Olivine as an Indicator of Convection in the Solar Nebula

C E KenKnight, 3819 Lake Dr, Robbinsdale, MN 55422

Convection at a late stage in the solar nebula formed pairs of loops through the midplane. Each pair extended radially about one atmosphere scaling height and was coherent (toroidal) in its motion for a large angle in azimuth around the Sun. Sediments were concentrated in ringlets in the midplane between vertical gas flows. Buoyancy waves propagated vertically and heated the upper atmospheres of the nebula. The convection lofted a mixture of growing crystals and smoke into the hot zone. Where aggregates of smoke on the crystals melted, the opacity of the atmospheres decreased markedly because the liquid densified the aggregate. Thus forming a liquid phase provided a "thermostat" for the convection. Isolated olivine crystals carried by the convection grew by this process, as revealed by an onion-like zoning of incompatible elements in the olivine crystals. Because the surface melts on olivine contained impurity crystals, transfers of volatiles controlled some fractionations in the nebula which have seemed puzzling.

Chondrules When the density of sediments exceeds that of the gas (an increase by 300x in the inner solar system), the sediments can push the gas around. They will tend to act like an oscillator coupled to the gas. The physics included in the simulation describes buoyancy waves of the same kind known to heat the Earth's middle and upper atmosphere. 

Crystal Growth Solid grains not trapped in the sediments will be pushed by the convection around the loops in Figure 1. Even if the convection were near Mach 1 (the simulation showed much less) the time interval for a particle to go around a loop would be several local years. The
Convection in the Solar Nebula; C E KenKnight

transit through a "warm" region is not a flash heating. The time for hydrogen to remove a layer of olivine of 1 \( \mu \)m dimension is of the order of an hour at 2000 K [6] with no material present to react back. The rate at 1500 K is of more interest; the extrapolation may be about an order of magnitude slower per 100 K decrease, thus a few years at 1500 K. However, the back reaction should be large for such slow changes of the gas temperature at the particle. Some additional information is available from the electronics industry, where devices are made by transfer of solid films between closely spaced plates held a few tens of \( \deg \) K different in the presence of various active atmospheres, including hydrogen plus water vapor [7].

First Liquid Thermodynamic calculations [8] for the system of oxides of Ca, Mg, Al, and Si (CMAS) have included effects of nonideality in a condensate liquid, so that the liquid is stable for a solar gas whose pressure is as low as 50 mbar, perhaps 10 mbar. At 1 mbar it is stable if the solid to gas ratio is enhanced as little as 15x, perhaps 5x. The liquid first appears at about 1550 K for a solar gas of 300 mbar, about the same as that for a 300x enhancement in solids at 1 mbar. That same temperature was needed to melt dark inclusions enriched in K by 10x in some LL chondrites [9]. They realized that the K (and Rb, Cs) enrichment plus Na depletion could be explained by vapor transport between feldspars held at different temperatures. In the same LL chondrites an attempt to use K-Ar dating revealed that the K was in a \( \mu \)m-sized phase, which was found to be a devitrified CMAS glass [10].

Olivine Zoning Relic isolated olivines of low FeO content [11] are rich in oxides of Ca, Cr, and Mn which are distributed smoothly, as though plenty of time for solid diffusion at elevated temperatures has elapsed. It is also rich in +3 ions, Al, Ti and V, which have much sharper gradients where the low-FeO core (with blue-CL) changes to a high-FeO mantle (with red or no CL). The cores also have oscillatory zoning in the +3 ions [12, 13], which is known only for insertion from a liquid. Given that \( ^{16}\text{O} \) was carried into the nebula by some refractory solid, the enrichment of core olivine in \( ^{16}\text{O} \) [14] is most easily understood if refractory dust stuck to the olivine and in contact with CMAS liquid contributed to core growth by melting, the liquid offering a barrier to large exchange with the surrounding gas. Zoning of the olivine mantle could be sought by etching a polished surface and viewing it in reflection [15].

References