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INTERSTELLAR RESIDENCE TIMES OF PRESOLAR SiC DUST GRAINS FROM THE MURCHISON CARBONACEOUS METEORITE

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ABSTRACT

The time span between the formation of presolar grains in stellar outflows and their incorporation into early solar-system solids is poorly constrained. Knowledge of this time span is essential for a better understanding of the processing of grains in the interstellar medium (ISM) and formation processes of the solar system. Here, we report interstellar residence times of ∼3–1100 Myr for large (∼5–50 μm) presolar SiC grains, based on their content of He and Ne produced by Galactic cosmic rays. A majority of these grains have interstellar residence times on the order of a few tens up to less than 200 Myr, considerably shorter than theoretical estimates of interstellar dust lifetimes (∼500 Myr), but long enough to require formation of the majority of the grains before that of the presolar molecular cloud. The age distribution may be explained by starburst activity 1–2 billion years prior to the birth of the Sun. Our findings provide essential "ground truth" to constrain models of interstellar dust lifetimes and destructive processes in the ISM.

Key words: circumstellar matter – cosmic rays – dust, extinction – ISM: kinematics and dynamics – stars: AGB and post-AGB – stars: winds, outflows

1. INTRODUCTION

Primitive meteorites contain microscopic grains that survived from times before the solar system existed. This pristine presolar archive is an important source of information about the formation of chemical elements in stars as well as the sources of material and the processes that led to the formation of our solar system. Isotopic studies of presolar grains, combined with nucleosynthetic model predictions and astronomical observations link the origin of the grains to a variety of stellar sources (e.g., Meyer & Zinner 2006). Silicon carbide (SiC) is the most widely studied type of presolar dust in meteorites. Most SiC grains originated in the outflows of asymptotic giant branch (AGB) stars, i.e., solar-like stars in their final stages. Some eventually ended up in the molecular cloud from which the Sun formed and were preserved in primitive meteorites. SiC grains are the main carrier of Ne–G (Tang & Anders 1988a), an important noble gas component in primitive meteorites produced by nucleosynthesis during He-shell burning in AGB stars (Gallino et al. 1990).

A reliable determination of the period between grain formation and their incorporation into the early solar system is very important for understanding interstellar processes. Conventional radiometric dating is hindered by small grain size, as well as the highly anomalous isotopic composition of essentially every element in SiC (e.g., Meyer & Zinner 2006). An alternative approach is to determine the length of time the grains were exposed to Galactic cosmic rays (GCRs) in the interstellar medium (ISM), by measuring GCR-produced nuclides, in particular noble gas isotopes (Tang & Anders 1988b; Lewis et al. 1994; Ott & Begemann 2000; Ott et al. 2005). These studies, made on collections of large numbers of approximately micron-sized presolar SiC grains ("bulk samples"), found GCR exposure ages of roughly 10^8 years or less, considerably shorter than estimated lifetimes of interstellar dust of 5×10^8 years (Jones et al. 1997). This led to the suggestion that the solar system formed partly from atypically young material (Tang & Anders 1988b), though later it was suggested that most of the GCR-produced (= cosmogenic) noble gases in bulk samples reside only in a small fraction of the grains which, if they were to be analyzed individually, might show presolar ages of up to more than 2×10^9 years (Lewis et al. 1994). The first results (Tang & Anders 1988a; Lewis et al. 1994), however, were thought to be invalid when it was realized that recoil losses of GCR-Ne from micron-sized grains are much larger than had been assumed and that the reported ^{21}Ne excesses are mainly of nucleosynthetic origin with an unknown fraction of cosmogenic ^{21}Ne (Ott & Begemann 2000). After this reassessment of recoil losses exposure ages of presolar grains were unknown. Spallation Xe in bulk SiC samples, which is much less affected by recoil loss, although difficult to measure, suggested GCR exposure ages of less than a few 10^7 years (Ott et al. 2005). Previously, there was no evidence of such short ages. Such low ages imply that the major fraction of ^{21}Ne measured by Lewis et al. (1994) is not of cosmogenic origin and confirm the suggestion by Ott & Begemann (2000) that it is mainly of stellar origin (see Ott et al. 2009 for a more detailed review of the recoil problem).

Longer presolar ages of between 4×10^7 and 1×10^9 years were recently inferred from Li data, under the assumption that ^{6}Li excesses measured in very large (5–60 μm) individual presolar SiC grains are entirely GCR-induced (Gyngard et al. 2007a, 2007b, 2009). For such large grains, recoil losses of Ne are small, and even a sizeable fraction of the cosmogenic He should have been retained. Thus, one can unequivocally determine their He and Ne presolar exposure ages, since the identification of GCR-produced ^{21}Ne and ^{3}He is quite straightforward and production systematics are relatively well understood. In this work we analyzed He and Ne isotopes in a

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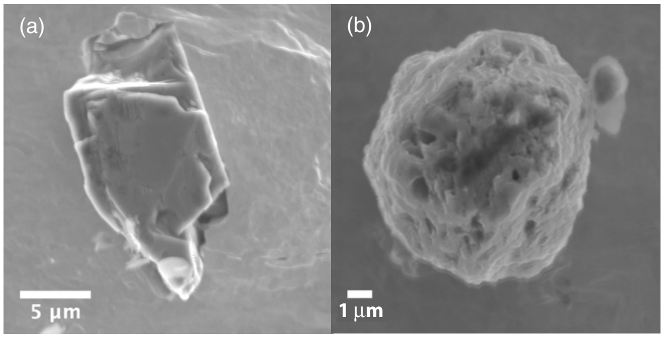

Figure 1. SEM images of two grains representative of the two distinct morphological types of LS+LU SiC grains. (a) Grain L2-9 might be a fragment of a larger interstellar grain. (b) Grain L2-19 is unlikely to be a fragment, shows euhedral surface features, and appears to be a well preserved SiC condensate.

suite of large presolar SiC grains and present their He and Ne isotopic composition, and their interstellar cosmic-ray exposure ages.

2. SAMPLES AND ANALYTICAL METHODS

Very large presolar SiC grains (diameter ∼2–50 μm; density ∼3.2 g cm^{-3}; the LS+LU fraction) were extracted at the University of Chicago from the Murchison carbonaceous chondrite (chondrite group/petrologic type CM2) during the L-series acid dissolution and density separation (Amari et al. 1994). With a micromanipulator, the grains were mounted on an ultraclean Au foil and then pressed into the Au with a quartz disk. Imaging and identification of SiC grains was performed at Washington University in St. Louis, with a scanning electron microscope (SEM) equipped with an energy-dispersive X-ray spectrometer (EDS) system (Figure 1). To verify the presolar nature of the grains, the C and Si isotopic compositions were measured with the Washington University NanoSIMS by using a primary Cs$^+$ ion beam and multicollection of ^{12,13}C$^-$ and ^{28,29,30}Si$^-$ secondary ions (Table 1).

Light noble gases from 22 of the 68 grains (diameters ∼5–50 μm; except for one 2 μm grain of a rare type, see below; Tables 1 and 2) were analyzed in Zurich using a slightly modified method developed for the analysis of micron-sized presolar SiC grains (Heck et al. 2007). Gases were extracted by melting the grains with a Nd-YAG laser. After purification with hot metal getters and cold traps, the sample gas was pumped by an inverse molecular drag pump into a small ionization chamber. The resulting high concentration of the sample gas in the ion source leads to a 2 orders of magnitude higher sensitivity for the isotopic analysis of He and Ne compared with that achieved with the same mass spectrometer without such a compressor ion source (Baur 1999). Helium-3,4 and ^{20,21,22}Ne were detected with an electron multiplier in ion counting mode. The memory and background signals of the system were recorded and subtracted from the sample data. Calibration gas amounts are accurate to ∼1% to ∼2%. Grain volumes were estimated from SEM images: the lengths of two axes were measured; the length of the third axis was estimated. Nonspheroidal grains very probably settled on the Au foil such that the third dimension tended not to be longer than any of the two measured axes. We therefore estimated grain volumes by fitting simple geometric shapes to the grains, e.g., we fitted rectangular prisms to 11 grains (e.g., grain L2-9, Figure 1) with two equal short axes and a long axis, and a hexagonal prism to one grain (L2-1). For seven spheroidal grains (e.g., grain L2-19, Figure 1) we assumed spheres with a diameter equal to the arithmetic mean of the shortest and longest measured grain diameters. Three grains were fitted with a pyramid (L2-4, L2-15, and L2-16). The resulting uncertainty in mass is estimated to be a factor of 1.5. Morphologies of the studied grains are clearly inconsistent with the grains being aggregates of smaller grains. While grains with morphologies like that of grain L2-9 (Figure 1(a)) may be fragments of larger grains, this possibility can be excluded for grains with euhedral surfaces (Figure 1(b)). We discuss the implications of larger interstellar parent grains and larger grain aggregates in Section 5.4.

