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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 $\phi_{\rm VLG} \sim 0.01(1-\varepsilon)/\varepsilon(\tau_{\rm SF}/5\times 10^9\ {\rm year})^{-1}(f_{\rm VLG}/0.5)(t_{\rm shat}/10^8\ {\rm year})$, 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 a timescale of $\sim t_{shat}$. Since, as mentioned above, t_{shat} is much shorter than the evolution timescale of the dust mass, the variation of $\mathcal{D}$ in t_{shat} can be neglected. Therefore, the total mass of VLGs in the Galaxy is estimated by the equilibrium between the formation and the destruction under a fixed $\mathcal{D}$:

$$M_{VLG} \sim \left[\frac{dM_{VLG}}{dt}\right]_{form} \cdot t_{shat} = \frac{1-\epsilon}{\epsilon}\mathcal{D}(1-\phi_{VLG})\psi f_{VLG} t_{shat}. \quad (5)$$

2.2. Estimations of various quantities

We adopt dust-to-gas ratio $\mathcal{D} = 0.01$, the same value as adopted in our previous calculations of coagulation in dense cores (Hirashita and Li, 2013). The star formation rate in the Galaxy can be estimated from the total luminosity of OB stars. Hirashita et al. (2007) obtained a star formation rate of 1.3 $M_\odot$ year^{-1} based on the total OB star luminosity derived observationally by Mathis et al. (1983). According to Hirashita and Li (2013), almost all the dust mass is in VLGs after coagulation in dense cores. Here we conservatively assume that half of the dust mass is converted into VLGs after coagulation in dense cores (i.e., $f_{VLG} = 0.5$). For t_{shat}, we adopt 10^8 year according to Hirashita (2010), who considered shattering under the grain motion driven by interstellar turbulence. As calculated by Jones et al. (1996), shattering can also take place in supernova shocks. Even if the supernova shocks are the main site of shattering (Jones et al., 1996), a similar timescale is obtained for shattering (Section 4.3).

Using the above values, we obtain

$$M_{VLG} \sim 5 \times 10^5 (1-\phi_{VLG}) \frac{1-\epsilon}{\epsilon}\left(\frac{\mathcal{D}}{0.01}\right) \times \left(\frac{\psi}{1 M_\odot\ \mathrm{year}^{-1}}\right)\left(\frac{f_{VLG}}{0.5}\right)\left(\frac{t_{shat}}{10^8\ \mathrm{year}}\right) M_\odot. \quad (6)$$

For comparison, we also estimate the total dust mass. The total gas mass in the Milky Way is $M_{gas} \sim 5 \times 10^9\ M_\odot$ (Mathis, 2000; Tielens, 2005). By multiplying the dust-to-gas ratio, the dust mass is estimated as

$$M_{dust} = M_{gas}\mathcal{D} \sim 5 \times 10^7 \left(\frac{\mathcal{D}}{0.01}\right)\left(\frac{M_{gas}}{5 \times 10^9 M_\odot}\right) M_\odot. \quad (7)$$

Dividing Eq. (6) with Eq. (7), we obtain the following expression by recalling that $\phi_{VLG} = M_{VLG}/M_{dust}$:

$$\frac{\phi_{VLG}}{1-\phi_{VLG}} = 0.01\frac{1-\epsilon}{\epsilon}\left(\frac{\tau_{SF}}{5 \times 10^9\ \mathrm{year}}\right)^{-1}\left(\frac{f_{VLG}}{0.5}\right)\left(\frac{t_{shat}}{10^8\ \mathrm{year}}\right), \quad (8)$$

where $\tau_{SF} \equiv M_{gas}/\psi$ is the star formation (gas consumption) time. The star formation efficiency ϵ in molecular cloud cores is around 0.1–0.3 (Alves et al., 2007; Curtis and Richer, 2010; Lada et al., 2010). Thus, we can assume that $\phi_{VLG} \ll 1$ in the Galaxy. In this case, we simply replace the left-hand side of Eq. (8) with ϕ_{VLG}.

