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A shock-wave heating model for chondrule formation II. Minimum size of chondrule precursors

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Abstract

Chondrule formation due to the shock wave heating of dust particles with a wide variety of shock properties are examined. We numerically simulate the steady postshock region in a framework of one-dimensional hydrodynamics, taking into account many of the physical and chemical processes that determine the properties of the region, especially nonequilibrium chemical reactions of gas species. We mainly focus on the dust particle shrinkage due to the evaporation in the postshock hot gas and the precursor size conditions for chondrule formation. We find that the small precursors whose radii are smaller than a critical value, $a_{\rm pre}^{\rm min}$, cannot form chondrules because they evaporate away completely in the postshock region. The minimum value of $a_{\rm pre}^{\rm min}$ is about 10 μm, though it depends on the shock speed and the preshock gas density. Furthermore, we demonstrate the chondrule size distributions which are formed through the shock-wave heating. These results indicate that the shock-wave heating model can be regarded as a strong candidate for the mechanism of chondrule formation.

Keywords: Meteorites; Origin; Solar System; Thermal histories

1. Introduction

Chondrules are millimeter-sized, once-molten, spherical-shaped grains mainly composed of silicate material. They are considered to have formed from chondrule precursor particles that were heated and melted through flash heating events in the solar nebula and cooled again to solidify in a short period of time (e.g., Jones et al., 2000). Since chondrules are ubiquitous (being contained in many chondrite meteorites and occupying up to 80% in volume of those meteorites), it is believed that they have great information on the early history of the Solar System. To reveal their history, many works have been carried out observationally, experimentally, and theoretically.

It is well known that chondrules have typical size distributions. Measured sizes of chondrules in some chondrite groups are listed in Table 1. We can see that diameters of most of chondrules are in a range from a few tens of μm to a few mm. It should be noticed that small chondrules whose diameter is smaller than 1 μm are quite rare. But this size distribution seems strange when we think of the size distribution of interstellar dust particles that must be ancestors of dust particles in the early solar nebula. The maximum size of interstellar dust particles is estimated to be about 1 μm or less (e.g., Mathis et al., 1977). This suggests that the chondrule precursors are formed through coagulation of small dust particles in the solar nebula. If this is the case, one can easily expect that the size distribution of the precursor particles should be in a range from sub-micron to a few mm or more. However, we do not see abundant small chondrules whose radius is smaller than 1 μm. Thus, the absence of small chondrules seems to imply the presence of a mechanism that determines the minimum size of chondrules, which were formed from large precursor particles.

Some mechanisms have been proposed that are responsible for the size distribution of chondrules. One of them is the turbulent concentration (Cuzzi et al., 1996, 2001).

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Table 1
Diameter range of chondrules determined by petrographic analysis of thin sections

Chondrite group	Chondrule type	No.	Diameter-range (μm)	Median diam. (μm)	Mean diam. (μm)	Reference
L_3	BO	173	140–5973		1038	RK84
L_3	RP + C	201	48–4278		852	RK84
L_3	BO	163	90–5080		680	RK84
L_3	RP + C	70	73–1780		622	RK84
EH_3	RP	86	30–1768		245	RG87
EH_3	C	35	49–676		183	RG87
EH_3	GP	10	62–158		110	RG87
EH_3	POP + PO	27	70–570		252	RG87
EH_3	PP	531	42–1350		219	RG87
CO_3	POP	1868	24–1790	137	144	Rubin89
CO_3	PP	494	31–967	146	146	Rubin89
CO_3	PO	203	40–1360	206	196	Rubin89
CO_3	BO	37	67–655	250	228	Rubin89
CO_3	RP	132	28–790	145	133	Rubin89
CO_3	C	96	34–830	119	120	Rubin89
CO_3	GOP	4	72–255		119	Rubin89

BO = barred olivine; RP = radial pyroxene; C = cryptocrystalline; PO = porphyritic olivine; PP = porphyritic pyroxene; POP = porphyritic olivine-pyroxene; GP = granular pyroxene; GOP = granular olivine-pyroxene. Abbreviations in the column of “reference” stand for Rubin and Keil (1984) (RK84), Rubin and Grossman (1987) (RG89), and Rubin (1989) (Rubin89), respectively.

Turbulence can be recognized as a superposition of various turbulent motions on various scales, and the smallest scale motion has the shortest time scale. According to Cuzzi et al. (1996), dust particles in the turbulence that have a stopping time (a function of the dust radius) comparable to the time scale of the smallest turbulent motion can have the maximum concentration in the turbulence. The estimated radius of the maximally concentrated particles is about 0.2 mm for the typical nebula parameters, which is consistent with the average radius of measured chondrules. However, the relation between the particle concentration and the chondrule formation conditions is not clear.

It is also suggested that a gas flow from the inner edge to the outer region of the protoplanetary nebula, which is often referred as the X-wind, may be a size selective mechanism (Shu et al., 1996). The dust particles are blown off and taken out above the nebula by the gas flow. The smaller the dust particles are, the further they are carried because such small particles are well coupled to the ambient gas flow. On the other hand, the larger dust particles are, the closer they fall by the gravity of the central star and the nebula. However, since this mechanism includes some unknown factors (e.g., a velocity of the gas flow, the location of dust particles, etc.), it is not clear whether size distributions of chondrules can be explained or not.

There are another attempts to explain the chondrule size distribution in the framework of dust heating mechanism. Shock-wave heating (Hood and Horanyi, 1991, 1993; Ruzmaikina and Ip, 1994; Iida et al., 2001 (hereafter INSN); Desch and Connolly, 2002; Miura et al., 2002; Ciesla and Hood, 2002) is one of the possible mechanisms for chondrule formation (Boss, 1996; Jones et al., 2000). This model can explain the peak temperature experienced by chondrules in the formation process and the cooling rates (Desch and Connolly, 2002; INSN). Also, the observed maximum size of chondrules and possible rotation rates can be understood naturally (Susa and Nakamoto, 2002, hereafter SN02). However, it is still unknown from works listed above how the minimum size of chondrules is determined.

In this paper, we propose a new mechanism that determines the minimum size of chondrule precursors in the framework of the shock-wave heating model. If shock waves with suitable strength for chondrule formation are generated in the solar nebula, the precursor particles may be melted and resolidified and become chondrules in the postshock region. However, the resolidified dust particles in the postshock region are exposed to the hot gas in that region until the gas cools by emission of radiation. The duration of the phase is about a few hundred seconds for a typical shock wave (INSN). In this phase, the temperature of the dust particles is kept very high (more than 1500 K) by thermal conduction with the hot gas. Then, it is naturally expected that evaporation from the surfaces of the dust particles should take place and the radii of the particles should shrink. Small dust particles may vanish in the postshock hot gas region and cannot form chondrules, while large particles can survive and form chondrules.

This paper is organized as follows. In Section 2, the basic idea of the shock-wave heating model is briefly summarized. In Section 3, numerical results are shown. Some discussion and a summary of the paper are given in Sections 4 and 5, respectively.

2. Model and basic equations

2.1. Overview of our shock-wave model

It may be useful to begin with clarifying the character of the shock. If the cooling time scale is longer than the time