 6400 s during 1990 June 17–28, following the period of "first light". It obtained an upper limit of 2.5×10^{34} ergs cm^{-2} s^{-1} in the 0.3–2.4 keV band (Trümper et al. 1991). We carried out a longer, more sensitive PSPC measurement of the region in 1991 and 1992 and detected an X-ray source at the expected position.

2. MEASUREMENTS

The dates and measurement times are given in Table 1. A contour diagram of the central region is shown in Figure 1. There is a very significant excess of ~ 60 counts above an expected background of 54 in a 1 square arcmin region. The emission is more extended than what is expected from a simple point source. A model consisting of two point sources was fitted to the data. Their positions and intensities plus a background level were treated as seven free parameters. A single source model was also fit, but the two-point source model provides a significantly better fit. However, a single extended source cannot be excluded. The positions of SN 1987A, and the two sources, source 1 and source 2, are given in Table 2.

The position of source 1 differs from that of SN 1987A by 9″.3. The 1 σ statistical error in source 1's position is 6″.6 in two dimensions. A study of a stellar association indicates there is a random systematic error of $\sim 3''$–$4''$ in PSPC positions across the central region of the detector (E. Feigelson, private communication). The combined statistical and systematic uncertainty in the position of source 1 is, thus, $\sim 8''$. This is sufficient to account for its offset from SN 1987A. The position of source 2 is 35″ from SN 1987A which is well beyond the range of uncertainty. Based upon the positional agreement, we identify source 1 with SN 1987A. Table 3 lists the number of counts detected in three pulse height bands of the *ROSAT* PSPC for sources 1 and 2.

To obtain spectral information from both sources, we compared the relative counts in the three spectral bands to a thermal spectrum (Raymond & Smith 1977, updated), as a function of temperature. Abundances of 1/3, 1, and 3 were considered. Interstellar absorption of soft X-rays was taken into account by applying the relationship between X-ray absorption and optical extinction of Gorenstein 1975, to derive $N_{\rm H} = 1.1 \times 10^{21}$ from the value of $E(B-V) = 0.17$ observed by Walker & Suntzeff 1990, for the reddening of stars near SN 1987A. The fact that the absorption takes place partly within our own Galaxy and partly in the LMC where the abundances relative to hydrogen may differ considerably is not of great significance, because both optical reddening and X-ray absorption are due to heavier elements.

The best-fit value of kT is 0.76 ± 0.20 keV (~ 1 σ error) for relative abundance of 1. The value of kT is essentially the same for abundances of 1/3 and 3. In each case, there is no upper limit to the allowed temperature at the 2 σ confidence level. At a distance of 51 kpc (Jakobsen et al. 1991; Panagia et al. 1991), the luminosity of source 1 is 8×10^{33} ergs s^{-1} and of source 2 is 4×10^{33} ergs s^{-1}. We did not analyze the data for periodic temporal variability. The small number of counts makes it difficult to search for a pulsar without prior knowledge of the period.

3. DISCUSSION

The source positions coincide with a B association within the LMC. We consider the possibility that the emission is due to stars. Walker & Suntzeff (1990) have published the *UBV* colors for the 39 brightest stars within 30″ of SN 1987A. They determine the reddening correction for these stars to be $E(B-V) = 0.17$, corresponding to $A_V = 0.51$ and $E(U-B) = 0.13$. Adopting a distance modulus of 18.5 for the LMC, we determine the intrinsic V magnitude, colors, and absolute visual magnitudes and used the tables given in Lang (1992) to assign the spectral types and the bolometric luminosities. We use a value of $\log L_X/L_{\rm bol} = (-6, -5, -6, -7)$ for (B1–B4, B5–B9, FGK, A) stars to obtain upper limits to the X-ray emission from the coronae of these stars (Maggio et al. 1990; Grillo et al. 1992). The most luminous stellar coronae in the association are early B giants with $L_X \leq 10^{32}$ ergs s^{-1}. The summed X-ray emission from all the stellar coronae should be $\leq 5 \times 10^{32}$ ergs s^{-1}. The $\log L_{\rm bol}/L_{\odot}$ limits used are valid for

