



# Revisiting the lifetime estimate of large presolar grains in the interstellar medium

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## ARTICLE INFO

### Article history:

Received 10 November 2015

Received in revised form

5 February 2016

Accepted 11 February 2016

Available online 22 February 2016

### Keywords:

Dust

Galaxy evolution

Meteorites

Milky Way

Presolar grains

## ABSTRACT

Some very large ( $> 0.1 \mu\text{m}$ ) presolar grains are sampled in meteorites. We reconsider the lifetime of very large grains (VLGs) in the interstellar medium focusing on interstellar shattering caused by turbulence-induced large velocity dispersions. This path has never been noted as a dominant mechanism of destruction. We show that, if interstellar shattering is the main mechanism of destruction of VLGs, their lifetime is estimated to be  $\geq 10^8$  yr; in particular, very large SiC grains can survive for  $\sim 1$  Gyr. The lifetimes obtained for VLGs are comparable to the longest residence time derived for some presolar grains based on the cosmic-ray exposure time. However, most presolar SiC grains show residence times significantly shorter than 1 Gyr, which may indicate that there is a more efficient mechanism than shattering in destroying VLGs, or that VLGs have larger velocity dispersions than  $10 \text{ km s}^{-1}$ . We also argue that the enhanced lifetime of SiC relative to graphite can be the reason why we find SiC among  $\mu\text{m}$ -sized presolar grains, while the abundance of SiC in the normal interstellar grains is much lower than graphite.

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## 1. Introduction

The elemental and isotopic compositions of presolar grains found in primitive meteorites provide us with clues to their origins. The peculiar isotopic ratios obtained for presolar grains, such as nanodiamonds, silicon carbide (SiC), and graphite, indicate that they are formed in the environments around particular types of stars (Anders and Zinner, 1993; Zinner, 2014). SiC is the species with the most detailed studies because it is relatively easy to be separated from the other substances in meteorites and its high trace element abundance allows us to perform isotope studies on a multitude of elements. Also, SiC is one of the most abundant  $\mu\text{m}$ -sized (in this paper, sizes are given as radius)<sup>1</sup> species identified in presolar grains (Amari et al., 1994). Most of the SiC grains are defined as mainstream grains, which have  $^{12}\text{C}/^{13}\text{C}$  isotope ratio = 10–100 (the solar ratio is 89) and enhanced  $^{14}\text{N}/^{15}\text{N}$  ( $> 272 = \text{solar}$ ) (e.g., Amari et al., 2001). The isotopic abundances in the mainstream SiC grains indicate an asymptotic giant branch (AGB) star origin (e.g., Gallino et al., 1994; Lugaro et al., 2003). Presolar

graphite grains are also identified: Amari et al. (2014) analyzed presolar graphite grains extracted from the Murchison meteorite, and showed based on isotopic ratios of various elements that some of them originated from supernovae and others from AGB stars. Theoretical studies of dust condensation in AGB star winds also suggest that large ( $\geq 0.1 \mu\text{m}$ ) SiC grains form (Yasuda and Kozasa, 2012). In this paper, we refer to grains larger than  $0.1 \mu\text{m}$  as very large grains (VLGs).<sup>2</sup>

After analysis of noble gas elements in SiC grains found in primitive meteorites, Lewis et al. (1990) showed that their isotopic and elemental ratios are consistent with the values theoretically expected for AGB stars. They also derived their presolar cosmic-ray exposure age (or residence time)  $\sim 135$  Myr based on the  $^{21}\text{Ne}$  abundance. Heck et al. (2009) inferred interstellar residence times of presolar SiC as 3–1100 Myr for large (diameter  $\sim 5\text{--}50 \mu\text{m}$ ) presolar SiC grains. The residence times estimated may be uncertain because recoil losses of Ne from  $\mu\text{m}$ -sized grains are large. The measurement of spallation xenon (Xe), which is much less affected by recoil loss, suggested shorter cosmic-ray exposure ages  $< 200$

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<sup>1</sup> However, a factor 2 difference in size does not matter for most of the statements in the Introduction. Whenever precision is required, we use the word “radius” or the notation  $a$ .

<sup>2</sup> The term ‘large grain’ or ‘big grain’ is often used to indicate the grain population which dominates the far-infrared emission, and it refers to such a size range as  $\sim 0.01\text{--}0.25 \mu\text{m}$  (Desert et al., 1990; Li and Draine, 2001). To avoid confusion with this convention, we refer to large grains of interest in this paper as VLGs.

