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Donald D. Clayton
Clemson University, claydonald@gmail.com

Bradley S. Meyer
Clemson University

Lih-Sin The
Clemson University

Mounib F. El Eid
American University of Beirut

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IRON IMPLANTATION IN PRESOLAR SUPERNOVA GRAINS

Donald D. Clayton,[1] Bradley S. Meyer,[1] Lih-Sin The,[1] and Mounib F. El Eid[2]
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ABSTRACT

We consider the potential of measured iron isotopic ratios within presolar grains from supernovae (as discovered in meteorites) for identifying the gas from which the grains condensed. We show that although iron isotopic ratios vary dramatically with radial coordinate in the initial supernova, it seems likely that the concentration of iron that thermally condenses in SiC grains within the supernova interior may be smaller than the concentration that will later be implanted by high-speed grain-gas collisions following the penetration of the reverse shock into the supernova flow. In that case, the Fe isotopic composition is much altered. We propose that the ^{58}Fe richness that is very evident in the three SiC grains analyzed to date is the result of ion implantation during the grain's rapid radial motion through the shocked and decelerated overlying supernova gas that is ^{58}Fe-rich. We point to other likely applications of this same idea and speculate that only the dominant isotopes of the SiC grains, namely ^{28}Si and ^{12}C, can be safely assumed to be initial thermal condensate. We conclude that a violent period of implantation plus sputtering has overprinted the initial thermal condensate. If correct, this points to a new technique for sampling the velocity mixing within young supernova remnants.

Subject headings: hydrodynamics — ISM: abundances — nuclear reactions, nucleosynthesis, abundances — shock waves — Sun: abundances — supernovae: general

1. INTRODUCTION

Presolar grains became trapped in the assembly of the parent bodies of the meteorites during solar system formation. Upon breakup of the parent bodies by collisions, these grains were transported to Earth by the meteorites and are now extracted and studied in terrestrial laboratories (Bernatowicz & Zinner 1997). Dramatic isotopic anomalies (in comparison with solar isotopic abundances) identify these grains as being presolar and even identify in many cases the type of star mass loss within which they condensed. The most thoroughly studied type are silicon-carbide crystals (see Amari et al. 2001 for a recent discussion of the families of SiC particles). As evidenced by extraordinary isotopic anomalies, such as huge enrichments in ^{44}Ca (due to condensation of live parent ^{44}Ti), SiC type-X grains condensed within the interiors of supernovae during their expansion and cooling (Amari et al. 1992). A Type Ia supernova origin for these supernova condensates (SUNOCONs) has been proposed on the basis of isotopic signatures (Clayton et al. 1997b); however, the outflow velocities may be too large to condense X grains. This Letter will follow the more common idea that the X grains formed in core-collapse supernovae (e.g., Clayton, Amari, & Zinner 1997a).

A major problem in the SUNOCON interpretation has been that although the grains clearly represent supernova interiors, it is not clear from which parcels of gas the grains condensed. The isotopic abundances signal contributions from a variety of regions within the supernova, which has led some authors to postulate mixing of material from different zones prior to grain condensation (e.g., Travaglio et al. 1999). A significant difficulty with this scenario, however, is that the timescale for the requisite microscopic mixing is prohibitively long, except at zone boundaries (Clayton, Meyer, & The 2000). We here suggest the possibility of mixing of a different type, namely, implantation of fast ions following the slowing of the gas by the reverse shock.

Technological advances are permitting new isotopic measurements of trace elements in SiC X grains, which in turn provide new constraints on grain formation and histories. In this work we, focus on Fe. Hoppe et al. (2000) measured the ^{54}Fe/^{56}Fe ratio in eight X grains and found a slight excess in that ratio (less than a factor of 2 over solar); however, they were unable to detect ^{58}Fe with their sensitivity. The experimental setup of Davis et al. (2002) permits increased sensitivity to all Fe isotopes, so we concentrate on their three X grain measurements. In particular, we interpret the measurements by Davis et al. (2002) of iron isotopes in X grains to illustrate our proposed scenario for their abundances within the grains and their potential for understanding supernova physics.

