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## CI CHONDRITES: COMPARISON AND CONTRAST TO OTHER METEORITE TYPES

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*The minerals of chondritic meteorites, particularly C2 and C3 are usually believed to be condensates of the (previously unfractionated) solar nebula. This implies two postulates: (1) that chemical reactions between phases ceased at various temperatures; (2) that Ni and Fe were mobilized by diffusion in the solid state. An alternate explanation is proposed, which obviates the two postulates: chondritic minerals may have condensed, in equilibrium with their own vapors, from a fraction already separated from the solar nebula at low temperature and low pressure.*

The minerals comprising chondritic meteorites reflect, in general, three broad, but distinct, degrees of oxidation, as characterized for example, by the mineral chemistry of sulfur compounds (Table I).

TABLE I  
MAJOR METEORITIC MINERALS

CI Chondrites	Ordinary Chondrites (including C2 and C3 Chondrites)	Enstatite Chondrites
Epsomite $MgSO_4 \cdot 7H_2O$	Troilite FeS	Complex mixed sulfides (e.g., (Ca, Mg, Fe, Mn) S)
Complex hydrous layer-lattice silicates e.g., $(Mg, Fe)_6$ $Si_4O_{10}(OH)_8$	Olivine $(Fe, Mg)_2 SiO_4$ Pyroxene $(Fe, Mg) SiO_3$	Pyroxene $MgSiO_3$
Magnetite $Fe_3O_4$	Metal (Fe-Ni alloy)	Metal (Fe-Ni-Si alloy)

The minerals of the CI chondrites attest to the inevitable consequence of chemical reactions occurring in solar matter at low temperatures and low pressures: virtually everything is oxidized, including sulfur. This is what is to be thermodynamically expected from this medium which has an O/Fe ratio of ~26. By contrast, the minerals of the enstatite chondrites are too highly reduced to have formed from unfractionated solar matter, except possibly at high pressures (Herndon and

Suess 1976). The minerals of the ordinary chondrites, however, contain iron in three different chemical states--as metal, sulfide and oxide. For iron to exist in three chemical states *in equilibrium* requires iron to be greater in molar abundance than the total available oxygen and sulfur. In other words, the minerals comprising the ordinary chondrites seem to have formed from a reservoir limited in oxygen, and perhaps also sulfur, relative to solar matter.

Consider minerals of ordinary chondritic chemical compositions in equilibrium with solar nebula gases. By specifying the compositions of both the condensate and the vapor and assuming a pressure, the system becomes thermodynamically *invariant* at a single temperature. Because oxygen and sulfur tend to be incorporated in the gas phase by chemical reactions, primarily with hydrogen, there is at most only a single temperature corresponding to the oxygen and sulfur activities appropriate for the minerals of the ordinary chondrites. The only way to preserve the state of oxidation of the condensed phase is to separate it from the nebula gases. The temperature and pressure at which gas-condensate separation occurs thus determines the bulk state of oxidation of the condensate--meteorite or planet.

In recent years, many attempts have been made to explain the minerals of chondritic meteorites, particularly C2 and C3 chondrites, as being condensates from the solar nebula [for references, see Grossman and Larimer (1974)]. However, to explain the minerals of ordinary chondritic meteorites (Table I) as condensates from *solar* matter requires, in general, the following postulates: (1) that chemical reactions between gas and mineral condensates ceased at various temperatures, assuming a low pressure; and (2) that Ni and Fe were mobilized by diffusion in the solid state at low temperatures, rather than by exchange with a gas phase at elevated temperatures. These postulates are necessitated by the relatively high elemental abundances of oxygen and hydrogen in solar matter. If however, as an alternative, one considers the possibility that the ordinary chondritic minerals condensed from matter which first had been separated from the nebula gases at a low temperature and low pressure, the necessity to make the above postulates is obviated and such minerals can condense in equilibrium with their own vapors (Herndon and Suess 1977). But once the primary condensate is separated from the nebula gases and its temperature and pressure changed, it is impossible from thermodynamics alone to make any unique statement about its former condensation, except to specify the approximate bulk composition of the condensate, assuming no additional mass transport across the system boundary.

