11-20-2003

A Presolar Galactic Merger Spawned the Sic-Grain Mainstream

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

The Astrophysical Journal, 598:313–324, 2003 November 20

A PRESOLAR GALACTIC MERGER SPAWNED THE SiC-GRAIN MAINSTREAM

Donald D. Clayton
Department of Physics and Astronomy, Clemson University, Clemson, SC 29634-0978; cdonald@clemson.edu
Received 2003 June 24; accepted 2003 August 6

ABSTRACT

The merger of a metal-poor satellite galaxy with the Milky Way about 5–6 Gyr ago is postulated to resolve three great unexplained conflicts presented by mainstream presolar stardust SiC grains. The model allows all of the asymptotic giant branch (AGB) carbon stars that donated these grains to have been formed nearly simultaneously in a starburst generated by gaseous mixing, despite their great apparent age differences when evaluated in terms of Galactic chemical evolution (GCE). The model explains why a precisely measured linear correlation exists between the ratios $^{29}Si/^{28}Si$ and $^{30}Si/^{28}Si$ in the initial compositions of those AGB stars. It suggests why the slope of that normalized correlation line is $m = 4/3$ rather than unity, as predicted by GCE. It also suggests why the solar silicon isotopes lie near the bottom of that mainstream correlation line rather than near its top, as expected by current astrophysical ideas. By addressing many isotopic puzzles found within the solar composition, the model also yields a fresh view of the origin of the Sun and of its relationship to the Galaxy. The model is remarkable in reading dynamic events of the presolar history of the Milky Way from precise isotopic ratios measured in terrestrial laboratories within individual micron-sized presolar grains that have been extracted from meteorites that formed 4.56 Gyr ago but that fell only recently to Earth.

Subject headings: galaxies: formation — ISM: abundances — nuclear reactions, nucleosynthesis, abundances — stars: AGB and post-AGB — supernovae: general

1. INTRODUCTION

The presolar mainstream SiC grains present unsolved astronomical puzzles. These are reviewed by Zinner (1998) and Clayton & Nittler (2003), who also describe the ways in which presolar stardust grains provide new tools for astronomy. The site of origin of presolar mainstream SiC grains by thermal condensation in asymptotic giant branch (AGB) carbon stars is undoubtedly correct, supported as it is by the thermally mineralized structure of the SiC grains, the AGB carbon abundance becoming greater than that of oxygen in carbon stars, and their C isotopes and *s*-process trace elements (Hoppe & Ott 1997; Zinner 1998; Lugaro et al. 1999; Clayton & Nittler 2003). But the Si isotopes present three dominating puzzles, each of which creates a crisis in the picture that monotonic chemical evolution of the Galaxy has generated the SiC mainstream correlation line by generating that correlation in the initial compositions of the AGB donor stars (Clayton 1988; Hoppe & Ott 1997). The first puzzle is the extent of the linear correlation of Si isotope ratios in the grains, which requires very large differences in times of birth for the donor AGB stars. The second puzzle is that most of the donor AGB stars appear to have evolved in higher metallicity regions of the Galaxy than has the Sun (Clayton 1988; Timmes & Clayton 1996), and the third puzzle is that the correlation line for excess $^{29}Si/^{28}Si$ versus excess $^{30}Si/^{28}Si$ is measured to have slope $m = 4/3$ rather than unit slope. Each of these three puzzles is illustrated in Figure 1.

Figure 1 places these problems in what is known as a three-isotope plot of measured Si isotopes in individual mainstream grains (*symbols*) overlaid on the temporal evolution of a one-zone interstellar medium (ISM; *right ordinate*). Each grain point represents a different AGB star, because the displacements of Si isotopes owing to the *s*-process and dredge-up in those stars are not parallel to the correlation line and are also much smaller than the extent of the observed correlation line (Lugaro et al. 1999). Later versions of the grain data displaying the other SiC-grain families, as well as references to their sources, can be found in Figures 1–3 of Lugaro et al. (1999) and in Figure 4 of Clayton & Nittler (2003). In Figure 1 $^{29}\delta$ represents the deviation of the abundance ratio $^{29}Si/^{28}Si$ in a grain from the solar ratio, expressed as parts per thousand of the solar ratio (see eq. [1] of Timmes & Clayton 1996). Unit slope is required by the accurately secondary nature of the nucleosynthesis of ^{29}Si and ^{30}Si if both the Sun and AGB donor stars formed within the temporal evolution of a well-mixed single-zone ISM (Timmes & Clayton 1996). A standard temporal interpretation leads to insuperable age problems. One notes in Figure 1 that an "age difference" of about 5 Gyr would be required in the formation times of AGB stars just to span from bottom to top of the mainstream line. Such a large age difference among the grains hardly seems credible. Therefore, the temporal interpretation will be discarded.

In this work I present a new dynamics-based interpretation of these puzzles in the attempt to mitigate these crises. It postulates a presolar merger of a low-metallicity satellite galaxy with the Milky Way solar neighborhood. I also discuss associated abundance features of the grains, the ISM, and the Sun that are thrown into new light by this Galactic-merger picture for generating the initial compositions of the AGB-star donors of the grains.

A previous but still untested explanation of the mainstream that discards temporal evolution was advanced by Clayton (1997). That explanation supposes that low-mass stars destined to become AGB stars and moving initially on nearly circular orbits could scatter from massive molecular clouds, or alternatively, from spiral density waves (Sellwood & Binney 2002) or concentrations of dark matter, into

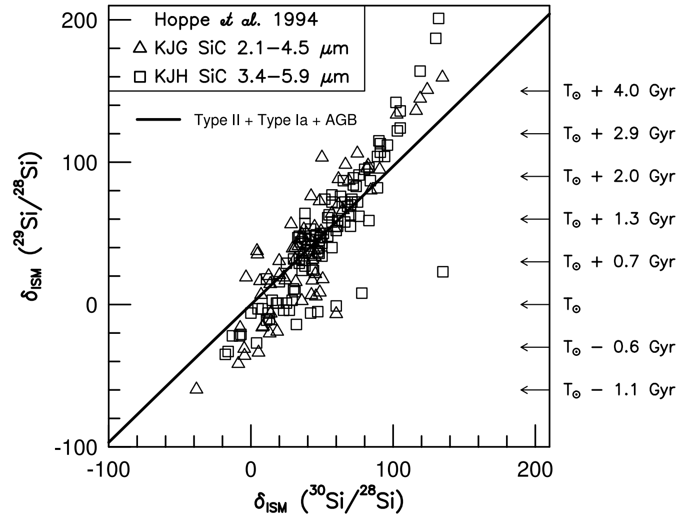

FIG. 1.—Normalized silicon isotopic ratios measured in SiC presolar stardust grains are plotted in the Si three-isotope plot (from Timmes & Clayton 1996). Ordinate $^{29}\delta$ represents the deviation of the abundance ratio ^{29}Si/^{28}Si in a grain from the solar ratio, expressed as parts per thousand of the solar ratio (see eq. [1] of Timmes & Clayton 1996). Analogously, abscissa $^{30}\delta$ represents the fractional deviation from solar of the measured ratio ^{30}Si/^{28}Si. Each point is a distinct grain (Hoppe et al. 1994) and is believed to differ only slightly from the initial isotopic composition of the presolar AGB star that donated that grain. Diagonal line of slope 1 represents GCE constructed with yields normalized (Timmes & Clayton 1996) to pass through solar Si isotopes as the secondary Si isotopes become progressively more abundant relative to primary ^{28}Si. Galactic times at right ordinate mark when interstellar Si isotopes reach that value. Unexplained puzzles are that most AGB stars seem to have formed after the Sun, that the particles define a mean line of slope 4/3 rather than unity, and the great apparent spread in birth times of the AGB stars.

orbits that become considerably more elongated and thus be found at the end of their lives (their AGB phases) at larger Galactocentric radii than their birthplaces. Calculations of this effect are still under way. A second approach gives a nontemporal interpretation to solar isotopes but keeps the temporal interpretation of initial AGB abundances (Clayton & Timmes 1997b). This approach maintains that only the Sun is peculiar. Clayton & Timmes showed the algebra for such a view and concluded that the Sun must lie far to the right of the initial AGB line but that Si in the AGB stars then suffers such large isotope shifts in their dredge-ups that their final, mainstream line falls, as if by a miracle, very near the Sun's composition. This doubly implausible explanation is unpalatable, although it can in principle be true. A third explanation of the mainstream that also discards the temporal evolution restriction was advanced by Lugaro et. al. (1999), who attempted to interpret the correlations of the initial compositions as being the inhomogeneous chemical evolution of the ISM. Their Monte Carlo model for Galactic gas enriched by random supernovae yields suggestive successes that make it a candidate solution. But it too probably needs more testing. These implausibilities preface this paper, which introduces another nontemporal interpretation for both solar and AGB star isotopes, namely, a Galactic merger.

2. THE MERGER HYPOTHESIS

It is now widely believed that Galactic mergers played a large role in the growth of the total mass of the Galaxy. Observations of galaxies provide ample evidence that galactic mergers leave stellar streams (e.g., Yanny et al. 2003) and stimulate star formation bursts in tidally shocked gas and in merging gas (e.g., Gillespie, Geller, & Kenyon 2003 and references therein). Bell et al. (2003) conclude from galactic photometry that the stellar mass in red galaxies may have increased by a factor of 2–3 between $z = 1$ and 0, but van Dokkum & Ellis (2003) find little evidence for mergers of gas-rich systems between $z = 1$ and 1.5, suggesting that assembly during that epoch was by merger of gas-poor satellites. I propose that the mainstream-grain Si-isotope correlation line is but a two-component mixing line between Galactic-disk gas and a satellite galaxy having significant interstellar gas that was cannibalized by the Galaxy about 5.5–6.5 Gyr ago. This should not in itself be viewed as improbable, being rather the current view of how much of the mass of the Galaxy was acquired (e.g., Shetrone et al. 2003, especially their § 1). The gaseous mixing occurred along initial hydrodynamic streams generated by the gaseous collision of these two earlier galaxies. My hypothesis is that the AGB donors of the solar mainstream grains arose predominantly from these mixtures.

