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Placing the Sun and Mainstream SiC Particles in Galactic Chemodynamic Evolution

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ABSTRACT

This work continues to seek a possible paradigm for the existence of the mainstream of presolar SiC particles having $^{29}Si/^{28}Si$ and $^{30}Si/^{28}Si$ isotopic ratios larger than those found in solar material. The isotopic trend of the mainstream SiC presolar particles extracted from the meteorites and the isotopic composition of the Sun are both interpreted within a framework of Galactic evolution in which the stars diffuse substantial distances but the interstellar gas remains homogeneous at each value of Galactocentric radius. Viewed from the radial position of solar birth, which lies outside the bulk of the molecular-cloud scattering centers, the presolar cloud (having solar composition) picks up asymptotic giant branch (AGB) star dust from AGB carbon stars that were primarily more metal-rich when they were born but have overwhelmingly diffused outward to reach the solar birthplace instead of diffusing inward. This would solve the fundamental problem facing any satisfactory paradigm, namely, the metal-richness of the presolar carbon stars in the solar-birth neighborhood. Other aspects of the mainstream characteristics are also commented on in this model.

Subject headings: Galaxy: evolution—ISM: abundances—nuclear reactions, nucleosynthesis, abundances—solar neighborhood—stars: ABG and post-AGB—Sun: abundances

§1. INTRODUCTION

Should the composition of the Sun be regarded as typical of the interstellar gas for its time of birth and current location? This question haunts studies of Galactic chemical evolution and the interpretation of presolar silicon carbide (SiC) grains extracted from the meteorites (Timmes & Clayton 1996; Clayton & Timmes 1997). Abundance measurements referred to by Clayton & Timmes (1997) may be taken to suggest an excess abundance of heavy elements in the Sun in comparison with other stars that formed about 4.6 Gyr ago at a Galactocentric radius of about 8.5 kpc. Galactic chemical evolution models of the mean interstellar medium (ISM) have generally attempted to reproduce the solar abundances at that time and location. I will abandon that assumption in this work. Hesitation in taking the solar abundances as representative of the mean ISM is perhaps even more justified when isotopic ratios are considered, since less observational information exists for isotopic abundances.

This Letter introduces a new method for relating the composition of presolar SiC STARDUST to the dynamical evolution of the presolar inner Galaxy. The discovery of presolar refractory SiC grains preserved in meteorites has allowed their isotopic compositions to be measured with an accuracy unprecedented (in parts per thousand) for astronomy (Virag et al. 1992; Anders & Zinner 1993; Hoppe et al. 1994a, 1994b, 1995, 1996). These works have shown that the silicon compositions of the grains are not random but correlate in a narrow band called "the mainstream" in a three-isotope plot. The mainstream band follows this rule: deviations of the $^{29}Si/^{28}Si$ ratio from the solar $(^{29}Si/^{28}Si)_{\odot}$ ratio are proportional to deviations of the $^{30}Si/^{28}Si$ ratio from the solar $(^{30}Si/^{28}Si)_{\odot}$ ratio. The best-fit slope of the correlation band for the fractional deviations is 1.35 (Hoppe et al. 1995b). The grain-by-grain deviations from solar composition (in parts per thousand) are shown in Figure 1, which is adapted from Timmes & Clayton (1996).

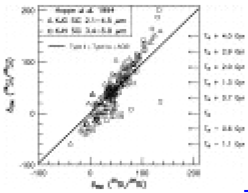
Fig. 1

The renormalized supernova-yield evolution, defined following Timmes & Clayton (1996) so that the mean ISM passes through solar composition at the time and place of solar birth, and how its isotopic ratios progress up the $m = 1$ slope line with time (*right ordinate*) are also shown in the three-isotope plot of Figure 1. This calculated evolution line has its deviations expressed with respect to the calculated silicon isotopic composition at the time of solar birth (note subscripts on axis labels and eq. [2] of Timmes & Clayton 1996). Temporal deviations of the mean local gas with respect to mean ISM at the time of solar birth and with respect to solar abundances are equal, $\delta_{\odot} = \delta_{ISM}$, if supernova-yield renormalization forces the mean ISM composition to pass exactly through solar abundances at $t = t_{\odot}$. That is the construction of Figure 1. Clayton (1988) and Timmes & Clayton (1996) demonstrated that the $^{29}Si/^{28}Si$ and $^{30}Si/^{28}Si$ number ratios increase linearly with time in the ISM of the disk. That conclusion rests on conventional models of Galactic history. It follows because ^{29}Si and ^{30}Si nuclei are both "secondary" nucleosynthesis products, whereas ^{28}Si is "primary."

