Non-Steady State Formation of Dust Grains in the Ejecta of Type Ia Supernovae

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Dust formation in supernovae is one of the most important issues for disclosing the inventory of interstellar dust in the early universe as well as in our Galaxy. Recent infrared to sub-millimeter observations have reported the presence of sub-solar mass of cool dust formed in the ejecta of SN 1987A, Cas A, and Crab, which are known as remnants of core-collapse supernovae. On the other hand, there has been no convincing evidence for dust formation in normal Type Ia supernovae that are likely to be thermonuclear explosions of white dwarfs. This indicates that the formation process of dust in the ejecta depends on the explosion mechanisms of supernovae.

Formation process of dust in the ejecta of supernovae has been studied mainly with the classical nucleation theory and its extension. In the nucleation theory, the condensation of dust is described by the formation of stable seed nuclei (critical clusters) and their growth, where the formation rate of critical clusters is derived by assuming the nucleation current to be in a steady state. However, it has been argued that the classical nucleation theory could not be applicable in the rarefied gas typical of dust-forming region of astrophysical interest, although the effect of a non-steady state on the formation process of dust has not been fully explored.

In this paper, we develop a method of calculations that manage dust formation processes without postulating a steady state, and compare the results of the calculations with those obtained with the steady state nucleation rate. We show that the steady state nucleation rate is a good approximation in the situation where the timescale of supersaturation is much longer than the timescale of gas collisions, and that this condition is met for the ejecta of core-collapse supernovae. We also illustrate that the average grain radii and condensation efficiency are uniquely determined by the ratio of the supersaturation timescale to the collision timescale of the gas at condensation.

Then, applying the non-steady dust formation formulae, we investigate the possibility of dust formation in the ejecta of Type Ia supernovae, for which the effect of a non-steady state is expected to be remarkable because of a much lower ejecta density than that in core-collapse supernovae. We show that the average radii of dust grains formed in Type Ia are significantly small but their mass is still a similar order to those in core-collapse supernovae. We discuss the inconsistency between the calculated and observed masses of newly formed grains in Type Ia, as well as the roles of Type Ia supernovae as sources of interstellar dust.