As this merger occurred, vigorous star formation was induced by the hydrodynamic shock waves set up by the gaseous collisions. Turbulence along those collision fronts mixed the gases of the two systems to variable degrees, so that new stars formed from linear mixtures of the two endpoints. Many of these stars evolved to AGB stars about 1–2 Gyr later, at which time many donated their SiC particles to the ISM at the solar radius of the Galaxy prior to the Sun's birth. Because of the starburst nature of the merger, the numbers of AGB stars formed having the mass range necessary to deliver SiC grains shortly before solar birth greatly exceeds the number that would otherwise have contributed. The Sun formed from a similar mixture of the two gases, but one which by then had been enriched somewhat by stellar nucleosynthesis during the roughly 1–2 Gyr prior to the Sun's birth.

Figure 2 illustrates succinctly the isotopic consequences of this idea by utilizing algebraic properties of the three-isotope plot (formed in this case in each gaseous sample by ratios of both ^{29}Si and ^{30}Si concentrations to the ^{28}Si concentration). Those ^{29}Si/^{28}Si and ^{30}Si/^{28}Si abundance ratios are then normalized for the purposes of Figure 2 to their values in the Sun by division by the solar ratios, $(^{29}\mathrm{Si}/^{28}\mathrm{Si})_\odot = 0.0506$ and $(^{30}\mathrm{Si}/^{28}\mathrm{Si})_\odot = 0.0336$. For ease I use a bracket notation for the normalized isotopic ratios, so the coordinates of Figure 2 are

$$[^{29}\mathrm{Si}/^{28}\mathrm{Si}] = (^{29}\mathrm{Si}/^{28}\mathrm{Si})/(^{29}\mathrm{Si}/^{28}\mathrm{Si})_\odot$$

and

$$[^{30}\mathrm{Si}/^{28}\mathrm{Si}] = (^{30}\mathrm{Si}/^{28}\mathrm{Si})/(^{30}\mathrm{Si}/^{28}\mathrm{Si})_\odot .$$

Therefore, the Sun's normalized composition falls in Figure 2 at the point (1, 1) by definition. The ^{29}Si/^{28}Si and ^{30}Si/^{28}Si ratios are measured directly in the mainstream grains as counting-rate ratios obtained during secondary-ionization mass spectrometry. The useful theorem about the three-isotope plot is that any mixture of two distinct gaseous reservoirs will have an isotopic composition lying along the line connecting the two end-member compositions, falling at distances from the two end members in inverse proportion to the numbers of Si atoms contributed by each to the

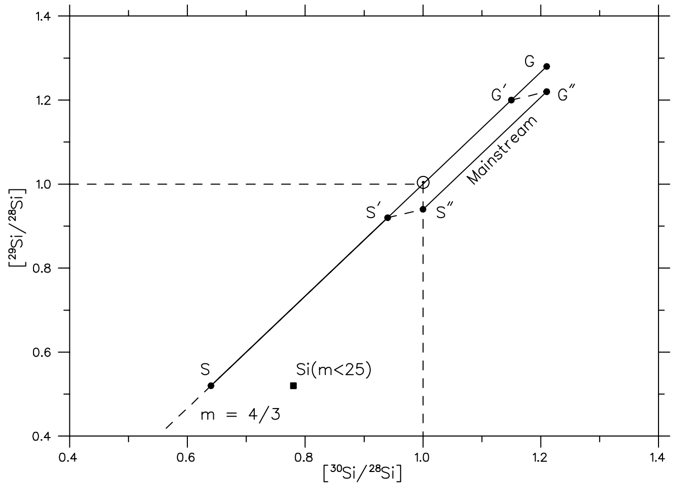

FIG. 2.—Merger and mixing between Galactic isotopic composition G and satellite galaxy composition S is illustrated in the Si three-isotope plot. Normalized isotopic-ratio coordinates are $[^i\mathrm{Si}/^{28}\mathrm{Si}] = (^i\mathrm{Si}/^{28}\mathrm{Si})/(^i\mathrm{Si}/^{28}\mathrm{Si})_\odot$. Mixtures of G and S lie along the line connecting them, with G′ and S′ representing the extreme mixtures of coeval AGB stars formed from the mixing gases. Neutron capture during the AGB phase shifts surface composition only about 0.4% rightward (shown as parallel line G″ to S″, which is the mainstream grains). The composition marked $m < 25$ represents supernova silicon in the satellite galaxy if supernovae yields (Woosley & Weaver 1995) are correct, if they had resulted in $[^{29}\mathrm{Si}/^{28}\mathrm{Si}] = 0.52$ and if supernovae more massive than 25 $M_\odot$ were excluded in the satellite (see text). The mainstream line could have been even steeper than $m = 4/3$ if it had been generated by mixings of the point $m < 25$ with Galactic composition G.

mixture. I take the upper end of the gaseous mixing line in the Si three-isotope plot to be G (for "Galaxy"), the Milky Way disk composition near the solar birth radius at the time of the merger. The lower end of the mixing line, S (for "satellite"), represents the Si composition of the gas in the satellite dwarf galaxy. The point S′ represents the most S-rich star formed after the S gas was diluted by the G gas of the Galaxy. The satellite companion may have been similar to, although not as distant as, the familiar Magellanic Clouds. The mixing-line end members, G and S, can lie anywhere beyond the extremities of the actual stars formed during the mixing. The most extreme AGB stars formed lie, according to my hypothesis, near the ends of the parallel mainstream line formed by the data points from the presolar mainstream SiC grains. The extreme gaseous mixtures that actually appeared in the stars formed, namely, G′ and S′, are translated to G″ and S″ by the *s*-process neutron irradiation of initial Si in the AGB stars, which later become the donors of the mainstream grains. This neutron irradiation translates each initial composition 3%–4% rightward and 1%–2% upward in this graph (e.g., Lugaro et al. 1999). This translation is small compared with the extent of the mainstream line (Figs. 1 and 2). As a consequence the mainstream-grain line parallels the initial stellar composition line but is slightly to the right of it (Fig. 2).

I suppose that the premerged Galaxy G lay near the upper end of the mainstream in the Si three-isotope plot, whereas the satellite S may have lain well below the mainstream's lower end S′. Because some AGB stars surely formed from undiluted (premerger) Galactic gas and would also have contributed their SiC particles to the solar cloud, it is tempting to think that G and G′ are identical. I make this assumption in what follows, in which case the presolar mainstream grains having the largest measured $^{29}\mathrm{Si}/^{28}\mathrm{Si}$ ratios were those donated by the pure G stars. The Sun is shown in Figure 2 as a large circle. As a first approximation the Sun is shown squarely on the S-G mixing line, lying at (1, 1) in terms of the normalized abundance ratio coordinates used in Figure 2. With the Sun placed on the mixing line the coordinates of G′ and S′ are, in (x, y) notation,

$$([^{30}\mathrm{Si}/^{28}\mathrm{Si}], [^{29}\mathrm{Si}/^{28}\mathrm{Si}]) = ((^{30}\mathrm{Si}/^{28}\mathrm{Si})/(^{30}\mathrm{Si}/^{28}\mathrm{Si})_\odot, (^{29}\mathrm{Si}/^{28}\mathrm{Si})/(^{29}\mathrm{Si}/^{28}\mathrm{Si})_\odot) = (1.15, 1.20) \quad \text{and} \quad (0.94, 0.92)\ ,$$

respectively. The reader will easily note that the slope through these points or through either of them and the solar point is 4/3, the observed mainstream correlation slope. The point S has been arbitrarily placed at (0.64, 0.52) in order that it lie on a slope $= 4/3$ line through G. The $^{29}\mathrm{Si}/^{28}\mathrm{Si}$ and $^{30}\mathrm{Si}/^{28}\mathrm{Si}$ ratios in satellite S are smaller than in G because S is of lower metallicity than G, and ratios of secondary to primary abundances increase with metallicity (see § 2.1). In § 2.2 I introduce a second reason for low $^{29}\mathrm{Si}/^{28}\mathrm{Si}$ and $^{30}\mathrm{Si}/^{28}\mathrm{Si}$ ratios in satellite S, namely, a lack of high-mass supernovae. Note that the satellite S must also be relatively ^{30}Si-rich (or ^{29}Si-poor) in comparison with the Galaxy, in the sense that its $[^{30}\mathrm{Si}/^{29}\mathrm{Si}]$ normalized ratio must exceed unity, in order that it might lie on the line of that slope. We return to an astrophysical reason for this in § 2.2.

All of this has been done by construction, but what the construction achieves immediately is the possibility of having most of the mainstream grains bearing larger $^{29}\mathrm{Si}/^{28}\mathrm{Si}$ and $^{30}\mathrm{Si}/^{28}\mathrm{Si}$ ratios than the Sun. The construction next takes two main branches that will be considered in turn: (1) the solar composition is itself a mix of only the two end members, or (2) the solar mix also was enriched in nucleosynthesis by the starburst stars that evolved during the time between the starburst and solar birth.

2.1. *A Sun Formed from Only a Binary Mixture*

For the first alternative, take the Sun to be a mix of only the two end members, G (taking G = G′) and S. Even if the G and S compositions were the results of the same Galactic chemical evolution (GCE) prescription, which carries a specific relationship between the metallicity achieved and its isotopic ratios involving secondary nucleosynthesis products such as $^{29}\mathrm{Si}/^{28}\mathrm{Si}$ and $^{30}\mathrm{Si}/^{28}\mathrm{Si}$ (Clayton 1988; Clayton & Timmes 1997a), the solar isotopes would not need to conform to that relationship. The solar isotopes are a mixture of two evolutions, which does not in itself constitute an evolution. Instead, the isotopes of the solar mix will lie on the straight line S-G, as in Figure 2. Data from mainstream grains set the upper and lower isotopic ratios. Because $^{29}\mathrm{Si}/^{28}\mathrm{Si}$ in mainstream grains exceeds solar by about 20%, the normalized ordinate for G must be $[^{29}\mathrm{Si}/^{28}\mathrm{Si}] = 1.20$. For this reason it is plotted at that value in Figure 2 (and similarly for $[^{30}\mathrm{Si}/^{28}\mathrm{Si}]$). Likewise, the lower mainstream end suggests that the most S-rich star formed, namely, at S′, plots at ordinate $[^{29}\mathrm{Si}/^{28}\mathrm{Si}] = 0.92$.

