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THE GAMMA-RAY LIGHT CURVES OF SN 1987A

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ABSTRACT

We report the fluxes in four γ-ray lines from ^{56}Co decay in the ejecta of SN 1987A, as measured by the *Solar Maximum Mission* Gamma-Ray Spectrometer over the period from 1987 February through 1989 May. Significant fluxes in these lines are found from mid-1987 through mid-1988. Analysis of data accumulated before 1987 February allows us to rule out the possibility that these features are instrumental and to evaluate the magnitude of possible systematic errors in the measured line fluxes. We find that the observed γ-ray light curves can be fitted quite well with analytic models in which a small fraction of the ^{56}Co has reached regions of very low γ-ray optical depth (of order unity) by 200 days after outburst. The data are not consistent with models in which all of the ^{56}Co remains at a single depth under a uniform, expanding envelope. Based on these simple models, we estimate the total luminosity in γ-ray lines and continuum as a function of time. Adding this to the luminosity observed from the ground, we find reasonably good agreement with the decay power of 0.07 $M_{\odot}$ of ^{56}Co in the ejecta. We also estimate the escape fraction of γ-rays from ^{57}Co, which will be needed to determine from future γ-ray line measurements the ejected mass of that radioisotope.

Subject headings: gamma rays: general — stars: individual (SN 1987A) — stars: supernovae

I. INTRODUCTION

A primary objective of γ-ray astronomy is the detection of freshly synthesized radioactivity. Such observations provide undeniable evidence of ongoing nucleosynthesis, further confirming the long-held idea that the elements originated in stars (e.g., Hoyle 1946). Supernovae, the dominant sites of nucleosynthesis of many nuclides, have been predicted to be sources of detectable γ-ray lines, especially those from the decay chain $^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$ (Clayton, Colgate, and Fishman 1969). The realization of this prediction is fundamental to the success of contemporary supernova theory.

SN 1987A in the Large Magellanic Cloud (LMC) has provided remarkable confirmation of theories of many aspects of Type II supernovae (see, for example, the review of Arnett *et al.* 1989 and references therein). That the explosion synthesized a significant quantity of radioactivity was convincingly demonstrated by the observation that the optical luminosity after the first few months followed the 113 day exponential decay of ^{56}Co (e.g., Catchpole *et al.* 1988; Hamuy *et al.* 1988). Further, the presence of large quantities of elemental cobalt was inferred from infrared line observations (e.g., Rank *et al.* 1988), also implying that radioactive cobalt was present in the ejecta. Finally, the unambiguous γ-ray line signatures of ^{56}Co were detected (e.g., Matz *et al.* 1988), as was the extremely hard X-ray continuum from multiple Compton scatterings of the γ-ray line photons in the ejecta (e.g., Dotani *et al.* 1987; Sunyaev *et al.* 1987).

In this work we further analyze data from the γ-ray spectrometer (GRS) on the *Solar Maximum Mission* (*SMM*) satellite and include data from that experiment through 1989 May. We show that at least four γ-ray lines of ^{56}Co have been detected from SN 1987A for a period of roughly 1 yr. Our results are consistent with earlier *SMM* results (Matz *et al.* 1988; Matz, Share, and Chupp 1988) and generally consistent with measurements by balloon-borne experiments (see § IV). In addition to proof of the existence of newly synthesized radioactivity, γ-ray line observations can provide a diagnostic of supernova structure (e.g., Clayton 1982). Although the modest energy resolution of the GRS precludes strong conclusions about the velocity of the γ-ray emitters, the instrument's constant monitoring capability allows us to follow the γ-ray fluxes over a long time, thus measuring the changing transparency of the ejecta. By fitting simple analytic models to the γ-ray light curves, we can derive information about the distribution of the radioactive ^{56}Co within the ejecta.

With the aid of these models we can then calculate the total escaping γ-ray line luminosity, including unmeasured lines, so we can semiempirically determine the high-energy luminosity as a function of time. An estimate of the luminosity in X- and γ-rays is needed to monitor completely the bolometric luminosity after the first 6 months or so. By comparing the observed luminosity with the decay power of the inferred ^{56}Co radioactivity, one can search for and place limits on additional energy sources. Further, our estimate of the γ-ray transparency of the ejecta allows us estimate the escape of γ-rays at later times, which is of particular importance for γ-rays from ^{57}Co decay (mean lifetime 392 days). Such estimates will be useful in deriving the total ejected mass of ^{57}Co, should measurements of γ-ray lines from it be made by future experiments.

II. INSTRUMENT CHARACTERISTICS

SMM was launched in 1980 February to observe the Sun during the peak of 11 yr solar cycle 21. The spacecraft operated for most of the time from then until its demise in 1989 December. A problem with the spacecraft attitude control system produced some uncertainty ($\sim 10°$) in the actual pointing direction from late 1980 until it was repaired by Space Shuttle astronauts in 1984. No data were recorded for 5 months before that time.

One of seven experiments on board, the GRS consists of seven 7.6 cm diameter × 7.6 cm thick cylindrical NaI detectors enclosed in an anticoincidence shield. It has a broad field of view for γ-rays, defined by a 2.5 cm thick CsI annulus aligned with and surrounding the detectors and a 7.6 cm thick CsI disk behind them. Plastic scintillation counters cover the front and rear of the instrument to reduce further the charged particle backgrounds. The spectrometer is sensitive to γ-rays from 0.3 to 8.5 MeV, with energy resolution of 6.4% FWHM at 1.0 MeV. The instrument is described in detail by Forrest *et al.* (1980). The spectrometer has been remarkably stable for more than 9 yr. A discussion of its performance can be found in Share *et al.* (1988).

The axis of the instrument is aligned with the spacecraft axis which is normally pointed at the Sun. Because the LMC is near the south ecliptic pole, γ-rays from that direction must pass through the CsI annulus to reach the central detectors. This significantly reduces the efficiency of the GRS for detecting those γ-rays but allows monitoring of the supernova with constant efficiency (i.e., the LMC direction is always nearly perpendicular to the detector axis so that the detector effective area at 847 keV is always ~ 41 cm^2). For roughly half of each year since the outburst of SN 1987A, the spacecraft was rolled slightly ($\sim 20°$) about the spacecraft-Sun vector to ensure that other substantial spacecraft structures did not intervene between the GRS detectors and the LMC.

III. DATA ANALYSIS

Our basic data base consists of 1 minute summations of 476 channel energy-loss spectra from 0.3 to 8.5 MeV, each accumulated at least 10^4 s after passages through the South Atlantic Anomaly (SAA). Data including solar flares, γ-ray bursts, known magnetospheric or man-made background events, or telemetry errors were excluded. We utilize such spectra accumulated from the time after the *SMM* repair in 1984 until 1989 May. This amounts to some 7×10^5 spectra and associated spacecraft information.

a) *Background Subtraction*

The counting rates of simple γ-ray detectors in satellite orbits are large. The raw GRS count rates in channels corresponding to the energies of ^{56}Co decay lines are hundreds of times larger than the expected peak rates from SN 1987A. The background rates also vary on time scales from seconds to 11 yr (e.g., Share *et al.* 1988). Dedicated astronomical γ-ray experiments on satellites have been designed so that count rates due to cosmic sources are modulated on time scales different from those of background variations. This usually involves rapidly chopping on/off, or scanning past, source positions. Because it was designed to observe solar transient emission, cosmic signals in the *SMM* GRS are modulated only by the slowly changing aperture response as the detector axis (following the Sun) annually traces the ecliptic, and as Earth occults a given source for part of an orbit. The former modulation has been used to successfully detect persistent emission from the Galactic plane (Share *et al.* 1985; Share *et al.* 1988; Harris *et al.* 1990) but is not useful for sources far from the ecliptic. The latter modulation (Earth occultation of sources) has been taken advantage of to detect ^{56}Co lines from SN 1987A (Matz *et al.* 1988; Matz, Share, and Chupp 1988). This method is problematic because the source signal is modulated on the time scale of the orbital period—the same time scale on which significant background variations occur, namely those variations due to Earth atmosphere albedo γ-rays and spacecraft activation by cosmic rays. Matz *et al.* were able to remove most short-term background effects by fitting the features remaining in the spectra in some detail. However, variations of the measured ^{56}Co line amplitudes in excess of statistical fluctuations demanded relatively large increases in the quoted uncertainties to allow for systematic errors. In this work we also use the data accumulated when the source (SN 1987A) is behind Earth as viewed by the detector to measure slowly varying backgrounds, but we first attempt to remove more rapid orbital background variations from all spectra. The method by which this is done is described in detail in the Appendix.

