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A Search for Gamma-Ray Lines from the Decay of Fe-59 in Supernova 1987A

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A search for γ-ray lines from the decay of ^{59}Fe in Supernova 1987A

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Abstract. We have searched spectra of SN 1987A, accumulated during several 35-day intervals after the explosion by the *Solar Maximum Mission* Gamma Ray Spectrometer, for γ-ray lines at 1.099 and 1.292 MeV from the decay of ^{59}Fe which may have been produced in the progenitor's helium shell. We find no evidence for these lines, down to 3σ upper limits $\sim 7\ 10^{-4}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for the 1.099 MeV line, or $\sim 4.5\ 10^{-4}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for the 1.292 MeV line, in any 35-day interval. We derive a conservative 3σ upper limit on the mass fraction of ^{59}Fe in the helium shell of $2.9\ 10^{-3}$.

Key words: supernovae: individual: SN 1987A – Magellanic Clouds – Gamma rays: observations

1. Introduction

The historic detection of γ-ray lines from the decay of ^{56}Co in SN 1987A (Matz et al. 1988) has brought to the fore the problem of the asymmetric hydrodynamics of the supernova explosion – the "mixing" problem (Woosley & Pinto 1988; Arnett et al. 1989; Nomoto et al. 1991). The detection of the lines occurred much earlier than had been expected from simple spherically-symmetric models of the explosion ($\sim$ 150 d after the explosion, rather than $\sim$ 400 d – see e.g. Woosley et al. 1987). The discrepancy has been explained by invoking instabilities in the expansion of the ejecta which carry a small fraction of the ^{56}Co from deep levels in the remnant (the central iron core of the presupernova star) out to higher levels from which the optical depth to γ-rays is small. The Rayleigh–Taylor instability (Chevalier 1976) in the expanding shock-wave at early times is expected to be exacerbated by a continuing energy input from the decay of ^{56}Ni in overdense regions (Woosley et al. 1988). Numerical simulations of this outward mixing of ^{56}Ni (and, later, ^{56}Co) have recently been performed by Hachisu et al. (1990), Fryxell et al. (1991), Herant & Benz (1991, 1992), and Ishikawa et al. (1992) in two dimensions, and by Müller et al. (1991) and Herant & Benz (1992) in three dimensions. In general, these simulations fail to reproduce the ^{56}Co γ-ray light-curve measured by Leising & Share (1990, hereafter LS), and in particular the high γ-ray flux at early times. There is a need for an additional degree of mixing of material from the original Fe core into the H-rich envelope at very early stages of the explosion. Enhancement of the Rayleigh–Taylor mixing by ^{56}Ni heating (Colgate 1991; Herant & Benz 1992) and rapid rotation of the progenitor (Ishikawa et al. 1992) remain to be explored.

A possible avenue for investigating the early mixing of the ejecta of SN 1987A would be the detection of γ-ray lines from nuclear species which are known to originate further out in the structure of the progenitor. The nucleus ^{59}Fe is a possible candidate for this purpose, since its half-life ($\tau_{1/2} = 44.6$ d) is long enough for it to survive the early stages of expansion, but short enough that a small abundance gives rise to a relatively high γ-ray line flux. Early calculations (Harris 1988; Prantzos 1989) predicted that rather large ^{59}Fe abundances (masses $\sim$ 4–8 $10^{-4} M_\odot$) would survive from the action of the s-process in the He shell of presupernova stars of about 20–25$M_\odot$. More recent work, with improved nuclear reaction rates and allowance made for the reduced ^{56}Fe abundance in the Large Magellanic Cloud, suggests a mass of ^{59}Fe smaller by about a factor of 10 (Weaver & Woosley 1993), much of which comes from explosive nucleosynthesis in the He shell rather than from the s-process.

The β-decay of ^{59}Fe gives rise to two γ-ray lines, at 1.099 MeV (branching ratio 0.57) and 1.292 MeV (branching ratio 0.43). We have searched for these γ-ray lines in the same spectra in which Matz et al. (1988) and LS detected ^{56}Co decay lines. Our analysis is described in Sect. 2 and the results are presented and discussed in Sect. 3.

