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Dense molecular cloud cores as a source of micrometer-sized grains in galaxies

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ABSTRACT

Coreshine in dense molecular cloud cores (dense cores) is interpreted as evidence for micrometer-sized grains (referred to as very large grains, VLGs). VLGs may have a significant influence on the total dust amount and the extinction curve. We estimate the total abundance of VLGs in the Galaxy, assuming that dense cores are the site of VLG formation. We find that the VLG abundance relative to the total dust mass is roughly $\phi_{\rm VLG} \sim 0.01(1-\epsilon)/\epsilon(\tau_{\rm SF}/5\times 10^9\ {\rm year})^{-1}(f_{\rm VLG}/0.5)(t_{\rm shat}/10^8\ {\rm year})$, where ϵ is the star formation efficiency in dense cores, $\tau_{\rm SF}$ is the timescale of gas consumption by star formation, $f_{\rm VLG}$ is the fraction of dust mass eventually coagulated into VLGs in dense cores, and $t_{\rm shat}$ is the lifetime of VLGs (determined by shattering). Adopting their typical values for the Galaxy, we obtain $\phi_{\rm VLG} \sim 0.02$–0.09. This abundance is well below the value detected in the heliosphere by *Ulysses* and *Galileo*, which means that local enhancement of VLG abundance in the solar neighborhood is required if the VLGs originate from dense cores. We also show that the effects of VLGs on the extinction curve are negligible even with the upper value of the above range, $\phi_{\rm VLG} \sim 0.09$. If we adopt an extreme value, $\phi_{\rm VLG} \sim 0.5$, close to that inferred from the above spacecraft data, the extinction curve is still in the range of the variation in Galactic extinction curves, but is not typical of the diffuse ISM.

1. Introduction

Dust grains play an essential role in some fundamental physical processes in the interstellar medium (ISM). First, they dominate the radiative transfer of stellar light in the ISM. In particular, the extinction curve, that is, the wavelength dependence of optical depth for dust absorption plus scattering is known to reflect the dust materials (e.g., Hoyle and Wickramasinghe, 1969) and grain size distribution (e.g., Mathis et al., 1977, hereafter MRN; Draine, 2003). Second, the dust surface is the main site for the formation of some molecular species, especially H_2 (e.g., Gould and Salpeter, 1963; Cazaux and Tielens, 2002). The rate of dust surface reaction is proportional to the total surface area of dust grains (e.g., Hollenbach and Salpeter, 1971; Yamasawa et al., 2011). Since the extinction curve and the total grain surface area both depend strongly on the grain size distribution, clarifying the regulating mechanism of grain size distribution is of particular importance in understanding those important roles of dust in the ISM.

MRN showed that a mixture of silicate and graphite with a grain size distribution (number of grains per grain radius) proportional to $a^{-3.5}$, where a is the grain radius ($a = 0.001$ –0.25 μm), reproduces the Milky Way extinction curve. This size distribution is referred to as the MRN size distribution. Kim et al. (1994) and Weingartner and Draine (2001) made more detailed models of the Milky Way extinction curve. In both these models, the abundance of grains whose radii are beyond the maximum in the MRN size distribution (0.25 μm) is so low that the contribution of such large grains to the total dust mass is negligible.

The existence of micrometer (μm)-sized grains is suggested in dense molecular cloud cores (called dense cores in this paper). The so-called "coreshine" refers to emission in the mid-infrared (especially the 3.6-μm Spitzer Infrared Array Camera (IRAC) band) from deep inside dense cores of molecular clouds (Steinacker et al., 2010; Pagani et al., 2010). It is detected in about half of the cores studied by Pagani et al. (2010). The emission is interpreted as light scattered by dust grains with typical sizes of ∼1 μm, which is much larger than the maximum grain radius in the diffuse interstellar medium (∼0.25 μm; MRN). We refer to μm-sized grains as "very large grains (VLGs)" in this paper.

