GAMMA-RAY LINES FROM SN1987A AND INTERPRETATION

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ABSTRACT. Gamma-ray lines from the decay of ^{56}Co in the SN1987A remnant have been detected by satellite and balloon experiments. The observations directly confirm the basic theoretical tenet that ^{56}Ni was explosively synthesized in the aftermath of core collapse of the blue super giant Sanduleak - 69 202. The flux level of the ^{56}Co lines at 847 keV and 1238 keV, from the Gamma-Ray Spectrometer (GRS) on the *SMM* satellite, is consistent with a constant level from 1987 August through 1988 May. The early appearence of the γ-ray lines and the continuum reported by the *Ginga* and *Mir-Kvant* satellite experiments require mixing, or clumping of a few percent of the newly synthesized ^{56}Ni in the expanding envelope. Results from balloon experiments, which are in the preliminary stage of analysis, do not give clear evidence for γ-ray line shifts from rest energies with a limit $\Delta E/E < 0.002$, nor is there definitive evidence, at this time, of line splitting, but γ-ray line widths are clearly wider than instrument resolution at $\Delta E/E \leq 0.02$. The continuum (50-500) keV/line ratio has stayed approximately constant at 8 from 1987 August to 1988 May indicating the origin of the continuum from Compton down-scattering of deeper lying ^{56}Co and lines from ^{56}Co at smaller γ-ray optical depths. Future balloon flights of the most sensitive high-resolution spectrometers, planned for 1988 November and 1989 April, are expected to be able to detect weaker γ-ray lines at a flux level of $\sim 10^{-4}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for the 847 keV line. SN1987A was just close enough to the Earth to confirm theory with existing instruments. In this report we review only γ-ray line results, since the continuum observations have been reviewed by Professor Trümper in this session.

1. Gamma-Ray Line Observations

The first detection of γ-ray lines from the remnant of SN1987A was made using the Gamma-Ray Spectrometer (GRS) on board the Solar Maximum Mission (*SMM*) satellite (Matz *et al.* 1988). In Figure 1, we show the satellite-Earth geometry for solar and LMC observations. Any extraterrestrial source of γ rays detectable by the GRS may be occulted by the Earth (in each orbit), depending on the source direction and the orientation of the orbital plane. For SN1987A observations occultation periods last for $\sim$ 30 days with $\sim$ 20 days during which no occultation of the source occurs. During the periods when the LMC is not occulted by the Earth any SN γ rays can reach the GRS, penetrate the side shield, and be detected. Figure 2 shows a schematic of the GRS with

D. McNally (ed.), Highlights of Astronomy, Vol. 8, 199–206.

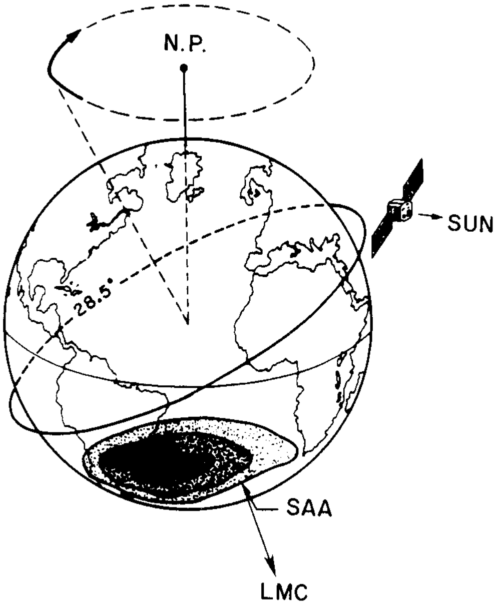


Figure 1. The geometry is shown for SN1987A viewing by the *SMM* Gamma Ray Spectrometer (GRS).

