Introduction: Recently, chondrule formation due to nebular shock waves has been examined from viewpoints such as thermal history [1-3] and size distribution of final products [4]. The authors of these studies agree with that chondrule formation due to nebular shock waves is consistent with those natures of chondrules. However, all of these investigations simplified or even ignored the processes during the formation of chondrules, such as melting and resolidification, internal flow of melted chondrules, transportation of the materials inside of chondrules and formation of compound chondrules. We examine two distinctive processes of nebular shock wave heating, transportation of iron-sulfide inclusions by internal flow of molten-silicate and formation of compound chondrules. A recent study has shown that if chondrules are melted by nebular shock waves, a high-speed (~10 cm s⁻¹) rotational flow occurs in chondrules during melting [5] and the final distribution of iron-sulfide inclusions in chondrules would be largely affected by the internal flow. And also, if molten or half molten chondrules are collide each other at a suitable range of relative velocity, they would stick and form compound chondrules. In order to investigate whether those microtextures of chondrules can be formed by shockwave heating, detailed two and three dimensional observation was performed on chondrules in some classes of primitive chondrites.

Results of our investigations showed that the distribution of iron-sulfide inclusions in chondrules and formation of compound chondrules are both difficult to be accounted by the nebular shockwave heating.

Iron-sulfide inclusions inside of chondrules: In previous studies, we have examined the nebular shock wave model of chondrule formation from the viewpoint of size and distribution of iron-sulfide inclusions in chondrules [6]. Figure 1 shows the X-ray CT image of a chondrule in Y-791717 (CO3) chondrite. As seen in the figure, large iron-sulfide inclusions are often contained inside (do not reach the surface) of chondrules. However, the results of numerical calculations show that the iron-sulfide inclusions must quickly (<< 1 s) reach the surface of chondrules if the radius ratio of the iron-sulfide inclusion to the host chondrule exceeds 0.2, because the high speed internal flow brings them to the surface of the melted chondrule.
Formation of compound chondrules: Here, we show another difficulty of chondrule formation by nebular shock wave heating. Compound chondrules, which consist of two or more chondrules sticking each other, are occasionally found in natural chondrites. When they formed, one of constituent chondrules has already solidified while the other has still molten (Fig. 2). We estimated the probability of sticking of chondrules in the nebular shock wave. In the nebular shock wave, the drag force varies between chondrules depending on their size and chondrules have different relative velocities.

Fig. 2 A transmitted light image of a compound chondrule in ALH-77260 (L3) chondrite. A radial pyroxene chondrule attached on a porphyritic pyroxene chondrule. Dark portions in the chondrules are oxidized iron or iron-sulfide inclusions.

If the relative velocity is sufficiently small, they can stick to each other without disruption. Figure 3 shows that the relative velocity of two different sized chondrules. As seen in Fig. 3, if the radii of chondrules differ by more than 10% at 0.3 mm, the relative velocity becomes very large. This means that nebular shock wave heating could not make the compound chondrules that have radius difference more than 10%, because the collision between those chondrules leads to disruption of them, not leads to sticking. Even the solid chondrules would be disrupted if the relative velocity exceeds 76 m s\(^{-1}\) [7].

In the nebular shockwave model, the thermal history and the degree of melting at a certain distance from the shock front strongly depend on the radius of chondrules. If the compound chondrules are formed in the nebular shock wave, their radius, and then their texture must always be similar or same. However, the natural compound chondrules have various combination of their texture [8]. This is the second difficulty of chondrule formation by nebular shock waves.

Discussion: We showed two inconsistencies between textures expected from theoretical shock-wave model and those observed in natural chondrules. These results indicate that the chondrule formation by nebular shock waves is considered to be unlikely.

Fig. 3 Relative velocity between two different sized chondrules. Each curve shows that the relative velocity between the chondrules that have radius shown by the captions and that have 10% smaller than the captions.