TABLE 1

ROSAT OBSERVATION TIMES OF SN 1987A

Date	Time (s)
1991 Oct 6	17320
1992 Apr 30	1520
1992 May 10	1159
1992 May 12–14	7208
Total	27207

TABLE 2

SOURCE POSITIONS (J2000)

Source	RA[a]	Decl.[a]
1	$5^{\rm h}35^{\rm m}26^{\rm s}.3 \pm 0^{\rm s}.8$	$-69^\circ16'\,9''.4 \pm 4''.9$
2	5 35 21.9 ± 1.7	−69 16 26.5 ± 6.5
SN 1987A	5 35 28.0	−69 16 11.7

[a] Including 1 σ statistical errors.

[b] West et al. 1987, processed to epoch 2000 coordinates.

TABLE 3

NET COUNTS FROM SOURCES 1 AND 2[a]

Pulse Height (keV)	Source 1 (SN 1987A)	Source 2
0.07–0.40...........	6.5 (+8.6, −6.5)	0.0 (+6.1, −0.0)
0.40–1.00...........	26.6 (+8.7, −7.6)	12.5 (+10.8, −9.1)
1.00–2.40...........	17.6 (+6.2, −5.4)	10.9 (+5.2, −4.5)

[a] *ROSAT* PSPC, 27 ks.

main sequence or giant stars, so this conclusion is unaffected if the G and K stars are foreground objects within our own Galaxy. From these numbers it is apparent that none of these stars, individually, can explain the observed X-ray sources, nor can their integrated X-ray emission. An undetected cataclysmic variable cannot explain the emission since CV X-ray luminosities are in the range $10^{31\pm1}$ ergs s^{-1} (Patterson & Raymond 1985).

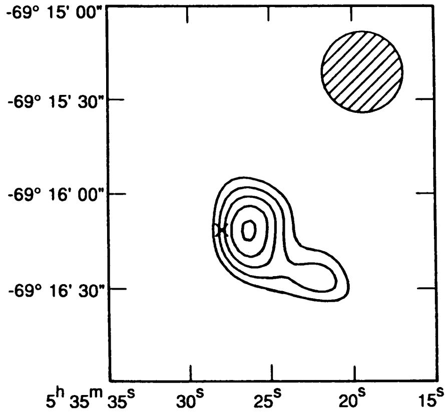

FIG. 1.—X-ray contours for the 27 ks of observing time. The contour levels are linear and range from 1.25×10^6 to 1.88×10^6 counts s^{-1} per square arcsecond. The "X" symbol denotes the position of SN 1987A. The coordinates are epoch 2000. The round cross-hatched circle shows the angular width of the *ROSAT* PSPC resolution function.

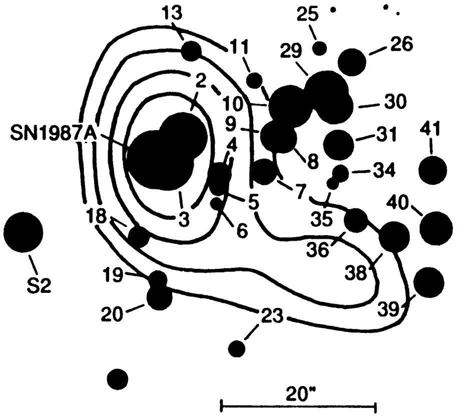

FIG. 2.—The X-ray contours superposed upon a star field derived from a *U*-band photograph by Walker & Suntzeff (1990) of the region near the SN 1987A. The contours were shifted to make source 1 coincident with SN 1987A. The stars' numbers correspond to those of Fig. 3 in Walker & Suntzeff (1990).