3. RESULTS

3.1. C and Si Isotopic Ratios

The Si and C isotopic compositions identify most of the analyzed SiC grains as presolar mainstream originating from AGB stars, while a few grains are so-called AB grains (Table 2, and Figures 2 and 3), for which a connection to J-type carbon stars and born-again AGB stars has been suggested (Hoppe et al. 1994, 1996; Amari et al. 2001). All data points in the Si three-isotope diagram (Figure 2) fall near the correlation line obtained for mainstream SiC grains, which originated from AGB stars of ∼1.5–3 $M_\odot$. However, four grains selected for noble gas analysis have ^{12}C/^{13}C < 12 (Figure 3), three of which have ^{12}C/^{13}C < 10, characteristic of presolar SiC grains of type AB. About 6% of the 68 grains from fractions LS+LU mounted for this study are thus AB grains. This is close to the abundance of 5% for AB grains among Jumbo SiC grains previously reported (Virag et al. 1992). In addition to the AB grains with ^{12}C/^{13}C < 12, the carbon isotopic ratios show two further clusters (Figure 3). Most grains have ^{12}C/^{13}C ratios between 40 and 60, while six grains have close to solar ^{12}C/^{13}C ratios. Three of these grains (L2-04, -05, -16) have anomalous Si isotopic compositions, clearly identifying them as extraterrestrial. L2-02 and L2-07 might be terrestrial contamination (see below).

3.2. Cosmogenic He and Ne—Noble Gas Deconvolution

Measured noble gases are mixtures of different noble gas components. A Ne three-isotope diagram allows identification of the most important Ne components (Figure 4). Our analyses of the LS+LU grains showed that the measured Ne is largely of atmospheric origin, because data points plot relatively close to the Ne isotopic ratios of air, whereas nucleosynthetic He-shell Ne in SiC has a ^{20}Ne/^{22}Ne ratio <0.1 (Gallino et al. 1990; Heck et al. 2007). This is due to large blank Ne contributions from degassing gold on the sample holder. These blank values are roughly 2 orders of magnitude higher than those in previous analyses of single presolar SiC grains (Heck et al. 2007) because pressing the large grains into the gold foil (necessary for the preceding NanoSIMS analysis) leads to a very good thermal contact between grain and gold. The highest blank values were observed in the first few analyzed grains, when the surrounding gold partly melted. Subsequently, gas from grains was extracted with less laser power, but noble gas extraction remained complete, as was verified by re-extraction. Despite the large blanks, excess ^{21}Ne of cosmogenic origin was found for most grains. This was done by a three-component deconvolution, assuming as endmember compositions (1) air, (2) nucleogenic Ne–G, taking the Ne–G isotopic ratios predicted by Torino models for an AGB star with 1.5 $M_\odot$ and solar metallicity (^{21}Ne/^{22}Ne $= 5.9 \times 10^{-4}$, Gallino et al. 1990; and ^{20}Ne/^{22}Ne $= 6.5 \times 10^{-2}$, Heck et al. 2007), and (3) interstellar

Table 1
Noble Gas, C, and Si Data of Jumbo SiC Grains

	Mass (ng)	Diam. (μm)	^{3}He (10^{-8} cm^{3} STP g^{-1})	^{4}He	^{20}Ne	^{21}Ne	^{22}Ne	^{21}Ne$_{cos}$	^{12}C/^{13}C	δ^{29}Si (‰)	δ^{30}Si
L2-01	2.69	7.3	207	260000	1551	21.3	305	16.7	42.28	156	116
			11	3490	388	10.3	30	8.4	0.20	5	7
L2-02	*4.23*	*11.0*	*0*	*4510*	*721*	*−7.4*	*65*	...	*93.19*	*−14*	*−10*
				1593	*256*	*7.6*	*24*		*0.56*	*5*	*6*
L2-03	144	35.6	43.7	38500	13600	257	1151	218	48.52	39	57
			1.8	6050	354	28	60	24	0.24	5	6
L2-04	0.82	9.2	−36	169000	120000	376	11300	20.1	91.06	−5	17
			43	9970	2110	29	438	27.1	0.47	4	6
L2-05	0.60	5.7	87	38000	11200	−83	471	...	92.06	−24	−11
			54	13200	2250	15	485		0.54	5	6
L2-06	16.6	17.3	20.5	3400	941	9.8	127	7.0	51.40	91	82
			1.4	228	33	0.7	10	0.5	0.24	5	6
L2-07	*2.20*	*8.8*	*10.2*	*14500*	*1270*	*0.6*	*284*	...	*90.33*	*9*	*10*
			9.4	3490	223	14.2	152		0.46	4	6
L2-08	18.8	18.0	25.9	2930	262	1.1	14.7	0.3	48.70	24	55
			6.0	330	15	1.3	8.6	0.8	0.24	5	6
L2-09	3.47	10.3	21	9810	4730	26	475	12.2	48.31	40	58
			14	2680	208	5	37	3.0	0.22	5	6
L2-10	2.33	9.0	65	15600	2150	14	315	7.5	58.07	−48	6
			19	1700	221	16	64	10.3	0.32	5	7
L2-11	2.75	11.8	60	21700	464	47	162	45.4	56.66	108	77
			15	2700	337	11	71	10.5	0.31	5	7
L2-12	2.22	11.0	287	22000	2860	57	368	48.2	3.59	−35	−7
			31	1900	172	8	58	7.0	0.01	5	7
L2-13	0.81	7.8	88	35000	8340	−3	962	...	65.25	27	32
			21	7470	828	24	70		0.41	5	7
L2-14	2.23	11.0	164	1270000	9090	62	858	35.1	48.89	12	28
			24	2620	478	10	82	6.4	0.26	5	7
L2-15	0.93	9.6	88	12700	9080	−4	1550	...	48.02	53	66
			35	8020	873	25	110		0.22	5	6
L2-16	0.57	8.1	−2	34400	9930	58	−172	29	93.01	−19	−21
			11	5320	1690	43	301	27	0.57	5	6
L2-17	1.93	8.4	35	10100	1420	−22	63	...	89.82	10	16
			11	1650	727	15	49		0.43	4	6
L2-18	12.2	15.6	29.5	28300	436	6.9	66	5.7	48.33	51	53
			5.1	597	50	2.8	26	2.3	0.21	5	6
L2-19	1.37	9.3	87	15700	6250	61	760	42.7	49.86	68	69
			12	3680	742	12	178	9.2	0.27	5	7
L2-25	0.19	4.9	166	121000	49900	328	6521	180	11.94	51	46
			57	31000	2530	122	1156	77.6	0.05	5	7
L2-27	0.025	2.0	263	952000	357000	2230	57900	1170	6.82	38	50
			362	257000	30900	1050	6160	657	0.03	5	7
L2-57	0.33	5.8	123	107000	76100	359	7698	135	3.23	58	41
			43	18300	3260	50	552	30.7	0.01	5	7