Although $\sim 90\%$ of the sky is occulted for some time each orbit, the fraction of the sky which is blocked long enough for a statistically significant background measurement to be performed is smaller. When the axis of the spacecraft orbit precesses such that it points close to the source, there is insufficient modulation of the source counts to reliably determine the source contribution to the total count rate (i.e., a useful background measurement is not made for those orbits). Unfortunately, this shortcoming of the method has not been overcome, and so the data with the greatest (100%) exposure to SN 1987A are not used in this analysis.

The net background-corrected difference spectra are accumulated as described in the Appendix for the source position of SN 1987A for every orbit where that position is occulted for at least 20% of the live time. This occurs for some 35 days out of each 53 day *SMM* orbital precession period. These spectra are then summed, weighted by their statistical uncertainties, to ~ 35 days. This is the maximum continuous observation we can perform with this technique and is about the integration time required to obtain statistically significant measurements of the predicted line fluxes.

We perform one further correction to these spectra. Because the right ascension of the LMC is near that of the Crab Nebula and nearly $12^{\rm h}$ from that of the Galactic center, our selection of source and background spectra based on the occultation of the LMC produces a net positive exposure to the Crab and net negative exposure to the inner Galactic plane. We must therefore subtract the contributions of these sources to the difference spectra. We subtract the count-rate spectra measured by Harris *et al.* (1990) for the Galactic center region (their Fig. 3) and the Crab (M. J. Harris 1989, private communication) multiplied by the fractional exposures to the Galactic center and the Crab positions, respectively, at each energy. The uncertainties inherent in this procedure make more detailed treatments no more meaningful. We expect that we have not completely removed the contributions of these sources, but neither source is known to emit γ-ray lines near the energies of the stronger ^{56}Co lines.

b) *Spectral Fitting*

We must model the resulting net "supernova" spectra in order to extract the actual fluxes in the lines of interest. We have chosen to perform fits to the count-rate spectra, approximating limited ranges of the continuum with smooth functions and fitting the peaks of known background and ^{56}Co lines with Gaussian functions. This technique, which has generally proved reliable in analysis of GRS data, is used because the photopeak response is the best known feature of the instrument response and because the procedure is quite stable. We can therefore quickly fit many spectra with identical initial models in an automated fashion.

To determine the SN 1987A ^{56}Co line fluxes we performed least-squares fits to two separate energy ranges of each count-rate spectrum. This is illustrated in Figure 1, where we show the actual fits to the spectrum accumulated from 1987 September 28 to October 31 (days 217–250). In the lower energy range,

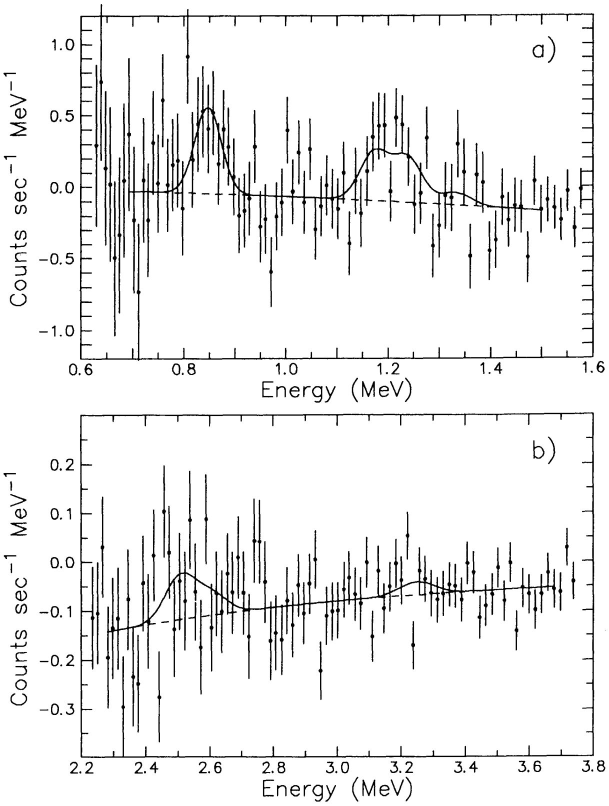

FIG. 1.—Illustration of the fits, as described in § III*b*, to the difference spectrum accumulated from 1987 September 28 to October 31 (days 217–250) in the two separate energy ranges. (*a*) The fit from 0.7 to 1.5 MeV including Gaussian lines fixed at 0.847, 1.173, 1.238, and 1.332 MeV. All widths were fixed at instrument resolution for these fits. (*b*) The fit from 2.3 to 3.7 MeV including lines at 2.505, 2.599, and 3.250 MeV.

we fitted a power-law continuum from 0.70 to 1.5 MeV with four lines superposed. The line energies were fixed at 0.847 and 1.238 MeV, from ^{56}Co decay, and at 1.17 and 1.33 MeV, the energies of expected residual background lines which result from nonvetoed photons from the on-board ^{60}Co calibration source. We also fitted each spectrum with a power-law continuum from 2.3 to 3.7 MeV and three lines, a ^{56}Co decay line at 2.599 MeV, a broad feature at 3.25 MeV, to measure three unresolved ^{56}Co lines at 3.202, 3.254, and 3.273 MeV, and a background line at 2.5 MeV (the sum peak of the two ^{60}Co lines). The widths of all lines except the 3.25 MeV line were fixed at the instrument resolution (from 57 keV FWHM at 0.847 MeV to 120 keV FWHM at 2.6 MeV). Note that any reasonable intrinsic width of the ^{56}Co lines from SN 1987A (of order 1%) will be dwarfed by the instrumental widths. Reported uncertainties are statistical and are determined for each line by fixing the amplitude at values increasingly different from the value at which the χ^2 statistic is minimized, allowing other fit parameters to be free, until χ^2 increased by unity from its minimum value (e.g., Lampton, Margon, and Bowyer 1976).

To check this method and to show that the Compton continua intrinsic to the supernova spectrum do not greatly affect the measured line fluxes, we also fitted models of the source photon spectrum convolved with the instrument response to the SN 1987A count-rate spectra (the difference spectra from after 1987 August). Such a procedure, fitting γ-ray spectra with models of the input photon spectra is generally preferred, but in the present analysis it is extremely complex and often unstable. The residual background spectra which we must model in addition to the source spectra are from photons which impinge on the detector from all angles, originate within the detector, and can have both positive and negative components in the net difference spectra. We cannot accurately model all these processes, but as a check of the fitting method described in the previous paragraphs, we fitted small energy ranges around the ^{56}Co lines with simplified photon models. These consist of power-law continua, Gaussian peaks with bounds on the energies and widths, and (approximate) Compton continua of fixed shapes and variable amplitudes. The models are convolved with the calculated detector response at 90° off-axis (from a Monte Carlo simulation; S. Matz and G. Jung 1987, private communication) and compared to the count-rate data. The success of this fitting procedure is variable and sensitive to the initial values of the model parameters. However, when good fits are obtained, the best-fit values of the line intensities are typically within 20% of the values obtained in the more straightforward count-rate fits reported here and are not systematically different (and therefore are within statistical uncertainties). We therefore conclude that our fits to the count-rate spectra give adequate estimates of the actual line fluxes.