3. Comparison with observational data

3.1. Direct detection

Interstellar dust grains with radii $a \gtrsim 0.1\ \mu$m can be detected directly in space (Mann, 2009). In Fig. 1, we show the grain mass distribution for interstellar grains in the heliosphere observed by the *Ulysses* and *Galileo* spacecraft (Frisch and Slavin, 2013). Small grains with typically $a < 0.1\ \mu$m are excluded from the heliospheric plasma because of large charge-to-mass ratios. Thus, we are only interested in the data at $a > 0.1\ \mu$m.

In Fig. 1, we also plot the grain mass distribution calculated by Hirashita and Li (2013) but scaled so that the total mass density of

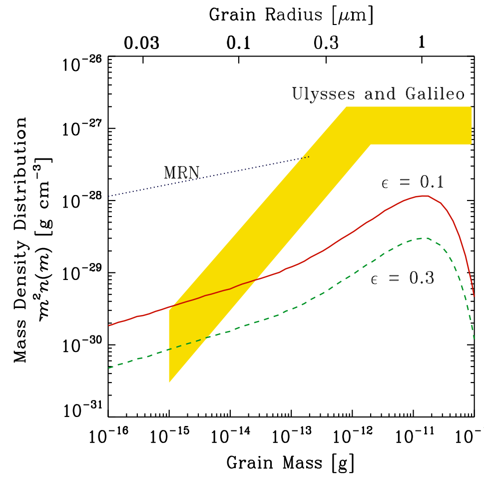

Fig. 1. Grain mass distributions. The solid and dashed lines show the grain mass distributions calculated by Hirashita and Li (2013), but scaled with the total VLG abundance appropriate for $\epsilon = 0.1$ and 0.3, respectively. The dotted line shows the MRN distribution, which is considered to be representative of the grain size distribution in the diffuse ISM. The data taken by the *Ulysses* and *Galileo* spacecraft are represented by the shaded area, the width of which shows the typical error (Frisch and Slavin, 2013). The corresponding grain radii are also shown on the upper axis with grain material density 3.3 g cm^{-3}.

VLGs is $\phi_{VLG}\mathcal{D}\mu m_H n_H$, where μ is the gas mass per hydrogen atom (1.4), m_H is the mass of hydrogen atom, $n_H = 0.1$ cm^{-3} is the number density of hydrogen nuclei in the local ISM (Frisch and Slavin, 2013). Draine (2009) adopted $n_H = 0.22$ cm^{-3}, but the difference by a factor of 2 does not affect the conclusions. The functional form of the distribution is taken from the maximal coagulation model with a number density of hydrogen nuclei of 10^5 cm^{-3} at $t = 5.5t_{ff}$ (t_{ff} is the free-fall time), when the peak is located at $a = 1\ \mu$m. The peak roughly reflects the mass density of VLGs, and is not sensitive to the choice of t in any case. From Eq. (8), we adopt VLG-to-total-dust mass ratio $\phi_{VLG} = 0.01(1-\epsilon)/\epsilon$ with star formation efficiency ϵ=0.1–0.3 (Section 2.2). Note that the grain mass distribution is expressed as $m^2 n(m) = (4\pi\rho_{gr}/9)n'(a)a^4$, where ρ_{gr} is the grain material density, and $n'(a)$ is the grain size distribution,[1] which is related to $n(m)$ by $n(m)\,dm = n'(a)da$. We adopt the same grain material density, $\rho_{gr} = 3.3$ g cm^{-3}, as in Hirashita and Li (2013).

As we observe in Fig. 1, the mass density of VLGs expected with $\phi_{VLG} \sim 0.02$–0.09 (for ϵ=0.3–0.1) is much lower than observed in space. This means that the large mass density observed in the heliosphere cannot be explained by the abundance of VLGs formed in dense cores. From the analysis of their velocities, the VLGs detected in space are not likely to be the remains of the large grains that were produced by coagulation in the dense core inside which the Solar System formed (Howe and Rafikov, 2013). If dense cores are the site of VLG formation, we need some mechanism for enhancing the VLG abundance locally to explain the spacecraft data. The physical mechanism of such an enhancement is still unknown (Draine, 2009).

