

FORMATION OF CHONDRITES BY REACTION OF DUSTY ICES WITH SOLAR NEBULA GAS.

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Introduction:

Chondritic meteorites contain components that are in extreme thermodynamic disequilibrium. Individual chondrules from a single meteorite formed at high temperatures, show a large spread in chemical composition, oxygen fugacity and oxygen isotopes. Matrix is compositionally very different from chondrules and contains exotic material that cannot survive high temperatures. Each of these components must have formed under very different conditions.

This variability on a sub mm scale is contrasted by a surprisingly uniform chemical composition on a cm scale even in the most unequilibrated chondrites. This suggests that now coexisting heterogeneous chondrule populations (on scales of cm³) and surrounding matrix formed from the same chemical reservoir. Chondrules of a given population, however, cannot have formed by rapid cooling from a single reservoir since they show large variations in oxygen fugacity (fa contents) and $\Delta^{17}\text{O}$.

The texturally most primitive meteorites are those that show the strongest compositional and isotopic variations. The expression *primitive* is meant to indicate that primitive meteorites are only slightly or not at all affected by parent body processes, primarily heating and intrusion of and reaction with water, which would affect mineralogy, petrology and texture. In another use of the word *primitive*, meteorites with the most solar-like composition are designated as the most primitive meteorites, irrespective of their texture and mineralogy. The two different meanings of “primitive” have led to considerable confusion among petrologists and geochemists.

Here we attempt to combine the microscopic and macroscopic properties of chondritic meteorites in a single formation model.

The lack of geochemical fractionation in chondrules:

The extremely variable chemistry among chondrules and of matrix is not the result of geochemical fractionation processes. The Mg/Si ratios of chondrules do not follow igneous trends. Very SiO₂-rich chondrules and aggregates that are found in all chondritic meteorites are not the result of fractional crystallization within larger parent asteroids [2].

Two large pyroxene chondrules of Allende have uniform enrichment of refractory lithophile elements, i.e. no fractionation between Sc and La). It is obvious

that pyroxene did not affect the RL trace element pattern although opx/melt partitioning coefficients are very different for Sc and La (Fig. 1).

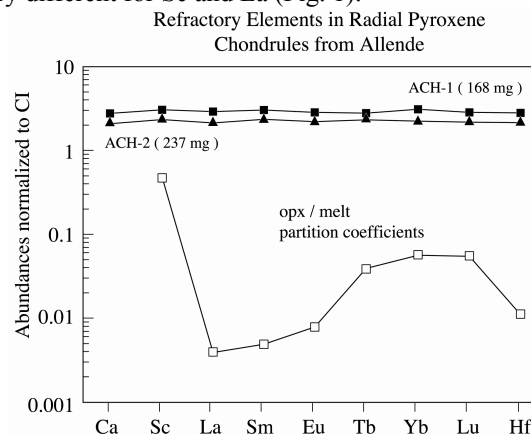


Fig. 1: Large pyroxene chondrules of Allende do not have the typical pyroxene pattern of trace elements; suggesting that they did not crystallize from a melt.

Such pyroxene chondrules and aggregates occur in all chondritic meteorites and they have in almost all cases unfractionated patterns of refractory-lithophile elements, indicating a similar origin [3]. Thus the chemical variability of chondrules requires condensation and/or evaporation. Modification of condensation by removal of early condensates and other kinetic processes can produce a wide range of compositions, particularly when liquid condensation is invoked [3].

Complementary chemical composition of matrix and chondrules in carbonaceous chondrites:

Most carbonaceous chondrites contain a non-trivial fraction of matrix, such that these meteorites can be essentially viewed as a mixture of chondrules and matrix. In Allende and other carbonaceous chondrites, chondrules and matrix have complementary chemical compositions. Renazzo has Mg-rich chondrules and SiO₂-rich matrix. Only a combination of both yields a bulk Mg/Si ratio that is chondritic (solar) [4]. Allende has higher than chondritic Ca/Al in matrix and a lower ratio in chondrules. Y-86751, a CV3-chondrite identical to Allende but that from the Yamato mountains has a high Al-matrix with low Al chondrules. Early condensed spinel grains are included in chondrules in Allende, but occur as tiny grains in Y-86751 matrix [5]. Similar fractionations were found in Renazzo, with

high Ti/Al in chondrules and low Ti/Al in matrix, but with a chondritic ratio of the bulk meteorite [6].