IV. RESULTS

We generated each of the ~35 day mean difference spectra for the position of the LMC, as described in § III*a* and in the Appendix, for roughly 5 yr of data. Generally, even before 1987 the spectra are not consistent with a null spectrum. The residual features probably result from incompletely subtracted Earth atmospheric and Galactic plane γ-rays. Those spectra are similar to each other in shape, so it is difficult to distinguish between them in our net difference spectra. The magnitudes of the residual features are at worst comparable to the known Galactic plane signals (e.g., in the continuum above 5 MeV, or in the 511 keV line) and are only a few percent of the average count rates due to Earth's atmosphere. The amplitudes of these features vary with a 1 yr period which is consistent with the variation of the exposures to both Earth's atmosphere and cosmic sources near the ecliptic plane. Other background features sometimes appear in these difference spectra, namely in the region between 600 and 700 keV, and at 1.17, 1.33, and 2.50 MeV (the last three are from the ^{60}Co calibration source). All of these residual features are present at rates typically less than 1% of those in the raw spectra. There are no other line features apparent which are not explained by known background effects or by ^{56}Co decay in the ejecta of SN 1987A. Because the 511 keV line is present in the difference spectra even before 1987, we cannot at present draw any meaningful conclusions about the flux in that line from SN 1987A.

Fortunately, none of these residual features significantly interfere with the most interesting ^{56}Co decay lines. The continua are well approximated locally by power laws, and the lines located in the regions of interest can be fitted well with simple Gaussians. Therefore the models described in § III*b* give acceptable fits to the count-rate spectra. The best-fit rates in each of the 0.847, 1.238, 2.599, and 3.25 MeV lines are shown in Figure 2. It is apparent that significant counts appear in these lines beginning in 1987 August and extend over one year or more (although the positive excesses of the individual points for the two higher energy lines are marginally significant). It is crucial to the credibility of the SN 1987A results that for the time before 1987 June the count rates in all four lines are

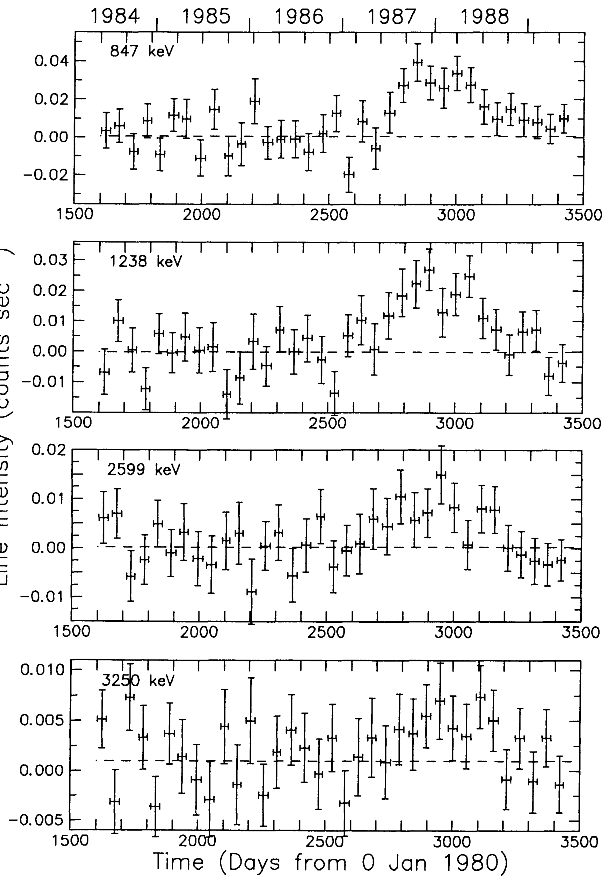

FIG. 2.—The best-fit amplitudes of the ^{56}Co lines from fits as shown in Fig. 1 to each of the ~35 day difference spectra. The dashed lines are the weighted means of the points before day 2611 (= 1987 February 23, the time of the core collapse and explosion). The mean counts in each line before SN 1987A are consistent with zero. The error bars shown are 1 σ statistical uncertainties.

completely consistent with zero (the mean amplitudes of the lines before 1987 February are shown by the dashed curves in Fig. 2). This ensures that we are actually measuring the count rates in the lines from SN 1987A and not variations of some background effects. Further, no other features of the spectra have time dependences similar to those of the ^{56}Co decay lines. These results are also consistent with earlier analyses of some of the same data (Matz *et al.* 1988; Matz, Share, and Chupp 1988).

Shown in Figure 3 is the integrated spectrum of SN 1987A from 1987 August through 1988 May. Also shown for comparison is the spectrum calculated for day 350 for model 3 described in § V, as it would appear in the GRS. The stronger ^{56}Co decay lines are clearly visible, and there is marginal evidence for weaker lines. No other lines which are not known background features are obviously present. We find from fits to this spectrum that the mean intensities of the 847, 1238, 2599, and 3250 keV lines over this interval are 8.0 ± 0.9, 5.4 ± 0.7, 2.6 ± 0.7, and 2.5 ± 0.5, in units of 10^{-4} cm^{-2} s^{-1}, respectively. The widths of all lines are consistent with the instrument resolution. The best-fit positions of the peaks are 838 ± 4, 1240 ± 6, 2553 ± 14, and 3250 ± 14 keV. The errors quoted here are statistical. Because the 1238 keV and 2599 keV lines are blended with instrumental lines, their measured positions are probably also subject to systematic errors in the fitting procedure.

The fluxes in each of these four lines are plotted in Figure 4, as are the best-fit light curves of the models described in § V. The line fluxes are also listed in Table 1. Several experiments flown on balloons have measured one or two of these lines (Cook *et al.* 1988; Mahoney *et al.* 1988; Sandie *et al.* 1988; Rester *et al.* 1989; Teegarden *et al.* 1989; and Tueller *et al.* 1990). The measurements of the 847 and 1238 keV lines are shown in Figure 5 for comparison with our fluxes. Generally these fluxes are consistent with the *SMM* measurements, given the statistical uncertainties and the difficulties inherent in comparing measurements made by very different γ-ray experiments.

V. DISCUSSION

a) Gamma-Ray Light Curve Models

In addition to the convincing detection of live ^{56}Co in SN 1987A they represent, these γ-ray data contain information on the structure of the supernova ejecta. The γ-ray light curves depend only on the amount of ^{56}Ni produced, the decay rates of ^{56}Ni and ^{56}Co, and the column depth of scatterers between the ^{56}Co and the observer at a given time. In the case of SN 1987A the mass of ^{56}Co present is quite well known from the optical light curve at intermediate times, so the γ-ray line luminosities are determined by the attenuation due to Compton scattering on all bound and free electrons.

