THEEmergence of X-Rays and Gamma-Rays from Supernova 1987A

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Abstract We discuss attempts to arrive at a unified scenario for the optical, X-ray, and γ-ray emission of SN 1987A. We discuss the X-ray and γ-ray spectra that should emerge from SN 1987A, as the expanding envelope expands to reveal the inner debris of the explosion. It is now almost certain that the supernova light curve is dominated by the radioactive decay of $^{56}$Ni to $^{56}$Co to $^{56}$Fe, although an X-ray emitting pulsar is possible at some level. Gamma rays from $^{56}$Co degrade in energy due to Compton scattering in the mantle and envelope, only emerging as lines when the Thomson optical depth at 1 MeV drops to $\tau_T \approx 1$. Hard X-rays emerge between 20 - 400 keV owing to Comptonization in the envelope. Theoretical spectra are in reasonable agreement with recent observations of hard X-rays by the Ginga and Mir satellites, but the early turn-on of X-rays suggests that the mantle and envelope may be “leaky”, perhaps as a result of Rayleigh-Taylor instabilities and clumping. The soft X-ray spectrum should be dominated by a 6.4 keV Fe Kα fluorescence line. The reported Ginga detection of 4-10 keV X-ray emission is also discussed.

1 INTRODUCTION

In the first months following the explosion of SN 1987A, numerous groups made theoretical predictions of the emergence of X-rays and γ-rays from the opaque envelope. McCray, Shull, and Sutherland (1987) discussed two likely scenarios: (1) that the core produces $^{56}$Co γ-ray lines which Comptonize and emerge as 20-400 keV X-rays from the envelope; and (2) that an X-ray emitting pulsar exists at the center. Similar calculations have been reported by Xu et al. 1987, Gehrels et al. (1987), Pinto and Woosley (1987), and Ebisuzaki and Shibazaki (1987). The emergent X-ray spectra in the two scenarios are not dissimilar, but the X-ray light curves can distinguish between these scenarios (Xu et al. 1987).

Among the exciting observations reported at this conference are three which affect these interpretations. First, we learned that the optical light curve is now tracking an exponential decay, with $\tau_0 = 113.6 \pm 0.6$ day (Feast 1987), suggesting that $^{56}$Co is a dominant energy source. Second, we learned that hard X-rays have been detected (Tanaka
1987; Trümper 1987; Dotani et al. 1987), with spectra similar to theory but with a turn-on somewhat earlier than predicted by Comptonization models. Finally, Tanaka announced that *Ginga* also detected a “soft X-ray” (4–10 keV) excess, fitted with a 4 keV thermal spectrum and containing a hint of an Fe line between 6 and 7 keV. The origin of the soft X-rays is unknown, although possible explanations include a leaky envelope, shocks, or reprocessing of hard X-rays by circumstellar matter.

In this review, we will describe Comptonization theories for the emergence of the hard X-rays and γ-rays. Taking advantage of the new observations, we will then present new results for theoretical X-ray and γ-ray spectra and “light curves” based on revised interior models kindly provided by Stan Woosley and Phil Pinto. The predicted spectra are in reasonable agreement with the data, but the early turn-on suggests that the mantle or envelope may be leaky due to clumping.

## 2 BASIC IDEAS

Theoretical models for SN 1987A require an internal energy source with luminosity \( L \approx 10^{41–42} \) erg s\(^{-1}\) to explain the late-time light curve. Two possibilities have been proposed (McCray, Shull, and Sutherland 1987; Arnett 1987; Shigeyama et al. 1987; Woosley, Pinto, and Enßman 1987): (1) radioactive decays of \(^{56}\)Ni and \(^{56}\)Co; or (2) a luminous X-ray emitting pulsar. For the first model, a mass \( M_{\text{Ni}} \approx 0.075M_\odot \) of \(^{56}\)Ni is required. Each \(^{56}\)Co decay results in a characteristic spectrum of γ-ray lines (Gehrels, MacCallum, and Leventhal 1987), with energies ranging from 0.511 MeV to 3.452 MeV and a mean lifetime \( \tau_0 \approx 114 \) days. A typical decay yields \( N_\gamma \approx 3 \) lines having net energy \( \sim 3 \) MeV. The γ-ray photon luminosity is then,

