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A CHONDRULE IN THE CHAINPUR METEORITE

by

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Abstract: The occurrence of glass as a major constituent in a chondrule from the Chainpur meteorite provides further evidence that the chondrules formed by rapid cooling of liquid droplets. The distribution of nickel and iron between metal and silicates shows that iron was present when the chondrules solidified, and that the metal formed by reduction in the molten stage, thus extracting virtually all nickel.

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The origin of chondrules has long been one of the most intriguing problems in the study of meteorites. Many diverse hypotheses were advanced to explain these strange spherical objects before the examination of thin sections under the microscope placed severe limitations on possible modes of formation. Early investigators of chondrites recognized their similarity to volcanic rocks and concluded that their internal structure indicated that the chondrules had been quenched from high temperatures. This point of view was very clearly stated by Sorby in 1877 who summarized his conclusions by stating that "the conditions under which meteorites were formed must have been such that the temperature was high enough to fuse stony masses into glass; the particles could exist independently one of the other in an incandescent atmosphere, subject to violent mechanical disturbances; that the force of gravitation was great enough to collect these fine particles together into solid masses, and that these were in such a situation that they could be metamorphosed, further broken up into fragments, and again collected together." At a time when sophisticated techniques have allowed the study of many of the more esoteric properties of meteorites it is perhaps instructive to review Sorby's conclusions, the validity of which remain unchanged.

Alternatives to the 'liquid droplet' hypothesis have been proposed by several authors. The formation of chondrules by metamorphic recrystallization of solid matter has been advocated by Levin (1958) and by Mason (1960). The chondrule which is described here displays several features which cannot be explained by metamorphic recrystallization. Rather it provides unusually clear evidence of having formed by quenching of a partly, or more likely, a wholly liquid droplet.

The Chainpur meteorite fell as a shower of stones on May 9, 1907 by the village of Chainpur (latitude 21°51'N, Longitude 83°29'E) in India. The meteorite was described by Cotter (1912) and, in greater detail, by Keil, et al, (1964) who demonstrated the unusual variability in composition of olivine and pyroxene in the chondrules. Keil, et al, concluded that individual silicate grains within single chondrules are not in equilibrium as a consequence either of rapid crystallization or of crystallization at temperatures too low to allow diffusion to eliminate the compositional variations.

Thin sections of the Chainpur meteorite show sharply delineated chondrules of widely varying internal structure, mostly 1-2 mm. in diameter (Figure 1). Figure 2 is a photomicrograph of the chondrule which has been studied in some detail. It is circular in section except where metal and sulphide grains straddle the chondrule-matrix border. A protrusion of the matrix into the chondrule can be seen in the bottom right hand corner of Figure 2. This indentation was apparently produced before the chondrule had completely solidified as the olivine crystallites in the chondrule are aligned parallel to the indented margin. Either the matrix material intruded the still plastic chondrule or, perhaps more likely, this indentation formed by shrinkage on cooling.

Within the chondrule crystals of olivine and pyroxene are set in a clear colorless glass. The major crystalline phase is a forsteritic olivine which forms elongate crystals, some in parallel growth patterns, with well developed crystal faces. No evidance could be seen of any reaction between the olivine and the glass (Table 1). In the plane of the thin section some olivine crystals completely enclose small areas of glass. Olivine is more abundant at the outer margins of the chondrule, which the elongate crystals tend to parallel. Pyroxene is prominent in the core of the chondrule where it forms elongate, parallel, feathery crystallites (Figure 3).. Some of the crystallites are made up of numerous small distinctively shaped crystalline units with a common orientation but separated by areas of clear glass. The glass itself is colorless, isotropic and homogenous. Metal occurs as thin seams within some of the larger olivines, Figure 5, and as a few globules in the glass, Figure 6.

Phase compositions determined with an ARL electron probe microanalyzer are shown in Tables 1 and 2. The distribution of selected elements among the major phases are shown in Figures 4, 5, and 6. In analyzing the pryoxene it was found that their skeletal habit made it impossible to avoid overlapping the microprobe beam into the adjacent glass. For this reason only minimum values of calcium and magnesium could be obtained. Figure 4 shows that the pyroxene contains less iron than the olivine or the glass. The variation in calcium and magnesium content across the pyroxene crystallites is illustrated in Figure 7 where the peak values attained correspond to 6 weight percent for calcium and 10 weight percent for magnesium. These values correspond to a very low iron pigeonite with a calcium content higher than most of the pyroxene in Chainpur, (Keil et al, 1964). Boyd and Schairer (1964) have shown that homogeneous pyroxenes with compositions midway between enstatite and diopside can be formed by quenching but that they are metastable even at elevated temperatures and unmix to yield two pyroxenes of contrasting magnesium to calcium ratios on prolonged heating or on slow cooling. The unusual composition of the pyroxene crystallites can only be explained by rapid cooling from high temperatures, an interpretation fully in accord with the skeletal habit of the crystallites.

