Formation of Dust Grains in the ejecta of Type Ia Supernovae

Takaya Nozawa[1], Keiichi Maeda[1], Takashi Kozasa[2], Masaomi Tanaka[1], Ken'ichi Nomoto[1], Hideyuki Umeda[3]

[1]IPMU (Institute for the Physics and Mathematics of the Universe), [2]Hokkaido University, [3]University of Tokyo

Introduction:

It has been suggested that Type Ia supernovae (SNe Ia) can be possible producers of interstellar dust. However, in contrast to core-collapse SNe, any observation of normal SNe Ia has never reported so far convincing evidence for the ongoing formation of dust grains in the expanding ejecta. We investigate the possibility of dust formation in the ejecta of SNe Ia, adopting the carbon-deflagration W7 model. The main aim of this study is (1) to reveal the composition, size, and amount of dust that can condense in the ejecta of SNe Ia, and (2) to clarify how the formation process of dust in the ejecta depends on the type of SNe. We also calculate the destruction of the newly formed dust by sputtering in the shocked hot gas inside the supernova remnants (SNRs), to estimate the mass of dust that can be finally injected from SNe Ia into the interstellar medium (ISM).

Model :

- **SN model : carbon-deflagration W7 model (Nomoto et al. 1984, Thielemann et al. 1986)**
  - **chemical composition in the ejecta (Figure 1)** stratified elemental composition with no mixing
  - **temperature, density, and velocity of the gas (Figure 2)** gas density is much lower than that in Type II-P SNe
- **Dust formation calculations (Nozawa et al. 2003, 2010)**
  - **nucleation and grain growth theory (Kozasa et al. 1989)**
  - **sticking probability : α = 0.1 and 1.0**
  - **CO and SiO molecules : complete and no formation**

Results :

- **For α = 1.0, a variety of dust species can condense, according to the elemental abundance in each layer.**
- **Condensation times of dust grains are 100-300 days after the explosion (Figure 3a).**
- **The average grain radii are below ~0.01 μm (Figure 3b), because of low gas density in SNe Ia with no H-envelopes.**
- **The total mass of dust formed in the ejecta is 3×10^{-4} Msun to 0.2 Msun, depending on the sticking probability and formation efficiency of CO and SiO molecules (Table 1).**

Discussion :

- **thermal emission from newly formed dust (Figure 4)**
  Formation of C grains must be suppressed to be consistent with the mid-IR spectra observed for normal SNe Ia.
  ➔ energetic photons and electrons should destroy small clusters of C grains efficiently (Nozawa et al. 2008) *"or"*
  ➔ outermost C-O layer of SNe Ia should be fully burned.
- **Survival of newly formed dust in SNRs (Figure 5)**
  Unless the gas density around SNe Ia is low ($n_{H,0}$ < 0.01 cm^{-3}), the newly formed grains are almost completely destroyed.
  ➔ SNe Ia is likely to be poor producers of interstellar dust.

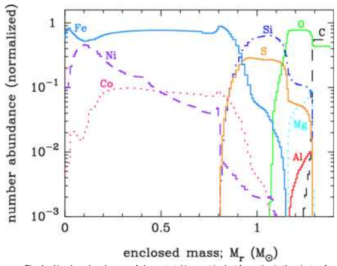

Fig. 1 – Number abundances of elements taking part in dust formation in the ejecta of the SNe Ia (W7 model) at 300 days after the explosion as a function of enclosed mass.

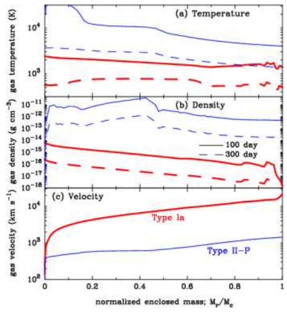

Fig. 2 – (a) Temperature and (b) density distribution of the gas in the ejecta of SNe Ia (W7 model) at day 100 (red solid lines) and day 300 (red dashed lines) after explosion, and (c) velocity structure of the W7 model (red line). The enclosed mass is normalized to the ejecta mass (1.38 M_{sun}) of SNe Ia. For comparison, shown are those for the SN II-P model (blue lines) with a M_{pr} = 20 M_{sun} and a E_{51} = 1 (Umeda & Nomoto 2002).