2. LOCAL IRON ISOTOPIC COMPOSITIONS

Evolution of the iron isotopic composition within a massive star follows the various stellar-burning phases. The initial Fe will persist unchanged to the depth at which helium burning occurs. Helium and carbon burning expose matter to the *s*-process, which alters the initial Fe composition. In particular, the *s*-process neutron captures shift abundance from initial ^{56}Fe into ^{57}Fe and ^{58}Fe and also deplete ^{54}Fe. The presupernova Fe abundances are primarily established, then, by helium burning in the convective core, followed by helium burning in the convective He shell, followed by carbon burning in the core, and later by carbon burning in a shell surrounding the carbon-exhausted core.

To discuss the local iron isotopic compositions expected in a presupernova star quantitatively, we present the results of a 25 $M_\odot$ stellar model that began with initial solar composition. We evolved this model with the code described in The, El Eid, & Meyer (2000), now updated to include the NACRE and NON-SMOKER rate compilations (Angulo et al. 1999; Rauscher & Thielemann 2000). Figure 1 presents the overabundances of the iron isotopes from our model outside of

[1] Department of Physics and Astronomy, Clemson University, 118 Kinard Laboratory of Physics, Clemson, SC 29634-0978.

[2] Department of Physics, American University of Beirut, 315 Emile Bustani Hall, Beirut, Lebanon.

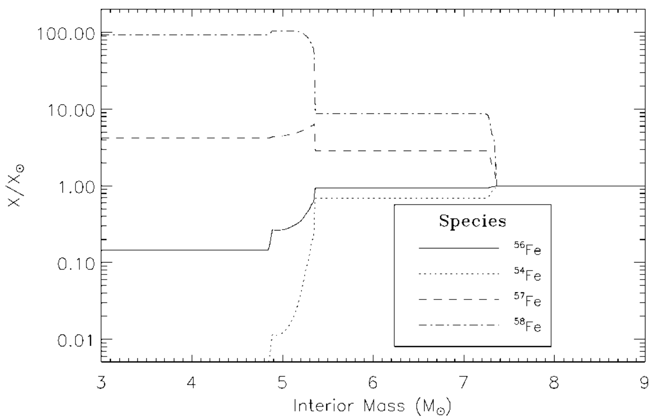

FIG. 1.—Mass fractions of presupernova iron outside of $M_r = 3\ M_\odot$ in the 25 $M_\odot$ model; ^{57}Fe and ^{58}Fe are strongly enriched, and ^{54}Fe and ^{56}Fe are depleted in the regions that experienced core helium and shell carbon burning. Shell helium burning ($M_r \approx 5.3$–$7.4\ M_\odot$) also gives the same trends, although less extreme.

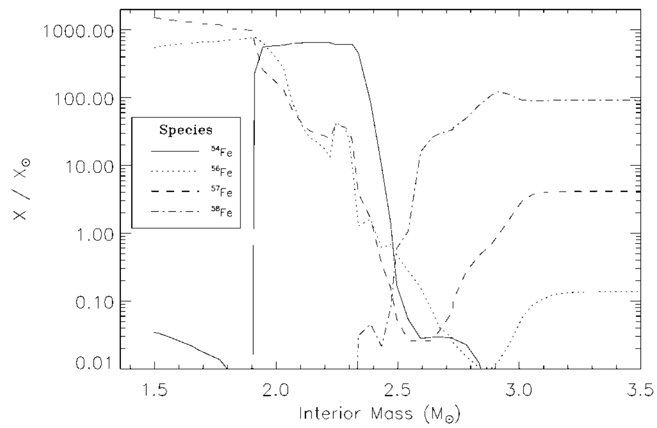

FIG. 2.—Mass fractions of "new iron" for the four stable Fe isotopes as a function of radial mass coordinate M_r (in units of solar mass) in a 25 $M_\odot$ model. The ^{54}Fe-rich silicon-burning ejecta lies in the range 1.9 $M_\odot < M_r <$ 2.5 $M_\odot$. The ^{56}Ni-rich α-rich freezeout is at $M_r < 1.9\ M_\odot$; ^{58}Fe dominance occurs at $M_r > 2.5\ M_\odot$. Any of these mass zones, or even random mixtures of them, would present huge Fe-isotope anomalies if SiC grains were to condense from that gas.

