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The Oriented Scintillation Spectrometer Experiment - Instrument Description

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ORIENTED SCINTILLATION SPECTROMETER EXPERIMENT OBSERVATIONS OF ^{57}Co IN SN 1987A

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ABSTRACT

The Oriented Scintillation Spectrometer Experiment (OSSE) on the *Compton Gamma Ray Observatory* has observed SN 1987A for two 2 week periods during the first 9 months of the mission. Evidence for gamma-ray line and continuum emission from ^{57}Co is observed with an intensity of about 10^{-4} gamma cm^{-2} s^{-1}. This photon flux between 50 and 136 keV is demonstrated by Monte Carlo calculations to be independent of the radial distribution of ^{57}Co for models of low optical depth, viz., models having photoelectric absorption losses of 122 keV photons no greater than several percent. For such models the observed ^{57}Co flux indicates that the ratio ^{57}Ni/^{56}Ni produced in the explosion was about 1.5 times the solar system ratio of ^{57}Fe/^{56}Fe. When compared with nearly contemporaneous bolometric estimates of the luminosity for SN 1987A, our observations imply that ^{57}Co radioactivity does not account for most of the current luminosity of the supernova remnant in low optical depth models. We suggest alternatives, including a large optical depth model that is able to provide the SN 1987A luminosity and is consistent with the OSSE flux. It requires a 57/56 production ratio about twice solar.

Subject headings: gamma rays: observations — nuclear reactions, nucleosynthesis, abundances — supernovae: individual (SN 1987A) — X-rays: general

1. INTRODUCTION

The supernova SN 1987A has provided a wealth of information about Type II supernovae. Gamma-ray measurements provided direct evidence (e.g., Leising & Share 1990 and references therein) for the production of ^{56}Ni in the event, as suggested by Clayton, Colgate, & Fishman (1969). Those detections confirmed that the radioactive decay $^{56}\text{Ni} \rightarrow {}^{56}\text{Co} \rightarrow {}^{56}\text{Fe}$ powers the exponential light curves of supernovae, as suggested by Colgate & McKee (1969). After 800 days the energy input from ^{56}Co decay cannot account for the observed luminosity. Other sources of energy which may contribute at these late times include radioactive decay of ^{57}Co or ^{44}Ti, energy from an undetected central compact object, or conversion of some form of stored energy from earlier phases of the supernova.

Nucleosynthetic models suggest that ^{57}Co (270 day half-life) and ^{44}Ti (48 yr half-life) may be the dominant sources of energy input into the nebula during the latter phases of the expansion (Clayton 1974; Woosley, Pinto, & Hartmann 1989). ^{57}Co is expected to be the major power source for the epoch of the OSSE observations, at which time we expect between one-third and two-thirds of the 122 keV gamma rays emitted by ^{57}Co to escape directly and the remainder to scatter in the expanding nebula. Most of those that interact (by Compton scattering) also escape, but with a slightly reduced energy. Therefore, a strong Compton continuum between about 50 and 122 keV is expected, but with the fraction in the continuum declining and the 122 keV line escape fraction increasing toward unity as the nebula becomes transparent. Because total absorption of the gamma radiation is unlikely at these late times for published models of SN 1987A, the sum of these two fractions is expected to be nearly constant and provides an approximately model-independent measure of the ^{57}Co yield. Woosley et al. (1989) expect a 122 keV line flux of 3.1×10^{-5} cm^{-2} s^{-1} at 1600 days for their 10HMM model. They take a ^{57}Ni/^{56}Ni production ratio (hereafter referred to as a "57/56 production ratio") equal to the solar system ^{57}Fe/^{56}Fe abundance ratio (Anders & Grevesse 1989). For model SN14E1 of Nomoto et al. (1988) and a 57/56 production ratio of 1.0 times solar, we expect a 122 keV line flux only slightly less: 2.7×10^{-5} cm^{-2} s^{-1}.