For comparison, we also show the MRN (Mathis et al., 1977) grain size distribution ($n'(a) \propto a^{-3.5}$, with the upper and lower limits of grain radius, 0.001 μm and 0.25 μm, respectively). The normalization of the MRN grain size distribution is determined so that the total dust mass density is $\mathcal{D}\mu m_H n_H$ with dust-to-gas ratio $\mathcal{D} = 0.01$. This MRN size distribution is representative of the grain size distribution in the diffuse ISM of the Galaxy. The abundance of

[1] The grain size distribution is defined so that $n'(a)\,da$ is the number density of dust grains with radii between a and $a + da$.

VLGs expected from star formation efficiency $\epsilon = 0.1$–0.3 is well below the extrapolation of the MRN grain size distribution to $a \sim 1$ μm. This is consistent with a small VLG-to-total-dust mass ratio, $\phi_{VLG} \ll 1$; that is, VLGs make only a small contribution to the total dust mass in the Galaxy.

3.2. Extinction curves

The wavelength dependence of interstellar extinction, the so-called extinction curve, is a viable tool to derive the grain size distribution. The MRN size distribution was derived by fitting the averaged interstellar extinction curve in the Milky Way. For the MRN size distribution, the upper limit of the grain radius is 0.25 μm. Here we examine if the inclusion of VLGs is consistent with the Galactic extinction curve or not.

A possible caveat of extinction curve fitting is that the solution is not unique. For example, MRN adopted graphite for the carbonaceous material because of the strong 2175 Å bump, while Jones (2012) proposed hydrogenated amorphous carbon. Compiègne et al. (2011) used the latter species for the carbonaceous dust component and reproduced both the extinction and emission of dust in the Galaxy. The relative contribution between silicate and carbonaceous dust also depends on the material properties adopted. Therefore, strictly speaking, adopting a specific model reproducing the extinction curve means that the following result only serves as an example of the effects of VLGs. However, our results below are valid at least qualitatively as long as large grains tend to show flat extinction curves in the optical and the 2175 Å bump is produced by small grains.

We assume that grains are composed of two species: silicate and graphite. Extinction curves are calculated by using the same optical properties of silicates and graphites as in Hirashita and Yan (2009). That is, we adopt the optical constants from Draine and Lee (1984) and calculate extinction cross-sections by the Mie theory (Bohren and Huffman, 1983). The cross-sections are weighted by the grain size distributions, and summed up for silicate and graphite. The fraction of silicates to the total dust mass is assumed to be 0.54, and the rest is assumed to be graphite (Takagi et al., 2003; Hirashita and Yan, 2009). The contributions from the MRN size distribution and from the VLGs to the total extinction are proportional to $(1-\phi_{VLG})$ and ϕ_{VLG}, respectively.

In Fig. 2, we show the results. The extinction is normalized to the V band (0.55 μm), and the normalized extinction at wavelength λ is denoted as A_λ/A_V. We find that, even for star formation efficiency $\epsilon = 0.1$ (equivalent to VLG-to-total-dust mass ratio $\phi_{VLG} = 0.09$), there is only a slight difference from the extinction curve for the MRN model[2] with a little enhancement in infrared extinction, and slightly lower carbon bump and ultraviolet extinction. All these differences can be explained by the contribution from VLGs, as is clear from the extinction curve of the VLG component (dashed line in Fig. 2). However, the difference is negligible compared with the typical variation in the Milky Way (Nozawa and Fukugita, 2013). $R_V \equiv A_V/(A_V - A_B)$, which is an indicator of the flatness of extinction curve, is 3.6 and 3.7 for MRN and $\epsilon = 0.1$, respectively. For $\epsilon = 0.3$, the difference is even smaller. Therefore, our estimate of the VLG abundance is within the acceptable range as far as the variation of extinction curve is concerned.

