

OXYGEN FUGACITY IN THE SOLAR NEBULA. J. T. Wasson, Institute of Geophysics and Planetary Physics, University of California, Los Angeles CA 90095, USA.

A major early success of cosmochemical modeling was the recognition that the constituents of chondrites are readily understood by sequential condensation in a cooling gas of cosmic (=solar) composition, tempered by the metastable survival of some high-temperature phases. Of particular importance is Fe, which prefers metallic bonds at high nebular temperatures (>1000 K) and bonds to O and S at low (<700 K) temperatures. Redox conditions in a canonical nebula (one with a solar composition) are controlled (buffered) by the abundance of gaseous H_2 and H_2O . The currently accepted canonical pH_2/pH_2O is 1500, and is relatively insensitive to nebular temperature. Thus, both the formation of Fe-Ni and its later corrosion by H_2O (and H_2S) are readily understood in terms of plausible processes in a canonical nebula.

Already two decades ago a few researchers began to try to model some features of chondrites by condensation from non-canonical nebulae [1]. About 12 yr ago there was an upsurge in the development of such models stimulated by several petrographic and cosmochemical observations that seemed to require nebular redox conditions orders of magnitude greater than present under canonical conditions. A large fraction of these observations involved late-formed deposits of oxidized Fe, especially fayalite, and many were made on the Allende CV chondrite. Two papers were particularly influential: (1) Fegley and Palme [2] observed that, in many refractory inclusions, Mo and W are depleted relative to other siderophiles having similar volatilities, and that W and Mo are much more volatile under oxidizing conditions whereas other siderophiles are scarcely affected; and (2) Peck and Wood [3] observed that ferrous olivine rims the common forsteritic olivine in Allende and that the minor-

element (Al, Cr, Ti) contents are too high to allow exsolution from forsterite. Other studies that developed these themes are Hua et al. [4], Rubin et al. [5], Palme and Fegley [6], Weinbruch et al. [7], and Matsunami et al. [8]; the latter two showed that MnO and FeO were well-correlated in much of the fayalite, inconsistent with condensation from a canonical nebula but roughly consistent with formation under oxidizing conditions.

Typical pH_2/pH_2O ratios in these nebular models are 10, i.e., >100 \times lower than in a canonical nebula. The common approach to explaining such extreme conditions is to assume that (1) the nebula was originally canonical; (2) dust settled to the midplane and was evaporated there by an unknown heat source, the O from the oxides being largely converted to H_2O ; and (3) grain (and, in some models, chondrule) condensation occurred before the turbulence led to remixing with the nebular gas outside the midplane.

The pendulum began to swing the other way. Blum et al. [9] showed that many CV opaque assemblages are best understood as asteroidal alteration products. Although Palme and Fegley [6] had reported that chromite condensed earlier than Fe-Ni under oxidizing conditions and thus the high Cr contents of fayalitic materials was an indication of such conditions, new calculations by Krot et al. [10] showed that chromite condensation behavior was essentially independent of redox conditions. They also noted that those refractory inclusions that formed as a result of heating during infall into the nebula might retain their original redox state, in which case the depletions of Mo and W would not be indicative of nebula-wide conditions. Wasson and Krot [11] showed that high-Fa olivine associated with silica in UOC probably formed by aqueous alteration on the

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parent bodies; Fe_2SiO_4 formed when Fe diffused from the surrounding matrix to the silica. The high Mn contents of these grains are readily understood if Mn condensed from the nebula as tiny, unstable grains that dissolved during aqueous alteration, the Mn diffusing to a suitable growing host such as fayalite. This model can also explain the MnO-FeO correlations observed by Weinbruch et al. [7] and Matsunami et al. [8].

Krot et al. [12] carried out an extensive review of CV alteration products and showed that they are pervasive, i.e., in chondrules, refractory inclusions, matrix and metal. Their view was that the alteration, whether involving formation of phyllo-silicates, Fe-alkali-halogen metasomatism, or oxidation/sulfidation of metal was best understood by low-temperature processes in the asteroidal parent body, as originally suggested for CV chondrites by Housley and Cirlin [13], and widely accepted for CM and CI chondrites since the work of Bunch and Chang [14] and Kerridge et al. [15].

There are two reasons it is easier to oxidize metal or aqueously alter other phases in the parent bodies than in the solar nebula. The $p\text{H}_2/p\text{H}_2\text{O}$ ratios are much lower in parent bodies, causing the stability fields of alteration phases to extend to higher temperatures, and H_2O pressures are much higher, leading to higher reaction rates. At a nebular pressure of 10^{-5} atm $p\text{H}_2\text{O}$ is only 7×10^{-9} atm; because H_2O was probably the dominant volatile in asteroids, its pressure could be as high as the overburden pressure, which reaches 1 atm at a depth of 1 km in a chondritic asteroid having a radius of 50 km.

In summary, the evidence for highly oxidizing conditions in the solar nebula is weak. Although there is evidence (e.g., Mo depletions) for the formation of refractory inclusions under oxidizing conditions, those

formed during infall heating could have been internally buffered. Other observations, mostly involving fayalite or magnetite, seem better understood in terms of aqueous alteration on the parent bodies.

There is no need to continue to invoke implausible events to flash evaporate nebular solids in the midplane (and to prevent the resulting gases from mixing with the other nebular gas). The more important global question now is whether the H_2O in the chondritic parent bodies condensed as ice or as hydrated silicates.

References: [1] Herndon J. M. and Suess H. E. (1977) *GCA*, 41, 233. [2] Fegley B. and Palme H. (1985) *EPSL*, 72, 311. [3] Peck J. A. and Wood J. A. (1987) *GCA*, 51, 1503. [4] Hua X. et al. (1988) *GCA*, 52, 1389. [5] Rubin A. E. et al. (1988) in *Meteorites and the Early Solar System*, p. 488. [6] Palme H. and Fegley B. (1990) *EPSL*, 101, 180. [7] Weinbruch S. et al. (1990) *Meteoritics*, 25, 115. [8] Matsunami S. et al. (1990) *Proc. NIPR Symp. Antarct. Meteorites*, 3, 147. [9] Blum J. D. et al., *GCA*, 53, 483. [10] Krot A. N. et al. (1993) *EPSL*, 119, 569. [11] Wasson J. T. and Krot A. N. (1994) *EPSL*, 122, 403. [12] Krot A. N. et al. (1995) *Meteoritics*, 30, 748. [13] Housley R. M. and Cirlin E. H. (1983) in *Chondrules and Their Origins*, p. 145. [14] Bunch T. and Chang S. (1980) *GCA*, 44, 1543. [15] Kerridge J. F. (1979) *EPSL*, 43, 359.