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Evolution of grain size distribution traced with gamma ray burst host galaxies

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Abstract. The extinction curves derived from observations of high-redshift quasars and gamma-ray bursts (GRBs) are viable tools to infer the dust properties in the early Universe. In order to identify what kind of processes are reflected in the extinction curve, we calculate the evolution of grain size distribution by considering dust production in supernovae and subsequent dust processing in the interstellar medium. In particular, we find that shattering by the grain–grain collisions driven by interstellar turbulence is efficient enough to modify the grain size distribution. We also show that the extinction curves observed in high-redshift quasars and GRB hosts can be reproduced if the dust grains produced by supernovae are ejected without significant shock destruction or if the dust supplied from supernovae is processed by shattering in interstellar turbulence. We also discuss other interstellar processes affecting the grain size distribution.

Key words. galaxies: ISM – galaxies: high-redshift – turbulence – dust, extinction – galaxies: evolution – galaxies: starburst

1. Introduction

Type II supernovae (SNe II), originating from the core collapse of massive stars, are considered to be one of the grain production sources in the Universe (e.g. Nozawa et al. 2003). The significance of SNe II in the dust enrichment is enhanced if the cosmic age is so young (typically at redshift $z > 5$) that low-mass stars are difficult to contribute significantly to the dust formation (Gall et al. 2011; but see Valiante et al. 2009). Thus, the dust production by SNe II has been tested by high-z objects (e.g. Maiolino et al. 2004a). We hereafter call dust formed in SNe II "SN dust".

In galaxies with high star formation activities, dust grains are not only produced and ejected from stars but also processed in the interstellar medium (ISM). Hirashita & Yan (2009) show that shattering occurs efficiently in diffuse medium, especially, warm ionized medium (WIM), where grains are efficiently accelerated by magnetohydrodynamic turbulence (Yan et al. 2004). Therefore, it is probable that the grains ejected from SNe II into the diffuse ISM are efficiently shattered by the motion driven by turbulence.

The extinction curves in high-z objects are often used as a useful probe of dust properties. Indeed, the extinction curve in a $z = 6.2$ quasar, SDSS 1048+4637 (hereafter, this extinction curve is called $z = 6.2$ extinction curve), has been used to constrain the composi-

Send offprint requests to: H. Hirashita tion and size distribution of SN dust (Maiolino et al. 2004a; Hirashita et al. 2005). GRB afterglows (hereafter simply called GRBs) are also useful to probe the extinction curve of their host galaxies because of their brightness and simple spectral shape. Stratta et al. (2007) show that the observed photometric data of a GRB at $z = 6.3$ can be reproduced by assuming the above $z = 6.2$ extinction curve. Zafar et al. (2011) also examine extinction properties of a GRB sample, although the number of high-z ($z > 5$) GRBs is still small.

In order to interpret extinction curves at high z, it is crucial to understand the source and processing of dust. Thus, we aim at understanding what kind of processes are reflected in observed extinction curves. In particular, the grain production by SNe II and the subsequent processing of SN dust are the main topics here.

2. Extinction curve modeling

2.1. SN dust

SNe II are considered to be the early dust source in the Universe because their progenitors have short lifetimes. We (Hirashita et al. 2005) calculated extinction curves of SN dust based on the dust production model by Nozawa et al. (2003) (the unmixed helium core model is adopted). Figure 1a shows our results. The extinction curve is averaged for various initial mass functions (IMFs). We observe that the $z = 6.2$ extinction curve is consistent with the model prediction.

However, the dust grains once formed in a SN II may suffer destruction in the shocked region before being injected into the ISM. Nozawa et al. (2007) calculate grain trajectory and sputtering in a SN II and show that small grains are efficiently trapped and sputtered in the shocked region. Based on their results, we (Hirashita et al. 2008) calculate the extinction curve as shown in Figure 1b for a SN with a progenitor mass of 20 $M_\odot$. We find that the extinction curve becomes flat because of the destruction of small grains. Practically, only grains with radius $a \gtrsim 0.1$ μm survive. If the ambient ISM whose hydrogen number density is denoted as n_H is denser, small grains are destroyed more, so that the extinction curve becomes flatter. Therefore, if the dust destruction in SNe is efficient, the extinction curve may be too flat to be consistent with the $z = 6.2$ extinction curve, which shows a rise toward shorter wavelengths. Finally, it is worth noting that flatness of extinction curve may explain some unreddened BAL quasars at $z > 5$ (e.g., SDSS 1044+01 and SDSS 0756+41) in Maiolino et al. (2004b).

