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OBSERVATIONS OF GAMMA-RAY LINE PROFILES FROM SN 1987A

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ABSTRACT

We report observations of fully resolved gamma-ray lines from the decay of ^{56}Co in SN 1987A. Data are from the first two balloon flights of the Gamma-Ray Imaging Spectrometer (GRIS), the first of a new generation of high-resolution gamma-ray spectrometers for astrophysics. On day 433 (after the initial optical sighting) the 847 and 1238 keV lines from ^{56}Co were observed at 2.3 and 4.3 σ significance. On day 613, the lines at 847, 1238, and 2599 keV were observed at 4.6, 3.4, and 1.9 σ, respectively. The combined significance for the three-line complex in both flights is 7.8 σ. Gaussian profiles yield acceptable least-squares fits to the lines. The line profiles are centered on the red side of the rest energy with typical velocity dispersions of $\sim$3500 km s^{-1} FWHM, consistent with an optically thin source, but the line intensities are $\lesssim$30% of those produced by the 0.075 $M_\odot$ of ^{56}Co determined from the bolometric light curve. Although the line fluxes derived from these fits are consistent with spherically symmetric mixed models of the supernova shell, the line profiles are not. These models predict lines blueshifted from the observed lines and narrower. The observed line profiles could potentially be explained by models that include fragmentation or nonspherical geometries.

Subject headings: gamma rays: general — line identifications — line profiles — nucleosynthesis — stars: supernovae

I. INTRODUCTION

SN 1987A in the Large Magellanic Cloud is a once-in-a-lifetime opportunity to observe gamma-ray emission from a Type II supernova. Fortunately, new instruments, with the combined sensitivity and energy resolution necessary to make these observations, were under construction at the time of the supernova and were rushed to completion. The initial discovery of gamma-ray lines from freshly synthesized radioactive elements was made by the gamma-ray spectrometer on the *Solar Maximum Mission* (*SMM*), a preexisting satellite experiment (Matz *et al.* 1988; Matz, Share, and Chupp 1988) and confirmed by balloon-borne experiments (see Fig. 2). The direct confirmation of the theories of nucleosynthesis in supernovae by the observation of lines from the decay of ^{56}Co rivals, in scientific significance, the confirmation of core collapse theory by the observation of the neutrino burst. Theories of the development of the early supernova remnant (Gehrels, MacCallum, and Leventhal 1987; Chan and Lingenfelter 1988; Pinto and Woosley 1988*a*) did not fare so well. The surprisingly early turn-on of the gamma-ray lines and the flat gamma-ray light curve after turn-on were inconsistent with these early models. The introduction of mixing allowed the escape of gamma rays at a time when the remnant was still optically thick (Bussard, Burrows, and The 1989; Pinto and Woosley 1988*b*; Grebenev and Sunyaev 1989). These spherically symmetric mixed models were adjusted to fit the early gamma-ray line light curves and the $\sim$0.075 $M_\odot$ of ^{56}Co determined from the bolometric light curve (Woosley *et al.* 1987). Although different in detail, the predictions of these models for the gamma-ray line profiles were similar: the lines would be blueshifted as the gamma rays escaped from the approaching surface, while the redshifted material was still mostly hidden by the optically thick remnant. Since gamma rays interact predominantly by Compton scattering, the line profiles yield a direct measure of the distribution of radioactive material in the supernova without the complications of ionization state and resonant scattering effects that confuse the interpretation of line profiles from atomic transitions. Since scintillation spectrometers like *SMM* do not have sufficient energy resolution to measure the supernova line profiles, these measurements could only be made by the balloon-borne germanium spectrometer experiments. Previous high-resolution measurements were made by other groups from Lockheed/MSFC, Florida/GSFC, and JPL (see Fig. 2). GRIS was the largest and most sensitive of the instruments available in time to observe the supernova lines.