A priori determination of the total numbers of electrons and their location relative to the ^{56}Ni synthesized in the shock heating of the inner ejecta requires solution of complicated problems of presupernova evolution and explosion hydrodynamics. However, the time evolution of the electron column depth after the explosion is much simpler. (We note that several groups have calculated γ-ray light curves from the expansion of one-dimensional numerical models which have been variously adjusted in attempts to explain many observations at various wavelengths [e.g., Pinto and Woosley 1988; Fu and Arnett 1989; Kumagai *et al.* 1989; Bussard, Burrows, and The 1989; and Grebenev and Sunyaev 1990]. In general, those authors achieve fair agreement with the observations

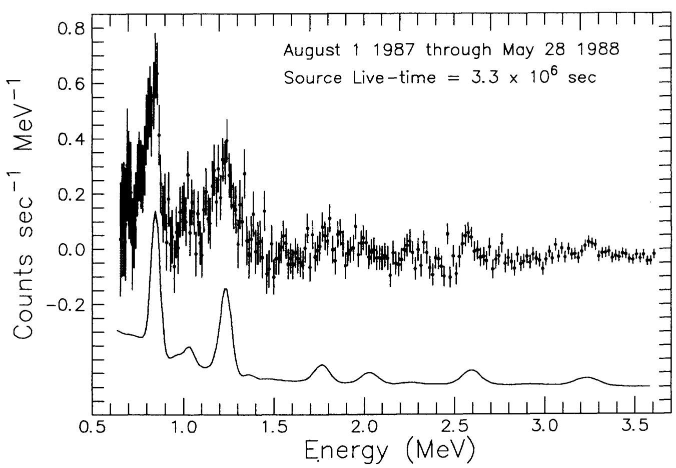

FIG. 3.—The mean spectrum from 1987 August 1 through 1988 May 28 (days 160–460), the time of peak fluxes of ^{56}Co γ-ray lines. Also shown for illustration is the γ-ray spectrum from a Monte Carlo calculation based on model 3 (see text) at day 350, convolved with the GRS response at 90° from the detector axis.

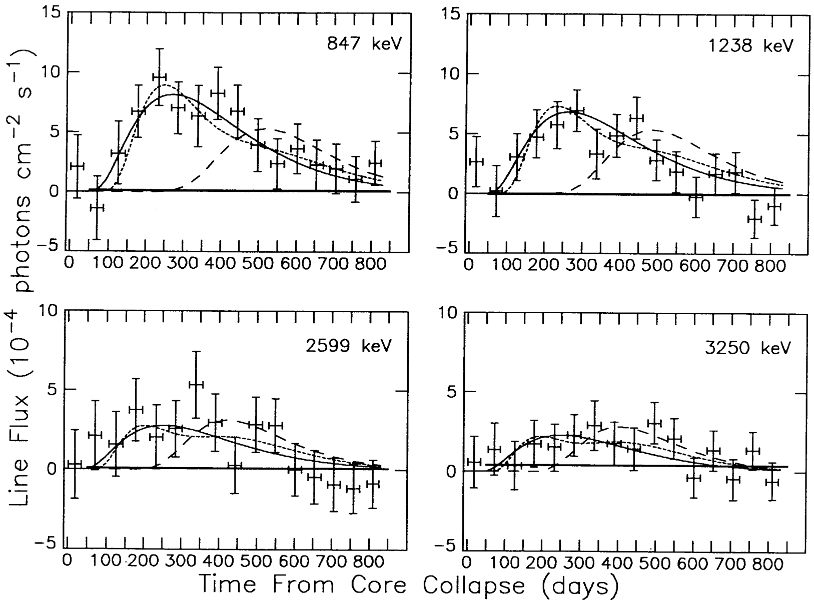

FIG. 4.—The measured fluxes in each of four ^{56}Co decay lines, derived from the amplitudes of the photopeak count rates of Fig. 2. The bold lines show the mean measured fluxes prior to 1987 February, which are all consistent with zero. The other curves are three analytic light curve models fitted simultaneously to all four data sets (see text). The long-dashed curve is model 1, a single component of 0.07 $M_\odot$ of ^{56}Co under uniform optical depth which decreases in time. The small-dashed curve is model 2, two components of ^{56}Co under two different depths. The thin solid line is model 3, with ^{56}Co extended over a finite optical depth, and under an additional uniform optical depth. Models 2 and 3 give acceptable fits to the data overall and, for the same parameters, each line individually.

reported here. We do not try to model the entire supernova, only the γ-ray light curves.) In theory the number of ^{56}Co nuclei per unit optical depth from the surface can be unfolded from measured γ-ray light curves, given sufficiently precise data. Because of the limited statistical precision of the data presented here, we investigate a few extreme distributions of ^{56}Co versus optical depth, to demonstrate what is ruled out, and what is required, by the data.

i) *Model 1*

Before SN 1987A the standard postexplosion picture of Type II supernova ejecta consisted of concentric regions of radially decreasing nuclear processing, from essentially the products of nuclear statistical equilibrium at the inner edge of the ejecta through the unprocessed outer layers. In this picture, all of the ^{56}Ni lies within a small mass range at the inner edge of the ejecta, and the γ-ray escape depends only on the electron column depth of the overlying matter. After the passage of the shock, for the times of interest here, material at a given mass coordinate in the ejecta moves at very nearly constant velocity. Then a very good approximation is that the column depth (integral number of electrons per unit area) of the entire ejected envelope varies as the reciprocal of the square of the elapsed time. With this in mind, we can write the escaping luminosity of a ^{56}Co γ-ray line at energy E from beneath a single thick expanding shell as

$$L_E(t) = b_E R_{^{56}\mathrm{Co}}(t)\, e^{-(\sigma_E/\sigma_{847})(t_{847}{}^2/t^2)}\,, \quad (1)$$

TABLE 1

MEASURED γ-RAY LINE FLUXES

INTEGRATION PERIOD (days from collapse)	LINE FLUXES (10^{-4} photons cm^{-2} s^{-1})			
	847 keV	1238 keV	2599 keV	3250 keV
1–35..........	2.06 ± 2.66	2.64 ± 2.09	0.31 ± 2.16	0.57 ± 1.61
54–87..........	−1.40 ± 2.67	0.19 ± 2.14	2.13 ± 2.20	1.38 ± 1.64
107–144.........	3.17 ± 2.62	3.05 ± 1.97	1.59 ± 2.04	0.36 ± 1.53
160–196.........	6.71 ± 2.18	4.72 ± 2.02	3.75 ± 1.96	1.74 ± 1.46
217–250.........	9.59 ± 2.37	5.74 ± 1.99	2.04 ± 2.01	1.55 ± 1.49
267–302.........	7.02 ± 2.17	6.92 ± 1.73	2.58 ± 1.76	2.28 ± 1.30
320–356.........	6.34 ± 2.56	3.33 ± 2.07	5.36 ± 2.11	2.91 ± 1.57
372–408.........	8.24 ± 2.19	4.85 ± 1.78	2.96 ± 1.81	1.78 ± 1.35
425–460.........	6.73 ± 2.21	6.36 ± 1.75	0.29 ± 1.78	1.45 ± 1.34
479–513.........	3.93 ± 2.20	2.82 ± 1.71	2.86 ± 1.74	3.07 ± 1.30
531–566.........	2.36 ± 2.10	1.86 ± 1.72	2.80 ± 1.70	2.10 ± 1.27
584–619.........	3.63 ± 2.07	−0.25 ± 1.69	0.03 ± 1.66	−0.30 ± 1.25
636–671.........	2.27 ± 2.09	1.68 ± 1.70	−0.40 ± 1.68	1.37 ± 1.26
689–723.........	1.96 ± 2.08	1.82 ± 1.73	−0.90 ± 1.68	−0.40 ± 1.28
740–774.........	1.09 ± 1.89	−2.06 ± 1.60	−1.10 ± 1.54	1.37 ± 1.18
793–826.........	2.44 ± 1.85	−0.98 ± 1.56	−0.80 ± 1.51	−0.58 ± 1.18

