Lifetimes of interstellar dust from cosmic ray exposure ages of presolar silicon carbide

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We determined interstellar cosmic ray exposure ages of 40 large presolar silicon carbide grains extracted from the Murchison CM2 meteorite. Our ages, based on cosmogenic Ne-21, range from 3.9 ± 1.6 Ma to ∼3 ± 2 Ga before the start of the Solar System ∼4.6 Ga ago. A majority of the grains have interstellar lifetimes of <300 Ma, which is shorter than theoretical estimates for large grains. These grains condensed in outflows of asymptotic giant branch stars <4.9 Ga ago that possibly formed during an episode of enhanced star formation ∼7 Ga ago. A minority of the grains have ages >1 Ga. Longer lifetimes are expected for large grains. We determined that at least 12 of the analyzed grains were parts of aggregates in the interstellar medium: The large difference in nuclear recoil loss of cosmic ray spallation products ^{3}He and ^{21}Ne enabled us to estimate that the irradiated objects in the interstellar medium were up to 30 times larger than the analyzed grains. Furthermore, we estimate that the majority of the grains acquired the bulk of their cosmogenic nuclides in the interstellar medium and not by exposure to an enhanced particle flux of the early active sun.

interstellar dust | presolar grains | exposure age dating | cosmochemistry | meteorites

Interstellar dust is an important component of our galaxy. It influences star formation as well as the thermal and chemical evolution of the galaxy. Although dust only presents ∼1% of the mass in the interstellar medium (ISM) (1), it carries a large fraction of the elements heavier than He (2), including the elements that form terrestrial planets and are essential for life. Thus, interstellar dust is a key ingredient of stars and habitable planetary systems, making increased knowledge about its composition and lifecycle desirable. Compositional, structural, and size information of interstellar dust can be obtained through astronomical spectroscopic observations (3), but dust lifetime estimates mainly rely on sophisticated theoretical models. These models, however, focus on the more common small dust grains and are based on assumptions with large uncertainties. These uncertainties mainly pertain to the residence time of the dust in various regions of the ISM, which exhibit different rates of dust destruction through sputtering and collisions in supernova shock waves (4–9). Most of these models currently predict an average lifetime of interstellar grains on the order of 100 Ma. However, more recent models and a few models for larger grains predict much longer survival times in the ISM of up to billions of years (10–12).

Here, we present a laboratory-based approach of determining the interstellar lifetimes of individual large presolar silicon carbide (SiC) stardust grains (Fig. 1). The presolar grains analyzed in the present study were isolated by chemical methods (see *Materials and Methods*) from the Murchison CM2 meteorite, where they had remained unaltered since their incorporation into the meteorite parent body in the early Solar System 4.6 Ga ago. These grains are identified as presolar by their large isotopic anomalies that exclude an origin in the Solar System (13, 14). Presolar stardust grains are the oldest known solid samples available for study in the laboratory, represent the small fraction of material that formed in circumstellar environments, and survived processing in the ISM and Solar System. The presolar stardust grain abundance in our parent interstellar cloud was a few percent of all interstellar dust present in this cloud (15), with the other dust having condensed in the ISM. In the solar nebula, more dust condensed from the cooling gas and presolar stardust became an even more minor component. Most presolar grains were subsequently destroyed after accretion in their parent bodies during thermal metamorphism and aqueous alteration. Thus, their abundance in the most primitive Solar System materials that evaded destructive parent body processing is a few parts per million (ppm) to ∼200 ppm (16) except for interplanetary dust presumably from comet Grigg-Skjellerup dust, which contains up to ∼1% presolar materials (17). We used mass spectrometry to analyze the abundance of nuclides produced in the grains by spallation reactions with galactic cosmic rays (GCR)—which comprise mostly high-energy protons and α-particles—during their residence in the ISM. When these high-energy particles hit a grain, small fractions of the target nuclides break up.

Significance

Dating of interstellar dust directly with astronomical methods is not possible. Neither is dating based on the decay of long-lived radioactive nuclides, due to current analytical limitations and unknown initial isotopic compositions. Here we present interstellar ages of individual presolar SiC grains from a meteorite. The ages are based on Ne isotopes produced by galactic cosmic rays. Lifetimes of ∼60% of our grains are $<3 \times 10^{8}$ y, while at least 8% are $>10^{9}$ y, in line with what is expected for large grains. The former could be the end products of stars originating in an enhanced star formation episode. Presolar grains are the oldest datable solid samples available and provide invaluable insight into the presolar chronology of our galaxy.