The only type of main-sequence or giant early B-type star known to produce X-rays of the intensity required is a Be/X-ray binary. Examples are X Per (Meurs et al. 1992) and Hen 715 (Grillo et al. 1992) both of which have been observed to have $L_X \sim 10^{34}$ ergs s^{-1} over a period of 2 decades since they were first observed by the *Uhuru* X-ray satellite (Forman et al. 1978). The recent report by Walborn et al. (1993) that star 3 of the stars within a few arcseconds of the supernova explosion (Sonneborn, Altner, & Kirshner 1987) is a Be star with a suggested spectral classification of B2II raises the possibility that source 1 is a Be/X-ray binary. However, the survey of Meurs et al. (1992) indicates that only one of the 114 stars OBe stars (X Per) in the Bright star Catalog were observed to have a luminosity within a factor of 3 of the level we measured for source 1. If the same ratio applies to the LMC, the probability that source 1 is a Be/X-ray binary is ~0.01.

It is not known whether any of the other 27 B stars of the association is a Be star, or more to the point, whether it is a Be/X-ray binary emitting at a level $\sim 10^{33.8\pm0.2}$ ergs s^{-1}. Grillo et al. (1992) found one such star (Hen 715) in a sample of 1545 B stars observed by the *Einstein* IPC, whereas Meurs et al. (1992) found one (X Per) in a sample of 1026 OB stars observed with *ROSAT*. The frequency of 1 Be X-ray binary per 1000 B stars is in agreement with the results of model calculations of the formation of Be stars through evolution of close binaries to a system with a neutron star and a rapidly spinning B star well inside its Roche lobe (Pols et al. 1992). Based on the above discussion, we estimate that the probability of one Be/X-ray binary in our sample of 27 B stars is ~0.03. From the *Einstein* Medium Sensitivity Survey (Gioia et al. 1990), we can estimate that the number of QSOs sources at the observed flux is about 60 per square degree, corresponding to a probability of ~0.02 of observing one QSO in a 1′ field of view.

On the basis of the positional agreement and the low probability of other explanations, we identify source 1 with SN 1987A. A neutron star remnant of SN 1987A should be shrouded by the ejecta that is opaque below 5 keV for radius at least 10 years after the explosion (Gorenstein et al. 1990).

We interpret the X-radiation from SN 1987A as being due to the reverse shock wave created by the interaction of the expanding ejecta with a blue giant wind, characterized by $1/r^2$ density profiles. Following Chevalier's (1982) treatment of this interaction, the luminosity of the reverse shock is $L_r = \langle n^2 V \Lambda(T)\rangle_r = 4\pi R_s^3(\Delta R_S/R_S)\langle n^2\Lambda(T)\rangle_r$, where n is the electron number density, $\Lambda(T)$ is the cooling function for a plasma of temperature T; $\langle\rangle_r$ represents an average over the reverse shock wave, and R_s is the radius of the leading shock wave, given by $R_s = 1.1 v_c\,\tau(t/\tau)^{6/7}$ for a similarity solution for ejecta with a $1/r^9$ density profile (Arnett et al. 1989) interacting with a $1/r^2$ blue giant wind. The characteristic velocity of the supernova ejecta is v_c and τ is the characteristic time for the leading shock wave to sweep up a mass in the blue giant wind equal to the ejecta mass.

If we interpolate between the figures and tables in Chevalier (1982) for the $1/r^7$ and $1/r^{12}$ models for the ejecta, we find $\langle n^2\rangle_r \approx 4000 n_b^2$ and $\langle T\rangle_r \approx 0.012 T_s$, where n_b is the density in the blue giant wind just in front of the leading shock wave and T_s is the temperature just behind the leading shock wave.

The radius of the leading shock wave is equated to the observed radio source (Stavely-Smith et al. 1992). Normalizing to the radio observations of 1991 July and using equation (2), the radius of the leading shock wave in 1991 October was $R_s = 3.7 \times 10^{17}$ cm. Its velocity was 20,000 km s^{-1}, corresponding to a temperature behind the leading shock of 400 keV, and an average temperature in the reverse shock of 5 keV. This, and higher values of kT, are not inconsistent with the observed temperature of source 1 at the 2 σ level.

