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33. We thank E. Anders for stimulating discussion and sharing unpublished data with us. We are indebted to L. E. Nyquist, B. R. Doe, and R. E. Zartman for reviewing this manuscript. Supported by NASA interagency transfer order T-2407A. Publication authorized by the director, U.S. Geological Survey.

26 April 1973; revised 20 July 1973

Chondrules: An Origin by Impacts between Dust Grains

Abstract. *A barred chondrule in the Ngawi meteorite contains a magnetite spherule embedded in it. The collision between these two objects fractured and partially remelted the chondrule, an indication that the impact velocity was 10^5 to 10^6 centimeters per second. This observation supports Cameron's and Whipple's recent predictions that grains achieved high velocities in the nebula and that the resulting impacts provide a suitable chondrule-forming mechanism.*

Chondrules are millimeter-sized spherules that occur in abundance in primitive stony meteorites. They commonly contain glassy silicate material which, together with their spherical shape, indicates formation as rapidly cooled molten droplets dispersed in space (*1*). Their presence in primitive meteorites has led to the suggestion that they formed in the solar nebula, just prior to or during the accretion of planetary matter.

Modern theories on their origin may be divided into two broad categories: primary and secondary. According to primary theories, chondrules are thought to condense directly from the cooling nebular gas as stable (*2*) or metastable (*3*) liquid droplets. According to secondary theories, chondrules are thought to be produced by the flash heating and remelting of the original dust-like condensate. Various mechanisms for these secondary theories have been proposed: impact events (*4*) or quasi-volcanic activity (*5*) on the surfaces of protoplanets and lightning discharges (*6*) or high-velocity ($\gtrsim 10$ cm/sec) collisions between dust grains (*7, 8*) in the nebula.

There is a growing body of evidence in support of those secondary theories, for example, lightning or collisions, in which some fraction of the nebular dust is heated and melted just prior to accretion. Both lightning and collision models predict that the isotopic and elemental composition of chondrules should resemble the unaltered dust minus whatever volatile materials are lost during heating. Those dust particles which escaped reheating should retain their volatile components and presumably comprise the fine-grained, volatile-rich groundmass, or matrix, found in chondritic meteorites (*9*). Oxygen isotope ratios measured on separated chondrules and matrix are similar, an indication that both components ceased to exchange oxygen with the gas phase at about the same temperature. The temperatures inferred are rather low, 450° to 475°K, probably close to the temperature at which chondritic material accreted (*10*). Moreover, each family of chondritic meteorites has its own chemically distinct, characteristic type of chondrules and matrix, a finding that suggests a close genetic link between the two components. Both chondrules and matrix are depleted to the same degree in metallic elements, notably iron and nickel plus moderately volatile gallium and germanium. The simplest explanation is that a fraction of the metal grains was lost from the original condensate (= matrix) sometime after the condensation of gallium and germanium but before the conversion of dust into chondrules (*11*).

Several other clues support the collisional mechanism of chondrule formation over the lightning model. If chondrules were produced by lightning discharges, a correlation between mass and composition would be expected because the heat input depends on the surface area-mass ratio of the particles. Small chondrules would be heated to higher temperatures, and this would result in more efficient outgassing of certain elements, such as the alkali metals. But no correlation between mass and composition has been observed (*12*). In the collision model, where energy input depends upon both the mass and the relative velocity of the particles, a strict correlation is not expected. Moreover, it has been established for nearly a century that chondrules display numerous features indicative of impacts: fragmented chondrules, compound chondrules, fractures, veins, and crater-like indentations on their surfaces (*13*).

However, none of these features can unambiguously be interpreted as evidence that chondrules are produced by collisions; they merely imply that collisions were common. More definitive evidence would be a chondrule that froze in the process of formation or one that clearly displays evidence of a highly energetic impact between two low-temperature particles which led to a partial but not complete melting. It seems probable that at least a few such cases should be preserved if, as seems likely, grain size, velocity, and, hence, impact energies were variable. But, given the number of conditions that must be satisfied, such encounters may have been very rare and the evidence could easily have been erased if the meteorite had been subsequently metamorphosed, as most apparently were. This gives an unusual chondrule discovered in the Ngawi meteorite special significance. This chondrule clearly displays evidence of a highly energetic collision between two particles, each containing relicts of an earlier low-temperature history.

