FORMATION OF CHONDRULES IN A DISK ENRICHED WITH VOLATILES BY PLANETARY ACCRETION.

E. Gaidos[1]. [1]Department of Geology & Geophysics, University of Hawaii, Honolulu, Hawaii USA.

Chondrules' High-Na Diet: One widely-recognized conundrum of chondrules is retention of moderately volatile elements in unaltered (Type II) chondrules despite the high equilibrium vapor pressure at their formation temperatures (~1900K). For example, essentially closed system behavior for Na requires vapor pressures of ~10^{-4} bar [1], 1-3 orders of magnitude above theoretical *total* gas pressures. The required enrichments in solids relative to the primordial dust-to-gas ratio exceeds 10^6[1]. Significant enrichment of solids (10^2-10^3) is expected at the disk mid-plane, required to explain oxygen fugacities and minimal isotopic fractionation during evaporation, and desirable for rapid formation of planetesimals. No plausible disk or shock model can achieve the ratios required to avoid Na loss and the required density of solids would have caused higher rates of compound chondrules than observed, and collapse from self-gravity [1]. Such densities could have occurred in protoplanetary impact plumes [2], but with the exception of CB/CH chondrules, this is inconsistent with bulk chemistry, presence of relic grains, and oxygen isotopes [3].

Salt of the Earth: I suggest that massive loss of Na and other volatiles did occur, but in earlier generations of solids, including chondrules and much larger objects. Melting of solids by shocks and accretion drove volatiles such as Na back into the disk. Evaporation has been invoked to explain the inability of sequential condensation models to explain trends of moderately volatile elements in the inner Solar System [4]. Most chondrules date to 1-3 Myr after CAIs, by which time protoplanetary accretion had proceeded considerably [5]. Earth is depleted by a factor of 3-4 in Na with respect to CI chondrites and Mars by a factor of 2 [6] and volatile loss must have happened before a planet developed a deep gravitational well. If terrestrial planet formation was highly efficient a majority of inner Solar System Na, but not refractory elements, was returned to enrich the disk. Sodium-rich glasses in Al-rich chondrules [7,8] might be explained by such enrichment. This enrichment would have continued until the partial pressure of Na reached the equilibrium vapor pressure over material of chondritic composition at the liquidus temperature.

A Grain of Salt: This scenario requires that most chondrules formed when ≥99% of solids had been depleted of Na. Loss with disk gas was curtailed by condensation and also if Na was released into “dead zones” with little turbulent mixing with the rest of the disk. Dispersal of Na must be reconciled with localization of chondrule formation in space and/or time, i.e. parent bodies consist of distinct, isotopically homogeneous chondrules. Older chondrules should be more Na depleted than younger chondrules. Other moderately volatile elements should show similar behavior. Shock- or accretion-driven enrichment might explain high S vapor pressure inferred from the glassy chondrule mesostasis of some enstatite chondrites [9] and potentially the sulfidation of silicates and loss of FeO [10]. Chondrules may thus indirectly record the progress of accretion in the inner Solar System.

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