Notes.
Diam.: geometric mean of length of three main grain axes. Diameter and mass do not perfectly correspond to each other, since different grain shapes (e.g., spheres, prisms, pyramids, etc.) were adopted to calculate volume. The cosmogenic ^{21}Ne$_{cos}$ is calculated as explained in the text. The measured ^{3}He is assumed to be entirely of cosmogenic origin. The carbon isotopic compositions given in absolute ratios, Si compositions in δ-values, permil deviations from terrestrial ^{29}Si/^{28}Si and ^{30}Si/^{28}Si ratios. Data of grains L2-02 and L2-07 are given in italics, since these grain may be terrestrial contaminants. Stated uncertainties are 1σ (given in the second row of each sample).

cosmogenic Ne in SiC (Reedy 1989). Adopting a higher ^{21}Ne/^{22}Ne ratio of 3.3×10^{-3} predicted for 3 $M_\odot$ solar-metallicity AGB stars (Karakas et al. 2008) and the upper limit for the ^{18}F(α,p)^{21}Ne reaction rate leads to slightly different calculated cosmogenic ^{21}Ne fractions, but the difference would be less than 5% in most cases and would not exceed 15% for any grain. The reason that the choice of the ^{21}Ne/^{22}Ne ratio of the G component is not critical is the fact that the measured ^{21}Ne/^{22}Ne ratios obtained in this study are considerably higher than those obtained from bulk analysis (Lewis et al. 1994). For our three-endmember deconvolution, we use the ^{21}Ne/^{22}Ne–G ratio predicted by Gallino et al. (1990). For grain L2-03, the deconvolution was also done by assuming one endmember to be solar Ne instead of atmospheric Ne (Figure 4), but the resulting amount of cosmogenic ^{21}Ne changes only slightly. It is unclear whether the relatively high ^{20}Ne/^{22}Ne ratio measured in this grain is due to a solar-like trapped component or fractionated atmospheric Ne from partly molten gold, as this grain had been heated considerably more than the grains analyzed later. For grains where the measured or He-shell-corrected ^{21}Ne/^{20}Ne ratio does not exceed the atmospheric composition by $>2\sigma$, we give an upper limit for cosmogenic ^{21}Ne by adding the 2σ

Table 2
Interstellar Exposure Ages of Presolar Jumbo SiC Grains

Sample	Size (μm)	Type	T_{21} (Myr)	T_3	$T_{21\mathrm{cor}}$	$T_{3\mathrm{cor}}$
L2-01	7.3	ms	29 ± 15	49 ± 3	57 ± 28	*271 ± 14*
L2-02	11.0	tc or ms				
L2-03	35.6	ms	389 ± 42	10 ± 1	433 ± 47	30 ± 1
L2-04	9.2	ms	<132	<11	<219	<58
L2-05	5.7	ms	<18	20 ± 13	<48	128 ± 80
L2-06	17.3	ms	12 ± 1	4 ± 1	15 ± 1	18 ± 1
L2-07	8.8	ms		1 ± 2		11 ± 11
L2-08	18.0	ms	<3	6 ± 1	<3	22 ± 5
L2-09	10.3	ms	21 ± 5	4 ± 3	32 ± 8	23 ± 16
L2-10	9.0	ms	<49	15 ± 5	<83	77 ± 23
L2-11	11.8	ms	80 ± 19	13 ± 4	117 ± 27	63 ± 16
L2-12	11.0	AB	85 ± 13	68 ± 7	128 ± 19	*314 ± 34*
L2-13	7.8	ms		20 ± 5		111 ± 27
L2-14	11.0	ms	62 ± 12	39 ± 6	93 ± 17	*179 ± 26*
L2-15	9.6	ms		20 ± 8		101 ± 41
L2-16	8.1	ms	51 ± 48	< 4	92 ± 86	<24
L2-17	8.4	ms	<22	7 ± 3	<39	42 ± 14
L2-18	15.6	ms	9 ± 4	7 ± 1	12 ± 5	27 ± 5
L2-19	9.3	ms	75 ± 16	20 ± 3	124 ± 27	102 ± 14
L2-25	4.9	AB or ms	319 ± 139	39 ± 1	1070 ± 460	264 ± 91
L2-27	2.0	AB	*2090 ± 1200*	<240	...	*<2639*
L2-57	5.8	AB	239 ± 55	29 ± 10	611 ± 139	179 ± 63

Notes.
Stated uncertainties (1σ) represent analytical uncertainties. Overall uncertainties are discussed in the text. $T_{21\mathrm{cor}}$ and $T_{3\mathrm{cor}}$ are recoil-loss-corrected exposure ages. Recoil corrections are considerable larger and hence more uncertain for ^{3}He than for ^{21}Ne. $T_{3\mathrm{cor}}$ values for three grains with much higher T_3 than T_{21} are thus given in italics. Classification of grains as presolar mainstream (ms) or AB SiC grains is based on their C and Si isotopic compositions (Table 1). Size is the geometric mean of the length of the three grain axes. Grain LS-02 (italicized) may be terrestrial contaminant (tc). See the main text.

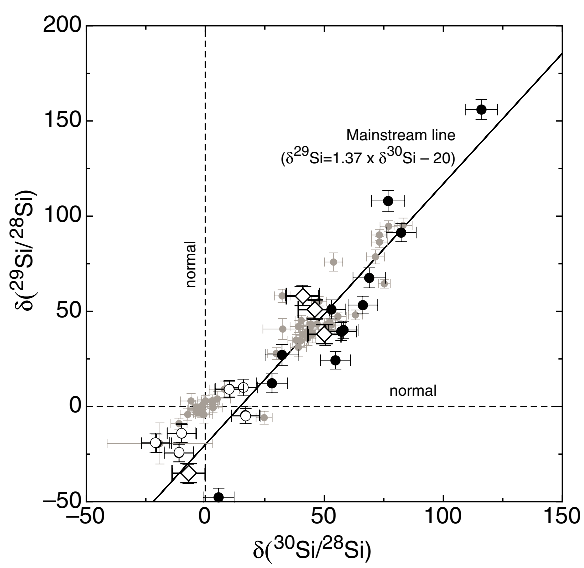

Figure 2. Si isotopic compositions of presolar LS+LU SiC grains. Shown are the permil deviations (δ-values) of ^{29}Si/^{28}Si and ^{30}Si/^{28}Si ratios from the solar ("normal") ratios 0.050823 and 0.033534 (Valkiers et al. 2005). All data points fall close to the line with a slope of 1.37 characteristic for mainstream SiC grains (Zinner et al. 2007). ^{12}C/^{13}C ratios <12 of the four grains marked by open diamonds indicate that these are AB grains. Grains with open circles have ^{12}C/^{13}C ratios close to 89 (normal). Grain L2-02 might be terrestrial SiC, all others have most likely a presolar origin from a number of different parent stars (see the text). Gray symbols depict the compositions of LS+LU SiC grains measured by Virag et al. (1992). Error bars are 1σ analytical uncertainties in all figures.

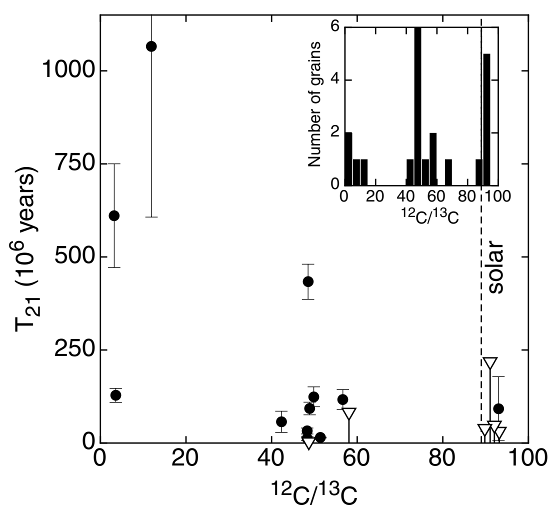

Figure 3. Recoil-corrected interstellar residence times ($T_{21\mathrm{cor}}$) vs. C isotopic compositions of the large SiC (LS+LU) grains analyzed. Triangles indicate grains for which only upper limits of T_{21} have been determined. The different interstellar residence times require the grains to have originated from more than one parent star. Inset: the histogram shows ^{12}C/^{13}C ratios of all grains analyzed.

uncertainty to the amount of ^{21}Ne determined. For four grains, the memory-corrected ^{21}Ne contents were negative even when adding the 2σ uncertainty. For these grains, no T_{21} values are reported.