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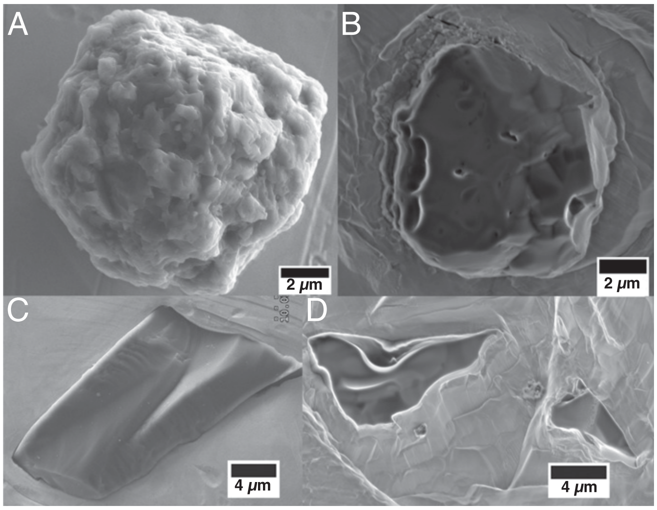

Fig. 1. Presolar SiC morphology. Scanning electron microscope images (secondary electrons) of representative samples of the two morphological types of presolar SiC grains studied here. Grain L3_01 has a euhedral shape indicating it evaded shattering; (*A*) before and (*B*) after pressing into gold and after nanoscale secondary ion mass spectrometry (NanoSIMS) and Sensitive High Resolution Ion Micro Probe (SHRIMP) analysis but before laser extraction of noble gases. Grain L3_20 has a shard-like appearance with fractures (*C*) before pressing and (*D*) got fractured further upon pressing into the gold substrate. Images of all grains are provided in *SI Appendix*.

The resulting atomic fragments accumulate in the grain, and their concentrations are proportional to the timespan the grains were irradiated. Suitable daughter elements to study are those with a very low initial abundance in the grains such that the cosmic ray-produced ("cosmogenic") fraction becomes detectable. This is the case for He, Ne, and Li. SiC is the best-suited interstellar phase for cosmogenic nuclide dating, due to its relatively large grain size, high retentivity of cosmogenic nuclides, and durability. Even though SiC is only a small fraction of the total amount of interstellar dust (9), due to its durability, we consider it a useful tracer. In the most common SiC grains, the ones that originate from low- to intermediate-mass asymptotic giant branch (AGB) stars (14), the initial He and Ne isotopic compositions, incorporated from their parent stars, are well known (18–20), so the cosmogenic fraction can be readily identified. Improved knowledge of production and retention of such cosmogenic nuclides enabled us to obtain ages with improved reliability. While radiometric dating based on the U−Pb decay system can provide ages with high accuracy (21) and is often the method of choice for samples of Solar System materials, it has not yet been successfully applied to presolar grains. These grains have masses that are orders of magnitudes smaller than samples dated so far. Furthermore, presolar grains have large isotopic anomalies in essentially every element, so each grain may have a distinct initial lead isotopic composition, uranium isotope ratio, and age, robbing the U−Pb system of some of its most desirable characteristics for geochronology. Until these obstacles are overcome, exposure age dating is the preferred method for determining presolar ages of individual stardust grains.

The first such studies were made on assemblages of thousands of SiC grains from chemical separates. Ages of ∼10^7 to 10^8 y were derived from ^{21}Ne, but it was suggested that individual grains might show much higher presolar ages of up to 2 Ga (18, 22). However, Ott and Begemann (23) showed that much of the measured ^{21}Ne was not cosmogenic but was implanted neon from the He shell of the parent AGB star, while, at the same time, they concluded that losses of cosmogenic ^{21}Ne upon production due to recoil out of the grains were much larger than assumed. Ott et al. (24) deduced much lower presolar ages for bulk SiC assemblages of a few times 10^7 y only, based on cosmogenic Xe, for which recoil losses are smaller. The first interstellar exposure ages on individual exceptionally large (∼5 to 60 μm) SiC grains were reported by Gyngard et al. (25) based on Li isotopes and by Heck et al. (20) with He and Ne. The large grains contain greater amounts of cosmogenic nuclides, and, more importantly, require a smaller recoil correction (26). The studies by Heck et al. (20) and Gyngard et al. (25) both reported ages of between a few megayears to about 1 Ga, but the average of the Li-based ages was considerably higher than the average noble gas age. Heck et al. (20) suggested that the many ages of <200 Ma may be explained by increased dust production after a galactic starburst 1 to 2 Ga prior to the birth of the sun.