II. OBSERVATIONS

The GRIS experiment incorporates a pointed array of seven very large high-purity *n*-type cryogenically cooled coaxial germanium detectors for high-resolution spectroscopy (see Tueller *et al.* 1988 for more detail). This is a state-of-the-art system, which included several of the world's largest detectors of this type. The total active volume of Ge was $>$1500 cm^3, and the effective area was 61.5 cm^2 at 847 keV and 47.4 cm^2 at 1238 keV. The detector array is completely surrounded by a very heavy (396 kg) active anticoincidence shield of NaI scintillator, which collimates the field of view to 19° FWHM at 847 keV. The shield was designed to provide $>$15 cm of attenuation pathlength for all gamma rays that do not enter through the

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collimator apertures. Special cryostats and shield housings were designed to minimize passive material inside the active shield, which is a significant source of background.

The energy response of Ge detectors is intrinsically very linear and strong narrow background lines of known energy provide excellent data to accurately calibrate the energy scale and resolution. The energy calibration in this range is determined by a linear interpolation between a strong vetoed 511 keV background line (~ 30 counts s^{-1}, a special coincidence mode analyzes vetoed events in a narrow window around 511 keV) and a line at 1461 keV from a ^{40}K source flown inside the shield (~ 0.6 counts s^{-1}). The maximum gain variation observed was 0.6%, and the values for the other detectors were $< 0.3\%$. During the fall flight, the detector resolution was 2.1 keV FWHM at 847 keV and 2.5 keV at 1238 keV, as determined from a linear fit to the widths of numerous narrow background lines distributed over the full energy range. An electronics problem, caused by saturating events due to charged particles, degraded the resolution in the spring flight to $\sim 1\%$. In both flights the uncertainty in the energy calibration was tested by fits to the strong background lines in the energy calibrated spectra at 844 and 1014 keV, and it was determined to be ≤ 0.2 keV.

Observations of SN 1987A were made during two balloon flights from Alice Springs, Australia in 1988. The supernova was observed during a single 12 hr transit in a flight launched on April 30 (spring flight) and during two transits in a flight launched on October 28 (fall flight). The observations during the spring flight and the first transit of the fall flight were divided into 20 minute intervals, alternating between source and background observations at the same elevation. In the spring flight, background was taken by rotating the instrument 180° in azimuth, and during the fall flight azimuth offsets of $\pm 65°$ were used alternately except where known sources would interfere. During the second transit of the fall flight the supernova was observed continuously, and the Galactic center observations from the same flight (Leventhal *et al.* 1989) were used to determine the background in the regions of the ^{56}Co lines. During the spring flight the average atmospheric slant range was 9.7 g cm^{-2}, and during the fall flight it was 10.4 g cm^{-2}.

III. DATA ANALYSIS

Spectra from each detector were gain-corrected, compressed by ~ 4 into 1 keV bins, and summed together into a single composite spectrum for the observing interval. The spring flight and the first transit of the fall flight were analyzed by subtracting background intervals from the source intervals after scaling for live-time. The count rates and model count spectra were summed in 3 keV bins to perform the fits, except for the spring 847 keV line (1 keV) and for the 2599 keV line (6 keV). In each case, we have verified that Gaussian line fits to data in smaller energy bins produce essentially the same results. All of the fits were performed on an energy band 180 keV wide centered on the observed line. Fits were derived by transforming the model photon spectrum through a matrix which contains the atmospheric corrections and the detector response including efficiency, resolution, and off-diagonal response resulting from Compton scattering. Nonlinear fitting to the line parameters was performed using the CURFIT program from Bevington (1969). One sigma errors were calculated by finding the deviation of the parameter of interest required to increase the minimum value of χ^2 by 1, with all other parameters free to vary (Lampton, Margon, and Bower 1976; Avni 1976). Three continuum models were tried in fitting each line: constant, linear, and smoothed step at the line. If the resulting parameters were not significant at the 1 σ level, they were not included in the reported fit. The 847 keV line fits include a constant continuum, and there was no evidence of statistically significant continuum in the other line fits. Data from the full energy range of the instrument clearly shows the continuum from SN 1987A, but it is not large enough to effect the results of fits in a narrow energy band around the line.