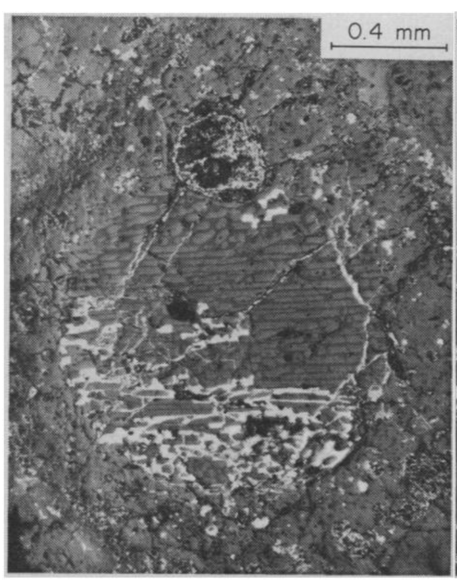
The fact that the chondrule is found in Ngawi is pertinent because this meteorite evidently escaped the thermal metamorphic event or events which altered most chondritic meteorites. Ngawi is classified as a petrologic type 3 chondrite, on a scale of 3 to 6; that is, it is one of the least metamorphosed chondrites known (*14*). Its minerals have large variations in composition; in fact, Ngawi is the most inhomogeneous member of the LL-chondrite family (*15*). Furthermore, the chondrule itself contains glass and unequilibrated minerals. We can therefore safely assume that the observed mineralogy and textures were developed prior to the incorporation of the chondrule into the meteorite; they could not be the result of some later high-temperature metamorphic event.

The chondrule was found in a polished thin section which could be studied in either transmitted or reflected light and chemically analyzed with an electron microprobe. It has a central core with a "barred" appearance (Figs. 1 and 2). This barred texture, in which aligned olivine [$(Mg,Fe)_2SiO_4$] grains are set in a sodium-rich glass, would not be especially noteworthy except that here a large portion of the material between the bars is troilite, FeS, not glass. Troilite is rarely found in chondrules; it is stable only below 680°K in a gas of cosmic composition (*16*) and presumably decomposes as sulfur is outgassed during chondrule formation. Its presence in this chondrule thus seems to imply that the temperature of formation was somewhat less than normal (*17*). The barred core of the chondrule is rimmed by a layer of fragmented olivine grains. These grains display a mildly distorted optical continuity with the bars suggesting that they have been reoriented as fragments. A relatively large (0.3 mm in diameter) magnetite grain is embedded near the top of the chondrule as it is oriented in the photographs. Magnetite is also considered a low-temperature mineral in primitive meteorites, becoming stable only below 400°K in a gas of cosmic composition (*16*). A pronounced bulge over the magnetite grain gives the chondrule a pear-shaped outline (Fig. 2).

The olivine in the chondrule obviously is unequilibrated. Each bar is zoned; the centers of most bars have a fayalite (Fe_2SiO_4) content of about 1.6 mole percent and the edges about 2.6 percent. In a few cases, where the olivine bars are surrounded by troilite, the fayalite content rises to about 5 percent near the center and 6 percent near the borders. The olivine in the rim is more inhomogeneous and generally has a higher fayalite content than that in the bars (2.6 to 21.7 percent, median 7.2 percent).

There are numerous troilite veins throughout the barred core of the chondrule, all of which appear to emanate from the main mass of troilite and extend upward toward the magnetite grain. Across these veins, some of the bars appear to be displaced a few micrometers. Some veins extend out into the rim of the chondrule, but none extend into the surrounding matrix. This implies that the troilite in the veins originated inside the chondrule, not outside in the matrix. The troilite is stoichiometric FeS [< 0.05 percent (by weight) copper, nickel, or cobalt]. A moderate amount of metal (γ-FeNi) and small grains of iron-nickel sulfides, pentlandite and mackinawite, are present in the massive troilite.

