Physical Conditions of Supernova Ejecta as Viewed from the Measured Sizes of Presolar Al_2O_3 Grains

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○ Abstract A few particles of presolar Al_2O_3 grains with sizes above 0.5 μm are believed to have been produced in the ejecta of core-collapse supernovae (SNe). In order to clarify the formation condition of such large Al_2O_3 grains, we investigate the condensation of Al_2O_3 grains for wide ranges of the gas density and cooling rate. We first show that the average radius and condensation efficiency of newly formed Al_2O_3 grains are successfully described by a non-dimensional quantity Λ_{on}, defined as the ratio of the timescale on which the supersaturation ratio increases to the collision timescale of reactant gas species at dust formation. Then we find that the formation of submicron-sized Al_2O_3 grains requires at least 10 times higher gas densities than those predicted by one-dimensional (1-D) SN models. This indicates that presolar Al_2O_3 grains identified as having their origin in SNe might be formed in dense gas clumps, allowing us to propose that the measured sizes of presolar grains can be a powerful tool for constraining the physical conditions in which they formed. We also briefly discuss the survival of newly formed Al_2O_3 grains against subsequent destruction by the reverse shock at the phase of the SN remnant (SNR).

○ Presolar Al_2O_3 grains

- About 10% of presolar Al_2O_3 grains are considered to have originated from core-collapse SNe (so-called Group 3/4 grains, Nittler et al. 1997, 2008).
- Some of SN-origin presolar Al_2O_3 grains have radii larger than 0.25 μm. (see Fig. 1, Choi et al. 1998; Nittler et al. 1998)

○ Theoretical predictions about sizes of Al_2O_3 grains (see Fig. 2)

- The calculated radii of newly formed Al_2O_3 grains are smaller than 0.01 μm.
  - ➜ Such small grains may be completely destroyed by the reverse shocks before injection into interstellar medium (ISM) (Nozawa et al. 2007).

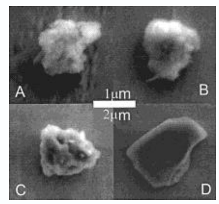

Fig. 1 – SEM images of (presolar) Al_2O_3 grains from samples of Choi et al. (1998). S-C122, a grain in (B), is inferred as a SN source from its anomalous O isotopic composition and has a size about 1 μm.

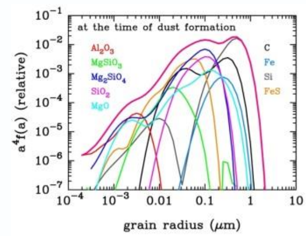

Fig. 2 – Size distributions of dust grains formed in the ejecta of a core-collapse SN, obtained from dust formation calculations (Nozawa et al. 2003). Note that the radii of Al_2O_3 grains (red) are < 0.01 μm.

○ Calculations of dust formation

- Formula of non-steady-state dust formation (Nozawa & Kozasa 2013)
- Evolutions of number density c(t) and temperature T(t) of the gas

$$\tilde{c}(t) = c_0 \left(\frac{t}{t_0}\right)^{-3}, \quad T(t) = T_0 \left(\frac{t}{t_0}\right)^{-3(\gamma-1)}$$

(c_0 and γ : parameters)

○ Results of dust formation calculations (Fig. 3)

- Average radius $a_{ave,\infty}$ and condensation efficiency $f_{con,\infty}$ of newly formed Al_2O_3 grains are scaled by a quantity $\Lambda_{on} \equiv \tau_{sat} / \tau_{coll}$;
  - τ_{sat} : timescale on which the supersaturation ratio increases
  - τ_{coll} : collision timescale of reactant gas species, $\Lambda_{on} \propto (\tau_{coll})^{-1} \propto c(t)$
- Λ_{on} should be higher than 3×10^4 in order to produce Al_2O_3 grains with radii larger than 0.25 μm (diameters of > 0.5 μm).
  - ➜ Formation of submicron-sized Al_2O_3 grains requires 10 times higher gas density than those inferred by 1-D SN models.
  - ➜ SN-origin presolar Al_2O_3 might be formed in dense clumps.

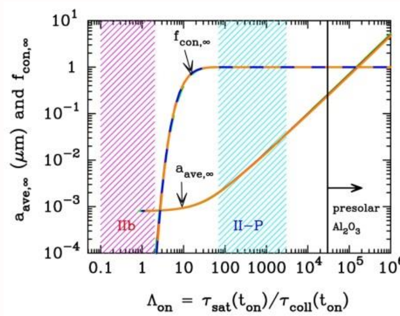

Fig. 3 – Dependence of the final average radii $a_{ave,\infty}$ and condensation efficiencies $f_{con,\infty}$ of newly formed Al_2O_3 grains on Λ_{on}. The results for four different γ (γ = 1.1, 1.3, 1.5, and 1.7) are shown in each color but they are plotted as almost the same curve. The hatched regions depict the expected ranges of Λ_{on} for the formation of Al_2O_3 grains in the Al-rich region, referring to 1D models of a Type II-P SN (cyan; Kozasa et al. 2009) and a Type IIb SN (Nozawa et al. 2010). The solid vertical line denotes the minimum value of Λ_{on} (=3×10^4) necessary for explaining the measured sizes (radius of 0.25 μm) of presolar Al_2O_3 grains.

○ Can newly formed Al_2O_3 grains survive in SNRs? (Fig. 4)

- Calculations of dust destruction by reverse shocks (Nozawa et al. 2007)
- Once submicron-sized Al_2O_3 grains are produced in dense clumps, they are likely to survive the destruction in the shock-heated gas.
  - ➜ The formation of large Al_2O_3 grains is indispensable in order that Al_2O_3 grains endure shock destruction and are injected into ISM.

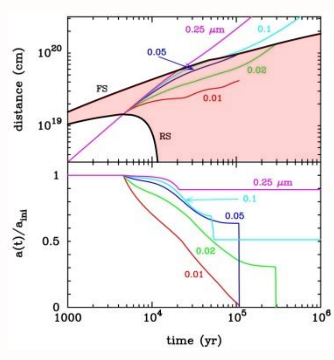

Fig. 4 – Time evolutions of the positions (upper) and the ratios of radii to the initial ones (lower) of Al_2O_3 grains in an SNR. The results are plotted for the initial grain radii of a_{ini} = 0.01, 0.02, 0.05, 0.1, and 0.25 μm. In the upper panel, the thick solid curves depict the trajectories of the forward shock (FS) and reverse shock (RS). The shaded region between the FS and RS is the shock-heated hot gas, in which dust grains are destroyed by sputtering. Small grains of a_{ini} < 0.02 μm are completely destroyed in the shocked gas. Grains with 0.02 μm < a_{ini} < 0.1 μm are eroded in the hot gas and are finally destroyed as soon as they encounter the cool dense shell created behind the forward shock after 5×10^4 years. On the other hand, Al_2O_3 grains with a_{ini} > 0.1 μm can be ejected from SNe without reducing their sizes significantly

○ Conclusion

- The average radius and condensation efficiency of newly formed Al_2O_3 grains are uniquely described by the non-dimensional quantity $\Lambda_{on} \equiv \tau_{sat} / \tau_{coll}$.
- Presolar Al_2O_3 grains with radii above 0.25 μm can be formed only in the gas with more than 10 times higher density than those estimated by 1-D SN models.
  - ➜ indicating the presence of dense clumps in the inhomogeneous SN ejecta
- The measured sizes of presolar grains are powerful probes for constraining the physical conditions and structure in which they formed.

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