\[
S_\gamma = \left( \frac{M_{\text{Ni}}}{m_{\text{Ni}}} \right) \left( \frac{N_\gamma}{\tau_0} \right) \exp(-t/\tau_0) = \left( 6 \times 10^{46} \right) \left( \frac{M_{\text{Ni}}}{0.1M_\odot} \right) \exp(-t/\tau_0).
\]  

In the pulsar scenario, a straightforward estimate for a Crab-like magnetic field and spin, gives a total luminosity \( L_x \approx (2 \times 10^{41} \) erg s\(^{-1}\)) with a photon spectrum \( dJ/d\epsilon \propto \epsilon^{-2} \) for photon energies \( 1 \) eV \( \leq \epsilon \leq 1 \) MeV. Of course, there is no guarantee that a pulsar is formed with a sufficient magnetic field or rotation period to produce a hard spectrum. In fact, current fits to the optical light curve appear to rule out a pulsar with a very short spin period.

In each scenario, γ-rays and X-rays from the core scatter repeatedly in the mantle and envelope, and at early times are destroyed by photoelectric absorption. For purposes of illustration, we assume a simple homogeneous model, in which an envelope of mass \( M_e \) (solar units) expands homologously at velocity \( V_{\text{exp}} = (10^4 \) km s\(^{-1}\))\( V_4 \). At time \( t = (100 \) days)\( t_{100} \), the outer radius, mean hydrogen density, and Thomson optical depth are,

\[
R = V_{\text{exp}} t = (8.64 \times 10^{15} \text{ cm})V_4 t_{100}
\]  

\[
n_H = (3M_e/4\pi R^3 \mu) = (3.17 \times 10^8 \text{ cm}^{-3})M_e(V_4 t_{100})^{-3}
\]  

\[
\tau_T = (1.2n_H \sigma_T R) = (2.19)M_e(V_4 t_{100})^{-2}.
\]
The envelope thins to $\tau_T = 1$ at a time,

$$t_{\text{thin}} \approx (148 \text{ days})M_e^{1/2}V_4^{-1},$$

marking the emergence of $\gamma$-ray lines. The Klein-Nishina optical depth at 1 MeV is $\tau_\gamma \approx 0.3\tau_T$, so the photon luminosity of unscattered lines should be $S_\gamma(t) \approx S_0 \exp(-0.3\tau_T)$. The Compton scattered $\gamma$-ray lines form a hard X-ray continuum which fades and hardens as the envelope thins due to expansion.

A simple analytic model shows how the X-ray emergence proceeds. In Compton scattering of a photon of energy $E$, the change in wavelength $\Delta \lambda = (h/m_e c)(1 - \cos \theta)$ implies a change in energy $\Delta E \approx -(E/m_e c^2)E$. Thus, the total number of scatterings, from initial energy $\epsilon_o$ down to a final energy $\epsilon$ is,

$$N_{sc} = \int_{\epsilon_o}^{\epsilon} \frac{dE}{(-E^2/m_e c^2)} \approx (m_e c^2)/\epsilon,$$

for $\epsilon \ll \epsilon_o$. For a random walk, we have $N_{sc} \approx \tau_T^2$, so that the 20 keV X-rays emerge after 511/20 $\approx 25$ scatterings, or a "straight-line" Thomson depth $\tau_T \approx 5$.

