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PROSPECTS FOR OBSERVATIONS OF NUCLEOSYNTHETIC GAMMA-RAY LINES AND CONTINUUM FROM SN 1987A

NEIL GEHRELS
Laboratory for High Energy Astrophysics, NASA/Goddard Space Flight Center
CRAWFORD J. MACCALLUM[1]
Sandia National Laboratories
AND
MARVIN LEVENTHAL
AT & T Bell Laboratories
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ABSTRACT

Expected flux levels for nucleosynthetic γ-ray line and continuum emissions from SN 1987A are calculated for several models. The dominant line emission is from freshly synthesized ^{56}Ni and its decay daughters, and the continuum is from Compton scattering of line photons. For a 15 $M_{\odot}$ Type II model, the light curve for the 0.847 MeV γ-ray line peaks in 1988 September at 3×10^{-4} photons cm^{-2} s^{-1}. This is detectable only by new, ultrasensitive balloon-borne spectrometers. For models with substantial mass loss from their envelopes, the peak is in early 1988 at $\sim 10^{-2}$ photons cm^{-2} s^{-1}, which is detectable at high significance levels by all current instruments. The continuum emission in the 0.05–0.5 MeV band peaks $\sim$ 100 days before the 0.847 MeV line peak. This Compton precursor is observable at about the same significance level as the lines. For the 15 $M_{\odot}$ model, the first evidence for upcoming γ-rays will be X-ray emission detectable by the *Ginga* satellite, preceding the line emission by $\sim$ 180 days. The strength of the X-ray precursor depends sensitively on the mass and metallicity of the envelope. Models with no mantle and low-mass envelopes are already ruled out by the lack of detection by *Ginga*.

Subject headings: gamma rays: general — stars: supernovae

I. INTRODUCTION

Supernova 1987A will be observed by a large complement of γ-ray spectrometers over the next several years. The hope is to detect γ-ray lines from the decay of radioactive isotopes produced by explosive nucleosynthesis in the event (Clayton, Colgate, and Fishman 1969). Measurements of the intensities of these lines and their spectral shapes will give the structure and isotopic abundances in the inner regions of the expanding envelope as well as the total ejecta mass (Gehrels, Leventhal, and MacCallum 1987, hereafter GLM). To facilitate observation planning and data interpretation, we present in this *Letter* calculations of γ-ray and X-ray emissions expected for various models of SN 1987A. Emissions from a buried pulsar are not included, although the photon transport considerations are similar.

Supernova 1987A is not a typical Type II event. There are hydrogen lines in the optical spectrum (Davidsen, Kimble, and Gregg 1987), but the event is underluminous and has an unusual light curve. The progenitor star is most likely the blue supergiant Sanduleak −69 202 (Woosley *et al.* 1987; Kirshner *et al.* 1987). Massive stars are thought to produce Type II events, but the standard model has a red giant progenitor. Helium lines were seen in the optical spectrum (Davidsen, Kimble, and Gregg 1987) within a day of the supernova discovery and grew in strength during the first weeks (Ryan 1987). The radial velocities derived from the Doppler shifts of these lines one week after discovery are 6500–8500 km s^{-1}, compared with 9000–13,500 km s^{-1} for hydrogen (Ryan 1987), implying that the helium is deeper than the hydrogen. One interpretation of the early, slow-moving helium is that the envelope is less massive than for typical Type II supernovae, and the emission is from helium in the underlying mantle. In addition, the UV spectrum is similar to that of the Type Ib (no envelope) event SN 1983N (Gry *et al.* 1987). Woosley *et al.* (1987) and Woosley, Pinto, and Ensman (1987) model SN 1987A as a 15–20 $M_{\odot}$ star that has lost approximately half of its mass prior to exploding. Arnett (1987) has a 15 $M_{\odot}$ progenitor with a low LMC metallicity explaining many of the peculiarities of the event. Harkness *et al.* (1987) propose that SN 1987A is a low-mass event with 1 $M_{\odot}$ of ejecta.