The amount of ^{57}Co produced in the explosion is of particular interest, for it is a measure of both the "neutron excess" in the region just outside the mass cut and the nuclear equilibrium mass that freezes out with excess alpha particles. This will ultimately provide information about the dynamics of the core bounce mechanism. Thus, a determination of the amount of ^{57}Co provides information about the presupernova object and the core explosion, whereas the ratio of the 122 keV line to Comptonized continuum measures the gamma-ray thickness of the ejecta. Nucleosynthetic models for SN 1987A and general nucleosynthesis constraints suggest that the production ratio of ^{57}Ni/^{56}Ni was between 0.7 and 3.0 times the solar ratio of ^{57}Fe/^{56}Fe (Thielemann, Hashimoto, & Nomoto 1990; Woosley 1991; Woosley & Hoffman 1991).

Based on the inferred bolometric luminosity in the optical and infrared, Suntzeff et al. (1992) have suggested that ^{57}Co was powering the luminosity at day 1300–1500 and, further-

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more, that the 57/56 production ratio in the remnant was about 5 times solar ^{57}Fe/^{56}Fe. Dwek et al. (1992) also infer a bolometric luminosity that suggests an enhancement of 4.6 ± 1.5 relative to solar. Varani et al. (1990), however, using infrared observations of cobalt lines 400 days after the explosion, infer a 57/56 production ratio of 1–2 times solar. Danziger et al. (1991) obtained a similar value. Gamma-ray observations of ^{57}Co provide a more direct determination of the radioactive power into the nebula from ^{57}Co. Sunyaev et al. (1991) have reported an upper limit of 1.5 times solar for the 57/56 production ratio obtained from observations in the period 1988 September–1989 June. However, their limit is quite model-dependent, since it was obtained when the supernova envelope was still optically thick at 122 keV. Recently, Gunji et al. (1992) have reported a limit of 3.0 times solar from a balloon observation 1373 days after the explosion. The OSSE results reported here provide the first direct measurement of the amount of ^{57}Co produced in the explosion.

2. OBSERVATIONS

The characteristics and performance of the Oriented Scintillation Spectrometer Experiment (OSSE) instrument have been described by Johnson et al. (1993). The OSSE experiment utilizes four identical detector systems employing large-area NaI(Tl)–CsI(Na) phoswich detectors. Each detector has a $3^{\circ}\!.8 \times 11^{\circ}\!.4$ (FWHM) field of view defined by tungsten collimators. The OSSE observation strategy is implemented by alternately pointing each detector at source and background positions on a time scale (131 s) which is short with respect to typical orbital background variations.

Two observations of SN 1987A have been obtained with OSSE. The first occurred from 1991 July 25 through 1991 August 8 (1613–1627 days after the explosion) and the second from 1991 December 27 through 1992 January 10 (1768–1782 days after the explosion). For both of these observations SN 1987A was one of two sources being studied with the OSSE experiment. Each of the sources was observed during some portion of every 93 minute orbit. The SN 1987A investigations used a "standard" pointing strategy where each OSSE detector alternately viewed SN 1987A and background regions offset to either side of SN 1987A. For the observations of SN 1987A, OSSE was operated at a gain which covered the spectral range from 50 keV to 5 MeV. One 256 channel spectrum covered the energy range from 50 to 700 keV used in the analysis presented here. The spectral resolution for the four detectors at 122 keV ranges from 13% to 15% FWHM. Pulse-height spectra were accumulated every 16.38 s from each detector, synchronized with the source/background offset pointing. The total observation times for SN 1987A were 5.3×10^5 and 5.4×10^5 s for the first and second observations, respectively. The 3 σ line sensitivity at 122 keV is approximately 3×10^{-5} gamma cm^{-2} s^{-1} for each observation period.

Several hard X-ray sources in the Large Magellanic Cloud (LMC) were also observed within the large OSSE field of view with appreciable but differing relative exposures. Any interpretation of the resulting observations must take into consideration the possible contributions from these other sources and the unique signature expected for the ^{57}Co feature. During the first observation the background regions did not contain any known hard X-ray sources; however, this was not the case for the second observation. In particular, the source LMC X-3, a black hole candidate and known variable source (Treves et al. 1988), was located in the source region during the first observation with an effective exposure of about 30%. During the second observation the orientation of the detector scan plane was such that LMC X-3 was viewed with about a 76% relative exposure for one of the background regions. If this source was active during the second observation, and if it was the dominant X-ray source at the time, the resulting spectra obtained for SN 1987A would exhibit an apparent "negative" component. We shall return to this.

