SUPERNOVA PUZZLES AND GAMMA-RAY ASTRONOMY [1]

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ABSTRACT

The significance of supernovae for the Compton GRO has lain primarily in the large amount of radioactivity that they eject. This activity and its daughters find their way into the interstellar medium and into other arenas of astrophysics. Direct measures of the quantity of such activity carries profound information that is not available from observations of stable nuclei. CGRO has had both success and disappointment: success at detecting or placing important limits to radiation from three of the brightest extragalactic supernovae of recent decades, disappointment that those three lay at the "plate limit" for OSSE and COMPTEL, and that nature has not smiled even wider upon us with a Galactic Type II or a Type Ia within 10 Mpc. While we review this situation we call attention to some exciting puzzles about supernovae and radioactive production within them. These puzzles place the CGRO mission into the larger framework of the science of cosmic radioactivity.

I. THE RADIOACTIVE UNIVERSE

The universe should be profoundly radioactive. Clayton & Silk (1969) pointed out that ^{56}Fe is overwhelmingly the most prolific activator because of its high abundance and because the parenting ^{56}Co decay occurs in a relatively transparent state of the expansion, owing to its long half-life (77d). The et al. (1993) reevaluated the relevant emission quantities in their assessment of this γ-ray background. They find that 60% of the total 847 keV γ-rays from Type Ia ^{56}Co escape, for example, and argue that 2/3 of ^{56}Co production in our own Galaxy has resulted from Type Ia

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supernovae. Their Figure 1 shows the composite ^{56}Ni, ^{56}Co spectrum for differing assumptions concerning the appropriate Friedmann model. Near 800 keV this computed background can approach 1×10^{-5} cm^{-2} s^{-1} ster^{-1} keV^{-1}, a significant fraction of the cosmic background at that energy.

The puzzle here lies in the density of ^{56}Fe nuclei in the universe. If we believe Big-Bang nucleosynthesis, we take the observed D/H ratio in the ISM to restrict the baryonic component of matter to about 10% of the critical density; i.e., about 5×10^{-31} g cm^{-3} of baryons. If on the other hand one takes the observed light from galaxies to measure the baryon density from standard mass/light ratios, one restricts it to no more than 1% of the critical density. The much larger mass inferred from virial arguments constitutes the so-called dark matter, whose density ranges up to almost the critical value, depending on the scale of gravitating systems studied. Because that matter is argued to be non-baryonic (on theoretical grounds), it is supposed not to contain ^{56}Fe. Contemporary cosmology wrestles with these problems. It is clear that a measure of the ^{56}Fe density of the universe would provide a useful cornerstone of fact for these uncertain arguments.

On a more astrophysical level we are even ignorant of what fraction of baryonic matter will have synthesized ^{56}Fe. The et al. used solar concentration of iron in the baryonic part. The massive-star Type II nucleosynthesis does not contribute much to the γ-ray background, because its ^{56}Co decays in opaque expanding cores. If the baryonic matter truly is 10% of critical, what is the Fe/H ratio owing to Type Ia nucleosynthesis in that 10%? Certainly a measurement would clarify that interesting astrophysical question about the history of baryonic matter.

II. ^{57}Co AND THE LATE LUMINOSITY OF SN 1987A

The OSSE detection of ^{57}Co in Supernova 1987A (Kurfess et al. 1992) four years after its explosion will remain one of the high points of the CGRO mission. But because the observations could not be made until it was so old, the detection was likely to be of modest statistical significance. The photon bump in excess of the best-fit continuum spectrum yielded a 5-sigma detection of ^{57}Co. Although the existence of radioactive

^{57}Co in supernovae was expected, its detection is still historically and scientifically quite significant. It is the third nuclear activity detected by astronomy (following ^{26}Al and ^{56}Co). It is only the second detection from a specific explosive object (SN 1987A for both ^{56}Co and ^{57}Co). It becomes the dominant activity in supernovae after about two years (Clayton 1974), affording an independent chance to confirm the theory of explosive nucleosynthesis in stars, and providing a unique measure of the structure of exploding stars and the hydrodynamic instabilities that allow the radioactivities to break through in streams toward the surface.