Several interpretive problems associated with Figure 1 have been described by Timmes & Clayton (1996), Clayton & Timmes (1997), and the groups who experimentally characterized these SiC particles (e.g., Anders & Zinner 1993; Hoppe et al. 1995). In brief, the problems include the following: the ISM evolution slope ($m = 1$) differs from the particle slope ($m = 1.35$); the particle line passes to the right of the solar composition; the Sun's composition may differ from that of the mean ISM; and the nuclear processes in the asymptotic giant branch (AGB) stars that are believed to be the condensation sites for mainstream SiC because of their *s*-process compositions for trace elements simultaneously translate the initial Si isotopic compositions of those stars some unknown distance rightward in Figure 1 along a line of slope $m = 1/2$ (see, e.g., Brown & Clayton 1992; Gallino et al. 1990). The most daunting obstacle, however, and the one to which a solution is herein proposed, is the ^{29}Si- and ^{30}Si-richness of the SiC grains with respect to the solar composition. If these SiC grains did originate in presolar AGB stars (STARDUST), their initial isotopic compositions are expected to have been lighter than those in the later-forming Sun rather than isotopically heavier, the latter contradicting conventional pictures of Galactic history that lead to the evolution line in Figure 1. The presolar SiC grains should be linearly aligned in a three-isotope plot because the initial compositions of the low-mass stars that made the grains were initially aligned (Clayton 1988; Alexander 1993). Because those different low-mass stars formed at different presolar times, they had different silicon isotopic ratios in their ejecta. The problem is clearly that mainstream SiC grains are richer in the heavier silicon isotopes than in the Sun, even though the grains must have originated in stars that formed prior to the Sun. Homogeneous chemical evolution curves are monotonic and simply cannot accommodate that experimental fact.

§2. DIFFUSION OF STARS

My interpretation of the heavy-isotope excesses in the majority of the mainstream SiC particles is based on the diffusion of their parent AGB stars from more central birthplaces of higher metallicity. Galactic zones of differing present metallicity evolved up the same line in Figure 1; however, the more metal-rich zones moved up that line faster. The presolar AGB stars that lost their wind-grown condensates (STARDUST; Clayton 1978) to the cloud mass from which the Sun was to be born had diffused outward from somewhat more central birth locations, which rendered them initially more metal-rich than the Sun. The outward diffusion may be likened to the "gravity assist" by which humans investigate Pluto by scattering from Jupiter. By the natural correlation between metallicity and secondary-isotope excess (Clayton & Pantelaki 1986; Timmes & Clayton 1996), as reflected in the isotopic evolution in Figure 1, those AGB stars condensed SiC grains having $^{29}\mathrm{Si}/^{28}\mathrm{Si}$ and $^{30}\mathrm{Si}/^{28}\mathrm{Si}$ number ratios greater than those of the cloud to which those particles were contributed. The chemical evolution variables, when normalized to unity for solar composition, may be either Fe/H or, with a small change of scale, $^{29}\mathrm{Si}/^{28}\mathrm{Si}$ or $^{30}\mathrm{Si}/^{28}\mathrm{Si}$ number ratios.

The situation is superficially confused by the metal-richness of the Sun itself (Edvardsson et al. 1993). That has been successfully accounted for in a diffusion model by Wielen, Fuchs, & Dettbarn (1996), who demonstrated that the Sun can be interpreted as also having diffused outward from gas of higher metallicity. They find that the Sun was born at Galactocentric radius $R = 6.6$ kpc and has in 4.5 Gyr diffused outward to its present location at $R = 8.5$ kpc. They show that that magnitude for spatial diffusion of the Sun is consistent with its velocity diffusion and that $\Delta R = 1.9$ kpc is not an atypical expectation for $\Delta t = 4.5$ Gyr. Wielen & Wilson (1997) have reanalyzed the C, N, and O isotopic ratios in the ISM for this model and find a satisfactorily improved interpretation. Accurate silicon isotopes in stars of differing metallicities would valuably aid the assessment of this interpretation but are not yet available.

