X-rays and γ-rays from Supernova 1987a

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SUMMARY

The observation of X-rays and γ-rays from SN 1987a can provide important constraints on parameters for models of this unique event. We present the results of detailed Monte Carlo calculations of the fluxes to be expected in several X-ray bands and for the strong line at 847 keV associated with the decay of ^{56}Co. Our calculations use Model 10H of Woosley, Pinto, and Ensman(1988), with $0.075M_{\odot}$ of radioactive material. If it is assumed that there is no mixing of this material with the layers above, then the X-ray fluxes do not become detectable as early as the observations made by the *Ginga* team in August, 1987. If these observations correspond to X-rays arising from γ-rays Compton scattered down in energy in the supernova ejecta, rather than the interaction of the ejecta with circumstellar matter, then they can only be explained by mixing outward of radioactive material or an envelope with some combination of less mass or greater kinetic energy per unit mass.

INTRODUCTION

It has by now become abundantly clear from the bolometric light curve of SN 1987a that the ejecta contain $0.075M_{\odot}$ of ^{56}Co. The ejecta are almost entirely opaque to the γ-rays released in the decay of ^{56}Co to ^{56}Fe, and after several months it is the rate of deposition of their energy that directly powers the light curve because the diffusion time for optical photons is then shorter than the dynamical time. This permits the determination of the radioactive mass to the accuracy of the distance of the LMC. The γ-rays are not immediately absorbed, however, but are instead repeatedly Compton scattered and degraded in energy and subsequently they may be photoelectrically absorbed by heavy elements or they may escape as X-rays. As the ejecta continue to expand, less scattering and energy degradation occur and a higher fraction of the photons escapes. Many groups have calculated the X-ray and γ-ray fluxes expected in this scenario (see McCray, Shull and Sutherland, 1987; Chan and Lingenfelter 1987; Gehrels, MacCallum, and Leventhal 1987; Xu *et al.* 1988; Ebisuzaki and Shibazaki 1987; Pinto and Woosley, 1988; Itoh *et al.* 1987). We present and discuss results for a representative calculation done in mid-summer 1987 at the University of Colorado.

Before proceeding to the details, it is useful to estimate the critical factors that determine the fluxes. If the γ-rays were unimpeded by the ejecta then their flux at Earth would be:

$$f_{\gamma} = 1.6 \times (M/0.075M_{\odot})exp(-t/t_c) \text{ counts s}^{-1} \text{ cm}^{-2}; \quad (1)$$

where $t_c = 113.6$ days is the mean life of ^{56}Co. In each decay of a ^{56}Co nucleus, on average 2.88 γ-rays are emitted with a mean energy of 1.24 MeV.

To estimate the critical epoch for the emergence of the X-ray flux we need to balance the effects of energy degradation through multiple-scattering and photoelectric absorption. A photon of energy E_0 has its energy reduced to

$$E_1 = E_0/[1 + (E_0/mc^2)(1 - cos\theta)] \quad (2)$$

by Compton scattering off a cold electron. For purposes of estimation, we may set $cos\theta \sim 0$ and

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then the energy loss equation may be iterated for n scatterings to yield:

$$E_n \sim mc^2/n \sim mc^2/\tau_s^2 \quad (3)$$

independent of the initial γ-ray energy. For ejecta in the homologous expansion phase, $\tau_s = \tau_{s,0}(t_0/t)^2$ where $\tau_{s,0}$ is a fiducial value for the scattering depth at time t_0. The photoelectric optical depth, as a function of X-ray energy, is:

$$\tau_a = 1.5\zeta(E/10\ \mathrm{keV})^{-3} \times \tau_s \quad (4)$$

where ζ is the metallicity relative to solar. At early times the characteristic energy of the "down-Comptonized" photons is very low, and these photons are absorbed with little chance of escape. The critical epoch for emergence of the X-ray flux occurs when the effective absorption optical depth $\tau_{a,eff} \sim [\tau_a(\tau_s + \tau_a)]^{1/2}$ falls below unity; τ_a is evaluated at the characteristic energy of the "down-Comptonized" photons. One readily finds that at this epoch $\tau_{s,crit} \sim 4\zeta^{-1/8}$ and the escaping X-rays have characteristic energy $\sim 30\zeta^{1/4}$ keV. The critical epoch is $t_{crit} \sim [\tau_{s,0}t_0^2/\tau_{s,crit}]^{1/2}$. Using naive scaling for the explosion itself, one finds $t_{crit} \propto M/K^{1/2}$ with M and K the total mass and kinetic energy of the explosion.