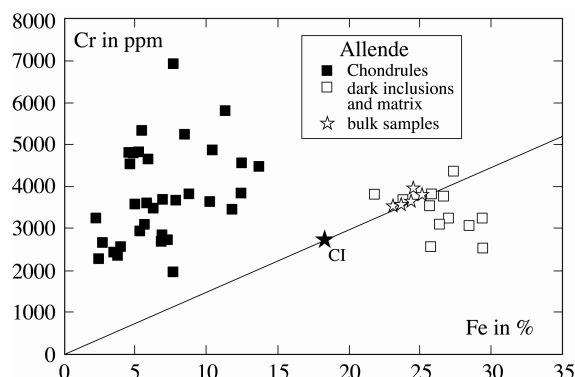


Fig. 2: High Cr and low Fe in Allende chondrules and low Cr and high Fe in matrix. A combination of both yields the chondritic ratio of the bulk [1].

Fig. 2 demonstrates the complementary relationship of Cr and Fe between matrix and chondrules in Allende [1].

Thus chondrules and matrix must have formed from a single reservoir. Rapid condensation may have produced a variety of minerals and mineral assemblages that were converted to chondrules. Alternatively condensation to liquids may have occurred. The complementary relationship excludes an origin of matrix by fragmentation of chondrules and an origin of chondrules by compaction and melting of matrix. Redistribution of elements such as Ti or Al within the parent body is excluded by too low temperature.

Limitations of the closed system model:

A number observations are not compatible with the closed system model: The large variations in non-mass dependent oxygen isotopes of chondrules [7], the presence of distinct nucleosynthetic isotope anomalies of some heavy elements and the presence of presolar grains that would not survive high temperatures require an open system for oxygen, low temperature components and isotopically exotic grains.

Model:

Chondritic meteorites are assumed to contain a once gaseous, isotopically equilibrated high temperature component and an icy low temperature component. Ices are loaded with dust grains from the outer solar system. When the inward drifting dusty ice grains hit the high temperature area temperature decreases and condensation starts. It is further assumed that the high T component is ^{16}O rich and the ices are rich in ^{16}O -poor H_2O . In its simplest form, the model is capable of explaining important properties of chondritic meteorites:

- 1.) The dust grains trapped in ice account for a certain fraction of the low temperature component of chondritic meteorites. This component may represent unaltered ISM and contains presolar grains such as SiC or some rare gas components that would not survive the high temperature environment where condensation occurs. The mass contribution of this material to the matrix of chondrites is unclear, but cannot be much higher than a few wt.%. Otherwise addition of this component would have affected the complementary relationship between chondrules and matrix.
- 2.) Each chondrite group represents a separate reservoir. The onset of condensation is determined by the arrival of the icy grain component. The decrease in temperature depends among other things on the size of ice grains and is independent of the global cooling of the nebula. The amount of ice grains and the extent of the reaction with the hot gas will determine the oxygen fugacity and the oxygen isotopes of the whole system.
- 3.) Large variations in C/O during condensation [8] maybe related to high-T evaporation of C-rich residua that were delivered with the ices.
- 4.) Oxygen isotopes of a chondrite are mixtures of the icy ^{16}O low-T material and the gaseous ^{16}O -rich component. Vaporizing ices produce an oxidizing atmosphere. This explains the increase in ^{17}O and ^{18}O with increasing degree of oxidation, observed in chondritic meteorites and their components: Forsteritic olivines present in all groups of chondrites condensed from an approximately canonical solar nebula. Later formed olivines are more oxidized and lower in ^{17}O [9]. The process may be chaotic and lead to heterogeneous distribution of oxygen isotopes in condensed mineral phases, depending on the fraction of gaseous oxygen from vaporized ices.
- 5.) The icy dust grains contain isotopically unequilibrated material, such as r- and s-process Os [10], and Zr [11]. The fraction of the total Os that is concentrated in dusty grains is unknown [12].

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