Myr (Ott et al., 2005). Gyngard et al. (2009) estimated that the interstellar exposure ages are 40 Myr–1 Gyr using  $^6\text{Li}$  excesses in presolar SiC grains. These exposure ages give us clues to the lifetime (or residence time) of VLGs in the interstellar medium (ISM). Since AGB stars are one of the most important sources of the interstellar dust (Ferrarotti and Gail, 2006; Ventura et al., 2012), the lifetime of dust grains formed in AGB stars is an important quantity in considering the lifecycle of dust in the ISM.

There have been some attempts of direct sampling of interstellar dust using dust-detecting instruments on spacecraft such as *Ulysses* (Grün et al., 1994; Baguhl et al., 1995; Krüger et al., 2015), *Galileo* (Baguhl et al., 1996), *Helios* (Altobelli et al., 2006), *Cassini* (Altobelli et al., 2003), and *Stardust* (Westphal et al., 2014). They indeed detected  $\mu\text{m}$ -sized grains whose velocities point to their interstellar origin. Interstellar grains smaller than  $\sim 0.1 \mu\text{m}$  are expelled by the solar radiation pressure and/or deflected by the interplanetary magnetic field (Levy and Jokipii, 1976; Sterken et al., 2013). Although the interpretation depends on the modeling of the radiation pressure and gravity of the Sun and the magnetic field in the solar system (Sterken et al., 2013), the large abundance of VLGs measured by the above spacecraft implies the existence of a significant abundance of grains larger than  $0.1 \mu\text{m}$  in the ISM.

The lifetime of dust grains in the ISM is governed by destructive processes, among which the most violent one is believed to be supernova shocks. Assuming tight coupling between the motions of gas and dust, Jones et al. (1996) argued that shattering in supernova shocks is the major destruction path for large  $\geq 0.1 \mu\text{m}$  grains and estimated the typical lifetime of the interstellar grains to be  $\sim a \text{ few} \times 10^8 \text{ yr}$ . However, VLGs are not necessarily coupled with the gas motion in the ISM. Indeed, Slavin et al. (2004) showed, solving explicitly the grain trajectories in the presence of magnetic field, that decoupling of the gas and dust is important for grains with radii  $> 0.1 \mu\text{m}$  in supernova shocks. Therefore, VLGs may have lifetimes much longer than  $\sim 10^8 \text{ yr}$ , unless there is another mechanism of limiting the lifetimes.

Although VLGs are decoupled from small-scale motions in the ISM, they are coupled with a large-scale ( $\sim 10$ – $100 \text{ pc}$ ) turbulent and magnetohydrodynamic motion in the ISM (Yan et al., 2004). Based on an analytical kinetic theory of dust grains, Yan et al. (2004) showed that grains larger than  $\sim 0.1 \mu\text{m}$  can obtain random velocities as large as  $10 \text{ km s}^{-1}$  in the diffuse ISM. Using their results, Hirashita and Yan (2009) showed that VLGs are efficiently disrupted by shattering in the diffuse ISM. Therefore, even if VLGs escape from supernova shocks by being decoupled from the gas motion, shattering in the diffuse ISM is unavoidable. This new destruction mechanism, not related to shocks, is worth considering for the purpose of constraining the lifetime of VLGs.

The existence of VLGs is also important in the following two aspects. One is that the size range is around the upper mass cut-off of grain radius of the grain size distribution in the ISM. A grain size distribution  $n(a) \propto a^{-3.5}$  ( $a$  is the grain radius) with an upper cut of grain radius at  $0.25 \mu\text{m}$  explains the Milky Way extinction curve (Mathis et al., 1977, hereafter MRN). More elaborate models for the grain size distribution also show a fall-off just above a similar grain radius ( $\sim 0.25 \mu\text{m}$ ), although it is not a rigid cut-off (Weingartner and Draine, 2001). The other important aspect of VLGs is that a significant fraction of the total dust mass is occupied by grains whose sizes are around the upper cut (fall)-off ( $\sim 0.1 \mu\text{m}$ ). If we assume that MRN grain size distribution in a grain radius range of  $0.001$ – $0.25 \mu\text{m}$ , the VLG regime ( $> 0.1 \mu\text{m}$ ) contains 39 percent of the dust mass. Therefore, the lifetime of VLGs has a large impact on the total dust abundance in the ISM.

In this paper, we reconsider the lifetime of VLGs, focusing on shattering in the diffuse ISM. This process has not been considered

to determine the VLG lifetime in previous studies. Moreover, as mentioned above, VLGs may be decoupled from supernova shocks. This means that the ‘classical’ picture in which the lifetime of dust grains is determined by the shock destruction may not be valid for VLGs. Therefore, the new destruction mechanism of VLGs proposed in this paper will give a new upper limit for the lifetime of VLGs. The lifetime estimated in this paper is compared with the residence time of presolar grains inferred from isotopic measurements. Here, the residence time indicates the time spent in the ISM before the formation of the solar system.