The physical picture is given in Figure 2. The interstellar gas is taken to have uniform composition in an annulus at each value of R. Indeed, Wielen et al. (1996) argue that the small metallicity dispersion observed for gas and young stars supports that assumption, whereas the dispersions in the metallicities of nearby stars increase with increasing age. They describe how the observed dispersions represent the diverse radial birth locations of stars that now find themselves within the solar neighborhood. Thorough mixing of gas at each value of R may not have obtained, however (Edvardsson et al. 1993; Fry & Carney 1997). I will take it to be homogeneously mixed in order to simplify and clarify the new model that I am presenting. The three solid curves in Figure 2 therefore represent the gradients of the gas metallicity at three different times: today ($t = 0$), the time of solar birth ($t = -4.5$ Gyr), and $t = -6.0$ Gyr. The magnitude of that gradient today, and the fact on which both Wielen et al.'s (1996) interpretation and my own rely, is $d[\mathrm{Fe}/\mathrm{H}]/dR = -0.09$ dex kpc^{-1}. My other curves in Figure 2 take the gradient to have been slightly larger into the past: -0.104 dex kpc^{-1} at $t = -4.5$ Gyr and -0.110 dex kpc^{-1} at $t = -6.0$ Gyr. This small temporal decrease in the magnitude of the metallicity gradient reflects my assumption about the history of the stellar birth rate per unit mass in the Galaxy, but its values are not crucial to the construction shown in Figure 2. The three metallicity gradients are tentatively taken to represent uniform gas compositions at each value of R; therefore, stars are taken to be born on the appropriate curve. The Sun's history adopts exactly the result of Wielen et al. (1996), although they actually took the radial gradient to be constant in time. The Sun was born at $t = -4.5$ Gyr at $R = 6.6$ kpc and has diffused spatially to $R = 8.5$ kpc today. For this reason the Sun is found to be almost as metal-rich as is the local ISM today at $R = 8.5$ kpc, but it is significantly more metal-rich than the stars that were born at $R = 8.5$ kpc at $t = -4.5$ Gyr. Figure 2 shows their proposed solar diffusion as an arrow, and its value is thoroughly explained by Wielen et al. (1996). I adopt their solution and proceed to extend it to presolar AGB stars.

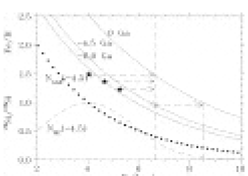
Fig. 2

My own construction proceeds analogously. Figure 2 contains three AGB stars, shown as star symbols. For ease of viewing they are drawn with even heavier Si isotopes than at the upper end of the mainstream. These are but three among the many that diffused from their birth positions to be in the solar birth cloud at $R = 6.6$ kpc at $t = -4.5$ Gyr. The middle AGB star was born at $t = -6.0$ Gyr, the other two somewhat before and somewhat later, respectively. Each arrives at the $R = 6.6$ kpc presolar cloud during the period of AGB loss of STARDUST to that cloud. Note particularly that all of the other possible AGB orbital diffusions are not shown and are not relevant. By historical selection we are interested in only those stars that were AGB STARDUST producers during their transit of the presolar cloud. It was they that contributed the presolar mainstream SiC STARDUST. Note also that the three examples shown, placed as they are by birth symbols at specific values of R and of metallicity, also correspond to AGB stars of specific ages. Stellar evolution must then attribute specific masses to these examples, as to all others involved. The one born at $t = -6.0$ Gyr (*middle star*) is clearly intended to have an age of 1.5 Gyr at the time it is in its AGB phase. This star would have a mass near 2 $M_{\odot}$. The masses of the examples born earlier and later than t = -6.0 Gyr would be, respectively, less and greater. Although Figure 2 seems to imply that AGB stars near 2 $M_{\odot}$ are the ones that contribute the mainstream particles, I do not allege that to be so. The actual masses of the AGB stars, as well as the exact evolutionary portion of the AGB phase involved, are not yet precisely known.

Figure 2 also shows two other quantities of relevance. The number of AGB stars per unit volume, N_{AGB} , increases toward the Galactic center and is shown schematically at t = -4.5 Gyr. Many of these stars will have diffused outward prior to that time. Their density increase toward the center reflects the greater gas density and stellar birth rate in the early central Galaxy. Their gradient ensures that AGB diffusion would be primarily outward even if their scattering sites were uniform. However, the space density N_{MC} of molecular clouds also declines toward the solar position, although it may have a maximum somewhere near 4 kpc (as shown for illustration). The importance of this density is that molecular clouds are the large masses from which the stars scatter and that cause the diffusion of their orbits. As stars having peculiar velocity scatter past a giant mass, they gain and lose energy and change direction, so that locally the diffusion may be more or less isotropic. But looked at in the large, as Wielen (1977) and Wielen et al. (1996) have done, it seems very clear that at R = 6.6 kpc, the flux of AGB stars must be overwhelmingly outward. The negative gradient in both the number of AGB stars and the mass centers from which they scatter causes the excess outward direction when viewed from a larger distance (R = 6.6 kpc). It seems not unlikely that the number diffusing outward across the R = 6.6 kpc line, per unit area so that they will intersect the presolar cloud that occupies a specific area, exceeds the number diffusing inward through that same area by at least an order of magnitude. It is this, I suggest, that accounts for the $^{29}Si/^{28}Si$- and $^{30}Si/^{28}Si$-richness of the SiC STARDUST plotted in Figure 1. The three example AGB stars shown in Figure 2 all lie at larger $^{29}Si/^{28}Si$ and $^{30}Si/^{28}Si$ number ratios than does the presolar cloud. There exist in Figure 1 some SiC grains having $^{29}Si/^{28}Si$ and $^{30}Si/^{28}Si$ number ratios lower than the Sun's, but they are few in comparison with the number above the solar value. In this way the basic problem confronting any paradigm for the existence of the SiC mainstream existence would be addressed by this model explanation. Outward diffusion of the AGB stars is not to be confused with their directions of motion when they pass through the presolar cloud. Their epicycles may be either outward or inward crossing of the solar birth radius. What matters is where those AGB stars were born.