The best prospects for detecting γ-ray lines from supernovae are the 0.847 and 1.238 MeV lines emitted in the ^{56}Ni → ^{56}Co → ^{56}Fe decay chain (GLM). The ^{56}Ni is produced by explosive nucleosynthesis and is the innermost layer

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of the ejecta for Type II events. Based on the current belief that radioactive heating from the ^{56}Ni decay chain is driving the SN 1987A optical light curve, the quantity of ^{56}Ni synthesized in the explosion is thought to be $\sim 0.15\ M_\odot$ (Woosley 1987).

II. MODELS AND CALCULATION TECHNIQUES

We have considered three models for the density, composition, and velocity profile of SN 1987A. For each model the ACCEPT three-dimensional electron/photon propagation code (Halbleib and Mehlhorn 1984) was run to calculate the escape probabilities, line fluxes, line shapes, and scattered continuum radiation for γ-rays emitted in the ^{56}Co decay. The simulations took $\sim$ 10 hr of Cray computer time. The models are as follows:

1. *15 $M_\odot$ Type II.*—Standard Type II model, with a 1.5 $M_\odot$ neutron-star core, 3 $M_\odot$ mantle of He, O, Ne, Si, and ^{56}Ni, and a 10.5 $M_\odot$ envelope of H and He. Densities were modeled as independent of radius in the mantle and envelope with values chosen to approximate those given by Weaver and Woosley (1980*b*, 15A model). Kinetic energy = 1.3×10^{51} ergs. ^{56}Ni mass = 0.1 $M_\odot$.

2. *10 $M_\odot$ Type Ib + H.*—A Type Ib with a 1 $M_\odot$ envelope of H and He. The degenerate core is 1.5 $M_\odot$. The mantle structure is an approximation to that of the 25 $M_\odot$ model (25A) of Weaver and Woosley (1980*a*). Kinetic energy = 1.8 $\times 10^{51}$ ergs. ^{56}Ni mass = 0.1 $M_\odot$.

3. *2 $M_\odot$ Harkness et al.*—An approximation to the model of Harkness *et al.* (1987). The degenerate core is 1 $M_\odot$ and there is a 1 $M_\odot$ envelope of H and He. The density dependence is r^{-7} in the envelope. Kinetic energy = 7×10^{50} ergs. ^{56}Ni mass = 0.01 $M_\odot$, which is the upper limit for this model.

Based on the probable identification of Sanduleak -69 202 as the progenitor and on the lack of X-rays observed to date by the proportional counter on *Ginga* (ASTRO-C; see § III*b*), we believe models 1 and 2 are better representations of SN 1987A than model 3. Models 1 and 2 were chosen as limiting cases of mass loss: Model 1 has a full Type II envelope, and model 2 has almost no envelope. The true gamma-ray and X-ray fluxes will likely lie between the predictions for these two models.

III. RESULTS

a) Gamma-Ray Lines

The expected flux in the 0.847 MeV line for the models is shown as a function of time in Figure 1. Shown for comparison are the detection sensitivities for γ-ray spectrometers that will be used to observe SN 1987A. The peak flux and time of peak flux are model dependent. For the 15 $M_\odot$ Type II model, the flux has a broad maximum in 1988 September (580 days after onset) at 3×10^{-4} photons cm^{-2} s^{-1}, which would be detectable only by the new balloon-borne spectrometers. The 1.238 MeV line has a slightly higher peak flux occurring 30 days earlier. The 2.599 MeV line (not shown) is the strongest line prior to 400 days (Chan and Lingenfelter 1987). For the 10 $M_\odot$ Type Ib + H model, the peak occurs in 1988 January (320 days after onset) at $\sim 10^{-2}$ photons cm^{-2} s^{-1}, which would be detectable by all instruments. Other weaker lines generated in the Co-Fe decay (see GLM for list) could be observed and the line shapes studied. Determining the γ-ray light curve during the exponential-decay phase gives the amount of ^{56}Ni synthesized. Measuring the time at which the various lines peak, the time dependence of the line ratios, and the spectral line shapes gives the mass and velocity of the ejecta (GLM; Chan and Lingenfelter 1987). The 2 $M_\odot$ model has a line flux that peaks in 150 days at 10^{-2} photons cm^{-2} s^{-1}, which would be detectable by 1987 May. Woosley, Pinto, and Ensman find 0.847 MeV line peak fluxes and times for their most promising models, that lie between our limiting cases of the Type II and Ib + H models. Their 15 $M_\odot$ Type II model for a blue supergiant has a peak flux within a factor of 2 of our standard Type II model that assumes a red giant progenitor.