2.2. Shattering in turbulence

As shown by Hirashita & Yan (2009), grain motions driven by interstellar turbulence enhance the grain–grain collision rate, leading to grain shattering in diffuse medium and grain coagulation in dense medium. Among various ISM phases, dust grains can acquire the largest velocity dispersion in WIM. We examined the effect of shattering in a WIM on the SN dust (Hirashita et al. 2010). We adopt the grain size distribution of dust ejected from a SN whose progenitor has a mass of 20 $M_\odot$ (shock destruction in the SN is considered under an ambient hydrogen number density of $n_\mathrm{H} = 1$ cm^{-3}; Nozawa et al. 2007) as an initial condition. The result is shown in Figure 2. We find that, although the grains ejected from SNe II are expected to be biased to large sizes ($a \gtrsim 0.1$ μm) because of the shock destruction in SNe, the shattering in a WIM is efficient enough in ~ 5 Myr to produce small grains. The shattering efficiency depends on the grain abundance, which is assumed to be proportional to metallicity. In Figure 3, we show the extinction curve for various shattering durations. We observe that the production of small grains by shattering, contributing to the steepening of the extinction curve. Thus, we conclude that, if the metallicity is nearly or above solar, shattering is efficient enough to modify the extinction curve in several Myr.

2.3. Other interstellar processes

There are other processes that affect the grain size distribution. Dust grains condensed in SNe are destroyed not only in the shocked region

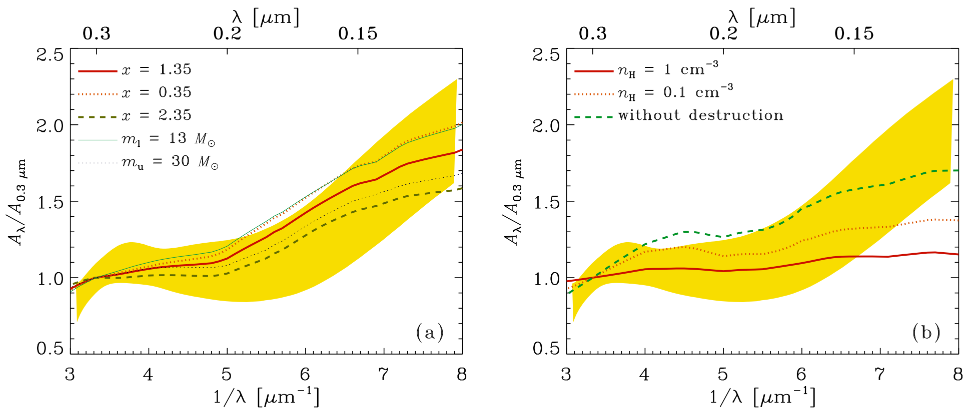

Fig. 1. Ultraviolet extinction curves normalized to the extinction at rest-frame wavelength $\lambda = 0.3\ \mu$m. The range observationally derived by Maiolino et al. (2004a) for SDSS 1048+4637 at $z = 6.2$, "$z = 6.2$ extinction curve", is shown by the shaded area in each panel. (a) Extinction curves of SN dust without shock destruction. Various lines correspond to various IMFs adopted for the averages: The thick solid, dotted, and dashed lines represent the results for $x = 1.35$, 0.35, and 2.35 (power-law index of the IMF, with $x = 1.35$ corresponding to the Salpeter IMF), respectively, with the upper and lower stellar masses $m_{\rm min} = 8$ and $n_{\rm max} = 40\ M_\odot$, respectively. The thin solid and dotted lines show the results for $m_{\rm min} = 13\ M_\odot$ and for $m_{\rm max} = 30\ M_\odot$, respectively, with $x = 1.35$. (b) Extinction curves of SN dust after shock destruction in SNe (20 $M_\odot$ progenitor) for various ambient hydrogen number densities ($n_H = 1$ and 0.1 cm^{-3} for the solid and dotted lines, respectively). The case without shock destruction is also shown (dashed line).

before ejection, but also in the ISM after being injected there. Yamasawa et al. (2011) have recently calculated the evolution of grain size distribution by considering dust production in SNe and subsequent destruction in interstellar shocks originating from SN remnants. The latter destroys small grains, so the extinction curve is expected to become flatter.

Grain growth in dense medium by the accretion of metals and the grain–grain coagulation are also important processes. Since these processes deplete small grains, the extinction curve becomes flatter.

