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THE ^{57}Co ABUNDANCE IN SN 1987A

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ABSTRACT

We discuss several astrophysical consequences of the detection by OSSE (Kurfess et al. 1992) of ^{57}Co gamma radiation from supernova 1987A. Models with low photoelectric absorption cannot account for both OSSE data and the bolometric luminosity. By burying the alpha-rich-freezeout portion at deeper gamma depths than in published models, we show that it remains barely possible that the bolometric luminosity during days 1200–1800 could derive from ^{57}Co power without requiring 57/56 production ratios greater than twice solar. We illustrate this by slowing the expansion within the inner four solar masses of ejecta in model 10HMM. A successful fit to both total radiated power and to OSSE ^{57}Co flux can be attained. However, that "slow core" model may then be too opaque near day 500–700 to allow for the suggested decline of the bolometric light curve below exponential during that earlier period.

We also propose alternative mechanisms which may contribute to the bolometric power at late times: (1) stored power owing to delayed emission of thermalized gamma-ray energy. Mechanisms include (a) delayed release of chemical power owing to decreasing ionization, for which we present a simple analytic theory; or, (b) increasing time delay for suprathermal electrons to strike dust grains; (2) dissipation at rate 10^{-13} s^{-1} of mechanical energy owing to collisions within the ejecta. Because of the importance of Fe isotopic ratios to chemical evolution of the Galaxy, we outline the resulting chemical evolution problem for the solar ^{57}Fe abundance.

Subject headings: abundances — nucleosynthesis — supernovae: individual (SN 1987A)

1. INTRODUCTION

The ^{57}Co decay is detected as a flux near 10^{-4} cm^{-2} s^{-1} from 50 to 140 keV from SN 1987A (Kurfess et al. 1992, hereafter Paper 1) by the OSSE aboard *Compton Gamma Ray Observatory*. See their Table 1. Here we discuss several implications of that flux and of the inferred ^{57}Co abundance.

Computations with an upgraded version of the The, Burrows, & Bussard (1990) Monte Carlo code give $f_{\rm esc}^{122} = \exp[-1.60 \times 10^6/t^2(\text{days})]$ for the direct escape fraction near day 1600 for model 10HMM (Woosley, Pinto, & Hartmann 1989) and a line flux at Earth using a ^{57}Ni mass = 0.0018 $M_\odot = (^{57}\text{Fe}/^{56}\text{Fe})_\odot \times 0.075$ $M_\odot$ of ^{56}Ni of $F_{122} = 3.09 \times 10^{-5}$ cm^{-2} s^{-1} at 1600 days for an assumed distance of 50 kpc. This line flux depends on the velocity structure, on the radial distribution of the ^{57}Co in the expanding ejecta, and on its total mass (Clayton 1974). That yield is not known for SN 1987A, unlike that of ^{56}Ni which is set by the exponential decline of the bolometric light curve at earlier times. The ^{56}Co radioactivity was radially mixed while maintaining spherical symmetry in model 10HMM by Pinto & Woosley (1988) to reproduce both the bolometric luminosity and the early X-and-gamma-ray emissivity of SN 1987A. Nomoto et al. (1988) solved the same problems by almost identical spherically symmetric techniques in their model SN14E1. Its 122 keV line flux, $F_{122} = 2.69 \times 10^{-5}$ cm^{-2} s^{-1} at 1600 days, is 13% less than for 10HMM. Our calculations show that because SN14E1 is also low-optical-depth model, suffering only 2% photoelectric absorption, as does 10HMM, its total flux greater than 50 keV is almost identical to that from 10HMM even though their 122 keV line fluxes differ by about 15% (see Table 1). As long as photoelectric absorption of scattered 122 keV photons is small, the flux greater than 50 keV from ^{57}Co decay is almost independent of the ^{57}Co radial distribution, making that feature a good measure of ^{57}Co abundance (Paper I).

