Re-evaporation of condensed matter during the formation of the solar system

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From the properties of matter the conclusion is derived that the mineral assemblage characteristic of most chondritic meteorites is not at all what is expected to form directly from solar matter. Rather, the major minerals of the ordinary chondrites have chemical compositions indicative of formation from a medium greatly depleted in hydrogen and somewhat deficient in oxygen relative to solar elemental abundance ratios. The re-evaporation of condensed material, after separation from a large fraction of the gaseous components of solar matter, will lead to a medium of the appropriate composition. Such re-evaporation must have occurred at a time prior to the formation of many primitive meteorites.

The primordial matter from which the Sun, the planets, and other objects in the solar system formed had a well defined chemical composition (figure 1 *a*). This follows from astronomical observations, from the essentially constant isotropic compositions of meteoritic and terrestrial elements, and from the observation that the abundances of the elements in chondritic meteorites are related, although in a complex manner, to the nuclear properties of matter (Suess & Urey 1956; Suess & Zeh 1973; Urey 1972). With the exception of noble gases and light elements (H, C, O, N) which are volatile or form volatile compounds, solar elemental abundance ratios, derived from the spectral analysis of sunlight, are nearly identical to corresponding ratios obtained from the chemical analysis of chondritic meteorites (Holweger 1977). The mineral constituents of chondritic meteorites formed at a very early time in the history of the solar system, as evidenced by their content of decay products of extinct radioactivities (Reynolds 1960; Rowe & Kuroda 1965; Lee, Papanastassiou & Wasserburg 1976). Some have physical morphologies which appear to have been the result of their formation as individual grains in space (Ramdohr 1973). It is therefore understandable that attempts have been made to explain the minerals of chondritic meteorites as being the condensate of a gas of solar composition (Anders 1968, 1971; Arrhenius & Alfvén 1971; Blander & Abdel-Gawad 1969; Grossman 1972). From the properties of matter it will be shown, however, that:

(1) The mineral assemblage [(Mg, Fe)$_2$SiO$_4$, (Mg, Fe)SiO$_3$, FeS and Fe] that characterizes most chondritic meteorites can exist in equilibrium in solar matter only at a single, low temperature if at all.

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(2) Boundary conditions for condensation require the ambient gas to be depleted in hydrogen by a factor of *ca.* 10^3 relative to solar matter and also to be somewhat deficient in oxygen.

From noble gas measurements it is well established that the gaseous components of solar matter were quantitatively separated from members of the inner solar system; even from bodies as massive as the earth (Brown 1948; Suess 1949). The possibility should be considered that most chondritic minerals condensed from a gas phase formed by the re-evaporation of condensed material which previously had been separated from the gaseous components of solar matter.
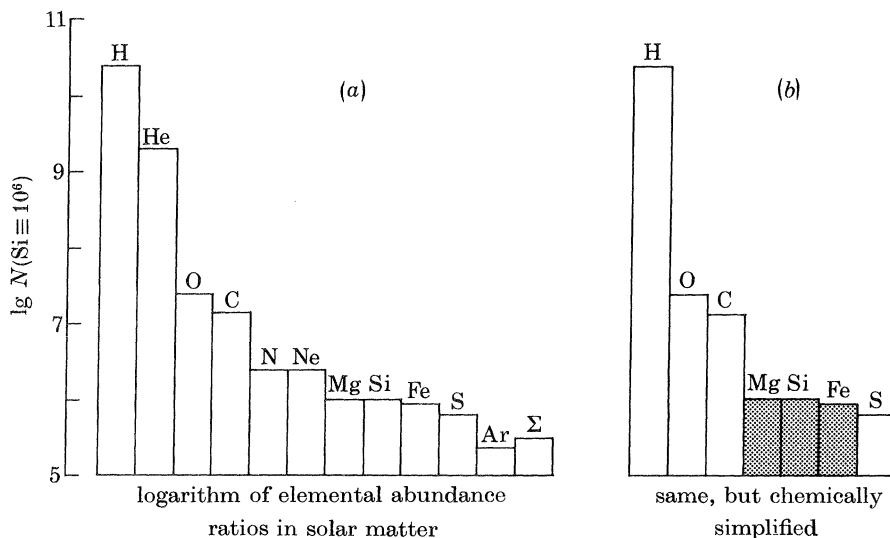

FIGURE 1. (*a*) Suess–Urey abundances of the elements in solar matter from a tabulation by Cameron (1968). All elements not specified are collected together and designated Σ. (*b*) The abundance of the chemically important elements obtained by eliminating unreactive elements (nitrogen and noble gases) and elements of low abundance. The elements indicated by dark shading in figure 1*b* are generally unreactive with hydrogen throughout the entire range of temperatures and pressures at which they can form solid compounds with oxygen and sulphur.