In this work, we provide presolar ages based on cosmogenic Ne isotopes, significantly increasing the total number of presolar grain ages. We also present reevaluated ages from previously published data. This will enable us to further advance our understanding of the lifetimes of interstellar dust. Previous interstellar production rates of cosmogenic nuclides were based on fluxes deep within the heliosphere that were extrapolated to interstellar space (20, 27, 28). Here, we use, instead, improved interstellar production rates that were determined with the purely physical model of Trappitsch and Leya (29) that uses a state-of-the-art nuclear cross-section database and an interstellar GCR spectrum based on data collected by NASA's Voyager 1 space probe at the edge of the heliosphere. Voyager 1 recorded the low-energy part of the GCR spectrum, something that is not possible deeper within the heliosphere. To correct for recoil losses of cosmogenic nuclides from SiC grains, we use a physical recoil model that considers the energies of GCR protons and α-particles from the new cosmic ray spectrum (29).

Another aspect that was not considered in previous studies is the potential exposure of presolar grains to the enhanced particle flux of the early active sun. Large excesses of cosmogenic noble gases in single olivine grains in some primitive meteorites have been attributed by some workers to a high flux of energetic particles from the early sun (e.g., refs. 30–32), although others contested this conclusion (33). Recently, however, unambiguous evidence for an enhanced exposure of hibonite (an aluminum−calcium oxide)—possibly the earliest solar nebula condensate—to energetic particles from the early active sun was reported by Kööp et al. (34). This implies that some of the presolar grains we studied might have been exposed to the same enhanced solar particle flux. We are, therefore, also required to estimate the upper limit of cosmogenic nuclides concentrations produced in the early Solar System rather than in the ISM.

Results and Discussion

Presolar Grain Ages. We processed our noble gas data from 27 SiC grains and reprocessed data from published results from 22 SiC grains (20) to calculate an internally consistent set of presolar cosmic ray exposure ages for nearly 50 grains with the improved cosmogenic nuclide production rates and nuclear recoil corrections (*SI Appendix*, Table S1). The cosmogenic Ne component can be clearly resolved from the two other main components, nucleosynthetic Ne (Ne−G) and adsorbed atmospheric Ne based on distinct isotopic Ne compositions (*SI Appendix*, Fig. S8*A*). Ne−G is implanted into circumstellar grains from the hot post-AGB star wind emanating from the exposed He shell, and its concentrations decrease with increasing grain size (*SI Appendix*, Fig. S8*B* and refs. 19 and 20). Using C, N, and Si isotopes, all but three grains have been classified as mainstream SiC, originating in the outflows of low- to intermediate-mass (post) AGB stars (14, 35) (*SI Appendix*, Fig. S1 and Table S2). The three other grains are of AB type, based on their low ^{12}C/^{13}C ratios (*SI Appendix*). All newly analyzed grains are mainstream SiC.

We determined ^{3}He and ^{21}Ne exposures ages (T_3 and T_{21}) of 30 and 24 grains, respectively, and obtained upper age limits for