We also show an extreme case where $\phi_{VLG} = 0.5$, considering that the above *Ulysses* and *Galileo* data show a mass density of

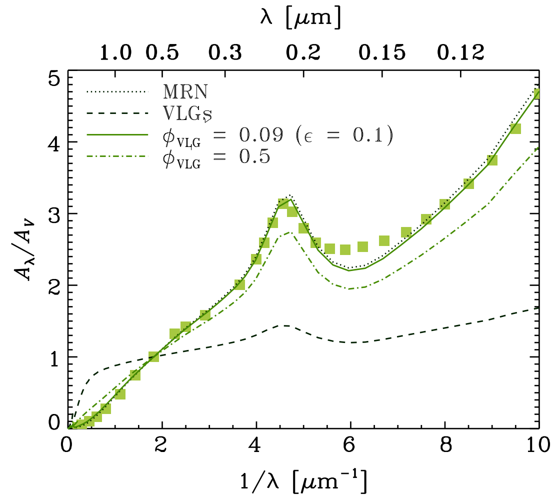

Fig. 2. Extinction curves. The solid and dot-dashed lines show the extinction curves calculated for $\phi_{VLG} = 0.09$ (corresponding to $\epsilon = 0.1$) and $\phi_{VLG} = 0.5$ (as an extreme case, based on the *Ulysses* and *Galileo* data), respectively. The dotted and dashed lines show the extinction curves for the MRN and VLG components, respectively. The filled squares show the observed Galactic extinction curve taken from Pei (1992).

VLGs comparable to the total dust mass density in the diffuse ISM (i.e., the MRN component in Fig. 1). The deviation from the mean Galactic extinction curve is clear in this case. For this extinction curve, we obtain $R_V = 4.6$, which is still in the range of the variation in the Milky Way extinction curve, but is not typical of the diffuse ISM (Cardelli et al., 1989; Fitzpatrick and Massa, 2007). This again supports the view that the high VLG abundance is due to local enhancement. Draine (2009) also calculated the extinction curve based on Weingartner and Draine (2001)'s model modified for the *Ulysses* and *Galileo* measurements. They obtained $R_V = 5.8$, the difference from our models being due to their higher abundance of VLGs. They also conclude that the large excess of μm-sized interstellar grains in the heliosphere is not representing the typical diffuse medium in the Milky Way but is probably due to local enhancement of VLG abundance.

4. Discussion

4.1. In the context of galaxy evolution

The above estimate of ϕ_{VLG} (the VLG-to-total-dust mass ratio) is applicable to the Milky Way. Galaxies in general are expected to have a variety in ϕ_{VLG}. The central hypothesis in this paper is that VLGs form in dense cores. This is probably true in solar-metallicity environments where dust-to-gas ratio is large enough for coagulation to occur efficiently in dense cores. In contrast, in a galaxy whose dust-to-gas ration is lower, coagulation in dense cores may not be efficient enough to produce VLGs; in other words, f_{VLG} is smaller if dust-to-gas ratio (or metallicity) is lower. Since dust-to-gas ratio has a positive correlation with metallicity (Schmidt and Boller, 1993), we expect that ϕ_{VLG} is smaller in lower-metallicity galaxies.

Asano et al. (2013b) showed that the major source of grains with $a > 0.1$ μm is stars (SNe and AGB stars) in low-metallicity (or low-dust-to-gas-ratio) environments. Therefore, if coagulation is not efficient, we expect that most of the VLGs (if they exist) are of stellar origin. As mentioned in Introduction, the size distributions of grains produced by AGB stars and SNe are suggested to be biased toward large ($\gtrsim 0.1$ μm) sizes. However, there is still an uncertainty in the size distribution of dust grains formed in stellar ejecta. For more quantitative estimates of relative importance

[2] The extinction curve calculated by the MRN model has some deviations from the observational data taken from Pei (1992): one is seen around $1/\lambda \sim 6$ μm^{-1} and another is the different value of R_V (note that the mean value of R_V is 3.1 (Pei, 1992)). However, the overall shape of the observed mean extinction curve (shown by filled squares in Fig. 2) is well reproduced by the MRN grain size distribution, and further fine-tuning does not affect the discussions and conclusion in this paper.

between stellar VLGs and dense-core VLGs, we need to construct a framework that takes into account all dust formation and destruction mechanisms as done by Asano et al. (2013b). Since they did not include VLG formation in dense cores, it is necessary to implement it into their framework in the future.

