Dust formation history of galaxies: a critical role of metallicity for the dust mass growth by accreting materials in the interstellar medium

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This paper investigate what is the main driver of the dust mass growth in the interstellar medium (ISM) by using a chemical evolution model of galaxy with metals (elements heavier than helium) in dust phase in addition to the total amount of metals. We consider asymptotic giant branch (AGB) stars, type II supernovae (SNe II) and the dust mass growth in the ISM as the sources of dust, and SN shocks as the destruction mechanism of dust. Further, to describe the dust evolution precisely, our model takes into account the age and metallicity (the ratio of metal mass to ISM mass) dependence of the sources of dust. We particularly focused on the dust mass growth, and found that the dust mass growth in the ISM is regulated by the metallicity. To quantify this aspect, we introduce a “critical metallicity”, which is a metallicity at which the contribution of stars (AGB stars and SNe II) equals that of the dust mass growth in the ISM. If the star formation timescale is shorter, the value of the critical metallicity is higher, but the galactic age at which the metallicity reaches the critical metallicity is shorter. From observations, it was expected that the dust mass growth was the dominant source of dust in the Milky Way and dusty QSOs at high redshifts. By introducing the critical metallicity, it is clearly shown that the dust mass growth is the main source of dust in such galaxies with various star formation timescales and ages. The dust mass growth in the ISM is regulated by metallicity, and we stress that the critical metallicity works as an indicator to judge whether the grain growth in the ISM is dominant source of dust in a galaxy, especially because of the strong and nonlinear dependence on the metallicity.

Key words: dust, extinction — galaxies: infrared — galaxies: evolution — galaxies: starburst — stars: formation

1. Introduction

Stellar light, in particular at shorter wavelengths, is absorbed by dust and re-emitted as the far-infrared thermal emission from the dust (e.g., Witt & Gordon, 2000, and references therein). Therefore dust affects the spectral energy distributions of galaxies (e.g., Takagi et al., 1999; Granato et al., 2000; Noll et al., 2009; Popescu et al., 2011). The existence of dust in galaxies also affects the star formation activity. Dust grains increase the molecular formation rate by two orders of magnitude compared to the case without dust (e.g., Hollenbach & McKee, 1979), and the interstellar medium (ISM) is cooled efficiently by molecules and dust. Consequently, star formation is activated drastically by dust. Hence, dust is one of the most important factors for the evolution of galaxies (e.g., Hirashita & Ferrara, 2002; Yamasawa et al., 2011).

The amount of dust in galaxies is one of the crucial factors to interpret the observational information of galaxies, since dust exists ubiquitously and the radiation from stars is always affected by dust attenuation. However, in spite of its importance, the evolution of dust amount has not been completely established yet. There are some key factors to understand dust evolution of galaxies. One of the keys is the ratio of metal (elements heavier than helium) mass to ISM mass, which is called “metallicity”. Since dust grains consist of metals, it is natural to think that the evolution of dust is closely related to metallicity. In general, galaxies are believed to evolve from the state with a very low metallicity and very small amount of dust to higher amounts of metal and dust. Hence, it is a mandatory to model the formation and evolution of dust grains in galaxies along with the evolution of metallicity (e.g., Dwek, 1980; Hirashita, 1999a,b; Inoue, 2003; Yamasawa et al., 2011).

Dust grains are formed by the condensation of metals. A significant part of the metals released by stellar mass loss during stellar evolution or supernovae (SNe) at the end of the life of stars condense into dust grains. Dust grains are not only supplied from stars but also destroyed by SNe blast waves (e.g., Jones et al., 1994; Jones, Tielens & Hollenbach, 1996; Nozawa et al., 2003; Zhukovska, Gail & Trieloff, 2008). In addition, we should consider the dust mass growth in the ISM by the accretion of atoms and molecules of refractory elements onto grains (e.g., Dwek, 1998; Liffman & Clayton, 1989; Draine, 2009; Jones & Nuth, 2011).

What kind of dust formation processes are dominant at each stage of galaxy evolution? It is a very important question for understanding the evolution history of the ISM and star formation in galaxies. However, since dust evolution

*the ratio of metal (elements heavier than helium) mass to ISM mass.
depends strongly on the age and metallicity of a galaxy, it is not easy to answer this question. Up to now, dust evolution has been studied with various models. For example, in young galaxies, SNe have been considered as the source of dust because they are the final stage of massive stars whose lifetime is short, and asymptotic giant branch (AGB) stars have been neglected because of their longer lifetime. However, Valiante et al. (2009) showed that the AGB stars also contribute to the dust production in young galaxies and cannot be neglected even on a short timescale of ~ 500 Myr. A more elaborate survey of the parameter space for the dust formation by SNe and AGB stars has been done by Gall et al. (2011a). They showed that the contribution of AGB stars exceeds that of SNe II at several 100 Myr if the ratio between metal and dust mass produced by SNe II is less ~ 0.01 and mass-heavy IMF with mass range 1~100 M⊙.