12 (^{3}He) and 16 (^{21}Ne) grains (*SI Appendix*, Table S3). For 18 grains, we have obtained both T_3 and T_{21}. Nominal recoil-corrected T_3 for 16 out of these 18 grains are higher than recoil-corrected T_{21}, whereas uncorrected ages show an opposite trend (Fig. 2). Helium is more easily lost through heating and through recoil than Ne, so both effects would result in lower nominal T_3 than T_{21} before a recoil correction. Hence, a recoil correction will be larger for ^{3}He than for ^{21}Ne. *SI Appendix*, Fig. S2 shows that, for grains of <10 μm, nominal cosmogenic ^{3}He recoil losses are >94% for the smallest grains analyzed here, whereas corresponding losses for ^{21}Ne are >40%. Hence, any uncertainties in recoil corrections will result in a larger uncertainty of T_3. Heating of grains to high temperatures (≥900 K) would result in near-complete He loss (36). Helium loss works in the opposite direction of the trend we see in the data. This implies that, while some He loss cannot be excluded, no significant loss occurred; otherwise, much more He than Ne would have been lost, and even overcorrected T_3 would be smaller than T_{21}. The T_3 are less reliable than T_{21}, mainly because of larger uncertainties in the ^{3}He recoil correction. The 16 recoil-corrected T_3 exceeding recoil-corrected T_{21}, consequently, indicate an overestimation of the recoil loss for ^{3}He. The reason for this may be that these grains were actually irradiated in the ISM as parts of larger grains or as grain aggregates, or the grains were coated with large mantles of ices and organics while in the ISM. We estimate the original sizes of the irradiated objects in the ISM by varying the grain size and modeling the resulting recoil correction until the recoil-corrected T_3 and T_{21} match (*SI Appendix*, Fig. S3). The estimated object diameters during irradiation are factors of ∼3× up to ∼30× higher than those of the analyzed grains. This results in ages of 44 to 85% of the original recoil-corrected ages (Fig. 3). In principle, it would be possible to test this result with cosmogenic Xe that has a much smaller recoil loss. Unfortunately, the amounts of cosmogenic Xe produced are below current detection limits for single-grain analyses, due to the low amounts of suitable target elements for Xe production in SiC (23). Bulk analyses of SiC give mixed signals and are not useful in this regard, as these do not resolve cosmogenic gas contributions from grains with different lifetimes. Seventy-five percent of the 16 analyzed grains that were part of much larger objects have euhedral shapes, which indicates they are not fragments of larger grains and were more likely parts of aggregates. The remainder look like they are shattered fragments of larger SiC grains (*SI Appendix*, Table S3 and Dataset S1), but, given the large object sizes estimated during ISM irradiation, larger than any known presolar SiC grain, they were likely also part of aggregates. Aggregates of minerals, suspected by some to be presolar, in an organic material matrix were recently observed in interplanetary dust particles (37). Bernatowicz et al. (38) observed organic coatings on ∼60% of pristine presolar SiC that they physically separated from their host meteorite without the use of chemical reagents. However, no aggregates or clustering of larger presolar grains have yet been observed during the in situ ion imaging searches of polished sections of meteorites (e.g., ref. 16). The lack of such clustering of larger grains could be due to preferred breakup of larger clusters of several dozen to hundred micrometers during accretion onto planetesimals in the early Solar System, while smaller clusters composed of smaller grains which have lower inertia, such as the ones observed by Ishii et al. (37), stayed intact. We propose that grains in the size range we analyzed formed in the outflows of (post) AGB parent stars (39) and coagulated there with organic matter to form larger aggregates. While large SiC dust grains are rare in the ISM, they are consistent with observations of circumstellar dust around AGB and post-AGB stars (40). Far-infrared excess associated with such dust may indicate the presence of up to millimeter-sized grains (41). Up to 5-mm-large dust grains were proposed to explain radio observations of dust around the Egg Nebula, a post-AGB star (42). Jura et al. also propose that the