The stellar origin of VLGs is worth considering further. As mentioned in Introduction, large interstellar grains ($> 1\ \mu m$) exist in chondritic meteorites. Given their large isotope anomalies that are reflective of stellar nucleosynthesis processes (Clayton and Nittler, 2004), the grains may have formed in stellar ejecta. However, it is unlikely that grains formed in stellar ejecta have such a high abundance as observed by the spacecraft, since the timescale of dust supply from stellar sources is likely to be longer than the destruction timescale by shattering (Hirashita, 2010) and sputtering (McKee, 1989; Jones et al., 1996). Recently, Jones and Nuth (2011) have suggested that the lifetime of silicate dust is comparable to the destruction timescale, which means that the possibility of VLG formation in stellar ejecta is still worth investigating.

The existence of VLGs can have a significant influence on the extinction curve if there is local enhancement of VLG abundance as indicated by the spacecraft missions (see the case of $\phi_{\rm VLG}=0.5$ in Fig. 2). Thus, if we are concerned with the local variation of extinction curves, the contribution from VLGs should be taken into account. On global scales of a galaxy, in contrast, the abundance of VLGs is not high enough to affect the extinction curve, as long as the values of the parameters in Eq. (8) are similar to the Galactic values.

The far-infrared spectral energy distribution is also affected by the existence of VLGs. The equilibrium temperature ($T_{\rm eq}$) of a dust grain depends on the grain radius as $T_{\rm eq}\propto a^{1/(\beta+4)}$, where $\beta(\sim 2)$ is the power-law index of the mass absorption coefficient κ_ν as a function of frequency ν, $\kappa_\nu\propto\nu^\beta$ (Evans, 1994). Because of this dependence, VLGs tend to be colder than "normal" grains with $a\lesssim 0.1\ \mu m$. If the abundance of VLGs is high, we should consider a significant contribution from such a "cold" dust component.

4.2. Star formation efficiency in dense cores

The star formation efficiency in dense cores, ε, is a key factor for the VLG-to-total-dust mass ratio $\phi_{\rm VLG}$. It enters our formulation in two ways. The first is through Eq. (1), in which the factor $(1-\varepsilon)$ expresses the fraction of dust that is not included in stars formed in dense cores. The second is through Eq. (2), which connects the core formation rate to the star formation rate. As a result, $\phi_{\rm VLG}\propto(1-\varepsilon)/\varepsilon$ (as long as $\phi_{\rm VLG}\ll 1$). If ε is nearly unity, $\phi_{\rm VLG}\sim 0$, which means that all VLGs once formed in dense cores are eventually included in stars. In contrast, if $\varepsilon\lesssim 0.01$, $\phi_{\rm VLG}\sim 1$. This corresponds to a case in which the total mass of dense cores is large.

The volume density of VLGs measured by *Ulysses* and *Galileo* is comparable to that of the entire dust population expected from the dust-to-gas ratio in the ISM, $\mathcal{D}=0.01$ (MRN in Fig. 1). For example, $\phi=0.5$ corresponds to $\varepsilon=0.01$, indicating an extremely low star formation efficiency. Considering that star formation efficiencies observationally estimated for dense cores are ~ 0.1–0.3 (Section 2.2), the high VLG abundance is probably due to local enhancement (see also Section 3.2).

4.3. Variation of other parameters

In galaxies, $\tau_{\rm SF}$ and $t_{\rm shat}$ may also change. The gas consumption time $\tau_{\rm SF}$ ranges from $\sim 10^8$ year to $\sim 10^{11}$ year for nearby galaxies (Kennicutt, 1998). In a starburst galaxy with $\tau_{\rm SF}\sim 10^8$ year, if we adopt $\varepsilon=0.1$, $f_{\rm VLG}=0.5$ and $t_{\rm shat}=10^8$ year, we obtain $\phi_{\rm VLG}\simeq 0.8$. This large value is due to the enhanced formation rate of dense cores. Therefore, the abundance of VLGs can be enhanced in starburst galaxies.