The interpretation of these end members in terms of the metallicities of their galaxies depends on the detailed rate of change of secondary isotopes with metallicity. If the ratio of the concentration of a secondary product to a primary product (e.g., $^{29}Si/^{28}Si$) were linear in metallicity, as it nearly is in idealized analytic models (Clayton & Pantelaki 1986; Clayton 1988, Table 1) of GCE, the metallicities of G and S′ would then simply be 1.20 and 0.92 $Z_\odot$, respectively. For that linear case the metallicity of the solar-isotope mix of G and S would also be solar. Numerical models of chemical evolution are not quite linear, however. Examination of Figure 4 of Timmes & Clayton (1996) demonstrates that at half-solar metallicity, for example, $^{29}Si/^{28}Si$ had evolved to 70% of its solar value. The value $[^{29}Si/^{28}Si] = 0.52$ would with the Timmes model suggest that the satellite S metallicity was near 0.22 $Z_\odot$. A rough rule of thumb ("the square-root rule") for this GCE model is that the deviation of the $^{29}Si/^{28}Si$ ratio from solar is the square root of the deviation of the metallicity from solar, based on Figure 4 of Timmes & Clayton (1996). Either value, $Z/Z_\odot = 0.52$ or 0.22, could be an appropriate metallicity for a satellite galaxy that merged about 6 Gyr ago with our Galaxy and that is plotted at $[^{29}Si/^{28}Si] = 0.52$ in Figure 2. This discussion makes it clear that the metallicity to be associated with all the points in Figure 2 depends on how $^{29}Si/^{28}Si$ ratios evolve with metallicity, for it is isotope ratios, not metallicities, that are explicitly shown in Figure 2. But it is also clear that metallicities can be associated with every point with the aid of a GCE model that maps them onto isotope ratios. I stress that the location of S in Figure 2 was placed arbitrarily, except that it lies on a slope = 4/3 line with G (and also with the Sun in cases where the Sun is also placed on the mixing line), and of course S must lie below S′ on that 4/3 line.

To conclude this section, it is of interest to calculate a few more sample numbers. Taking the isotopic compositions of G and S as plotted in Figure 2, the location of the "center of gravity" (see Fig. 4, Clayton & Timmes 1997a) in the three-isotope plot gives the relative numbers of Si atoms from G and S respectively in each mixture of the two. With G = G′ at (1.15, 1.20) locating the Galactic-disk upper end and (0.64, 0.52) locating the satellite galaxy S at the lower end, the relative numbers of Si atoms from each pool, Si_G/Si_S, can be calculated. This simple arithmetic yields the relative numbers of Si atoms from the two end members as $Si_G/Si_S = 2.40$ for the Sun and $Si_G/Si_S = 1.43$ for the lower end AGB star S′. In other words, 29% of the solar Si atoms came from the satellite S, whereas 41% of the S′ Si atoms are from S. The initial compositions of the AGB stars made in the starburst would therefore range from a 41% S mixture at the lower end to 100% G (no S mixture) at the upper end. The reader will appreciate that these are only illustrative numbers, but interesting nonetheless. Especially amusing is the thought that 29% of solar Si atoms did not originate in our own Galaxy! If we take a GCE model having a linear dependence of $^{29}Si/^{28}Si$ on Z, so that the respective metallicities of the end members are $Z_G = 1.20$ and $Z_S = 0.52$, the relative masses for the Sun in this case would be given by $Si_G/Si_S = (Z_G/Z_S)M_G/M_S = 2.40$, or $M_G/M_S = 1.04$, meaning that 49% of the solar mass would have been inherited from S. Using instead a square-root rule relating $^{29}Si/^{28}Si$ to metallicity, which gives $Z_S = 0.22$ (see above) and $Z_G = 1.44$, one would find for the same isotopic diagram in Figure 2 that $M_G/M_S = 0.37$, meaning that 73% of the solar mass came from S. Other GCE models will yield their own values for the relative masses.

It is this huge fraction of the solar mass that was donated by the satellite S that opens the door to reinterpretation of puzzling solar isotope ratios. We return to this later.

2.2. *Why Is Mainstream* Si *Slope* $m = 4/3$? (*The Basic Model*)

To explain the Si-isotope correlation slope $m = 4/3$ in this merger picture, the Galaxy G locally must have contained before the merger isotopes characterized by a 33% greater $^{29}Si/^{30}Si$ ratio than the accreted gas S, because in that case the straight line connecting them in the three-isotope plot would have a slope of 4/3. This happens plausibly if low-metallicity Type II supernovae in the satellite had produced a smaller $^{29}Si/^{30}Si$ ratio than had the higher metallicity (and higher mass) Type II supernovae that form preferentially in the giant molecular clouds of the Galaxy disk. A better figure than Figure 1 of the data quality of the mainstream correlation can be seen in Figure 3 of Lugaro et al. (1999).

Why should the ISM of satellite S reasonably be expected to have a smaller $^{29}Si/^{30}Si$ ratio than the Galactic disk into which it merged? The difference can be interpreted as one of differing mass functions for the stars that have synthesized the elements contained in the respective galaxies. The supernovae from the lower-density ISM of satellite S probably have been of smaller average mass than Type II supernovae typically born in the evolutionary history of Galactic-disk gas G. This plausible suggestion (e.g., Tolstoy et al. 2003, § 4.1.3) raises a consequence for mainstream SiC. A plot of Si isotope ratios from supernova models in Figure 3, which is adapted from Figure 2 of Timmes & Clayton (1996), shows strikingly that the Woosley & Weaver (1995) supernova models having masses of less than 25 $M_\odot$ produce isotopically light Si (viz., $^{29}Si/^{28}Si$ and $^{30}Si/^{28}Si$ ratios roughly half of solar), whereas heavier supernovae result in very much heavier Si isotopically. An example of the ^{29}Si-rich mass zone is shown in Figure 10 of Deneault, Clayton, &

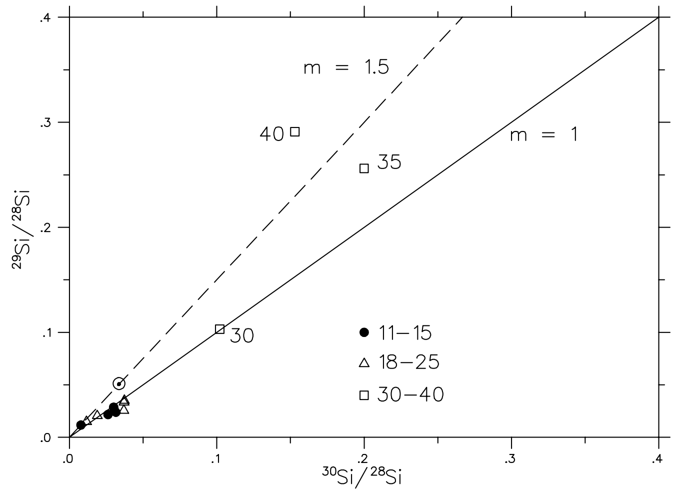

FIG. 3.—Each point marks the Si-isotope production ratio from one of the Woosley & Weaver (1995) series S supernova models of solar metallicity (after Fig. 2 of Timmes & Clayton 1996). Models having mass less than 25 $M_\odot$ produce isotopically light Si (viz., $^{29}Si/^{28}Si$ and $^{30}Si/^{28}Si$ ratios roughly half of solar), whereas heavier supernovae result in very much heavier Si isotopically. Models of lower initial metallicity eject proportionately smaller Si isotope ratios. The line $m = 1$ traces $^{29}Si/^{30}Si$ production ratios of unity, whereas solar $^{29}Si/^{30}Si = 1.5$ (*dashed line through the solar symbol*). The mass of Si ejected also generally increases with supernova mass. The key point for the distinction between the Galaxy and the merged satellite is that masses greater than 25 $M_\odot$ produce isotope ratios much greater than those of lesser mass. Therefore, $[^{29}Si/^{30}Si]_G > [^{29}Si/^{30}Si]_S$.

Heger (2003) for a recent 25 $M_\odot$ model, and the width of that mass zone increases dramatically above 25 $M_\odot$, apparently accounting for this difference between models of less than 25 $M_\odot$ from those of greater mass. The isotopic difference between moderate-mass and high-mass supernovae is large in comparison with the total spread between the top and the bottom of the mainstream correlation line (Fig. 1). It is therefore plausible that the satellite's supernova history had generated Si that was isotopically lighter (in S) than the full initial mass function (IMF) of massive stars that generated the Galactic Si isotopic composition (in G). The working assumption is that the Galaxy makes more massive supernovae from its massive molecular clouds than the satellite did from its smaller clouds. As described two paragraphs below, however, recent supernova calculations (Limongi & Cieffi 2003) do not yield the same large difference for the high-mass members.

That is but half the story of Figure 3. The $^{29}Si/^{30}Si$ (unnormalized) ratio in supernovae less than 25 $M_\odot$ is seen to be near unity, about two-thirds of the solar value, so that the solar composition plots well above the correlation trend from moderate-mass supernovae. By contrast, the 35 and 40 $M_\odot$ models by Woosley & Weaver (1995) produce $^{29}Si/^{30}Si$ ratios that are considerably larger, so that they too fall above the correlation line. The 35 and 40 $M_\odot$ models each eject 2–10 times more silicon mass as well (than do those of less than 20 $M_\odot$). Those more massive supernovae in the disk seem to be primarily responsible for the solar $^{29}Si/^{30}Si = 1.5$ ratio being as large as it is, but in the satellite S, enriched by assumption primarily by the less massive supernovae, the $^{29}Si/^{30}Si$ ratio may plausibly be as low as unity. If $^{29}Si/^{30}Si = 1$ in S, the plotted position of satellite S having enough ^{28}Si to lie at $[^{29}Si/^{28}Si] = 0.52$ (as in Fig. 2) would have been accompanied by $[^{30}Si/^{28}Si] = 0.78$. This point is plotted for reference in Figure 2 as a black square labeled "Si($m < 25$)." A mixing line through the Sun from that point would produce an AGB initial line even steeper ($m = 2.2$) than the experimental correlation line ($m = 4/3$), so the assumed moderate-mass composition for S would be too severe. Allowing the satellite's IMF to include some massive supernovae (but less than in the Galaxy), I have plotted S at (0.52, 0.64) instead of (0.52, 0.78), so that it falls as observed on the observed slope $m = 4/3$ line through the Sun, although there exist many other compositions for S that also lie on the 4/3 line. In this way a plausible difference of IMF between G and S can generate the slope $m = 4/3$.