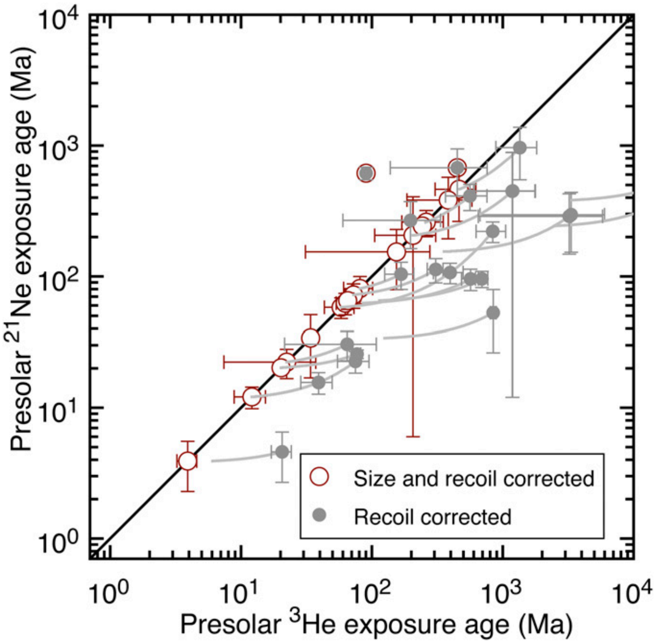

Fig. 2. Comparison of Ne and He exposure ages. Only data for samples for which we obtained He and Ne ages are shown; no upper limits. The data of grains with higher nominal He ages than Ne ages indicates that the recoil correction for He is overestimated because, in the ISM, these grains were part of larger objects (aggregates or larger grains). For those inferred to be part of larger objects, we modeled a recoil correction for object sizes that resulted in equal ^{3}He and ^{21}Ne ages (1:1 line). Here and elsewhere, 1σ error bars do not include systematic errors and are visible if larger than the symbol (see text and *SI Appendix*).

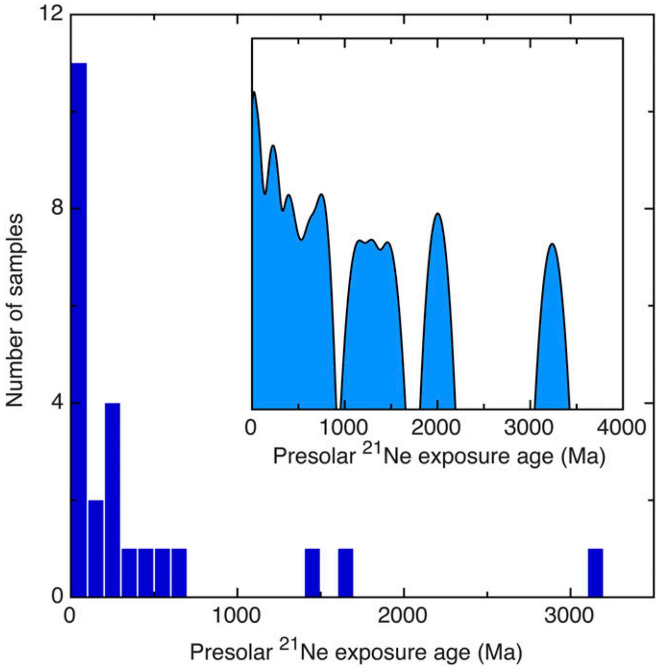

Fig. 3. Presolar Ne exposure ages. Histogram showing the distribution of presolar SiC ^{21}Ne exposure ages. (*Inset*) Plot of the kernel density estimation (KDE, bandwidth = 36.1; ref. 62) of presolar SiC ^{21}Ne exposure ages. Samples with upper age limits are not included in the histogram but are included in the KDE plot.

high-density winds from post-AGB stars are the sources of the large presolar SiC grains, such as the size fraction studied here.

We also obtained Li isotope data for 19 SiC grains. Many of these grains have a ^{7}Li/^{6}Li ratio below the chondritic ("solar") value of 12.06 ± 0.03 (43), indicating the contribution of a cosmogenic Li component [the end-member cosmogenic ^{7}Li/^{6}Li ratio is ∼1.2 (29)]. However, the nominal Li ages determined from different spots on the same grains are highly variable. Li ages also correlate with the total, noncosmogenic Li concentration (*SI Appendix*, Fig. S4 and Table S4). These observations could be due to a combination of contamination with terrestrial or Solar System Li, matrix effects (25), or additional, unidentified Li components that would have contributed to the measured Li concentration. Because of low concentrations of cosmogenic Li and high abundance of normal Li, a reliable determination of cosmogenic Li is very difficult. Currently, Li does not allow us to obtain reliable ages, as discussed in more detail in *SI Appendix*.

Evidently, the Ne ages are more reliable than the Li and He ages, and we will base the following discussion mainly on ^{21}Ne ages. They range from 4 ± 2 Ma (±1σ) to 3,200 ± 2,300 Ma (Figs. 2 and 3), and upper limits range from 3 to 3,300 Ma. We obtained ^{21}Ne ages for two out of three AB grains; the calculated ages, 65 ± 9 Ma and 260 ± 59 Ma, fit into the age range of the mainstream grains. No age was determined for the third AB grain, due to an insufficient gas amount; the 2-μm-sized grain was the smallest one analyzed in this study.

