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Overall dust inputs from core-collapse supernovae in the Galaxy

T. Nozawa

National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan
e-mail: takaya.nozawa@nao.ac.jp

Abstract. We examine the evolutions of dust masses that are injected from core-collapse supernovae (CCSNe) and asymptotic giant branch (AGB) stars into the interstellar medium. Using a simple dust evolution model, we demonstrate that the total masses of dust supplied by AGB stars and CCSNe are comparable when condensation efficiency of dust is identical in their ejected gases. We also show that, if every CCSN ejects 0.5 $M_{\odot}$ (2×10^{-4} $M_{\odot}$) of dust, the global dust input from CCSNe is >10 times (<0.01 times) that from AGB stars. We find that the contribution of dust mass from CCSNe is reduced by a factor of $\simeq$1.5 by lowering their upper mass from 100 $M_{\odot}$ down to 18 $M_{\odot}$. Our simple model and the results could be useful to have a radical perception of the overall dust inputs from CCSNe in galaxies.

Key words. Dust, extinction – ISM: evolution – Galaxy: abundances – galaxies: ISM – Stars: AGB and post-AGB – Supernovae: general

1. Introduction

There are increasing pieces of evidence that core-collapse supernovae (CCSNe) are competent producers of dust grains; far-infrared observations with *Herschel* (Matsuura et al. 2011; De Looze et al. 2017), as well as analyses of optical line emissions (Bevan & Barlow 2016, 2017), have revealed the presence of dust above 0.1 $M_{\odot}$ in the ejecta of young supernova remnants such as SN 1987A and Cassiopeia A. This indicates that explosions of massive stars can potentially play vital roles in enrichment of the interstellar medium (ISM) with dust grains.

On the other hand, theoretical studies show that, even if large amounts of dust grains are formed in the SN ejecta, only a fraction of them would be finally injected into the ISM as a result of efficient destruction of dust through the passage of the reverse shocks (e.g., Nozawa et al. 2007; Bocchio et al. 2016). In particular, stripped-envelope CCSNe like Type IIb and Ib SNe, which occupy about half of the observed fraction of CCSNe (Smith et al. 2011), are likely to inject less than $\simeq 10^{-4}$ $M_{\odot}$ of dust into the ISM (Nozawa et al. 2008, 2010). Hence, ability of CCSNe as supplying interstellar dust relies on dust yield per CCSN, which is limited by destruction of dust in the reverse shocks and by envelope mass of the star at explosion.

In this article, taking a variety of masses of dust ejected by CCSNe, we systematically examine the overall inputs of dust from CCSNe in galaxies. We focus on the relative contribution of dust masses from asymptotic giant branch (AGB) stars and CCSNe, based on a simple dust evolution model. This allows us to have a basic knowledge about the consequence of CCSNe as sources of interstellar dust.

2. Evolution of dust mass in the ISM

Here we aim at giving the fundamental idea about the contributions of dust masses made by two primary stellar sources, AGB stars and CCSNe. For this purpose, we use a simple model of mass evolution of interstellar dust; we consider neither destruction of dust in interstellar shocks driven by SNe nor consumption of interstellar dust through astration. This would not largely affect the results as long as we are interested in the relative contribution of dust masses from AGB stars and CCSNe.

We suppose that AGB stars arise from intermediate-mass stars (IMSs) with initial masses between $m_1 = 2\ M_\odot$ and $m_2 = 8\ M_\odot$, and that CCSNe result from high-mass stars between $m_2 = 8\ M_\odot$ and $m_3 = 100\ M_\odot$. We assume that they inject dust grains into the ISM when their lives end. Since we do not consider any destruction processes of dust in the ISM, the cumulative masses of dust originating from these stellar sources are determined by their injection rates. Namely, the time evolutions of dust masses supplied by AGB stars ($M_{\rm d,1}$) and CCSNe ($M_{\rm d,2}$) are written as

$$\frac{dM_{{\rm d},i}(t)}{dt} = \int_{m_i}^{m_{i+1}} m_{\rm dust}(m,t)\phi(m)\psi(t-\tau_{\rm m})dm,$$

where $\phi(m)$ is the stellar initial mass function (IMF), $\psi(t)$ is the star formation rate (SFR), and $\tau_{\rm m}$ is the lifetime of a star, which is evaluated with the formula by Raiteri et al. (1996) as a function of stellar initial mass m, assuming $Z = 0.01$. Dust yield per each stellar source is $m_{\rm dust}(m,t) = m_{{\rm d},i}(m)$ for $t - \tau_m \geq 0$, otherwise $m_{\rm dust}(m,t) = 0$, where $m_{\rm d,1}(m)$ and $m_{\rm d,2}(m)$ are, respectively, masses of dust grains injected by AGB stars and CCSNe, given in what follows.