That portion of the barred chondrule immediately beneath the magnetite grain is of special interest. The proportion of glass is greater there than anywhere else. The olivine bars appear to be reoriented, and all are distinctly more rounded than usual. Those bars in contact with the bottom of the magnetite grain have been reoriented to conform to its outline. These observations clearly indicate that the energy released when the chondrule and magnetite grain collided was sufficient to partially melt the material immediately beneath the point of impact. Evidently it was also sufficient to fracture the chondrule and mobilize sulfide which then flowed into the cracks. The chondrule thus appears to have had a two-stage history: (i) formation of the barred and rimmed chondrule followed by (ii) a highly



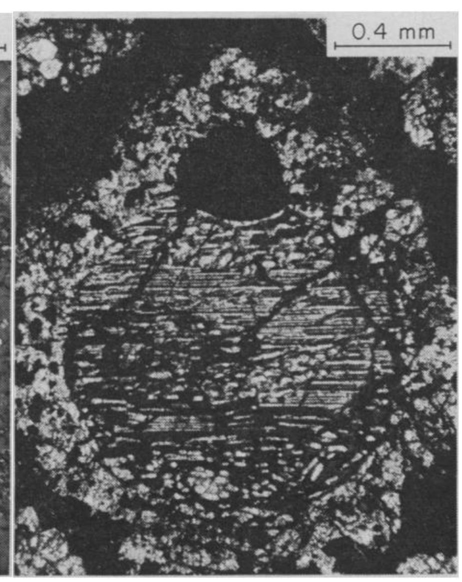


Fig. 1 (left). The barred chondrule from the Ngawi meteorite contains a large (0.03 cm in diameter) magnetite grain embedded in it (shown near the top of the photograph). Note that the outer rim of the chondrule extends to the edges of the photograph. In reflected light, the troilite (FeS) in the veins and the lower third of the chondrule as well as the magnetite appear white, whereas the olivine bars are gray and the glass is dark gray to black. (The black region in the magnetite grain is simply a hole in the slide.) Immediately beneath the magnetite grain, the olivine bars appear rounded and slightly reoriented and the proportion of glass is distinctly greater than elsewhere in the chondrule. Across the veins and cracks, some olivine bars have been displaced a few micrometers. Fig. 2 (right). As viewed in transmitted light, the overall appearance of the chondrule is pear-shaped, owing to a pronounced bulge over the magnetite grain. Except for the olivine in this bulge, the bars and the remainder of the rim are optically continuous. This suggests that, as the grain tunneled through the rim, it pushed aside and reoriented the olivine grains. The olvine bars immediately beneath the grain have been bent to conform to its shape.

energetic collision with the magnetite grain.

All evidence of the mechanism by which the barred chondrule formed has been erased, but the presence of troilite points to one of the secondary processes in which the original condensate is flash heated. The presence of troilite implies that the material comprising the chondrule, that is, the preexisting dust grains, had cooled to at least 680°K before being reheated and melted. The flash-heating event must therefore have raised the temperature from less than 680°K to greater than 1700°K, sufficient to completely melt the silicates. The molten droplet must have then cooled rapidly through the freezing points of the silicates and sulfides (1700° to 1400°K), giving rise to the barred and rimmed texture. Rapid cooling is, of course, expected if the temperature of the surrounding gas and dust was less than 680°K. After this texture was frozen in, the chondrule collided with the magnetite grain.

That both chondrule and grain survived the impact can perhaps be attributed to the cushioning effect of the outer rim. The pronounced bulge over the grain consists of an aggregate of olivine grains which display little or no optical continuity with the remainder of the rim and bars. This suggests that in the immediate vicinity of the impact the rim material was crushed into an aggregate of fine-grained material and pushed aside as the grain burrowed in from the perimeter to its present position.