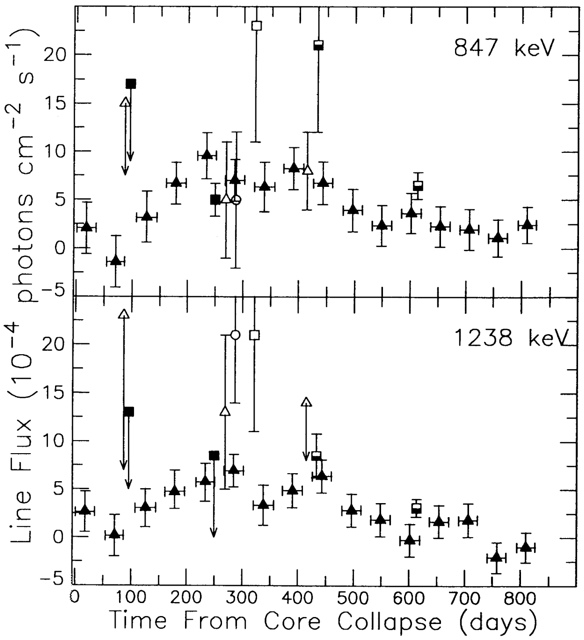

FIG. 5.—The same measured fluxes for the 847 keV and 1238 keV lines as Fig. 4 (*solid triangles*), compared with other measurements of those lines: Cook *et al.* (1988) (*open triangles*), Sandie *et al.* (1988) (*solid squares*), Mahoney *et al.* (1988) (*open circles*), Rester *et al.* (1989) (*open squares*), and Teegarden *et al.* (1989) and Tueller *et al.* (1989) (*half-filled squares*).

where b_E is the branching ratio of the line, $R_{^{56}Co}$ is the ^{56}Co decay rate, the σ's are the total Klein-Nishina scattering cross sections, and t_{847} is the time at which the escape luminosity of 847 keV photons is $1/e$ of the input luminosity (i.e., when the effective optical depth at 847 keV is unity). This last parameter can be recast as the electron column depth, or given a composition, the mass column depth, at some fiducial time (e.g., Clayton 1974; Woosley 1988). There is a dependence of this conversion on geometry, because the effective optical depth at a given energy is greater than the usual radial optical depth, if the thickness of the shell is less than its radius and the photons are emitted isotropically at its inner edge. Our Monte Carlo simulations and analytic treatments suggest that the effective optical depth at 847 keV equals unity when the Thomson optical depth ($\tau_T \equiv 1$ when the column depth $= 1/\sigma_T = 1.5 \times 10^{24}$ electrons cm^{-2}), measured radially, is approximately $\tau_T = 2$, for reasonable supernova ejecta geometry.

For a given supernova, the parameters to be determined are the intrinsic luminosity, or the mass of ^{56}Ni synthesized (here $R_{^{56}Co}$), and the thickness of the envelope at some time (here t_{847}). We note that any theoretical Type II supernova γ-ray light curve published before 1988 can be described quite accurately with such a function and appropriate values of these two parameters. We can determine the two parameters from the data by fitting the measured light curves at all measured energies with this model. In the case of SN 1987A the mass of ^{56}Ni produced has been quite accurately inferred from the apparent ^{56}Co decay power input to the optical light curve (e.g., Woosley, Pinto, and Ensman 1988). Thus we are justified in fixing $R_{^{56}Co}$ (we use the decay rate resulting from 0.07 $M_\odot$ of ^{56}Ni at $t = 0$; we also assume a distance of 50 kpc) and fitting with a single free parameter to determine the thickness of the overlying envelope. We find that we cannot obtain a satisfactory simultaneous fit to the light curves of the four lines of ^{56}Co. The best fit is shown as model 1, the long-dashed curves, in Figure 4. Clearly this model is inadequate to describe the supernova ejecta. If all of the radioactivity lay at a single depth, under a thinner-than-expected envelope so that there was already ~1% escape at 200 days, the continued thinning of the envelope would cause the line fluxes to quickly rise off-scale in Figure 4 rather than to decline as actually observed.

That such a simple model cannot explain the data is not surprising, as earlier observations suggested that the envelope structure is more complex than in the simplest picture. The broad peak of the optical light curve at maximum already suggested that the composition of the envelope was somewhat homogenized, that is the opacity was more uniform than stratified (e.g., Arnett 1988). The early appearance, near-constancy, and intensity relative to the γ-ray lines of the hard X-ray emission also suggested a range of optical depths from the ^{56}Co to the X-ray photosphere (Itoh *et al.* 1987; Pinto and Woosley 1988; Leising 1988).

ii) *Model 2*

We wish to increase the complexity of the model to allow for some distribution of depths to the ^{56}Co. We consider two different possibilities. The first, referred to as model 2, consists of two delta functions of ^{56}Co abundance at two different depths. We can easily describe this mathematically by allowing for two independent components treated just as in equation (1). Then the γ-ray line light curves are given by

$$L_E(t) = b_E R_{^{56}Co}(t)[f_1\, e^{-(\sigma_E/\sigma_{847})(t_{1,847}^2/t^2)} + (1 - f_1)\, e^{-(\sigma_E/\sigma_{847})(t_{2,847}^2/t^2)}] , \quad (2)$$

where f_1 is the fraction of the ^{56}Co which lies under the portion of the envelope with unit effective 847 keV optical depth at time $t_{1,847}$. The rest $(1 - f_1)$ resides under a different depth which becomes comparably thin at $t_{2,847}$.

Assuming the ^{56}Ni mass at $t = 0$ was 0.07 $M_\odot$, we fitted equation (2) with three free parameters to the four measured light curves simultaneously. A good fit to the data is obtained (reduced $\chi^2 = 0.8$ for 61 degrees of freedom), and is shown in Figure 4 as model 2 (*small dashes*). The best-fit parameters are $f_1 = 0.95 \pm 0.01$, $t_{1,847} = 940 \pm 50$ days, and $t_{2,847} = 260 \pm 25$ days. Thus the γ-ray data are consistent with a situation where 95% of the ^{56}Co lies under matter with $\tau_T = 200$ (100 days/t)^2 and 5% under only $\tau_T = 16$ (100 days/t)^2. We note that the smaller Thomson depth is equivalent to that of a shell of only 1 $M_\odot$ of hydrogen expanding at 3000 km s^{-1}.

Conceptually, one can think of at least two different physical situations whose light curves follow equation (2). This variation of the γ-ray line escape could result in the case of fragmentation of the thick envelope even if all the ^{56}Co remains at the inner edge of the ejecta. If the envelope breaks into relatively opaque regions with intervening thin regions (e.g., Brown 1987), the two regions become thin at different times, although the optical thickness of each varies as 1/time^2. The parameter f_1 describes the relative areas of the two regions. The scale of the fragmentation would have to be small enough that both thick and thin areas of the envelope intervened between the observer and the (presumably small) ^{56}Co-rich region.

A second, physically distinct situation which could produce numerically similar light curves would result if small quantities of ^{56}Co were moved by some mechanism to thinner regions as suggested by Clayton (1974). Common descriptive terms are "jets" or "bubbles." The evolution of the γ-ray line fluxes might well be described by equation (2), with the two ^{56}Co components being physically separated. It is probably an oversimplification to assume two discrete components of ^{56}Co, as there will almost certainly be some at intermediate optical depths.