radial mass coordinate $M_r = 3\ M_\odot$. In this model, all material in the inner ~7.5 $M_\odot$ has experienced helium burning. Convective core helium and shell carbon burning (inside of $M_r \approx 5.4\ M_\odot$) overproduces ^{58}Fe by a factor of roughly 90 while depleting ^{54}Fe and ^{56}Fe, the latter to ~13% of its initial abundance. Shell helium burning from $M_r \approx 5.4$ to 7.5 $M_\odot$ continues this isotopic evolution. Because this shell burning does not finish by the time of the explosion, however, the iron overproduction factors are less extreme than in the core. In brief, in this model, the inner ~7.5 $M_\odot$ of the ejecta are characterized throughout by large ^{58}Fe excess at the time when oxygen and silicon burning begin the last central phases of the presupernova stability. These central zones will synthesize "new Fe."

Within Type II supernova events, the "new iron" originates in silicon burning and from the α-rich reassembly of matter broken down by the shock wave into α-particles and neutrons. To illustrate the composition of "new Fe," we modeled an explosion of our presupernova star by depositing 10^{51} ergs in a zone near $M_r = 1.5\ M_\odot$ and followed the subsequent evolution as the outer layers were ejected. The resulting iron composition in the inner 3.5 solar masses is shown in Figure 2. Owing to the gradient of the peak postshock temperature, the Fe isotopes have widely varying ratios within the inner 3 solar masses of ejecta.

We consider here SiC grains of type X that, owing to their ^{28}Si richness, will be taken to have preferentially condensed within the O-burning matter where Si first turns ^{28}Si-rich. In the 25 $M_\odot$ model, that Si is located inside of $M_r \approx 2.5\ M_\odot$. This environment is strongly enriched in oxygen relative to carbon. In many stellar environments in which the oxygen abundance exceeds that of carbon, the strongly bound CO molecule locks up all carbon and prevents condensation of carbonaceous dust. Recent work has shown, however, that the strongly radioactive supernova environment inhibits CO buildup and permits condensation of carbonaceous material even in strongly oxidizing environments such as the ^{28}Si-rich supernova zones (Clayton, Liu, & Dalgarno 1999; Clayton, Deneault, & Meyer 2001).

The peak in ^{54}Fe concentration between mass coordinates ($M_r = 1.9\ M_\odot$ and $M_r = 2.5\ M_\odot$) represents the silicon-burning ejecta. This region is the main source of supernova synthesis of ^{54}Fe, which is greatly in excess relative to ^{56}Fe on average. In the completed portions of silicon burning ($M_r \leq 1.9\ M_\odot$), the ^{56}Fe isotope dominates the mass. This transition is explained by Bodansky, Clayton, & Fowler (1968; see their Fig. 12) and by Woosley, Arnett, & Clayton (1973; see their Fig. 19). If SiC growth thermally condenses Fe from this range, large positive excess in ^{54}Fe/^{56}Fe can be expected accompanied by interesting variations of the ^{57}Fe/^{56}Fe ratio. From the present models, we expect negligible ^{58}Fe in the initial condensate; however, a new 25 $M_\odot$ model by S. E. Woosley & A. Heger (2002, private communication) shows the transition to ^{28}Si richness as far out as $M_r \approx 2.7\ M_\odot$. Such an extended range for ^{28}Si allows the iron initially condensed to be either ^{54}Fe- or ^{58}Fe-rich, although in general we expect ^{54}Fe excesses to be most prevalent.

It is worth emphasizing that ample carbon is present in these regions to condense the observed fraction of silicon in SiC X grains. Within models of 25 $M_\odot$ supernovae, Si turns ^{28}Si-rich inside $M_r \approx 2.5$–$2.7\ M_\odot$, where ^{12}C/^{13}C > 500. Although the mass fraction $X(^{28}\mathrm{Si})$ is quite high, X(C) is approximately 10^{-3}, decreasing to about 5×10^{-5} near $M_r \approx 2.5\ M_\odot$, where X(Si) reaches its peak and to 10^{-6} at $M_r = 2.3\ M_\odot$. All of this C probably condenses as SiC, for which sufficient time exists (Clayton et al. 2001). The size of the SiC grains, however, depends on the nucleation number density, and the resulting grains can be large in size if that number density is small (see § 3.2 of Clayton et al. 2001). Although the observed X grains are large, in bulk they constitute only 10^{-6} or less of all Si in meteorites. Therefore, it seems highly plausible that condensation of initial SiC in the ^{28}Si- and ^{54}Fe-rich regions consumed all the carbon and a small fraction of all the silicon and resulted in large grains.