In order to produce a luminosity in the *ROSAT* PSPC band of 8×10^{33} ergs s^{-1}, the density in the blue giant wind immediately in front of the leading shock wave must be $n_b \sim 3$ cm^{-3}. For temperature of the order of 5 keV most of the emission is due to thermal bremsstrahlung so the derived value of n_b is not sensitive to the assumed abundances. Since $n_b \propto (dM_b/dt)/4\pi v_b r^2$, a ratio of the mass-loss rate and wind velocity in the blue giant wind $(dM_b/dt)/v_b \sim 2 \times 10^{-6}$ $M_\odot$ yr^{-1}/300 km s^{-1} is required. This value is within the range deduced for this ratio from a consideration of the early radio emission (Chevalier & Fransson 1987) and the expansion of the observed elliptical ring (Blondin & Lundqvist 1993).

The predicted angular diameter of the supernova leading shock wave is $\approx 1''$. The X-ray luminosity should continue to decrease ($\propto R_s^{-1}$) until the supernova shock encounters the inward moving wind shock produced by the interaction of the blue giant wind with the red giant wind. At this time the luminosity should exhibit an increase ($\propto R_s^3$) and a significant hardening of its spectrum. Following that, sometime around the turn of the century, the supernova shock should encounter the inner boundary of the red giant wind and become a luminous (10^{37}–10^{38} ergs s^{-1}) source of soft X-rays (e.g., Chevalier 1982; Luo & McCray 1991).

The picture of the circumstellar environment of SN 1987A that has emerged is a complex one, involving three stellar winds, from the main-sequence, red giant, and blue giant phases; and six shock waves: forward and reverse shocks due to the interaction of supernova ejecta and blue giant wind; the interaction of the blue giant and red giant wind; and the interaction of the red giant wind or the main-sequence wind with the interstellar medium.

The structures produced by these shocks depend on the mass-loss rates, velocities, and angular symmetries of the various winds and the pressure of the ambient interstellar medium. A number of investigators have used theoretical arguments and observations at various wavelengths to piece together a fairly coherent, but uncertain, picture of the circumstellar environment of SN 1987A. Thus, for example, the early radio emission can plausibly be identified with the supernova-blue giant wind shocks (Chevalier & Fransson 1987), as can the X-ray emission that we observe. The reverse shock produced by the interaction of the blue giant and red giant winds can explain the bipolar nebular and the forward shock can explain the elliptical ring (Wampler et al. 1990; Jakobsen et al. 1991), if the red giant wind was highly asymmetric (Luo & McCray 1991; Wang & Mazzali 1992; Blondin & Lundqvist 1993).

Blondin & Lundqvist (1993) have emphasized the need for a low-momentum blue giant wind to explain the observed low expansion rate (≈ 10 km s^{-1}) of the compact circumstellar ring structure (Wampler et al. 1990; Jakobsen et al. 1991). They favor a blue wind velocity $v_b \approx 300$ km s^{-1}. In the context of our model this wind velocity implies $dM_b/dt \approx 2 \times 10^{-6}$ $M_\odot$ yr^{-1}. The numerical simulations of Blondin & Lundqvist (1993) for these parameters and the appropriate red giant wind parameters needed to explain the elliptical ring ($dM_r/dt \approx 2 \times 10^{-5}$ $M_\odot$ yr^{-1}; equator-to-pole density ratio ~ 20) produce a thin, clumpy bipolar nebula. The density in the nebula is ~ 10 cm^{-3} if the wind has been blowing for 20,000 yr. The radiative cooling time of this bubble would be $\approx 20{,}000$ yr, comparable to the age of the bubble. This indicates that the temperature of the bubble, which would be ≈ 1 million degrees in the absence of cooling, has probably cooled below a million degrees. Assuming a temperature in the nebula of 700,000 K, $L_X \sim 5 \times 10^{31}$ ergs s^{-1}; well below our range of detectability. One problem with this model for the nebula is that the position for the inward-moving shock is too far away from the supernova to be consistent with Chevalier's (1992) interpretation of the observed rise in the radio emission between days 1300 and 1500 (Stavely-Smith et al. 1992) as the interaction of the supernova shock wave with the inward-moving shock produced by the interaction of the blue and red giant winds. Our observations, coupled with Blondin & Lundqvist's model calculations, suggest that some other process (e.g., interaction with density enhancements in the blue giant wind) is needed to explain the rise in the radio emission.