The paper is organized as follows: we explain the formulation adopted to estimate the lifetime of VLGs in Section 2. We show the results in Section 3. We discuss the significance of the results in Section 4. Finally we conclude in Section 5.

## 2. Models for shattering

### 2.1. Collision rate

We consider a VLG once formed in stellar ejecta and injected into the ISM. We denote the radius and root-mean-square (rms) velocity of a VLG as  $a_{\text{VLG}}$  and  $v_{\text{VLG}}$ , respectively. For simplicity, we assume that all VLGs have the same velocity  $v_{\text{VLG}}$  since the velocity distribution function of grains in turbulent medium is unknown.<sup>3</sup> The interstellar turbulence is a viable mechanism that causes the random velocities of grains (e.g., Völk et al., 1980). Since larger-sized grains are coupled with larger-scale motions in the ISM and larger-scale turbulent motions usually have larger velocity dispersions (e.g., Yan et al., 2004; Ormel and Cuzzi, 2007), we assume that VLGs obtain the largest velocity dispersions, as large as  $\sim 10 \text{ km s}^{-1}$  (this value is taken from the velocity dispersion of the diffuse neutral ISM in the solar vicinity; Spitzer, 1978; Mathis, 2000). This means that we can approximate the collisional velocity between a VLG and a grain in the ISM (referred to as an ISM grain in this paper) with  $v_{\text{VLG}} \sim 10 \text{ km s}^{-1}$ , which is treated as a constant parameter in this paper.

While a VLG travels in the ISM, it encounters the ISM grains. The grain size distribution of the ISM grains,  $n(a)$ , is defined so that  $n(a) da$  is the number density of grains whose sizes are between  $a$  and  $a + da$ . The rate at which a VLG traveling in the ISM encounters the ISM grains with radii between  $a$  and  $a + da$  is denoted as  $df_{\text{coll}}$  and estimated as

$$df_{\text{coll}} = \pi(a_{\text{VLG}} + a)^2 v_{\text{VLG}} n(a) da. \quad (1)$$

### 2.2. Destroyed fraction

In collision with an ISM grain, a certain fraction of the VLG is destroyed by shattering. In what follows, we adopt the formulation in Kobayashi and Tanaka (2010) to estimate the shattered fraction (the fraction of the volume fragmented into smaller grains) of a VLG. They estimate the shattered fraction of a grain as

$$F_{\text{sh}} = \frac{\phi}{1 + \phi}, \quad (2)$$

<sup>3</sup> This assumption is not likely to affect the results significantly. As shown in Section 3, the destruction rate of a VLG is proportional to  $v^3$ , where  $v$  is the velocity of the VLG. If the velocity distribution function,  $f(v)$ , follows the Gaussian weighted by the phase-space volume ( $f(v) = (l^3/\pi^{3/2}) \exp(-l^2 v^2) \cdot 4\pi v^2$ , where  $l^2 = 3/(2\langle v^2 \rangle)$ ), we obtain  $\langle v^3 \rangle = 1.23 \langle v^2 \rangle^{3/2}$ , where  $\langle \cdot \rangle$  means the ensemble average. Thus, if we represent the velocity  $v_{\text{VLG}}$  with the rms velocity  $\langle v^2 \rangle^{1/2}$ ,  $v_{\text{VLG}}^3 = \langle v^2 \rangle^{3/2}$  approximates  $\langle v^3 \rangle$  well (unless we adopt a peculiar velocity distribution function).

**Table 1**  
Dust properties adopted ( $s$ ,  $P_1$ , and  $Q_D^*$ ) and calculated (the others).

Species	$s$ (g cm $^{-3}$ )	$P_1$ (erg cm $^{-3}$ )	$Q_D^*$ (erg g $^{-1}$ )	$\eta$	$\tau_{\text{VLG}}^a$ (yr)	$\eta\tau_{\text{VLG}}$ (yr)	$M_{\text{VLG}}^{\text{AGB}}$ ( $M_\odot$ )	frac. <sup>b</sup> (%)
Silicate	3.3	$3 \times 10^{11}$	$4.5 \times 10^{10}$	$1.0 \times 10^{-4}$	$2.1 \times 10^8$	$2.1 \times 10^4$	$6.3 \times 10^4$	0.13
Graphite	2.2	$4 \times 10^{10}$	$9.1 \times 10^9$	$2.2 \times 10^{-4}$	$4.4 \times 10^7$	$9.7 \times 10^3$	$2.9 \times 10^4$	0.058
SiC	3.1	$1.7 \times 10^{12}$	$2.7 \times 10^{11}$	$2.1 \times 10^{-5}$	$1.2 \times 10^9$	$2.5 \times 10^4$	$7.5 \times 10^4$	0.15

<sup>a</sup> The lifetime is estimated at  $a_{\text{VLG}} = 1 \mu\text{m}$ .