As for the dust mass growth, the ISM is considered to be the main source of dust in various galaxies. For example, the present dust amount observed in the Milky Way cannot be explained if the source of dust would have been only stars, suggesting that we must consider the dust mass growth in the ISM in evolved galaxies (e.g., Dwek, 1998; Lifshman & Clayton, 1989; Draine, 2009; Jones & Nuth, 2011). Recently, dusty quasars (total dust mass > 10⁹ M⊙) have been discovered at high redshifts (e.g., Beelen et al., 2006; Wang et al., 2008), and theoretical studies on dust sources at high redshifts are currently carried out actively (e.g., Michelowski et al., 2010b; Gall et al., 2011a,b; Pipino et al., 2011; Valiante et al., 2011). They showed that it is hard to explain the total dust amount in these QSOs only with stellar contributions, and then they discussed the importance of the dust mass growth in the ISM. Next question is what controls the point where the dust mass growth in the ISM becomes efficient to the total dust mass in galaxies. Therefore, although each physical process has been already extensively discussed in preceding studies, there emerges a crucial question: what kind of dust production process is dominant at each stage of galaxy evolution? Particularly, when does the dust mass growth become dominant as a source of dust mass? The central aim of this work is to address this question. In this paper, we investigate what is the main driver of the dust mass growth in the ISM. Since all sources of dust production are tightly related to each other on dust evolution, it is crucial to treat these processes in a unified framework to understand the evolution of dust in galaxies. Here, we adopt the model based on chemical evolution model in a same manner as Hirashita (1999b); Calura, Pipino & Matteucci (2008); Inoue (2011). This is because their models consider main dust production/destruction processes that affect the dust evolution of galaxies, and it is easy to compare our results to the previous ones. From this work, we find that the dust mass growth in the ISM is regulated by metallicity. We refer to this metallicity as the critical metallicity, whose details are described in Sect. 3.2. Although the dust mass growth can occur at any time of a galaxy age, but we stress this point because there is a moment at which the dust mass growth overwhelms the contribution from other sources of dust.

This paper is organized as follows. In Sect. 2, we describe the model developed for this work. In Sect. 3, we show and discuss the basic results obtained by our model. The main topic of this paper, critical metallicity, is introduced and extensively examined in Sect. 3.2. Section 4 is devoted to the conclusions. The solar metallicity is set to be Z⊙ = 0.02 (Anders & Grevesse, 1989) throughout this paper.

2. Dust evolution model of galaxies

In this section, we show the simple chemical evolution model with dust which examine what determines the point where the dust mass growth in the ISM becomes effective. The dust evolution model is built with the same manner as in Hirashita (1999b) and Inoue (2011).

2.1 Equations of galaxy evolution

In this subsection, we describe the equations of mass evolution of stars and the ISM which contains metal and dust in galaxies. We treat a galaxy as one-zone because we are interested in global properties of galaxies. Also, we assume a closed-box model. Thus, the total baryon mass Mtot (the sum of the stellar mass and the ISM mass) is a constant. However, since Mtot is just a scale factor in our model, this value does not affect the physical properties of galaxies non-linearly.

In this work, we do not consider the effects of inflow and outflow. However, they may not influence the properties of dust and metal enrichment in galaxies because of the following reasons: An inflow makes not only metallicity but also dust-to-gas mass ratio small, because usually an inflow is considered to be metal- and dust-poor. As for an outflow, it expels ISM components (gas, metal and dust) out of a galaxy. However, if all ISM components flow out together, the metallicity and dust-to-gas mass ratio do not change.

Under these settings, equations of the time evolution of the total stellar mass M∗, ISM mass MISM, metal mass MZ, and dust mass Md are (e.g., Lisenfeld & Ferrara, 1998; Hirashita, 1999b)

\[ \frac{dM_\ast(t)}{dt} = \text{SFR}(t) - R(t), \]

\[ \frac{dM_{\text{ISM}}(t)}{dt} = -\text{SFR}(t) + R(t), \]

\[ \frac{dM_Z(t)}{dt} = -Z(t)\text{SFR}(t) + R_Z(t) + Y_Z(t), \]

\[ \frac{dM_d(t)}{dt} = -D(t)\text{SFR}(t) + Y_d(t) - \frac{M_d}{\tau_{\text{SN}}} + \frac{M_d(1 - \delta)}{\tau_{\text{acc}}}, \]