3. DATA ANALYSIS AND RESULTS

For each of the 131 s observations of SN 1987A, an estimated background spectrum was generated by fitting the three or four closest background spectra, channel by channel, with a quadratic function in time. Evaluating this function at the source time provides the estimated background in each channel. This estimated background was then subtracted from the source spectrum to obtain a difference spectrum for the 131 s period. Typically, 8–10 such difference spectra per detector are obtained for each orbit, for a total of about 500 day^{-1}. Summing these difference spectra results in an average source spectrum over the entire observation period for each detector.

The spectral analysis was accomplished by folding assumed photon spectra through the OSSE instrument response and fitting to the observed count spectra using least-squares fitting techniques. The summed spectrum for the first OSSE observation is shown in Figure 1*a*. The spectrum exhibits a soft excess in the 50–80 keV region which is probably associated with one of the X-ray sources in the LMC. Emission at these energies and at this intensity is not expected from radioactivity in the supernova at this time (Woosley et al. 1989). We cannot,

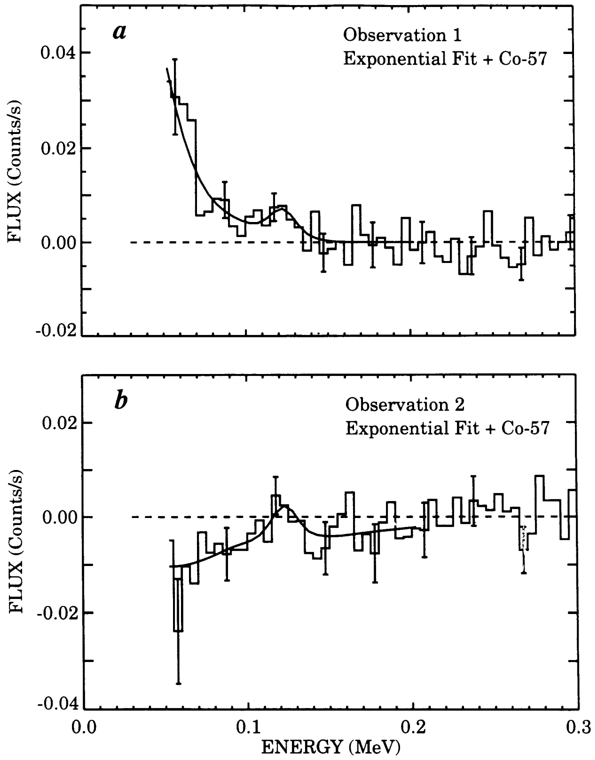

FIG. 1.—(*a*) Energy spectrum for the 1991 July observation. The solid curve is the best fit for an exponential plus a model 10HMM ^{57}Co template. (*b*) Energy spectrum for second observation. The best-fit exponential plus model 10HMM ^{57}Co template is shown. The negative exponential component probably reflects an LMC X-3 contribution during background pointings.

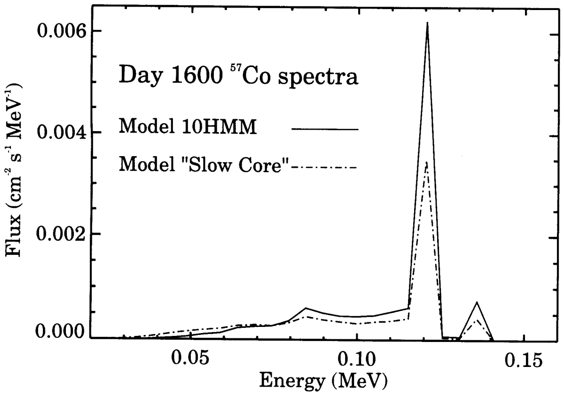

FIG. 2.—^{57}Co templates for 10HMM and "slow core" models, for a 57/56 production ratio of 1.0 times solar. The model photon spectra have been binned into 5 keV wide channels.

however, rule out that this emission originates from a pulsar or a central accreting compact object associated with SN 1987A. We consider this possibility later.