<sup>b</sup> Fraction to the total dust mass.

where  $\phi$  is the impact energy normalized to the threshold impact energy per mass for catastrophic disruption,<sup>4</sup>  $Q_D^*$ :

$$\phi = \frac{v_{\text{VLG}}^2 y}{2Q_D^* (1+y)}, \quad (3)$$

with  $y$  being the mass ratio,  $m/m_{\text{VLG}}$  ( $m$  and  $m_{\text{VLG}}$  are the masses of the ISM grain and the VLG, respectively).

The contribution of the ISM grains with radii between  $a$  and  $a+da$  to the shattered fraction of a VLG per unit time is estimated as  $F_{\text{sh}} df_{\text{coll}}$ . Therefore, the total shattered fraction of the VLG increases at rate  $d\Phi/dt$  estimated as

$$\frac{d\Phi}{dt} = \int_{a_{\text{min}}}^{a_{\text{max}}} F_{\text{sh}} \frac{df_{\text{coll}}}{da} da = \int_{a_{\text{min}}}^{a_{\text{max}}} \pi(a_{\text{VLG}} + a)^2 v_{\text{VLG}} n(a) \frac{\phi}{1+\phi} da. \quad (4)$$

Note that  $\phi$  is a function of  $a$ . If both the ISM grain and the VLG have the same material density,  $y = (a/a_{\text{VLG}})^3$  in Eq. (3). We hereafter assume this expression for  $y$ . The lifetime of the VLG is estimated as

$$\tau_{\text{VLG}} = 1 / \left( \frac{d\Phi}{dt} \right). \quad (5)$$

### 2.3. Choice of parameter values

As mentioned in the Introduction, we are primarily interested in SiC, which is well sampled for presolar grains, but we also examine silicate and carbonaceous (graphite) dust as they are known to be representative dust species in the ISM (e.g., [Draine and Lee, 1984](#)). [Hirashita and Kobayashi \(2013\)](#) showed that  $Q_D^*$  is estimated using the critical pressure ( $P_1$ ), above which the solid becomes plastic, as

$$Q_D^* \simeq \frac{P_1}{2s}, \quad (6)$$

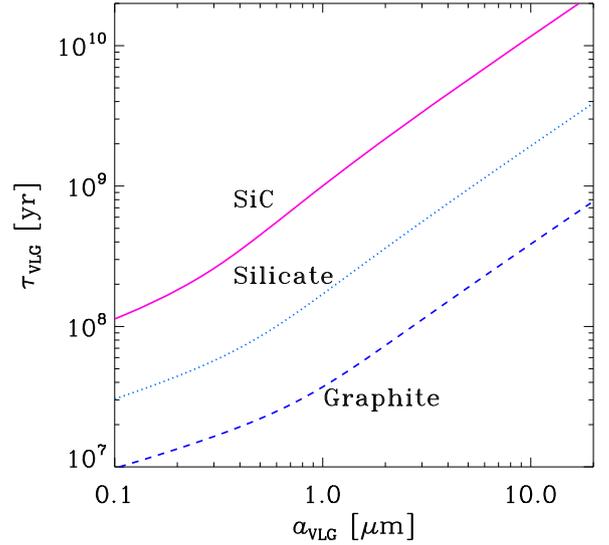
where  $s$  is the grain material density. We list  $s$  and  $P_1$  as well as the obtained  $Q_D^*$  for each grain species in [Table 1](#).

Now we need to specify the grain size distribution of the ISM grains,  $n(a)$  (Eq. (4)). We assume the MRN grain size distribution  $n(a) \propto a^{-3.5}$  with the minimum and maximum grain radii  $a_{\text{min}} = 0.001 \mu\text{m}$  and  $a_{\text{max}} = 0.25 \mu\text{m}$ , respectively. This grain size distribution is consistent with the Milky Way extinction curve (MRN). The results below do not change significantly even if we adopt the grain size distributions proposed for the Milky Way dust by [Weingartner and Draine \(2001\)](#). The normalization of the grain size distribution is determined by

$$\mathcal{D} \mu m_{\text{H}} n_{\text{H}} = \int_{a_{\text{min}}}^{a_{\text{max}}} \frac{4}{3} \pi a^3 s n(a) da, \quad (7)$$

where  $\mathcal{D}$  is the dust-to-gas ratio,  $\mu = 1.4$  is the gas mass per hydrogen nucleus,  $m_{\text{H}}$  is the hydrogen atom mass, and  $n_{\text{H}}$  is the number density of hydrogen nuclei. To fix the number density of ISM grains, we always adopt  $s = s_{\text{ISM}} = 3 \text{ g cm}^{-3}$  in Eq. (7) with

<sup>4</sup> Catastrophic disruption is defined as a disruption event in which a significant fraction (half in the definition of [Kobayashi and Tanaka, 2010](#)) of the grain is shattered.