Overall, the ^{21}Ne age distribution trend (Fig. 3) is similar to what was previously reported for a smaller sample set (20), with most exposure ages below 300 Ma (60%) and 50% below 200 Ma. This is consistent with most theoretical lifetime estimates for much smaller, <1 μm interstellar dust of 100 to 300 Ma (4–9), but in contrast to the longer lifetimes expected for large grains (10–12). Assuming constant dust production rates from AGB stars and constant dust destruction rates, we would expect to encounter younger grains more frequently than older grains simply because older ones have a higher probability of encountering a destructive process. However, our age distribution does not fit any of the assumed steady-state models for different average lifetimes (*SI Appendix*, Fig. S5*A*). Having many large grains in a relatively narrow age range seems to require an explanation other than simply a lifetime effect, which would apply to small grains. We propose that this age distribution can be explained by these large grains being late-stage products of AGB stars with initial masses of ∼2 $M_\odot$ that formed together. While less massive stars were more abundant, their evolutionary lifetimes were too long to reach the dust-producing AGB phase before the formation of the Solar System, and, hence, their dust has not been incorporated into meteorite parent bodies. The rarer, more massive AGB stars (with initial masses of >3 $M_\odot$) are not likely to be a source of large SiC grains, as their higher radiation pressures would have ejected circumstellar grains before they grew to the large grain sizes observed here (44). It was previously suggested that the grains' parent stars originated in a presolar starburst that could have been triggered by a galactic merger (20, 24), which Clayton (45) first proposed to explain the Si isotopic compositions of presolar mainstream SiC. Most observational and theoretical work on the history of the star formation rate (SFR) of our galaxy does not see evidence of a large starburst event in presolar times as hypothesized previously (20, 24), nor a flat SFR, but most studies conclude that the SFR only mildly fluctuated (46–50). These studies find a moderately enhanced SFR around 7 to 9 Ga ago. Several of the observational studies show that this broad peak consists of two peaks, with the more recent one close to 7 Ga ago (*SI Appendix*, Fig. S5 and ref. 46). Recent modeling work by Noguchi (49) based on observations of the chemical compositions of stars in the solar neighborhood reveals a moderately enhanced SFR that peaked around 7 Ga ago. In this model, this enhancement was caused by streams of cold matter that accreted onto the galactic disk from the halo (49). Based on stellar main-sequence lifetime calculations, we estimate that stars with ∼1.6$_\odot$ to ∼1.9 $M_\odot$, that formed together during this enhanced SFR episode ∼7 Ga ago, reached their dust-producing AGB phase between ∼4.9 and ∼4.6 Ga ago (*SI Appendix*, Fig. S5). These dust grains would then have been exposed to interstellar GCR for <300 Ma before being shielded in the forming Solar System. What we are seeing in the SiC age peak are the first arrivers of dust formed in the late stages of stars originating in the presolar enhanced SFR peak (*SI Appendix*, Fig. S5). The rest of the peak must be more recent than the start of the Solar System and was not sampled in the presolar grain population. Although speculative, this scenario is consistent with our data and, barring another explanation, may be a plausible reason for the observed presolar SiC age distribution for large grains with presolar ages of <300 Ma. While we see older grains, we do not see older peaks (other than from individual grains) in our age distribution. We explain this by two effects. First, grain destruction reduced the number of surviving old grains, and, second, the signal to noise ratios farther back in time are currently too low to show peaks within our dataset. Older interstellar ^{21}Ne exposure ages obtained for at least 7 grains are >300 Ma and, for a few grains (3 out of 24, excluding those with upper limits; 5 out of 40 including upper limits), are consistent with what is expected for large grains (10, 12). In particular, if these grains were >100-μm aggregates in the ISM, long lifetimes are expected. Erosion by sputtering is slower than the time the grain is exposed to shock-heated gas, but large grains can erode significantly when they get slowed down in the cooled postshock gas and experience rare collisions with other large grains (10). Gradual erosion by collisions with smaller grains would leave cratered surfaces (10), something that has not been observed with SiC grains to date (38). Possible evidence of a microimpact crater was so far only found in a large presolar aluminum oxide grain (51). Some of the old grains could have been shielded from destructive processes in clumps. Such protective density inhomogeneities have been observed astronomically in shocked regions of the ISM (e.g., ref. 52).

