# CHONDRULE FORMATION THROUGH COLLISIONS BETWEEN PLANETESIMALS CONTAINING VOLATILE MATERIALS

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**Introduction:** From a physical point of view, the two most important quantities of chondrules still to be understood are size and cooling rate. Although many models have been proposed, consistent explanation of these two quantities is still lacking. The collision of molten planetesimals [1,2] is a promising candidate mechanism for chondrule formation. However, the nebula gas is too rarefied to break the silicate melt ejected by the collision down to chondrule size (0.1 – 2 mm [3]). Here we propose that collisions of low temperature planetesimals containing volatile material naturally explain the size and cooling rate of chondrules, since the rapidly heated volatile material quickly expands and break up the silicate melt down to the required small sizes.

**Numerical Simulations:** To verify this idea, we performed three sets of simulations: 1: Orbital evolution of a swarm of planetesimals in the solar nebula undergoing the dynamical excitation induced by Jupiter's formation with the Mercury-Arχes n-body code [4,5]. From these simulations, the impact probability and collision velocity distributions are determined. 2: Collision of planetesimals. We performed iSALE [6] hydrocode simulations of collisions between planetesimals with sizes of 100 and 400 km and determined the amount of silicate melt produced during a collision. 3: 1-D hydrodynamical simulations of gas-melt mixture expansion. A layer of gas-melt mixture expands due to the volatile materials contained in a planetesimal. Size of melt droplets and their cooling rates are determined.

**Numerical Results:** From simulation 1, we found that about 5% of collisions has impact velocity higher than 4 km/s when planetesimals are embedded in a gaseous protoplanetary nebula. The high velocity collisions continue 1 Myr after Jupiter formation. From simulation 2, we obtained that the amount of melt exceeds 50% of the projectile volume if the collision velocity is higher than 4 km/s. From simulations 1 and 2,we could estimate that the total amount of silicate melt is about 10% of the total volume of planetesimals. In simulation 3, there are three key parameters: initial temperature, thickness of mixture, and gas (volatile) mass fraction. We determined the evolution of cooling rate and size (Fig. 1) for various sets of parameters. The size and cooling rate fall within 0.26-1.6 mm and 20-2000 K/h, respectively, consistently with measured values of chondrules.

**Conclusions:** Collisions of planetesimals containing volatile materials consistently explain both the size and the cooling rate of chondrules. The beginning of the formation period of chondrules coincides with Jupiter's formation and the resulting dynamical excitation of planetesimals.

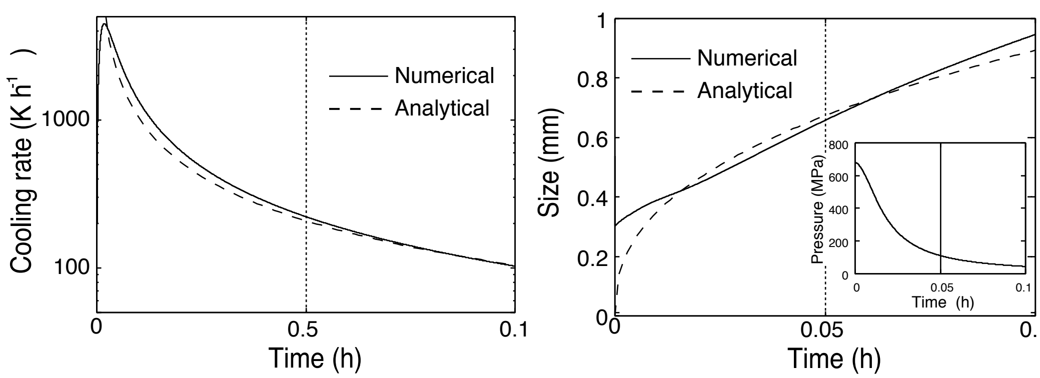


Fig. 1. Evolution of cooling rate (left) and size (right) of silicate melt. Initial temperature is 1800 K, thickness of mixture is 10 km, gas mass fraction is 10%. Solid and dashed curves are simulation results and analytical formula, respectively. Right inset: evolution of gas pressure.

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