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GAMMA-RAY CONSTRAINTS ON SUPERNOVA NUCLEOSYNTHESIS

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ABSTRACT

Gamma-ray spectroscopy holds great promise for probing nucleosynthesis in individual supernova explosions via short-lived radioactivity, and for measuring current global Galactic supernova nucleosynthesis with longer-lived radioactivity. It was somewhat surprising that the former case was realized first for a Type II supernova, when both ^{56}Co and ^{57}Co were detected in SN 1987A. These provide unprecedented constraints on models of Type II explosions and nucleosynthesis. Live ^{26}Al in the Galaxy might come from Type II supernovae, and if it is eventually shown to be so, can constrain massive star evolution, supernova nucleosynthesis, and the Galactic Type II supernova rate.

Type Ia supernovae, thought to be thermonuclear explosions, have not yet been detected in γ-rays. This is somewhat surprising given current models and recent ^{56}Co detection attempts. Ultimately, γ-ray measurements can confirm their thermonuclear nature, probe the nuclear burning conditions, and help evaluate their contributions to Galactic nucleosynthesis. Type Ib/c supernovae are poorly understood. Whether they are core collapse or thermonuclear events might be ultimately settled by γ-ray observations.

Depending on details of the nuclear processing, any of these supernova types might contribute to a detectable diffuse glow of ^{60}Fe γ-ray lines. Previous attempts at detection have come very close to expected emission levels. Remnants of any type of age less that a few centuries might be detectable as individual spots of ^{44}Ti γ-ray line emission. It is in fact quite surprising that previous surveys have not discovered such spots, and the constraints on the combination of nucleosynthesis yields and supernova rates are very interesting. All of these interesting limits and possibilities mean that the next mission, *INTEGRAL,* if it has sufficient sensitivity, is very likely to lead to the realization of much of the great potential of γ-ray spectroscopy for understanding supernovae.

Subject headings: nuclear reactions, nucleosynthesis, abundances — supernovae: individual (SN 1987A, SN 1991T)

1. INTRODUCTION

The prospects for detecting γ-ray lines from supernovae have been reviewed by Clayton (1982). Since that time, the expectations have not changed greatly, but significant opportunities for observations have presented themselves, and substantial effort to make those observations has been expended. Potentially detectable radioactive nuclei from supernovae are outlined in Table 1. The decay chains, with mean lifetimes and photon energies, are shown. Those that have been detected are also indicated, along with the dominant nucleosynthesis process for producing the radioactive parents. Much of this information is summarized by Woosley (1986). The last column indicates whether the majority of the abundance of the stable daughter derives from the radioactive parent. When this is the case, we can use observed Galactic abundances of the daughters, along with some chemical evolution arguments, to make predictions about the current nucleosynthesis rate of the parent, and therefore the expected γ-ray line fluxes. Ultimately, and in some cases, already, we can turn this around and use γ-ray observations to constrain models of Galactic evolution. All of these nuclei are produced in some quantities in Type II (core collapse) supernovae, while all but ^{59}Fe and ^{26}Al are probably produced in Type Ia (thermonuclear) supernovae. Other nuclei, such as ^{7}Be and ^{22}Na, will probably be detected in a Galactic supernova someday, but current limits are not yet interesting. We now describe the observations and their implications, with emphasis on more recent observations.

2. OBSERVATIONS OF SN 1987A

The historic detection of live radioactive ^{56}Co in SN 1987A (Matz et al. 1988) was a great triumph for Type II supernova theory. The early epoch of the detection demanded significant mixing of ^{56}Co outward in the ejecta. The shape of the γ-ray line light curves further described this mixing (Leising & Share 1990). These observations should have also taught us the value of even modest, reliable instruments in orbit when an opportunity is presented. The many different instruments that observed these γ-ray lines provided a very good measure of the levels of systematic errors in γ-ray spectroscopy. High-energy-resolution instruments offered further insight into the supernova dynamics (Teegarden 1994).

Even though late, the launch of the *Compton Observatory* offered the opportunity to measure another radioactivity, ^{57}Co. Details of two OSSE observations (Kurfess et al. 1992) of SN 1987A and their interpretation (Clayton et al. 1992) have been recently reported. Here we summarize the important features. The first observation began on 1991 July 25 (1613 days after the explosion), the second on 1992 January 10 (1768 days). Each of these spectra was fitted with a model, consisting of an exponential continuum plus a ^{57}Co template, convolved with the OSSE instrument response. The template was derived from a supernova model evolved to those times and included the 122 and 136 keV lines plus a Compton-scattered continuum. For example, the model 10HMM of Pinto & Woosley (1988) has roughly equal numbers of photons in the 122 keV

