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Supernovae as sources of dust in the early universe

T. Nozawa[1], T. Kozasa[2], H. Umeda[3], K. Maeda[1], K. Nomoto[1], N. Tominaga[4], D. Ỹamasawa[2], A. Habe[2], and H. Hirashita[5]

[1] Institute for the Physics and Mathematics of the Universe, University of Tokyo, Kashiwa, Chiba 277-8583, Japan, e-mail: takaya.nozawa@ipmu.jp
[2] Department of Cosmosciences, Graduate School of Science, Hokkaido University, Sapporo 060-0810, Japan
[3] Department of Astronomy, School of Science, University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan
[4] Department of Physics, Faculty of Science and Engineering, Konan University, Okamoto, Kobe 658-8501, Japan
[5] Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei 10617, Taiwan

Abstract. We report the mass and size distribution of dust ejected from supernovae (SNe) that are considered to be important sources of dust in the early universe. We find that Type II-P SNe supply ∼0.1–1.0 $M_{\odot}$ of dust and enrich the interstellar medium (ISM) with large grains of ≥0.01 μm. Hence, if SNe are dominant dust sources at high redshift, the interstellar extinction curve is expected to be flat. We also demonstrate that the size distribution of dust controls the formation of H_2 molecules on the grain surfaces and greatly affects the evolution of galaxies. Finally, we examine the formation and evolution of dust in envelope-deficient Type IIb/Ib/Ia SNe and show that they are unlikely to be efficient sources of dust.

Key words. Dust, extinction – ISM: supernova remnants – Shock waves – Stars: Population III – Supernovae: general – Ultraviolet: ISM

1. Introduction

Submillimeter and millimeter observations have detected the rest-frame infrared (IR) emission from dust in the host galaxies of quasars at redshift $z > 5$ (see Nozawa et al. 2009 for a review). The observed total IR luminosity exceeds 10^{13} $L_{\odot}$, and the estimated mass of the dust is well above 10^8 $M_{\odot}$. This indicates that the high-redshift quasar systems have been already enriched with dust up to the level comparable to or more than nearby dusty galaxies. Thus, this discovery has raised an important question about the origin of an enormous amount of dust in the early universe.

It has been considered that, at $z \geq 5$ when the cosmic age is younger than about 1 Gyr, interstellar dust can be only supplied by supernovae (SNe) evolving from short-lived massive stars. In this scenario, ∼1.0 $M_{\odot}$ of dust must be ejected by each SN for explaining the dust mass observed in the high-z quasars (e.g.,

Send offprint requests to: T. Nozawa

Dwek et al. 2007). In contrast, recent chemical evolution models argue that, even in such an early epoch, grain growth in molecular clouds, as well as dust production by asymptotic giant branch stars, would make great contributions to dust budget, as is the case in our Galaxy (Gall et al. 2011 and references therein).

On the other hand, the properties of dust at high redshift seem to be different from those at low redshift. In general, the extinction curves of quasars at $z \leq 4$ are described by the interstellar extinction law in the Small Magellanic Cloud (SMC, e.g., Hopkins et al. 2004). However, the extinction curves obtained for several quasars at $z \gtrsim 5$ are flatter than the SMC extinction curve and show no bump at 2200 Å that is seen in our Galaxy (Maiolino et al. 2004; Gallerani et al. 2010). Thus, the extinction properties at $z \gtrsim 5$ are incompatible with the nearby ones, suggesting different origin and evolution of dust at high redshift.

In this paper, we present the mass and size of dust grains injected from SNe which are expected to be major sources of dust in the early universe. Then we discuss the roles that such dust grains play in interstellar extinction and star formation history (SFH) in young galaxies. Finally we describe the formation and ejection processes of dust in various types of SNe.

2. Dust ejection from primordial SNe

A single massive star whose initial metallicity (Z_{pr}) is very low could not undergo intensive mass loss during the evolution stage (e.g., Heger et al. 2003). Thus, it is expected that metal-poor massive stars with the progenitor mass of M_{pr} = 8–40 $M_\odot$ explode as Type II-P SNe (SNe II-P) retaining massive H envelopes. Moreover, in the early universe, very massive stars with M_{pr} = 140–260 $M_\odot$ are believed to explode as pair-instability SNe (PISNe, Umeda & Nomoto 2002; Heger et al. 2002).