2. Analysis

The Gamma Ray Spectrometer (GRS) aboard the *Solar Maximum Mission (SMM)* spacecraft acquired spectra in

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Table 1. Gamma-ray lines in the region 0.9–1.6 MeV

Nucleus	$\tau_{1/2}$	Line energy (MeV)	Branching ratio	Expected source
^{59}Fe	44.5 d	1.099	0.57	SN 1987A
—	—	1.292	0.43	SN 1987A
^{56}Co	77.7 d	1.038	0.14	SN 1987A
—	—	1.238	0.68	SN 1987A
^{60}Co	5.3 yr	1.173	1.0	On-board calibration source
—	—	1.332	1.0	On-board calibration source

the energy range 0.3–8.5 MeV during most of the period 1980 February to 1989 December. The spacecraft orbit was inclined at 28° to the equator, at an altitude which decayed from about 573 km to below 400 km during this period (the precession period of the orbit plane therefore declined from 55 d to 50 d during the mission). The GRS instrument consisted of seven 7.6×7.6 cm NaI crystals, surrounded by a 2.5 cm thick annular CsI shield, with a 7.6 cm thick CsI disk in the rear (Forrest et al. 1980). Front and back were also protected by plastic scintillation detectors which monitored the charged-particle environment of the GRS. For 1.2 MeV photons, the FWHM spectral resolution was about 72 keV; according to Monte Carlo simulations of the instrument (S.M. Matz & G.V. Jung 1988, private communication) the FWHM aperture was about 155° and the photopeak effective area in the central field-of-view was about 105 cm^2, at 1.2 MeV. The instrument was continually pointed at the Sun, so that SN 1987A, being close to the south ecliptic pole, was always at an angle of about 90° to the detector axis. Its γ-ray emission was thus attenuated by the CsI annular shield; the detector efficiency at 90° off-axis was about 37% at 1.2 MeV.

Our method of analysis closely follows that used by LS. The GRS spectra were accumulated over 1 min intervals; data from times within $\sim 10^4$ s of a passage through the South Atlantic Anomaly (SAA) were rejected, as were data contaminated by simultaneous solar flares, γ-ray bursts, or other known background events. Spectra obtained after 23 February, 1987 were binned into those for which SN 1987A was visible to the spacecraft ("unocculted"), and those for which it was occulted by the Earth. Spectra accumulated between April 1984 and February 1987 were used to eliminate backgrounds, by subtraction, from the "source" spectra taken after 23 February 1987.

The background subtraction method has been described by LS, and is merely summarized here. It was shown by LS that the short-term backgrounds in the 1 min spectra depended upon four main parameters – the Earth–Sun–satellite angle, the time since SAA passage, the geomagnetic latitude, and the back plastic detector count rate. All spectra taken between April 1984 and January 1989 were binned according to the values of these parameters. For each spectrum taken after 23 February 1987, the mean value of the background (prior to 23 February 1987) spectra in the same bin was subtracted, to remove short-term backgrounds. These background-corrected 1 min spectra were then summed for each satellite orbit, into separate bins according to whether SN 1987A was unocculted or occulted by the Earth. The occulted spectrum was subtracted from the unocculted spectrum, to yield a ~ 90 min residual spectrum of SN 1987A from which backgrounds varying on time-scales longer than 90 min had been canceled[1].

The low inclination of *SMM*'s orbit meant that high-latitude targets such as SN 1987A were sometimes not occulted by the Earth at all during many orbits. The subtraction of occulted from unocculted spectra was only performed for orbits in which the occulted spectrum contained at least 20% of the live time. About 18 d out of each $\simeq 53$ d orbital precession period were unusable for this reason. The residual SN 1987A spectra from each orbit were summed over the remaining 35 d periods.