The relative abundance ratios of the elements that comprise solar matter are shown in figure 1*a*. For the chemical considerations which follow, this group of elements can be reduced to those shown in figure 1*b* by eliminating chemically unreactive elements (noble gases and nitrogen) and by eliminating elements with abundances so low that their exclusion cannot possibly alter the conclusions which will be derived. The matter that comprises chondritic meteorites can be divided into three distinct groups on the basis of the major chemical compounds of these three condensable elements. These groups, characterized by the mineral assemblages shown in table 1, represent three radically different states of oxidation. The highly oxidized C1 chondrites and the extremely reduced enstatite chondrites are rare,

together accounting for only about 1% of the total number of chondritic meteorites. The great majority of the approximately 1600 known chondrites consist principally of the mineral assemblage characteristic of ordinary chondrites (Keil 1962).

TABLE 1. MINERAL ASSEMBLAGES CHARACTERISTIC OF THE PRINCIPAL COMPONENTS OF THE CHONDRITIC METEORITES

C1 chondrites	*ordinary chondrites (including C2 C3 chondrites)*	*enstatite chondrites*
epsomite, $MgSO_4 \cdot 7H_2O$	troilite, FeS	complex mixed sulphides
complex hydrous layer-lattice silicates, e.g. $(Mg, Fe)_6Si_4O_{10}(O, OH)_8$	olivine, $(Fe, Mg)_2SiO_4$ pyroxene, $(Fe, Mg) SiO_3$	pyroxene $MgSiO_3$
magnetite, Fe_3O_4	metal (Fe–Ni alloy)	metal (Fe–Ni–Si alloy)

The equilibrium oxygen partial pressure as a function of temperature for an L6 ordinary chondrite, measured by Brett & Sato (1976), is shown in figure 2. Their results, represented by the solid portion of the curve designated L6, are extrapolated to lower temperatures. The oxygen partial pressure expected for solar matter, calculated from thermodynamic data for the reaction $H_2 + \frac{1}{2}O_2 \rightleftharpoons H_2O$, is also shown. The intersection of these two curves defines the single temperature at
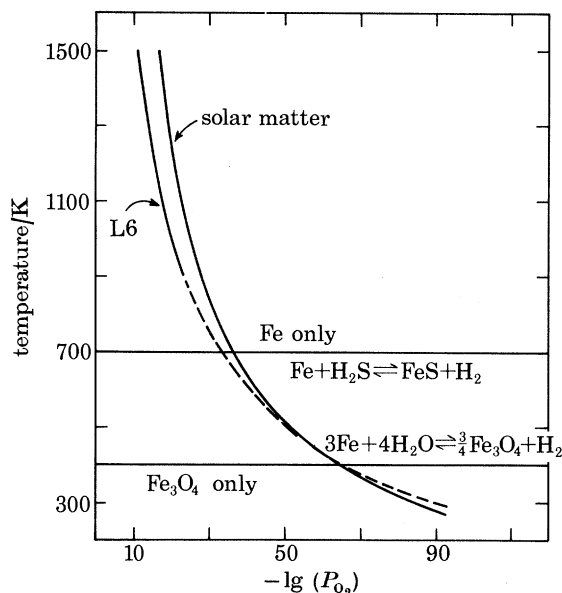

FIGURE 2. Oxygen partial pressure for an L6 ordinary chondrite measured by Brett & Sato (1976), extrapolation being indicated by the broken curve. The intersection of this curve with that calculated from thermodynamic data for solar matter describes the single temperature at which this mineral assemblage can exist in thermodynamic equilibrium in solar matter. For reference, temperatures defining other mineral equilibria stability boundaries from reactions (1) and (2) are also shown.

which this mineral assemblage can exist in equilibrium in a medium of solar composition. At elevated temperatures oxygen and sulphur are partitioned to a relatively greater extent into gas phase compounds containing hydrogen, thus leading to a more reduced condensed phase. At lower temperatures, a more highly oxidized condensate is expected. This concept is illustrated in a more general manner by the condensation–evaporation equilibria shown in table 2. These reactions are written with iron, magnesium and silicon in the form of their principal gas phase species in uncondensed solar matter. The chemical activities of these species are essentially proportional to their abundances; the elements involved being unreactive with hydrogen throughout the entire range of temperatures and pressures at which they can form solid compounds with oxygen and sulphur. The chemical activities of oxygen and sulphur, which result from reactions with hydrogen, are functions of temperature but are essentially independent of pressure. Consequently, a change in temperature is sufficient to change the oxidation state of the condensate. There is only a single temperature which can yield oxygen and sulphur activities appropriate for the mineral assemblage characteristic of ordinary chondrites.