Formation of VLGs by coagulation in dense cores has been theoretically investigated by Hirashita and Li (2013) (see also Ormel et al., 2009, 2011). Based on the timescale on which grains grow up to μm sizes by coagulation, they argued that dense cores are sustained over several free-fall times. Since their main aim was to constrain the lifetime of dense cores, the impact of VLG formation on the grain size distribution in the entire ISM was beyond their scope. A certain fraction of VLGs formed in dense cores may be injected into the diffuse ISM when the dense cores

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disperse. Efficient formation of VLGs would contradict the MRN grain size distribution in which the maximum grain radius is $\sim 0.25\ \mu$m. Thus, based on an estimation of the total abundance of VLGs in the Milky Way, we examine the consistency between the formation of VLGs suggested by coreshine and the Galactic extinction curve (or the MRN grain size distribution). In this paper, the abundance of VLGs stands for the ratio of the total VLG mass to the total dust mass (including VLGs), and is denoted as $\phi_{\rm VLG}$ (see Section 2). By definition, $0 \le \phi_{\rm VLG} \le 1$.

There are some indications that VLGs exist in the ISM. One of the indications of interstellar VLGs is provided by meteorites. Large interstellar grains ($>1\ \mu$m) are known to exist in chondritic meteorites. Such grains were identified based on their extremely anomalous (way off from the average solar system isotope ratios) isotopic compositions (Clayton and Nittler, 2004). This implies that interstellar dust grains must have resided and survived in a dense core that ended up forming the solar system.

Another indication of interstellar VLGs comes from direct detection of interstellar grains in the heliosphere by *Ulysses* and *Galileo*. These experiments have shown that the volume mass density of VLGs is comparable to the total dust volume mass density derived from the typical dust-to-gas ratio in the diffuse ISM in the Galaxy (Landgraf et al., 2000; Krüger et al., 2007; Frisch and Slavin, 2013). This seems contradictory to the above grain size distribution derived by MRN, who found that most of the dust grains have radii less than $0.25\ \mu$m. Thus, it has been argued that the density of VLGs is enhanced in the solar neighborhood (Draine, 2009; Frisch and Slavin, 2013). Nevertheless, it is still interesting to compare the VLG abundance expected from the formation in dense cores with the measurements, in order to quantify what fraction of the observed VLGs can be explained by the formation in dense cores.

We may also need to consider stellar sources of dust grains, especially asymptotic giant branch (AGB) stars and supernovae (SNe) for the production of VLGs. Indeed, the size distribution of grains produced by AGB stars is suggested to be biased toward large ($\gtrsim 0.1\ \mu$m) sizes from the observations of spectral energy distributions (Groenewegen, 1997; Gauger et al., 1999; Norris et al., 2012), although Hofmann et al. (2001) showed that the grains are not single-sized. Theoretical studies have also shown that the dust grains formed in the winds of AGB stars have typical sizes $\gtrsim 0.1\ \mu$m (Winters et al., 1997; Yasuda and Kozasa, 2012). SNe (Type II SNe) are also considered to produce relatively large ($>0.01\ \mu$m) grains because small grains are destroyed by reverse shocks before they are ejected into the ISM (Nozawa et al., 2007; Bianchi and Schneider, 2007). However, the timescale of dust supply from stars is longer than the shattering timescale (Hirashita, 2010) by an order of magnitude. Therefore, even if VLGs are supplied from stars, they probably fail to survive in the ISM. In this paper, we do not treat the stellar production of VLGs because of the difficulty in their survival, but focus on their formation in dense cores, motivated by the new evidence of VLGs – coreshine.

In this paper, we estimate the abundance of VLGs in the Galaxy, assuming that dense cores are the main sites for the formation of VLGs. This paper is organized as follows. In Section 2, we formulate and estimate the abundance of VLGs in the Galaxy. In Section 3, we compare our estimates with some observations. In Section 4, we discuss our results and implications for the dust evolution in galaxies. In Section 5, we give our conclusions.

2. Estimation of the total VLG mass

2.1. Formation rate of VLGs in the Galaxy

We estimate the supply rate of VLGs (μm-sized grains) in the Galaxy. Motivated by coreshine as evidence of VLGs in dense cores, we examine the hypothesis that dense cores are the main sites for the formation of VLGs in the Galaxy (see also Introduction). We assume that all dense molecular cloud cores (dense cores) eventually convert a significant fraction of dust grains into VLGs by coagulation after their lifetimes. The formation rate of VLGs (the total mass of VLGs is denoted as $M_{\rm VLG}$) in dense cores in the Galaxy, $[dM_{\rm VLG}/dt]_{\rm form}$, is estimated as