The abundance of ^{57}Co is 1.5 ± 0.3(statistical)±0.2(systematic) times greater than inferred from the solar abundance ratio ^{57}Fe/^{56}Fe. This means that if ^{56}Fe is populated by the ^{56}Ni-^{56}Co-^{56}Fe decay chain (Bodansky, Clayton & Fowler 1968), as indeed is now known, then so too has ^{57}Fe resulted from ^{57}Ni-^{57}Co-^{57}Fe. In particular, the ^{57}Fe is not the result of a weak s-process (Peters, Fowler & Clayton 1972) irradiation of Fe re-mixed through stars. OSSE's abundance of ^{57}Co is what one expects from supernova nucleosynthesis theory (e.g., Thielemann, Hashimoto & Nomoto 1990; Woosley & Hoffman 1991). It may not be appreciated that the ratio ^{57}Ni/^{56}Ni increases from about 1/2 of the solar ratio for normal freezeout to about 2.5 times that ratio for the most α-rich freezeouts expected from the shock energy. Thus the ratio 1.5 ± 0.5 tells us that the dynamics has produced about the anticipated ratio of α-rich/normal freezeouts. Such arguments would be very telling indeed with a more precise measurement. Added interest follows from the nucleosynthesis of ^{44}Ti in α-rich freezeouts and its promise as a γ-ray astronomy target. The correlation between ^{57}Co and ^{44}Ti yields can best be seen from the parameterized study by Woosley & Hoffman (1991), and it is confirmed in detailed models of supernovae. The matter that has undergone oxygen burning in the presolar evolution will have had its neutron excess increased to several times solar; therefore the measurements suggest that this matter was not ejected. That is, the position of the mass cut and the mass of the neutron star are also limited by OSSE observations. Kumagai et al. (1993) have discussed this point and conclude that it favors the late-time neutrino heating mechanism and a baryonic mass 1.65–1.80 $M_\odot$, corresponding to a gravitational mass 1.45-1.60 $M_\odot$.

This constitutes a major contribution of CGRO to supernova knowledge.

Clayton et al. (1992) point to puzzling problems for the chemical evolution of our Galaxy. How has it managed, after 7 Gyr of presolar supernovae, to have a ^{57}Fe/^{56}Fe abundance ratio as small as solar when a lower metallicity object in the LMC has produced 1.5 times solar? If the observations do indeed restrict the neutronized matter (that with oxygen already burned), which would have made even more ^{57}Co, to have fallen onto the neutron star, one would have expected recent Galactic Type II's to have made more ^{57}Co than did one in the LMC. This conflict is weakened by Type Ia's being the major source of ^{56}Fe, and probably but not necessarily of ^{57}Fe. Calculations of Type Ia's, however, have not altered the old conclusions that they also produce ^{57}Ni/^{56}Ni greater than solar (Thielemann, Nomoto, & Yokoi 1986). So appeal to Type Ia synthesis does not seem to alleviate the problem. At the present time there seems to be no convincing explanation of the low 57/56 ratio in the solar system. One speculation (Clayton et al. 1992) is that the solar system may be abnormally low in ^{57}Fe content because the solar cloud contained a major contribution of Fe from a recent local supernova of rare type that does have a low ratio. A connection may exist to the high ^{12}C/^{13}C and ^{16}O/^{18}O ratios in solar matter. This raises again the question of understanding the isotopic composition of the solar system and of the isotopic anomalies and extinct radioactivities within it.

Another contribution of the OSSE measurement of 2.7×10^{-3} $M_\odot$ of ^{57}Co in SN 1987A is to our understanding of the late luminosity of supernovae. Because of the success of the ^{56}Co-deposition interpretation of the earlier luminosity decline, many tacitly assumed that ^{57}Co radioactivity would become the major source of luminosity (unless a luminous pulsar or black hole powered the nebula from its center). Indeed, infrared measurements of a growing clear excess of luminosity above the ^{56}Co-deposition (Suntzeff et al 1992; Dwek et al 1992) were interpreted in this way. Both groups concluded that the 57/56 production ratio in SN 1987A had been fivefold solar. The OSSE measurement forbade such a large ^{57}Co yield, and turned attention to other sources of late-time luminosity. Clayton et al. (1992) presented some physical possibilities, of which the most plausible and interesting is a transition from nuclear power to chemical power. The rapidly falling density delays electron recombination, so that the free-electron density exceeds that to be expected from steady-state by increasing amounts. As a result, the recombination rate becomes larger than equilibrium would require, and extra power is injected by that recombination. Clayton et al. (1992) showed that a simple analytic treatment produced a good match to the SN 1987A luminosity. This has been verified by Fransson & Kozma (1993). CGRO γ-ray measurements led to this discovery of a new mechanism of late-time supernova luminosity.