The expected spectrum in the region containing the ^{59}Fe lines consists of six possible source and residual-background lines which are listed in Table 1, plus a residual continuum which could locally be approximated by a power-law in energy. The 35 d residual SN 1987A spectra were fitted between 0.9 and 1.6 MeV by a model spectrum consisting of these Gaussian lines and continuum. The amplitudes of the lines and continuum, and the continuum power-law index, were the free parameters in the fit; the amplitudes of the two ^{56}Co lines and the two ^{59}Fe lines were fixed in the proportions of the respective branching ratios. The intrinsic line widths were assigned the nominal value of 1 keV, since they are expected to be much narrower than the instrumental resolution.

After folding the model with the GRS instrument response and comparing with the SN 1987A spectra, the parameters were varied so as to derive the best-fitting values of each, according to the method of least squares. Errors in the value of each parameter were estimated by the usual

[1] The SN 1987A spectra and the background spectra had systematically different exposures to emission from the Crab Nebula and the Galactic center region. The spectra measured from these sources by Harris et al. (1990), weighted by the relative exposure to the GRS of each source, were therefore also subtracted from the residual SN 1987A spectra.

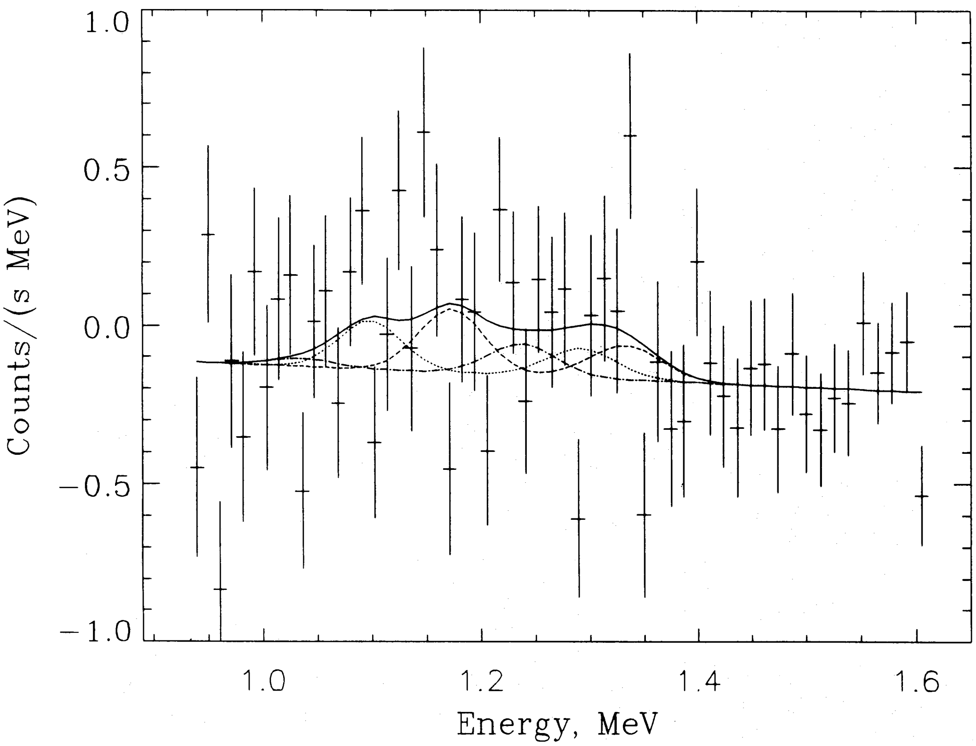

Fig. 1. GRS spectrum from exposure to SN 1987A during the period 10 June 1987 to 13 July 1987 (days 107–140). The best-fitting model spectrum (full line) with continuum plus six lines, as described in the text, is shown after folding with the instrument response. The lines are the 1.099 and 1.292 MeV lines from ^{59}Fe (dot line), the residual 1.17 and 1.33 MeV lines from the ^{60}Co on-board radioactive calibration source (dash line), and the 1.038 and 1.238 MeV lines from ^{56}Co (dot-dash line). The ^{59}Fe and ^{56}Co line amplitudes were constrained to be in the ratios implied by the branching ratios in Table 1