TABLE 1

OBSERVABLE RADIOACTIVITY FROM SUPERNOVAE

Decay Chain	Detected?	Nuclear Process	Main Source?
$^{56}\mathrm{Ni} \xrightarrow[158{,}812\ \mathrm{keV}]{9\ \mathrm{days}} {}^{56}\mathrm{Co} \xrightarrow[847{,}1238{,}\ldots\ \mathrm{keV}]{112\ \mathrm{days}} {}^{56}\mathrm{Fe}$	Yes	NSE	Yes
$^{57}\mathrm{Ni} \xrightarrow{36\ \mathrm{hr}} {}^{57}\mathrm{Co} \xrightarrow[122{,}136\ \mathrm{keV}]{391\ \mathrm{days}} {}^{57}\mathrm{Fe}$	Yes	α-NSE	Yes
$^{59}\mathrm{Fe} \xrightarrow[1099{,}1292\ \mathrm{keV}]{64\ \mathrm{days}} {}^{59}\mathrm{Co}$	No	*s*, *n*-in He shell	No
$^{60}\mathrm{Fe} \xrightarrow[59\ \mathrm{keV}]{2.2 \times 10^{6}\ \mathrm{yr}} {}^{60}\mathrm{Co} \xrightarrow[1173{,}1332\ \mathrm{keV}]{7.6\ \mathrm{yr}} {}^{60}\mathrm{Ni}$	No	*n*-NSE	No
$^{44}\mathrm{Ti} \xrightarrow[68{,}78\ \mathrm{keV}]{96?\ \mathrm{yr}} {}^{44}\mathrm{Sc} \xrightarrow[1157\ \mathrm{keV}]{3\ \mathrm{days}} {}^{44}\mathrm{Ca}$	No	α-NSE	Yes
$^{26}\mathrm{Al} \xrightarrow[1809\ \mathrm{keV}]{10^{6}\ \mathrm{yr}} {}^{26}\mathrm{Mg}$	Yes	expl − Ne, H (static H)	No

line and in its Compton-scattered continuum at these times. Both observations show an excess consistent with this template, but atop very different continua. The flux in the template, lines plus continuum, was $(9.0 \pm 2.2) \times 10^{-5}$ for the first observation, and essentially the same, although with a larger uncertainty, for the second observation. For a variety of continuum models and supernova templates, the best-fit value of the flux varies by less than the 1 σ statistical uncertainty. Fitting the 122 keV line only, without its scattered continuum, plus an exponential continuum yields a line flux consistent with one-half that measured for the template. This has been interpreted as a detection of ^{57}Co in the SN 1987A ejecta.

In the model of Pinto & Woosley, as in all models published prior to the ^{57}Co detection, essentially all ($\simeq$98%) of the ^{57}Co decay photons escape at these late times, either directly in the lines or after very few scatters. Assuming this is correct, we can convert the flux into the ejected mass of ^{57}Co, which is $2.7 \times 10^{-3}\ M_{\odot}$ extrapolated back to $t = 0$, assuming a distance of 50 kpc. Compared to the ^{56}Co mass of 0.075 $M_{\odot}$ inferred from the early UVOIR light curve, the production ratio of the parents, $X(^{57}\mathrm{Ni})/X(^{56}\mathrm{Ni})$, is 1.4 ± 0.35 times the solar ratio of the daughters, $(^{57}\mathrm{Fe}/^{56}\mathrm{Fe})_{\odot}$. This measurement is inconsistent with earlier inferences (Suntzeff et al. 1992; Dwek et al. 1992) that this production ratio was five times the solar value, in order to explain the late optical/infrared luminosity in the context of the same supernova model, 10HMM.

The OSSE flux and the ground-based measurements can be reconciled with a 57/56 production ratio roughly twice the solar value *and* a supernova model that is thicker to ^{57}Co γ-rays than published models. The thicker supernova, which could be a result of lower expansion velocity in the inner ejecta, would yield a lower escaping hard flux per ^{57}Co nucleus because of increased photoelectric absorption, and would have a larger fraction of the ^{57}Co power thermalized (roughly 40% at the OSSE epoch rather than 20% in, e.g., 10HMM).

However, the late-time optical/infrared luminosity is not necessarily derived entirely from ^{57}Co. Other power sources, each of which, except for the last, should be present at some level include: (1) Delayed release of a small fraction of the earlier large power from ^{56}Co; (2) Conversion of a fraction ($\simeq 10^{-13}\ \mathrm{s}^{-1}$) of the mechanical energy of the ejecta into infrared emission; (3) Other radioactivity, for example, ^{44}Ti; and (4) Accretion onto or rotational energy extracted from a compact remnant. The first effect should be important because the processes between γ-ray emission and optical escape—Compton scattering, then electron energy loss (via ionization), and subsequent recombination—have inherent delays. The most important delay is probably due to recombination, because the rapidly declining density in the ejecta causes the recombination time to grow progressively longer, delaying the release of the stored ionization power (Clayton et al. 1992).