It was claimed that measurements (Varani et al. 1990) of atomic gaseous Co/Fe abundance ratio in SN 1987A had already determined the 57/56 production ratio. But that is not the case. That analysis omitted important factors, including the freshly synthesized ^{59}Co, which is especially important in the α-rich freezeout portion of ^{57}Co synthesis, and the plausible speculation that the high entropy portion containing the new ^{59}Co would remain more gaseous than the lower-entropy normal freezeout portion. Both effects cause the gaseous Co/Fe ratio to increase with time relative to the trend expected from pure ^{56}Co, thereby emulating ^{57}Co. Similar masking comes from the more efficient condensation of Fe than Co at the low density of a supernova remnant. This occurs because of the thermodynamic tendency of Fe (but not Co) to condense within olivine, $(Mg, Fe)_2SiO_4$, with Fe in solid solution with Mg (Grossman & Larimer 1974, Fig. 7; Saxena & Eriksson 1983, Fig. 1). The initial Fe content of the progenitor and the differential condensation of the envelope was also omitted by Varani et al. Gamma-rays, on the other hand, are unambiguous about the isotopes.

The question of whether a pulsar remains from SN 1987A, or whether the young neutron star collapsed to a black hole remains open. Do the OSSE data have something to say about this? Yes, but not very conclusively. Clayton et al. (1993) are preparing a summary of the measurements of the hard continua detected during five separate viewing periods. The changing continua are confused by LMC X-3 and LMC X-1.The fate of the SN 1987A core is an important question in astrophysics, but the OSSE data to be reported will require careful assimilation with other observations of the confused field.

III. SUPERNOVAE 1991T and 1993J

Because 1991T was the brightest SN Ia in two decades and 1993J was a core-collapse Type II/Ib transition object in nearby M81, observations of their spectra and light curves are revolutionizing astronomical knowledge. But neither was "the big one" that strongly motivated a part of the Compton GRO mission. There exist dozens of nearer galaxies within which a SN Ia would have been easily detectable. The SN 1991T limits (Lichti et al. 1993; Leising et al. 1993a; Leising et al. 1993b) near $4\times10^{-5}\text{cm}^{-2}\ \text{s}^{-1}$ at 847 keV are not a great surprise at the expected distance (13 Mpc, but not well known) except for its optical brightness, which also derived from ^{56}Co decay at the time of CGRO observation. That brightness demands a nearer SN Ia for most theoretical models, so that the γ-ray lines should also have been detected! New models, which more efficiently trap the γ-rays for some months after explosion, are called for by the CGRO limits. This requirement might ultimately help in resolving the puzzles of the SN Ia progenitors and explosion dynamics which currently allow a vast array of models.

Supernova 1993J is now thought to be a core-collapse event, and even though it had a low-mass hydrogen envelope it is now clear that a detection of ^{56}Co lines was unlikely. Its nature was not known at the time, however, so CGRO observed SN 1993J soon after outburst (at 9–15 days and 23–37 days). The result was somewhat surprising. Supernova 1993J was the first supernova to be detected in hard X-rays at such an early time. The OSSE detected emission from 50–150 keV in both these intervals (Leising et al. 1993c). The flux was too high to be attributed to Compton-scattered γ-ray line photons, and is probably due to shock-heated electrons from the supernova ejecta–stellar wind interaction. The hard X-rays probably come from the shocked presupernova wind with electron temperature approaching 10^9 K. The large hard X-ray luminosity, near 5×10^{40} ergs s^{-1}, remains something of a puzzle at this writing, because simple extrapolations of the spectrum to lower energies exceed the soft X-ray fluxes measured at nearly the same times.