method of varying the quantity χ^2 (Press et al. 1986). The fit is illustrated for a typical case in Fig. 1. It is clear that the γ-ray lines in this energy range are seriously blended, since the separations between them are comparable to, or less than, the GRS energy resolution. Since it is known from the measurements of LS and others (Cook et al. 1988; Mahoney et al. 1988; Rester et al. 1989; Tueller et al. 1990) that the 1.238 MeV line had a systematic positive amplitude from the fall of 1987 onwards, the blendings between this line and the 1.292 MeV ^{59}Fe line, and between the lines at 1.038 and 1.099 MeV which are respectively correlated with them, are a possible source of systematic error.

3. Results and discussion

3.1. Results

In Fig. 2 we plot the amplitudes measured in SN 1987A spectra for the ^{56}Co line at 1.238 MeV and the ^{59}Fe line at 1.099 MeV. The contrast between the two is apparent. The 1.238 MeV line measurements are in very good agreement with those presented by LS. The evolution of the line flux is consistent with zero flux up until the time of the explosion (day 0), and for $\sim$ 150 d thereafter; a positive flux is evident from day 150 onwards. The 1.099 MeV line flux, however, is consistent with zero both before and after day 150. Weak systematic excursions, up to $4\ 10^{-4}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, are apparent between days $\sim$ 100–200, during which the 1.238 MeV line began to appear. These excursions are due largely to blending between this line and the 1.292 MeV ^{59}Fe line (from which, it will be recalled from Sect. 2, the 1.099 MeV line amplitude is not independent).

We conclude that γ-ray line emission from ^{59}Fe has not been detected in SN 1987 A. We express our upper limits on the flux in the form of conservative 3σ upper limits upon the 1.099 MeV line flux during each 35 d precession period following the explosion, as in Fig. 3[2]. These limits are defined as the absolute value of the systematic error, plus three times the statistical error (cf. Harris et al. 1991); they are seen to be in the range $\simeq 6$–$10\ 10^{-4}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

3.2. Abundance of ^{59}Fe in the helium shell

We interpret our results in terms of a simple approximation of the simulation by Herant & Benz (1992) of the expansion of the SN 1987A ejecta, which is the only hydrodynamical simulation for which results at late times in the expansion (90 d after explosion) have been published. We note that this simulation fails to predict γ-ray line emission from ^{56}Co decay at sufficiently early times (as measured by LS), and therefore probably underestimates the degree of outward mixing of material from the presupernova Fe core. If this is true also of material from the presupernova He shell, the upper limits which we will derive for the ^{59}Fe abundance will be very conservative.

The top left panel of Herant & Benz's (1992) Fig. 3 presents their two-dimensional simulation of the state of the ejecta from presupernova model 14E of Saio et al. (1988)

[2] Our measured 1.292 MeV line fluxes are of course equal to 43/57 times the 1.099 MeV line fluxes.