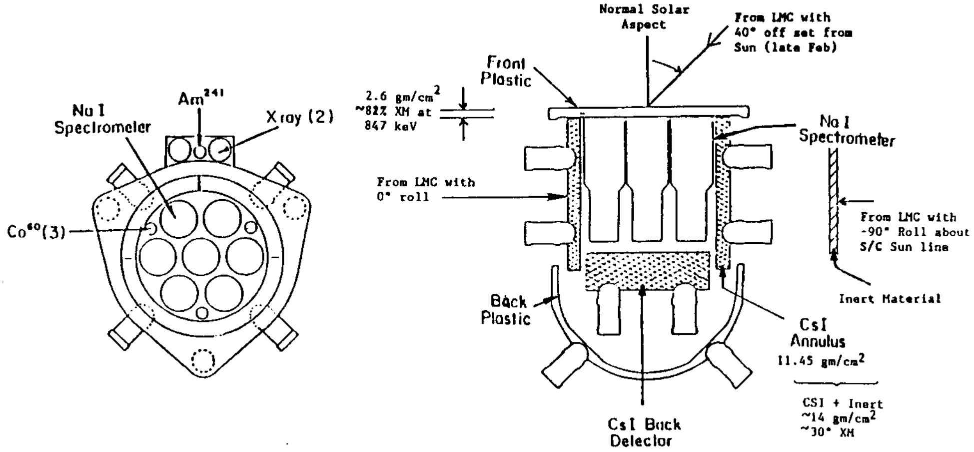


Figure 2. The schematic drawing for the *SMM* GRS is shown along with absorbers for different SN1987A viewing.

top and side views. The side view shows the amount of absorber that γ rays from the LMC must penetrate. For example, the 847 keV line is attenuated by about a factor of 3, giving an effective area of ~ 40 cm^2. The basic technique used with GRS for determining the γ-ray line flux is to form a net γ-ray spectrum by subtracting, in each orbit, the occulted (or background) spectrum from the spectrum obtained when the LMC is exposed and accumulating these for several days or weeks. This procedure eliminates spectral features present in unsubtracted spectra which are due to induced radioactivity in the spacecraft and instrument. However, there is unequal exposure to atmospheric radiation in the two spectra so a net atmospheric residual remains after subtraction.

These background subtracted spectra are then examined for evidence of excess γ-ray line flux at the expected ^{56}Co energies of 847 keV, 1238 keV and 2599 keV. To determine the specific line flux values the net spectra are fitted in the regions near a given line with a power law continuum and a Gaussian peak with a width fixed at the instrument's resolution including background lines. The best fit yields the line fluxes and the parameters of the power law continuum. Figure 3 shows the intensities of the 847 keV and 1238 keV lines after the event resulting from approximately 30 day data accumulations. Beginning with the accumulation starting in early 1987 August flux increases in the 847 keV and 1238 keV lines appear, followed by a continuing succession of positive flux enhancements through 1988 May. Matz *et al.* (1988) have shown that prior to 1988 August and for the seven years preceding SN1987A, there is no significant evidence for flux enhancements at the ^{56}Co line energies. The first and last *SMM* GRS results are listed in Table 1.

In 1987 May, NASA inaugurated its Souther Hemisphere balloon campaign (Riegler *et al.* 1988) to study the ^{56}Co γ-ray line emissions from the SN1987A remnant. The balloon experiments were carried out at atmospheric depths, ranging from ~5 g cm^{-2} to ~ 3 g cm^{-2}. To view the LMC the γ-ray telescopes must point off the zenith direction by some angle, θ_z, depending on the balloon's location. This requires a secant θ_z correction (typically ~ 40%) to the atmospheric thickness any SN γ-ray must penetrate to reach the detector. The geometry (greatly exaggerated) for balloon observations of the LMC, from two Southern Hemisphere locations, is shown in Figure 4; i.e. a launch from Alice Springs, Australia (S 23°) and from Antarctica (S 79°). The zenith angles shown for the two cases pertain only to the case of maximum elevation of the LMC source or at culmination.