Several theoretical studies investigated the condensation of dust in these types of primordial (Z_{pr} = 0) SNe (Todini & Ferrara 2002; Nozawa et al. 2003; Schneider et al. 2004, see also Cherchneff & Dwek 2010). All of these studies conclude that the total mass of dust formed in the ejecta is 0.1–1.0 $M_\odot$ for SNe II-P and a few tens $M_\odot$ for PISNe.

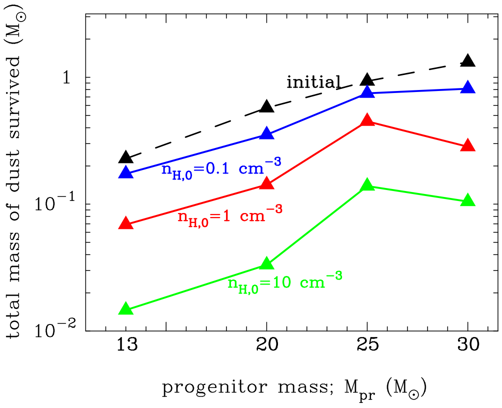

Fig. 1. Total mass of dust ejected from primordial SNe II-P with M_{pr} = 13, 20, 25, and 30 $M_\odot$ (unmixed case). The results after destruction by the reverse shock are shown for $n_{H,0}$ = 0.1 (blue), 1.0 (red), and 10 cm^{-3} (green). Dust masses at the time of dust formation are connected by the dashed line.

However, dust grains condensed in the ejecta are subsequently swept up by the reverse shock and are processed through destruction due to sputtering in the shocked gas (Bianchi & Schneider 2007; Nozawa et al. 2007). The destruction efficiency of dust depends on the initial size distribution of dust, as well as the gas density in the ISM. Hence, to estimate the properties of dust finally ejected from SNe, it is necessary to investigate the formation of dust in the SN ejecta and the destruction of dust by the reverse shock, self-consistently.

Here we focus on the properties of dust that is formed in the unmixed ejecta of primordial SNe II-P and then is released to the ISM; there has been no clear evidence for the presence of PISNe (Nagao et al. 2008). Figure 1 shows the total mass of dust that can survive the destruction by the reverse shock and be injected into the ISM for the interstellar hydrogen number density of $n_{H,0}$ = 0.1, 1.0, and 10 cm^{-3} (Nozawa et al. 2007). Dust destruction is more efficient for higher ISM density, and more than 80 % of the initial mass are destroyed for $n_{H,0}$ = 10 cm^{-3}. Meanwhile, if $n_{H,0} \leq 1.0$ cm^{-3}, the dust mass ejected from SNe II-P is 0.07–0.8 $M_\odot$, which would be high enough to make

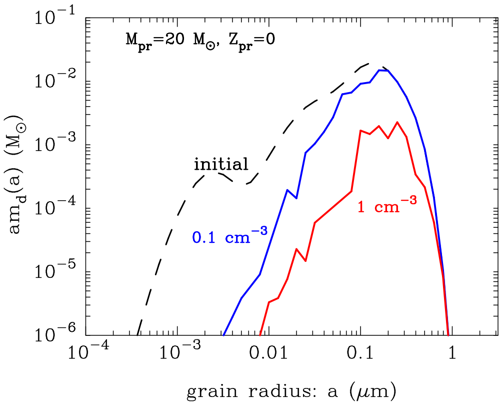

Fig. 2. Comparison of size distribution function of dust before destruction (dashed line) and after destruction (solid lines) by the reverse shock for the SN II-P model of $M_{\rm pr} = 20\ M_\odot$ and $Z_{\rm pr} = 0$. The results after destruction are shown for $n_{\rm H,0} = 0.1$ cm^{-3} (blue) and 1.0 cm^{-3} (red). The vertical axis represents the mass of dust in units of $M_\odot$ with $m_{\rm d}(a)$ being differential dust mass spectrum.