A preliminary analysis of the 1238 keV line from the spring flight has been published (Teegarden *et al.* 1989). Included in Tables 1 and 2 are the results of a new analysis of this line that uses improved postflight gain and live-time corrections and includes a small amount of additional data. The resulting line flux and profile are essentially unchanged from the previous report (variations $\ll 1$ σ). This analysis used data from the Galactic center observation to improve the background determination, which is justified by the absence of any strong background lines near 1238 keV. Analysis of the 847 keV line from the spring flight is seriously compromised by the strong background line from ^{27}Al at 844 keV, which is broadened by our resolution problem to cover more than half the energy range of the supernova line. We have considered the possibility that the extreme southern position of SN 1987A and the 180° azimuth offsets used for background in the spring flight may have resulted in an imperfect cancellation of the 844 keV line. This problem was suggested by a detailed examination of the high-resolution line profile and supported by a small (1 σ) negative feature at the energy of the 1014 keV background line, which comes from the same isotopic source as the 844 keV background line and has about half the rate. We have also observed a modulation of the shield rates between source and background intervals that suggests an azimuthal asymmetry, with more irradiation of the north surface of the instrument. This suggests a possible origin for a variable 844 keV line due to inelastic scattering of cosmic-ray particles on ^{27}Al in the top of the shield housing near the aperture holes. The 844 keV line thus produced can leak through the short shield pathlengths at

TABLE 1

GRIS SN 1987A GAMMA-RAY LINE FLUXES

Day Number (after explosion)	Line Rest Energy (keV)	Flux (photons cm^{-2} s^{-1})	χ^2/d.o.f.[a]	Fraction of Emission from 0.075 $M_\odot$ of ^{56}Co
433............	846.8	$(21.^{+12.}_{-9.}) \times 10^{-4}$	187.3/190	$20^{+11}_{-8}\%$
	1238.3	$(9.1 \pm 2.1) \times 10^{-4}$	67.8/57	13 ± 3
613............	846.8	$(6.5 \pm 1.4) \times 10^{-4}$	53.1/56	31 ± 7
	1238.3	$(3.1 \pm 0.9) \times 10^{-4}$	74.6/58	22 ± 6
	2598.6	$(1.3^{+1.1}_{-0.7}) \times 10^{-4}$	27.8/27	37^{+31}_{-19}

[a] Degrees of freedom in the fit.

TABLE 2

GRIS SN 1987A GAMMA-RAY LINE PROFILES

	PEAK ENERGY [keV] DOPPLER SHIFT (km s^{-1})			FWHM [keV and (km s^{-1})]	
DAY NUMBER	Measured	E_0[a] Corrected	Model (10HMM)[b]	Measured	Model (10HMM)
433	844.6 ± 1.2[c]	846.0	848.7	$8.7^{+4.9}_{-3.3}$[c]	5.4
	(500 ± 425)		(−950)	(3100 ± 1700)	(1900)
	1235.5 ± 2.2	1237.2	1240.1	14.8 ± 5.2	7.3
	(400 ± 525)		(−700)	(3600 ± 1300)	(1800)
613	844.2 ± 1.3	846.0	848.0	$10.8^{+2.9}_{-2.4}$	5.5
	(650 ± 450)		(−700)	(3800 ± 1000)	(1900)
	1233.5 ± 1.8	1237.2	1239.6	$11.0^{+3.7}_{-3.1}$	6.5
	(900 ± 425)		(−575)	(2700 ± 900)	(1600)
	2589^{+16}_{-6}	2596.2		$20.2^{+23.6}_{-9.9}$	
	(825^{+700}_{-1850})			(2300^{+2700}_{-1100})	

[a] Rest energy of line corrected for LMC redshift.
[b] The model values were decreased to correct for the LMC redshift.
[c] Statistical errors only (systematic background subtraction effects may be significant).

the edges of the aperture holes. To account for an imperfect background subtraction, we have included in our fits to the 847 keV line an 844 keV residual with the same profile as the background line. This technique produces a good fit to our data with negative amplitudes for the residual. Because of the large uncertainty in the amplitude of the residual, the uncertainties in the 847 keV flux are also large. The model dependence of the derived line profile limits its usefulness as a confirmation of the 1238 keV results, but, taking the uncertainties into account, the 847 keV line data are consistent with the observed 1238 keV line in flux and profile.