Evidence for ^{57}Co emission from SN 1987A is seen in the excess emission in the 80–130 keV range. This excess is attributed to a combination of unscattered ^{57}Co radiation at 122 and 136 keV plus a Compton-scattered component of these lines which would extend down to about 80 keV, before declining more rapidly at lower energies. We have used Monte Carlo calculations to investigate the shape of the ^{57}Co feature near the time of the OSSE observations. Figure 2 shows the expected photon spectrum in 5 keV bins for two models which represent realistic limits for the fraction of 122 keV line emission which scatters in the envelope. The first model is 10HMM, and the second is a modification of 10HMM in which most of the ^{57}Co is more deeply buried than in 10HMM. See Clayton et al. (1992, hereafter Paper II) for details. Both models are shown for a 57/56 production ratio of 1.0 times solar. While the shapes of the two spectra are not very different, fewer photons escape from the thicker model. The uncertainty in the gamma-ray opacity ultimately provides the largest uncertainty in our determination of the ^{57}Co mass.

The least model-dependent way to measure the mass of ^{57}Co at these late times is to measure the total 50–136 keV flux. Most of the scattered photons only scatter one or two times and then escape in the continuum. For models having no more than a few percent photoelectric absorption, the total 50–136 keV flux is almost independent of the radial mixing. For more opaque models it is a better measure of the ^{57}Co mass than the 122 keV line alone.

We have fitted the spectrum from the first observation with model SN 1987A spectra consisting of the ^{57}Co template (lines and scattered radiation) and an additional low-energy component assumed to originate from another source in the LMC. The latter component was assumed to be either a simple power-law or thermal bremsstrahlung spectrum. The best-fit results are given in Table 1. Both of these fits require a ^{57}Co component with an intensity which corresponds to a ^{57}Ni/^{56}Ni production ratio which is about 1.5 times solar ^{57}Fe/^{56}Fe for low optical depth models such as 10HMM and SN14E1 (see Paper II). We have also used the F-test to determine the requirement for the ^{57}Co component and find that it is required at levels consistent with the errors reported. This supports the ^{57}Co interpretation of the hard component we observe. Fits to the simple continuum models plus a single Gaussian line at 122 keV were also done. These typically result in a line intensity of $(6 \pm 1.5) \times 10^{-5}$ photons cm^{-2} s^{-1}, although in this case some of the scattered component is included in the fitted line flux. We also tried more complex fits, such as two–power-law models plus the ^{57}Co feature; these also require ^{57}Co components comparable to the simple models.

A similar analysis has been carried out for the second observation period, which was approximately 150 days later. At that time the ^{57}Co emission would be expected to be about 30% lower than during the first observation. As seen in Figure 1*b*, the background-subtracted spectrum below 100 keV is negative, suggesting a contribution from one or more of the LMC sources in one or both of the background regions. LMC X-3 is the most likely candidate. We have also fitted the second observation with model spectra which include the model ^{57}Co template and single power-law or thermal bremsstrahlung component. The fitted parameters are given in Table 1.

We have also fitted the two observations simultaneously, allowing for the exponential decay between the two and independent continuum components for each period. Combining the results from the two OSSE observations in this way, we detect emission consistent with a partially scattered ^{57}Co spectrum with intensity $(9.0 \pm 2.0) \times 10^{-5}$ photons cm^{-2} s^{-1} in both line and continuum (epoch = day 1600). This corresponds to a ^{57}Ni/^{56}Ni production ratio of 1.5 ± 0.3 times solar for relatively thin models. We assign an additional systematic

TABLE 1

BEST-FIT RESULTS

Model	χ^2	Continuum Component (photons cm^{-2} s^{-1} MeV^{-1})	^{57}Co Flux (photons cm^{-2} s^{-1})[a]	^{57}Co Mass[b]
		Observation 1 (epoch days 1613–1727)		
Exponential + ^{57}Co	0.90	$(0.034 \pm 0.007) \exp[-(E - 50)(\mathrm{keV})/(11.2 \pm 2.1)]$	$(9.0 \pm 2.2) \times 10^{-5}$	1.4 ± 0.4
Power law + ^{57}Co	0.89	$(0.038 \pm 0.008) [E(\mathrm{keV})/50]^{-5.8 \pm 1.0}$	$(8.2 \pm 2.3) \times 10^{-5}$	1.3 ± 0.4
		Observation 2 (epoch days 1768–1782)		
Exponential + ^{57}Co	0.96	$(-0.0063 \pm 0.0022) \exp[-(E - 50)(\mathrm{keV})/(68 \pm 28)]$	$(10.0 \pm 4.2) \times 10^{-5}$	2.3 ± 0.9
Power law + ^{57}Co	0.99	$(-0.0088 \pm 0.0033) [E(\mathrm{keV})/50]^{-1.6 \pm 0.6}$	$(9.0 \pm 3.9) \times 10^{-5}$	2.1 ± 0.9

[a] This is the total 50–136 keV flux in the ^{57}Co template when the counts are fitted to that template and the indicated continuum component.