This argument is superficially complicated by the fact that Timmes & Clayton (1996) also demonstrated that computed Galactic evolution does not reproduce the correct solar $^{29}Si/^{30}Si = 1.5$ ratio. Figure 3 shows that this problem is evident from the supernova yields by Woosley & Weaver (1995). Therefore, Timmes & Clayton (1996) introduced a renormalization that compares computed chemical evolution not to measured solar abundances but instead to the ISM ratios that result from the calculations themselves (see their eq. [2]). This reasoning showed that the normalized Si-isotope slope must be unity in any well-mixed model that generates an ISM evolution that also passes through the Sun's composition. Timmes & Clayton (1996) advocated thinking of this shortfall as an underestimate by a factor 1.5 of the calculated $^{29}Si/^{30}Si$ bulk yield ratio from supernovae, without suggesting whether this shortcoming applies uniformly to all supernova masses or specifically to those more massive ones that produce the highest $^{29}Si/^{30}Si$ ratios and the largest Si mass. However, this numerical failure of current chemical evolution models does not invalidate the IMF contrast advocated here as the explanation for the slope 4/3 for mainstream grains in the present merger model. The slope argument remains valid as long as the true supernova yields continue to produce higher $^{29}Si/^{30}Si$ ratios in their most massive supernovae. However, new calculations with a different stellar evolution code by Limongi & Cieffi (2003) do not confirm such large $^{29}Si/^{28}Si$ and $^{30}Si/^{28}Si$ ratios in most of their most massive models. Of their 30 and 35 $M_\odot$ models, only models 30A and 35B yield heavy-isotope ratios significantly greater than solar and also eject more ^{29}Si than ^{30}Si. These two models are those leaving the most massive neutron star remnants. That this is the key (in spherical symmetry) to heavy Si is evident from Figure 10 of Deneault et al. (2003), where one sees that if fallback of the central ^{28}Si-rich portions augments the neutron star mass, the overlying ejecta will contain quite heavy silicon. The Si isotopic yields of massive core-collapse supernovae therefore remain a significant uncertainty not only for the discord between solar abundances and GCE but also for the interpretation of component S of the merged satellite that is being proposed here.

These ideas suggest a specific model for S that is compellingly simple. Suppose that Figure 3 is taken at face value for moderate supernova masses, so that they do indeed eject $^{29}Si = ^{30}Si$, as calculation shows. In that case the true massive supernovae must be even more ^{29}Si-rich than those in Figure 3 in order to evolve to the solar Si isotope ratio. Suppose also that the combination of two factors governing Si isotope ratios in chemical evolution, lower supernova masses and lower metallicity in S, has resulted in an average $[^{30}Si/^{28}Si]$ ratio of about 1/2. In that case, because their unnormalized ^{29}Si and ^{30}Si yields are equal (Fig. 3), the average normalized $[^{29}Si/^{28}Si]$ in S must be 1/3 after the required factor 1.5 reduction of 1/2 owing to the larger solar abundance of ^{29}Si. One therefore can reasonably locate this example for S in the three-isotope plot at the point $[^{30}Si/^{28}Si] = 1/2$, $[^{29}Si/^{28}Si] = 1/3$. Although that composition lies slightly off the bottom of Figure 2, one easily sees that the slope from it through the Sun is $m = (1 - 1/3)/(1 - 1/2) = 4/3$. Viewed this way, the observed mainstream slope $m = 4/3$ can be a natural consequence of the merger model in which the satellite S evolves with a deficit of high-mass supernovae ($M > 25\ M_\odot$) but the Galaxy G evolves with abundant high-mass supernovae so that its $[^{29}Si/^{28}Si]/[^{30}Si/^{28}Si]$ ratio slightly exceeds unity (by the ratio $1.20/1.15 = 1.04$, which comprises the coordinates of G in Fig. 2). I refer to this as "the basic model" when making estimates of numerical quantities. In this simplest form the Sun is a mixture of S and G; however, in the next section the basic model is enlarged to also include subsequent nucleosynthesis additions to the solar mix. From the isotopic ratios at points G, the Sun, S′, and S one again finds that the relative numbers of Si atoms contributed are $Si_G/Si_S = 3.33$ for the Sun and 2.11 for S′, meaning that 23% of solar Si atoms are from S and 32% of S′ Si atoms are from S. For estimating their relative masses the metallicity values are needed in the relation $Si_G/Si_S = (Z_G/Z_S)M_G/M_S$. Using as a simple approximation the square-root rule relating $^{30}Si/^{28}Si$ to metallicity, which gives $Z_S = 0.25$ and $Z_G = 1.44$ in the basic model, one would find for the same isotopic diagram in Figure 2 that for the Sun $M_G/M_S = 0.58$, meaning that 63% of the solar mass came from S and

37% of the solar mass came from G. For the lower end AGB star on the mainstream (S′), 73% of the mass came from S. It will be noted that if the square-root rule is used, these mixing fractions do not differ greatly from those obtained earlier for the model shown in Figure 2, where $S = (0.64, 0.52)$ instead of (0.50, 0.33), so once again I caution that it is the large fraction of the solar mass that was donated by the satellite S that opens the door to reinterpretation of many puzzling solar isotope ratios.

It must be counted a plus for this merger idea that it so plausibly produces the observed slope 4/3 in what is believed to be the initial compositions of the AGB stars that donated the SiC grains. It also produces the large extent of the mainstream without need of lengthy age differences for the AGB donor stars. The precision of isotopic ratios measured in the mainstream grains is about 1%, far better than other astronomical techniques can achieve. Because of this precision the conceptual conflicts presented by the mainstream line must be significant for Galactic astronomy, whatever their resolution. One may object that all two-component mixtures (S and G) yield compositions that lie exactly on the mixing line, whereas the points in Figure 1 reveal dispersion about an $m = 4/3$ line (that line is not shown in Fig. 1), but dispersion in realistic models of G and S already exists between differing portions of their Galactic gases. G and S are not unique compositions, but a spectrum of compositions that reflects the histories of their individual interstellar mixings. Inhomogeneity forms the basis of the Lugaro et al. (1999) treatment, although their goal was to generate the mainstream from inhomogeneity in G alone. From known metallicity dispersion in the Galaxy it may be concluded that the observed dispersion about the $m = 4/3$ mixing line is also plausible in the merger model.

Dispersion in metallicity will also occur as the two gases of differing mean metallicity merge. The metallicities of distinct mixtures will range from Z_G to Z_S. In the numerical examples above these range (using the square-root rule) from 0.25 to 1.44 $Z_\odot$ (and from 0.50 to 1.20 $Z_\odot$ in the linear model). In a well-mixed GCE, a star's metallicity depends only on its time of birth (and on its radial position if one takes radially differing rates of GCE to explain radial metallicity gradients). The postulated merger with a low-metallicity companion galaxy results in stimulated star birth (near the solar Galactocentric position) in which the metallicities of individual stars lie between those of G and S. Such an event increases the dispersion of metallicity in stars of that age. If the Galaxy were to become again well mixed and homogeneous after a certain time period following the merger, the metallicity dispersion would again be small. A corollary of the picture advanced here might be, therefore, that a graph of stellar metallicity versus stellar age might show larger dispersion (say a factor of 2–6) for stars born while the merger gas was being homogenized (say about 6 Gyr ago) but less metallicity dispersion among stars younger than the Sun. Although the data of Edvardsson et al. (1993) do suggest such a change in dispersion, other mechanisms for metallicity dispersion may be responsible. The SiC-grain data seem not to reveal AGB stars over the full range between G and S, however, but only between G and S′, a considerably smaller range (depending on the model parameters). It is conceivable that the initial starburst utilized only partial mixtures of S whereas stars forming later might be from more purely S gas, but that seems too speculative at present knowledge. My goal here is but to insert this new connection with mainstream SiC grains into the existing framework of ideas on metallicity dispersion.

2.3. *A Sun Subsequently Enriched by Starburst Nucleosynthesis* (*Basic Model 2*)

During the time between the postulated merger and the isolation of the solar cloud, perhaps 1–2 Gyr, nucleosynthesis from the starburst will no doubt have enriched that gaseous mixture of S and G that is to become the Sun, so that the final Sun need not lie on the Si mixing line as in Figure 2 even in the basic model. From the supernovae the Sun will also have acquired metallicity greater than the gaseous mixture from which it was born. Most of this nucleosynthesis was probably associated with the supernovae born during the starburst merger and new star formation stimulated by those supernovae; at least I will assume so. For silicon this means Type II supernovae, since Timmes & Clayton (1996) showed that they dominate silicon chemical evolution. Thus, the Sun will move up the $m = 4/3$ mixing line only if the yield ratio from mixtures from the intervening supernovae, $y(^{29}\mathrm{Si})/y(^{30}\mathrm{Si})$, is $4/3(^{29}\mathrm{Si}/^{30}\mathrm{Si})_\odot$. Otherwise, the Sun's composition will move somewhat off the mixing line, as well as up (or down) it (depending on the amount of ^{28}Si added). Although a full Galactic IMF of supernovae would tend to move the Sun up the line (enrichment of secondary Si isotopes), it is both interesting and perhaps relevant that the Sun moves down the line if the supernovae induced by the merger are also characterized by $M < 25\ M_\odot$ (as shown in the previous § 2.2). Supernovae having $M < 25\ M_\odot$ move composition *downward* in the three-isotope plot (Figs. 1 and 2) *even while increasing the metallicity* (^{28}Si, ^{16}O, ^{12}C, etc.)! This is a consequence of moderate-mass supernovae producing equal masses of ^{29}Si and ^{30}Si and therefore falling in Figure 2 at a point near $S = (1/2,\ 1/3)$ in the basic model. This surprising realization may be relevant to the Sun's actual Si-isotope position near the bottom of the mainstream. Furthermore, if that were the case, the correlation used in §§ 2.1 and 2.2 (between deviation of gaseous $^{29}\mathrm{Si}/^{28}\mathrm{Si}$ from solar and deviation of its Z-value from solar) would not be valid. This liberalizes the numerical interpretation of Figure 2. It cannot be determined in advance where on the mixing line the solar gas initially lay.