**Fig. 1.** Lifetime of VLG against shattering as a function of radius  $a_{\text{VLG}}$ . The solid, dotted, and dashed lines show the results for SiC, silicate, and graphite, respectively.

$\mathcal{D} = 0.01$  for the ISM grains. We adopt  $n_{\text{H}} = 0.25 \text{ cm}^{-3}$  ([Jones et al., 1996](#)) for the typical density for the diffuse ISM, keeping in mind that the grain lifetime is proportional to  $n_{\text{H}}^{-1}$ . We also assume that VLGs spend most of their lifetime in the diffuse ISM before being incorporated into the molecular cloud from which the solar system was formed.

### 3. Result and analysis

We calculate the lifetime of VLGs,  $\tau_{\text{VLG}}$ , using the method described in the previous section. In [Fig. 1](#), we show  $\tau_{\text{VLG}}$  as a function of VLG radius  $a_{\text{VLG}}$  for the three dust species. We observe that SiC VLGs have lifetimes longer than  $10^8$  yr, while silicate and graphite VLGs have significantly shorter lifetimes than SiC VLGs. In particular, SiC grains with  $a_{\text{VLG}} \gtrsim 1 \mu\text{m}$  (the radii appropriate for actually sampled SiC VLGs) survive for more than 1 Gyr as long as shattering in the ISM is the main mechanism of grain destruction.

The above result can be roughly reproduced by an analytic argument as follows. As long as we consider VLGs,  $a_{\text{VLG}} \gg a$  or  $y \ll 1$  gives a good approximation for most of the collisions. Therefore,  $\phi \simeq v_{\text{VLG}}^2 (a/a_{\text{VLG}})^3 / (2Q_D^*)$ . Since  $a < 0.25 \mu\text{m}$ ,  $\phi \lesssim 1$  holds for  $a_{\text{VLG}} \gtrsim 1 \mu\text{m}$ , which means that  $\phi/(1+\phi) \simeq \phi$ . With these approximations, Eq. (4), combined with Eq. (7), is reduced to the following expression for  $\tau_{\text{VLG}} = (d\Phi/dt)^{-1}$ :

$$\tau_{\text{VLG}} \simeq \frac{8a_{\text{VLG}} Q_D^* s_{\text{ISM}}}{3v_{\text{VLG}}^3 \mathcal{D} \mu m_{\text{H}} n_{\text{H}}} \simeq 1.2 \times 10^9 \text{ yr} \left( \frac{a_{\text{VLG}}}{1 \mu\text{m}} \right) \left( \frac{Q_D^*}{2.7 \times 10^{11} \text{ erg g}^{-1}} \right) \left( \frac{s_{\text{ISM}}}{3 \text{ g cm}^{-3}} \right)$$

$$\times \left( \frac{v_{\text{VLG}}}{10 \text{ km s}^{-1}} \right)^{-3} \left( \frac{D}{0.01} \right)^{-1} \left( \frac{n_{\text{H}}}{0.25 \text{ cm}^{-3}} \right)^{-1}. \quad (8)$$

This explains the values of  $\tau_{\text{VLG}}$  at  $a_{\text{VLG}} \gtrsim 1 \mu\text{m}$  in Fig. 1. At  $a_{\text{VLG}} < 1 \mu\text{m}$ , the proportionality ( $\tau_{\text{VLG}} \propto a_{\text{VLG}}$ ) does not hold primarily because the approximation of  $\phi \ll 1$  does not hold. Yet, the above expression gives a good approximation within a factor of  $\sim 2$  for the entire regime of VLG (i.e.,  $a_{\text{VLG}} > 0.1 \mu\text{m}$ ).

The above results indicate that SiC VLGs have long lifetimes against interstellar shattering because of its high  $Q_D^*$  value, and that, as a grain becomes larger, its lifetime becomes longer. This suggests that SiC VLGs tend to preserve the memory of its formation site more than silicate and graphite, which have shorter lifetimes.

#### 4. Discussion

We discuss the implication of the lifetimes estimated above. We focus on the comparison with presolar grains, whose residence times in the ISM can actually be obtained. We also discuss the expected abundance of VLGs in the ISM.