All grains have ^{3}He/^{4}He ratios much higher than the atmospheric ratio of 1.4×10^{-6}. Corrections for blank ^{3}He are therefore negligible. Nucleosynthetic He–G accompanying Ne–G is

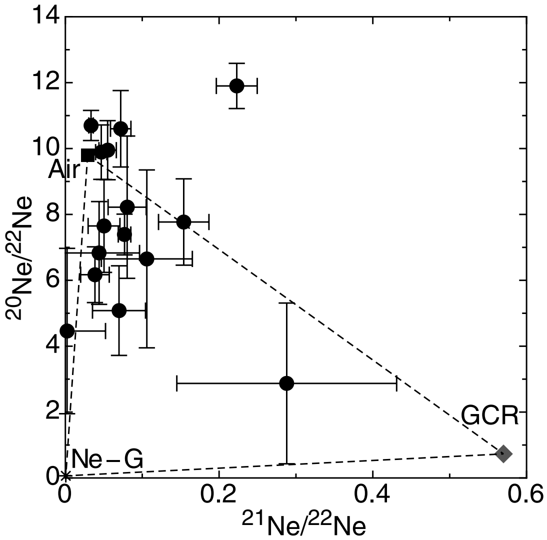

Figure 4. Ne isotopic composition of the large LS+LU SiC grains measured in this study. Most data points in this three-isotope diagram plot in the mixing field spanned by the endmember compositions of terrestrial atmosphere "air", intrinsic AGB star He-shell Ne "Ne–G" (Gallino et al. 1990; Heck et al. 2007), and interstellar cosmogenic Ne "GCR" (Reedy 1989).

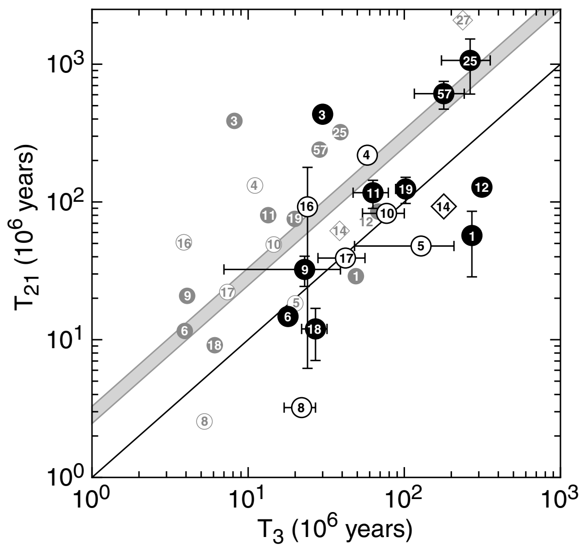

Figure 5. Interstellar residence times derived from GCR-produced ^{21}Ne (T_{21}) and ^{3}He (T_3). Raw ages (gray symbols) and recoil-corrected ages (black symbols) are shown labeled with the sample identifier. Filled circles: both, $^{3}He_{GCR}$ and $^{21}Ne_{GCR}$ detected. Open circles: for one or both isotopes only an upper limit could be deduced. Open diamonds: measured ^{3}He/^{4}He ratio close to solar wind value, with ^{3}He assumed to be entirely GCR-produced. Interstellar production rates are based on Reedy (1989). Error bars (1σ) are shown for the corrected ages if larger than symbol size and include analytical uncertainties only. Uncorrected ages have the same relative uncertainty. Uncertainties due to uncertainties in grain masses and in interstellar ^{3}He and ^{21}Ne production rates are not included. These uncertainties lead to overall uncertainties in reported nominal ages of about a factor of 3, whereas the age ratio T_3/T_{21} has a systematic uncertainty of about 40%. For the size range of the analyzed grains, the retention ratio ^{3}He/^{21}Ne is between 0.3 and 0.4 (gray band) and should be consistent with uncorrected ages. Data points lie on the solid line representing $T_3/T_{21} = 1$ if their recoil-corrected ages match. See the text for a more detailed discussion on productions rates and uncertainties.

expected to be essentially free of ^{3}He (Gallino et al. 1990). We assume therefore that all measured ^{3}He is cosmogenic and do not correct for a potential trapped component. Note that most grains also have ^{3}He/^{4}He ratios considerably higher than the solar wind value of 4.53×10^{-4} (Heber et al. 2008), the highest likely ratio for a putative trapped He component. This indicates that even an unlikely solar He component in the SiC grains would not lead to a major correction for $^{3}He_{cos}$. This is corroborated by the position of the data points of the few grains with measured ^{3}He/^{4}He ratios below the solar wind value in Figure 5 (open diamonds). These data points fit well within the data pattern of the other grains.

3.3. Nucleosynthetic He-shell Ne

The large presolar LS+LU SiC grains analyzed here are significantly different than the smaller SiC grains from the K-series separates (Lewis et al. 1994) and the small SiC grains from Murchison and Murray extracted in Mainz (Heck et al. 2007). They are not only larger but also have a distinct morphology, and have lower trace element concentrations (Virag et al. 1992; Amari et al. 1995; Gyngard et al. 2009) and they also have much lower ^{22}Ne–G concentrations. The LS+LU SiCs continue the trend of decreasing ^{22}Ne–G concentrations with increasing grain size, observed for the micron-sized Mainz SiC grains (Heck et al. 2007), to larger grain sizes (Figure 6). This trend is also consistent with Ne–G concentrations determined from bulk analyses of grain size fractions KJF, KJG, and KJH from the KJ-series (Lewis et al. 1994). Such a trend is expected if Ne–G is implanted into the surface of already condensed SiC grains (Gallino et al. 1990) by a high-speed wind of pure He-shell composition during the post-AGB phase when the envelope has already been lost. Verchovsky et al. (2004) explained the variation of Ne–G with grain size in the bulk SiC data obtained by Lewis et al. (1994) with a Transport of Ions in Matter (TRIM; Ziegler 2004) implantation model. Models with implantation energies consistent with high-speed post-AGB star winds lead to ^{22}Ne-ion stopping depths in SiC of ~0.8 μm (Verchovsky et al. 2004). Thus, larger grains, such as the LS+LU SiCs, will have Ne implanted only into their outer layers and the overall Ne–G concentration decreases with increasing grain size, qualitatively consistent with the trend in Figure 6. On the other hand, concentrations decrease in grains smaller than the Ne-ion stopping distance, as most Ne ions will simply traverse the small grains, as evidenced by bulk data of the small grain fractions (KJA, KJB, KJC, KJD, and KJE; Lewis et al. 1994).

4. PRESOLAR AGES

4.1. Interstellar He and Ne Production Rates

In order to determine interstellar cosmic-ray exposure ages we need to know interstellar production rates of noble gas nuclides in SiC by GCRs. Production rates of He and Ne in interstellar dust particles (<1 cm) have been estimated by Reedy (1989). In contrast to micron-sized and larger objects, secondary neutrons do not play a major role in producing cosmogenic nuclides. The interstellar rates are based on the assumption that the GCR flux >4.5×10^{9} years ago was the same as today and flux estimates are based on modern spectra of interstellar protons measured by balloon and spacecraft experiments (e.g., Webber & Yushak 1983). A further assumption is that the GCR flux was on average constant in space. The GCR flux and spectra are discussed in Reedy (1987) and cross sections are discussed in Reedy (1989, 2008). We multiply Reedy's values given for interstellar protons by a factor of 1.33 to account for contributions by α-particles. This mean scaling factor was obtained by Ott et al. (2005) from a comparison of experimental production rates for different target–product combinations of