Although these two physically different situations yield similar γ-ray light curves, they do produce potentially observable differences, namely in the velocities of the emitting material. In the fragmentation picture, all the ^{56}Co, including the component at lower optical depth, could have low velocity (several hundred kilometers per second) and therefore relatively narrow lines. In the absence of some fragmentation, however, ^{56}Co would have to be accelerated to higher velocity ($\sim 0.01c$) to reach low optical depths at early times, and the line energies would be shifted. Unfortunately, the GRS has insufficient energy resolution, given the significance of the fluxes, to distinguish between these two possibilities. The balloon observations at higher energy resolution suggest that fragmentation *alone* does not explain the early γ-ray leakage. Those experiments (Mahoney *et al.* 1988; Sandie *et al.* 1988; Rester *et al.* 1989; Teegarden *et al.* 1989; and Tueller *et al.* 1990) all indicate line widths of order 1% FWHM, suggesting some acceleration of the emitting nuclei to velocities higher than those expected for the innermost ejecta. Similar evidence is found in the infrared iron (Erickson *et al.* 1988) and cobalt (Rank *et al.* 1988) line observations.

iii) *Model 3*

We consider another light curve, model 3, where the ^{56}Co is distributed over a finite region of the inner ejecta (i.e., homogeneous "mixing" of the ^{56}Co). In the simplest but somewhat unrealistic picture, this distribution is uniform in mass. The envelope outside the mixed, ^{56}Co-rich region will attenuate the γ-rays just as in model 1 (see eq. [1]), and only a fraction of the γ-rays, roughly those emitted in outer unit optical depth of the mixed region, will escape that region. The fraction of ^{56}Co nuclei within this depth will increase with time, approximately as the square of the elapsed time. This approximation is best at early times, and obviously this fraction will increase only until all of the inner zone is thin. Thus

$$L_E(t) = b_E R_{^{56}\mathrm{Co}}(t)\, e^{-(\sigma_E/\sigma_{847})(t_{o,847}{}^2/t^2)} \times \frac{\sigma_{847}}{\sigma_E}(t^2/t_{i,847}^2) \quad \text{for} \quad t < t_{i,847}\,, \quad (3)$$

where $t_{i,847}$ is the time when the inner region is essentially thin to 847 keV γ-rays, $t_{o,847}$ is the time when the effective 847 keV optical depth of the outer, unmixed, region reaches unity, and the other notation is as before. Assuming we know the initial ^{56}Ni mass, this function requires only two parameters to define the light curves in all the ^{56}Co γ-ray lines.

We fitted the four light curves of Figure 4 simultaneously with this function and again find an acceptable fit (reduced $\chi^2 = 0.7$ for 62 degrees of freedom), shown as model 3 (*solid line*) in Figure 4. The best-fit values of the parameters are $t_{o,847} = 124 \pm 31$ days and $t_{i,847} = 1860 \pm 111$ days. That is, nearly the entire ejected envelope must be mixed to explain the γ-ray data. The column depth of the outer region is the same as that of only 0.33 $M_\odot$ of hydrogen expanding at 3000 km s^{-1}. Clearly the data require some of the ^{56}Co at very low optical depth at very early times. This model also requires a very thick, either massive or slow moving, inner region which hides a large fraction of the ^{56}Co and keeps the fluxes small at later times.

Although we can fit the γ-ray light curves with such a model, there is evidence that such a simple picture is not entirely valid. This spherically symmetric model, as noted by many authors, predicts blue shifted line centroids because the photons from emitters approaching the observer suffer less attenuation. However, the high-resolution γ-ray observations show no evidence of blueshifted lines. It is apparent that the ^{56}Co in SN 1987A is found under a very large range of thicknesses of matter, which could be due to such phenomena as mixing, jets, or fragmentation. It is also apparent there is not enough information in the γ-ray light curves alone to distinguish among these very different physical situations. Because we can satisfactorily fit the γ-ray line data with simple parameterizations, we are not justified in testing more detailed ^{56}Co distributions.

b) Gamma-Ray Contribution to the Bolometric Luminosity

With these simple models which sufficiently describe the observed γ-ray light curves, we can also calculate quantities relevant to other observations. Great effort has been expended to measure the bolometric luminosity of SN 1987A to compare it with the power output of the inferred mass of ^{56}Co and to test for additional energy sources. A significant component of the bolometric luminosity, especially at later times, is the hard emission, the γ-rays and X-rays. We have measured only a few of the ^{56}Co γ-ray lines, but we can infer from the models of § Va the escape of all lines. Also, we can obtain the escape fraction of γ-rays from any other emitters collocated with the ^{56}Co (e.g., ^{57}Co) at any time from equation (2) or (3). Further, we can perform calculations of the scattering of the γ-ray lines in simple models of expanding shells with properties determined from the measured γ-ray light curves to estimate the escaping hard X-ray continuum intensity and its contribution to the bolometric luminosity.

The total γ-ray line luminosity can be determined from equation (2) or equation (3) by multiplying by the energy of each line and summing over all ^{56}Co lines. We should also add a term to include the γ-rays from annihilation of the ^{56}Co positrons which are emitted in 19% of the decays. We simply use a branching ratio of 0.38 and the Klein-Nishina cross section at 511 keV to account for the annihilation γ-rays. Actually most positrons will probably form positronium and then decay into either two 511 keV γ-rays or a three-photon continuum. Because the scattering cross sections are larger at the lower energies of the continuum photons, we very slightly overestimate the escaping luminosity by assuming two-photon annihilation. Shown in Figures 6 and 7 are the resulting γ-ray line luminosities (*long dashes*) for models 2 and 3, based on equations (2) and (3), respectively.

To calculate the hard X-ray escape we employ Monte Carlo calculations of Compton scattering and photoelectric absorption in a uniform density spherical shell. The shell is defined by the thickness required to give the γ-ray attenuation of the light curve model in question at a particular time. We set the geometry of the problem to be similar to that of a supernova envelope by assuming the inner edge of the shell moves at 1000 km s^{-1} and the outer edge at 3000 km s^{-1}. We then uniformly distribute enough electrons over the shell to give the required attenuation of 0.847 MeV γ-rays at the appropriate t_{847}. Photons are emitted isotropically, at the inner edge of the shell in model 2, or evenly distributed over a finite region of the shell defined by its optical thickness in model 3. To determine the photoelectric opacities, we use the elemental abundances of the 18 $M_\odot$ model of Table 2 of Arnett *et al.* (1989). In model 2 we

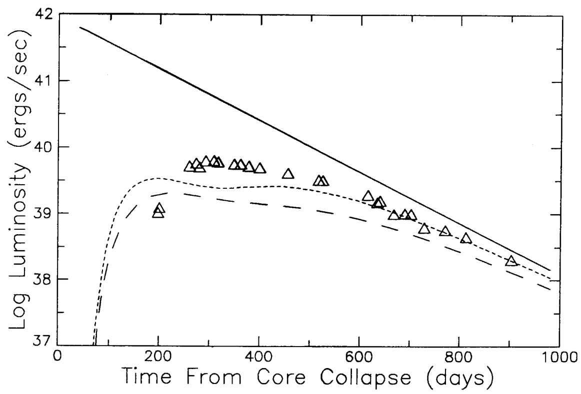

FIG. 6.—A semiempirical estimate of the high-energy contribution to the bolometric luminosity of SN 1987A from model 2. The long-dashed line shows the total escaping γ-ray line luminosity as given by applying eq. (2) to all ^{56}Co lines. The short-dashed line shows the total luminosity above a few keV (lines plus continuum) as given by Monte Carlo calculations which give the same γ-ray line escape as eq. (2). The solid line shows the decay power of 0.07 $M_\odot$ of ^{56}Co. The triangles are the solid line *minus* the measured uvoir luminosity of Suntzeff and Bouchet (1989), i.e., the expected luminosity outside the uvoir bands.

perform two separate calculations on shells of different thicknesses, as if the low-depth and high-depth regions were independent, and add the results weighted by the fraction of ^{56}Co in each. The heavy elements are distributed over the inner 10% of the mass of the thicker component only. For model 3 the same total abundances are distributed over the entire region containing ^{56}Co, i.e., over most of the ejecta. Regions external to the ^{56}Co-rich ones are assumed to have photoelectric opacity of solar matter. Our simple treatment of the heavy element distributions makes our conclusions regarding the softest X-rays questionable but should not greatly affect our estimate of the total continuum luminosity.