The first positive observation of a ^{56}Co line from the balloon campaigns was made by the Lockheed/Marshall Space Flight Center in late 1987 October, using a large high-energy resolution γ-ray spectrometer (Chase *et al.* 1988). The flux for the 847 keV line is quoted as $(10 \pm 2.8) \times 10^{-4}$ γ cm^{-2} s^{-1}, where the experimenters quote the errors as statistical. It is also of significance that these observers do not report a positive detection of the 1238 keV ^{56}Co line, but the flux cannot be greater than 0.4 times the flux of the 847 keV line (Chase *et al.* 1988). This result is not inconsistent with the positive report by *SMM*, because of the large errors involved (cf Table 1 and Figure 3).

The first image of SN1987A remnant in γ rays was made by the Caltech group, using a coded aperture telescope on 1987 November 19 (Cook *et al.* 1988). The first reports gave results on the continuum spectrum consistent with the Mir-Kvant results, (Sunyaev *et al.* 1987). In the energy intervals (801–833) keV and (1185–1281) keV, the integral flux

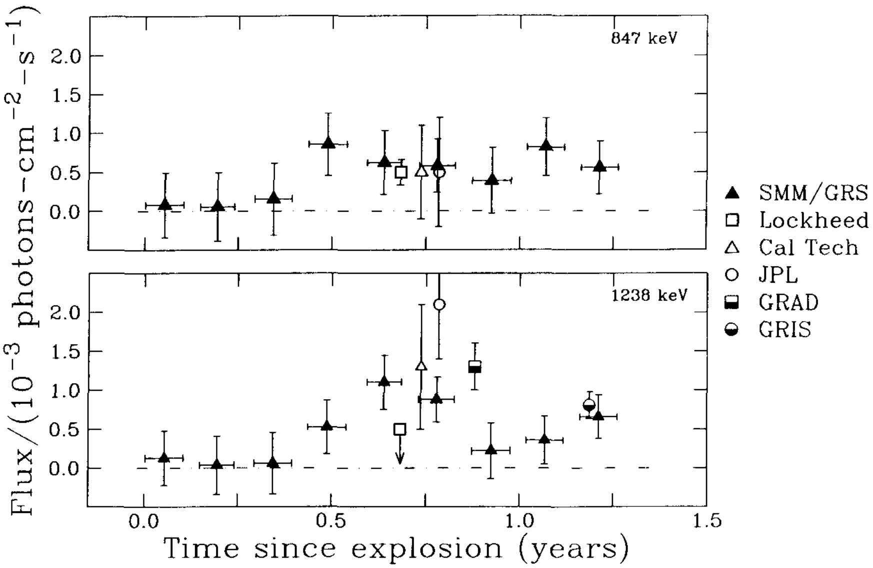


Figure 3. The flux time history of the 847 keV and 1238 keV ^{56}Co lines is shown as measured by the *SMM* GRS. Flux values obtained by balloon experiments are also shown as discussed in the text.

Table 1.
SN1987A Gamma-Ray Lines - Capabilities and Selected Fluxes

Instrument	Date(s)	Flux Limit (1 σ) (10^{-4})γ cm^{-2} s^{-1}	Flux Reported (10^{-4})γ cm^{-2} s^{-1}	Peak Position keV
SMM GRS	87 Aug 1 - Sept 7	847 (2) 1238 (1.6)	8.6±4 5.3±3.5	840±6 1239±10
LPARL/MSFC	87 Oct 29 - Oct 31	847 (3.5) 1238 (4.5)	10+2.8 -	838 - 850
CIT GRIP	87 Nov 19	847 (3.2) 1238 (4.9)	5±6 13±8	
JPL	87 Dec 7	847 (2.5) 1238 (3.9)	- 21±7	1240.8±1.7
UF/GSFC GRAD	88 Jan 8 - Jan 11	847 (8.6) 1238 (10.2) 2599 (12.3)	13±3 3.6 ± 2.1	1239.6±1.5 2602.5±1.7 3.6±2.1
SMM GRS	88 Apr 22 - May 29	847 (1.7) 1238 (1.4)	5.6±3.4 6.6±2.9	840±6 1239±10
GSFC/BL/SD GRIS	88 May 2	847 (1.4) 1238 (1.7)	8.1±1.7	$1234.9^{+1.1}_{-2.3}$