By "basic model 2" I mean the basic model modified by intervening supernovae driving the Si isotopes down the slope $= 4/3$ line from their initial position while bringing its initial metallicity up to solar. For definiteness in a numerical example I assume $Z_G = Z_\odot$ from Galactic evolution, leading to the Galactic Si composition at $G = (1.15,\ 1.20)$ in the Si plot. Using the square-root rule $[^{30}\mathrm{Si}/^{28}\mathrm{Si}]/[^{30}\mathrm{Si}/^{28}\mathrm{Si}]_G = (Z/Z_\odot)^{1/2}$ also for definiteness, the point S at (0.50, 0.33) would then have metallicity $Z_S/Z_\odot = (0.5/1.15)^2 = 0.189$. I will assume these metallicities for G and S for the subsequent discussion of the model. The metallicities of S′ and of the Sun are determined instead by their respective mix fractions of G and S.

As an illustrative trial for the Sun, let the solar mix initially lie halfway between S′ [at (0.94, 0.92)] and G in Figure 2, namely, an initial Sun at (1.045, 1.06). Requiring the initial Sun to lie at the "center of mass for Si atoms," the relative numbers of Si atoms in the initial Sun would then be

$Si_G/Si_S = 5.19$ (amounting to 16% from the satellite S). Taking the relative metallicities of G and S into account, the mass ratio in the initial Sun would have been $M_G/M_S = 0.98$. In other words, equal masses from each reservoir is equivalent to 5.2 times more Si atoms coming from reservoir G because the metallicity of G is 5.2 times greater than that of S. It will be clear that other assumptions about the initial solar mix and about the rule relating isotopic ratio to metallicity ratio will yield somewhat differing mass ratios. My focus here is on neither the exact numbers nor the metallicity rule but rather on the method.

Taking for this example the mass ratio $M_G/M_S = 0.98$ as established, one next considers the initial metallicity of the solar mix. It is a weighted mean of those of its end members, namely, $Z_{\odot,i} = (M_G Z_G + M_S Z_S)/(M_G + M_S)$, which has the value $Z_{\odot,i} = 0.590\ Z_\odot$ for the choice of the basic model 2 parameters defined above. Since the observed Sun has solar metallicity by definition, the initial Sun must have subsequently accrued nucleosynthesis amounting to 41% of its primary nuclei in order that $Z_\odot = 1$. What this argument yields is the quantity of intervening supernova nucleosynthesis required by this model between the times of merger and solar formation. A metallicity increase of 41% during the occurrence of starburst supernovae over 1–2 Gyr is clearly not implausible. What is achieved by this model is a mainstream explanation as before, but one in which *both the upper end (G) and the Sun have solar metallicity*. On top of that, it suggests why the Sun lies near the bottom of the mainstream. If the supernovae induced by the merger are also of $M < 25\ M_\odot$, the solar Si isotopes are driven down the $m = 4/3$ line while solar metallicity is increasing!

Before estimating what this supernova addition to the Sun yields for the final solar Si isotopes, it is helpful to recall that 41% of the Si atoms represents by no means 41% of the solar mass. Since the supernova overproduction factor of ^{28}Si is in the range of 10–20, 41% of the Si atoms amounts to only 4%–2% of the solar mass added by the supernovae. It is also helpful to recall that although intermediate-mass AGB stars formed in the starburst will also mix into the solar gases, they do not much disturb the Si isotope budget. The scientific question is what the Si isotopic composition from those supernovae was. If the induced supernovae were also of $M < 25\ M_\odot$, the added Si might lie at (1/2, 1/3), just as S did. Simple arithmetic would then give a final solar Si composition $[^{30}Si/^{28}Si] = 0.83$, $[^{29}Si/^{28}Si] = 0.77$. This solar composition would lie completely below the bottom of the mainstream SiC grains at S′, rather than above it as observed, so the numerical example is not quite satisfactory. If one instead thinks that the merger-induced supernovae should represent the full mass spectrum of the Galaxy, then one might expect the added Si isotopes to be solar. Since this initial Sun at (1.045, 1.06) was already close to solar isotopically, addition of 41% of Si atoms at (1, 1) would clearly produce very nearly solar isotopes in the solar metallicity Sun. It is clearly close enough that minor adjustments of parameters of the model make this version a physical possibility. I see no way to assess a priori the probability of the actual solar history; it simply is what it is.

The above example was not very general, however; even with the assumption of the basic model 2, placing the Sun initially midway between G and S′ was totally arbitrary, equivalent to postulating that 16% of the Si atoms came from S and 84% came from G. A more general representation of basic model 2 would let the initial mix fraction for the solar gas be a parameter. Let the initial solar mix of S and G lie at a fraction f (rather than 0.16) of the total displacement from G to S. The mix parameter f then becomes a parameter to be varied. If the points G, S, and S′ have the same values as in basic model 2 above, and if the same square-root rule for metallicity is used, so that only the solar initial mix f differs, one easily sees the following results:

1. From the mixing theorem for three-isotope plots, the relative numbers of Si atoms from G and S are $Si_G/Si_S = (1-f)/f$, meaning that f represents the fraction of Si atoms in the initial solar mix that came from reservoir S.
2. The relative masses in the initial mix are given by $Si_G/Si_S = (Z_G/Z_S)M_G/M_S$, implying numerically that $M_G/M_S = (Z_S/Z_G)(1-f)/f = 0.189(1-f)/f$.
3. The initial isotopic compositions of the solar mix are $[^{29}Si/^{28}Si] = 1.20 - 0.867f$ and $[^{30}Si/^{28}Si] = 1.15 - 0.65f$.
4. The initial metallicity of the solar mix is

$$[Z_{\odot,i}] = (M_G[Z_G] + M_S[Z_S])/(M_G + M_S) = 0.189/(0.811f + 0.189)\ ,$$

where $[Z]$ represents metallicity normalized to solar metallicity.

5. If the final Sun is required to have solar metallicity, the fraction of final solar Si atoms that must be delivered by the supernovae is $(1 - [Z_{\odot,i}]) = 0.811f/(0.811f + 0.189)$.
6. After supernovae bring $[Z_\odot]$ to unity, the final solar compositions are

$$[^{29}Si/^{28}Si] = [Z_{\odot,i}](1.20 - 0.867f) + (1 - [Z_{\odot,i}])[(^{29}Si/^{28}Si)_{SN}]$$

and

$$[^{30}Si/^{28}Si] = [Z_{\odot,i}](1.20 - 0.867f) + (1 - [Z_{\odot,i}])[(^{30}Si/^{28}Si)_{SN}]\ ,$$

which become

$$[^{29}Si/^{28}Si] = (0.227 + 0.106f)/(0.811f + 0.189)$$

and

$$[^{30}Si/^{28}Si] = (0.217 + 0.283f)/(0.811f + 0.189)\ .$$

7. Requiring that $[^{29}Si/^{28}Si] = 1$ and $[^{30}Si/^{28}Si] = 1$ for the Sun requires an initial mix fraction for the Sun of $f = 0.0539$. Such solar initial Si would then be 95% Galactic. This mixing arithmetic shows that even if $Z_G = 1$, the Sun can also have solar metallicity and solar isotopes and lie near the bottom of the mainstream mixing line that was generated by linear combinations of the Galactic disk G and a merged satellite S; 5.39% of the initial solar Si has come from S, and the intervening supernovae have a Si composition that also falls at the point S because of having masses less than 25 $M_\odot$ and producing equal masses of ^{29}Si and ^{30}Si. The Sun remains on the mixing line, but near its lower end, as observed.
8. Returning to result 6 to assume instead that the low-mass supernovae produce ^{29}Si and ^{30}Si at their solar ratio to each other of [1/2, 1/2] in Figure 2, one finds that

$$[^{29}Si/^{28}Si] = (0.227 + 0.241f)/(0.811f + 0.189)$$

and

$$[^{30}\mathrm{Si}/^{28}\mathrm{Si}] = (0.217 + 0.283f)/(0.811f + 0.189) .$$

By choosing $f = 0.0667$ to obtain $[^{29}\mathrm{Si}/^{28}\mathrm{Si}] = 1$, one also finds that $[^{30}\mathrm{Si}/^{28}\mathrm{Si}] = 0.967$, just 33 parts per million left of the initial mixing line for the AGB stars. This last position is about right for the Sun's measured position just left of the mainstream line in Figure 1.

These two simple models derived from the postulated Galactic merger have been seen in these examples to be capable of explaining the great puzzles of the mainstream SiC stardust grains. These puzzles were all evident from Figure 1, namely, a correlation among the initial compositions of AGB stars that does not require long Galactic evolution times, a slope of 4/3 for that correlation, and initial AGB compositions that mostly lie above (isotopically heavier than) the Sun's in the three-isotope plot.

3. OTHER ISOTOPES

The merger model gives a new picture of the history of the solar neighborhood prior to the formation of the Sun. Although the model seems at first an extreme assumption, it has the merit of solving naturally the three great puzzles of the SiC mainstream grains, as mentioned in the preceding paragraph. In this section I therefore consider several other isotopic consequences for interpretation of solar composition. Although many possible differences between solar composition and that of routine Galactic stars born at the same time can be envisioned under this merger model for Sun and mainstream grains, they can be seen to fall into two main categories.

1. The first category focuses on abundance differences between the Galactic gas G and the lower metallicity satellite gas S. If S is a significant component of the mixtures, its expected differences in isotopic composition from that of G might reveal itself in grain differences between the top and bottom of the mainstream correlation line (Fig. 1), in differences between solar isotopes (very precise) and those of mainstream grains (precisions approaching 1%), or in differences between solar isotopes and those (less precise) measured astronomically in routine Galactic stars that were uninfluenced by the merger. This first category exists in the basic merger model of § 2.1.

2. The second category focuses on abundance differences between mainstream grains and the solar composition owing to the intervening starburst nucleosynthesis that occurred between the merger that generated the AGB stars and the solar birth. This second category includes those differences of category 1 if the Sun also formed from a merger mixture, as I have assumed throughout but which is not necessary to the model, but it reveals itself primarily as observable abundances added to the category 1 abundances. Basic model 2 in § 2.3 set a stage for this with an emphasis on silicon isotope differences. A severe challenge will be found in distinguishing a starburst nucleosynthesis component in the solar abundances from routine ongoing Galactic nucleosynthesis. If the solar gases carry no component from S, solar birth may be unrelated to the merger that generated the AGB donor stars, in which case it may be more natural to think of the nucleosynthetic additions to solar gas that occurred between the time of the starburst and solar birth as being routine for its birth location rather than associated with the merger starburst. The circumstantial evidence that links them is the abundant presence of the mainstream grains in the solar birth cloud. If these AGB nucleosynthesis fossils exist in the solar cloud, surely it seems plausible that the starburst nucleosynthesis is also present in the solar cloud. However, see the reservations in § 3.7 below concerning uncertainties about mixing the shocked ISM into molecular clouds.