We calculate the entire spectra from the ^{56}Co decay for models 2 and 3, at 20 day intervals. The total luminosities in the lines plus the continuum are shown as the small dashes in Figures 6 and 7. The total line luminosities from the Monte Carlo calculations, which are not shown, agree extremely well with the analytic results (*long dashes*). We also show in Figures 6 and 7 the *difference* between the decay power of 0.07 $M_\odot$ of ^{56}Co (*solid curves*) and the measured ultraviolet, optical, and infrared (uvoir) luminosity of Suntzeff and Bouchet (1990) for the time beginning 200 days after outburst (*triangles*). Assuming there are no other sources of energy, these points

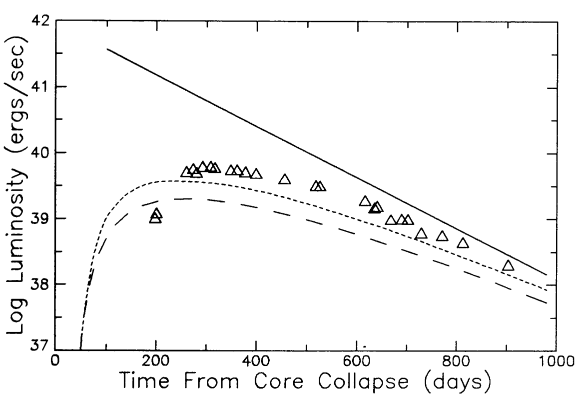

FIG. 7.—Similar to Fig. 6, but for γ-ray light curve model 3 (using eq. [3])

represent the escaping luminosity not accessible to ground-based observatories, most of which is thought to be in the γ-ray lines and continuum. Although the shape of our estimates of the hard luminosity are similar to that of the observed points, the amplitudes are somewhat lower. We do not regard this difference as being very significant given the many assumptions that go into the conversion of the γ-ray line fluxes, and to a lesser extent the optical and infrared photometry, to actual luminosities. We note that this discrepancy would be smaller if we were to use the U–M photometry of Catchpole *et al.* (1989) for comparison at early times when those bands contain most of the uvoir luminosity. We also note that our calculated continuum spectra are in good agreement with measured continua above 100 keV (e.g., Grebenev and Sunyaev 1990) but appear to be systematically lower at energies below 50 keV. Because only a small fraction of the continuum luminosity is at those lower energies, this is probably not the reason for the discrepancies of Figures 6 and 7.

c) ^{57}Co *γ-Ray Escape*

Another very interesting γ-emitter potentially detectable in SN 1987A is ^{57}Co because its production (actually that of its short-lived parent ^{57}Ni) depends on the neutron richness of the ejected matter (e.g., Clayton 1974; Woosley, Pinto, and Hartmann 1989). Further, because the number of neutrons relative to protons increases toward the center of the star, measurement of the ejected ^{57}Ni mass helps to estimate the location of the boundary between ejected and accreted matter (Thielemann, Hashimoto, and Nomoto 1990). The lines emitted in ^{57}Co decay, at 122 keV and 136 keV, will still be somewhat attenuated by the ejecta during the next few years when they might be observable by satellite detectors. Thus some estimate of the optical depth of the ejecta will be needed to convert measured line fluxes into ejected mass of ^{57}Co. It is still possible that the presence of ^{57}Co will be inferred from its effect on the optical and infrared light curves. This becomes more difficult as time goes on because a smaller fraction of the bolometric luminosity is accessible to ground-based telescopes, and it also requires an estimate of the trapping (or the inverse of the escape) of ^{57}Co γ-ray energy to derive the ejected ^{57}Co mass.

We have in effect measured the attenuation of γ-rays at earlier times so we can extrapolate the escape fraction of ^{57}Co photons to later times. Shown in Figure 8 are the fluxes of ^{57}Co 122 keV γ-rays predicted by equations (2) and (3) assuming that 1.7×10^{-3} $M_\odot$ of ^{57}Ni was ejected by the explosion (i.e., that the solar ratio of ^{56}Fe/^{57}Fe holds for the production of the radioactive progenitors). Theoretical estimates vary from this value to a factor of 2 greater (e.g., Thielemann, Hashimoto, and Nomoto 1990). These line fluxes are possibly detectable by the γ-ray detectors SIGMA (Mandrou 1984) and GRO OSSE (Johnson *et al.* 1989) at the times of their expected launches in late 1989 and mid-1990, respectively.

Besides using the measured line flux and an estimate of the γ-ray escape fraction, there are several ways to obtain the ejected mass from γ-ray measurements. Repeated measurements of the line fluxes over a few years would allow fitting of the light curves as we have done here for ^{56}Co γ-ray lines, although with the mass of ^{57}Co as a free parameter. Given the sensitivities of the planned detectors and the expected fluxes, this method is not the most promising. Our models predict continuum spectra in 1990 which are nearly flat from about 50 keV to 122 keV with intensities near 10^{-6} photons cm^{-2} s^{-1}

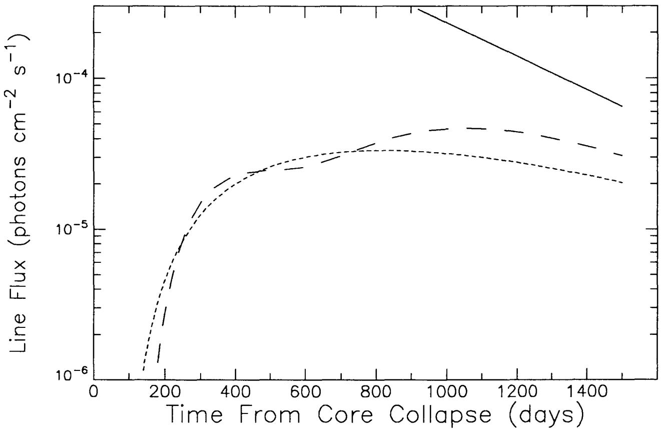

FIG. 8.—The flux of the 122 keV line from ^{57}Co assuming $1.7 \times 10^{-3}\ M_{\odot}$ of ^{57}Ni was ejected by the explosion. The long-dashed line is based on the escape of those γ-rays given by eq. (2); the short-dashed line, by eq. (3). The solid line is the flux from that mass of ^{57}Co if the ejecta were completely transparent.

keV^{-1}. This continuum is also nominally detectable by SIGMA and GRO OSSE. Measurements of the line-to-continuum ratio of sufficient significance could be used to determine the optical depth of the ejecta and therefore the mass of ^{57}Ni ejected. Again, because of the moderate resolution of the detectors and their sensitivities, this measurement will be difficult. Perhaps the most accurate determination of the ^{57}Co mass will come from a measurement of the integral photon flux over the range roughly 40–136 keV. The low-energy cutoff of the continuum at these late times occurs because photons cannot scatter enough times in the ejecta to reach lower energy, not from photoelectric absorption as is the case earlier. Therefore, the number of ^{57}Co photons is very nearly conserved. In mid-1990, the continuum from scattered ^{56}Co γ-rays will be much smaller, so an accurate measurement of the total flux in and below the ^{57}Co lines should provide an extremely important datum for nuclear astrophysics.