The emergent X-ray flux will reach a maximum when $\tau_T$ is just large enough to Comptonize the $\gamma$-rays to X-ray energies that are just hard enough to escape the envelope without photoelectric absorption. For a random walk, the Thomson scattering optical depth along the total path length is $\tau_p \approx \tau_T^2$. An approximate fit to the photoelectric opacity (Morrison and McCammon 1983) relative to $\tau_p$ is,

$$\tau_\alpha (\epsilon) \approx (1500\tau_p)\zeta \epsilon^{-3}; \epsilon > 8 \text{ keV}$$

$$\tau_\alpha (\epsilon) \approx (320\tau_p)\zeta \epsilon^{-2.5}; 0.5 < \epsilon < 8 \text{ keV},$$

where $\epsilon$ is measured in keV and where $\zeta$ is the metallicity factor ($\zeta = 1$ for solar abundances, $\zeta \approx 10^2$ for the mixture of heavy elements in the mantle of SN 1987A, but $\zeta \approx 0.25$ for the envelope, formed with LMC abundances). Substituting the emergent X-ray energy, $\epsilon_{em} \approx (m_e c^2)/N_{sc} \approx (m_e c^2/\tau_T^2)$, into eq. (7), we find

$$\tau_\alpha (\epsilon_{em}) = \frac{1500\zeta}{(m_e c^2)^3} \tau_T^8 \approx (1.12 \times 10^{-5}) \zeta \tau_T^8.$$

The hard X-rays emerge when $\tau_\alpha (\epsilon_{em}) \approx 1$, and therefore when $\tau_T \approx 4.2\zeta^{-1/8}$. The characteristic photon energy is $\epsilon_{em} \approx (30 \text{ keV})\zeta^{1/4}$. Since most of the Comptonization occurs in the H/He envelope, $\zeta \approx 0.25$ and the X-ray light curve is controlled primarily by the rate at which $\gamma$-rays escape the mantle.

Monte-Carlo simulations of the Compton scattering and absorption of X-rays in an expanding envelope (McCray, Shull, and Sutherland 1987) confirm the validity of this formula. The hard X-rays emerge at $\tau_T \approx 6$, corresponding to a time,

$$t \approx t_{\text{thin}}/6^{1/2} \approx (60 \text{ days})M_e^{1/2}V_4^{-1}.$$

Thus, for $V_4 \approx 1$ and envelope masses $M_e$ between 5 and 10 $M_\odot$ (Woosley, Pinto, and Enssman 1987; Nomoto 1987), we would expect hard X-rays and $\gamma$-rays to begin leaking out of the envelope after 130 to 200 days. To make further comparisons with the observations, we turn now to more detailed models of the interior mass and velocity distribution.
3 RESULTS OF MODELS

Theoretical modeling of the X-ray emission from SN 1987A has proceeded in three phases. The first phase was a study of homogeneous expansion, as described above. The second phase used detailed models for the interior density, velocity, and elemental stratification to compute the scattering and absorption optical depths. Xu et al. (1987) and Pinto and Woosley (1987) have performed Monte-Carlo simulations of the transfer of X-rays and γ-rays through various interior models of varying envelope mass. The early emergent X-ray spectrum is due entirely to down-Comptonization of the γ-rays or hard X-rays that can penetrate the envelope. The models with $M_e \approx 10 M_\odot$ predicted X-ray emergence some 2 to 3 months later than is now observed.

Attempts to reconcile this early emergence and the subsequent X-ray light curves with interior models have led to a third phase of modelling. These models have generally followed three approaches: (1) lowering the mass of the envelope; (2) “mixing” the radioactive debris in the mantle and partially into the envelope; and (3) examining the effects of “clumping” the mantle in order to produce a range of optical depths. These hybrid models preserve some aspects of the homogeneous models; for example, once the optical depths are determined at a given epoch (say 100 days), the constant expansion velocities assumed for each shell imply that $r \propto t^{-2}$ thereafter.

There are some constraints on these new approaches. Lowering the envelope mass $M_e$ will allow an earlier turn-on, but the lower optical depths mean that the emerging X-rays undergo insufficient Compton scatterings to downgrade to 10 - 20 keV. Mixing the mantle allows the γ-rays to penetrate the envelope more easily, and thus directly influences the turn-on. However, there may be insufficient energy from the radioactive core to mix the heavy elements into the H-He envelope as far as required. Clumps in the mantle may arise from Rayleigh-Taylor instabilities associated with the $^{56}$Ni “bubble”, but modeling them in a convincing fashion is probably the most difficult task awaiting us.