Table 1. Mass of Each Dust Species Formed in the Ejecta of the SNe Ia (W7 model)

dust species	A1	A0.1	B1	B0.1
C	5.66×10^{-3}	2.84×10^{-4}	3.73×10^{-2}	2.40×10^{-2}
MgO	3.17×10^{-6}	1.85×10^{-9}	9.26×10^{-8}	1.93×10^{-9}
$MgSiO_3$	7.59×10^{-3}	1.31×10^{-6}	1.95×10^{-2}	1.11×10^{-5}
Mg_2SiO_4	7.01×10^{-3}	1.50×10^{-6}	6.08×10^{-3}	6.49×10^{-6}
SiO_2	1.47×10^{-2}	9.94×10^{-6}	4.91×10^{-2}	2.21×10^{-3}
Al_2O_3	8.18×10^{-7}	7.48×10^{-10}	8.53×10^{-6}	7.71×10^{-10}
FeS	1.78×10^{-2}	1.53×10^{-5}	1.78×10^{-2}	1.53×10^{-5}
Si	6.30×10^{-2}	3.15×10^{-5}	6.40×10^{-2}	3.21×10^{-5}
Fe	9.52×10^{-5}	1.09×10^{-8}	9.52×10^{-5}	1.09×10^{-8}
Ni	1.48×10^{-6}	2.22×10^{-10}	1.48×10^{-6}	2.22×10^{-10}
Total	1.16×10^{-1}	3.44×10^{-4}	1.94×10^{-1}	2.63×10^{-2}

Note – The dust mass is given in units of M_{sun}. The models A1 and A0.1 are the cases where formation of CO and SiO molecules is assumed to be complete, with the sticking probability α = 1.0 and 0.1, respectively. In the model B1 with α = 1.0 and the model B0.1 with α = 0.1, it is assumed that any molecule never form in the ejecta of SNe Ia.

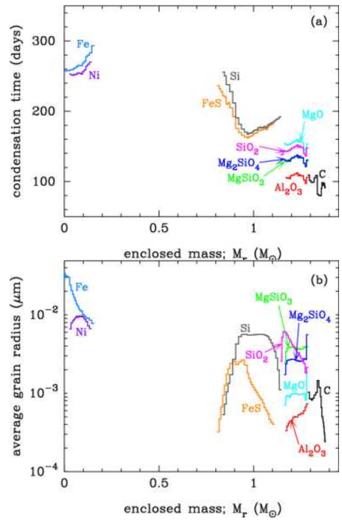

Fig. 3 – (a) Condensation times and (b) average radii of dust grains formed in the ejecta of the W7 model as a function of enclosed mass for the model A1 with the complete formation of CO and SiO molecules and with the sticking probability of α = 1.0.

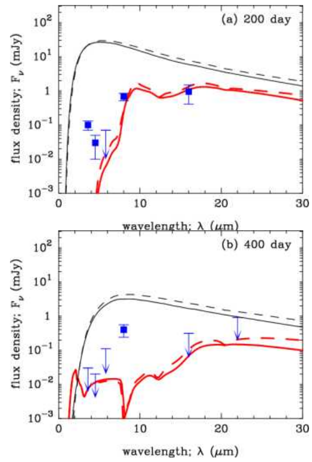

Fig. 4 – Spectral energy distributions by thermal emission from newly formed dust for the mode A1 (solid lines) and model B1 (dashed lines) at (a) 200 days and (b) 400 days after the explosion. The thin lines are the thermal emission spectra summed up over all of the grain species formed in the ejecta, while the thick lines are the mid-infrared spectra obtained assuming the absence of C grains. The observational data are the photometric results of SN 2005bf by the *Spitzer* (Gerardy et al. 2007).

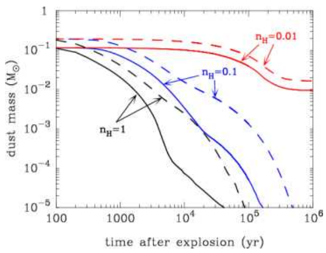

Fig. 5 – Time evolutions of the total mass of the newly formed dust within the Type Ia SNRs expanding into the uniform ISM with the hydrogen number density of $n_{H,0}$ = 0.01, 0.1, and 1.0 cm^{-3}. The solid and dashed lines are for the model A1 and B1, respectively.

Summary:

- **For the sticking probability of unity, C, silicate, Si, and FeS grains can condense in the ejecta of SNe Ia at 100-300 days, which is much earlier than those (>300 days) in Type II-P SNe.**
- **Due to the low gas density in the ejecta of SNe Ia with no H-envelope, the average radii of newly formed grains are basically less than 0.01 μm and are smaller than those (>0.01 μm) in Type II-P SNe.**
- **The total mass of dust that can form in the ejecta of SNe Ia ranges from 3×10^{-4} Msun to 0.2 Msun.**
- **For the ISM gas density of $n_{H,0}$ > 0.1 cm^{-3}, dust grains formed in the ejecta are almost completely destroyed before being injected into the ISM.**

References:

Gerardy et al. 2007, ApJ, 661, 995
Kozasa, Hasegawa, & Nomoto 1989, ApJ, 344, 325
Nomoto, Thielemann, & Wheeler 1984, ApJ, 286, 644
Nozawa et al. 2003, ApJ, 598, 785
Nozawa et al. 2007, ApJ, 666, 955
Nozawa et al. 2008, ApJ, 684, 1313
Nozawa et al. 2010, ApJ, 713, 356
Thielemann, Nomoto, Yokoi 1986, A&A, 158, 17
Umeda & Nomoto 2002, ApJ, 565, 385