IV. INTERSTELLAR ^{26}Al AND OTHER EXTINCT RADIOACTIVITIES

Both COMPTEL (Diehl et al. 1993) and OSSE results presented at this meeting contribute to the important problem of interstellar ^{26}Al. Its initial detection came as a surprise and its interstellar abundance has continued to raise questions. Clayton (1984) argued that supernovae could not be the source of ^{26}Al without overproducing (by tenfold) the interstellar mass of stable ^{27}Al. On the other hand Woosley and collaborators have found supernovae to be adequate sources. They argue that three per century ejecting 0.7×10^{-4} $M_\odot$ of ^{26}Al (Weaver & Woosley 1993) clearly produce the observed 2 $M_\odot$ during the Myr lifetime of ^{26}Al. This conflict is puzzling. Both arguments are sound and have their own limitations. We have no good evidence that the Galaxy has had three supernovae per century; indeed, the lack of detected ^{44}Ti hotspots (see below) contradicts that presumption for the last few centuries. The supernova production ratio ^{26}Al/^{27}Al appears to be a more reliable estimate. Here is how the numbers now seem to be falling into line.

The production ratio p(^{26}Al)/p(^{27}Al)= 6×10^{-3} for Type II supernovae (Weaver & Woosley 1993) is three times larger than the value used in Clayton's (1984) argument. That argument was based on a closed-box model of Galactic chemical evolution, saying that the interstellar ratio ^{26}Al/^{27}Al equals their production ratio times the ratio of the ^{26}Al lifetime to the age of the Galactic disk. That result, which is exactly true in simple closed models, leads with the new production ratio to an expected interstellar abundance ratio ^{26}Al/^{27}Al=5×10^{-7}. The observed 2 $M_\odot$ of ^{26}Al seems to lie within the solar galactocentric radius, where no more than 5×10^{5} $M_\odot$ of stable ^{27}Al reside in the interstellar medium. This amounts in the ISM to 0.3 $M_\odot$ of ^{26}Al. This shortfall in comparison with observation reproduces Clayton's (1984) argument, but it is now slightly less severe.

A bigger change is the growing belief that the mass of the Galactic disk was not in place from its beginning but instead grew while low-metallicity material fell onto that disk. Clayton (1988) presented many of the reasons for this and also its effect on the interstellar concentrations of radioactive nuclei. In a family of exact solutions advocated by Clayton (1985) as a "standard model of chemical evolution" the infall is characterized by a parameter k; namely the infall rate f(t) is given by $k/(t+\delta)$ times the current mass of ISM. The net effect is that all interstellar radioactivities stand in higher concentration with respect to a stable reference isotope by a factor (k+1). Clayton, Hartmann & Leising (1993) adopted these ideas and explained that the values k=3 to 4 needed to solve many Galactic observations also bring the ^{26}Al mass almost into line. If k=4, today's steady-state ISM ratio becomes $^{26}Al/^{27}Al=3\times10^{-6}$, which amounts to 1.5 $M_\odot$ of ^{26}Al from supernovae. This lends credence to the possibility that almost all ISM ^{26}Al has been ejected by Type II events (including their Wolf-Rayet antecedents). How tantalizing to think that γ-ray measurements yield profound implications for the structural history of the Galactic disk! COMPTEL observations (Diehl et al. 1993) of localized concentrations of ^{26}Al further demonstrate that young objects, probably SN II and WR stars, contribute significantly to Galactic ^{26}Al.

There exists a powerful interplay between γ-ray astronomy and extinct radioactivities discovered in meteorites. These daughter excesses confirm the existence of their parents at the time the meteorites were assembling. This interplay is most direct for ^{26}Al. Meteorite observations suggest that the solar system formed from matter containing an abundance ratio $^{26}Al/^{27}Al = 5\times10^{-5}$, tenfold greater than the value observed in the ISM by 1809 keV γ-rays! This meteoritic evidence is also telling something important about ^{26}Al;viz. that it can be enhanced by tenfold in some locations, presumably also at places today in the ISM unless the circumstances of solar birth were almost unique. It also suggests that some ^{26}Al ejecta can be slowed and assimilated by a molecular cloud core before great dilution. Furthermore, individual grains from meteorites reveal initial ratios as high as $^{26}Al/^{27}Al=0.1$ (Zinner et al. 1991). Such huge concentrations surely represent "fossil excesses", as predicted two decades ago (Clayton 1975), in which particles condense in the outflow of the star, before mixing with the ISM. This ^{26}Al presumably has decayed within those particles in the ISM, rather than in the meteorites. To find values as large as 0.01 seems to require that those particles condensed in matter contained in or recently processed in the hydrogen burning shells of stars. But those individual grains are true fossils. The value 5×10^{-5}