2.1. Dust yields from AGB stars

In this study, we consider two cases for the mass of dust from an AGB star. Since IMSs finally evolve to white dwarfs (WDs) via AGB stars, the mass of gas returned into the ISM by an IMS is $(m - m_{\rm WD})$, where $m_{\rm WD}$ is the mass of a WD. Then, we consider that a fraction $f_{\rm AGB}$ of this returned gas condenses into dust grains;

$$m_{\rm d,AGB1} = f_{\rm AGB}(m - m_{\rm WD})\ \ M_\odot, \tag{1}$$

which is hereafter invoked as Case 1 of AGB-dust ($m_{\rm d,AGB1}$).

The other case (Case 2 of AGB-dust, $m_{\rm d,AGB2}$) assumes that AGB stars supply a fixed dust mass of

$$m_{\rm d,AGB2} = 6 \times 10^{-3}\ \ M_\odot, \tag{2}$$

irrespective of the initial stellar mass. This dust yield refers to, for example, the results by Dell'Agli et al. (2017), who calculated the dust formation in mass-loss winds of solar-metallicity AGB stars and found that $\simeq 10^{-3}$–$10^{-2}\ M_\odot$ of dust is produced per AGB star.

In Equation (1), we adopt $m_{\rm WD} = 1.4\ M_\odot$ and $f_{\rm AGB} = 0.01$, which accounts for relatively efficient formation of dust in AGB stars. Accordingly, $m_{\rm d,AGB1}$ offers a higher dust yield than $m_{\rm d,AGB2}$.

2.2. Dust yields from CCSNe

For the mass of dust injected per CCSN, four cases are considered. Case 1 of SN-dust ($m_{\rm d,SN1}$), as is Case 1 of AGB-dust, supposes that a fraction $f_{\rm SN}$ of gas ejected from CCSNe is locked up in dust grains;

$$m_{\rm d,SN1} = f_{\rm SN}(m - m_{\rm NS})\ \ M_\odot. \tag{3}$$

Here, $m_{\rm NS}$ is the mass of a neutron star (NS), and we adopt $m_{\rm NS} = 2\ M_\odot$ and $f_{\rm SN} = 0.01$.

Case 2 of SN-dust is introduced as the optimistic case with the highest dust yield:

$$m_{\rm d,SN2} = 0.5\ \ M_\odot. \tag{4}$$

Such a high dust mass as $\simeq 0.5\ M_\odot$ is estimated from *Herschel* and ALMA observations of SN 1987A and Cassiopeia A (e.g., Matsuura et al. 2011; De Looze et al. 2017). However, this dust mass is at the time of formation and will be reduced due to destruction by the reverse shocks before being injected into the ISM.

Dust mass after the reverse-shock destruction depends on the initial grain size distribution and gas density ($n_{\rm H}$) in the ISM. Previous works suggested that 0.01–0.8 $M_\odot$ of dust is injected into the ISM for $n_{\rm H} \simeq 0.1$–1 cm^{-3} (Bianchi & Schneider 2007; Nozawa et al. 2007). Recently, Bocchio et al. (2016) predicted that the final masses of dust ejected from

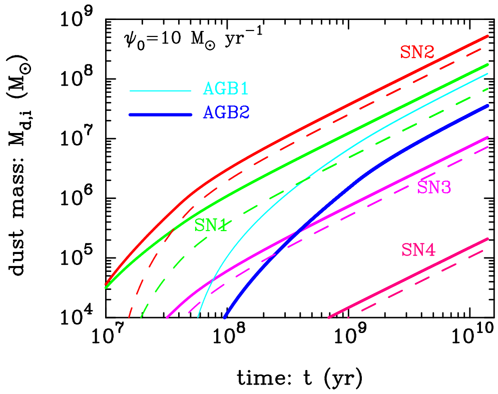

Fig. 1. Time evolutions of dust masses that are injected by AGB stars and CCSNe for the fiducial model (see text). The colored lines discriminate the results for different dust yields from AGB stars and CCSNe. The dashed lines indicate the results in the case that the upper limit of progenitor mass of dust-forming CCSNe is $m_3 = 18\ M_\odot$.