##### 4.1. Comparison with presolar grains

The lifetime given above provides an upper limit for the residence time of presolar grains in the ISM. Experimentally, the residence time of presolar grains in the ISM can be constrained by using the excesses of spallogenic isotopes, from which one can derive the fluence of cosmic rays, hence the exposure time.

Gyngard et al. (2009) estimated that the interstellar exposure ages are 40 Myr–1 Gyr using  $^6\text{Li}$  excesses in presolar SiC grains with radii  $> 1 \mu\text{m}$ . The range is consistent with the lifetime estimated above (note that the lifetime gives an upper limit for the residence time). Based on cosmogenic  $^3\text{He}$  and  $^{21}\text{Ne}$ , Heck et al. (2009) derived the interstellar exposure ages as  $\sim 3$ –200 Myr for most of the sampled presolar SiC grains with radii  $> 1 \mu\text{m}$ , although a few grains show longer interstellar residence times of 400 Myr to 1 Gyr. It seems that most of the sampled SiC grains show much shorter residence times than the lifetime estimated in this paper. Moreover, no trend of exposure ages with grain size is observed in their sample, which is not in accordance with our expectation that larger grains have longer lifetimes. Since the estimations of exposure age also have uncertainties in the correction for recoil losses of the elements and the poorly known Galactic cosmic ray flux at the formation epoch of the solar system, it is still premature to judge whether or not we need to take these discrepancies seriously.

It is worth mentioning that the estimated VLG lifetime is sensitive to the assumed velocity,  $v_{\text{VLG}}$  (Eq. (8)). If we adopt a larger value for the velocity, for example,  $v_{\text{VLG}} = 20 \text{ km s}^{-1}$  as expected by the acceleration by gyroresonance in the interstellar magnetic field (Yan et al., 2004), the lifetime of  $\mu\text{m}$ -sized SiC VLGs is  $\sim 10^8 \text{ yr}$ . Therefore, if an acceleration mechanism of VLGs, such as gyroresonance, works in the ISM to make the velocity dispersion of VLGs larger than that of gas, the grain lifetime can be more consistent with the residence times derived for a large part of the above samples. A higher velocity dispersion of VLGs than  $20 \text{ km s}^{-1}$  is excluded since the lifetime of  $\mu\text{m}$ -sized SiC grains becomes shorter than 100 Myr, which contradicts the residence times measured.

We further discuss other possibilities of explaining the short exposure ages in Section 4.3.

##### 4.2. Expected abundance of VLGs in the ISM

We formulate the theoretically expected total mass of VLGs, assuming that AGB stars are the major production sources and that interstellar shattering is the major destruction mechanism. We consider the total dust budget in the Milky Way. The total mass of VLGs originating from AGB stars in the Milky Way is denoted as  $M_{\text{VLG},i}^{\text{AGB}}$ , where  $i$  stands for the grain species (silicate, carbonaceous dust, and SiC). The time evolution of  $M_{\text{VLG},i}^{\text{AGB}}$  is described as

$$\frac{dM_{\text{VLG},i}^{\text{AGB}}}{dt} = \left[ \frac{dM_{\text{VLG},i}}{dt} \right]_{\text{AGB}} - \frac{M_{\text{VLG},i}^{\text{AGB}}}{\tau_{\text{VLG},i}}, \quad (9)$$

where  $[dM_{\text{VLG},i}/dt]_{\text{AGB}}$  is the production rate of VLGs of species  $i$  in AGB star winds and  $\tau_{\text{VLG},i}$  is the shattering time-scale of VLGs in their collisions with the ISM grains. We use the lifetime of VLGs estimated in Eq. (5) for  $\tau_{\text{VLG},i}$ . The production rate of VLGs in AGB stars is related to the star formation history, the statistics of stellar mass (specified by the initial mass function), and the total dust produced by individual stars (e.g., Asano et al., 2013):

$$\left[ \frac{dM_{\text{VLG},i}}{dt} \right]_{\text{AGB}} = \int_{m_t}^{8 M_{\odot}} \psi(t - \tau_m) m_i(m) \phi(m) dm \simeq \bar{\psi} \eta, \quad (10)$$

where  $\psi(t - \tau_m)$  is the star formation rate (SFR) in the Galaxy at  $t - \tau_m$  ( $t$  is the current age, and  $\tau_m$  is the lifetime of a star with mass  $m$ ; note that the dust production occurs at the end of stellar life),  $m_t$  is the turn-off mass (the mass of a star whose lifetime is equal to the age of the Galaxy; assumed to be  $1 M_{\odot}$  in this paper),  $m_i(m)$  is the total mass of dust species  $i$  produced by the star with mass  $m$ ,  $\phi(m)$  is the stellar initial mass function, and  $\eta \equiv \int_{m_t}^{8 M_{\odot}} m_i(m) \phi(m) dm$ . From the first to the second line in Eq. (10), we approximate the SFR with the time-averaged SFR ( $\bar{\psi}$ ) assuming that the SFR does not vary drastically as a function of time. We do not consider a strong enhancement of SFR at a particular time as discussed in Clayton (2003) (see also Section 4.3).