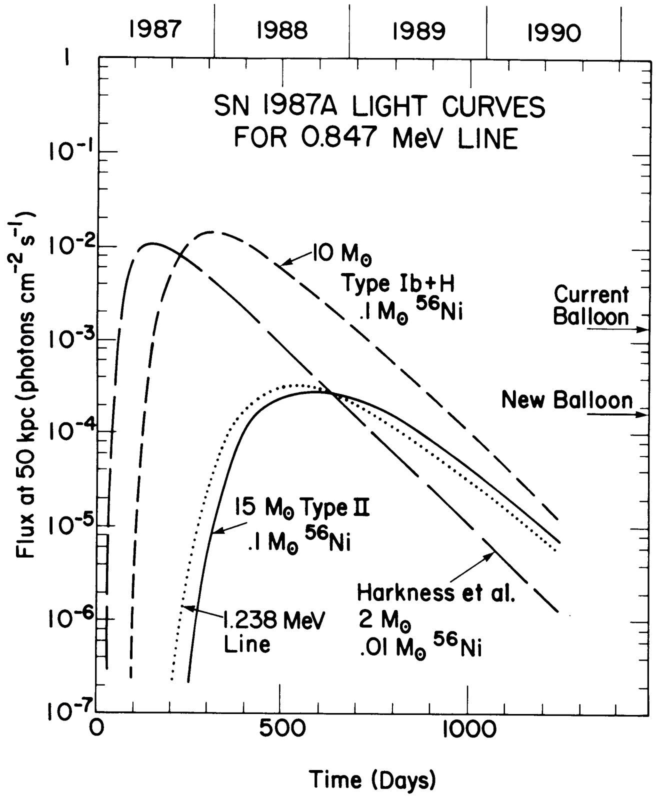

FIG. 1.—Light curves for the 0.847 MeV γ-ray line for three models. The 1.238 MeV line light curve is shown for the 15 $M_\odot$ model. The 3 σ detection sensitivities (assuming 8 keV line widths) for current and new-generation high-resolution balloon-borne spectrometers are indicated.

The 0.847 MeV line width is $\sim$ 7 keV for the 10 and 15 $M_\odot$ models which have expansion velocities of ~ 1200 km s^{-1} for the ^{56}Co shell, and $\sim$ 23 keV for the 2 $M_\odot$ model which has ^{56}Co velocities of ~ 4000 km s^{-1}. The line shape will depend on the density and velocity profiles of the ^{56}Co layer. If the mantle cleanly separates from the core during