Table 1: Initial Planetary Supernova Radioactivities

(A, Z)/(A', Z)	$\frac{^{26}\mathrm{Al}}{^{27}\mathrm{Al}}$	$\frac{^{129}\mathrm{I}}{^{127}\mathrm{I}}$	$\frac{^{107}\mathrm{Pd}}{^{108}\mathrm{Pd}}$	$\frac{^{244}\mathrm{Pu}}{^{238}\mathrm{U}}$	$\frac{^{53}\mathrm{Mn}}{^{55}\mathrm{Mn}}$	$\frac{^{146}\mathrm{Sm}}{^{144}\mathrm{Sm}}$
SN process	expl-Ne	r	r, s	r	expl-Si	expl-Ne
$p_A/p_{A'}$	6(-3)	1.4	0.65	0.7	0.13	0.04
τ (Myr)	1.05	23.1	9.4	118	5.3	150
<ISM>[1]	3(-6)	0.018	3(-3)	0.07	4(-4)	5(-3)
<MC>[2]	3(-9)	3(-3)	2(-4)	0.04	7(-6)	3(-3)
Meteor.	4(-5)	1(-4)	2(-5)	7(-3)	8(-6)	7(-3)
Meteor./MC	1(4)	0.03	0.1	0.2	1	2

[1] $< ISM > = p_A/p_{A'}$ (k+1) (τ/7400 Myr), with k=3

[2] $< MC > = < ISM > \times \mathrm{X}_{MC}/< X >$ ratio from eq. (10) of Clayton (1983).

on the other hand is believed to be truly alive ^{26}Al at the time of solar formation (Lee et al. 1977), because it is found in larger mineral assemblies that are themselves believed to have been constructed by heating events from initial interstellar dust. There exists a large and confusing literature on this topic (Kerridge & Mathews 1988). Because the arguments in favor of a fossil interpretation (Clayton 1986) for such macroscopic mineral assemblages have not been convincing to chemists, the community interpretation is that ^{26}Al was live in the solar cloud at a concentration tenfold higher than seen today by γ-ray detectors in the mean ISM. This remains a puzzle.

This confluence of puzzles surrounding ^{26}Al — fivefold more in the ISM than initially expected, but tenfold less than the ^{26}Mg excesses in early-solar-system minerals — has fascinating parallels for many other extinct radioactivities, those radioactive nuclei from which we do not see γ-radiation in the ISM but from which we see extinct daughters in solar system materials. Correct interpretation of ^{26}Al probably cannot be made outside the context of the full data on interstellar radioactivity, *including* data from meteorites. So we summarize in Table 1 the well documented cases, production ratios, and anticipated interstellar ratios using k=3 at the time of solar birth .

^{129}**I:** This is the oldest known extinct radioactivity. The excess ^{129}Xe found correlated with stable ^{127}I in all classes of meteorites was demonstrated three decades ago by John Reynolds (1960) and coworkers since (Podosek & Swindle 1988). Its early solar system abundance is low, about $^{129}I/^{127}I = 1\times10^{-4}$, but with 40% variations from one meteorite to another. Curiously, the amount expected in the ISM is almost 100 times greater than the meteoritic value! Because both ^{129}I and ^{127}I are in the r-process nucleosynthesis peak from supernovae, the relative abundances of solar ^{129}Xe and ^{127}I set their production ratio quite accurately as p(129)/p(127)=1.4. With its mean lifetime 23.1 Myr, ^{129}I should have existed in the ratio $^{129}I/^{127}I=0.018$, fully 180 times the meteoritic record. The underabundance is in the opposite sense of ^{26}Al. So here is another puzzle. Although the ISM ratio 0.018 is theoretical, it can hardly be wrong, because the very successful r-process theory (Seeger, Fowler & Clayton 1965; Meyer et al. 1992) fits well the expectation that stable ^{129}Xe owes its high abundance to r-process nucleosynthesis of ^{129}I, and 1.4 times more abundantly than ^{127}I. What is wrong with this picture?