The oldest grains based on both ^{3}He and ^{21}Ne ages are the smallest, and an inverse trend between age and grain size is apparent (Fig. 4 and *SI Appendix*, Fig. S6), consistent with the preliminary trend observed by Ott and Begemann (23) in Xe from bulk SiC analyses but in contrast to the prediction by Hirashita et al. (12). The trend persists in the recoil-corrected data and in the size-corrected subset but gets less prominent in the latter. Smaller grains are more abundant than larger grains in the ISM (3), resulting in a higher number of smaller grains that are old compared to larger ones. We can exclude a sampling bias, as we have not disproportionally analyzed small grains; on the contrary, only 12 of the 49 grains are <4 μm.

Gyngard et al. (53) proposed that grains with presolar ages older than the sun's galactic year [∼230 Ma (54)] might have had the time to radially migrate from the inner parts of the galaxy toward the galactocentric distance of the forming Solar System. Because of the compositional gradient within our galaxy, we would expect these grains to reflect the metallicity of their parent stars. However, we do not observe a correlation between age and Si isotopic composition, which is a proxy for metallicity of stellar sources (55). Either our dataset is too small to reveal such a trend, the grains did not migrate as suggested, or there is no galactic gradient for Si isotopic composition, in contrast to O isotopic composition (56) and [Fe/H] (57). Recent astronomical observations (58) did not find a galactocentric δ^{29}Si trend within ∼200‰, a range that was less than expected from galactocentric variations in other isotope ratios but similar to the one measured in presolar SiC mainstream grains.

We should highlight that, at the end of their interstellar journey, the presolar grains could have been exposed to enhanced particle

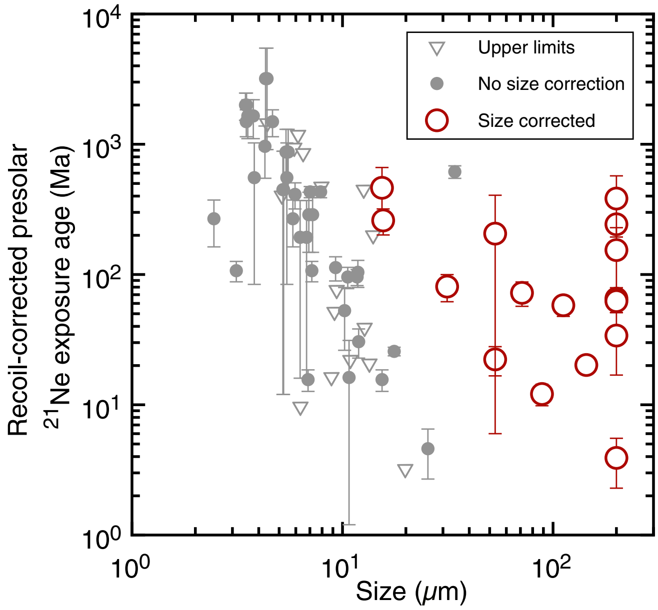

Fig. 4. Older grains are smaller. Size is given as the geometric mean of the diameter of the grains. Size-corrected data are for aggregates during irradiation in the ISM. Aggregates of >200 μm are shown at 200 μm. Size measurements of all grains are given in *SI Appendix*.