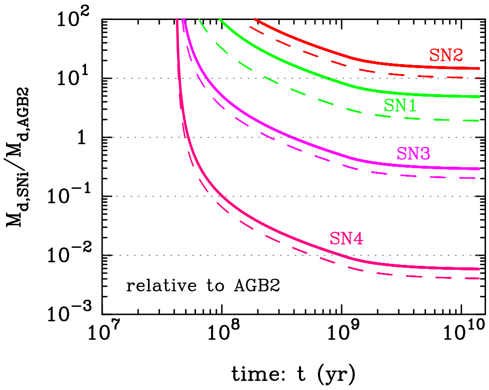

Fig. 2. Time evolutions of mass ratios of SN-dust to AGB-dust (adopting Case 2 of AGB-dust), taken from the results in Figure 1. The dashed lines represent the results when the upper mass limit of SN progenitors is $m_3 = 18\ M_\odot$.

SN 1987A and Cassiopeia A are likely to be $\simeq 0.01\ M_\odot$. Here, as Case 3 of SN-dust, we take

$$m_{\rm d,SN3} = 0.01\ \ M_\odot. \tag{5}$$

Finally, it has been claimed that, if CCSNe explode after their progenitor stars lost most of their outer envelopes, dust grains formed in the ejecta are small and will be almost completely destroyed by the reverse shocks (Nozawa et al. 2010). Taking this into account, we consider as the most pessimistic case

$$m_{\rm d,SN4} = 2 \times 10^{-4}\ \ M_\odot, \tag{6}$$

which is referred to as Case 4 of SN-dust.

3. Results

Figure 1 shows the time evolutions of dust masses that are supplied by AGB stars and CCSNe for different dust yields given in Equations (1)–(6). In this dust evolution model, a constant SFR of $\psi_0 = 10\ M_\odot\ {\rm yr}^{-1}$ is assumed, and the mass range of stars is set to be from $m_{\rm low} = 0.1\ M_\odot$ to $m_{\rm up} = 100\ M_\odot$ for the Salpeter IMF $\phi(m) \propto m^{-2.35}$ (hereafter referred to as the fiducial model).

As expected, the dust mass from Case 1 of AGB-dust is higher than that from Case 2 of AGB-dust; $M_{\rm d,AGB1} = 8.7 \times 10^7\ M_\odot$ and $M_{\rm d,AGB2} = 2.5 \times 10^7\ M_\odot$ at $t = 10^{10}$ yr. We find that, if condensation efficiency of dust in AGB winds and SN ejecta is the same ($f_i = 0.01$ in this study), the contributions of dust from these stellar sources are almost the same (see AGB1 and SN1 in Figure 1). We also note that the overall dust inputs from CCSNe well reflect the difference in dust yield for each case; at $t = 10^{10}$ yr, $M_{\rm d,SN2} = 3.7 \times 10^8\ M_\odot$, $M_{\rm d,SN3} = 7.5 \times 10^6\ M_\odot$ and $M_{\rm d,SN4} = 1.5 \times 10^5\ M_\odot$, showing the difference by a factor of 50.

Figure 2 plots the total dust masses in the different cases of SN-dust relative to Case 2 of AGB-dust. If CCSNe can eject 0.5 $M_\odot$ of dust (SN2), the mass of interstellar dust that originated from CCSNe is more than one order of magnitude higher than that from AGB stars. When every CCSN injects 0.01 $M_\odot$ of dust (SN3), the contribution of dust masses from CCSNe is somewhat smaller than that of AGB stars; $M_{\rm d,SN3}/M_{\rm d,AGB2} \simeq 0.3$ at $t \geq 10^9$ yr. On the other hand, if dust mass per CCSN is as low as $2 \times 10^{-4}\ M_\odot$ (SN4), the interstellar dust of SN origin is less than 1 % of AGB-dust.