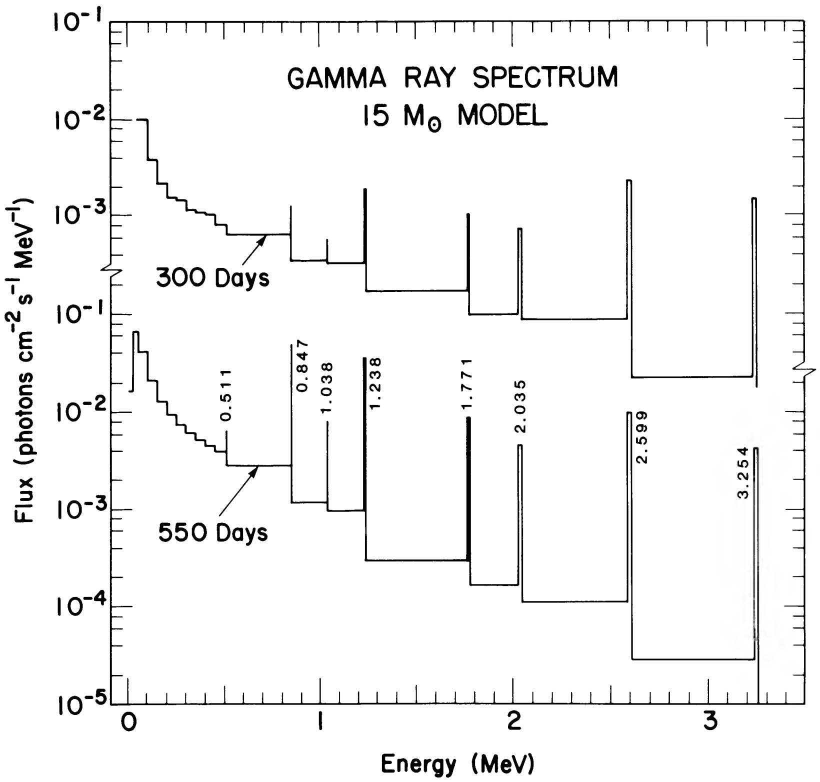

FIG. 2.—Energy spectra for the 15 $M_{\odot}$ model at 300 and 550 days. Line energies in MeV are shown.

shock passage (Wilson *et al.* 1986), a shell of ^{56}Ni is formed and double-peaked line shapes are expected (GLM).

b) *Continuum Emission*

The dominant nucleosynthetic X-ray and γ-ray continuum emission from Type II or Ib supernovae is expected to be from Compton scattering of the ^{56}Co γ-ray lines. We have calculated this component for the three models using the ACCEPT code. Inputs include all ^{56}Co decay lines and the positronium continuum. The energy spectrum from the 15 $M_{\odot}$ Type II model is shown at 300 and 550 days in Figure 2. The continuum-to-line ratio is large at early times due to the large column depth overlying the ^{56}Co, and decreases with time as more line photons escape unscattered.

Continuum-emission light curves are shown in Figure 3. The 0.05–0.5 MeV continuum flux peaks before the 0.847 MeV line flux. For the 10 and 15 $M_{\odot}$ models, this Compton precursor precedes line emission by ~ 100 days. The indicated 3 σ detection sensitivities are for the same instruments as in Figure 1 and show that the 0.05–0.5 MeV continuum will be detectable at a similar significance level as the lines.

The X-ray continuum is sensitive to the mass and metallicity of the envelope. X-rays produced by scattering in the mantle have short attenuation lengths for photoabsorption by the $Z > 2$ elements and do not escape. Even in the envelope, where H and He are the most abundant elements, the trace $Z > 2$ elements from the protostellar material dominate the absorption at low energies. The 10–25 keV continuum emission from radioactivity is shown in Figure 3 for the 15 $M_{\odot}$ model, assuming a protostellar metallicity of one-fourth solar, typical for the LMC (Arnett 1987). At this metallicity, the spectrum cuts off below ~ 10 keV at peak flux. For solar metallicity, the cut is at ~ 20 keV. X-ray spectral observations will thus give a sensitive measure of the envelope metallicity.

The 10–25 keV continuum peaks in 400 days (1988 March) for the 15 $M_{\odot}$ model at 10^{-2} photons cm^{-2} s^{-1}. This is a factor of ~ 4 lower and 9 months later than the X-ray flux estimates of McCray, Shull, and Sutherland (1987) for a model with 4 $M_{\odot}$ of ejecta, but no mantle. The flux is easily detectable by *Ginga* which has a 5 σ sensitivity in this range of $\sim 2 \times 10^{-3}$ photons cm^{-2} s^{-1} for a single scan (Kunieda 1987). For this model, the first evidence for upcoming γ-ray emission will be X-ray emission detected by *Ginga*. The 10–25 keV emission from the Type Ib + H model (not shown in figure) peaks at the much lower level of $\sim 10^{-4}$ photons cm^{-2} s^{-1}, which is probably not detectable by *Ginga*. This is due to the low mass of the envelope relative to the mantle and shows that not all models produce X-ray precursors. The 2 $M_{\odot}$ model with no mantle and only envelope produces bright X-ray emission. The 10–25 keV flux falls monotonically from 2×10^{-2} photons cm^{-2} s^{-1} for our earliest run at 50 days. The lack of detection to date by *Ginga* appears to rule out this model, assuming that more than 10^{-3} $M_{\odot}$ of ^{56}Ni is synthesized.