where SFR is the star formation rate, Z(t) ≡ MZ/MISM is the metallicity, D ≡ Md/MISM is the dust-to-gas mass ratio, \( \delta \equiv M_d/M_Z \) is the fraction of the metals in dust. \( \eta \) is the mass fraction of cold clouds where the accretion process occurs. \( \tau_{\text{SN}} \) and \( \tau_{\text{acc}} \) are the timescales of dust destruction and accretion, respectively. The definitions of these timescales are described later. Also, R(t) and RZ(t) are the total baryon mass returned by stars and the total metal mass once injected in stars and just returned in the ISM per unit time, respectively. YZ(t) and Yd(t) are the total metal mass newly produced and ejected by stars and the total dust mass ejected by stars per unit time, respectively. There is another notation which YZ includes RZ (e.g., Inoue, 2011). In this case, the value of YZ is different from that in this paper because of the different definition.
For the SFR, we adopt the Schmidt law (Schmidt, 1959): SFR \propto M_{\text{ISM}}^{n}$. Here, we adopt $n = 1$ for simplicity. Thus, the SFR is expressed as

$$SFR(t) = \frac{M_{\text{ISM}}(t)}{\tau_{\text{SF}}}.$$  \hspace{1cm} (5)

where $\tau_{\text{SF}}$ is the star formation timescale. Also, $R(t), R_{Z}(t), Y_{Z}(t)$ and $Y_{d}(t)$ are written by

$$R(t) = \int_{m_{\text{cut}}(t)}^{100 M_{\odot}} \left[ m - \omega(m, Z(t - \tau_{m})) \right] \times \phi(m) SFR(t - \tau_{m}) dm,$$

$$R_{Z}(t) = \int_{m_{\text{cut}}(t)}^{100 M_{\odot}} \left[ m - \omega(m, Z(t - \tau_{m})) \right] \times \phi(m) SFR(t - \tau_{m}) Z(t - \tau_{m}) dm,$$

$$Y_{Z}(t) = \int_{m_{\text{cut}}(t)}^{100 M_{\odot}} m_{Z}(m, Z(t - \tau_{m})) \times \phi(m) SFR(t - \tau_{m}) dm,$$

$$Y_{d}(t) = \int_{m_{\text{cut}}(t)}^{100 M_{\odot}} m_{d}(m, Z(t - \tau_{m})) \times \phi(m) SFR(t - \tau_{m}) dm,$$

where $\phi(m)$ is the initial mass function (IMF), $\omega(m, Z(t))$, $m_{Z}(m, Z(t))$ and $m_{d}(m, Z(t))$ are the remnant mass, metal mass newly produced and ejected, and dust mass produced and ejected by a star of initial mass $m$ and metallicity $Z$, respectively. The lifetime of a star of initial mass $m$ is expressed as $\tau_{m}$, is taken from Raiteri, Villata & Navarro (1996). In this work, since its metallicity dependence is weak, we always adopt the lifetime of the case of the solar metallicity. The lower limit $m_{\text{cut}}(t)$ is the mass of a star with the lifetime $\tau_{m} = t$. As for IMF, we adopt Larson IMF (Larson, 1998) in the stellar mass range $0.1-100 M_{\odot}$,

$$\phi(m) \propto m^{-(\alpha + 1)} \exp \left( -\frac{m_{\text{ch}}}{m} \right).$$  \hspace{1cm} (10)

Here we adopt $\alpha = 1.35$ and $m_{\text{ch}} = 0.35 M_{\odot}$. Also, we normalize it as

$$\int_{0.1 M_{\odot}}^{100 M_{\odot}} m \phi(m) dm = 1.$$  \hspace{1cm} (11)

To calculate above four equations [Eq. (6)-(9)], we quoted the data of remnant mass $(\omega(m, Z))$, metal mass $(m_{Z}(m, Z))$ and dust mass $(m_{d}(m, Z))$ of stars with mass $m$ and metallicity $Z$ from some of previous works.

In this work, we consider AGB stars and SNe II as stellar sources, but neglected the SNe Ia for simplicity. Nozawa et al. (2011) recently proved that SNe Ia produce little amount of dust. Further, Calura, Pipino & Matteucci (2008) showed that the dust destruction rate by SNe Ia is about 1/10 of that by SNe II. As for the metals ejected by SNe Ia, they play an important role in the chemical evolution of galaxies (e.g., Matteucci et al., 2009). However, since we discuss not the abundance ratio of each metal but the total metallicity, we did not take into account the contribution of SNe Ia.