Other puzzles relevant to these issues have long been recognized. Although astronomers traditionally have regarded solar abundances as a representative target for models of chemical evolution of the Galaxy, some lines of evidence may suggest that this is not be so. Many have observed that the Sun's metallicity is high for its time and place of birth, prompting at least one study (Wielen, Fuchs, & Dettbarn 1996) to suggest outward radial diffusion of the Sun following its birth in more central, more metal-rich regions of the Galactic disk. Isotopic ratios introduce special problems of similar nature. The $^{12}\mathrm{C}/^{13}\mathrm{C}$ solar ratio (89) is significantly larger in the Sun than in the local ISM today (50–70), and it is not clear that chemical evolution could cause it to decline that much in 4.6 Gyr (e.g., Timmes, Woosley, & Weaver 1996; Prantzos, Aubert, & Audouze 1996). A third example may be the large $^{18}\mathrm{O}/^{17}\mathrm{O}$ solar ratio (5.3), which exceeds by 65% measurements in the ISM today (Penzias 1981; Bieging 1997) despite the secondary-nucleosynthesis nature of both heavy oxygen isotopes. Caution applies as well to the silicon isotopes in the Sun. Solar Si isotopes are used to normalize the Si isotopic ratios measured in presolar stardust grains (Figs. 1 and 2), so it is reasonable to be alert to any role of the solar normalization, such as in § 2.3, when reconciling unexpected behavior of isotopic ratios in stardust grains. For clarity to readers it may be commented in this regard that the treatment of Clayton & Timmes (1997b) considered how an abnormal solar Si composition with respect to the ISM could lead to a 4/3 correlation slope instead of unit slope, but they retained the conventional temporal evolution of secondary isotopes up the three-isotope line. In the merger picture, temporal evolution is not involved in the mainstream line. The next subsections itemize several implications.

3.1. *Solar Metallicity Enrichment by Stimulated Supernovae*

The Sun has not traditionally been thought of as a low-metallicity star. To the contrary, many have noted the large metal richness of the Sun in comparison with what might be expected for star birth 4.5 Gyr ago at the Sun's Galactocentric distance. It may be described as a paradox, therefore, that the Sun seems metal-rich when discussing its metallicity but metal-poor when its isotopic measures of metallicity, $^{13}\mathrm{C}$ and $^{29,30}\mathrm{Si}$, are discussed. This paradox poses major isotopic questions about the correct interpretation of the Sun. Both the low $^{13}\mathrm{C}/^{12}\mathrm{C}$ ratio of the Sun and its low $^{29,30}\mathrm{Si}/^{28}\mathrm{Si}$ ratios would, in any well-mixed chemical evolution model, suggest solar birth in an early era of low metallicity. Merger model 2 may resolve this puzzle without requiring high metallicity for the premerger Galaxy G. On the other hand, recent observations and analyses of solar spectra have lowered the solar abundance of both C and O (Allende Prieto, Lambert, & Asplund 2001, 2002). Their results yield solar C and O that match abundances in Orion and B stars. Since solar birth was 4.6 Gyr ago and Orion and B stars are today, the Sun may still be metal rich for its time of birth. In any case, the degree of solar enrichment described in § 2.3 is still not well known and depends on a detailed interpretation of the chemical evolution of the solar neighborhood.

3.2. *Solar and Galactic* D/H *Ratios*

The astration that increases metallicity of the gas also reduces its D/H ratio (e.g., Clayton 1985). If model metallicities are comparable to $[Z_G] = 1$ and $[Z_S] = 0.189$, as described in model 2, it follows that D/H in gas from the accreted satellite S may be significantly larger than in the metal-rich disk at G, perhaps even twice as great. Detailed realistic models are needed to quantify that difference, although analytic models (Clayton 1985) give useful approximations. However, it is clear that if the Sun's mass arose in significant part from the S component, as in the § 2.1 basic model, where it is about half of the total, evidence would show D/H larger in the initial Sun than in contemporary undiluted portions of the Galactic disk.

3.3. *Solar and Galactic* $^{13}C/^{12}C$ *Ratios*

The low-metallicity satellite gas should have a low $^{13}C/^{12}C$ ratio not only owing to the secondary nature of ^{13}C but also if AGB production of ^{13}C had been less significant in the satellite than in the Galaxy. However, because S also carries a lower elemental carbon content owing to its low metallicity, mixtures of comparable masses of G and S will not greatly dilute the $^{13}C/^{12}C$ ratio of G. Category 1 differences will therefore be small unless the Sun had been primarily of S composition. Category 2 differences may be larger if the nucleosynthesis additions to the Sun by the starburst had a larger ratio of supernova carbon to AGB carbon than did the continuous Galactic history. Perhaps the most plausible path to this possibility would be contributions to the Sun from the starburst supernovae but insufficient time until solar birth for the low-mass AGB stars to evolve to contribute their larger $^{13}C/^{12}C$ ratio to the presolar gases. The mainstream grains would then have to have been donated from the upper range of AGB masses, those that evolved fast enough to contribute prior to solar birth. Supernova yields by Woosley & Weaver (1995; see their Table 6) give ratios of overproduction factors $[^{13}C/^{12}C]$ near 0.5 in solar metallicity supernovae (and considerably smaller ratios in lower Z supernovae), so that supernova additions of carbon to the Sun do dramatically lower its $^{13}C/^{12}C$ ratio. The supernova starburst may account for that ratio being so small. This explanation seems to have first been advanced by Clayton (1977, p. 266). See also Reeves (1978), Henkel & Mauersberger (1993), and Olive & Schramm (1982). If half of solar C nuclei arose from the starburst supernovae (roughly 5% of the solar mass contributed by the supernovae), for example, it would lower a Galactic ratio $(^{13}C/^{12}C)_G = 60$ to near the observed value $^{13}C/^{12}C = 89$ in the Sun. It remains therefore an important question whether routine, well-mixed GCE should be realistically expected to lower ISM $^{13}C/^{12}C$ ratios from values near 89 at solar birth to values near 60 today. If not, both the large solar C abundance and its low $^{13}C/^{12}C$ ratio may support merger model 2.

3.4. *Solar and Galactic Oxygen and Presolar Oxide Stardust*

No explanation exists for the puzzling fact that solar $^{18}O/^{17}O = 5.3$ is 65% greater than Galactic measurements, $^{18}O/^{17}O = 3.2$ (Wilson & Rood 1994; Bieging 1997). Not only that, but the current local ISM $^{16}O/^{18}O$ ratio (560 ± 25; Wilson & Rood 1994) is even greater than the solar value (499), whereas the opposite is expected in simple GCE. In the merger model the relationship of both ^{18}O and ^{17}O to ^{16}O is similar to that described for ^{13}C to ^{12}C. Although $[^{18}O/^{16}O]$ and $[^{17}O/^{16}O]$ should be small in the S composition, and although S may even have a larger $^{18}O/^{17}O$ ratio than G does, the low metallicity of S implies that only a small change in $^{18}O/^{17}O$ results from dilution of G with S. Normalized isotopic correlations from the mixing are expected to be of the same order of magnitude in the oxygen three-isotope plot as those for Si isotopes in Figure 2.

It may not be possible for O isotopes to be accurately measured in mainstream SiC grains because of their tiny O abundance. If measurement can be achieved, one will expect in the merger model that $^{17,18}O/^{16}O$ ratios in mainstream grains should correlate with $^{29,30}Si/^{28}Si$ ratios in those grains, similarly to Figure 1. Instead of mainstream grains, presolar oxide stardust (Nittler et al. 1997) must be employed. The same mixing issues for star formation during the merger apply to oxide grains that condense in red giant winds prior to the C star transition that occurs midway into the AGB phase. An immediate problem is that the O isotope variations observed in the oxide grains (Nittler et al. 1997) are much greater than the evolution effects linking their initial compositions. The deep burning in the stellar envelopes so greatly and variably depleted ^{18}O and somewhat increased ^{17}O in most oxide grains that the measurements reflect those changes associated with that nuclear burning in the AGB stars. Nonetheless, Nittler et al. (1997) addressed all of this very carefully and were able to conclude that initial oxygen isotope ratios consistent with GCE were indeed revealed by the oxide grains. Category 1 effects in oxygen thus do seem to underlie the larger nuclear anomalies created in the stars themselves.

Category 2 effects are more promising. The burst of post-merger supernovae caused by the merger may have enriched solar gas preferentially in ^{18}O prior to solar birth. Assuming that the $^{16}O/^{18}O$ ratio in today's ISM applied to the solar-metallicity point G as well, that value, $^{16}O/^{18}O = 560$ at G, would in that case have been diluted in the solar mix by ^{18}O-enriched supernova ejecta to reach the lower solar ratio (499). Computed models (Woosley & Weaver 1995) show that supernovae having $M < 20\ M_\odot$ do produce much larger $^{18}O/^{16}O$ ratios than do more massive supernovae. Therefore, the solar enrichment from the starburst supernovae may have made the Sun more ^{18}O-rich even while increasing its oxygen metallicity. Much of Galactic ^{17}O, on the other hand, may have been produced not only by massive supernovae but also by low-mass red giants, but these may not contribute during the time available before solar birth in the starburst situation. It is noteworthy that NASA's *Genesis* mission has the goal of soon making the first high-precision measurement of solar O isotopes, for these may not only distinguish between solar and planetary oxygen but, in the present context, between solar oxygen and oxygen found in presolar grains and in the ISM.