[b] This is the ^{57}Co mass in units of 0.0018 $M_{\odot}$, or, equivalently, the ratio of the ^{57}Ni/^{56}Ni production to the solar system ^{57}Fe/^{56}Fe ratio when the observed flux in the ^{57}Co template is interpreted in terms of low optical depth models. We assume 0.075 $M_{\odot}$ ^{56}Ni production in SN 1987A at a distance of 50 kpc.

uncertainty of ±1.0 × 10^{-5} photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ full range in the intensity and ±0.2 in the 57/56 production ratio due to the dependence of the result on the shape of the additional continuum component. If one chooses to treat this as an upper limit to the production of ^{57}Co in SN 1987A, the corresponding 3 σ upper limit would be 2.6 times solar. On the other hand, simultaneous fits to both observations for the "slow core" model results in a 57/56 production ratio of 2.6 ± 0.6. This higher value results from the increased opacity of that model and not from any difference in the assumed ^{57}Co spectrum (see Fig. 2).

4. DISCUSSION

The OSSE results present compelling evidence for ^{57}Co emission from SN 1987A in the period between 1600 and 1800 days after the explosion. This result addresses the source of the power radiated by SN 1987A. The recent photometric data of Suntzeff et al. (1992) and Dwek et al. (1992) have led them to conclude that the ^{57}Ni production was about fivefold greater than solar when compared to the ^{56}Ni. Our data indicate a ^{57}Co flux (direct plus scattered component) of $\sim 10^{-4}$ gamma $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, which implies a ^{57}Co/^{56}Co ratio that is 1.5 times solar for low optical depth models. The OSSE data thus stand in conflict with the conclusions from the photometric arguments. We suggest here several possibilities to resolve this conflict. Details and additional possibilities are presented in Paper II (Clayton et al. 1992).

The ^{57}Co may be much more deeply buried than in 10HMM or in SN14E1. These models are characterized by escape of 82% and 81%, respectively, of the ^{57}Co power at $t = 1700$ days. If half of the ^{57}Co power is absorbed as in the "slow core" model described in Paper II, the enhancement of the ^{57}Co power would be a factor of 2.5. Therefore, production of ^{57}Co at 1.0 times solar could provide half the bolometric requirement (Dwek et al. 1992; Suntzeff et al. 1992). In Paper II we show that the "slow core" model with a ^{57}Co content about twice solar characterizes both the bolometric luminosity and the OSSE data reasonably well.

Another potential energy source is a central pulsar or accreting object which is the remnant of the supernova explosion. If the 50–80 keV flux we observed in observation 1 were associated with a central object, about a third of the energy in this region would be absorbed in the envelope for reradiation at longer wavelengths and would correspond to an energy input of $\sim 1 \times 10^{37}$ ergs s^{-1} for a source at the distance of the LMC and for low optical depth models. This is approximately the bolometric luminosity at the time of our observations. However, extrapolating this soft spectrum to lower energies where a much higher fraction of the X-ray energy would be absorbed in the nebula would make the inferred X-ray input into the nebula larger than the bolometric luminosity. The negative low-energy component in our second observation suggests that the 50–80 keV flux in the first observation is associated with one of the other sources in the LMC (probably LMC X-3), or that a central object in SN 1987A has changed intensity markedly between the two observations.

Alternatively, the ^{56}Co power might not all be radiated instantaneously. We point out in Paper II (Clayton et al. 1992) that only a very small percentage of the energy released by the decay of ^{56}Co need be stored and released at a later time to explain the apparent excess luminosity for the period 1200+ days after the event. Several mechanisms for storing and releasing the energy are presented there.

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