The dashed lines in Figures 1 and 2 exhibit the dust masses in the case that the upper limit of progenitor mass of dust-forming CCSNe is $m_3 = 18\ M_\odot$, not $m_3 = m_{\rm up} = 100\ M_\odot$. This case is motivated by the works showing that the progenitor mass of Type II-P SNe (SNeIIP), which would be efficient sources of dust, is lower than 18 $M_\odot$ (Smartt 2009) and that stripped-envelope CCSNe, which would arise from more massive stars, hardly inject dust grains into the ISM (Nozawa et al. 2010). As can be seen from these figures, adopting $m_3 = 18\ M_\odot$ reduces the dust mass from CCSNe by a factor of 1.45. Thus, the upper mass of dust-forming CCSNe has a moderate effect on dust inputs from them into the ISM.

If the age of a galaxy is much longer than the lifetimes of stars ($t/\tau_m \gg 1$), we can put $m_{\rm dust}(m, t) = m_{{\rm d},i}(m)$ and $\psi(t - \tau_m) \simeq \psi(t)$. This study assumes that the lower mass limit of AGB stars is 2 $M_\odot$, whose lifetime is $\simeq 10^9$ yr. Thus, at a galactic age of $t \simeq 10^{10}$ yr, the above approximation is reasonable for both AGBs stars and CCSNe. When this approximation holds, the dust masses at a given time t can be derived analytically. For instance, if dust yield per stellar source is independent of the initial stellar mass, the total mass of dust supplied by this stellar source is given as

$$M_{{\rm d},i} = \psi_0 t m_{{\rm d},i} I_n(m_i, m_{i+1}), \qquad (7)$$

where

$$I_n(m_i, m_{i+1}) = \frac{A}{1-\alpha}(m_{i+1}^{1-\alpha} - m_i^{1-\alpha}) \qquad (8)$$

with $A = 0.172$ (normalization factor of the IMF for $m_{\rm low} = 0.1\ M_\odot$ and $m_{\rm up} = 100\ M_\odot$) and $\alpha = 2.35$ (Salpeter IMF). Then, the mass ratio of SN-dust to AGB-dust is written as

$$\frac{M_{\rm d,SN}}{M_{\rm d,AGB}} = \frac{m_{\rm d,SN} I_n(m_2, m_3)}{m_{\rm d,AGB} I_n(m_1, m_2)}. \qquad (9)$$

This means that the relative contribution of total masses of dust injected into the ISM is determined only by dust yield per AGB star and CCSN, as well as the stellar IMF.

Table 3 presents the mass ratios of SN-dust (SN2, SN3, and SN4) relative to Case 2 of AGB-dust, obtained from Equation (9), where $I_n(2, 8) = 0.0422$, $I_n(8, 100) = 0.00742$, and $I_n(8, 18) = 0.00511$. It can be seen that the results in Table 3 are fully consistent with the numerical results at $t \simeq 10^{10}$ yr in Figure 2. Thus, this analytical approach is useful to estimate the contribution of dust from stellar sources as long as the galactic age is old enough.

Table 1. Analytically derived ratios of dust mass injected from CCSNe/SNeIIP (Case 2, 3, 4) to dust mass from AGB stars (Case 2).

	$M_{\rm d,CCSN}/M_{\rm d,AGB2}$ CCSN/AGB2	$M_{\rm d,SNIIP}/M_{\rm d,AGB2}$ SNII-P/AGB2
SN2	14.65	10.09
SN3	0.293	0.202
SN4	5.86×10^{-3}	4.04×10^{-3}

Our results imply that the mass ratio of SN-dust to AGB-dust is a good measure to probe their significance as sources of interstellar dust. In reality, size distributions of dust grains from AGB stars and CCSNe would not be the same. Hence, the efficiency of their survival in the ISM is different, and their mass ratios could not be simply determined by dust yield and stellar IMF. Nevertheless, the simple analyses and results as given here are helpful in discussing the dust inputs from stellar sources and should be kept in mind in interpreting the results from more elaborated dust evolution models.

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