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Heating and evaporation of icy dust in transient heating events induced by nebular shocks

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Icy dust plays an important role in chemical evolution from molecular clouds to protoplanetary disks. Simple organic molecules such as formaldehyde (H_2CO) and methanol (CH_3OH) can form in H_2O-CO ice by consecutive addition of hydrogen atoms to CO molecule (Watanabe & Kouchi 2002). Deuterium enrichment in these organic molecules was confirmed to occur by H-D substitution on icy dust surfaces (Nagaoka et al. 2005). More complex organic molecules such as amino acids were detected in the room-temperature residue of an interstellar ice analogue that was ultraviolet-irradiated in a high vacuum at 12 K (Munoz Caro et al. 2002). Sublimation of such icy dust will change the chemical composition of a gas phase in molecular clouds or protoplanetary disks. It is important to elucidate the thermal history of icy dust because it affects the chemical evolution of these organic molecules significantly.

In this paper, we investigated the transient heating event of icy dust induced by nebular shocks. In protostellar or protoplanetary disks, gas accretion from its parent molecular cloud or formation of planetary systems induces shock waves in various conditions. When icy dust passes through the shock front together with the ambient gas, the gas changes its velocity suddenly but the icy dust retains its velocity because of its large inertia. This results in a large relative velocity between them. The high-velocity collision of gas molecules to the icy dust surface raises the dust temperature and leads to its evaporation. Since the relative velocity is reduced by collisions with gas molecules, the heating event should cease within a short period of time. We calculated thermal history and evaporation experienced by icy dust during shock passage for various shock conditions systematically.

The physical model is as follows. We assume that the temperature and density of the post-shock gas are uniform. For simplicity, we consider a spherical icy dust composed of pure H_2O or CO. The icy dust temperature changes much faster than its velocity because of its small thermal inertia. It is shown that the evaporation fraction of individual icy dust defined by the ratio of the decrease in radius to the initial one depends only on the post-shock gas density (ρ_g) and the relative velocity between icy dust and gas just behind the shock front (v_0). We calculated the equations of motion and evaporative shrinkage of the icy dust to obtain the peak temperature and evaporation fraction experienced by the icy dust.

In general, icy dust experiences high temperature and significant evaporation for large v_0 and ρ_g. In addition, we obtained the results as follows: (i) Icy dust does not evaporate completely before it stops relative to the ambient gas even for quite large v_0 and ρ_g. This is due to a negative feedback between the evaporative shrinkage and the duration of heating. (ii) Icy dust hardly evaporates if v_0 is smaller than a certain value. For example, when $v_0 <\sim 3$ km/s for pure H_2O ice or $v_0 <\sim 1$ km/s for pure CO ice, the icy dust shrinks less than by 1% in radius for any gas density. (iii) Icy dust can experience an extremely high temperature at which it would evaporate completely if it were in equilibrium. This is a remarkable feature of the transient heating event that the short heating duration allows the icy dust to survive against superheating.

We elucidated the conditions of icy dust evaporation induced by nebular shocks for various shock conditions systematically. Our results would be useful to discuss the relation between the changes in chemical composition of molecular clouds or protostellar/protoplanetary disks and the evaporation of icy dust by shocks.

Keywords: icy dust, shock heating, evaporation, chemical evolution, protostellar disk, protoplanetary disk