Calculated fluxes at day 1600 are listed in Table 1 for three models: 10HMM, 14E1, and a variant (to be described below) of 10HMM having "slowed core" expansion and also differing radial extents for the alpha-rich and normal-NSE freezeouts of Ni yields. Model "slow core" is also tabulated at 1750 days to show the time dependence in a more opaque model. The photon spectra for two of these models (10HMM and "slow core") were displayed in Figure 2 of Paper I, which used them as templates to estimate the total ^{57}Co emission from SN 1987A. The ^{57}Co abundance was derived from that total flux greater than 50 keV and from Table 1.

At the epoch of the OSSE observations ^{57}Co is expected to be the major nuclear power source (Clayton 1974; Woosley et al. 1989). Suntzeff et al. (1992) and Dwek et al. (1992) have recently presented photometric data for the bolometric luminosity of SN 1987A that have led them to conclude that the ^{57}Co/^{56}Co ratio is about fivefold greater than solar. They showed that the radioactive energy deposition rates *in 10HMM* for ^{57}Co at fivefold solar (0.009 $M_\odot$) fits better than solar concentration. Independent confirmation is provided by our own calculations and by those of Kumagai et al. (1991) for several 57/56 production ratios. But because the total ^{57}Co flux would then be 3.2×10^{-4} cm^{-2} s^{-1} (see Table 1), the OSSE data rule out (Paper 1) a radiometric interpretation of the UVOIR luminosity for low-optical-depth models. We are

TABLE 1

THREE MODELS OF SN 1987A AT 1600 DAYS[a]

Model	57/56[b] $(57/56)_\odot$	Photons Greater than 50 keV per ^{57}Co Decay: 122 keV	50–136 keV	Total	$f_{abs}(122)$[c]	f_{dep}[d]	F_{122}	F_{total} (10^{-5} cm^{-2} s^{-1})
10HMM	1.0	0.475	0.510	0.985	2.0%	19.0%	3.09	6.41
SN14E1	1.0	0.415	0.566	0.980	2.1	20.7	2.69	6.35
"Slow core"	1.5	0.266	0.407	0.673	31.2	47.1	2.58	6.53
"(1750d)"[a]	1.5	0.295	0.408	0.703	28.2	44.2	1.96	4.69

[a] Model "slow core" is also listed at 1750 days to show time dependence of opaque model.
[b] Production ratio ^{57}Ni/^{56}Ni in multiples of $(^{57}Fe/^{56}Fe)_\odot$ abundance ratio.
[c] Photoelectric absorption fraction of photons emitted initially at 122 keV.
[d] Fraction of ^{57}Co-decay energy deposited in the model.

led to ask whether instantaneous radioactive power could nonetheless be the correct idea but with a more opaque model.

2. BURIED ^{57}Co

The ^{57}Co may actually be much more deeply buried than in models 10HMM or SN14E1. Those models are characterized by escape of 81.1% and 79.3%, respectively, of the ^{57}Co power at $t = 1600$ days, increasing to 82.5% and 81.1% at $t = 1700$ days. Such large escape fractions are not required by the early X-and-gamma-ray light curves, which could also be fit with a large buried fraction and a small fraction mixed far out (i.e., bimodal) for the radioactive Co isotopes (e.g., Leising & Share 1990). If 47% of the ^{57}Co power can be absorbed, as in the "slow core" entry in Table 1, the bolometric enhancement of the ^{57}Co power would be 2.5 times greater than in 10HMM, yielding half of the bolometric requirement (Dwek et al. 1992; Suntzeff et al. 1992) without any enhancement of ^{57}Co. We illustrate this in Figure 1, which shows radioactive deposition power in "slow core," a variant of 10HMM having progressively reduced expansion velocity in the inner 4 $M_\odot$ of ejecta. Figure 1 confirms that the luminosity requires only 1.5 × solar ^{57}Co in that model.