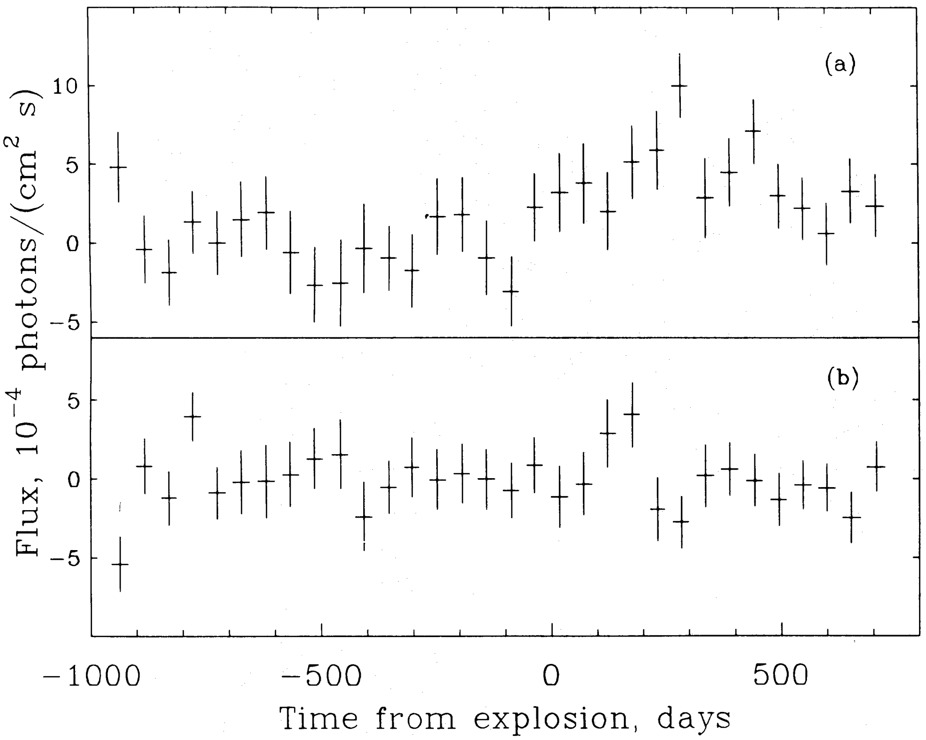

Fig. 2a and b. Flux measured in **a** the 1.238 MeV ^{56}Co line; **b** the 1.099 MeV ^{59}Fe line, during 35 d intervals before and after the explosion

and Shigeyama & Nomoto (1990) at 90 d after the explosion. We choose the results from this particular model because they exhibit the greatest degree of outward mixing (of all shells) of any of the four presupernova models which Herant & Benz considered. The very complex simulation of the He shell may be summarized by a picture in which the He shell has been completely broken up into "fingers" extending approximately radially outwards through the H envelope; a small fraction of the shell, at the high-velocity end of each finger, has broken away into discrete "bullets" travelling outwards at almost 30 000 km s^{-1}.

We estimate that about 1/8 of the original mass $2.1 M_\odot$ of the He shell resides in the "bullets" in the hemisphere facing Earth, which we assume to be essentially free from overlying material. In order to be conservative, we neglect any contribution to the γ-ray emission from the material in the "fingers", which is overlain by some part of the H envelope. The ^{59}Fe γ-ray line flux from the "bullets" can then be expressed as the product of two factors: the production of γ-rays by the decay of the ^{59}Fe in $0.2625 M_\odot$ of He shell material, which takes the form $\lambda_{59} N_{59} \exp(-\lambda_{59} t)$, where N_{59} is the original abundance of ^{59}Fe and λ_{59} is the ^{59}Fe decay rate, modulated by the attenuation of these γ-rays by the material in the "bullets" themselves. It was shown by LS that, in the approximation that each mass of material expands with constant velocity after passage of the shock, the factor by which the flux is attenuated has the form $\exp(-C/t^2)$, where C is some constant. We used Herant & Benz's (1992) calculated velocity dispersion in the "bullets" at $t = 90$ d, together with the Klein–Nishina scattering formula, to estimate that $C \approx 5600$.

In terms of the mass fraction X_{59} of ^{59}Fe, we obtain an expected flux ϕ_{1099} in the 1.099 MeV γ-ray line of

$$\phi_{1099} = 1.825 X_{59} \exp(-t/64.2\,\mathrm{d} - C/t^2)\,. \quad (1)$$

By fitting Eq. (1) to our results presented in Fig. 3, by the method of least squares, with X_{59} as a free parameter, we obtain $X_{59} = 7.6 \pm 7.0\ 10^{-4}$ (this best-fitting light-curve is shown as the full line in Fig. 3). We therefore conclude that the conservative 3σ upper limit on the ^{59}Fe abundance in the He shell is $X_{59} < 2.9\ 10^{-3}$.