The emergent flux in a γ-ray line can be estimated with a simple escape probability: take equation (1) above and multiply by the angle-average of $exp(-\tau_l)$ where τ_l is the scattering optical depth at the line energy. This simplicity is a consequence of the fact that a single scattering will almost certainly remove the γ-ray from the line because of the large energy loss to recoil. The γ-ray lines will emerge from the continuum after the peak in the X-rays since the latter depends upon multiple-scattering and the former is suppressed by it.

For Model 10H of Woosley, Pinto and Ensman (1988) the radial optical depth to the radioactive shell is $\sim$ 10 at $\sim$ 1 year and this implies that it would be unlikely for X-rays to become detectable until spring, 1988.

It is clear from the above simple analysis that quantitative predictions demand a Monte Carlo calculation, for the following reasons: (i) for the first few scatterings when the photon energy is still relatively large, the Klein-Nishina cross-section is appropriate and this is considerably smaller than the Thomson value, (ii) the scatterings at high energy are strongly forward-peaked, (iii) the ejecta are very inhomogeneous and compositionally stratified so that absorption cannot be treated with a single, global parameter, and (iv) crucial to confrontation with observations is the precise determination of the distribution of X-ray flux with energy. The results presented below are similar to those given in Xu *et al.* (1988) but have been augmented with results for the 847 keV γ-ray flux and with results for a model in which fractions of the central core have been mixed in an attempt to match the recent observations from *Ginga* (Tanaka, 1987; Dotani *et al.* 1987). The code used was a modification of one developed by Ambwani and Sutherland (1988) and implemented the scheme of Pozdnyakov, Sobol, and Sunyaev (1983) which is crucial when there is a high probability of photon interaction and a low probability of escape. A derivative of this code is used by Pinto and Woosley (1988).

RESULTS

The results of our calculation for the Woosley, Pinto, and Ensman (1988) Model 10H are shown in Figure 1. The continuum flux below 10 keV is very low because to lower a photon's energy that much requires very many scatterings, and below 10 keV absorption strongly dominates scattering. There is, however, a not insignificant line flux at 6.4 keV due to fluorescence of Fe by photons well above the Fe K edge. The fluxes in the 10-20 and 20-30 keV bands are predicted to be marginally detectable by the *Ginga* satellite, about 1 year after the explosion. Tanaka (1987) and Dotani *et al.* (1987) have reported that *Ginga* detected SN 1987a in August, 1987 at a level $\sim 2\times10^{-11}$ ergs cm^{-2} s^{-1} or $\sim 8\times10^{-4}$ counts s^{-1} cm^{-2}. Although the flux level is approximately

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that expected, it was observed substantially earlier than we expected. If the observations indeed correspond to the multiple-scattering of the γ-rays from the radioactive shell then some aspect of the model must be modified.

The models for SN 1987a advocated by Woosley and his group (see Woosley, 1988, for a review of these models: the label 10H is first used there – this model was previously known as 2BF7) by Arnett (1987), by Nomoto, Shigeyama, and Hashimoto (1987), and by Hillebrandt, Höflich, Truran, and Weiss (1987) have in common, as their progenitors, $6M_{\odot}$ helium cores with primordial main sequence masses $\sim 15 - 20M_{\odot}$, as befits the identification of the star Sanduleak 69-202 as the site of the supernova. Beyond this, there are differences about the mass and composition of the envelope at the instant of explosion. Since the model explosions are intended to reproduce the observed light curve and the velocity distribution within the ejecta, with such uncertainties about the envelope must go uncertainties about the energy of the explosion. To get an earlier turn-on of the X-ray flux requires a less massive envelope and/or more energy per unit mass. This qualitative statement has been quantitatively confirmed by Pinto and Woosley (1988) where they evaluate the constraints placed on a variety of models by both the optical and the X-ray observations.

An alternative explanation for the early X-ray emergence is the possibility of mixing of the radioactive material with the overlying layers. As pointed out by Woosley, Ensman, and Pinto (1988) the thin shell of ^{56}Ni will form a "bubble" that is Rayleigh-Taylor unstable with respect to the material above it. This is because the ^{56}Ni shell is very slowly moving once the reverse shock from the envelope has moved through the core, and the energy per unit mass to be released through radioactive decay is comparable to the kinetic energy in the shell. No one has yet modelled this instability, and it is not known whether relatively thorough mixing will occur or whether a "salt-finger" instability will develop. We have made a very crude attempt at modelling the effects of mixing, and the results are shown if Figure 2. For the 3 calculations shown, we have taken a certain central mass in Model 10H and thoroughly mixed it, using momentum conservation to set the density, and then repeated our Monte Carlo calculations. We find that when $\sim 5M_{\odot}$ are mixed we are able to match the August 1987 *Ginga* observations. If there is any merit in these calculations, then it follows that the flux should increase by a factor of 2-3 by October-November 1987 after which it should show a gradual decline. Preliminary results from Dotani *et al.* do *not* seem to show a flux increase in late September 1987.