The increase in the ^{57}Co deposition is, however, accompanied by a corresponding excess efficiency of ^{56}Co deposition during days 500–700, when the observed luminosity seems to fall below the exponential power. We tried (with very limited success) to counter the excess 500–700 days power by mixing the ^{56}Co further from the center than the ^{57}Co, supposing that the alpha-rich-freezeout portion of the Ni nucleosynthesis remains within the inner 4 $M_\odot$ (with ^{57}Ni/^{56}Ni = 2.5 × solar) while the normal-freezeout portion (with ^{57}Ni/^{56}Ni = 0.5 × solar) is mixed rather uniformly out to 8 $M_\odot$. The intermixing may be inhibited by the large entropy difference. Those ^{57}Ni/^{56}Ni choices were from tables in Woosley & Hoffman (1991) rather than from an exploding model, which would give continuously declining 57/56 with increasing radius (Thielemann, Hashimoto, & Nomoto 1990). Equal masses of the two zones give a bulk production of 1.5 × solar for the 57/56 ratio in "slow core." Figure 1 shows that "slow core" does pass through the 1100–1500 days photometry points used by Suntzeff et al. (open points in Figure 1). This opaque model provides a counterexample to their inference that fivefold solar ^{57}Co would be required, although it requires that about 20% of the luminosity becomes unobserved after 500 days. This model cannot fit the alternate photometry of Bouchet et al. (1991, solid points in Fig. 1), which present a large problem for any spherical representation unless one appeals to sudden luminosity change of a central compact object. The 122 keV flux is 2.58×10^{-5} cm^{-2} s^{-1} at 1600 days in "slow core" (Table 1), 17% less than for 10HMM despite having a bulk 57/56 abundance ratio larger by 50%; but the total fluxes greater than 50 keV are nearly equal (6.4–6.5 × 10^{-5} cm^{-2} s^{-1}) in those three models. Therefore, the observed OSSE flux would need a production ratio 2.6 ± 0.6 × solar for "slow core" (Paper 1). The associated 73% increase in luminosity would still fit the day 1100–1500 points, but a more opaque model would not. "Slow core" is as opaque as a model could be without the observed OSSE flux requiring even larger production ratio and therefore too much bolometric power, so it and 10HMM represent extreme differences of photoelectric absorption (Table 1). A slightly different model could be fine-tuned to exactly satisfy both bolometric power and OSSE mean flux. We believe that a nonspherical model based on cooler denser clumps of ^{57}Co-rich ejecta will be very similar to "slow core" if the photoelectric absorption can be made as great as 31% in that model as well. We present this variant of 10HMM only to illustrate that the γ-ray depth is not well known and can play a role in providing "excess" luminosity at late times. There are other possible explanations for the late-time luminosity.

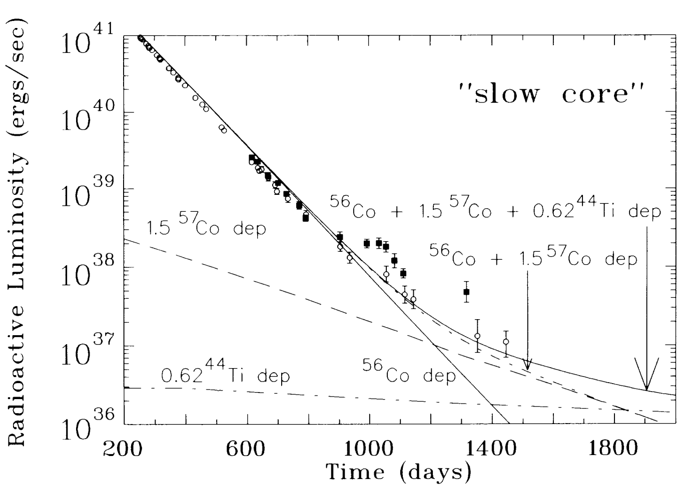

FIG. 1.—Model "slow core" light curve. Suntzeff et al. (1992) photometry is open circles. With 57/56 = 1.5 × solar (the meaning of coefficients in this figure), this model suffices for late time power from radioactivity alone because its larger optical depth deposits a larger fraction of the ^{57}Co power.