VI. CONCLUSION

We have measured significant γ-ray fluxes from the decay of radioactive ^{56}Co in the ejecta of SN 1987A and monitored their evolution over 2 yr. This has allowed us to infer the thickness of the envelope and, to a degree, the distribution of ^{56}Co within it. It is clear that the ^{56}Co was found over a large range of optical depths, with a small fraction at very low depth, but our data do not allow us to construct a more complete picture. Probably some fragmentation of the ejecta and acceleration of the emitting radioactivity within it are required to explain the γ-ray line fluxes described here and the γ-ray and infrared line positions and widths reported by other authors. With simple descriptions of the structure of the ejecta which can explain the γ-ray line fluxes, we have derived the total escaping luminosity in all γ-ray lines and in the scattered continuum. We find that the γ-ray contribution to the bolometric luminosity accounts for most, if not all, of the ^{56}Co power escaping outside of the uvoir bands. This increases our confidence in our own measurements and in the overall picture of the energy budget of SN 1987A. We have also estimated the escape of γ-ray lines from ^{57}Co at later times, so that reliable estimates of its ejected mass can be made, should it be detected by future experiments.

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APPENDIX

BACKGROUND SUBTRACTION

Background corrections can be performed by either (*a*) modeling the background sources and the instrument response to them and removing the calculated background from the data or (*b*) finding spectra accumulated under the same background conditions as a spectrum of interest and directly subtracting them. Our efforts to predict the variations of backgrounds (method a) have been successful at the level of only $\sim 10\%$, which is insufficient accuracy for measuring cosmic source contributions in the GRS data. For this reason we employ an entirely empirical method of correcting for the background variations. The premise is that over its long life, *SMM* has experienced all possible background conditions many times, so one need only compare data taken at different times under the same conditions, but with different exposures to cosmic sources. The reality is that identical background conditions are never encountered twice, even over the long *SMM* lifetime. Thus we actually must perform multiple spectral subtractions.

As described in the text, we subtract spectra with the source occulted by Earth from those with the source visible to the detectors, within a given orbit. This removes all backgrounds which vary on times longer than ~ 1 hr. To remove the backgrounds which vary more rapidly than this, we subtract many spectra taken at different times when parameters which determine those backgrounds had very similar values. Precisely because these spectra were accumulated at very different times, however, they will have different long-term backgrounds in them. We therefore first have to remove these long-term backgrounds from each spectrum used to measure the short-term backgrounds.

We form a background data base from 1-minute spectra accumulated before 1987 February 23 to ensure that no counts from SN 1987A are included in background spectra. It is important that we get essentially the same results when using *any* of several subsets of our data to construct the background data base. This assures us that there is nothing special about the data before 1987, except that we know that SN 1987A does not contribute to the counts then. We first identify the important parameters which determine the cosmic-ray–induced backgrounds (internal and atmospheric albedo) and then sort the spectra according to the values of each important parameter, averaging the spectra with nearly equal values of all parameters. If we had removed other long-term backgrounds and identified all important parameters on which the short-term background depends, all spectra within a single bin would be identical, except for varying exposure to cosmic sources, within the statistical uncertainties.

Before averaging the spectra within each range of the short-term background parameters we first "correct" all background spectra for long-term variations (such as SAA–induced, long-lived radioactivity). We again choose to perform this correction empirically, by subtracting from each spectrum the average radioactive decay spectrum for that day. This average, which will necessarily also include some more rapidly varying backgrounds (e.g., atmospheric emission), is formed by taking the mean of spectra accumulated with Earth in the instrument aperture (to minimize the exposure to cosmic sources) within a limited range of McIlwain L parameter ($1.2 \leq L \leq 1.4$). This is to ensure that each "daily average" spectrum has similar short-term background contributions which then cancel each other when spectra are finally subtracted within a single orbit.

After subtracting the average radioactive spectrum from each 1-minute spectrum, these difference spectra are binned according to the values of each short-term background parameter, and the mean within each bin is calculated. We have chosen to use four different parameters to determine the short-term background in this analysis. One parameter is Earth aspect angle—the angular separation of the Sun (spacecraft pointing direction) and Earth center as viewed by *SMM*. Obviously, the count rate due to atmospheric albedo γ-rays depends on the position of Earth relative to the detectors, shields, and spacecraft material. Also, the only variation of the detector count rate due to the omnidirectional diffuse cosmic γ-ray emission results from Earth blockage of a fraction of that emission in directions of varying detector sensitivity.

A second, clearly important parameter must reflect the local variation of cosmic-ray intensity due to variations in the geomagnetic field which deflects the cosmic rays. This affects both the activation of spacecraft material and the emissivity of the nearby atmosphere. We use the integral count rate measured by a charged particle detector, a plastic scintillator behind the spectrometer, as a monitor. A third division of background spectra is simply based on the sign of the geomagnetic latitude of the spacecraft. For still unexplained reasons, the count rate due to atmospheric γ-rays in the spectrometer is different in the southern hemisphere from that in the north, all else being equal. A fourth parameter on which the spectral binning was based is the time from the last significant SAA passage. This parameter monitors the decay of nuclides with lifetimes of order 1 hr produced by SAA activation. Including this parameter yields only slight overall improvement in reducing backgrounds.

The 4×10^5 spectra in our background data base are thus divided into 36 ranges of Earth-angle, 25 ranges of plastic detector rate, four ranges of time since SAA passage, and two ranges of magnetic latitude. Because these parameters are not completely orthogonal, a total of about 5000 bins are actually occupied by five or more spectra (which we require for their use). On average each bin contains some 80 spectra. It should be noted that many different such parameterizations are possible, and many have been tried. It is important that the γ-ray line results which are the thrust of this work are not significantly changed by choosing different reasonable parameterizations.

This data base is used as follows: For each 1-minute spectrum of an orbit, the mean of all background spectra with the same background parameters is subtracted. Then the mean of all source-occulted, background-subtracted spectra is subtracted from the mean of all source-*un*occulted, background-subtracted spectra within the orbit. Stated symbolically, the net difference spectra are created through the procedure:

$$S_i = \langle M_{i,p} - \langle M'_{i,p'} - D_i \rangle_{\text{all } p'=p} \rangle_{\text{orbit, source unocculted}} - \langle M_{i,p} - \langle M'_{i,p'} - D_i \rangle_{\text{all } p'=p} \rangle_{\text{orbit, source occulted}} ,$$

where S_i is the net count rate in channel i, $M_{i,p}$ is the mean count rate in 1 minute in channel i accumulated with background parameters p, and D_i is the mean count rate for the day (as described above) on which an $M'_{i,p'}$ (background spectrum) was accumulated. The indicated means are weighted by live time.

Because we reuse background spectra, we keep track of how many times each is used, and the sign and weight with which it is used, in a given difference spectrum, and in summations of the individual orbital difference spectra (our 35 day accumulations). First we calculate the uncertainties assuming all spectra are statistically independent. Then we make approximate corrections to the statistical uncertainties, increasing them when spectra are used multiple times with the same sign, decreasing them when spectra are used with opposite signs such that their statistical fluctuations cancel out. The corrections are based on an estimate of how much that spectrum contributed to the initial uncertainty, assuming all background spectra contribute equally. In practice this results in very small increases in estimates of the uncertainties. Although this procedure is not strictly correct, it has very little effect on the results; the uncertainties are dominated by the unprimed spectra which are statistically independent.

If one considers that any given spectrum has a long-term background, a short-term background, and some celestial contributions, then in theory, the subtraction of the primed spectra removes short-term backgrounds, the subtraction of the occulted spectra removes long-term backgrounds, and the residual difference is due to differing exposure to cosmic sources, which is dominated by the occultation. In the current formulation, photons from SN 1987A can only affect the $M_{i,p}$ spectra. How well this works depends on the completeness of the parameterization of the backgrounds and on the cancellation of the short-term backgrounds in the different sets of daily averages.

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