^{53}**Mn:** This 5.3 Myr activity reveals itself in meteorites as excess ^{53}Cr associated with Mn. This is not surprising, because virtually all of ^{53}Cr was synthesized as radioactive ^{53}Fe, which decays quickly to ^{53}Mn. The synthesis is by the same explosive silicon burning (Bodansky, Clayton & Fowler 1968; Woosley, Arnett & Clayton 1973) by which we understand γ-ray targets ^{56}Ni, ^{57}Ni, and ^{44}Ti. Regrettably, the ^{53}Mn decay emits no γ-ray, for if it did it would be twice as bright as ^{26}Al! Lugmair et al. (1992) have convincingly shown that angrite meteorites, dated by Pb-Pb chronology to have formed 4.5578 Gyr ago, contained the ratio $^{53}Mn/^{55}Mn = 1.3\times10^{-6}$. Those meteorite ages are 10 Myr younger than the most primitive solar system samples, so allowing for decay, the initial abundance was $^{53}Mn/^{55}Mn=8.6\times10^{-6}$. Theoretically, the production ratio $p(^{53}Mn)/p(^{55}Mn)=0.13$ is known quite accurately from solar abundances; therefore, the Galactic evolution models anticipate $^{53}Mn/^{55}Mn= 3.7\times10^{-4}$ in the mean ISM. This is 40 times more than the meteoritic concentration, but in agreement with the mean, <MC>, expected in molecular clouds.

^{244}**Pu:** One of the great science stories is that ^{244}Pu was alive in the meteorites. Telltale evidence from both etched fission tracks and from Xe-isotope fission fragments indicate that its abundance was 0.7% that of ^{238}U (e.g., Podosek & Swindle 1988). It reminds us of the ^{254}Cf hypothesis of supernova light curves (Burbidge et al. 1957), and also that that hypothesis formed the basis for the first paper (Clayton and Craddock 1965) to examine the prospects for testing nucleosynthesis theory by γ-ray spectroscopy of young supernova remnants. The Cf hypothesis was incorrect, and we now see that transbismuth radioactivity from the Crab should be only about 1×10^{-7} cm^{-2} s^{-1} (the 390 keV line from ^{249}Cf). Mean ISM emission should give even less. But even so, the very existence of ^{244}Pu is of interest to the larger purposes of CGRO. With production at 70% of ^{238}U and with 118 Myr lifetime, the mean ISM should carry the ratio ^{244}Pu/^{238}U = 0.07 in steady state. Thus ^{244}Pu is tenfold less abundant in the early solar system than it is expected to be in the mean ISM.

^{60}**Fe:** This is an especially interesting nucleus because it has been found extinct in meteorites (Shokulyukov & Lugmair 1993), because it was one of the earliest good candidates identified for γ-ray astronomy (Clayton 1971), because its Galactic abundance has already been limited by γ-ray radiation measured by SMM (Leising & Share 1993), and because its nucleosynthesis is many faceted. In the meteorite Chervony Kut the isotopic excess of ^{60}Ni correlates with the Fe/Ni element abundance ratio, as it would if the excess ^{60}Ni is the result of in situ ^{60}Fe decay. The required amount of ^{60}Fe at the time the meteorite solidified is small, ^{60}Fe/^{56}Fe = 3.9×10^{-9}. Its solidification probably required about 10$\pm$2 Myr (Shukolyukov & Lugmair 1993), which requires an initial ratio near 3.5×10^{-6}, with an uncertainty factor of 3.9 owing to the 2 Myr age uncertainty. In short, the initial solar value may lie between 1 and 14 parts per million of Fe. This rather large range, taken together with the considerable nucleosynthesis uncertainty over ^{60}Fe, renders the comparison between observed and expected interstellar abundance indecisive at the present time, therefore we omit it from Table 1. Leising & Share (1993) have turned it around to conclude that their limits on 1.17 and 1.33 MeV radiation from the Galactic plane correspond to having less than 1.7 $M_\odot$ of interstellar ^{60}Fe, which allows them to say that no more than 1.5% of ^{60}Ni was synthesized as ^{60}Fe parent. It also means that the present interstellar ratio

$^{60}Fe/^{56}Fe$ is less than 1.7 $M_\odot$ /1×10^7 $M_\odot$, which is considerably less than the inferred solar initial value.