3. MECHANICAL DISSIPATION

Alternatively, the SN 1987A luminosity may be provided by mechanical rather than radioactive power. The kinetic energy of the outflow is of order 10^{51} ergs. A luminosity 10^{38} ergs s^{-1} (10 times the 1400 days luminosity) could be generated by a physical mechanism converting 10^{-13} s^{-1} of kinetic energy to thermal radiation. Such a small efficiency is hard to rule out. A dust mass 0.01 $M_\odot$ of 0.01 μm particles would radiate 10^{38} ergs s^{-1} if its temperature can be maintained at 20–30 K, for example. Understanding this mechanical power requires a description of interactions that dissipate differential-velocity fields within the expanding remnant. Free suprathermal electrons would have to strike each dust particle with 10–100 eV s^{-1} of collisional energy. Since the total (bound + free) electron density near 1600 days is of order 10^8 cm^{-3}, the free-electron density may be of order $n_e = 10^5$ cm^{-3}, and the collision rate of free hot electrons with grains can be shown to be of order $10^{-2}n_e$, the required product $10^{-2}n_e\langle E\rangle = 10$–100 eV s^{-1} per grain may be available.

We point out that the blast wave is certainly sweeping up matter and therefore dissipating power at the needed rate even if no special circumstellar structures are appealed to. Chevalier & Liang (1989) describe both the blue-supergiant (BSG) wind carrying away 2×10^{-6} $M_\odot$ yr^{-1} at a speed 500 km s^{-1} prior to the explosion and the subsequent supernova blast wave, which will at 10^4 km s^{-1} sweep up 4×10^{-5} $M_\odot$ yr^{-1} of BSG wind. The associated dissipation, 10^{39} ergs s^{-1}, would be more than adequate for the observed bolometric excess if it can be reprocessed into the bands observed. Chevalier (1992) described this dissipation with emphasis on the eventual collision with the prior red-supergiant wind (and reverse shock into SN 1987A), but without remarking on the portion that might appear as UVOIR. Other manifestations of such power need investigation now that the luminosity has fallen to 10^{37} ergs s^{-1}.

4. DELAYED POWER

Another alternative is that the bolometric luminosity may be delayed with respect to the radioactive input owing to the increasing delay of fundamental atomic processes of thermalization. The simplest example arises from chemical energy liberated as the degree of ionization decreases. The SN 1987A ejecta contains of order 10^{56} metal particles ($A > 12$). If each were ionized (see Dwek et al. 1992 for Fe^+ discussion), with perhaps 3 eV per ion available from recombination, the total energy store chemically would amount to about 10^{45} ergs. Releasing all of that during the 170 days decline rate of ionization, as calculated by Xu et al. (1992) for hydrogen, would radiate 10^{38} ergs s^{-1}, which would be adequate for the bolometric luminosity after 1100 days. On the other hand, if the optically thick [O I] emission doublet requires O to be neutral (Li & McCray 1992) ionization energy may not be as great as 10^{45} ergs.

To illustrate a quantitative model, let N_e represent the number of free electrons per gram, let the recombination rate per unit volume be given by $\alpha(\rho N_e)^2$, and let r_0 be the ionization rate per gram at $t = t_0$ owing to ^{56}Co radioactive power. Then $dN_e/dt = r_0 \exp - [(t - t_0)/\tau_{56}] - \alpha\rho N_e^2$. The density dependence $\rho(t) = \rho_0(t_0/t)^3$ and the recombination coefficient $\alpha = 2.07 \times 10^{-11}T^{-1/2}$ allow integration of that equation. The Compton electrons, whose initial spectrum (Clayton & The 1991) may roughly be characterized by $\langle E_{\rm compt}\rangle = 100$ keV, start a cascade of collisional ionization that will terminate when $\langle E_{\rm ion}\rangle = 3$ eV falls below the subsequent ionization thresholds of metal atoms. Figure 2 shows the integral when 0.075 $M_\odot$ of ^{56}Co power is absorbed by a mean density $\rho_0 = 9.6 \times 10^{-16}$ g cm^{-3} at $t_0 = 1000$ days. The upper panel shows the ionization rate per gram (exponential, *dashed curve*) along with the recombination rate (*solid curve*) from equation (1). Although these two rates are balanced at early times, it is also evident that as time progresses the recombination rate exceeds the ionization rate by an escalating factor. *Because of the declining density and lengthening recombination time, the recombination rate becomes unable to fall as rapidly as the radioactive power.* Since recombination restores power, the rate ratio in Figure 2 may be approximately the ratio of powers as well. At late times the recombination power exceeds the ionizing power by increasing factors, similar to the luminosity shown in Figure 1.