If the typical dust size in starburst galaxies is really large and VLGs are continuously supplied there, it may have important consequence for the dust destruction efficiency by sputtering. Since the timescale of dust destruction by thermal sputtering is proportional to the grain size (Draine and Salpeter, 1979), the VLGs survive longer than smaller grains. In particular, extreme starbursts at high redshift seem to have more dust than can be produced by stars with a dust lifetime expected for the "normal-sized" grains (Valiante et al., 2011; Mattsson, 2011). The discrepancy is explained by grain growth through accretion of gas-phase metals in the ISM (Michałowski et al., 2010; Mattsson, 2011; Valiante et al., 2011; Kuo and Hirashita, 2012). However, if the VLGs dominate the total dust mass, their longer survival would make the discrepancy smaller, requiring less grain growth than is thought in previous studies. This is also true for nearby starburst galaxies.

However, in starburst galaxies, shattering may also be efficient. Grains acquire larger velocities in the ionized medium than in the neutral medium because less dissipative magnetohydrodynamic nature of the ionized medium leads to more efficient gyroresonance (resonance between the magnetohyrodynamical waves with the gyromotion of a grain) acceleration of grains (Yan et al., 2004; Hirashita and Yan, 2009). As a result, $t_{\rm shat}$ is shorter in the ionized medium. Therefore, if the ISM is highly ionized as a result of high star formation activities in starburst galaxies, $t_{\rm shat}$ may decrease, compensating the decrease of $\tau_{\rm SF}$ in Eq. (8).

In this paper, we have considered turbulence as the source of grain motion for shattering. Shattering also occurs in supernova shocks (Jones et al., 1996). Hirashita et al. (2010) showed that shattering in supernova shocks is as efficient as shattering in turbulence. They derived the timescale of shattering in supernova shocks $\sim 0.01\tau_{\rm SF}$, which gives the same order of magnitude as $t_{\rm shat}$ above. If we adopt this expression, the dependence of $\phi_{\rm VLG}$ on $\tau_{\rm SF}$ cancels out (Eq. 8). Therefore, if supernova shocks are the main site of shattering, the VLG abundance is insensitive to the star formation activity.

In summary, it is not clear if the abundance of VLGs increases or decreases in starburst galaxies. Nevertheless, the expression in Eq. (8) is useful to understand the dependence of the VLG abundance on star formation activity and shattering timescale.

5. Conclusion

We have estimated the abundance of very large grains (VLGs), whose radii are typically $\gtrsim 1\ \mu m$, in the Galaxy. Coreshine in dense molecular cloud cores (dense cores) is taken as evidence for such VLGs. Assuming that VLGs are formed in dense cores, we have estimated the abundance of VLGs in the Galaxy. The VLG abundance relative to the total dust mass is estimated as $\phi_{\rm VLG}\sim 0.01(1-\varepsilon)/\varepsilon(\tau_{\rm SF}/5\times 10^9\ {\rm year})^{-1}(f_{\rm VLG}/0.5)(t_{\rm shat}/10^8\ {\rm year})$, 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 clouds, and $t_{\rm shat}$ is the lifetime of VLGs (determined by shattering). Adopting typical star formation efficiencies $\varepsilon\sim 0.1$–0.3, we obtain $\phi_{\rm VLG}\sim 0.02$–0.09 for the Galaxy. This abundance is well below the value detected by *Ulysses* and *Galileo*. Thus, if the VLGs originate from dense cores, local enhancement of VLG abundance in the solar neighborhood is necessary. We have also examined the effect of VLGs on the extinction curve, finding that the effect is negligible even with the upper value of the above range, $\phi_{\rm VLG}\sim 0.09$. With $\phi_{\rm VLG}\sim 0.5$, which is near the value of 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. This again supports the idea that the high VLG abundance in the heliosphere is due to local enhancement. Finally, it is worth noting that the explicit dependence of ϕ_{VLG} on τ_{SF}, f_{VLG}, and t_{shat}, can be used to estimate the VLG abundance in galaxies as well as in the Milky Way.

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