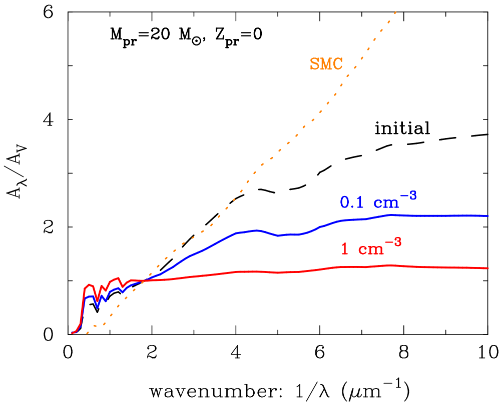

Fig. 3. Extinction curves derived from the dust models for the SN II-P with $M_{\rm pr} = 20\ M_\odot$ and $Z_{\rm pr} = 0$. The results for the dust models after destruction by the reverse shock are shown for $n_{\rm H,0}$ = 0.1 cm^{-3} (blue) and 1.0 cm^{-3} (red), while the result for the dust model before destruction is indicated by the dashed line. The SMC extinction curve taken from Gordon et al. (2003) is given for comparison.

large contributions to a huge amount of dust detected in the high-z quasars.

Figure 2 compares the dust size distributions summed up over all grain species before and after destruction by the reverse shock. Before destruction, the radii of newly formed grains span a wide range from 0.0005 μm to 1.0 μm. However, once these newly formed grains are swept up by the reverse shock, the small grains are trapped in the shocked hot gas and are predominantly destroyed by sputtering. Thus, only large grains of >0.01 μm are finally supplied from SNe II-P to the ISM.

Figure 3 shows the extinction curves calculated on the basis of the size distribution of dust in Figure 2 (Hirashita et al. 2005, 2008). Since the average radius of dust at the time of formation is relatively large ($\simeq$0.06 μm), the extinction curve is flatter than the SMC extinction curve in UV region ($1/\lambda > 4\ \mu$m^{-1}). On the other hand, the size distributions after destruction are dominated by large grains of $\gtrsim$0.01 μm with still larger average radii (>0.1 μm). As a result, the extinction curves become even flatter, being almost independent of wavelengths.

The size distribution of dust also plays a key role in the SFH. The surfaces of dust grain provide formation sites of H_2 molecules, which promotes the formation of stars in metal-poor galaxies (Hirashita & Ferrara 2002). Figure 4 illustrates how the SFH can be changed by the difference in the dust size distribution under the assumption that the star formation rate (SFR) is proportional to the amount of H_2 (Yamasawa et al. 2011). For the size distribution without destruction, which includes a significant number of small grains, the ratio of the total surface area to the total dust volume is large. Thus, H_2 molecules form very efficiently, and the SFR is enhanced rapidly with time. However, as shown in the lower panel of Figure 4, the intensive destruction of small grains due to sputtering substantially suppresses the H_2 formation, and the SFR does not increase remarkably.

In summary, SNe II-P are actually efficient sources of dust in the early universe, supplying ~0.1–1.0 $M_\odot$ of dust grains to the ISM. The grain radii are relatively large, which makes the extinction curve quite flat and prevents H_2 molecules from forming much enough to elevate the SFR dramatically. We emphasize that the size distribution of dust heavily affects the SFH, so its effect should be taken into account in modelling the evolution of galaxies.

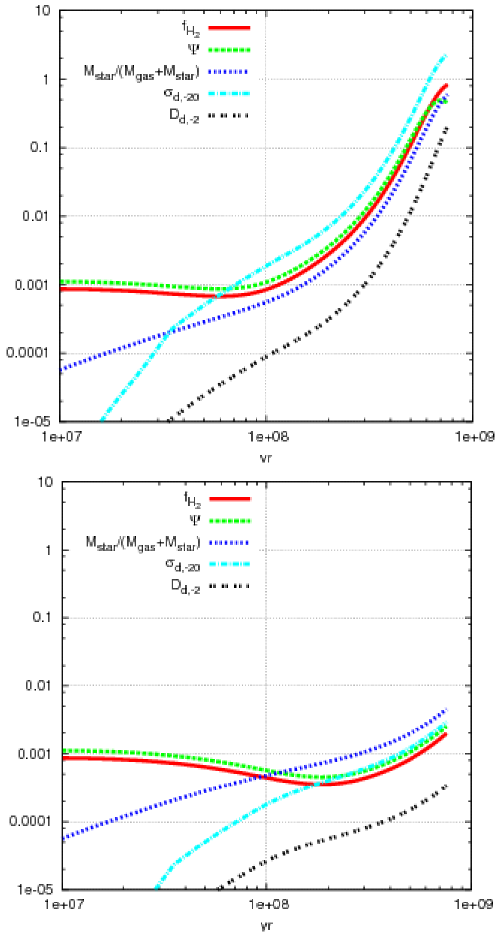

Fig. 4. *Upper panel*: Star formation and dust enrichment histories as a function of galaxy age in the case where dust destruction is not considered. Shown are the mass fraction of H_2 molecules (f_{H_2}), star formation rate (ψ) in units of $M_\odot$ yr^{-1}, star-to-gas mass ratio ($M_{star}/(M_{gas} + M_{star})$), total dust cross section per unit volume (σ_{d-20}), and dust-to-gas mass ratio (D_{d-2}) in units of 10^{-2}. *Lower panel*: Same as the *upper panel*, but in the case where dust destruction for $n_{H,0} = 1.0$ cm^{-3} is considered.