In this section, we present results from new Monte Carlo models employing the first two approaches, and speculate on the effects of the third. Pinto and Woosley (1987) discuss two models (5L and 5LM) in which the explosion energy was reduced ($6 \times 10^{50}$ ergs) and an envelope of mass $M_e = 5 M_\odot$, was added to a $6 M_\odot$ helium core with $M_{N1} = 0.075 M_\odot$. Model 5L gave a good fit to the optical light curve, but had its slowest hydrogen moving at 1800 km s$^{-1}$ (compared to the observed 2100 km s$^{-1}$) and the X-rays still emerged too late. We have performed Monte-Carlo simulations of the X-ray transfer for model 5LM, in which the heavy elements are mixed throughout the mantle. The X-ray and γ-ray light curves are presented in Figs. 1 and 2, and the spectra at selected epochs are shown in Figs. 3 and 4. According to our predictions and those of Pinto and Woosley (1987), the γ-ray lines peak at a flux near $10^{-3}$ cm$^{-2}$ s$^{-1}$ between 400 and 450 days following the explosion. Since this flux is at the threshold of sensitivity, the γ-ray detections may be difficult.

The prospects for late detection of X-rays from the inner mantle (or a pulsar) are illustrated in Fig. 5, which gives the photoelectric opacity at 1, 3, and 10 yrs. However, the envelope may be leaky, and soft X-rays could emerge sooner than we predict.

The X-ray spectra (Fig. 3) show the expected hardening of spectral index between
Figure 1: X-ray fluxes in various energy bins (labelled in keV) versus time for Woosley-Pinto model 5LM. Also shown is the 6.4 keV Kα fluorescence line of Fe.

Figure 2: Light curves for selected γ-ray lines of 56Co (847 and 1238 keV are the strongest), plus the 511 keV e+ annihilation line.
Figure 3: X-ray spectra at 4 epochs for Model 5LM, including the 6.4 keV Fe-line, for 200 equally spaced bins with $\Delta E/E = 0.0342$ between 4 keV and 4 MeV. Note the appearance of $\gamma$-ray lines after 300 days.
Figure 4: Gamma-ray spectra at 4 epochs for Model 5LM. The energy bins are linearly spaced, with $\Delta E = 0.018 \text{ MeV}$. Note the appearance of lines at 511, 847, 1238 keV, as well as weaker lines up to 3.452 MeV.

Figure 5: Photoelectric absorption optical depths of the envelope in Model 5LM after 1, 3, and 10 yrs. Note the K-shell edges of Si (1.84 keV), S (2.47 keV), and Fe (7.1 keV).
200 and 500 days as the envelope thins. Chi-square fits to the Monte-Carlo spectra of hard X-rays yield power-law photon spectra $J(\epsilon) \propto \epsilon^{-\alpha}$, where $\alpha$ declines steadily, from $1.53 \pm 0.07$ (200 days), $1.42 \pm 0.04$ (300 days), $1.20 \pm 0.05$ (400 days), and $1.04 \pm 0.04$ (500 days). Monitoring the behavior of the spectral index with time will provide a good observational test of the Comptonization model.

The early emergence of the hard X-rays is still problematic, even in Model 5LM with its lower-mass envelope. The GINGA observations suggest turn-on at about 130 days with a peak at about 200 days following the explosion, whereas the Monte-Carlo theory predicts a 10 - 30 keV peak between 250 and 300 days. Efforts to explain the early turn-on by mixing mantle material into the envelope were not entirely successful.