radiation from the young sun. Based on cosmogenic He and Ne concentrations in hibonite, an aluminum–calcium oxide, from the Murchison meteorite, the solar cosmic ray (SCR) flux these grains might have been exposed to was orders of magnitudes higher than today, consistent with what is expected during the T Tauri phase of the sun (30–32, 34). Hibonites were among the first condensates in the protoplanetary disk (59) and were transported to the disk surface far enough from the sun to evade significant heating, where they were irradiated by an enhanced SCR flux (34). If the presolar SiC grains had a similar exposure history to solar energetic particles in the protoplanetary disk as the hibonites, they would also have acquired a similar concentration of SCR-produced noble gases. The difference in irradiation time on the disk surface between presolar SiC and hibonites is not known. Given that the high-temperature condensate hibonite was present very early in the disk (59), the short disk lifetime of a few megayears (60, 61), and the exposure required to explain the cosmogenic hibonite data (34), we consider that the time difference between the hibonite and SiC exposure duration was probably small. Our results show that the majority of the cosmogenic ^{21}Ne was acquired during presolar GCR exposure (*SI Appendix*, Fig. S7 and *Calculation of He and Ne Exposure Ages*). Specifically, at least 80% of the cosmogenic ^{21}Ne for grains with ^{21}Ne ages greater than 100 Ma was acquired by presolar GCR exposure. For these grains, the amount that might have been acquired during early Solar System formation is smaller than the uncertainty of the presolar exposure ages and, hence, not detectable. These findings only apply if the presolar grains were exposed to the early active sun at all. At most, the five grains with the lowest ages might have acquired all their cosmogenic ^{21}Ne in the early Solar System (*SI Appendix*, Fig. S7). Early Solar System exposure does not significantly affect our interpretation of presolar ages, except, possibly, for these five grains.

However, our observation has implications for the origin of hibonites that formed in the solar nebula: The cosmogenic nuclide concentrations in the hibonites are typically much lower than that observed in presolar SiC grains, indicating that the irradiated hibonites are indeed early Solar System products and not of presolar origin.

We note that a presolar exposure age of a SiC grain is a nominal age and that the actual residence time in the ISM might have been shorter if the grains were exposed to a high energetic particle flux from other nearby stars in addition to background GCR exposure. We estimate that the chances of such a close encounter for the average interstellar SiC are low and that such exposure could have also led to destruction of the grain. Modeling of this probability is difficult due to many unknowns and beyond the scope of this work.

Conclusions

With this study, we have increased the number of presolar SiC grain Ne exposure ages, calculated with improved recoil corrections and cosmogenic nuclide production rates. Based on Ne isotopes, we conclude that a majority (∼60%) of the large presolar SiC grains analyzed have interstellar cosmic ray exposure ages below 300 Ma before the formation of the Solar System. This is compatible with most theoretical estimates of interstellar dust lifetimes of 100 to 200 Ma. This age distribution is also consistent with the hypothesis that these grains originate from stars that initially formed during an enhanced SFR ∼7 Ga ago and became dust-producing AGB stars between ∼4.9 and ∼4.6 Ga ago. Furthermore, a significant fraction has presolar ages above 300 Ma, with at least ∼8% above 1 Ga, making them the oldest dated samples so far. These old ages require that these grains evaded destruction in supernova shockwaves, possibly in dense clumps that formed in such shockwaves. Based on a comparison of cosmogenic He and Ne, it is clear that some grains were part of larger particles or aggregates and might have had large mantles of ices and organics during cosmic ray exposure in the ISM.

The studied presolar grains might have acquired a small but, in most cases, undetectable fraction of their cosmogenic Ne during exposure of energetic particles from the early active sun. However, only particularly young grains with very low interstellar residence times might have received a significant fraction of their cosmogenic nuclides in the early Solar System, before accretion onto planetesimals. The specifics of this exposure, such as the solar particle flux and exposure, are currently unknown.

We conclude that Ne exposure age dating is currently the only viable method to date presolar grains. While the method provides ages relative to the start of the Solar System and suffers from relatively large uncertainties, it can provide unique information about the interstellar dust cycle and star-forming events in the Galaxy before the birth of the sun.

Materials and Methods

This paragraph describes the materials and methods in brief. More detailed information, data and figures of the samples, analytical methods, and models are provided in *SI Appendix*. Large presolar SiC from the original so-called "LS+LU" separation from the Murchison meteorite were characterized with electron microscopy and classified with nanoscale secondary ion mass spectrometry (NanoSIMS). Isotopes of Li were analyzed with NanoSIMS, and He and Ne isotopes were analyzed with noble gas mass spectrometry. We determined cosmogenic components and recoil corrections before calculating cosmic ray exposure ages with interstellar production rates. The systematic uncertainties of the ages include uncertainties in the production rates and recoil corrections. The uncertainties of the data are based on counting statistics, blank corrections, and sample mass errors. A detailed discussion of the uncertainties is given in *SI Appendix*. Ages are considered upper limits if their uncertainty is larger than the age.

Data Availability Statement. All data discussed in the paper is available in the *SI Appendix*.

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