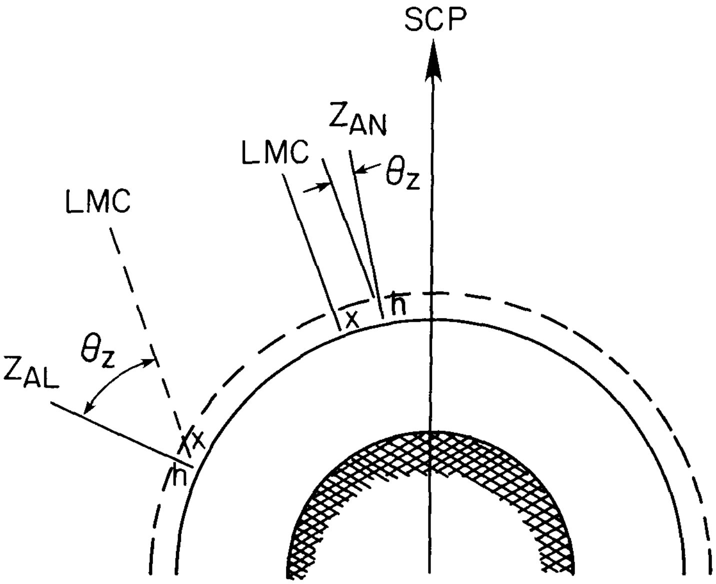
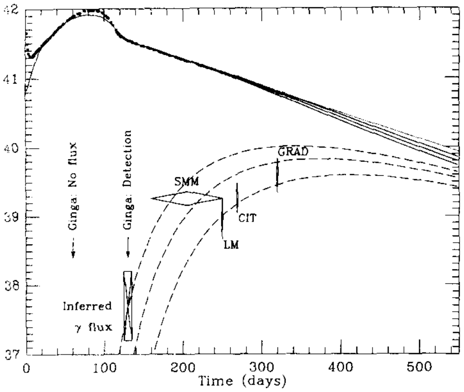


Figure 4. The geometry is shown for SN1987A viewing at culmination by balloon instruments at balloon altitudes in the Southern Hemisphere. The minimum zenith angle θ_z is shown.



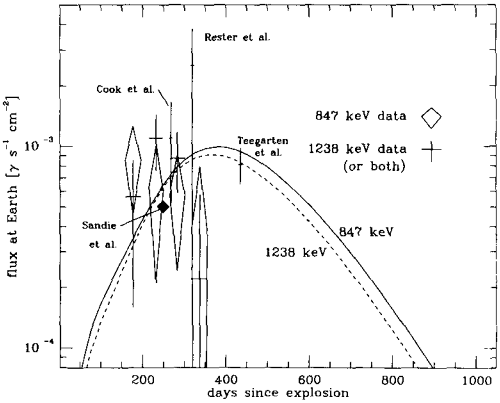


Figure 5. (left) The theoretical γ ray light curves are shown for ^{56}Co mixing models from Arnett and Fu (1988).

Figure 6. (right) The theoretical γ ray light curve is shown for Pinto and Woosley (1988) mixed model 10 HMM.

values are (1.1 ± 0.6) and (1.2 ± 0.7), respectively, in units of 10^{-3} photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. It is important to remember that these flux values contain both continuum and any line contribution. When lines at the instrument width are fit to the spectrum, the resulting flux values ($\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$) are $(5 \pm 6) \times 10^{-4}$and $(13 \pm 8) \times 10^{-4}$ for the 847 keV and 1238 keV lines, respectively. These values (of low significance) are shown in column 4 of Table 1 and are consistent with the average *SMM* fluxes for the time period November 16 – December 22 of 1987, which are shown in Figure 3.