Rapid cooling has also allowed the preservation of forsteritic olivine in intimate contact with a silica rich glass. Glass is a rare constituent of all but the youngest terrestrial rocks. Glass in meteorites is of particular interest as most meteorites appear to have formed early in the history of the solar system. True glass is not common in meteorites but the textures of many fine-grained aggregates in chondrules, in barred chondrules for example, suggest that they have formed by the devitrification of glass. The glass in Chainpur has not devitrified because the meteorite has not been subjected to any significant thermal metamorphic effects and because of the composition of the glass.

The first column in Table 1 represents the composition of the glass as analyzed with an ARL electron probe microanalyzer. Sodium is not included. Sodium in the glass presents a special problem as the sodium content of the small volume excited by the electron beam decreases to about 25 percent of its original value in 20 seconds. The first analysis in Table 1 is thus an analysis of the glass after it has lost most the original sodium. The true soda content of the glass is approximately 8 percent. Escape of sodium from the glass, and the low counting rates make this figure less reliable than the other data presented. Examination of data obtained under a variety of instrumental conditions does, however, indicate that this value is substantially correct. The second column in Table 1 shows the glass composition, recalculated to 100 percent, for a value of Na_2O=8 weight percent.

The glass composition represents an arrested stage in the continuum of compositions embraced by the liquid portion of the chondrule as crystallization progressed. If this particular chondrule is not atypical in bulk composition then the glass composition can indicate one direction in which differentiation of chondritic material can proceed if governed by crystal-liquid fractionation. Segregation of a liquid fraction with the composition of the Chainpur glass, Table 1, could probably only be achieved by a rapid, catastrophic process. Recalculation of the glass analysis in terms of normative minerals, Table 3 shows 68 percent albite and 1 percent quartz. The glass in this respect resembles the glass-like material in barred olivine chondrules.

The presence of glass in Chainpur, the association of forsterite with silica-rich glass, the composition of the pyroxene and the skeletal habit of the crystallites all argue strongly that the chondrule formed from a 'liquid droplet'. Recrystallization by thermal metamorphism in the solid state cannot account for the occurrence of glass nor the lack of equilibrium in this high temperature assemblage. This paper discusses one chondrule from the Chainpur meteorite but Chainpur contains a great diversity of chondrule types. The few occurrences of glass studied to date are all in the more reduced chondrules i.e. those in which there is little iron in the silicates. The silicates in the glassy chondrule are low in iron and also in manganese, some of which is present in the sulphides. The varying texture and phase compositions of the different chondrules may reflect slight variations in redox conditions, composition, cooling rate and solidification temperature, all of which are intimately related.

The manganese content of the olivine is related to the iron to magnesium ratio. As shown by Keil and Fredriksson (1963), manganese appears in the sulphide phase under strongly reducing conditions. The distribution of nickel is quite different from that of manganese. Olivines of widely varying iron content in Chainpur all contain little or no nickel, Table 2. Apparently nickel was effectively removed as immiscible liquid metal, Table 2 and Fig. 6, formed by reduction before crystallization of the silicates. The final distribution of nickel and iron is undoubtedly influenced by this early segregation of some of the iron and virtually all of the nickel. Experimental studies presently in progress together with textural studies of chondrites (e.g. see Figure 8) suggest that iron, nickel and sulphur may be redistributed in a chondrite at temperatures well below the crystallization temperature of the silicates. The distribution of iron, nickel and sulphur in chondrites may be controlled by both a high temperature fractionation of contrasting phases and a low temperature redistribution in the solid.

The contrast in nickel content between the chondrule silicates and the matrix surrounding the chondrules is shown in Figure 5. Figure 9 shows that a similar pattern exists in the carbonaceous chondrite Murray. The nickel distribution cannot be explained by an in situ transformation of either matrix into chondrules by solid-state recrystallization (Mason, 1960) or chondrules into matrix by weathering (DuFresne and Anders, 1962). The contrast in composition between matrix and chondrules in these meteorites implies that they are mechanical mixtures of materials formed under different conditions (Fredriksson and Keil, 1964).

On the subject of meteoritic chondrules Merrill in 1929 wrote - "such interesting and peculiar forms are now known to be due to the cooling and partial crystallization of molten drops of stony matter; - - - their origin has been made the subject of much discussion and wordy warfare among students, but the matter need not be gone into further here." Concurrence with Merrill's conclusions and with the fact that iron was present when the chondrules solidified allows advance to the even greater problem of the conditions under which these liquid droplets may form.

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