In this paper, we assume that the mass ranges of AGB stars and SNe II are $1-8 M_{\odot}$ and $8-40 M_{\odot}$, respectively. Also, we assume that all stars with initial masses $m > 40 M_{\odot}$ evolve to black holes without SN explosions (Heger et al., 2003).

As for the remnant and metal masses, the data are taken from van den Hoek & Groenewegen (1997) for AGB stars with mass range $1-7 M_{\odot}$ and metallicities $Z = (5.0 \times 10^{-2}, 0.2, 0.4, 1.0) Z_{\odot}$ and from Woosley & Weaver (1995) for SNe II with mass range $12-40 M_{\odot}$ and metallicities $Z = (5.0 \times 10^{-2}, 0.1, 0.2, 0.4, 0.75, 1.0) Z_{\odot}$.

Also, since we discuss not the abundance ratio of each metal but the total metallicity, we did not take into account the contribution of SNe Ia. However, since dust yields have slight uncertainties, we can discuss the activation mechanism for the dust mass growth in the ISM without ambiguity.

2.2 Dust destruction timescale

It is thought that SNe are the main source of the dust destruction. This dust destruction process depends on various parameters (density and temperature of the ISM, the explosion energy of SNe, and etc.), is very complex (e.g., Jones et al., 1994; Jones, Tielens & Hollenbach, 1996; Nozawa et al., 2006). In this work, we adopt the formula presented by Mckee (1989).

The timescale of dust destruction $\tau_{\text{SN}}$ is expressed as

$$\tau_{\text{SN}} = \frac{M_{\text{ISM}}(t)}{\epsilon m_{\text{swept}} \gamma_{\text{SN}}(t)},$$  \hspace{1cm} (12)

where $\epsilon$ is the efficiency of dust destruction by SN shocks, and is defined as the ratio of the destroyed dust to the total swept dust by SN shocks, $m_{\text{swept}}$ is the swept ISM mass by a SN shock, $\gamma_{\text{SN}}(t)$ is the SN rate. In this work, we assume $\epsilon = 0.1$ (Mckee, 1989; Nozawa et al., 2006).

The SN rate $\gamma(t)$ is expressed as

$$\gamma_{\text{SN}}(t) = \int_{m_{\text{cut}}(t) > 8 M_{\odot}} \phi(m) SFR(t - \tau_{m}) dm.$$  \hspace{1cm} (13)

The range of the integration is the mass range where the SNe can occur (Heger et al., 2003). So, if $t < \tau_{40 M_{\odot}}$, $\gamma_{\text{SN}}(t) = 0.0$.

The swept ISM mass by SN shocks $m_{\text{swept}}$ depends on both the density and metallicity of the ISM. In the case of a higher density, since the amount of materials which block SN blast wave is larger, the swept mass becomes smaller. Further, the fine cooling by metals is more efficient in the
ISM of a higher metallicity, as a result, the swept mass becomes smaller. To consider these effects, we adopt the fitting formula derived by Yamasawa et al. (2011)

\[ m_{\text{swept}} = 1535 \rho_{\text{SN}}^{-0.202} \left( \frac{Z}{Z_{\odot}} \right) + 0.039 \left( \frac{M_{\odot}}{3} \right) \]

where \( \rho_{\text{SN}} \) is the ISM density around SNe, we assume \( n_{\text{SN}} = 1.0 \) cm\(^{-3} \) as a representative value.

### 2.3 Metal accretion timescale

Dust mass in galaxies increases due to not only supply from stars but also accretion of refractory elements onto preexisting dust in clouds (e.g., Liffman & Clayton, 1989; Draine, 2009; Jones & Nuth, 2011). This accretion process is called “dust mass growth”. Here, we use a term “clouds”, so that it stands the cool component in the ISM. In our study, we neglect volatile dusts. Although, indeed, they exist in clouds, if clouds disappear or the temperature goes up, such dusts evaporate. More precise treatment will be shown in future work. The dust mass growth rate in clouds can be expressed as (e.g., Hirashita, 2000; Inoue, 2003, 2011)

\[ \frac{dM_d}{dt} = \eta N \pi \langle a^3 \rangle \alpha \rho_{\text{gas}}^2 \langle v \rangle, \tag{15} \]

where \( \eta \) is the mass fraction of the clouds, \( N \) is the number of dust grains, \( \langle a^3 \rangle \) is the 2nd moment of a grain size \( a \), \( \alpha \) is the mean sticking coefficient of metals, \( \rho_{\text{gas}}^2 \) is the mass density of gaseous metals that are not contained in dust, and \( \langle v \rangle \) is the mean velocity of metals in gas phase. Since we assume a spherical dust grain for simplicity, we have

\[ m_d = \frac{4\pi \langle a^3 \rangle \sigma}{3}, \tag{16} \]