The relative velocity of the two particles at the time of collision can be obtained from the relation:

$$v = (2C \times \Delta T \, M_2/M_1)^{1/2}$$

where v is the velocity, C is the heat capacity, ΔT is the temperature increase, M_1 is the mass of the magnetite, and M_2 is the mass of the chondrule. The heat capacity is about 10^7 ergs per gram per degree Kelvin. The ratio of the masses, as calculated from their dimensions and known densities, is about 50. This estimate is subject to a modest error since the orientation of the section through the particles is not known. However, ΔT is subject to an even larger error. The temperature increase may have been in excess of 1000°K, the difference between the melting point of glass and sulfide (1400°K) and the temperature at which magnetite becomes stable (400°K), or it may have been only a few tens of degrees if the collision occurred shortly after the glass and sulfide crystallized. With this uncertainty, the calculations yield a possible velocity range of between 10^5 and 10^6 cm/sec.

Interestingly, velocities of this magnitude have been predicted to occur in the nebula under two possible circumstances. Whipple (*7*) has pointed out that such velocities can be achieved in the flow of gas and dust around accreting bodies since the planetesimals will be moving in substantially different orbits relative to the nebular dust. According to Cameron's (*8*) model, particles are predicted to collide with velocities equal to or greater than 10^5 cm/sec in the region between two convection cells where the material is moving in opposite directions. Both Whipple and Cameron point out that collisions at these velocities should commonly lead to complete melting and partial vaporization. They were thus independently led to propose a collisional mechanism for chondrule formation.

Of course, had such velocities been the norm, there would have been no accretion because these impact velocities exceed the escape velocities of even the largest asteroids and, when this occurs, more mass is eroded than accreted. But in both Whipple's and Cameron's models, this problem is easily circumvented. Whipple notes that those particles which leak through the gaseous flow lines around a growing body arrive at the surface with substantially lower velocities. Cameron proposes that accretion takes place in the center of convection cells where velocities are much lower, not at the edges where chondrules are produced. In this context, Wasson (*18*), who also suggests that chondrules are produced by grain collisions, points out that chondrule production by impact on the surfaces of protoplanets is an unlikely process for just this reason, namely, because the impact velocities required to melt silicates are so great relative to the escape velocities that chondrules thus produced would be ejected rather than accreted.

It would, of course, be a fallacy to generalize that all chondrules are produced by an impact process on the basis of a single observation. But it is possible that additional evidence exists which has been overlooked or not considered in this framework. The important conclusion to be drawn from this preserved impact is that grains did achieve high relative velocities in the nebula, high enough to melt silicates, metal, and sulfides.

David E. Lange*
John W. Larimer

Center for Meteorite Studies,
Arizona State University,
Tempe 85281

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17. It has been suggested that owing to extensive supersaturation of iron vapor, FeS may form a metastable condensate at considerably higher temperatures (> 1000°K) (*3*). However, this possibility can be ruled out here because such extensive supersaturation should also lead to much higher iron contents in the coexisting silicates than have been observed. The extent to which the iron vapor must be supersaturated in order to form metastable FeS is (*3*):

$$\log S_{\mathrm{Fe}} = \log S_{\mathrm{FeS}} + 4.43\,[1 - (680/T)]$$

where T is the temperature (in degrees Kelvin) and S is the supersaturation factor. This factor is equivalent to the partial pressure of the species in the gas relative to the equilibrium vapor pressure of the species at the specified temperature. The right side of this equation is predicted to have a value of about 2.5 to 3.0 when $T = 1100°$ to 1400°K (*3*). Thus S_{Fe} must have a value of 500 to 1000. According to the theory outlined by Blander and his co-workers [see (*3*)], the activity of FeO in the silicate liquid would thus be 500 to 1000 times greater than the predicted equilibrium value, ~0.001, or 0.5 to 1.0. However, the observed mole fraction of FeO in the silicates is only 0.01 to 0.05, lower by about a factor of 10 to 100 than what the supersaturation theory predicts.
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19. We thank the staff of the British Museum of Natural History for providing us with the sample. This work was supported in part by NSF grant 32297 and NASA grant NGL 03-001-001.
* Present address: Institute of Meteoritics, University of New Mexico, Albuquerque 87131.

13 April 1973; revised 28 August 1973