The next balloon borne spectrometer which observed the LMC region was launched by the JPL group on 1987 December 6 (Mahoney *et al.* 1988). A positive flux value was found only for a line at (1240.8 ± 1.7) keV at a level $(2.1 \pm 0.7) \times 10^{-3}$ photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. This value is higher than the *SMM* value given above for the corresponding time interval but the reason for this discrepancy is not known. The flux for a line at 847 keV was $(5 \pm 7) \times 10^{-4}$ photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, clearly an upper limit which is not inconsistent with the corresponding *SMM* average (see Figure 3).

A DOD supported payload (*GRAD*) was launched by the University of Florida/ Goddard Space Flight Center group from Antarctica (McMurdo) on 1988 January 8 and stayed aloft until late January 10. Rester *et al.* (1988) have reported the presence of strongly red-shifted components of ^{56}Co γ-ray lines at 847 keV, 1238 keV, 2599 keV. They also reported slightly blue-shifted peaks at (1239 ± 1.5) keV and (2602 ± 1.7) keV which are very near the rest energies for the 847 keV and 1238 keV lines. For direct comparison with the other results discussed in this report we discuss only the "blue-shifted" lines and leave the reader to the experimenter's report (Rester *et al.* 1988) for other details. Column 4 of Table 1 gives the reported flux values for the 847 keV line, which again is somewhat higher than the *SMM* average value for the corresponding time period. This experiment gave the only evidence for detectable flux for the 2599 keV line, but the experimenters' significance is $< 2\ \sigma$.

The largest germanium spectrometer (*GRIS*) used thus far for SN1987A observations was launched by the GSFC/Bell Laboratory/Sandia Laboratory consortium on 1988 May 2 (Barthemly *et al.* 1988). The analysis of the experimental results (at the time of this report), is still preliminary, however, a very significant ($\sim 5\ \sigma$) flux value for the 1238 keV line is reported at ($(8.1 \pm 1.7) \times 10^{-4}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, with the error only statistical. This value is also consistent with the last *SMM* average value, shown in Table 1. The statistics were good enough in this flight to determine that the 1238 keV line width was $\sim (25 \pm 5)$ keV, centered at $1234^{+2.1}_{-2.3}$ keV (Teegarden 1988). These latter values are preliminary and include an estimate of systematic errors. Future flights of the largest high-resolution spectrometers will clearly be needed to measure the rate of decay of the ^{56}Co line fluxes and it is heartening to learn that NASA will include *GRIS* in its 1988 November Australia Campaign.

2. Spectrometer Capabilities

We now review the capabilities of the γ-ray spectrometers (to measure a line flux) under the actual experimental conditions encountered during SN1987A observations. The method used for this assessment is to calculate for each spectrometer, the 1 σ statistical limit (expressed in flux units) for a null flux observation.

This is

$$\mathrm{F}_{\mathrm{min}}(\mathrm{Line}) = \frac{3}{\mathrm{S(cm^2)}}\left(\frac{2\dot{\mathrm{B}}\Delta\mathrm{E}}{\mathrm{T_{S,B}}}\right)^{1/2} e^{\mu_\ell x} \qquad (1)$$

where $\dot{\mathrm{B}}$ (counts s^{-1} keV^{-1}) is the measured background count rate, $\Delta\mathrm{E}$ is the FWHM band width for a given line observation, $\mathrm{T_{S,B}}$ is the source or background observation time (whichever is smaller) and $\exp(\mu_\ell x)$ is the correction factor for an observation made under an atmospheric thickness $x(\mathrm{g\ cm^{-2}})$ where $\mu_\ell(\mathrm{cm^2\ g^{-1}})$ is the absorption coeffecient for a given line and finally $\mathrm{S(cm^2)}$ is the effective area for a given line.