so

\[ N = \frac{M_d}{m_d} = \frac{3M_d}{4\pi \langle a^3 \rangle \sigma}, \tag{17} \]

where \( m_d \) is the mean mass of the grain, \( \langle a^3 \rangle \) is the 3rd moment of a grain size, and \( \sigma \) is the mass density of solid matter within the grains. Also,

\[ \rho_{\text{gas}}^2 = \rho_{\text{ISM}}^2 (1 - \delta), \tag{18} \]

where \( \rho_{\text{ISM}}^2 \) is the averaged mass density of the interstellar clouds where the accretion process occurs and \( \delta \) is the dust abundance in the metal mass. Thus, defining the accretion timescale as

\[ \tau_{\text{acc}} = \frac{4\langle a^3 \rangle \sigma}{3\langle a^3 \rangle \alpha \rho_{\text{ISM}}^2 \langle v \rangle}, \tag{19} \]

we obtain the fourth term in right hand side of Eq. (4). Also, the mass density \( \rho_{\text{ISM}}^2 \) is estimated in terms of the hydrogen number density, \( n_{\text{H}} \), as \( \rho_{\text{ISM}}^2 = \mu n_{\text{H}} \), where \( \mu \) is the mean atomic weight (we assume \( \mu = 1.4 \); i.e. the ratio of the number of a hydrogen atom and a helium atom is \( 10 : 1 \) in clouds), and \( n_{\text{H}} \) is the mass of a hydrogen atom.

We assume that \( \alpha = 1.0 \) (i.e. if a molecule/atom collides a dust grain, it sticks certainly) and \( \sigma = 3 \) g cm\(^{-3} \) (silicate). Considering that the dust mass growth depends on the volume-to-surface ratio of the grains, then we obtain

\[ \tau_{\text{acc}} \approx 2.0 \times 10^7 \times \left( \frac{\bar{a}}{0.1 \mu \text{m}} \right) \left( \frac{n_{\text{H}}}{100 \text{ cm}^{-3}} \right)^{-1} \left( \frac{T}{50 \text{ K}} \right)^{-\frac{1}{2}} \left( \frac{Z}{0.02}\right)^{-1} \text{yr}, \tag{20} \]

where \( \tau_{\text{acc},0} \approx 4.0 \times 10^5 \) yr, and we adopted \( \bar{a} = 0.1 \mu \text{m} \), \( n_{\text{H}} = 100 \text{ cm}^{-3} \), and \( T = 50 \text{ K} \) [1]. The typical size of grains \( \bar{a} \) is defined as \( \langle a^3 \rangle / \langle a^2 \rangle \) in Hirashita & Kuo (2011).

As mentioned above, we conservatively adopt \( \bar{a} = 0.1 \mu \text{m} \) as a fiducial value (e.g., Inoue, 2011). Small grains may be depleted by coagulation in molecular clouds (Hirashita & Yan, 2009), which strengthens the importance of large grains. The importance of large grains is further enhanced given that the grain size distribution tends to be biased to large (\( a \sim 0.1 \mu \text{m} \)) size by the destruction within SN remnants (Nozawa et al., 2007). Thus, we assume \( \bar{a} \sim 0.1 \mu \text{m} \) to estimate the dust mass growth timescale. Although we basically adopt \( \bar{a} = 0.1 \mu \text{m} \), we also examine \( \bar{a} = 0.01 \mu \text{m} \) for a quick growth case later. Indeed, the MRN grain size distribution (Mathis, Rumpl & Nordsieck, 1977) has \( \bar{a} = 0.01 \mu \text{m} \) (Hirashita & Kuo, 2011). In reality, the grain size distribution in galaxies changes with time due to some processes (e.g., SN shocks, accretion, and etc.). As for the contribution of the evolution of the grain size distribution, we have been preparing Asano et al. (2012).

In this paper, we adopt only \( \eta = 0 \) (no accretion growth) or 1 in order to avoid any fine-tuning. In fact, the effect of a different choice of \( \eta \) can be offset by a different choice of \( n_{\text{H}} \) and \( T \). This allows us to merge uncertainties of \( \eta, n_{\text{H}}, \text{and} \ T \) into the value of \( \tau_{\text{acc},0} \). We set \( \tau_{\text{acc},0} = 4.0 \times 10^5 \) yr as a fiducial value (e.g., Inoue, 2011). Other choices of \( \tau_{\text{acc},0} \) result in a different timing of the growth activation. This is explicitly expressed in Eq. (27) later.

### 3. What drives dust mass growth in the ISM?

In this section, we investigate what determines the point where the grain growth in the ISM becomes effective to the total dust mass in galaxies.

