

**Impact Jetting and the Origin of Ordinary Chondrites.** Y. Hasegawa<sup>1</sup>, Y. Matsumoto<sup>2</sup>, S. Wakita<sup>2</sup>, S. Oshino<sup>2</sup>, N. J. Turner<sup>1</sup>, and J. Masiero<sup>1</sup>, <sup>1</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA (YH:yasuhiro@caltech.edu), <sup>2</sup>Center for Computational Astrophysics, National Astronomical Observatory of Japan, Osawa, Mitaka, Tokyo 181-8588, Japan.

**Introduction:** Ordinary chondrites contain the profound information of how the solar system formed [1]. Such fossil records are concentrated especially in chondrules that are the most abundant ingredient (up to 80 % by volume) in the chondrites. Chondrules are mm-sized spherical particles, and were formed from molten droplets of silicate [2]. It is widely accepted that chondrule formation is the outcome of transient heating events that took place in the solar nebula. Since such events can be used as a tracer of the disk properties of the solar nebula, understanding of chondrule formation can shed light on the evolution history of the solar nebula. Investigating origins of ordinary chondrites can also provide invaluable clues as to the formation mechanism of the solar system. This is simply because planetesimals that are the parent bodies of chondrites [3], serve as the building blocks of planets. Thus, exploration of chondrule formation and the origin of ordinary chondrites enables a careful examination of how the solar system formed from the solar nebula.

A number of the interesting studies have recently been developed in order to understand mechanisms of forming chondrules and to examine the origin of ordinary chondrites. For instance, numerical simulations based on a shock physics code have revealed that planetesimal collisions and the resulting impact jetting can reproduce the thermal history of chondrules [4]. As another example, the accretion process of chondrules onto massive bodies such as protoplanets and planetesimals is investigated by realistically modeling the dynamics of chondrules in the nebular gas [5]. Here, we present the recent results of our work, wherein a series of independent, but well-connected projects are undertaken, by focusing on the impact jetting scenario to form chondrules and on the subsequent accretion of chondrules onto the surrounding planetesimals. We find that while impact jetting is a promising mechanism to generate a large amount of chondrules, chondrule accretion onto the existing planetesimals may not be efficient to fully account for the high abundance of chondrules in ordinary chondrites.

**Chondrule formation and accretion:** We discuss the results of our recent studies.

*Impact jetting as a chondrule-forming event.* As already demonstrated by the previous, pioneering work [4], planetesimal collisions can serve as a chondrule-forming process when the impact velocity ( $v_{imp}$ ) ex-

ceeds  $2.5 \text{ km s}^{-1}$ . Under such collisions, ejected materials that emerge from the collisional surface experience melting due to a high temperature ( $> 1300 \text{ K}$ ), and can escape from the system due to a high ejection velocity. The previous study also shows that the total amount ( $F_{ch}$ ) of chondrule formed by single collisions is about 1 % of the colliding planetesimals' mass. Since  $v_{imp}$  of  $2.5 \text{ km s}^{-1}$  can readily be achieved for collisions between planetesimals and protoplanets because of a high escape velocity of the system, protoplanet-planetesimal collisions were examined before. In this work, we explore a larger parameter space, especially focusing on planetesimal-planetesimal collisions [6]. More specifically, we make use of the iSALE-2D shock physics code to investigate how different types of collisions can affect the resulting chondrule formation.

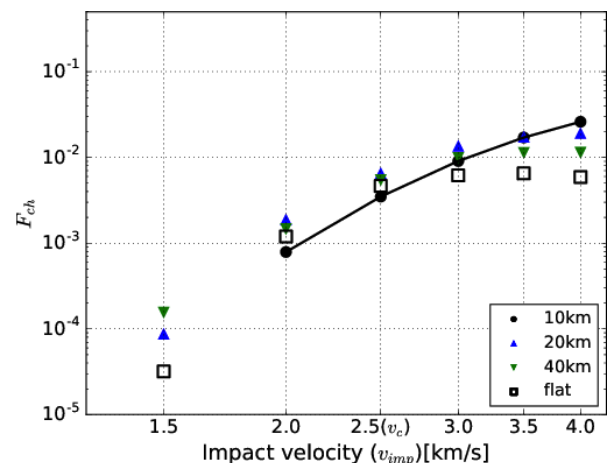


Figure 1. The resulting value of  $F_{ch}$  for different kinds of collisions [6].

Figure 1 shows our results. In this plot, the results of a number of simulations are summarized, where the impactor planetesimals that are 10 km in diameter collide with the target planetesimals that are 10-40 km in diameter with a wide range of  $v_{imp}$  ( $= 1.5\text{--}4.0 \text{ km s}^{-1}$ ). For comparison purpose, collisions between planetesimals and protoplanets are also simulated (see the open squares). We find that  $F_{ch}$  increases with increasing  $v_{imp}$ , and  $v_{imp}$  should be larger than  $2.0 \text{ km s}^{-1}$  to generate a non-negligible amount of chondrules. It is nonetheless reasonable to conclude that the criteria ( $F_{ch} \sim 1\%$  when  $v_{imp} \sim 2.5 \text{ km s}^{-1}$ ) proposed by the previous work are applicable for a various kinds of collisions.