For  $m_i(m)$  we adopt the calculation of dust condensation in AGB star winds in Zhukovska et al. (2008) for silicate, carbonaceous dust, and SiC. Silicate in our calculation includes all the species other than carbonaceous dust and SiC, so that the total dust mass is equal to the sum of the mass of SiC, graphite, and silicate.

Now we are only interested in equilibrium states since the grain lifetime is significantly shorter than the age of the Galaxy. Even if this does not hold (i.e.,  $\tau_{\text{VLG},i} \gtrsim t$ ), the equilibrium value gives the maximum VLG mass expected in the Milky Way since  $dM_{\text{VLG},i}^{\text{AGB}}/dt > 0$  holds (i.e., the VLG mass originating from AGB stars still continues to increase until it reaches the equilibrium value because the first term on the right-hand side in Eq. (9) dominates over the second term). Considering the equilibrium  $dM_{\text{VLG},i}^{\text{AGB}}/dt = 0$  in Eq. (9), combined with Eq. (10), we obtain

$$M_{\text{VLG},i}^{\text{AGB}} \simeq \bar{\psi} \eta \tau_{\text{VLG},i}. \quad (11)$$

In Table 1, we show  $\eta$ ,  $\tau_{\text{VLG}}$  (estimated for  $a_{\text{VLG}} = 1 \mu\text{m}$ ) and  $\eta \tau_{\text{VLG}}$  for each dust species. We observe that  $\eta \tau_{\text{VLG}}$  of SiC is as large as that of silicate because the long lifetime of SiC VLGs compensates the small yield of SiC in AGB stars. This explains the fact that SiC is found in presolar grains although SiC is a minor dust species in the ISM compared with silicate and graphite; that is, if we sample only  $\mu\text{m}$ -sized grains originating from AGB stars, SiC VLGs are found as easily as other species because of their long lifetime.

The SFR in the Galactic disk has been rather constant: indeed, the current SFR is estimated as  $\sim 3 M_{\odot} \text{ yr}^{-1}$ , and this level of SFR explains the total stellar mass in the disk if the disk age is  $\sim 10 \text{ Gyr}$  (Trimble, 2000). Therefore, we assume that  $\psi \simeq \bar{\psi} \simeq 3 M_{\odot} \text{ yr}^{-1}$ . Multiplying this value with  $\eta$  obtained above (for  $a_{\text{VLG}} = 1 \mu\text{m}$ ), we get  $M_{\text{VLG},i}^{\text{AGB}}$  for each species as listed in Table 1.

The total dust mass in the Milky Way is estimated to be  $\sim 5 \times 10^7 M_{\odot}$  (Hirashita et al., 2014). We also list the ratio of  $M_{\text{VLG}}^{\text{AGB}}$  of each species to the total dust mass in Table 1. The fractions are on the order of 0.1 percent. Therefore, the existence of VLGs in the ISM does not contradict the observational properties reflecting the interstellar grains such as extinction curves and infrared emission because of the negligible fractions.

However, these fractional abundances of VLGs cannot be directly compared with the fraction in primitive meteorites. The actual fraction of sampled SiC grains in meteorites (up to 150 ppm; Zinner, 2014) is much smaller than those values estimated above probably because additional processing in the solar system may have destroyed SiC grains by exposure to hot ( $\geq 1000$  K) gas (Mendybaev et al., 2002). It is also interesting to compare the calculated and measured silicate/SiC ratios. We predict a silicate/SiC ratio of 0.13/0.15  $\sim 1$  (Table 1) while measurements of presolar grains indicate a ratio of  $\sim 5$  (Leitner et al., 2012). Although processing of SiC and silicate grains in the solar system makes the direct comparison difficult, it is encouraging that both theory and measurement show silicate/SiC ratio of the same order of magnitude.

#### 4.3. Grain processing mechanisms other than shattering

Sputtering in SN shocks is the dominant mechanism of dust destruction for the ISM grains (Dwek and Scalo, 1980; McKee, 1989; Jones et al., 1994; Nozawa et al., 2006). However, Jones and Nuth (2011) pointed out that the destruction rate of dust by supernova shocks is highly uncertain. Moreover, as mentioned in the Introduction, the motion of VLGs tends to be decoupled from the shocks, which indicates that some VLGs are likely to escape destruction by sputtering in shocks. In this paper, we have considered shattering in the diffuse ISM, not associated with supernova shocks, and have given another constraint on the lifetime of VLGs.