$$\left[\frac{dM_{\rm VLG}}{dt}\right]_{\rm form} \equiv \frac{X_{\rm core}M_{\rm dust}(1-\phi_{\rm VLG})f_{\rm VLG}(1-\varepsilon)}{\tau_{\rm core}}, \tag{1}$$

where $X_{\rm core}$ is the mass fraction of dense cores to the total gas mass, $M_{\rm dust}$ is the total dust mass in the Galaxy ($X_{\rm core}M_{\rm dust}$ is the total dust mass contained in the dense cores), $\phi_{\rm VLG} \equiv M_{\rm VLG}/M_{\rm dust}$ is the ratio of the VLG mass to the total dust mass (the factor $1-\phi_{\rm VLG}$ means that we need to subtract the dust that has already become VLGs), $f_{\rm VLG}$ is the fraction of dust that is eventually coagulated to μm sizes in the dense cores, ε is the star formation efficiency in the dense cores (the factor $1-\varepsilon$ means that the gas that is not included in stars is assumed to be dispersed into the ISM), and $\tau_{\rm core}$ is the lifetime of dense core (i.e., the timescale of VLG formation). Note that Eq. (1) *should not* be regarded as an ordinary differential equation, but just gives an estimate for the VLG formation rate. Since dense cores are also the sites of star formation, the star formation rate of the Galaxy is estimated by dividing the total gas mass contained in the dense cores with their lifetime (i.e., the timescale of star formation):

$$\psi = \frac{\varepsilon X_{\rm core}M_{\rm gas}}{\tau_{\rm core}}, \tag{2}$$

where $M_{\rm gas}$ is the total gas mass in the Galaxy ($X_{\rm core}M_{\rm gas}$ is the total gas mass in dense cores). This equation converts the core formation rate ($X_{\rm core}M_{\rm gas}/\tau_{\rm core}$) into the star formation rate, and serves to eliminate the core formation rate, which is unknown observationally compared with the star formation rate. By introducing the dust-to-gas ratio, $\mathcal{D} \equiv M_{\rm dust}/M_{\rm gas}$ and using Eq. (2), we obtain

$$\frac{X_{\rm core}}{\tau_{\rm core}} = \frac{\mathcal{D}\psi}{\varepsilon M_{\rm dust}}. \tag{3}$$

Inserting Eq. (3) into Eq. (1), we finally get the following estimate for the VLG formation rate:

$$\left[\frac{dM_{\rm VLG}}{dt}\right]_{\rm form} = \frac{1-\varepsilon}{\varepsilon}\mathcal{D}(1-\phi_{\rm VLG})\psi f_{\rm VLG}. \tag{4}$$

This VLG formation rate could be implemented in a larger framework of dust enrichment, which is capable of calculating the evolution of the total dust mass in the Galaxy, to calculate the evolution of $M_{\rm VLG}$ in a consistent way with $M_{\rm dust}$ or $\mathcal{D}$. However, this is not necessary for the purpose of estimating the total VLG mass in the Galaxy. The timescale of dust enrichment (i.e., the timescale of the variation of $M_{\rm dust}$ or $\mathcal{D}$) in the Galaxy is roughly the metal-enrichment timescale ($\sim$ several Gyr) (e.g., Dwek, 1998; Zhukovska et al., 2008; Inoue, 2011; Asano et al., 2013a), which is much longer than the lifetime of VLGs (typically determined by the shattering timescale $\sim 10^8$ year; Hirashita, 2010). Therefore, we can assume that $M_{\rm dust}$ and $\mathcal{D}$ are constant within the lifetime of VLGs. In such a case, the total mass of VLGs can be approximately estimated as follows.

It is shown that μm-sized grains are shattered in the diffuse ISM by grain–grain collisions under the grain motion induced by turbulence (Yan et al., 2004; Hirashita, 2010). Shattering also occurs in supernova shocks (Jones et al., 1996). Thus, we assume that the lifetime of VLGs is determined by the shattering timescale, $t_{\rm shat}$ ($\sim 10^8$ year; Hirashita, 2010). The destruction rate of VLGs can thus be approximately estimated as $M_{\rm VLG}/t_{\rm shat}$, and the equilibrium between the VLG formation and destruction is achieved on