CONCLUSIONS

A flux of X-rays with a sharp cut-off near 10 keV and detectable by the *Ginga* satellite is a natural consequence of the "down-Comptonization" of γ-rays released by the radiaoactive material in the ejecta of SN 1987a. There is considerable confidence that the mass of this radioactive material has been accurately ($\pm 5\%$) determined by the bolometric light curve. The X-ray light curve can be used to constrain properties of the envelope of the exploding star and the degree of mixing of the radiaocative material within the core. The detection of the strong γ-ray lines will provide additional information as these sample the properties of the envelope in a different way. In principle, γ-ray line profiles could tell us a great deal about the structure and velocity distribution of the radioactive core (Chan and Lingenfelter, 1987; Pinto and Woosley 1988).

If the *Ginga* observations do not entirely fit the above view (and there is some evidence for a "soft" component in the spectrum: see Dotani, *et al.* 1987) then serious consideration has to be given to the possibility that we are seeing the interaction of the supernova with circumstellar matter (Nomoto *et al.* , 1987).

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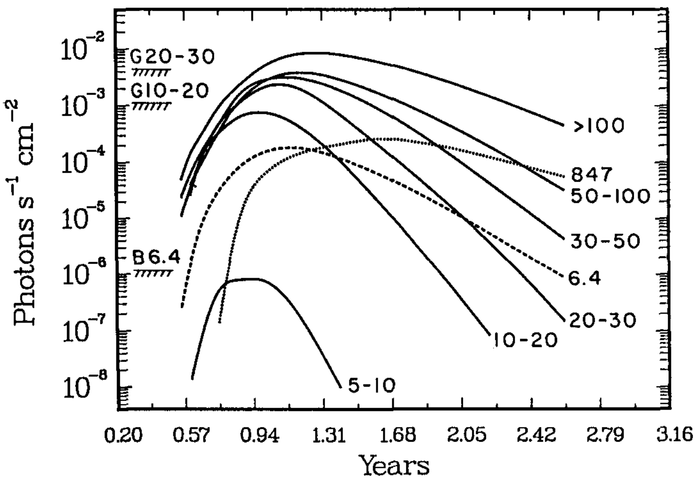

Figure 1: X-ray and γ-ray fluxes for Model 10H (no mixing). The numbers (with the solid curves) indicate the energy bands in keV; the dotted curve is for the γ-ray line at 847 keV and the dashed curve is for the Fe K_α line at 6.4 keV. The 5σ thresholds for detection by the *Ginga* satellite and a hypothetical detector of the BBXRT-class are also indicated.

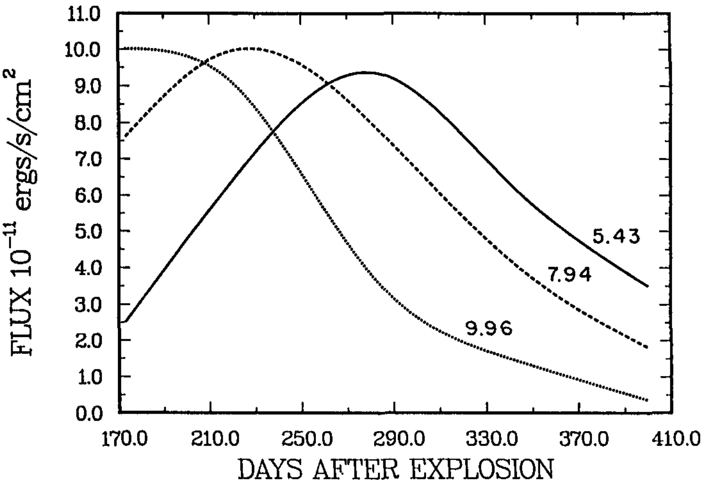

Figure 2: The effects of mixing the radioactive material with the overlying layers. The 3 curves correspond to different total masses (in $M_\odot$) into which the $0.075 M_\odot$ of radioactive material has been homogeneously mixed. The original model was 10H of Woosley, Pinto, and Ensman (1988) and momentum was conserved in the mixing. The flux is for the 10-20 keV band.

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