§3. DISCUSSION

Although Figures 1 and 2 present a graphical representation of a possible solution, many astrophysical questions will require considerable study. One such question is whether the stars can diffuse to the solar cloud in the time available. The middle example, born at t = -6.0 Gyr, must diffuse 1.9 kpc during its lifetime. This is coincidentally the same distance that the Sun has diffused in 4.5 Gyr. STARDUST carrying even larger $^{29}Si/^{28}Si$ and $^{30}Si/^{28}Si$ number ratios would have to diffuse even farther. But note carefully the highly anomalous composition of the middle example star in Figure 2; namely, $\delta^{29}_{\odot}$ = 400, as plotted, which is larger than the upper end of the mainstream by a factor of 2. So the stars in Figure 2 have had their displacement from the solar birth location exaggerated for clarity of presentation. Suggestive arguments about diffusion might note that a star having an average radial velocity of 1 km s^{-1} will move 1.5 kpc in 1.5 Gyr, which is precisely the requirement of the middle example star. Such a small mean radial velocity, though not the norm, may be maintained for the minority of stars that actually make it (i.e., by selection a posteriori). Argued somewhat differently, if the radial diffusion can be likened to a random walk, the mean squared distance $\langle \Delta R^2 \rangle$ will be proportional to the travel time; so if the Sun can diffuse 2 kpc in 4 Gyr, the AGB stars could be expected to diffuse 1 kpc in 1 Gyr. This $t^{1/2}$ dependence on radial diffusion distance will play a role in determining the populations of particles along the mainstream. Wielen's (1977) Tables 2, 3, and 4 already showed from the increase of velocity dispersion with stellar age that 2 kpc is a typical root-mean-square deviation for ΔR for the age of the sun. Those tables also reveal the $t^{1/2}$ dependence of ΔR on stellar age that one expects from a random walk. By these simplistic arguments I by no means pretend to dismiss this problem. Rather, I emphasize that a much more thorough study is needed to profile those carbon stars that actually do enter the solar cloud mass. That number depends on the history of star formation during the first half of the Galactic lifetime, and it depends on their own spatial density and gradient and on an analogous gradient in the density of massive molecular clouds.

A second related question concerns the masses of the AGB stars that have produced the mainstream SiC grains. STARDUST yield from carbon stars of different mass need not be proportional to the numbers of such stars, nor even to the total mass of their C-star ejecta, although the latter might make a reasonable first guess. Mainstream SiC grains are, after all, atypically large for interstellar dust. Those whose $^{29}Si/^{28}Si$ and $^{30}Si/^{28}Si$ number ratios are plotted in Figure 1 are larger than 1 μm in diameter, with smaller ones (Hoppe et al. 1996) suppressed to minimize confusion in that diagram. These large sizes may be selecting for AGB stars either of specific mass range or of a specific epoch in the carbon-star phases when the largest STARDUST can grow (Clayton & Timmes 1997). The stellar lifetime τ = 12 Gyr $(M/M_\odot)^{-3}$ determines the time available for diffusion; however, a star that is excessively old will have been born with a metallicity less than solar metallicity and will thus fall only on the bottom end of the mainstream. The trace elements Xe, Kr, Ba, and Nd in the SiC grains are known to be almost pure *s*-process (see, e.g., Srinivasan & Anders 1978; Ott & Begemann 1990; Zinner, Amari, & Lewis 1991; Guber et al. 1997), which first led (Clayton 1978, 1983; Clayton & Ward 1978) to the identification of carbon-star origin. But this second question clearly couples intimately with the first above.