The second source, mechanical energy, is available only if the ejecta interact with external material. Even the blue supergiant wind, if it blew at $2 \times 10^{-6}\ M_{\odot}\ \mathrm{yr}^{-1}$ at 500 km s^{-1} prior to the explosion, could cause significant dissipation. The ejecta, at 10^{4} km s^{-1}, is sweeping up this wind at $4 \times 10^{-5}\ M_{\odot}\ \mathrm{yr}^{-1}$, and conservation of momentum demands that $\simeq 10^{39}$ ergs s^{-1} is being dissipated. If 10% of this is emitted as light, all the luminosity in excess of ^{56}Co power can be accounted for. The rest of this dissipation luminosity might be detectable in another band (e.g., radio, X-ray), or might go into further expansion.

As for the last two effects in the list, it is doubtful, based on straightforward nucleosynthesis arguments (Woosley & Hoffman 1991), that ^{44}Ti is a dominant contributor to the luminosity, and there is yet no conclusive evidence for a contribution from a compact object. However, it could not be ruled out that the soft continuum detected in the first OSSE observation came from within SN 1987A.

Harris & Leising (1993) recently examined the *SMM* spectra for evidence of ^{59}Fe in the helium shell, from hydrostatic or explosive n-captures on ^{56}Fe, of SN 1987A. None was found. They conservatively estimate a limit on the mass fraction of $X(^{59}\mathrm{Fe}) < 10^{-3}$ in the helium shell. This is substantially more than reasonable predictions.

Finally, at some time in the next century, assuming civilization survives as we know it, ^{44}Ti γ-ray lines will be detected in SN 1987A. It is quite reasonable that ^{44}Ti was produced in solar proportions relative to ^{56}Ni, and so we expect a flux near $2.5 \times 10^{-6}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ in each of the lines, decaying on the timescale of a century. This flux may be just in reach of the *INTEGRAL* spectrometer.

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3. OBSERVATIONS OF SN 1991T

Prior to SN 1987A, it was generally considered that a Type Ia supernovae would yield the first detection of ^{56}Co γ-rays, because it is thought that the energy of these events is entirely thermonuclear in origin (Woosley & Weaver 1986, for example). The Type Ia light curve is supposed to be powered by ^{56}Ni decay initially and later ^{56}Co. This is the result of the thermonuclear disruption of a white dwarf near the Chandrasekhar mass, a large fraction of which is converted to ^{56}Ni. Calculations indicate that 0.5–1.0 $M_\odot$ of ^{56}Ni is ejected, depending on the nature of the burning, which remains uncertain (Nomoto, Thielemann, & Yokol 1984; Woosley, Taam, & Weaver 1986; Woosley & Pinto 1991; Khokhlov 1991; Yamaoka et al. 1992). In addition to the large mass of ^{56}Ni, very large expansion velocities are expected and observed in Type Ia supernova, so they become thin to γ-rays in a matter of months, before significant decay.

Supernova 1991T was discovered on 1991 April 13 (Waagen & Knight 1991) in NGC 4527, a spiral galaxy on the edge of the Virgo cluster. Its premaximum spectrum, which lacked lines of intermediate mass elements, was unusual for a Type Ia supernova, but its postmaximum spectrum and its light curves were similar to normal Type Ia's throughout (Filippenko et al. 1991; Phillips et al. 1992). SN 1991T peaked at about $V = 11.5$ on about 1991 April 30 (Phillips et al. 1992), making it the brightest Type Ia supernovae since SN 1972E.

The *Compton Observatory,* launched only a week before the SN 1991T discovery, was thus provided with an opportunity to test the idea of Type Ia supernovae as thermonuclear explosions. The spacecraft axis was pointed toward the supernova during the periods 1991 June 15–29 and October 3–17, so both the OSSE and the COMPTEL experiment could observe it. The OSSE was also able to observe SN 1991T as a "secondary" target during 1991 August 22–September 5. Both experiments have good sensitivity for the two strongest lines of ^{56}Co decay at 847 and 1238 keV. No evidence was found for either line in any of the observations. Upper limits from both experiments are near 3×10^{-5} cm^{-2} s^{-1} in the 847 keV line at 73 days (Leising et al. 1993; Lichti et al. 1993).