#### 3.1 Contribution of each physical process to the total dust mass in galaxies

To examine the point where the dust mass growth becomes efficient as a main source of dust in galaxies, at first, we compare each process of dust production. In Fig. 1, we show the contributions of stars (solid and dotted lines), dust destruction (dashed line) and the dust mass growth (dotted-dashed line) to the total dust mass in a galaxy. Solid, dotted, dashed and dot-dashed lines represent the contributes of the 1st, 2nd, 3rd and 4th terms in r.h.s. of Eq. (4), respectively. The total baryon mass \( M_{\text{tot}} \) (the sum of the total mass of stars and ISM in a galaxy) and \( \eta \) are \( 10^{10} \text{ M}_{\odot} \) and 1.00, respectively. However, as mentioned in Sect. 2.1, since \( M_{\text{tot}} \) is just a scale factor, \( M_{\text{tot}} \) just changes the values of the contributions of these processes linearly.

\[ ^1 \text{This temperature corresponds to} \langle v \rangle = 0.14 \text{ km s}^{-1}. \text{ We assume} \quad A_m (\langle v \rangle^2)^2 = kT \text{ and adopt} \quad A = 20 \text{ (} A_m \text{ is the mean mass of the colliding atoms)} \text{ (Spitzer, 1978).} \]
From these figures, we find that although the contribution of the ejected by stars is the biggest in the early stages, as the time passes, the main contributor of the dust production switches to the dust mass growth in the ISM at a point ("switching point"). For example, Liang & Li (2009) pointed out that dust produced by SNe II is predominant to the dust budget in galaxies at high-$z$ Universe ($z > 5$) using the extinction curves of GRB host galaxies at high redshifts. Their results are in good agreement with this work. Further, the process of the dust mass growth is expected to explain the dust amount in the Milky Way or dusty QSOs at high redshifts (e.g., Zhukovska, Gail & Trieloff, 2008; Draine, 2009; Michałowski et al., 2010a; Valiante et al., 2011). So, what determines the switching point? We will discuss the point in next subsection (this is the main topic in this paper).

After the dust mass growth took place, the contribution of dust destruction by SN shocks approaches that of the dust mass growth. Thus, after the dust mass growth becomes efficient, dust amount in galaxies determines the balance between the contribution of dust destruction and that of the dust mass growth in the ISM (see also Inoue, 2011).

In addition, we also observe that the increase of the contribution of the dust mass growth (dot-dashed line) has a peak, after that, the increase slows down. In other words, the dust mass growth becomes ineffective. We consider the reason of this. In Fig. 2, we show the time evolution of $\delta (= M_Z/M_d)$ with various star formation timescales. We find that after the value of $\delta$ increases rapidly, the value saturates. Hence, after the dust mass growth becomes effective, most of metals form dust. Thus, the reason why the dust mass growth becomes ineffective is the depletion of metals.

As shown in Fig. 2, the values of $\delta$ for all $\tau_{\text{SF}}$s converge to $\sim 1$. In contrast, the value for the Milky Way is about $0.5$. However, since it can be adjusted by adopting different $\eta$, we do not try to fine-tune the convergence value of $\delta$ in this study. Inoue (2011) showed that the convergence value of $\delta$ is determined by the balance between the contribution of dust destruction by SN shocks and that of the dust mass...
growth (for details, the product of $\tau_{\text{acc},0}$ and $\epsilon m_{\text{swept}}$).

### 3.2 Critical metallicity for dust mass growth

In this subsection, we introduce the main topic of this paper, the critical metallicity. This is a metallicity at the switching point (see Sect. 3.1). In our model, the sources of dust are stars (AGB stars and SNe II) and the dust mass growth in the ISM.

In order to find the critical metallicity, we compare the second term with fourth term in right hand side of Eq. (4). First we consider the second term [Eq. (9)]. From Eq. (9), if $D$ is defined as

$$\int^{100 \, \text{M}_\odot}_{m_{\text{acc}}(t)} m_d(m, Z(t - \tau_m)) \phi(m) dm \equiv D,$$

then Eq. (9), with Eq. (5) can be approximated as

$$Y_d \simeq D \frac{M_{\text{ISM}}}{\tau_{\text{SF}}}. \tag{22}$$

This equation is exact if SFR is constant.