^{107}**Pd:** The mean lifetime 9.4 Myr is sufficiently great that a healthy ratio $^{107}Pd/^{108}Pd$ may be expected in the mean ISM. From their abundances and the s-process theory, we know that the production ratio in the r-process events that must have made most of the ^{107}Ag was $p(^{107}Pd)/p(^{108}Pd)=0.65$. Thus we expect the mean ISM to contain the steady-state ratio $^{107}Pd/^{108}Pd=3.3\times10^{-3}$. Continuing the trend of other r-process products, this is 150 times more than has been found in meteorites, but the expected cloud concentration <MC> is tenfold less than <ISM>. The correlation of excess ^{107}Ag with the Pd/Ag elemental ratio in samples from iron meteorites shows that they solidified with $^{107}Pd/^{108}Pd = 2\times10^{-5}$ (Kelly & Wasserburg 1978). Of course, the initial ratio would have been somewhat higher, depending on the solidification age of the iron meteorites. Kelly & Wasserburg (1978) argued that this solidification was often rapid, taking no more than a few Myr, in which case the true initial ratio is not much larger than 2×10^{-5} since the half-life is 6.5 Myr.

Astrophysical connections: There exist two fundamental differences between γ-astronomy of the ISM and extinct radioactivity in meteorites. The ISM is seen today, whereas the solar system formed 4.56 Gyr ago. This time difference is not, however, believed to cause much physical difference in the interstellar abundances. All chemical evolution models for the Galaxy show that the abundance ratios today differ by only small amounts from those at that earlier time. A much more significant difference is that γ-ray astronomy surveys the mean ISM, whereas the solar system is believed to have formed near a molecular-cloud core. The reader may consult many chapters in the book edited by Levy & Lunine (1993). For radioactivity this means that the solar system might have been expected to have the radioactive concentrations found in molecular cloud cores. Those activities are surely smaller (on average) than in the mean ISM, because most supernova products will be violently ejected into a badly disrupted and heated local ISM. Considerable time will, on average, be required for that matter to find itself undergoing a cooling transition joining a molecular cloud– and more to get into molecular-cloud cores. Table 1 summarizes a very simple model for this by Clayton (1983). Considering that molecular clouds and diffuse clouds each constitute about half the ISM mass, the mass rate of disruption of molecular clouds by star formation must equal the mass rate of condensation of diffuse media into molecular phase. Taking the phase transformation times T1 and T2 to be each 50 Myr and the phases to mix continuously (on average) as Clayton (1983) described, we list the mean expected concentration ratio <MC> in molecular clouds. The situation can be seen to be as follows: the r-process activities ^{107}Pd, ^{129}I and ^{244}Pu are all expected to be 10 times more abundant in the average molecular cloud than they are observed to have been in the initial solar system; the explosive products ^{53}Mn and ^{146}Sm are expected to have concentrations near the observed values; the ^{26}Al has negligible expected molecular-cloud abundance.