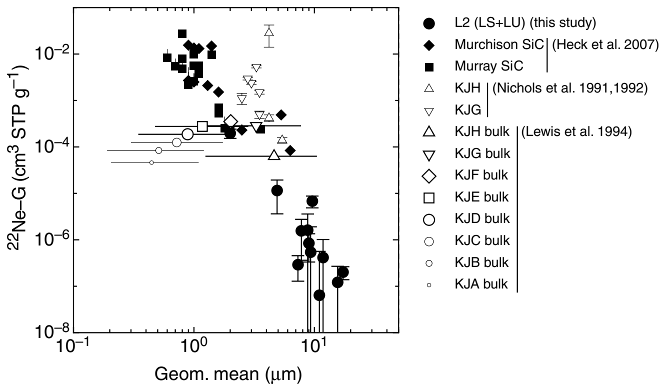

Figure 6. Grain sizes and Ne–G concentrations of presolar SiC grains. A trend of Ne–G concentrations decreasing with increasing grain size can be observed for the large LS+LU Murchison SiC grains studied here and for the micron-sized Murchison and Murray SiC grains studied by Heck et al. (2007). This trend is also consistent with most single grain analyses from Murchison KJH and KJG grains by Nichols et al. (1991, 1992) and bulk analyses of Murchison KJH, KJG, and KJF SiC by Lewis et al. (1994). An opposite trend is observed for Lewis et al. (1994)'s bulk analyses of size fractions of smaller grains KJA to KJE (see the text). Horizontal bars display the grain size range for each bulk size fraction from Lewis et al. (1994). Vertical bars are 1σ analytical uncertainties. STP, standard temperature and pressure.

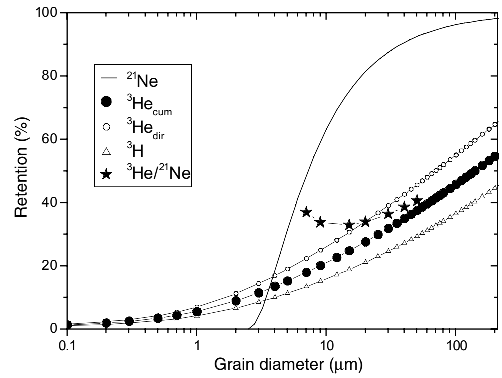

Figure 7. Retained fractions of cosmogenic ^{3}He and ^{21}Ne in spherical SiC grains. Fractions of directly produced $^3He_{dir}$, ^{3}H, as well as cumulative ^{3}He ($^3He_{cum}$, assuming a production ratio $^3He_{dir}/^3H = 1{:}1$) are shown. Calculations are based on the recoil momentum distribution of ^{3}He and ^{3}H produced by fragmentation of ^{12}C and ^{16}O projectiles on a variety of target elements (Greiner et al. 1975) and the range of energetic ions in SiC calculated by the SRIM code (Ziegler 2004). The ratio of retention factors for ^{3}He and ^{21}Ne (the latter calculated as described in the text) is fairly constant (between 30% and 40%) over the entire grain size range relevant here (stars; the slight apparent increase toward small grain sizes is an artifact caused by the overestimate of the ^{21}Ne loss fraction at small grain sizes due to the simplified assumption of a single recoil distance of ^{21}Ne).

light elements. It expresses the fact that the cross section for α-particles is ~2.5 times that of protons, which is the ratio of geometrical cross sections (Ott et al. 2005). We determine the following interstellar ^{3}He and ^{21}Ne production rate for SiC dust: $P(^3\mathrm{He})_{\mathrm{SiC}}$ = ~2120 atoms minute^{-1} kg^{-1} = 4.15 × 10^{-8} cm^3 STP g^{-1} Myr^{-1} and $P(^{21}\mathrm{Ne})_{\mathrm{SiC}}$ = 286 atoms minute^{-1} kg^{-1} = 5.60 × 10^{-9} cm^3 STP g^{-1} Myr^{-1}. Recoil corrections are not included in these rates and are applied later to each grain (see Section 4.2). Uncertainties of these production rate estimates are discussed below. The interstellar values are about a factor of 2 higher than corresponding ^{3}He and ^{21}Ne production rates in the heliosphere for both SiC grains embedded in average-sized meteorites as well as values for average-sized bulk carbonaceous chondrites (Leya et al. 2000). Given the short recent GCR exposure age of Murchison of ~10^6 years (Roth et al. 2008), a correction for He and Ne produced in the SiC grains during this recent exposure is thus in most cases negligible. All ages presented here have nevertheless been corrected for this recent exposure.

4.2. Recoil Loss of Cosmogenic He and Ne

4.2.1. Neon-21

All presolar grains have sizes where loss of cosmogenic nuclides by recoil is important and has to be corrected for. An approximate estimate of losses due to spallation recoil can be made by assuming spherical grains and a single mean recoil distance (Tang & Anders 1988a, 1988b). Adopting a recoil distance of 2.5 μm as measured by Ott and Begemann (2000) and following the formalism of these authors (Equations (1) and (2) in Ott and Begemann 2000), we obtain a recoil loss of $^{21}Ne_{cos}$ of about 70% from SiC grains of 5 μm diameter, about 40% for 9 μm grains and ~20% for ~20 μm grains. For most of our grains, ^{21}Ne recoil losses are thus 40% or less. Note also that, especially for small grains, the approximation of a single recoil distance leads to an overestimate of the actual recoil loss, since some of the recoiling nuclei will have a considerably lower momentum than the average, depending on the shape of the momentum distribution (Ott & Begemann 2000). In Table 2 and Figure 5 we give—in addition to the uncorrected ages—recoil-corrected ages $T_{21\mathrm{cor}}$ and $T_{3\mathrm{cor}}$ by assuming spherical grains with diameters equal to the geometric means of the lengths of the three grain axes. Recoil loss is discussed in more detail in Ott et al. (2009).

4.2.2. Helium-3

Recoil losses for ^{3}He have been estimated based on the momentum distribution of isotopes produced by fragmentation of C and O projectiles (Greiner et al. 1975) and using the SRIM ion implantation code (Ziegler 2004). This approach is discussed in more detail by Ott et al. (2009) and Huss et al. (2008). Figure 7 shows the calculated percentage of retained ^{3}H and directly produced $^3He_{dir}$, respectively, for spherical SiC grains as a function of grain diameter. The cumulative ^{3}He retention also shown assumes equal production rates for ^{3}H and $^3He_{dir}$. As an example, grains of 10 and 100 μm diameter lose about 80% and 55% of their total ^{3}He, respectively. Given the large mean recoil distance (defined here as the range exceeded in 50% of cases) of 90 μm and 20 μm of ^{3}H and ^{3}He, respectively, the calculated retention fractions may seem surprisingly high compared with the corresponding values for ^{21}Ne, especially for small grains. This result is caused by the broad momentum distribution of recoiling ^{3}H and ^{3}He atoms. Figure 7 also shows the ratio of the retained fractions of $^3He_{cum}$ and ^{21}Ne. Remarkably, this ratio is fairly constant over the grain size range shown (the increase at the low end of the considered range is presumably an artifact due to the slightly overestimated ^{21}Ne loss from small grains when assuming a single recoil distance of 2.5 μm). Retention of ^{3}He is thus roughly three times lower than ^{21}Ne retention for essentially all grains of this study.

4.3. Interstellar Cosmic-ray ^{21}Ne and ^{3}He Exposure Ages

Ne and He isotopes of 22 large presolar SiC grains were measured (Table 1 and Figure 4). For 19 grains, cosmic-ray-produced ^{21}Ne and/or ^{3}He was found, while for the remaining grains only upper limits were obtained.

Nominal ^{21}Ne and ^{3}He exposure ages (T_{21} and T_3) are given in Table 2 and plotted in Figure 5. Apart from the ages corrected for recoil losses, we also show the uncorrected ages.