The probability of detecting the γ-ray lines from ^{56}Co decay depends on the mass of ^{56}Ni produced and on the distance to the supernova. The distance to NGC 4527 is uncertain, even relative to the uncertain Virgo cluster center distance (Peletier & Willner 1991). SN 1991T was somewhat brighter at maximum than the typical Virgo Cluster Type Ia supernovae ($V = 12.0$, corrected for extinction and distance from the cluster center; Leibundgut & Tammann 1990; Leibundgut 1991). This could be because it had a peak luminosity typical of other Type Ia supernovae but is somewhat closer (Phillips et al. 1992), or because it was anomalously luminous and at nearly the same distance as the cluster center (Filippenko et al. 1991). Significant extinction requires even smaller distance or higher luminosity. Regardless of these uncertainties, we expect the γ-ray line flux also to be larger than for typical Virgo cluster Type Ia supernovae. However, we do not know what typical fluxes are, because we do not have any entirely successful model and we do not know the distance to Virgo. Still, any theoretical model is safe from the contradiction by this upper limit as long as the distance can be large enough. However, as pointed out by Arnett (1979), both optical and γ-ray fluxes scale the same way with distance and approximately the same way with ^{56}Ni mass, so the ratio of γ-ray to optical flux at their respective peaks should be roughly constant for Type Ia supernovae.

As shown by Leising et al. (1993), current Type Ia models either do not or only barely satisfy both the optical and γ-ray measurements of SN 1991T. However, the conflict is not so great that we can rule out the basic thermonuclear explosion paradigm. Models that more efficiently convert the decay power into optical luminosity at maximum, possibly by storing for a short time the large premaximum ^{56}Ni decay power, can probably be developed.

As for future observations of Virgo cluster supernovae, we can scale to the SN 1991T results. There was some extinction to SN 1991T (Filippenko et al. 1991; Ruiz-lapuente et al. 1992), from which we estimate that it was ≥ 1 mag brighter than the typical Virgo Cluster center Type Ia. So its γ-ray line fluxes were at least a factor 2.5 greater. Combining the COMPTEL and OSSE limits, we estimate that the peak flux from SN 1991T was less than 2×10^{-5} cm^{-2} s^{-1}. Then a firm upper limit to γ-ray line flux from the mean Virgo cluster Type Ia supernova, if SN 1991T is typical, is less than 8×10^{-6} cm^{-2} s^{-1}, and the actual flux could easily be one-half of that. *INTEGRAL* might then be able to detect the nearer Virgo cluster supernovae if its promised sensitivity is achieved.

4. TITANIUM 44 FROM GALACTIC SUPERNOVA REMNANTS

Titanium 44 is produced primarily in the α-rich freezeout from nuclear statistical equilibrium, that is, when the density is low enough as the reactions fall out of equilibrium that α-particles avoid reassemblage into carbon and are available for capture on heavier nuclei (Woosley, Arnett, & Clayton 1973; Woosley & Hoffman 1991). The site for this can be Type Ia (Nomoto et al. 1984; Woosley et al. 1986) or Type II supernovae (Woosley, Pinto, & Weaver 1988; Thielemann, Hashimoto, & Nomoto 1990). The Galactic recurrence time of these events is comparable to the ^{44}Ti lifetime, so with current sensitivities we expect to be able to see at most a few ^{44}Ti remnants at any given time. Like most Galactic supernovae, these events will have been undetected optically, so the entire Galactic plane must be searched to find the events, if any, which produce detectable line fluxes.

Mahoney et al. (1982) and Mahoney et al. (1992) used the γ-ray spectrometer on the *HEAO 3* spacecraft to set upper limits on Galactic emission from ^{60}Fe and ^{44}Ti, respectively, and discussed some of the implications of those limits. Recently, Leising & Share (1994) have searched the *SMM* data for emissions from the same nuclei. They also obtained only upper limits.

It is likely that most ^{44}Ca is produced as ^{44}Ti in nature. Therefore there are almost as many 1.16 MeV photons in the universe as there are ^{44}Ca nuclei, and expectations of current ^{44}Ti production can be determined from the requirement that presolar nucleosynthesis produce the solar abundance of ^{44}Ca. Very simple arguments lead to the expectation that about 4×10^{-4} $M_\odot$ of ^{44}Ca are produced per century (Leising & Share 1994). The product of the supernova frequency (of whatever type produces ^{44}Ti) times the ^{44}Ti yield per event must equal this number. The upper limit on the γ-ray line flux, for example, 8×10^{-5} cm^{-2} s^{-1} from the Galactic center direction (Leising & Share 1994), can be converted to a lower limit on the time since the latest supernova with a given ^{44}Ti yield at a given distance. Assuming a Poisson random process for the occurrence of supernovae, one can derive the probability that we have had to wait so long given the rate (or product of rate and yield).