Given that all these processes in this subsection flatten the extinction curve, shattering is worth investigating, since as shown in Section 2.2 shattering can actually contribute to the rising extinction curve toward shorter wavelengths as observed in the $z = 6.2$ extinction curve.

3. Discussion

Summarizing the results in the previous section, it seems that there are two possibilities of explaining the $z = 6.2$ extinction curve, if we assume that SNe II are the dominant source of dust grains. One is that the SN dust is ejected into the ISM without being destroyed significantly in the shocked region in the SNe (Figure 1). The other is that small dust grains are selectively destroyed in the shocked region with subsequent disruption of remaining large grains by shattering (Figure 3). Although it would be difficult to distinguish these two possibilities, it is worth noting that the $z = 6.2$ extinction curve is within the range predicted by the above theories.

Because GRBs are bright and have simple spectral shapes, they are useful probe of the extinction properties of their host galaxies. Perley et al. (2010) study GRB 071025 and show that the extinction curve of SN dust in Maiolino et al. (2004a) fits the observed spectrum. Jang et al. (2011) confirm their results by using the extinction curve of SN dust in Hirashita et al. (2005). Jang et al. (2011) also show that if we adopt the extinction curves in Hirashita et al. (2008), who consider the dust destruction in SNe II, the fit becomes worse. The extinction

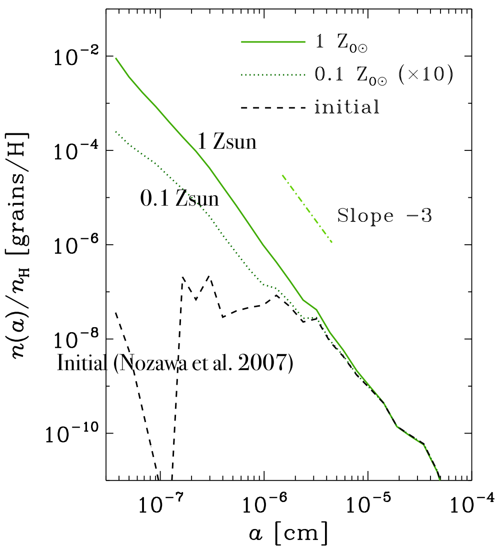

Fig. 2. Variation of grain size distribution by shattering in a WIM ($n_H = 1$ cm^{-3} and $T = 8000$ K). Shattering duration of 5 Myr is assumed, and two cases for the oxygen abundance (1 and 0.1 solar; solid and dotted lines, respectively) are examined (note that the oxygen abundance is proportional to the dust abundance). The dashed line shows the initial condition (dust injected into the ISM from a SNe II; Nozawa et al. 2007).

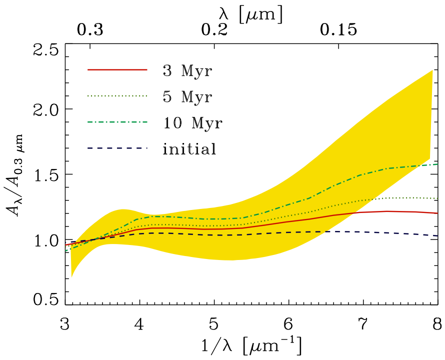

Fig. 3. Evolution of extinction curve by shattering in a WIM ($n_H = 1$ cm^{-3}, $T = 8000$ K, and solar oxygen abundance). The extinction curve is normalized to the value at 0.3 μm ($A_{0.3\,\mu m}$). The shaded region shows the $z = 6.2$ extinction curve (Maiolino et al. 2004a). The solid, dotted, and dot-dashed lines present the extinction curves for various shattering durations (3, 5, and 10 Myr, respectively). The initial extinction curve is shown by the dashed line.

properties of a large GRB sample have been investigated by Zafar et al. (2011), but the number of GRBs at $z > 5$ is still small. A larger high-z sample of GRB extinction properties in the future can be interpreted by using our theoretical work.

4. Summary

SNe II are the most viable candidate of the first dust source in the Universe because their progenitors have short lifetimes. Since the shocks within SNe II selectively destroy small grains, the extinction curve of SN dust may be flat. Therefore, in order to explain the $z = 6.2$ extinction curve, the production of small grains by shattering should be considered. Indeed, according to Hirashita et al. (2010), shattering occurs in WIM and steepens the extinction curve on a time-scale much shorter than the galaxy age. Therefore, interstellar processing, especially shattering in interstellar turbulence, should be taken into account in the grain size evolution even at high z.

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