Uncorrected T_3 ages are typically lower than corresponding uncorrected T_{21} ages. Within 2σ errors the (uncorrected) T_3/T_{21} ratios mostly agree with the ratio of 0.3–0.4 expected due to the larger recoil loss of ^{3}He. Corrected ages range from ~3 to ~1100 Myr. Most grains (~80%) have corrected ages below about 200 Myr, and more than half of these grains have ages of less than a few tens of million years. Three grains have ages in the range of expected interstellar lifetimes (grains L2-03, L2-25, L2-57: 433 ± 47, 1070 ± 460, and 611 ± 139 Myr, respectively). L2-27 is the smallest grain in our study (2 μm diameter) and has only been selected because of its classification as the rare AB type. Because of its small size, a reliable recoil correction of its ^{21}Ne age of 2.1 ± 1.2 Gyr (1σ) is impossible (the grain is even smaller than our adopted mean recoil range of ^{21}Ne). However, from the irradiation experiments by Ott and Begemann (2000) it can be roughly estimated that at least 90% of the cosmogenic Ne would have recoiled out of this grain if its size in interstellar space had been the same as it is today. Its nominal recoil-corrected ^{21}Ne age would thus exceed the age of the universe and even its recoil-corrected 1σ lower limit would still be on the order of 10^{10} years. Since the 2σ error interval of this grain's ^{21}Ne age overlaps with zero, we discard this grain from further discussion. If we apply a 2σ error age rejection criterion to all other grains, only one additional grain (L2-16, $T_{21\mathrm{cor}} = 92 \pm 86$ Myr) is affected. Interestingly, two of the three grains with high ages are AB-type grains, which have different stellar sources than the other grains. Three other grains have $T_{3\mathrm{cor}}$ ages between ~200 and 300 Myr (numbers in italics; Table 2), but these are three out of four grains with T_3/T_{21} being higher than expected from the difference in recoil loss. Since recoil correction is more uncertain for ^{3}He than for ^{21}Ne, we prefer the smaller $T_{21\mathrm{cor}}$ values for these grains. A possible explanation for the high apparent $T_{3\mathrm{cor}}$ ages is presented below, where we also address grain L2-03 with an exceptionally low T_3/T_{21} ratio of ~0.028. Only upper limits of ^{21}Ne exposure ages are obtained for grains L2-17 and L2-05, which have close to solar ^{12}C/^{13}C ratios. However, both grains have ^{3}He exposure ages that differ from zero by 3σ and 1.6σ, respectively, and L2-05 has also a δ^{29}Si value of 4.8σ below solar. For grain L2-02, we do not report an exposure age and its ^{12}C/^{13}C ratio is slightly above solar. For grain L2-07, only a ^{3}He exposure age, consistent with zero within 1σ, is reported, and its ^{12}C/^{13}C ratio is consistent with solar. Since SiC is a high-temperature condensate we deem it unlikely that grains L2-02 and L2-07 condensed in the presolar molecular cloud or in the solar system as proposed for some graphite grains with solar ^{12}C/^{13}C ratios, based on their large enrichments in ^{15}N (Zinner et al. 1995). This leaves grains L2-02 and L2-07 who cannot unequivocally be classified as presolar grains; they might be terrestrial SiC.

The reported exposure ages do not correlate with ^{12}C/^{13}C ratios. Hence, the grains must have originated from a larger number of parent stars than suggested by the three clusters of carbon isotopic ratios (Figure 3). A multiple-star origin is also supported by the distribution of the Si isotopic data.

4.4. Overall Uncertainties of Reported Exposure Ages

The reported ages are rather imprecise, due to several sources of uncertainties, which are discussed in the following. Most of the uncertainty in the amount of cosmogenic ^{21}Ne is caused by the correction for atmospheric Ne (uncertainty 1), hence mainly the uncertainty of the measured ^{21}Ne/^{20}Ne ratio, whereas the correction for nucleogenic ^{21}Ne–G (uncertainty 2) does not lead to a large uncertainty (see Section 3.3). An additional large source of error for the concentration of ^{21}Ne$_{\mathrm{cos}}$ is the estimation of grain volume (uncertainty 3), which has uncertainties of roughly a factor of 1.5. Grain size and shape also dominate the uncertainty in the recoil losses of ^{21}Ne$_{\mathrm{cos}}$ (uncertainty 4). As discussed above, this uncertainty is usually much smaller than the other errors, except for the few smallest grains, which have very inaccurate ages anyway. Altogether, the uncertainties in $T_{21\mathrm{cor}}$ due to the above sources of error are roughly a factor of 2. Gas loss by diffusion is not significant in most of the grains, possibly except for grain L2-03 (uncertainty 5; see the discussion in Section 5.2). In addition, there is an uncertainty when extrapolating from the heliosphere to the ISM. The systematic uncertainty of interstellar production rates of ^{21}Ne is about a factor of 2 (uncertainty 6; Reedy 1989; R. C. Reedy 2008, private communication). Quadratically, adding these different errors thus leads to an overall uncertainty in individual $T_{21\mathrm{cor}}$ values of about a factor of 2.8, whereby the factor of 2 from the interstellar production rates has to be considered as a systematic uncertainty. The uncertainty in the interstellar production rate ratio $P(^3\mathrm{He})/P(^{21}\mathrm{Ne})$ is 30%–50%, mainly due to uncertainties in the interstellar GCR spectra and cross sections (uncertainty 7; R. C. Reedy 2008, private communication).

The assumption that the GCR flux some 4.6×10^9 years ago was the same as today obviously cannot be verified, since no meteorites with such long exposure ages are available. Although it has been suggested that the GCR flux in the past few megayears has been about 40%–50% higher than the average over the past ~10^9 years or so (Voshage 1984; Lavielle et al. 1999), new data on iron meteorites and new model calculations of the cosmogenic nuclide production do not confirm this and suggest, if anything, rather a slightly lower GCR flux in the past few megayears compared with the long-term average (Ammon et al. 2008). Therefore, we do not assign an uncertainty to our GCR flux assumption.

4.5. Long Regolith Irradiation or Irradiation by an Early Active Sun?

We discussed above that only a small fraction of the cosmogenic He and Ne in the SiC grains has been acquired during the recent transfer of the Murchison meteorite from its parent asteroid to Earth and we corrected our results accordingly. However, a minor fraction (about 1%) of olivine grains in Murchison (and other CM chondrites) contains higher concentrations of cosmogenic ^{21}Ne than what can have been produced during the meteoroid exposure stage (Hohenberg et al. 1990). Some of these olivine grains have ^{21}Ne$_{\mathrm{cos}}$ excesses of the same order of magnitude as the majority of the SiC grains studied here. The gas-rich olivine grains also contain solar flare tracks, i.e., radiation damage induced by heavy energetic particles from the Sun. The ^{21}Ne excesses and the solar flare tracks must have been produced by an energetic particle irradiation prior to the compaction of Murchison, perhaps in the early solar system. It remains controversial, however, whether the excess cosmogenic Ne is the result of a high flux of energetic particles emitted by an active early Sun (Hohenberg et al. 1990), or whether it is evidence for a long (~10^8 years) irradiation by GCRs in the parent-body regolith of Murchison (Wieler et al. 2000).

The question here is whether the cosmogenic noble gas excesses in the presolar SiC grains were actually also produced in the same way as the excess ^{21}Ne in the irradiated olivines, rather than by a presolar GCR irradiation as we assume here. The answer is: no. Tang and Anders (1988b) have already pointed out that it would require a Maxwellian demon to preferentially target most crystals of a rare mineral such as SiC to receive a high radiation dose in the Murchison parent-body regolith, when only about 1% of the olivine grains of solar-system origin have been irradiated. To expose the olivines (and putatively also the SiC grains) to an early active Sun as individual grains in the solar nebula requires a very improbable scenario, in which most presolar SiC grains but only a very small fraction of olivines of solar-system origin were exposed to similar doses of solar energetic particles. This is very unlikely and we therefore can safely assume that the cosmogenic noble gas excesses in SiC grains are indeed the result of a presolar irradiation by GCRs.