Next, we consider the fourth term in right hand side of Eq. (4). Since $\tau_{\text{acc}} = \tau_{\text{acc},0} \, Z^{-1}$ and $M_d = \delta M_Z = \delta Z M_{\text{ISM}}$, the dust mass growth term is

$$\frac{\eta M_d(1 - \delta)}{\tau_{\text{acc}}} = \frac{\eta \delta (1 - \delta) Z^2 M_{\text{ISM}}}{\tau_{\text{acc},0}}. \tag{23}$$

From Eq. (22) and (23), the metallicity at which the increasing rate of dust mass by the dust mass growth exceeds the dust production rate by stars is, then, presented as follows:

$$Z = \left[ \frac{D}{\eta \delta (1 - \delta)} \right]^{\frac{1}{2}} \left( \frac{\tau_{\text{acc},0}}{\tau_{\text{SF}}} \right)^{\frac{1}{2}}. \tag{24}$$

Thus, if the metallicity of a galaxy is larger than above metallicity, we should consider the effect of dust mass growth in the galaxy. Here, we refer to the metallicity as the critical metallicity $Z_{\text{crit}}$, which is the metallicity at the switching point. To obtain the value of $Z_{\text{crit}}$, hereafter, we adopt $\delta = 0.02$ and $D = 5 \times 10^{-4}$. As for the value of $\delta$, from Fig. 2, the value of $\delta$ ranges 0.01–0.04 at the switching point for each $\tau_{\text{SF}}$. Further, although $\delta$ is dependent on time, before the dust mass growth becomes effective to the total dust mass, the $\delta$ is determined only by the contribution of stars (see Appendix A). This contribution of stars ranges 0.01–0.04 in our calculation (Fig. 8 in Appendix A). Thus, we adopt $\delta = 0.02$ as a representative value. Also, since we found from numerical calculation that the range of $D$ is $10^{-4}$ to $10^{-8}$, we adopt $D = 5 \times 10^{-4}$ as a representative value.

For the reader’s convenience, we compare our discussion with a similar work by Inoue (2011). Inoue (2011) defined a critical metallicity to compare the contribution of the dust destruction by SN shocks with that of the dust mass growth. Thus, the critical metallicity in Inoue (2011) is a metallicity which the contribution of the dust mass growth exceeds that of the dust destruction. In contrast, our critical metallicity is a metallicity which the dust mass growth becomes the main source of the increase of dust (the contribution of dust mass ejected by stars is the main source of dust at early stage of galaxy evolution). Readers who are interested in both works should keep this difference in mind.

In Fig. 3, we show the relation between the metallicity and dust-to-gas mass ratio (left panel is normalized by the critical metallicity, while right panel is not normalized) for $\tau_{\text{SF}} = 0.5, 5, 50 \, \text{Gyr}$. In Fig. 3, we find different evolutionary tracks depending on $\tau_{\text{SF}}$ in right-hand panel, whereas these tracks with metallicity normalized to the critical one are well overlaid on each other in the left-hand panel. This clearly shows that the critical metallicity is truly essential: The dust mass growth becomes efficient not when the galactic age reaches a certain value but when metallicity exceeds the critical value. In the left panel, the dust-to-gas mass ratio increases rapidly after metallicity exceeds the point of the critical metallicity. Thus, dust produced by the dust mass growth becomes efficient to the dust mass of a galaxy if $Z > Z_{\text{crit}}$ in the galaxy.

In Fig. 4, we show the critical metallicity as a function of $\tau_{\text{SF}}$. As shown in the figure, the critical metallicity becomes larger if the star formation timescale is shorter. As mentioned in Sect. 1 and 3.1, the dust mass growth is expected to be the dominant source of dust in various galaxies (e.g., the Milky Way: Draine (2009) and dusty QSOs at high redshifts: Valiante et al. (2011), among others), in spite of different star formation timescales and ages of the galaxies. In terms of the critical metallicity, we can explain the reason of it in a coherent manner; metallicity in the galaxies just exceeds the critical one.

Here we emphasize the importance of the metallicity dependence in the accretion growth timescale, $\tau_{\text{acc}}$. Pipino et al. (2011) argued that the dust mass growth was important to explain the observed huge mass of dust in high-$z$ QSOs. However, they did not seem to consider the metallicity dependence in $\tau_{\text{acc}}$. Fig. 5 shows the effect of the metallic-
Fig. 3. The metallicity - dust-to-gas mass ratio with $\eta = 1.00$ and $M_{\text{tot}} = 10^{10} M_\odot$. Left panel: normalized by the critical metallicity. Right panel: not normalized. Solid, dotted and dashed lines represent $\tau_{\text{SF}} = 0.5, 5, 50$ Gyr, respectively. Dashed and solid horizontal lines represent $\beta = 1.0$ and 10.0, respectively.

Fig. 4. Critical metallicity as a function of $\tau_{\text{SF}}$ with $\eta = 1.00$. We consider the dependence properly, the timing where the dust mass growth becomes effective is delayed until the metallicity exceeds the critical value as discussed above. On the other hand, if we omit the dependence and adopt a constant value for $\tau_{\text{acc}}$, the timing of the growth becomes effective on the total dust mass is determined by just the adopted $\tau_{\text{acc}}$.