Even assuming that only the latest event would be seen, rates in excess of 2 century^{-1} are ruled out at $\geq 97\%$ confidence. Only rates less than 0.5 century^{-1} are acceptable at greater than 10% confidence, and this means that the yield per event must be $\geq 10^{-3}\,M_\odot$ to produce the requisite ^{44}Ca. Rates this low are incompatible with current estimates for Type II supernovae (Tammann 1994), and yields this high are also very difficult to understand for any standard supernova models. This situation is puzzling. Perhaps some very rare type of event, such as helium detonation supernovae (Woosley et al. 1986), produces most of the ^{44}Ca. If the preceding considerations are on the right track at all, even a slightly more sensitive instrument has a very high probability of detecting ^{44}Ti in some young supernova remnants.

5. DIFFUSE GALACTIC IRON 60

The *SMM* Galactic plane 1.17 MeV flux limit of $<8 \times 10^{-5}$ cm^{-2} s^{-1} rad^{-1} corresponds to a limit (99.5%) of 1.7 $M_\odot$ in the present interstellar medium. Given the usual assumption of steady state between production and decay, the current rate of synthesis of ^{60}Fe is less than 1.7 $M_\odot$/2.2 Myr.

It has been suggested that a neutron-rich NSE occurs in small regions in both Type Ia supernovae supernovae and in core collapse supernovae (Hartmann, Woosley, & El Eid 1985). Either type might eject significant quantities of ^{60}Fe. If we know the frequency of a particular type of ^{60}Fe-producing event in the past few million years, then we can limit the mean ^{60}Fe mass ejected per event. Taking 1.7 $M_\odot$/2.2 Myr, which is $8 \times 10^{-5}\,M_\odot$ century^{-1}, we have

$$M_{\rm ej}(^{60}{\rm Fe}) \leq \frac{8 \times 10^{-5}}{R_{\rm SN}}\,M_\odot\,, \qquad (1)$$

where $R_{\rm SN}$ is the frequency of the supernovae which eject ^{60}Fe, in number per century. Woosley (1991) estimates that Type Ia supernovae eject roughly $10^{-4}\,M_\odot$ of ^{60}Fe, which is very close to this limit for rates near 1 century^{-1}.

This limit can be viewed in another way. We can also constrain the fraction of stable ^{60}Ni which derives from ^{60}Fe, and this limit turns out to be 1.5%. Other nuclides, in particular ^{48}Ca and ^{50}Ti, probably originate primarily in the neutron rich NSE (Woosley 1986). Estimating the current production of these stable isotopes from their solar abundances suggests that there should be about 0.9 $M_\odot$ of ^{60}Fe in the interstellar medium, less than a factor 2 below the current limit. This indicates that ^{60}Fe could soon be detected with a slightly more sensitive instrument, possibly one on the *Compton Observatory.* Comparing the estimated production rates of stable isotopes with the γ-ray limits on those of ^{60}Fe already allows us to constrain some models of Galactic chemical evolution (Leising & Share 1994). Again, the current limits are so close to the expectations, that it is very likely that an experiment with significantly improved sensitivity, such as *INTEGRAL,* will detect live ^{60}Fe in the interstellar medium.

6. CONCLUSIONS

We already have some very important measurements of radioactivity in a Type II supernova. Supernovae might also contribute significantly to the ^{26}Al content of the interstellar medium (Meynet 1994; Clayton, Hartmann, & Leising 1993). From several lines of reasoning it appears that we are on the threshold of detecting other live radioactive species from galactic and extragalactic supernovae. All that is required is sensitivity. One order of magnitude improvement, such as might be achieved by *INTEGRAL,* will very likely provide detections of diffuse galactic ^{60}Fe, ^{44}Ti from multiple galactic supernova remnants, and ^{56}Co from at least some Virgo Cluster Type Ia supernovae. The insights gained into the nature of supernovae and the mechanisms that drive them will be manifold.

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Note added in proof.—SN 1993J, an extensively studied recent supernova of intermediate type, indicates that Type Ib supernovae result from core collapses. The *Compton Observatory* COMPTEL instrument has apparently detected 1.156 MeV emission from the supernova remnant Cas A (Iyudin, A., et al., in Proc. 2d Compton Symp., ed. J. Norris, in press [1994]; see, however, The, L.-S., et al., same volume). That this relatively old (300 yr) remnant is detectable suggests that a number of younger remnants could also be detectable, unless it is a relatively rare event.