5. DISCUSSION

5.1. Presolar Exposure Ages

The presolar exposure age ratios T_3/T_{21} of most of the grains are in broad agreement with expected values from production rate estimates. We note three salient points derived from this observation. First, the adopted production rate ratio $P(^3\text{He})/P(^{21}\text{Ne})$ is approximately correct. Second, as most grains appear to have retained much of their cosmogenic ^{3}He, they will also have retained most of their ^{21}Ne. Otherwise, ^{3}He ages would be much lower than ^{21}Ne ages, since He in presolar grains is more prone to loss than Ne (Heck et al. 2007). Third, the assumption that the entire measured ^{3}He is of cosmogenic origin is essentially correct, otherwise some grains would show much higher nominal T_3 than T_{21} values. Note that in the following discussion all of our age values have considerable systematic uncertainties of perhaps a factor of 2 (see Section 4.4), and that $T_{21\text{cor}}$ values (if available) should be more accurate than $T_{3\text{cor}}$ values, since recoil correction for ^{21}Ne is less uncertain. The relatively large uncertainties do, however, not compromise the basic conclusions.

In summary, most of the large SiC grains studied here have a discernible presolar exposure age. Most recoil-corrected ages range from about 3 to 200 Myr, while three of the 22 grains have ages of several hundred million to a billion years. The relatively low age of most grains is in broad agreement with values inferred from Xe data for SiC bulk samples of smaller grain size (Ott et al. 2005), although these latter values have large inherent uncertainties and are only upper limits. A majority of the grains thus is younger than theoretical lifetimes of interstellar grains of several 10^8 years (Jones et al. 1997). Based on our data, in particular also the basic agreement between $T_{3\text{cor}}$ and $T_{21\text{cor}}$, we argue, at least for the larger grains examined here, against the suggestion by Lewis et al. (1994) that the nominally low mean ages of bulk SiC samples may be the result of diffusive gas loss from most grains while the remainder may have presolar ages of up to $>2 \times 10^9$ years. Note that relatively short interstellar residence times of presolar grains found in meteorites are also suggested by the lack of evidence for significant surface sputtering of gently separated grains (Jones et al. 1997; Bernatowicz et al. 2003).

5.2. Grains with Long Interstellar Exposure Ages

Three grains studied here have exposure ages in the range of expected interstellar grain lifetimes (Jones et al. 1997). One of these grains (L2-03) exhibits two further remarkable features. It is the largest grain measured and it has by far the lowest T_3/T_{21} ratio. Because a much larger recoil loss of ^{3}He than assumed is not a viable explanation for this large grain, it seems likely that it lost ^{3}He by diffusion. If so, also some ^{21}Ne may have been lost and the true $T_{21\text{cor}}$ age of this grain might be even higher than the $\sim 4 \times 10^8$ years listed in Table 2.

The two grains with the highest interstellar exposure ages are AB-type SiC grains (L2-25 and L2-57). Their T_3/T_{21} exposure age ratio is consistent with the ratio expected from recoil models (Figure 5). Another AB grain measured for He and Ne, L2-12, has a recoil-corrected T_{21} age (128 $\pm$ 19 Myr) in the range of the majority of the grains, but a high ^{3}He age ($T_{3\text{corr}} = 314 \pm 34$ Myr). The number of analyzed AB grains is currently too small to argue on a statistically significant basis that AB grains have a longer residence time in the ISM than mainstream grains. The two AB grains L2-25 and L2-57 were selected for noble gas analyses despite their relatively small grain size because of their unusual stellar provenance.

The ages of the three old grains discussed here (L2-03, L2-25, L2-57) are in the same range as ages based on Li reported for a few Jumbo SiC grains. However, only two out of eight grains have Li ages of less than 10^8 years (Gyngard et al. 2007a, 2009). Correlated studies of Li isotopes and noble gases on the same Jumbo SiC grains are needed to clarify whether the appearance of Li ages being higher than ^{21}Ne ages is real or is the result of limited statistics and/or systematic uncertainties.

Most of the ages we obtain are larger than the estimated lifetimes of $\sim 10^7$ years of molecular clouds (Tassis & Mouschovias 2004). This is additional evidence of the presolar nature of the grains, independent of their isotopic signatures. The range of ages of the grains indicates that the grains originated from several stars, independent of a similar conclusion based on their isotopic compositions. Different studies investigating the star-formation history of our Galaxy applied a variety of independent stellar chronometers. Chromospheric activity (e.g., Barry 1988; Rocha-Pinto et al. 2000), luminosity functions of white dwarfs (Noh & Scalo 1990), star formation history of open clusters (Lada & Lada 2003) and Hα emission from M dwarfs (Fuchs et al. 2009) have been calibrated and constrain the ages of stars or star clusters. These studies concluded that star formation in our Galaxy was dominated by several bursts, i.e., dramatic increases of the star formation rate, each lasting for about 1–3 Gyr. The grains with the higher exposure ages might have formed in stars originating from the 7 to 9 Gyr burst (starburst C in Majewski 1993; Rocha-Pinto et al. 2000).

5.3. Origin of Grains with Short Interstellar Exposure Ages: Indication for a Galactic Merger?

Most of the SiC grains analyzed here have considerably shorter presolar exposure ages than theoretical lifetimes of interstellar dust. Ott et al. (2005) suggested a possible explanation based on work by Clayton (2003). This author proposed to explain the Si isotopic compositions of mainstream presolar SiC grains by the merger of a metal-poor satellite galaxy with the Milky Way around 6×10^9 years ago. The starburst associated with this event would have led to the emergence of a large number of AGB stars shortly before solar-system formation. Only stars having more than about two solar masses, hence lifetimes lower than about 1.5×10^9 years, would have reached their AGB stage at a time before the solar nebula was formed. Since these stars are less abundant than lower-mass stars ($<2\ M_\odot$) with longer lifetimes, only few of the stars from the proposed starburst origin could have contributed SiC grains with old ages typical of average interstellar dust. If so, the majority of SiC grains we find in meteorites may only be the first ones arriving—shortly before the Sun was born—from those stars whose formation was triggered by the proposed merger of two galaxies. This would be the case at least for the large grains studied here, but presumably also for smaller SiC grains if their low average exposure ages based on cosmic-ray-produced Xe (Ott et al. 2005) can be substantiated.

A further explanation of young presolar ages would be that the grains that survived to be incorporated into the solar nebula had not been processed in the ISM, e.g., by sputtering or comminution due to collisions (Bernatowicz et al. 2003). In this case, it might not be surprising to find no evidence for diffusive loss of ^{3}He except for the one mainstream grain (L2-03) whose ^{21}Ne age is in the range of theoretical interstellar lifetimes. This grain may be from a different population. As noted above, the pristine appearance of gently separated interstellar SiC grains also suggests a relatively short interstellar residence (Bernatowicz et al. 2003).

5.4. *Interstellar Grain Aggregates?*

We mentioned above that a few grains have even higher T_3/T_{21} ratios than expected from estimated recoil loss for grains in the size range studied here (<50 μm). One possible explanation is that these grains are fragments of grains that had been considerably larger in interstellar space or were part of aggregates, perhaps held together during much of their interstellar residence by icy or organic mantles. Although mantles are expected to grow rather slowly and remain thin even in dense molecular clouds (Cuppen & Herbst 2007), they can help to form grain agglomerates (Jones et al. 1997). However, in order to retain most of the ^{3}He, grain or aggregate sizes of several hundred microns are required. We reiterate here that the cosmogenic nuclide production rates in such aggregates would not differ from rates in smaller particles (see Section 4.1). If many smaller grains were remnants of larger ones, they would tend to have ages higher than or comparable to the ages of larger grains. On the other hand, if most SiC grains in Murchison originate from stars formed by a relatively recent starburst (Clayton 2003), one would not expect a dependence of exposure age on grain size, since the observed age spread would then largely be the result of different stars having reached the AGB phase at slightly different times. The limited data available so far do not yet allow us to decide whether such a grain size dependence of exposure ages exists. Indeed, the two smallest grains have the longest exposure ages but these grains are of type AB (see above).