There is yet considerable uncertainty as to the mechanism by which condensed matter was separated from the nebula gases. If, however, the great majority of chondritic meteorites formed after gas-condensate separation, as the chemical evidence indicates, then this important cosmochemical process must have occurred at a very early time during the formation of the solar system.

A more extensive paper on this subject matter will appear in the Proceedings of the National Academy of Sciences (USA).

#### ACKNOWLEDGEMENTS

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#### REFERENCES

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#### DISCUSSION

**GROSSMAN:** *In the light of the abundance of sulphate in C2's, why do you classify them with the ordinary chondrites?*

## CARBONACEOUS CHONDRITES

HERNDON: There are many reasons why the C-2 chondrites are similar to ordinary chondrites and distinct from C1 or enstatite chondrites. The classification based on sulfur chemistry is a convenient, but not necessarily unique criterion. You could devise others, with the same result.

GROSSMAN: Have you done full equilibrium calculations? Your condensation temperatures cannot be accurate for those specific mineral phases requiring elements which have already condensed.

HERNDON: No, I have not, but the results are sufficiently general so as not to be very inaccurate. It's not our point in determining specific condensation temperatures. What we are showing is that the condensation temperatures in the literature are based on arbitrary assumptions (for example, the bulk chemical composition of the gas phase).

GROSSMAN: You quite correctly point out that the Ca-Al silicates and oxides will condense well above their melting points in the H-depleted case if your condensation temperatures are correct. Won't the Mg-silicates condense in solution in this liquid phase, preventing the observed separation of Ca and Al from Mg and Si in carbonaceous chondrites?

HERNDON: There is a great variety of chondrule textures, particularly the porphoritic variety, observed in the ordinary chondrites. Again, our results are sufficiently general as to embrace a considerable number of possibilities that might result from variations in surface tension, supercooling, etc.

ANDERS: Your scheme creates more problems than it solves:

1. C2 chondrites contain olivine chondrules of highly variable composition, from less than 1 to more than 50 mol. percent  $Fe^{++}$ . Since you want to control the  $Fe^{++}$  content by the  $H_2/H_2O$  ratio, you thus need a continuum of gas compositions, from solar to 1000 fold depleted in  $H_2$ . And since you make chondrules after the primary condensation from a hydrogen-poor nebula, you'll have to put the hydrogen back again.

2. In your condensation sequence, silicates condense before metal, yet chondrules often contain metal inclusions, which must have condensed first.

3. It is not at all clear that your scheme can account for the hundreds of facts which are explained by the conventional model (equilibrium condensation of a solar gas, modified by kinetic factors at the low-temperature end).

HERNDON: (1) In your 1964 review paper you refer to the problem of the unequilibrated meteorites as being the "touchstone" of any theory. I'm confident that, when this problem is understood, a logical causally-related solution will appear.

(2) John Wood discussed the potential variability that is implied here.

(3) I attempted to emphasize that our approach preserves most of the very good parts of "the conventional model," while eliminating the trouble spots.

SMOLUCHOWSKI: Many models of the giant planets especially of Jupiter would be much more satisfactory if some mechanism of lowering the hydrogen concentration could be found. Clearly the problem of the suitable sequence of events occurring during the formation of solids in the solar nebula is crucial. What mechanism of depletion of  $H_2$  do you propose and when should it operate?

HERNDON: I don't yet understand solar system physics sufficiently well to propose a mechanism for hydrogen loss, although I suspect that it might be related in some way to the sun coming to thermonuclear equilibrium. In any event, if the chemical evidence is to be believed, then gas-condensate separation must have occurred at a very early time, pre-dating the formation of ordinary chondrites.