3.5. *Titanium Isotopes in Mainstream Grains*

Linear isotopic correlations are a corollary of binary mixtures (as called upon for this model). They should exist as

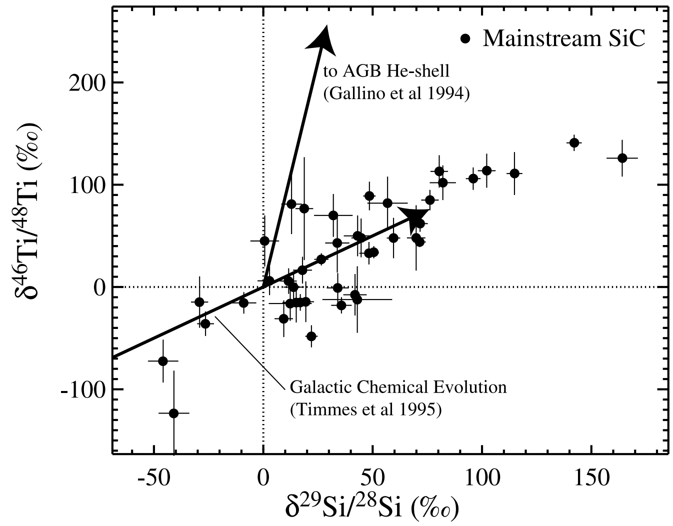

FIG. 4.—Run of $^{46}Ti/^{48}Ti$ ratios measured (Hoppe et al. 1994) in individual mainstream SiC grains as a function of the $^{29}Si/^{28}Si$ ratio in the same grain (reproduced from Clayton & Nittler 2003, Fig. 5). It is evident that a correlation exists between [$^{46}Ti/^{48}Ti$] and [$^{29}Si/^{28}Si$] in the mainstream grains. Such correlation is automatic in the merger mixing model provided that $[^{46}Ti/^{48}Ti]_G > [^{46}Ti/^{48}Ti]_S$, a result expected from GCE whenever $Z_G > Z_S$, as it is in the merger model.

well among isotopes of elements other than silicon. Carbon isotopes are subject to too many burning and dredge-up processes in the AGB stars themselves (as is oxygen above) and thus cannot be looked to for tests of this model. Titanium, however, is an abundant trace element whose isotopes are routinely measured in mainstream SiC grains (Hoppe et al. 1994) and whose modifications by dredge-up are modest and predictable (Gallino et al. 1994). Figure 4 (reproduced from Clayton & Nittler 2003, Fig. 5) shows the run of $^{46}Ti/^{48}Ti$ ratios for individual grains as a function of the $^{29}Si/^{28}Si$ ratio in the grain (a ratio which spans the mainstream and correlates also with the $^{30}Si/^{28}Si$ ratio). It is evident that a correlation exists between [$^{46}Ti/^{48}Ti$] and [$^{29}Si/^{28}Si$] in the mainstream grains. Gallino et al. (1994) showed that this correlation cannot be interpreted as the result of the *s*-process component in the AGB atmosphere, because $^{46}Ti/^{48}Ti$ ratios rise much more rapidly than $^{29}Si/^{28}Si$ during *s*-process irradiations. This is made evident in Figure 4, which includes the calculated *s*-process correlation. The observed correlation does exist in GCE (Timmes et al. 1995), however, and is also displayed in Figure 4 for evolutions using the same IMF. This result stems from ^{46}Ti having a secondary nucleosynthesis component, one for which its yield increases with initial metallicity. In basic model 2 (§ 2.3) the metallicity of the satellite S ($Z_S = 0.189\ Z_\odot$) is much less than that of G. In the present merger model, $[^{46}Ti/^{48}Ti]_S$ would therefore be smaller than $[^{46}Ti/^{48}Ti]_G$ because G is more evolved than S. The observed correlation is therefore anticipated by application of chemical evolution to the merger model. This difference is not another effect of differing supernova IMFs, because the Woosley & Weaver (1995) models 30B, 35B, and 40B used here do not significantly increase the Ti abundance, although they do eject larger $^{46}Ti/^{48}Ti$ ratios. The correlation of Figure 4 is thereby also explained by the merger model. This same reasoning can be applied to any other isotope ratio that may systematically differ between S and G.

3.6. *Y and Z Stardust* SiC *Grains*

Long-standing puzzles have been presented by the Y and Z grains of SiC. These are thoroughly described by Amari et al. (2001), who find them similar to mainstream SiC grains but seemingly condensed from AGB stars of lower metallicity. See especially their Figure 2 for their location in the same Si three-isotope plot as in Figure 1. Figures 8 and 12 of Amari et al. (2001) suggest a metallicity relationship schematically for these three SiC-grain types. Lower metallicity in the donor stars is not measurable directly but is rather a model-dependent inverse relationship between the neutron fluence during the *s*-process and the metallicity of the star; the $^{12}C/^{13}C$ surface ratio after dredge-up also increases inversely with the metallicity. The larger fluence produces a larger excess of [$^{30}Si/^{28}Si$] in comparison with the mainstream grains, with the Z grains even more enhanced. The Y and Z grains are relatively rare, about 1% of the mainstream-grain population.

The point here is not these technical details but rather that the Galactic-merger model suggests a new natural interpretation of either or both of these related SiC grains. Analogs of mainstream SiC grains already existing in the satellite galaxy may resemble Y and/or Z grains, because the satellite S, and therefore its own AGB stars, is supposed to be of quite subsolar metallicity. Thus Y, or perhaps more likely Z, grains may have already been residing in the ISM of S when it was brought into the Galaxy by the gaseous merger. If that be so for Z grains, the Y grains may be the Galaxy grains from its earlier eras of lower metallicity (in G) and which survived in its ISM until the time of the merger.

3.7. *Extinct Radioactivity in the Sun*

The intervening supernova nucleosynthesis that the solar gas received during approximately 1–1.5 Gyr between the merger epoch and the epoch of solar birth, most likely from starburst Type II supernovae spawned by the merger itself, may have introduced larger levels of radioactivity into the Sun than existed in most AGB mainstream stars. Measured concentrations in solar meteorites of extinct radioactive nuclei attest to these supernovae mixings over a range of time (Meyer & Clayton 2000) comparable to that between the merger and solar birth, whereas a subgroup of short-lived radioactivities attests to a final nearby supernova that injected that group into the forming Sun. A new model (Meyer & Clayton 2000; Meyer et al. 2003) of the distributions of nucleosynthesis origins of the full set of extinct radioactivities, both in time and in supernova type, shows promise of finally bringing order to this venerable and complicated topic. This model has two key innovative features: first, its attribution of extinct solar ^{26}Al, ^{36}Cl, ^{41}Ca, ^{60}Fe, ^{107}Pd, and ^{182}Hf specifically to the mixture of only that matter outside the 7 $M_\odot$ core (in a 25 $M_\odot$ model) of the final supernova rather than its entire ejecta; second, its use of a steady state model for mixing supernova radioactivity continuously (Clayton 1983) from the hot ISM into molecular clouds. This last short-lived group may also have been provided by a presolar AGB star (Wasserburg et al. 1994), but here I describe it in terms of the last supernova. The particle-irradiation models, which have a longer history, seem unable to account for the heavy neutron-rich isotopes ^{60}Fe, ^{107}Pd, and ^{182}Hf, so I also omit them from consideration.

The model by Meyer & Clayton (2000) finds that ^{53}Mn and ^{146}Sm were present in the solar cloud at levels expected in molecular clouds generally if Type Ia ejecta were widely distributed through the hot ISM and continuously mixed into clouds with a timescale set by the disruption timescale of molecular clouds (50 Myr), but the model finds that Type II ejecta, specifically *r*-process ^{107}Pd, ^{129}I, ^{182}Hf, and ^{244}Pu, required much longer mean times for mixture into molecular clouds, at least as judged by solar concentrations.

With dozens of supernovae expected in the solar neighborhood subsequent to the merger that spawned the AGB mainstream mixing line, how is it that their new *r*-process ejecta were so scarce in the solar cloud? The answer lies in gasdynamics of superheated ISM. Supernovae occurring in concert, as in the merger starburst, repeatedly reheat the low-density medium, creating an entropy barrier to its mixture into clouds. Instead of injecting into clouds, most Type II ejecta heats and ionizes cloud surfaces, leading to evaporation from them rather than incorporation into them. The reheated low-density ISM from multiple supernovae will usually expand hydrodynamically to form a long X-ray–emitting flow, as in the Eridanus region (Burrows et al. 1993). The *r*-process ejecta is of especially high entropy, whether neutron star wind or polar jets established by a young neutron star and its disk (Cameron 2001). It will mix even more poorly than other Type II ejecta. At least this is suggested by the physical picture introduced for this purpose by Clayton (1983), who calculated that the hot ISM carried large steady state concentrations of *r*-process radioactivity, but that it mixes so slowly into molecular clouds that the clouds contain concentrations less than the bulk interstellar average. I call again on this picture, as did Meyer & Clayton (2000), to rationalize the low *r*-process ^{107}Pd, ^{129}I, ^{182}Hf, and ^{244}Pu concentrations that were present in the presolar cloud. The supernova starburst is seen as less likely for mixture into a cloud, at least until the long waiting time needed for it to cool and slowly join cold cloud matter. For the *r*-process, something even more specific may also be at play. Qian & Wasserburg (2003) cite phenomenological evidence for restricting at least the heavy *r*-process production to accretion-induced core collapse events of about 8–10 $M_\odot$. They cite as evidence the decoupling of iron-peak abundances in metal-poor stars from those of the heavy *r*-process. Since it is not known where the *r*-process occurs, it is possible that the entire *r*-process arises from the relatively bare neutron stars produced in accretion-induced collapse events. Should this suggestion be correct, it makes the *r*-process frequency about 28% of the frequency of Type II events. Moreover, if the *r*-process ejecta are also directed in jets, *r*-process injection into the presolar cloud from the merger starburst events may be much less likely than mixture of their supernova shells (metallicity raising). Moreover, if low-mass X-ray binaries live 10^9 yr, the accretion-induced collapse for many stars born during the merger may not even have occurred prior to solar collapse. At any rate, it does not seem hard to accept that *r*-process ejecta may have been more delayed in entering the presolar cloud than was supernova shell nucleosynthesis and the widely dispersed Type Ia nucleosynthesis. This suggests that only ^{129}I and ^{244}Pu live long enough for mixture from those *r*-process events (Meyer & Clayton 2000), so that *r*-process products ^{107}Pd and ^{182}Hf must instead have arrived in the solar cloud from *s*-process shells within the trigger supernova (or perhaps an AGB star) responsible for ^{26}Al, ^{41}Ca, and ^{60}Fe. It is exactly this shell production of ^{107}Pd and ^{182}Hf that the Meyer et al. (2003) calculations display.