This is a remarkable situation calling for several speculations. The first might seem to be the underabundance of r-nuclei with respect to others (^{53}Mn and ^{146}Sm) that are also supernova products. This suggests that not all supernovae eject r-process yields, so that the solar cloud was simply deficient in recent supernova ejecta from r-events. This deficiency may have been the result of inhomogeneous mixing in the presolar ISM. Mathews & Cowan (1990) have speculated that only the lower mass range of the Type II events produces an r-process, on the grounds that O and Fe rise more rapidly than do r-abundances in the most metal deficient early stars of the Galaxy. A second observation is that there is simply so much solar ^{26}Al that one is forced to assume some event that synthesized it and mixed it quickly into the collapsing solar cloud. The discoverers of meteoritic ^{26}Al stated this from the outset (Lee et al. 1977). The only possible escape would be fossil ^{26}Mg produced by prior ^{26}Al decay within Al-rich ISM grains (Clayton 1986; Podosek & Swindle 1988). Cameron (1993) attributes the live ^{26}Al to a nearby AGB star at the time of solar birth. None of the other activities require a special event to admix them into our cloud, although Cameron (1993) attributes many to that event and also considers other less well documented radioactivities that will, if confirmed, greatly clarify the problem. Third, if a special event is needed for ^{26}Al, then that same event may indeed have been responsible for some of the other activities, in which case our comparison to the mean molecular clouds in the mean ISM is irrelevant. And therein lies the point; that the relevance to the early solar system lies not in the radioactive abundances themselves but rather in their deviations from those expected in a mean-ISM picture. Discovery of clearly patchy structure in ISM ^{26}Al γ-ray emission (Diehl et al., these proceedings) strongly impacts these considerations, all of which are uncertain today.

V. ^{44}Ti AND THE GALACTIC SUPERNOVA RATE

This parent ($\tau_{1/2}$=67 y) of the natural abundance of ^{44}Ca fascinates on many counts. It was among the first predicted γ-ray diagnostics from young supernova remnants (Clayton, Colgate & Fishman 1969). A few should be visible at all times in the Galaxy, giving it the potential for recording recent unseen supernovae. It may be (Clayton 1973) a contributor of the positrons annihilating in the Galactic plane. It was among the first predicted (Clayton 1975) extinct radioactivities within supernova dust. Candidates for such supernova condensates bearing large ^{44}Ca excess have now been found (Amari et al 1992). For such reasons ^{44}Ti has been a high hope for γ-ray astronomy and a profound potential companion for extinct radioactivity in stardust. Two surprises now intensify that interest:(1) Leising & Share (1993) found that there exist no remnants brighter than 8×10^{-5} cm^{-2} s^{-1} at 1.16 MeV, so that if supernovae have identical yields of ^{44}Ti that produced the natural ^{44}Ca abundance, a rate greater than 2 century^{-1} for the past two centuries is ruled out with 90% confidence! This again calls somewhat into question the required 3 century^{-1} needed to maintain ^{26}Al at the observed level from supernovae; (2) At this meeting the COMPTEL team (Iyudin et al., these proceedings) reported the detection of ^{44}Ti in the $\geq$3 century-old Cas A remnant, whereas the OSSE team (The et al., these proceedings) report only upper limits. In the meantime we observe that the lack of any detected neutron star in Cas A may suggest it collapsed into a black hole, in which case the ^{44}Ti-producing α-rich freezeout would seem to have not had the necessary strong bounce shock. These opening salvos begin a promising future for ^{44}Ti studies, especially when a higher-sensitivity instrument follows CGRO.

VI. CONCLUSION

The past three decades of astrophysics research have witnessed a steady growth in knowledge about supernovae and in frontier questions that depend on that knowledge. That emphasis of the CGRO mission was and is, therefore, well placed. Our limited opportunities to date have whetted appetites even more, because brilliant related studies have made it ever clearer how fundamental is the γ-ray radioactivity to unequivocal understanding of explosive objects. Armed with theoretical insights it is painfully obvious how much more we would have learned had the CGRO launch not unavoidably been delayed until so long after SN 1987A, or if SN 1991T had been in the local group of galaxies rather than the Virgo cluster. Our sights are now well beyond the issues of confirming explosive nucleosynthesis in supernovae; they now focus on questions of Type II supernova mass cut, remnant, and energization, and on the controversial Type I mechanism. In both we see the possible elucidation of post-explosion hydrodynamics and mixing, upon whose uncertainties so many new questions now stand. We have no choice but to await what nature gives us. To date she has been a tease. We remain on alert, awaiting the big one, while we work to extract small clue upon small clue from the opportunities already presented. We must make the most of our limited opportunities by remaining broadly cognizant of the rich fabric of astrophysical issues with which cosmic radioactivity deals. When the big one arrives, it will color and tear that fabric across its breadth.

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