Inside of $M_r = 1.9\ M_\odot$, the material has reassembled in an α-rich freezeout. It is here that the largest concentration of ^{44}Ti exists, which ultimately manifests itself as huge ^{44}Ca anomalies in many SUNOCONs and thereby provides proof of their supernova origin (e.g., Clayton et al. 1997a); ^{56}Fe and ^{57}Fe dominate the abundances in nearly solar proportions (as ^{56}Ni and ^{57}Ni before decay), and both ^{54}Fe and ^{58}Fe are of such low abundance (10^{-5} of ^{56}Fe) that they are essentially absent. Such large isotopic anomalies would signal clearly the matter from which the iron was taken into the type-X SiC grains. Because the α-rich freezeout matter has little Si, most of that abundant

TABLE 1
^{i}Fe/^{56}Fe Overabundance Ratio in Three SiC Grains

Grain ID	54/56[a]	57/56[a]	58/56[a]
153-8	1.20	1.23	1.33
113-3	0.77	1.46	1.85
113-2	0.87	1.19	1.40

[a] Errors are not given here but are at least 10% (Davis et al. 2002).

Fe cannot condense in SiC grains and instead will probably condense in many metal drops of Fe (and Ni). Figure 2 therefore suggests that the most likely a priori signature of Fe in X grains will be ^{54}Fe richness. Rather than indicating condensation within α-rich freezeout material, the ^{44}Ti present in the grains plausibly arose from incorporation of ^{44}Ti-rich titanium carbide (TiC) subgrains into the growing SiC X grains. Enough carbon exists in the α-rich freezeout zones to condense about 0.1% of the titanium into TiC, which is likely sufficient to account for the observed ^{44}Ca excesses, and TiC subgrains are known to exist within SiC grains (e.g., Bernatowicz, Amari, & Lewis 1992; Hoppe et al. 2000).

3. IRON IMPLANTED AFTER THE REVERSE SHOCK

Following thermal condensation, each SUNOCON initially comoves in gas having the characteristic velocity of the supernova shell, as set up by the postexplosive hydrodynamics. It had condensed from the gas within the first year or two of expansion. After a few years, the gas becomes cold, and the grain moves with the local gas at speeds between 1000 and 2000 km s^{-1}, depending on the ejecta mass and energy of the core-collapse event. As described above, for ^{28}Si-rich X grains in the 25 $M_\odot$ supernova, that matter lies within $M_r = 2.6\ M_\odot$ and is likely to be ^{54}Fe-rich. For the sake of discussion, we take its velocity in a spherically symmetric model to be of order 1500 km s^{-1} but note that velocity mixing following postexplosive instabilities may result in faster ^{28}Si-rich gas, as evidenced in general terms by the fast-moving knots in the Cas A remnant (Reed et al. 1995).

A reverse shock moves back into the ejected matter after the blast wave has swept up an external mass comparable to the mass of the ejecta. Figure 1 of Truelove & McKee (1999) shows that the reverse shocked ejecta is decelerated to about 60% of its preshock velocity, say, 1000 km s^{-1} for a preshock shell speed of 1500 km s^{-1}. At this time and later, the SUNOCONs move forward through the reverse shocked gas at speeds of about 500 km s^{-1}. This may occur as early as 300 yr if, as in the Cas A case (Reed et al. 1995; Gotthelf et al. 2001), the circumstellar matter has density higher than 1 cm^{-3}. At this time, the expansion has lowered the shell particle density to $n = 100$ cm^{-3}. Therefore, overlying atoms impact the thermally condensed SUNOCON at speeds of order 500 km s^{-1} and perhaps greater. These impacts implant the atoms within the SiC X grain to depths of 0.04–0.1 μm, just as when the solar wind strikes fine grains on the lunar surface (Kiko, Kirsten, & Ries 1978; Zinner et al. 1978).