What then of that last-moment Type II supernova that has been speculated (in order to rationalize its coincidence in place and time) to have triggered the solar collapse (Boss 1995)? The conditions for it to mix its extracore matter (Meyer & Clayton 2000) must have been favorable in ways that were not typical. Boss (1995) and Vanhala & Boss (2000) remind us that the supernova material containing the radioactivity, which follows the primary shock in time rather than lying within it, must hit the cloud at speeds of less than 45 km s^{-1} in order that it not disrupt the cloud. This speed, a factor 100 less than its ejection speed, indicates that the ejecta has almost stopped! This can happen at the location of the solar cloud core only if the geometry of the situation was initially correct for this deceleration to have happened. The interstellar matter and the peripheral cloud material that initially surrounded the solar cloud core must have been set in motion by the primary shock, clearing it out of the way for the almost-stopped ejecta to arrive at the best of all times for its inclusion. I paint an improbable picture perhaps, one that long made me doubt the realism of supernova injection but which the isotopic evidence seems to advocate. Within the context of this paper we take it to have happened just so, as described (Vanhala & Boss 2000). Given this suite of extinct radioactivities, the merger scenario may offer the chance for a new understanding of the relationship of the origin of the Sun to its local Galaxy.

4. SUMMARY

The merger of a metal-poor satellite galaxy with the Milky Way about 5–6 Gyr ago has been postulated in order to resolve three great unexplained conflicts presented by precisely measured isotopic ratios in individual mainstream presolar stardust SiC grains. The merger allows all of the AGB carbon stars that donated these grains to have been formed nearly simultaneously during a starburst generated by the gaseous mixing, despite their great apparent age differences when evaluated in terms of Galactic chemical evolution. The starburst explains why these AGB stars dominate the SiC dust in the solar neighborhood. The model explains why a linear correlation exists between ^{29}Si/^{28}Si and ^{30}Si/^{28}Si in the initial compositions of those distinct AGB stars. The model suggests why the slope of that normalized correlation line, [^{29}Si/^{28}Si] versus [^{30}Si/^{28}Si], is $m = 4/3$ rather than unity, as predicted by GCE. The model suggests why the solar silicon isotopic ratios lie near the bottom of that mainstream correlation line rather than near its top, as expected for AGB stars born before the Sun. The model has also readdressed many isotopic puzzles known within the solar composition. These yield a fresh view of the origin of the Sun and of its relationship to the Galaxy. The model has the remarkable property of reading dynamic events of the presolar history of the Milky Way from precise isotopic ratios measured in terrestrial laboratories within individual micron-sized presolar grains that have been extracted from meteorites that formed 4.56 Gyr ago but that fell only recently to Earth.

This work has also illuminated the importance for astronomy of understanding why numerical computations of GCE fail to reproduce the solar ^{29}Si/^{30}Si abundance ratio, accounting for only two-thirds of that value. Should the ^{29}Si/^{30}Si yield from all supernovae be increased by the factor 1.5 owing to some systematic unknown nuclear error, as Timmes & Clayton (1996) suggested? Or, as I suggest here, are those $^{29}Si/^{30}Si$ yield ratios nearly correct for moderate-mass supernovae, but massive supernovae are even more prolific ^{29}Si producers than current models suggest, perhaps because mixing effects in massive stars increase the width of the mass zone wherein $[^{29}Si/^{30}Si] > 1$? Figure 10 of Deneault et al. (2003) showed this ^{29}Si-rich zone in one specific supernova model. Because Si isotopes do dominate the meaning of the mainstream grains, this is a nuclear astrophysical problem that cries out for solution.

The postulated gaseous merger between two gas reservoirs of differing metallicity need not be restricted to mixing between the solar neighborhood of the Galaxy and a low-metallicity satellite galaxy. Alternative reasons for a large-scale gaseous mixing event may exist. Any large infall event might work equally well. Differing radial Galactic gas zones of differing metallicities and therefore differing $^{29}Si/^{28}Si$ ratios may have suffered induced mixing by an unspecified Galactic dynamics, perhaps even by a merger. These alternative scenarios might account for the puzzles of the mainstream correlation line in an analogous way to the details proposed here. The end members will then be isotopically nearer in Figure 2. The slope 4/3 then would require more detailed explanation. The merger model as presented seems attractive, however, because it calls on an event that must have happened several times during presolar history.

Although this proposal is highly speculative, the excellent quality of the data on mainstream grains enables the support that they provide. That data has seemed contradictory with more conventional ideas. Exploring the consequences of the merger idea will be necessary to expose it to the scientific scrutiny needed to evaluate it, but there is the sense of a large issue here. The mainstream SiC data and the search for its correct interpretation may be likened to the classical astronomical problem found in the clustering of stellar positions in the stellar color-magnitude (Hertzsprung-Russell) diagram, and its impact on understanding the origin of the Sun may be analogously large.

I thank Larry Nittler and Ernst Zinner for several useful discussions as these ideas were being developed, and also the referee, Maria Lugaro, for suggestions that significantly improved the paper. This research has been supported by NASA Origins of the Solar System Program grant NAG5-11871.

REFERENCES

Allende Prieto, C., Lambert, D. L., & Asplund, M. 2001, ApJ, 556, L63
———. 2002, ApJ, 573, L137
Amari, S., Nittler, L. R., Zinner, E., Gallino, R., Lugaro, M., & Lewis, R. S. 2001, ApJ, 546, 248
Bell, E. F., Wolf, C., Meisenheimer, K., Rix, H.-W., Borch, A., Dye, S., Kleinheinrich, M., & McIntosh, D. H. 2003, ApJ, submitted
Bieging, J. H. 1997, in AIP Conf. Proc. 402, Astrophysical Implications of Laboratory Study of Presolar Materials, ed. T. J. Bernatowicz & E. Zinner (New York: AIP), 265
Boss, A. P. 1995, ApJ, 439, 224
Burrows, D. N., Singh, K. P., Nousek, J. A., Garmire, G. P., & Good, J. 1993, ApJ, 406, 97
Cameron, A. G. W. 2001, ApJ, 562, 456
Clayton, D. D. 1977, Icarus, 32, 255
———. 1983, ApJ, 268, 381
———. 1985, ApJ, 290, 428
———. 1988, ApJ, 334, 191
———. 1997, ApJ, 484, L67
Clayton, D. D., & Nittler, L. R. 2003, in Origin and Evolution of the Elements, ed. A. McWilliam & M. Rauch (Cambridge: Cambridge Univ. Press)
Clayton, D. D., & Pantelaki, I. 1986, ApJ, 307, 441
Clayton, D. D., & Timmes, F. X. 1997a, in AIP Conf. Proc. 402, Astrophysical Implications of Laboratory Study of Presolar Materials, ed. T. J. Bernatowicz & E. Zinner (New York: AIP), 237
———. 1997b, ApJ, 483, 220
Deneault, E. A.-N., Clayton, D. D., & Heger, A. 2003, ApJ, 594, 312
Edvardsson, B., Anderson, J., Gustaffson, G., Lambert, D. L., Nissen, P. E., & Tomkin, J. 1993, A&A, 275, 101
Gallino, R., Raiteri, C. M., Busso, M., & Matteuchi, F. 1994, ApJ, 430, 858
Gillespie, E. B., Geller, M. J., & Kenyon, S. J. 2003, ApJ, 582, 668
Henkel, C., & Mauersberger, R. 1993, A&A, 274, 730
Hoppe, P., Amari, S., Zinner, E., Ireland, T., & Lewis, R. S. 1994, ApJ, 430, 870
Hoppe, P., & Ott, U. 1997, in AIP Conf. Proc. 402, Astrophysical Implications of Laboratory Study of Presolar Materials, ed. T. J. Bernatowicz & E. Zinner (New York: AIP), 27
Limongi, M., & Cieffi, A. 2003, ApJ, 592, 404
Lugaro, M., Zinner, E., Gallino, R., & Amari, S. 1999, ApJ, 527, 369
Meyer, B. S., & Clayton, D. D. 2000, Space Sci. Rev., 92, 133
Meyer, B. S., The, L.-S., Clayton, D. D., & El Eid, M. 2003, Lunar Planet. Sci. Conf., 34, 2074
Nittler, L. R., Alexander, C. M. O'D., Gao, X., Walker, R. M., & Zinner, E. 1997, ApJ, 483, 475
Olive, K., & Schramm, D. N. 1982, ApJ, 257, 276
Penzias, A. 1981, ApJ, 249, 513
Prantzos, N., Aubert, O., & Audouze, J. 1996, A&A, 309, 760
Qian, Y.-Z., & Wasserburg, G. J. 2003, ApJ, 588, 1099
Reeves, H. 1978, in Protostars and Planets, ed. T. Gehrels & M. S. Matthews (Tucson: Univ. Arizona Press), 399
Sellwood, J. A., & Binney, J. J. 2002, MNRAS, 336, 785
Shetrone, M. D., Venn, K. A., Tolstoy, E., Primas, F., Hill, V., & Kaufer, A. 2003, AJ, 125, 684
Timmes, F. X., & Clayton, D. D. 1996, ApJ, 472, 723
Timmes, F. X., Woosley, S. E., & Weaver, T. A. 1995, ApJS, 98, 617
Tolstoy, E., Venn, K. A., Shetrone, M. D., Primas, F., Hill, V., Kaufer, A., & Szeifert, T. 2003, AJ, 125, 707
van Dokkum, P. G., & Ellis, R. S. 2003, ApJ, 592, L53
Vanhalla, H., & Boss, A. P. 2000, ApJ, 538, 911
Wasserburg, G. J., Busso, M., Gallino, R., & Raiteri, C. M. 1994, ApJ, 424, 412
Wielen, R., Fuchs, B., & Dettbarn, C. 1996, A&A, 314, 438
Wilson, T. L., & Rood, R. T. 1994, ARA&A, 32, 191
Woosley, S. E., & Weaver, T. A. 1995, ApJS, 101, 181
Yanny, B., et al. 2003, ApJ, 588, 824
Zinner, E. 1998, Annu. Rev. Earth Planet. Sci., 26, 147