For the fall flight supernova lines, data from the second transit were combined with the first transit. Background for the second transit was derived from the sum of the Galactic center data taken before the second pass and Galactic plane data taken after the second pass. At 1238 and 2599 keV, where there are no strong background lines and no evidence for variability of the background shape, this procedure should work well. Although the superior energy resolution in the fall flight reduces the influence of the strong background line at 844 keV, great care is still required when fitting the 847 keV line. We have made several checks for systematic errors. Fits were performed on the first transit only and on the total data set with counts between 842.5 and 845.5 keV removed, and they produce results statistically consistent with the total data set. Unlike the spring flight, any residual errors in the subtraction of the 844 keV line affect only one 3 keV energy bin, which has a very large uncertainty due to the high background and therefore does not influence the fit significantly. The 844 keV line flux for each 20 minute segment was determined by subtracting continuum bins on either side of the line from a bin covering the line and correcting for live-time. The resulting values are statistically consistent with a constant flux, and there are no $>3\ \sigma$ deviations from the mean. The data in the region of the background line at 1014 keV were examined, and the subtracted spectra show no excess residuals in the region of this background line. We conclude that there is no evidence for significant systematic errors in the subtraction of the 844 keV background line in the second pass. Figure 1 displays the total background-subtracted photon spectrum in the region of the 847 keV line and a model Gaussian line fit for comparison (see Tueller *et al.* 1989 for spectra of the other lines). Table 1 shows Gaussian line fluxes and Table 2 shows shape parameters derived from least-squares fits to the ^{56}Co lines at 847, 1238, and 2599 keV. These results are in good agreement with the results of the Lockheed/MSFC and the Florida/GSFC instruments, which also show broad lines that are mostly redshifted from the models. The JPL results, for the 1238 keV line only, are narrower and blueshifted, but the significance of the difference between their results and ours is only 2 σ.

IV. CONCLUSIONS

Figure 2 shows the flux predictions of the 10HMM model of Pinto and Woosley (1988*b*, *c*), which are typical of the spherically symmetric mixed models, for comparison with our fits and the results from other instruments. While the flux values we measure are consistent with the predictions of this model, the observed line profiles differ significantly. The line profile from the 10HMM model for the 847 keV line on day 613 is shown by the dashed line in Figure 1 for comparison. The peak energies of all the lines are consistently lower and the line widths are consistently greater than predicted. The combined

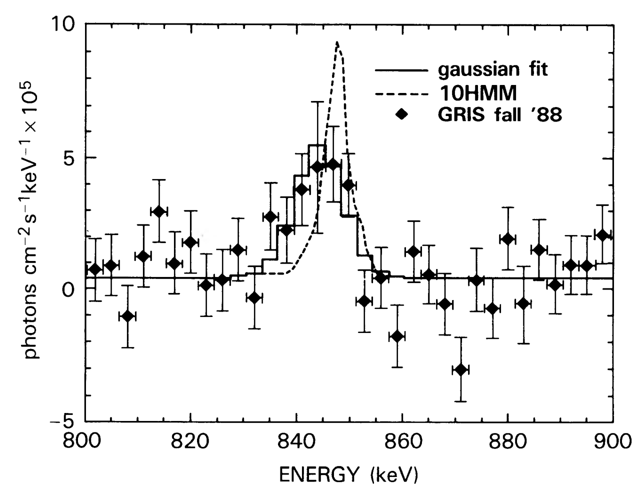

FIG. 1.—GRIS data for the 847 keV line from the decay of ^{56}Co in SN 1987A is shown for day 613. The top-of-atmosphere photon spectrum is shown in 3 keV bins which are larger than the FWHM resolution of the instrument. The solid line is a best fit to a Gaussian line profile. The dashed line is the predicted line profile for the 10HMM model. Although this model and similar spherically symmetric mixed models predict the line flux correctly, there is a clear discrepancy with the measured line profile.