Two observational tests could determine whether the X-ray emission we detect is due to shock waves produced by explosion ejecta or to the fact that the Be system Star 3 is indeed an X-ray emitter, despite the low a priori probability. One test is detection of variability. If shock waves are responsible, the flux will decrease at a modest rate $\sim 25\%$ per year (until the ejecta encounters the dense red giant wind). If an X-ray–emitting Be star is the source, then taking X per and Hen 715 as examples, we can expect variability by factors of 3 to 7. The other test is the detection of a finite size. The size is expected to be $\sim 1''$ for the shock wave source.

As described above, there is a small probability ($\sim 3\%$) that source 2 is a Be/X-ray binary. The models of Pols et al. (1992) indicate that, in order for a neutron star companion to have been formed, the B star must be of type B2 or earlier. Stars 38, 39, or 40 would appear to be the prime suspects by virtue of their spectral type and positions.

An intriguing alternate possibility is that source 2 represents an X-ray echo of SN 1987A. Chevalier & Emmering (1989) have presented a model in which the visible light echo observed 9″ from SN 1987A (Bond et al. 1989; Couch & Mailin 1989; Crotts & Kunkel 1991) is due to a shock wave produced by the interaction of the presupernova red giant wind with the interstellar medium. They estimate the radial distance R of the shock from the supernova to be ~ 15 light years.

For a thin shell the apparent angular radius of the echo ring is $\theta = 1.4(t-t_e)\{[2R/(t-r_e)] - 1\}^{1/2}$ arcsec, where t is the time of observation and t_e is the time of emission, both in years (Chevalier & Emmering 1989). For $R = 15$ light years and $t_e \ll 1$ yr, we find that the echo should have moved from 10″ at $t = 2$ yr to 15″ at $t = 5$ yr. Given the uncertainties in the radius and thickness of the shell, and our position for source 2, the predicted angular size of the echo is consistent with our observations. The required asymmetry of the echo is not inconsistent with the trend toward increasing fragmentation with time observed by Crotts & Kunkel (1991).

The brightness of the echo requires that the supernova was a luminous source of X-radiation. Taking a column density through the red giant shell of $N_{\rm H} = 3 \times 10^{18}/{\rm cm}^2$ (cf. Chevalier & Emmering 1989), the fraction $f_{\rm sc}$ of scattered X-ray luminosity from the shell is $\sim 3 \times 10^{-5}$ (cf. Mauche & Gorenstein 1986; Gorenstein 1975) and a fraction, 3×10^{-14} of the energy of the supernova X-ray burst will appear in the echo (cf. Chevalier & Emmering 1988). An X-ray burst of the order of 10^{47} ergs is required to explain our source 2 in terms of an X-ray echo. In their study of the UV and optical emission lines of SN 1987A, Fransson & Lundqvist (1989) found that blackbody temperatures in the range 3×10^5 to 8×10^5 K are favored and that at least 10^{56} photons above 100 eV were required. If we assume that $\sim 3 \times 10^{56}$ photons of average energy 200 eV (8×10^5 K blackbody) were emitted, the emitted energy in soft X-rays is 10^{47} ergs, which is not inconsistent with the data, given the uncertainties in the spectrum of source 2.

The X-ray echo hypothesis makes a number of predictions: (1) the distance of source 2 from SN 1987A should increase with time; (2) the intensity of source 2 should decrease by 25% yr^{-1} due to changes in the scattering angle; (3) the spectrum of source 2 should be soft, corresponding to a blackbody temperature 8×10^5 K.

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