Instead, we may be seeing the effects of a distribution of optical depths in the mantle. If some of the $\gamma$-rays can escape the mantle more easily than others, we would witness a distribution of light curves such as Fig. 1, each with a different peaking time. We have investigated an idealized model of escape from the mantle, approximating the distribution of optical depths from fully transparent to fully opaque. If the mantle is filled with fully opaque “clumps” of constant size and total projected area $A_{\text{total}}$, the emergent X-rays will be “gated” by the fraction,

$$f_\gamma = \left[1 - \left(\frac{A_{\text{total}}}{4\pi R^2}\right)\right] = \left[1 - \frac{\alpha^2}{t^2}\right],$$

of $\gamma$-rays which penetrate the envelope. Since $R = V_o t$, where $V_o$ is the velocity of mantle material, we have $\alpha^2 \equiv \left(\frac{A_{\text{total}}}{4\pi V_o^2}\right)$. As the envelope expands, the clumps intercept fewer of the $\gamma$-rays and the X-ray flux will have the time dependence,

$$J_x(t) = J_o \left[1 - \frac{\alpha^2}{t^2}\right] \exp(-t/113.6 \text{ days}).$$

We have fitted the GINGA data (Dotani et al. 1987) to this functional form (Fig. 6), and find $\alpha = 130 \pm 5$ days (95% confidence limits) with a reduced $\chi^2 = 1.04$. Clearly, the next step is to determine whether Rayleigh-Taylor instabilities at the core - mantle boundary can produce such clumps.

There is one final enigma remaining in the 4-10 keV GINGA detection reported by Tanaka (1987). As is clear from the discussion earlier, photoelectric absorption in the expanding envelope puts a strong cutoff below 10 keV (see Fig. 2). As the envelope expansion proceeds, the X-ray peak moves to harder energies since the escaping X-rays have had less chance for down-Comptonization. Empirical fits of the lower energy spectra (8 keV $\leq \epsilon \leq 40$ keV) follow the form,

$$J(\epsilon) = J_o \exp \left[-\left(\frac{\epsilon_o}{\epsilon}\right)^{\beta}\right],$$

where $\beta$ ranges between 2.9 (300 days) and 2.1 (500 days), and $\epsilon_o$ ranges between 17.4 keV (300 days) and 32.7 keV (500 days).

Although it is yet too soon to tell, these “soft” X-rays may arise from the same mechanism that explains the early turn-on of harder X-rays. If there are leaks in the
Figure 6: Fit of *Ginga* data for 10 - 30 keV counts (Dotani et al. 1987) to the functional form of eq. 12, with $\alpha = 130 \pm 5$ days.

core and envelope, soft X-rays might escape near the light curve peak. Alternative, and perhaps more reasonable explanations include reprocessing of the 10 - 30 keV X-rays by gas in the outer envelope or shock waves in circumstellar gas. The reports of CO emission lines between 3 - 5 $\mu$m (Larson 1987; Danziger 1987) and the *IUE* detection of N-rich ultraviolet emission lines (Kirshner and Sonneborn 1987) could be interpreted as evidence for interactions with a wind containing CNO-processed material. Certainly the energetics of an outflowing shock wave are consistent with the soft X-rays. For a shock wave of velocity ($1000$ km s$^{-1}$) $V_{1000}$ striking circumstellar gas of baryon density ($10^{3}$ cm$^{-3}$) $n_{1000}$ in a shell of radius ($10^{16}$ cm) $R_{16}$, the radiated luminosity, ($\rho v^2/2)(4\pi R^2)\xi$, is approximately,

$$L_{\xi} \approx (10^{36} \text{ erg s}^{-1}) R_{16}^2 n_{1000} V_{1000}^3 \xi,$$

(14)

where $\xi$ is an efficiency factor for converting the inflowing bulk energy into radiation. At 150 days following the explosion, the expanding envelope should be at $R \approx 10^{16}$ cm; a red giant wind of $10^{-6} M_{\odot}$ yr$^{-1}$ and velocity 10 km s$^{-1}$ would have a density $\sim 3 \times 10^4$ cm$^{-3}$ at this distance, and the shock velocities could easily exceed 1000 km s$^{-1}$. The B-star wind would alter this, however. Further analysis of the *Ginga* data, particularly the wavelength and strength of an Fe line or absorption edge, could help distinguish among a leaky mantle, thermal reprocessing, and X-ray fluorescence.

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