In Table 1, column 3 is shown the 1 σ statistical flux limits (in parenthisis) for the conditions of the first *SMM* observation in August 1987 and for several later balloon observations and for the last completed *SMM* observation. In column 4 of Table 1. are shown the line flux values reported for each observation along with the quoted error. These errors should be compared with the values in parenthesis in column three.

In using Equation (1) to calculate the flux limits shown in column three, the experimenters stated line width for each specific line with a quoted flux value was used. Also, some experimental flux errors include estimates for systematic errors with the exception of the LPARL/MSFC and the GSFC/BL/SL values. In most cases, the statistical 1 σ limits are well below the quoted flux errors so the significance of the flux values can be judged with some confidence. In two cases, the second and fifth entries, the quoted errors are somewhat below the statistical limits indicating that the corresponding flux values are probably not as significant as indicated. The general conclusion that one can make from Table 1 is that several experiments have confirmed positive flux values for the 847 keV and 1238 keV lines.

3. Comparison with Theory

It is now widely appreciated that the earlier than expected appearance of γ-ray lines in 1988 August required that some small fraction ($\sim$ 1%) of the ^{56}Co expected at that time had to be fully exposed with the greater portion of ^{56}Co at sufficient depths to explain the hard X-ray continuum spectrum (Sunyaev *et al.* 1987) by Compton down scattering of the lines. The time of appearance of detectable γ-ray line fluxes at 847 keV and 1238 keV was expected several months later than observed if the requisite amount of original ^{56}Ni was confined to a thin layer under the expanding and thinning envelope. Under these conditions one would expect to first see the down-scattered hard X-ray continuum and later the lines. The (near) simultaneous appearance of the lines and continuum suggests that some form of redistribution of the radioactive material is taking place, such as mixing, fragmentation, etc. Several theoretical calculations are now available that model the expanding envelope with various assumptions about mixing etc.. In Figure 5 we show an example of the γ-ray light curve of Arnett and Fu (1988), which corresponds to the case of initial production of 0.073 $M_\odot$ of ^{56}Ni and 7.5 $M_\odot$ of ejecta and for different choices for the density structure in the ejecta, giving the three different γ-ray light curves shown dotted in the figure. In all three cases it was assumed that mixing of ^{56}Co occurred out to a fractional radius of 0.4 into the ejecta. The corresponding bolometric light curves are also shown in the figure. Another example for a theoretical γ-ray light curve, with mixing of ^{56}Co in the envelope, is given by the 10 HMM model of Pinto and Woosley (1988) (see Figure 6). In this case the envelope model is 10 $M_\odot$ with 0.075$M_\odot$ of synthesized ^{56}Ni. The mixing is accomplished by radioactive heating of a small amount of the ^{56}Co which is accelerated to a high velocity, and then plows into the envelope and core. Only a few percent of the *^{56}Co needs to be redistributed to low γ-ray optical depths to drastically affect the* γ-ray line light curve.

4. Conclusions

The basic result of this review is that *SMM* GRS and several balloon instruments have confirmed the detection of ^{56}Co γ-ray lines at 847 keV and 1238 keV. Further, the observations are consistent with a constant flux level for the two lines through 1988 May with $\bar{F}(1238)/\bar{F}(847) \simeq 1 \pm 0.5$. There is, in this authors' opinion, no evidence for a significant shift of the centroids of the lines from their rest energies. Some experimenters claim measurable, small blue shifts from the rest energies, but intercalibration of instruments is required. At this point we conclude that $(\Delta E/E_0) < 0.002$, corresponding to $v_- < 700$ km s^{-1}. There is, however, now good evidence that the 1238 keV line is broadened to ~ 25 keV (FWHM) about the rest energy. Finally, Gehrels *et al.* (1988) in a recent summary have pointed out that the ratio of the γ-ray continuum flux in the energy range (50–500) keV to the 847 keV flux has remained constant at about 8 through 1988 April. This ratio should be about 30 if all the ^{56}Co were at a constant depth. Further analysis of the balloon and *SMM* results is in progress.

5. References

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