This result is about a factor of seven larger than the most optimistic prediction (Prantzos 1989: $X_{59} = 4\ 10^{-4}$). Since the ^{59}Fe abundance cannot exceed the original "seed" abundance of ^{56}Fe prior to helium burning, which in the SN 1987A progenitor's He shell must have been $X_{56} \leq 5\ 10^{-4}$, neither nucleosynthesis in the He shell nor the outward mixing during the subsequent explosion is constrained by our measurement. Our result might be improved somewhat by re-interpreting the data points in Fig. 3 in terms of improved models of the post-explosion state of the He shell, since Eq. (1) probably errs on the side of conservatism, as noted above. However, significant insights into these questions must probably await the occurrence of a Galactic supernova, from which γ-ray line fluxes at least a factor of 10 higher are expected; furthermore, a detector such as the now-available *Compton* Observatory's Oriented Scintillation Spectrometer Experiment (OSSE) is about a factor of 6 more sensitive than the *SMM* GRS. In view of the problem of blending of the γ-ray lines at 1.238 and 1.292 MeV, mentioned in Sect. 3.1, it is desirable that measurements be

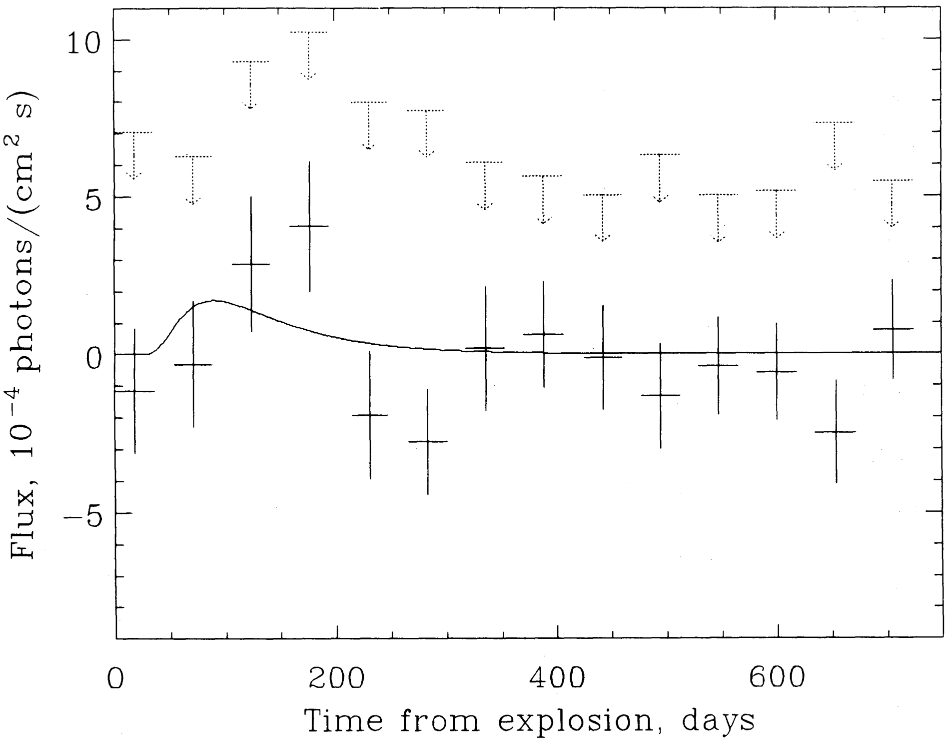

Fig. 3. Flux measured in the 1.099 MeV ^{59}Fe line during 35 d intervals after the explosion (data points), and corresponding 3σ upper limits (dotted arrows), compared with the flux from the best-fitting model of the He shell based on Herant & Benz's (1992) simulation [full line: $X_{59} = 7.6\ 10^{-4}$ in Eq. (1)]

made with the best possible energy resolution, for example, by Ge detectors rather than the NaI scintillation detectors employed by *SMM* and OSSE.

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