*Formation history of chondrules.* While single planetesimal collisions generate a small amount of chondrules via impact jetting, it is important to realize that a large number of collisions occurred in the solar nebula to form planets. To trace down such a collisional history of planetesimals, we develop a semi-analytical model of planetary accretion and compute how many of chondrules are formed through the formation of a protoplanet [7].

Figure 2 shows the time evolution of the protoplanet mass ( $M_p$ ), the corresponding impact velocity ( $v_{imp}$ ), and the resulting amount of chondrules formed by impact jetting from the top to the bottom panel, respectively. We find that chondrule formation begins at  $t \sim 10^6$  yr after the onset of planetary growth. At that time, the protoplanet is already in the oligarchic growth stage [8]. Then, chondrule-forming impacts continue for about 3 Myr when disks are 3 times more massive than the minimum mass solar nebula. It is interesting that these timescales are consistent with the meteoritic data [9]. Furthermore, the total amount of chondrules generated by planetesimal collisions is characterized well by  $F_{ch}M_{p,iso}$  where  $M_{p,iso}$  is the isolation mass of protoplanets. Thus, when the growth timescale of protoplanets is shorter than the disk lifetime, the final amount of chondrules formed by impact jetting can be readily estimated.

*Chondrule accretion onto planetesimals.* We finally examine how many of chondrules can be accreted onto the existing planetesimals [10,11]. This is motivated because the present asteroids may be fragments of planetesimals that might originally be more massive [3]. In other words, there may be the following possibility: even if a first generation of planetesimals might not contain chondritic materials, the subsequent accretion of chondrules onto such planetesimals may generate the parent bodies of ordinary chondrites as long as fragments originate only from their chondrule-rich surfaces. Based on this idea, we develop an analytical model of chondrule accretion onto planetesimals [11].

Figure 3 shows our results. We find that chondrule-rich surface layers are too thin for a wide range of the planetesimal mass. This is simply because the accretion efficiency of chondrules onto planetesimals is not high. Thus, it is unlikely that chondrule accretion onto planetesimals can account for the majority of ordinary chondrites.

**References:** [1] Davis A. M., Alexander C. M. O. and Ciesla F. J. (2014) in *Protostars and Planet VI*, 809. [2] Hewins R. H. et al. (2005) in *ASP Conf. Ser.* 341, 286. [3] DeMeo et al. (2015) in *Asteroid IV*, 895. [4] Johnson B. C. et al. (2015) *Nature*, 517, 339. [5] Johansen A. et al. (2015) *Science Advance*, 1, 1500109. [6] Wakita S. et al (2017) *ApJ*, 834, 125. [7]

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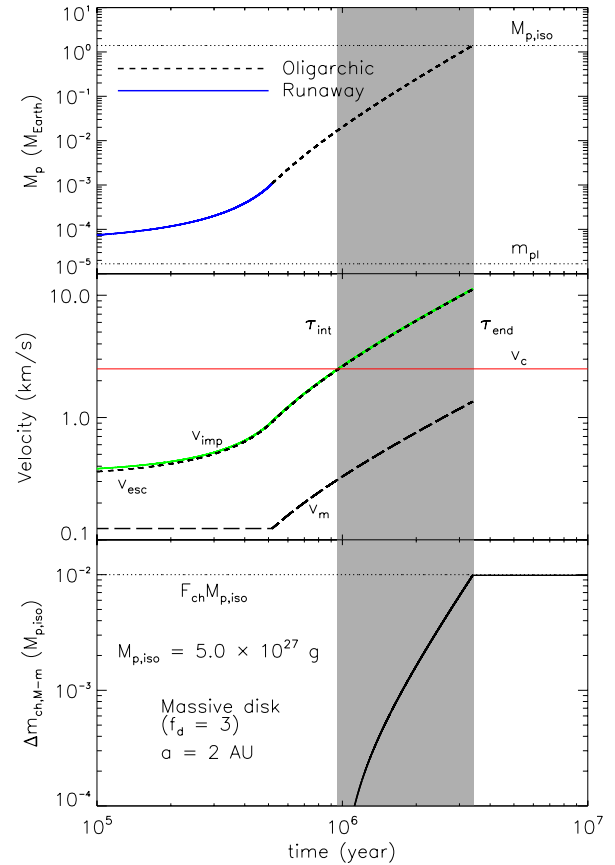


Figure 2. The time evolution of the protoplanet mass, the impact velocity of planetesimals, and the resulting amount of chondrules formed by impact jetting during planetary accretion on the top to the bottom panel, respectively [7].

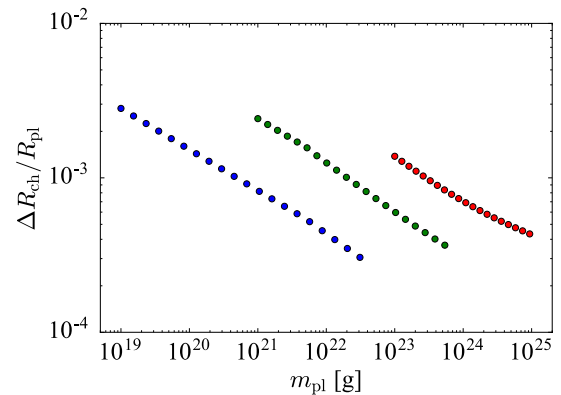


Figure 3. The thickness of chondrule-rich surface layers as a function of the planetesimal mass ( $m_{pl}$ ).