Mass of Dust in Core-Collapse Supernovae as Viewed from Energy Balance in the Ejecta

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○ Abstract **Core-collapse supernovae (CCSNe) are considered to be one of the major sources of interstellar dust. Recent far-infrared (FIR) observations revealed the presence of freshly formed dust above 0.1 Msun in young supernova remnants (SNRs) such as SN 1987A and Cassiopeia A. However, dust masses estimated from near- to mid-infrared (N/MIR) observations of CCSNe a few years after explosions are more than two orders of magnitude lower than those from FIR. Here we explain this big difference in dust mass by invoking energy balance between photon absorption and thermal emission by dust. In other words, we should keep in mind that, as long as the heating source of newly formed dust is the SN radiation, the expected IR luminosity should not exceed the optical luminosity of the SN. From this constraint, we can naturally show that the mass of dust which can be heated up to several hundreds kelvin as observed by N/MIR observations is only on the order of 10^{-5}-10^{-2} Msun. This means that, even if dust grain of >0.1 Msun already formed in the ejecta a few years post explosion, only a part of them have temperatures high enough to emit N/MIR radiation. This indicates that the majority of dust grains form inside dense gas clumps in the ejecta so that their temperatures are too low to be detected at N/MIR wavelengths.**

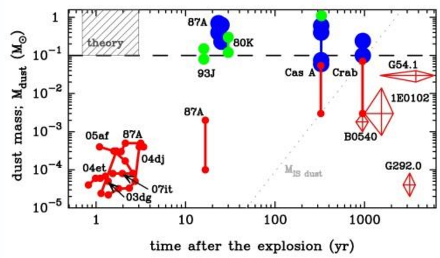
○ Summary of dust mass estimated from observations (Fig 1)

- **N/MIR observations 1-4 years after SN explosions**
  - ➜ **detect only 10^{-5}-10^{-3} Msun of dust mass**
- **FIR observations of young SNRs 20-1000 years after explosions**
  - ➜ **show dust mass as high as 0.06-0.7 Msun**

○ What is this order-of-magnitude difference in dust mass?

- **This reflects the fact that the mass of dust gradually increases with time?**
- **N/MIR observations underestimates the mass of newly formed dust?**

In order to gain insight into this issue, we should consider the energy balance between luminosity of SNe and IR luminosity of heated dust.



Refs of the important data:
87A: Wooden et al. (1993)
Matsuura et al. (2011)
03dg: Meikle et al. (2007)
04dj: Meikle et al. (2011)
Szalai et al. (2011)
04et: Kotak et al. (2009)
07it: Andrews et al. (2011)
05af: Szalai & Vinke (2013)
Cas A: Rho et al. (2008)
Barlow et al. (2010)
De Looze et al. (2016)
Crab: Gomez et al. (2012)

Fig. 1 – Summary of dust masses estimated from N/MIR (red) and FIR (blue) observations as a function of time after the SN explosions. The green points are dust masses derived from extinction of blue-shifted line emissions by Bevan et al. (2016). The hatched regions are theoretical predictions of dust mass by Nozawa et al. (2003). The diagonal dotted line indicates the swept-up mass of interstellar dust (Tanaka et al. 2012).

○ Bolometric luminosity of CCSNe

- **Theoretical estimate of SN luminosity, L_{SN}, (Woosley et al. 1989)**

$$L_{SN}(t) = 9.54 \times 10^{41} \exp\left(-\frac{t}{\tau_{56}}\right)\left\{1 - \exp\left[-\kappa_{56}\phi_0\left(\frac{t}{t_0}\right)^{-2}\right]\right\} \quad \mathrm{erg\ s^{-1}}$$

(τ_{56}=111.2 day, κ_{56}=0.033 cm2/g, ϕ_0=7x10^4 g/cm, t_0=11.6 day)

- **At t = 300-800 days, the SN luminosity ranges from 6x10^{40} erg s^{-1} down to 8x10^{38} erg s^{-1}.**

○ IR luminosity of dust thermal emission

- **Luminosity of IR dust emission, L_{IR},**

$$L_{IR}(M_{dust}, T_{dust}) = 4\pi M_{dust} \int_0^\infty \kappa_\lambda B_\lambda(T_{dust}) d\lambda \quad \mathrm{erg\ s^{-1}}$$

(κ_λ: mass absorption coefficient, B_λ: Planck function)

➜ **L_{IR} is determined by dust mass (M_{dust}) and temperature (T_{dust})**

- **N/MIR observations shows that the temperature of newly form dust is 300-700 K at 300-700 days.**
- **We assume that the dust is heated by absorbing half of SN radiation, that is, L_{IR} = 0.5 L_{SN} = 4x10^{38}-3x10^{40} erg s^{-1} at 300-700 days.**

➜ **Under these requirements, dust mass seen by N/MIR observations is at most 10^{-2} Msun for both silicate and carbon dust (see Fig 2).**

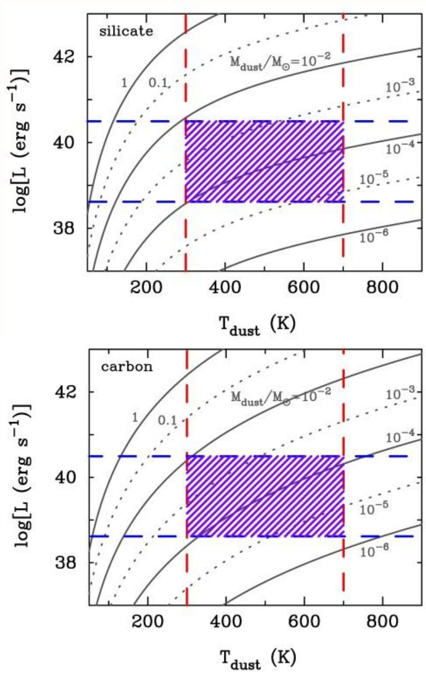


Fig. 2 – Dust masses of silicate (upper) and carbon (lower) for given IR luminosity and dust temperature. The luminosity of IR dust emission at 300-700 days is taken to be in the range from 4x10^{38} erg s^{-1} to 3x10^{40} erg s^{-1}, assuming that dust is heated by absorbing half of the SN radiation (blue horizontal dashed lines). Dust temperatures at 300-700 days are found to be 300-700 K from the observed N/MIR SEDs (red vertical dashed lines). Dust masses that satisfy both the ranges of luminosity and dust temperature (purple hatched regions) are 10^{-5}-10^{-2} Msun for silicate dust and 5x10^{-6}-10^{-2} Msun for carbon dust.

○ Results and Conclusions

- **Even if large amounts of dust grains in excess of 0.1 Msun are formed in the ejecta a few years after explosion, the SN luminosity is not high enough to heat all of dust grains above ~150 K.**
- **Hence, from a viewpoint of energy balance, it is natural that N/MIR observations, which are sensitive to dust emission with > 200 K, detect only the dust mass smaller than 10^{-2} Msun.**
- **The difference in dust mass estimated from IR observations does not reflect the history of dust formation but is just caused by the balance between the SN luminosity and dust temperature.**

References:

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