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

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ABSTRACT

Some very large (> 0.1 μm) 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 $\gtrsim 10^8$ yr; in particular, very large SiC grains can survive for ~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 km s^{-1}. We also argue that the enhanced lifetime of SiC relative to graphite can be the reason why we find SiC among μm-sized presolar grains, while the abundance of SiC in the normal interstellar grains is much lower than graphite.

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 μm-sized (in this paper, sizes are given as radius)[1] species identified in presolar grains (Amari et al., 1994). Most of the SiC grains are defined as mainstream grains, which have $^{12}C/^{13}C$ isotope ratio = 10–100 (the solar ratio is 89) and enhanced $^{14}N/^{15}N$ (> 272 = 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 ($\gtrsim$0.1 μm) SiC grains form (Yasuda and Kozasa, 2012). In this paper, we refer to grains larger than 0.1 μm as very large grains (VLGs).[2]

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) ~135 Myr based on the ^{21}Ne abundance. Heck et al. (2009) inferred interstellar residence times of presolar SiC as 3–1100 Myr for large (diameter ~ 5–50 μm) presolar SiC grains. The residence times estimated may be uncertain because recoil losses of Ne from μm-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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[1] 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.

[2] 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 ~0.01–0.25 μm (Désert 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.

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Myr (Ott et al., 2005). Gyngard et al. (2009) estimated that the interstellar exposure ages are 40 Myr–1 Gyr using ^{6}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 μm-sized grains whose velocities point to their interstellar origin. Interstellar grains smaller than ~0.1 μm 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 μm 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 ≳0.1 μm grains and estimated the typical lifetime of the interstellar grains to be ~a few $\times$ 10^8 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 μm in supernova shocks. Therefore, VLGs may have lifetimes much longer than $\sim 10^8$ 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 (~10–100 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 ~0.1 μm can obtain random velocities as large as 10 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 μm 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 (~0.25 μm), 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 (~0.1 μm). If we assume that MRN grain size distribution in a grain radius range of 0.001–0.25 μm, the VLG regime (>0.1 μm) 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 $a_{\rm VLG}$ and $v_{\rm VLG}$, respectively. For simplicity, we assume that all VLGs have the same velocity $v_{\rm VLG}$ since the velocity distribution function of grains in turbulent medium is unknown.[3] 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 ~10 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 $v_{\rm VLG} \sim 10$ 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 $n(a)\,{\rm d}a$ is the number density of grains whose sizes are between a and $a+{\rm d}a$. The rate at which a VLG traveling in the ISM encounters the ISM grains with radii between a and $a+{\rm d}a$ is denoted as ${\rm d}f_{\rm coll}$ and estimated as

$$ {\rm d}f_{\rm coll} = \pi(a_{\rm VLG}+a)^2 v_{\rm VLG}\, n(a)\,{\rm d}a. \tag{1} $$

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

$$ F_{\rm sh} = \frac{\phi}{1+\phi}, \tag{2} $$

[3] 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 ($f(v) = (l^3/\pi^{3/2})\exp(-l^2v^2)\cdot 4\pi v^2$, 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 $v_{\rm VLG}$ with the rms velocity $\langle v^2\rangle^{1/2}$, $v_{\rm VLG}^3 = \langle v^2\rangle^{3/2}$ approximates $\langle v^3\rangle$ well (unless we adopt a peculiar velocity distribution function).