The consequences of that reverse shock on Fe isotopes can be dramatic. A 1 μm SiC X grain will impact about 10% of its own mass while traversing the C, O overlying core, but in doing so, it sweeps up an amount of Fe comparable to that in the initial condensate. The mass fraction of ^{58}Fe within that C, O shell is enriched by a factor of ~90, whereas ^{56}Fe is reduced to 11% of its initial value there and ^{54}Fe is almost absent. The iron atoms implanted will therefore be very ^{58}Fe-rich and ^{54}Fe-deficient, greatly altering the ^{54}Fe-rich and ^{58}Fe-deficient mixture that is expected in the initial SUNOCON. We calculate that if the concentration of ^{56}Fe was initially 100 parts per million, the ^{58}Fe/^{56}Fe ratio in the grain would be increased to nearly 60 times the solar ratio by the implanted ions. The ^{57}Fe/^{56}Fe ratio would be enriched by a smaller factor near 2.5, and the ^{54}Fe/^{56}Fe ratio will be diminished by a small factor that is hard to calculate without detailed assumptions about the initial composition. Significantly, these ^{54}Fe and ^{58}Fe excesses are still much larger than their excesses as measured in X grains. But the collisions do not end with the traversal of the C, O shell. That process must continue until the grain has impacted several times its own mass. As a consequence, most of the Fe atoms may in the end be circumstellar atoms, perhaps having isotopic compositions similar to the initial abundances from which the presupernova formed. Because each SiC X grain would, in a spherical model, do this, ^{58}Fe richness will be expected to be more prominent than whatever ^{54}Fe richness may have condensed initially.

Measured Fe isotope ratios, normalized to solar ratios, in three X grains studied by Davis et al. (2002) are given in Table 1. Each grain studied has anomalous Fe isotopes. But their small values (20%–80% excesses and deficits) in comparison with local Fe anomalies suggest that the necessarily much larger initial anomalies have been diluted by implanting many more Fe atoms than were condensed initially within the grain. The likely explanation is that local Fe thermally condenses very inefficiently within SiC that is cooling very slowly through 2000 K; so the thermal component, although anomalously large in isotopic ratios, is small in actual numbers. The apparently common (from only three examples) ^{58}Fe richness suggests implantation from the *s*-process shells overlying the ^{28}Si-rich Si where the X grains presumably condensed.

4. OTHER CONSIDERATIONS AND OPEN QUESTIONS

Other isotopes may be amenable to interpretation via implantation. Meyer, Clayton, & The (2000) showed that a neutron burst in the supernova-burning shells accounts for the ^{95}Mo and ^{97}Mo richness of molybdenum in X grains. Four of seven X grains studied (Pellin et al. 2000) contain this ^{95}Mo and ^{97}Mo richness. This seems to be too frequent to represent local supernova matter because the neutron bursts are limited to thin mass shells at the base of burning shells producing neutron emission. But if SUNOCONs first condense interior to such shells and move through them later at high speed, the ^{95,97}Mo can be interpreted instead as implanted ions. This occurs frequently rather than rarely. Similar considerations may be relevant for other isotopes (^{29,30}Si, ^{26}Al, ^{18}O, ^{13}C, ^{14}N, etc.), which we now see may be implanted in X grains rather than condensed.

Other astrophysical problems and consequences will also need addressing in future work. For example, what is the physics of the reverse shock and the differential slowing of gas relative to the grains at these low number densities? How do the implanted grains avoid being removed by subsequent sputtering? How do the particles become relatively homogeneous rather than remaining ^{58}Fe-rich in only their surface layers?

Instabilities that result in the velocity mixing of the ejecta are unquestionably significant. If an early plume convects X grain matter through the CO overlying shell, it will not encounter the large gaseous ^{58}Fe excesses for implantation at a later time, and it will be moving much faster than the 1500 km s^{-1} that characterizes the ^{28}Si-rich zones in spherical models. We suggest that when large numbers of X grains have been studied for these isotope peculiarities among the rare trace isotopes, their distributions may reveal the distributions of velocity mixing in supernova ejecta.

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