Radioactive heating at a delayed rate exp $[-(t - t_Q)/\tau_{56}]$, where $t_Q(t)$ is the time delay between decay and thermalization, can arise for other physical reasons. Another example is the increasing time required for a fast electron to strike a dust grain, which will be relevant if that mechanism is central to the IR power. If 0.001 $M_\odot$ of 0.1 μm dust grains are radiating the IR power, for example, the time at 900 days for a 10 eV electron (end of an ionization-loss cascade) to strike such a grain is 100 days, already rather long, so that at later times it is 100 $(t/900 \text{ days})^3$ days. This delay leads to a situation similar to equation (1) and the corresponding integration similarly flattens the IR power. One consequence is that the IR power will remain above the radioactive power.

5. NUCLEOSYNTHESIS AND CHEMICAL EVOLUTION

If photoelectric absorption is unimportant, the OSSE detection (Paper 1) of ^{57}Co gamma rays suggests that ^{57}Ni/^{56}Ni = [1.5 ± 0.3(statistical) ± 0.2(systematic)] × (^{57}Fe/^{56}Fe)$_\odot$. Pro-

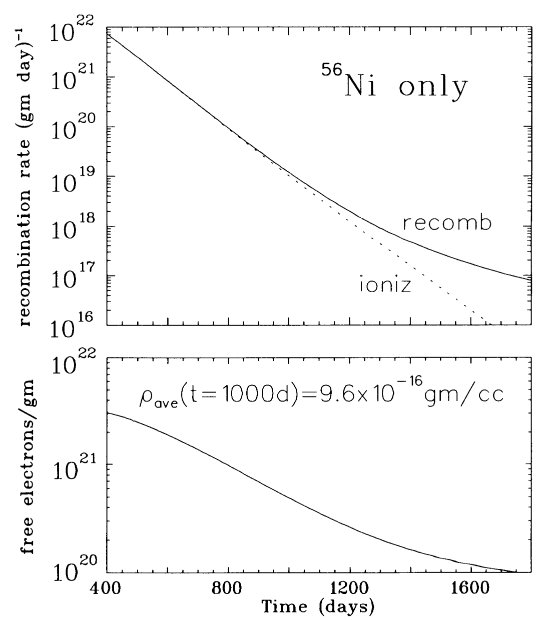

FIG. 2.—Excess recombination becomes increasingly important after 1000 days in an elementary model (see text). This delayed power (and other manifestations of that idea) must be present in SN 1987A, and must therefore be modeled to reach bolometric conclusions concerning the ^{57}Co and ^{44}Ti masses.

duction ratios in this range can agree with the bolometric power only with the aid of increased optical depth and/or temporal storage, delay and release of energy. More opaque models such as "slow core" require even larger production ratios, up to 2.6 ± 0.6, to account for luminosity and gammas. How do these fit into nucleosynthesis theory?