A third question concerns the distribution of isotopic ratios of silicon isotopes along the mainstream. It is here that rich astronomical future lies. The upper end of the mainstream must derive from the most metal-rich presolar AGB stars that can diffuse to the solar cloud in the time allotted; moreover, that number density should be sparse because it requires a more rare conspiracy of scattering histories. But the exact manner in which that number density declines as it is approached carries a subtle history of Galactic evolution. In analogous manner, the decreasing population at the lower end may reflect the increasing difficulty faced by rarer lower metallicity C stars to diffuse inward toward the solar cloud. I would interpret the maximum in the concentration near $\delta^{29}_{\odot}$ = 40–60 as representing the best compromise between the outward direction of the diffusion with the time available for that diffusion (the stellar lifetimes) and the $t^{1/2}$ dependence of the root-mean-squared radial displacement. The flux of AGB stars contains their velocity with respect to the local rest frame, and that factor favors those that have diffused substantial distances over those that have not.

In summary, if AGB-star diffusion is the correct reason for the isotopic heaviness of the silicon in mainstream SiC particles, a rich connection to the dynamic and chemical evolution of the Milky Way will have been identified. It would provide yet another example of why it is that the study of presolar grains is truly a "new astronomy," a sobriquet in the title of my 1981 George Darwin Lecture (Clayton 1982). It would connect the early chemical evolution of the inner Galaxy and the spatial densities of both the star formation rate and of molecular clouds with the isotopic composition and dynamic history of the Sun. It would in part answer the question that I have frequently stressed: What is the Sun? Conversely, if this formulation is wrong, we remain stuck with the heretofore intractable question of the isotopic heaviness of the SiC mainstream. How else shall presolar stars near the sun be metal-rich in comparison with a Sun that is already metal-rich with respect to its present age and location?

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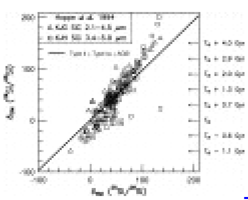
FIGURES



Full image (27kb) | Discussion in text

FIG. 1.—Silicon isotope deviations in a three-isotope plot. The renormalized mean-ISM evolution of Timmes & Clayton (1996) and its progression up the $m = 1$ slope line with time (*right ordinate*) at the location of solar birth are shown as the solid line. This evolution line is expressed as deviations (in parts per thousand) with respect to the mean ISM at solar birth (note subscripts on axes labels and see their eq. [2]). The times displayed on the right ordinate shift to increasingly earlier values for ISM locations increasingly close to the Galactic center. Deviations of the silicon isotopic compositions from the solar composition for Murchison grain data series KJG and KJH (177 data points; Hoppe et al. 1994a, 1994b) are shown; the full data set (584 data points; Hoppe et al. 1994a, 1994b, 1995, 1996) containing the smaller grain series, KJE, is omitted for clarity. These SiC grains are mostly isotopically heavier than the solar isotopic composition, which requires that they have been formed in carbon stars of higher metallicity than the Sun.

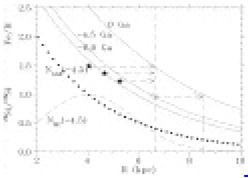
 Full image (17kb) | Discussion in text

FIG. 2.—Representation of the diffusion of the Sun and of three stars that intersected the presolar cloud as AGB carbon stars. The three solid curves represent the gradients of the gas metallicity at three different times: today (t = 0), the time of solar birth (t = -4.5 Gyr), and t = -6.0 Gyr. The magnitude of that gradient today, and the fact on which both Wielen et al.'s (1996) interpretation and my own rely, is $d[Fe/H]/dR$ = -0.09 dex kpc^{-1}. Other curves take the gradient to have been slightly larger into the past: -0.104 dex kpc^{-1} at t = -4.5 Gyr and -0.110 dex kpc^{-1} at t = -6.0 Gyr. Because those carbon stars are born in locations metal-rich with respect to the Sun, the three example AGB stars shown here all lie at larger $^{29}Si/^{28}Si$ and $^{30}Si/^{28}Si$ number ratios than does the presolar cloud. The numbered ordinate may be any of these three quantities, normalized to unity for the Sun. The number of AGB stars per unit volume, N_{AGB} , increases toward the Galactic center and is suggested schematically at t = -4.5 Gyr. Similarly, the space density N_{MC} of molecular clouds declines toward the solar position, although it may have a maximum somewhere near 4 kpc (as shown for illustration). At R = 6.6 kpc, where the Sun was born, the flux of AGB stars must be overwhelmingly outward. The negative gradient in both the number of AGB stars and the molecular clouds from which they scatter causes the excess outward direction when viewed from a larger distance (R = 6.6 kpc).
