Inhomogeneous temperature distribution in chondrules in the shock wave heating

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Chondrules are main inclusions of chondrites. They are millimeter-sized, once molten, spherical shaped objects. It is considered that the dust particles were heated and melted through flash heating events in the solar nebula, rounded by surface tension, cooled again to solidify in a short period of time, and formed chondrules. The shock wave heating model is considered to be one of the plausible models for chondrule formation. The mechanism of the shock wave heating is rather simple. In the post-shock region, the gas flow is decelerated abruptly due to the gas pressure, while the dust particle is not decelerated. So, a relative velocity between the gas and the dust particle rises. And the gas drag due to the relative velocity heats the dust particle.

There are various studies for chondrule formation in the framework of the shock wave heating model. Almost all the studies so far assumeed that the temperature in the dust particle is homogeneous. However, the dust particle is first heated its surface and thermal energy is conducted toward the inside of the dust particle. Thus, the dust particles heated by the shock wave heating may have inhomogeneous temperature distribution.

We reported in the JSPS fall meeting in 2004 that inhomogeneous temperature distribution in no-rotating dust particles was found. However, dust particles in the solar nebular might rotate. If it is the case, the rotation may have some effects on the temperature distribution in the dust particles. In this work, we numerically simulate that temperature distribution in the dust particles heated by shock wave heating. We solve the 3-D conduction equation with some physical processes.

We found that three types of temperature distribution appear depending on the radius (rs), the rotation frequency (w) of the dust particle, and the heating duration: layered, spherically symmetric, and homogeneous distribution. These types of the temperature distribution can be understood in terms of following three timescales (1) timescale of heating (t_h), (2) timescale of rotation (t_r), and (3) timescale of conduction (t_c). If (1) t_h is less than t_r and t_c, the temperature of the dust particle changes before allocation of thermal energy, so the temperature distribution becomes layered. If (2) t_h is less than t_c and greater than t_r, the surface of the dust particle becomes hotter than the center. So, the temperature distribution becomes spherically symmetric. If (3) t_h is greater than t_c and less than t_r, the temperature distribution becomes layered because the rotation does not influece much. And if (4) t_h is greater than t_c and t_r, because timescale of the heating is longer than those of rotation and conduction, the temperature distribution becomes homogeneous. When r is less than r_c, where r_c is defined as the radius at which t_h = t_c is realized, t_h is less than t_c and the distribution becomes inhomogeneous temperature distribution (layered or sphere symmetric). When w is less than w_c, where w_c is defined as the frequency at which t_h = t_r is met, t_h is less than t_r and the distribution becomes layered. For example, if the initial radius is 1 mm, the gas density of pre-shock region is n_g = 1.0*10^14 cm^-3, and the velocity of the shock is v_sh = 12 km/s, the critcal values become r_c = 0.264 mm and w_c = 4.17 s^-1. If n_g = 1.0*10^11 cm^-3 and v_sh = 40 km/s, r_c = 4.1 mm and w_c = 0.27 s^-1. When the dust particle has spherically symmetric temperature distribution, the temperature difference between the surface and the center of the dust particle (T_fc) does not approach to 0 K, even when the rotational velocity is fast. For instance, the value of T_fc = 40 K in the above case.

Additionally, we discuss the condition of shock waves for chondrule formation in the case of inhomogeneous temperature distribution in dust particles.