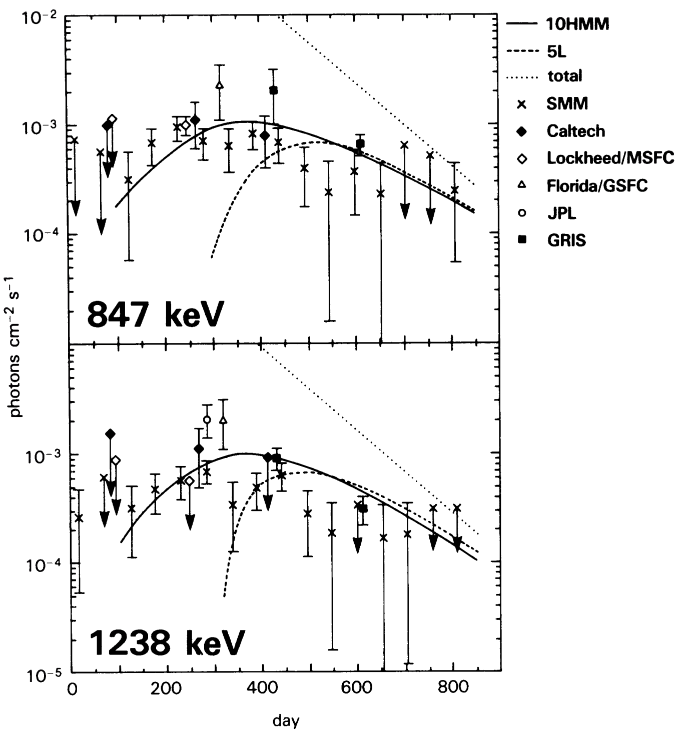

FIG. 2.—The GRIS line flux measurements are shown with theoretical predictions and the measurements of other instruments. All of the measurements are in reasonably good agreement with the 10HMM model. *Solid line*: 10HMM model; *dashed line*: 5L model without mixing; *dotted line*: unattenuated line flux; all models from Pinto and Woosley 1988*a*, *b*. Measured values from *SMM*: Leising 1989; Caltech: Cook *et al.* 1987, Cook *et al.* 1988*a*, Cook *et al.* 1988*b*; Lockheed/MSFC: Sandie *et al.* 1987, Sandie *et al.* 1988; Florida/GSFC: Rester *et al.* 1988; JPL: Mahoney *et al.* 1988.

significance of the differences between our data and the 10HMM model is 4.9 σ for the line centroids and 2.9 σ for widths (spring 847 and fall 2599 keV lines not included). The large widths associated with the lines imply high velocities for the ^{56}Co, which must have been mixed or accelerated into the higher velocity layers of the expanding supernova shell. Unmixed models produce line widths which are <6 keV full width (Gehrels, MacCallum, and Leventhal 1987). The observed line profiles are consistent with a transparent source, but the line flux values require a significant optical depth (see Table 1) to explain the bolometric light curve, which is primarily powered by radioactive decay. To resolve this apparent paradox, it is necessary to drop the assumptions of spherical symmetry or homogeneity or possibly both. An example of a possible model is one containing dense knots or filaments, which are optically thick, with ample space between them to see the receding back side of the remnant. Another possible model is a flattened disk where one can see over the top of the disk to the receding material. The general conclusion is that the gamma-ray line profiles indicate the need for further changes in the geometry of the models of the expanding remnant.

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