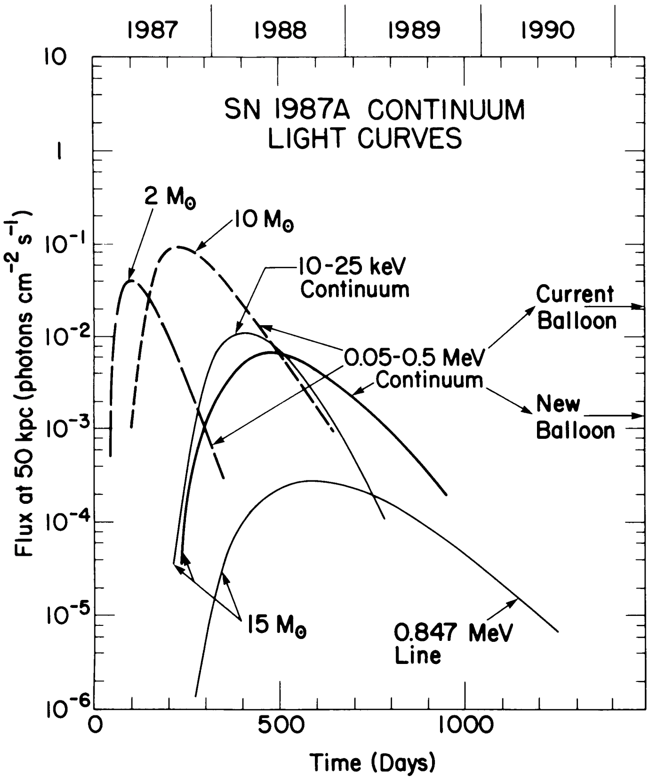

FIG. 3.—Gamma-ray continuum light curves in the 0.05–0.5 MeV band for three models. The continuum in the 10–25 keV band and the 0.847 MeV line for the 15 $M_{\odot}$ model are also shown. The sensitivity limits in the 0.05–0.5 MeV band for current and new balloon-borne spectrometers are given by the arrows.

IV. CONCLUSIONS

Assuming a ^{56}Ni mass of 0.1 $M_{\odot}$, a 15 $M_{\odot}$ Type II model of SN 1987A gives a flux in the 0.847 MeV ^{56}Co line that peaks in 1988 September and is detectable only by new, ultrasensitive balloon-borne spectrometers. For a 10 $M_{\odot}$ model in which the progenitor has undergone mass loss leaving only 1 $M_{\odot}$ of envelope, the flux peaks in 1988 January and is detectable at high significance levels by all existing instruments. The continuum emission in the 0.05–0.5 MeV band from scattered γ-ray lines peaks ~ 100 days before the 0.847 MeV line.

The X-ray continuum emission is sensitive to the mass and metallicity of the envelope. Assuming an envelope metallicity that is one-fourth solar, the 10–25 keV continuum flux from radioactivity peaks ~ 180 days prior to the 0.847 MeV line for the 15 $M_{\odot}$ model and is detectable by the *Ginga* satellite. This will be the first evidence for upcoming γ-ray emission. At peak flux, the spectrum cuts off below 10 keV, with the cutoff energy dependent on metallicity. For the 10 $M_{\odot}$ model, the flux is down by two orders of magnitude due to the low mass of the envelope relative to the mantle and is unlikely to be detected. The 10–25 keV emission from the 2 $M_{\odot}$ Harkness *et al.* (1987) model should have already been detected by *Ginga*.

The critical measurements and expectations are as follows:

1. *Ginga* may detect continuum emission prior to γ-ray detections, depending on the mass of the envelope. Comparison of X-ray and γ-ray continuum emission will give the envelope mass. X-ray spectral measurements of the cutoff energy will give the envelope metallicity.
2. Gamma-ray continuum detection will indicate that γ-ray lines are due within ~ 100 days.
3. Observations of the light curves of the lines and high-resolution spectral observations of their shapes will give direct measures of the amount of ^{56}Ni synthesized and the mass and velocity of the ejecta. Observations throughout the γ-ray light curve are required. At early times, the ejecta is studied by measuring the rapid change in the line ratios. At late times, the exponential-decay phase of the light curves directly gives the ^{56}Ni mass.

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NEIL GEHRELS: Code 661, NASA/Goddard Space Flight Center, Greenbelt, MD 20771

MARVIN LEVENTHAL: Room 1E-349, AT & T Bell Laboratories, Murray Hill, NJ 07974

CRAWFORD J. MACCALLUM: Division 1271, Sandia Laboratories, Albuquerque, NM 857185