In the above discussion, we have focused on the critical metallicity. One may be, however, interested in its relation to the time, $t_{\text{cr}}$, which is a galactic age when the metallicity in a galaxy reaches the critical metallicity. Here, in order to understand the importance of the dust mass growth in various galaxies with various star formation timescale more clearly, we demonstrate the relation between the critical metallicity $Z_{\text{cr}}$ and the time $t_{\text{cr}}$. However, we stress that the metallicity is more fundamental because $t_{\text{cr}}$ is determined by the critical metallicity.

We derive the relation with using Eq. (2) and (3). If $A$ is defined as

$$ A = \int_{100 M_\odot}^{m_{\text{cut}}(t)} m Z(m, Z(t - \tau_m)) \phi(m) dm \equiv A, $$

then, the relation is expressed as

$$ t_{\text{cr}} = \frac{\tau_{\text{SF}}}{A} Z_{\text{cr}}, $$

where $A$ is a constant, and is about 0.018 in our calcula-
tion. If inflow process occurs, since dust-to-gas mass ratio and metallicity become smaller than the case without inflow, it is sufficient to consider the larger 

From Fig. 7, we find that the evolutionary tracks with different 

Next, we discuss the effect of the grain size distribution. Recently, Hirashita & Kuo (2011) showed that the dust mass growth in the ISM depends on the grain size distribution of a galaxy. To examine the effect of the grain size on the dust mass growth, we consider the case with \( t_{cr} \) as a function of \( \tau_{SF} \). From this figure, we find that \( t_{cr} \) becomes shorter if \( \tau_{SF} \) is shorter, while in the case of \( Z_{cr} \), the trend is opposite (Fig. 4). This is explained by following reason. If the \( \tau_{SF} \) is short, the fast progress of the star formation makes the metallicity become large at an early stage of galaxy evolution. Hence, although the critical metallicity is large in the case with short \( \tau_{SF} \), \( t_{cr} \) is short due to the fast evolution of metallicity. From the relation between \( z_{cr} \) and \( t_{cr} \), we can understand that the dust mass growth is the main dust production of the Milky Way (evolved galaxy) and dusty QSOs (in high-z Universe).

4. Conclusions

In this work, we constructed a galaxy evolution model taking into account the metallicity and age dependence on the various dust sources (AGB stars, SNe II and growth in the ISM) to investigate what is the main driver of the grain growth which is expected to be the dominant source of dust in various galaxies with various star formation timescales. We have found that the timing that the dust mass growth in the ISM becomes effective is determined by metallicity. If metallicity in a galaxy exceeds a certain critical value, critical metallicity, the dust mass growth becomes active and the dust mass rapidly increases until metals are depleted from the ISM. This critical metallicity is larger for a shorter star formation timescale. The dust mass growth is thought to be the dominant source of dust in evolved galaxies like the Milky Way and young but dusty and massive QSOs at high redshifts. The importance of the dust mass growth in such a diversity of galaxies can be explained clearly in terms of the critical metallicity; the dust mass growth in the ISM is regulated by metallicity, and we stress that the critical metallicity works as an indicator to judge whether the grain growth in the ISM is dominant source of dust in a galaxy, especially because of the strong and nonlinear dependence on the metallicity.

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Fig. 8. Time evolution of the ratio of dust mass produced by stars to metal mass ejected by stars. Solid, dotted and dashed lines represent $\tau_{SF} = 0.5, 5, 50$ Gyr, respectively. For comparison, the results of Fig. 2 with thin lines are overlaid on the panel. Cross symbols mark the switching point for each $\tau_{SF}$.

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Appendix A. What dominates $\delta$ before the dust mass growth becomes effective?

Figure 8 shows the time evolution of the ratio of dust mass produced by stars to metal mass ejected by stars, $\delta_{\text{star}}$ (thick lines) and $\delta$ (thin lines) with $\tau_{SF} = 0.5, 5, 50$ Gyr. From Eq. (7)–(9), the ratio $\delta_{\text{star}}$ is expressed as

$$\delta_{\text{star}}(t) = \frac{Y_d(t)}{R_Z(t) + Y_Z(t)}.$$  \hspace{1cm} (A.1)

From Fig. 8, we observe that the evolutionary tracks of $\delta_{\text{star}}$ are the almost same tracks before the dust mass growth becomes effective to the total dust mass in galaxies. Hence, $\delta$ before the dust mass growth becomes effective is determined by $\delta_{\text{star}}$.

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