TABLE 2. CONDENSATION–EVAPORATION REACTIONS FOR MINERALS CHARACTERISTIC OF ORDINARY CHONDRITES

	condensate	vapour
olivine	$Mg_2SiO_4(c)$	$\rightleftharpoons 2Mg(g) + SiO(g) + 3O(g)$
solid solution	$Fe_2SiO_4(c)$	$\rightleftharpoons 2Fe(g) + SiO(g) + 3O(g)$
pyroxene	$MgSiO_3(c)$	$\rightleftharpoons Mg(g) + SiO(g) + 2O(g)$
solid solution	$FeSiO_3(c)$	$\rightleftharpoons Fe(g) + SiO(g) + 2O(g)$
troilite	$FeS(c)$	$\rightleftharpoons Fe(g) + S(g)$
iron metal	$Fe(c)$	$\rightleftharpoons Fe(g)$

Many of the individual grains that comprise the meteorites grouped in table 1 as ordinary chondrites have physical morphologies which appear to have resulted from formation in space. Certain chondrules, for example, bear the unmistakable signs of once having been molten droplets that obtained their nearly spherical shapes from the surface tension of the melt (Kurat 1967; Nelson, Blander, Skaggs & Keil 1972). At the temperatures at which the major minerals of ordinary chondrites are molten ($t > 1300\,°K$), chemical reactions between milimeter-sized droplets and the ambient vapour progress rapidly and equilibrium is approached. The equilibria represented by the reactions

$$Fe + H_2S \rightleftharpoons FeS + H_2, \tag{1}$$

$$3Fe + 4H_2O \rightleftharpoons \tfrac{3}{4}Fe_3O_4 + 4H_2 \tag{2}$$
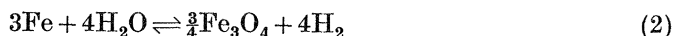
impose boundary conditions on the composition of the ambient vapour. In solar matter these reactions have pressure independent equilibrium temperatures of 700 and 400 °K, respectively (figure 2). Such low equilibrium temperatures are the

result of large $H_2:H_2S$ and $H_2:H_2O$ ratios. Smaller ratios lead to higher equilibrium temperatures, as shown in figure 3. The upper curve in this figure represents a boundary in those coordinates above which iron sulphide is subject to complete reduction by hydrogen. From this curve it is concluded that at the time iron sulphide bearing chondrules were molten droplets, the ratio of $H_2:H_2S$ in the ambient vapour was 100–1000 times smaller than that of solar matter. The lower curve represents a boundary below which iron metal (if not also iron sulphide) is subject to complete oxidation, provided sufficient oxygen is available. From this curve it is concluded that at the time iron metal bearing chondrules were molten droplets, the abundance ratio of oxygen in the ambient vapour to iron in the condensate was < 1, instead of > 20. In solar matter oxygen is about eight times more abundant than
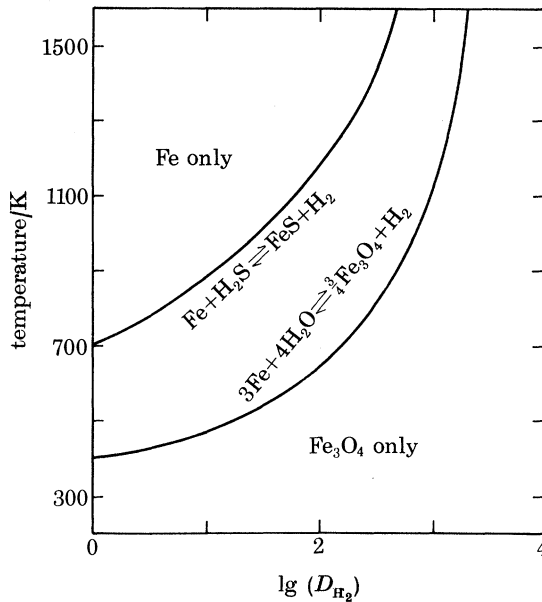

FIGURE 3. Equilibrium temperature for the indicated reactions as a function of hydrogen depletion relative to solar matter, calculated from thermodynamic data. For unfractionated solar matter the hydrogen depletion factor $D_{H_2} \equiv 1$.

the three elements indicated by dark shading in figure 1 b. The condensate of such a medium should bear a state of oxidation similar to the major minerals of the C1 chondrites (table 1). The mineral assemblage characteristic of the ordinary chondrites, however, is not at all what is expected to form from solar matter. Rather, the major minerals of those meteorites grouped in table 1 as ordinary chondrites have chemical compositions indicative of formation from a medium greatly depleted in hydrogen and somewhat deficient in oxygen relative to solar matter. The relative elemental abundances of such a medium are similar, although not identical, to those of C1 chondritic material, namely condensate separated at a low temperature and low pressure from the gaseous portion of solar matter. The re-evaporation of such

condensed material, after separation from the gaseous components of solar matter, would lead to a gas phase of the appropriate composition from which the minerals of the ordinary chondrites could condense in equilibrium with the ambient vapour.

There is yet considerable uncertainty as to the mechanism by which the gases were separated from the condensed portion of solar matter. But it is clear that this important cosmochemical process occurred at a time prior to the formation of most primitive chondritic meteorites.

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