VLGs may also form as a result of coagulation in the dense ISM (Ormel et al., 2009; Hirashita et al., 2014). The anomalous isotopic compositions of presolar grains (Introduction) often support the formation in specific types of stars. VLGs formed as a result of coagulation are expected to be compounds, which do not show uniformity of composition. Thus, it is expected that VLGs of coagulation origin, even if they are contained in a meteorite, are hard to be identified as single presolar grains. At the same time, VLGs of coagulation origin would be less isotopically anomalous because coagulation of many grains dilutes the peculiarity of isotopic compositions. Although dust can also grow through the accretion of gas-phase metals (e.g., Draine, 2009), VLGs cannot have been formed through accretion: as shown by Hirashita and Kuo (2011), accretion only modifies a few nm of the dust surface, which is too thin compared with the radii of VLGs.

Bernatowicz et al. (2003) studied 81  $\mu\text{m}$ -sized pristine presolar SiC grains. They found that a large fraction of the SiC grains are coated with an apparently amorphous, possibly organic phase. This may indicate that the surface of SiC is affected by accretion in the ISM or in the solar system. On the other hand, their SiC grain surface studies did not show strong evidence for cratering or sputtering. They suggested that surface coatings protected the SiC grains from destructive processing in the ISM.

As mentioned in Section 4.1, most of the sampled SiC presolar grains have lifetimes much shorter than the theoretically estimated shattering time-scale ( $\sim 1$  Gyr). Ott et al. (2005) suggested, based on efficient amorphization in the ISM inferred from the high amorphous fraction (or low crystalline fraction) of silicate by Kemper et al. (2004), that a large part of interstellar SiC grains are amorphized. Provided that amorphous SiC is easily destroyed in the early solar system, the amorphization time-scale is more

relevant than the shattering time-scale for the lifetime in the ISM since the amorphized SiC grains are not sampled as presolar grains.

Another solution for the short residence time of presolar grains is to consider an enhancement of AGB star dust production just before the solar system was formed. This means that an enhancement of SFR (or a starburst) occurred 1–2 Gyr before the formation of the solar system (Ott et al., 2005). In this star formation history, AGB stars originating from stars with  $m \sim 2 M_{\odot}$  form SiC dust grains just before the formation of the solar system, so that their residence times are observed to be short. Clayton (2003) also explained the isotopic ratios of the mainstream SiC presolar grains by considering a starburst activated by a merger of a metal-poor satellite galaxy with the Milky Way.

## 5. Conclusion

We have investigated interstellar shattering as a mechanism of determining the lifetime of very large grains (VLGs with radii  $a_{\text{VLG}} > 0.1 \mu\text{m}$ ) in the interstellar medium (ISM). Sputtering in supernova shocks, which is considered to be the main destruction mechanism for the interstellar dust, may not work for VLGs because such large grains are decoupled from the gas motion on the spatial scale of shocked regions (Slavin et al., 2004). On the other hand, VLGs are coupled with a large-scale turbulent motion in the ISM and attain random velocities as high as  $\sim 10 \text{ km s}^{-1}$ . Therefore, we have considered shattering of VLGs under successive collisions with the grains present in the ISM (ISM grains). Estimating the shattering time-scale for VLGs, we have shown that SiC VLGs have lifetimes as long as  $\sim 1$  Gyr.

We have also compared the destruction time-scale obtained above with the residence time of presolar SiC grains sampled in meteorites. We referred to laboratory studies in the literature for the residence time estimated from the cosmic ray exposure time in the ISM using the excesses of isotopes caused by Galactic cosmic ray spallation. Indeed, some presolar SiC grains show residence times as long as 1 Gyr, which is consistent with our estimate of lifetime above. However, most presolar grains have residence times significantly shorter than 1 Gyr, which may indicate that there is a more efficient mechanism than shattering in destroying VLGs, that a large abundance of dust was produced by AGB stars shortly before the birth of the solar system, or that VLGs have larger velocity dispersions than assumed in this paper (i.e.,  $> 10 \text{ km s}^{-1}$ ).

SiC VLGs have a longer shattering time than VLGs composed of silicate and carbon. The long lifetime of SiC VLGs may serve to enhance the abundance of SiC in presolar  $\mu\text{m}$ -sized grains.

## Acknowledgment

We are grateful to S. Tachibana and the anonymous referees for useful comments. H.H. is supported by the Ministry of Science and Technology (MoST) Grant 102-2119-M-001-006-MY3. T.N. is supported in part by the JSPS Grant-in-Aid for Scientific Research (26400223).

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