3. Dust from various types of SNe

3.1. Type IIb/Ib SNe

In contrast to SNe II-P, SNe IIb/Ib have lost almost all of the H envelopes before the explosions, so that the ratio of the explosion energy to the ejecta mass is quite large. As a result, the expansion velocities of SNe IIb/Ib are very high, which causes three orders of magnitude lower gas densities than in SNe II-P.

The results of dust formation calculations (Nozawa et al. 2008, 2010) show that, because of the low gas density in the ejecta, dust grains cannot grow to the radii larger than 0.01 μm. This indicates that the radius of newly formed dust depends on the mass of H envelope and is significantly smaller in SNe IIb/Ib with less massive envelopes than in SNe II-P with more massive envelopes. The total masses of dust formed in SNe IIb/Ib are 0.1–1.5 $M_\odot$, which is in the range of dust mass for SNe II-P.

However, these dust grains cannot be injected into the ISM. The calculations of dust destruction in the SN IIb show that, for typical ISM density ($n_{H,0} \geq 0.1$ cm^{-3}), the newly formed grains are entirely destroyed inside the SN remnant (SNR) before 10^6 yr. This is due to small size of newly formed dust and due to the early arrival of the reverse shock at the dust-forming region, both of which result from the thin H envelope. Thus, envelope-stripped SNe IIb/Ib are likely to be minor sources of dust.

Here it would be worth noticing that the model of dust formation and evolution in the SN IIb can naturally reproduce the IR observations of Cas A SNR. The model finds that the IR emission of Cas A comes from shock-heated warm dust of 0.008 $M_\odot$ and unshocked cool (~40 K) dust of 0.072 $M_\odot$ (Nozawa et al. 2010). Soon after this work, the presence of the unshocked dust component was confirmed by far-IR observations of Cas A with the *AKARI* and *Herschel*, which detected cool dust with temperature of ~35 K and mass of 0.06–0.075 $M_\odot$ (Sibthorpe et al. 2010, Barlow et al. 2010).

3.2. Type Ia SNe

Type Ia SNe (SNe Ia) are considered to be thermonuclear explosions of white dwarfs with the Chandrasekhar mass. SNe Ia can be potential sources of interstellar dust in the early universe if there exists a prompt component of SNe Ia with ages shorter than 0.1 Gyr.

The calculations of dust formation in the ejecta of SNe Ia (Nozawa et al. 2011) find that ~0.1 $M_\odot$ of dust can condense within one year after the explosion. However, as a result of the small ejecta mass ($\simeq$1.4 $M_\odot$), the gas density is much lower than SNe II-P, and dust grains form with radii smaller than 0.01 μm. Therefore, as is the case of SNe IIb/Ib, these small grains cannot survive the destruction within SNRs for $n_{\rm H,0} > 0.1$ cm^{-3}. This allows us to conclude that SNe Ia are poor sources of interstellar dust.

4. Discussion

JIM BEALL: What is the physical cause of such a flat extinction curve?
TAKAYA NOZAWA: Extinction curve represents the wavelength-dependence of extinction properties of interstellar dust. According to Babinet's theorem, the extinction efficiency of dust approaches two when $2\pi a/\lambda \gg 1$. Thus, for grain radii of $a \gtrsim 0.1$ μm, the optical–UV extinction curve is independent of grain radius and becomes flat.
MAURI VALTONEN: Could a similar flat extinction curve arise also in galaxy mergers in nearby universe?
TAKAYA NOZAWA: Galaxy mergers trigger starburst where numerous SNe are expected to occur. SNe II-P primarily supply large grains, so the extinction curves in merging galaxies may be more or less flat. In fact, the spectral energy distribution of star-forming galaxies at $z \sim 1$ can be well reproduced by the flat extinction curve obtained from our SN-dust model (Kawara et al. 2011; Shimizu et al. 2011).

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