One answer comes from models of the SN 1987A explosion. Thielemann, Hashimoto, & Nomoto (1990) have presented a thorough study of its nucleosynthesis. They find that the alpha-rich-freezeout ejecta mass depends on the location of the mass cut; placing it at 1.6 $M_{\odot}$ gives $^{57}Ni/^{56}Ni = 0.046$, or 1.9 times solar. The expectation lies between 1.3 (their Table 4) and 3 times solar (their Fig. 12*a*) as the mass cut moves from 1.63 to 1.53 $M_{\odot}$. They prefer the 1.6 $M_{\odot}$ compromise giving $1.9 \times$ solar for several subtle reasons. Quite clearly this expectation of $1.9 \times$ solar is consistent with our findings. Kumagai et al. (1991) obtained the ratio $1.7 \times$ solar. Woosley, Pinto, & Weaver (1988) found comparable values. So we find no conflict of OSSE data with supernova theory at its present state of development. On the other hand the value $5 \times$ solar called for by Suntzeff et al. (1992) and Dwek et al. (1992) would strain present understanding (e.g., Woosley & Hoffman 1991).

This is not the only nucleosynthesis issue. SN 1987A was a low-metallicity Type II, so that it had a smaller initial neutron excess, η, than comparable-mass Galactic Type II SN. This smaller η remains in the presupernova O shell but is almost equalized by electron captures in the Si core, where most of the Ni production probably occurs. Any larger η in Galactic Type II would raise the ^{57}Ni yield relative to that of ^{56}Ni (Woosley, Arnett, & Clayton 1973; Woosley & Hoffman 1991), with their production scaling roughly as $\eta^{1/2}$. As a consequence average Galactic Type II might be expected to have a production ratio greater than SN 1987A. It then becomes necessary to address how the solar ratio can have come about. To achieve consistency with so great a yield of ^{57}Ni from Type II's it will be necessary that Type I supernovae, which produce most of the Fe, did so with a 57/56 production ratio less than the solar ratio.

Calculations of differing Population I Type I explosions, which dominate Fe nucleosynthesis, are also characterized by 57/56 production ratios greater than solar. One well studied case is the carbon-deflagration model W7 (Thielemann, Nomoto, & Yokoi 1986), from which $^{57}Fe/^{56}Fe = 1.5 \times$ solar emerges. It includes not only radioactive Ni production but also Fe production in the neutronized central regions. The neutron-rich center might be avoided if the explosions of less-massive white dwarfs resulting from off-center ignition during mergers are relevant, as Shigeyama et al. (1992) have advocated for SN 1990N; but the 57/56 ratio will still be at least solar unless the white dwarfs had low initial metallicity, thereby reducing 57/56 by $(Z/Z_{\odot})^{1/2}$. Khohklov's (1992) delayed-detonation models are similar, with four separate examples all having 57/56 greater than solar by factors of about 1.2–1.3. The η dependence of NSE expansions (Woosley, Arnett, & Clayton 1973) offers little latitude for any other result in a Type I model. We thus face the impasse of having the main source of Fe (SN Ia) be already ^{57}Fe rich by small factors. From their relative rates and yields it appears that about 2/3 to 3/4 of ^{56}Fe has originated in Type Ia explosions (e.g., Thielemann, Nomoto, & Hashimoto 1991), but even so it leaves no room for ^{57}Fe overproduction in Type IIs. Even twice solar in SN II creates a major astrophysical problem.

This yield problem could grow into a major one for nucleosynthesis theory unless a new source of ^{56}Fe having low 57/56 can be identified. Enough of them could then result in a Galactic 57/56 ratio near solar. An interesting alternative use for a single such object would be a ^{56}Fe-rich explosion mixed into the presolar cloud, perhaps doubling its concentration there and lowering its 57/56 ratio to the known solar value, a value atypical for the Galaxy's chemical evolution. Such an admixture might have also raised solar O/H in comparison with average H II regions (e.g., Shaver et al. 1983) and also elevated both $^{16}O/^{18}O$ (Schramm 1985) and $^{12}C/^{13}C$ (Clayton 1977). Such far reaching speculations may be necessary, since even the modest OSSE ^{57}Co yield of about 1.5 ± 0.5 solar leaves a challenging problem for chemical evolution.

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