6. CONCLUSIONS

1. 19 of 22 large LS+LU SiC grains from Murchison contain cosmogenic ^{21}Ne and/or ^{3}He. Noncosmogenic explanations for the excesses of ^{21}Ne and ^{3}He are unlikely. Irradiation of the presolar SiC grains in the parent-body asteroid can be ruled out as an explanation for the high cosmogenic ^{21}Ne and ^{3}He concentrations. The interstellar exposure ages based on cosmogenic ^{21}Ne are in reasonable agreement (within a factor of ~2) with ages based on ^{3}He for most of the grains.
2. Interstellar cosmic-ray exposure ages are between ~3 and ~200 Myr for 17 grains—shorter than interstellar dust lifetimes expected from theoretical models. Except for one grain, all of these grains are mainstream SiC. The short ages can be explained by an origin of the grains in AGB stars which evolved from stars formed during a starburst event about 1–2 Gyr before the formation of the solar system.
3. Only three out of 22 grains have high interstellar residence times of ~400 Myr to ~1 Gyr consistent with theoretically expected interstellar lifetimes. They originate from a different population of stars. Two of these old grains are AB-type SiC, one grain is a mainstream SiC grain.
4. No trend of exposure ages with grain size is observed. However, the concentration of nucleosynthetic He-shell ^{22}Ne (G component) in the LS+LU SiC grains decreases with increasing grain size. This provides evidence for a previously proposed scenario where He-shell Ne, highly enriched in ^{22}Ne, is implanted through a high-speed wind emanating from the exposed He-shell of a post-AGB star into already condensed SiC grains in the circumstellar dust shell.

The interstellar residence times of the presolar dust grains presented here are central to constrain model lifetimes of interstellar dust. This "ground truth" is essential in assessing destructive processes in the ISM.

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REFERENCES

Amari, S., Hoppe, P., Zinner, E., & Lewis, R. S. 1995, Meteorit. Planet. Sci., 30, 679
Amari, S., Lewis, R. S., & Anders, E. 1994, Geochim. Cosmochim. Acta, 58, 459
Amari, S., Nittler, L. R., Zinner, E., Lodders, K., & Lewis, R. S. 2001, ApJ, 559, 463
Ammon, K., Masarik, J., & Leya, I. 2008, Meteorit. Planet. Sci., 43, 685
Barry, D. C. 1988, ApJ, 334, 436
Baur, H. 1999, Eos Trans., 46, F1118
Bernatowicz, T. J., Messenger, S., Pravdivtseva, O., Swan, P., & Walker, R. M. 2003, Geochim. Cosmochim. Acta, 67, 4679
Clayton, D. D. 2003, ApJ, 598, 313
Cuppen, H. M., & Herbst, E. 2007, ApJ, 668, 294
Fuchs, B., Jahreiß, H., & Flynn, C. 2009, AJ, 137, 266
Gallino, R., Busso, M., Picchio, G., & Raiteri, C. M. 1990, Nature, 348, 298
Greiner, D. E., Lindstrom, P. J., Heckman, H. H., Cork, B., & Bieser, F. S. 1975, Phys. Rev. Lett., 35, 152
Gyngard, F., Amari, S., Zinner, E., Gallino, R., & Lewis, R. S. 2007a, Lunar Planet. Sci. Conf., 38, 1963
Gyngard, F., Amari, S., Zinner, E., & Lewis, R. S. 2007b, Meteorit. Planet. Sci., 42, A61
Gyngard, F., Amari, S., Zinner, E., & Ott, U. 2009, ApJ, 694, 359
Heber, V. S., Baur, H., Bochsler, P., Burnett, D. S., Reisenfeld, D. B., Wieler, R., & Wiens, R. C. 2008, Lunar Planet. Sci. Conf., 39, 1779
Heck, P. R., Marhas, K. K., Hoppe, P., Gallino, R., Baur, H., & Wieler, R. 2007, ApJ, 656, 1208
Hohenberg, C. M., Nichols, R. H., Jr., Olinger, C. T., & Goswami, J. N. 1990, Geochim. Cosmochim. Acta, 54, 2133
Hoppe, P., Amari, S., Zinner, E., Ireland, T., & Lewis, R. S. 1994, ApJ, 430, 870
Hoppe, P., Strebel, R., Eberhardt, P., Amari, S., & Lewis, R. S. 1996, Geochim. Cosmochim. Acta, 60, 883
Huss, G. R., Koscheev, A. P., & Ott, U. 2008, Meteorit. Planet. Sci., 43, 1811
Jones, A. P., Tielens, A. G. G. M., Hollenbach, D. J., & McKee, C. F. 1997, in AIP Conf. Proc. 402, Astrophysical Implications of the Laboratory Study of Presolar Materials, ed. T. J. Bernatowicz & E. Zinner (Melville, NY: AIP), 595
Karakas, A. I., Lee, H. Y., Lugaro, M., Görres, J., & Wiescher, M. 2008, ApJ, 676, 1254
Lada, C. J., & Lada, E. A. 2003, ARA&A, 41, 57

Lavielle, B., Marti, K., Jeannot, J.-P., Nishiizumi, K., & Caffee, M. 1999, Earth Planet. Sci. Lett., 170, 93
Lewis, R. S., Amari, S., & Anders, E. 1994, Geochim. Cosmochim. Acta, 58, 471
Leya, I., Lange, H.-J., Neumann, S., Wieler, R., & Michel, R. 2000, Meteorit. Planet. Sci., 35, 259
Majewski, S. R. 1993, ARA&A, 31, 575
Meyer, B. S., & Zinner, E. K. 2006, in Meteorites and the Early Solar System II, ed. D. S. Lauretta & H. Y. McSween, Jr. (Tucson, AZ: Univ. Arizona Press), 69
Nichols, R. H., Jr., Hohenberg, C. M., Amari, S., & Lewis, R. S. 1991, Meteoritics, 26, 377
Nichols, R. H., Jr., Hohenberg, C. M., Hoppe, P., Amari, S., & Lewis, R. S. 1992, Lunar Planet. Sci. Conf., 23, 989
Noh, H.-R., & Scalo, J. 1990, ApJ, 352, 605
Ott, U., Altmaier, M., Herpers, U., Kuhnhenn, J., Merchel, S., Michel, R., & Mohapatra, R. K. 2005, Meteorit. Planet. Sci., 40, 1635
Ott, U., & Begemann, F. 2000, Meteorit. Planet. Sci., 35, 53
Ott, U., Heck, P. R., Gyngard, F., Wieler, R., Wrobel, F., & Zinner, E. K. 2009, PASA, in press
Reedy, R. C. 1987, J. Geophys. Res., 92, E697
Reedy, R. C. 1989, Lunar Planet. Sci. Conf., 20, 888
Reedy, R. C. 2008, Lunar Planet. Sci. Conf., 39, 1907
Rocha-Pinto, H. J., Scalo, J., Maciel, W. J., & Flynn, C. 2000, A&A, 358, 869
Roth, A. S. G., Baur, H., Heber, V. S., Reusser, E., & Wieler, R. 2008, Meteorit. Planet. Sci., 43, 5217
Tang, M., & Anders, E. 1988a, Geochim. Cosmochim. Acta, 52, 1235
Tang, M., & Anders, E. 1988b, ApJ, 335, L31
Tassis, K., & Mouschovias, T. C. 2004, ApJ, 616, 283
Valkiers, S., Russe, K., Taylor, P., Ding, T., & Inkret, M. 2005, Int. J. Mass Spectrom., 242, 321
Verchovsky, A. B., Wright, I. P., & Pillinger, C. T. 2004, ApJ, 607, 611
Virag, A., Wopenka, B., Amari, S., Zinner, E., Anders, E., & Lewis, R. S. 1992, Geochim. Cosmochim. Acta, 56, 1715
Voshage, H. 1984, Earth Planet. Sci. Lett., 71, 181
Webber, W. R., & Yushak, S. M. 1983, ApJ, 275, 391
Wieler, R., Pedroni, A., & Leya, I. 2000, Meteorit. Planet. Sci., 35, 251
Ziegler, J. F. 2004, Nucl. Instrum. Methods B, 219, 1027
Zinner, E., Amari, S., Wopenka, B., & Lewis, R. S. 1995, Meteoritics, 30, 209
Zinner, E., et al. 2007, Geochim. Cosmochim. Acta, 71, 4786