CONDENSATION EVENTS NEAR THE TOTAL EVAPORATION FRONT WITHIN THE PRIMITIVE SOLAR NEBULA. A.G.W. Cameron and M.B. Fegley, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138.

The primitive solar nebula may be modelled using the frictionally-induced transport theory of Lynden-Bell and Pringle (1,2,3) if the principal frictional mechanism within the nebula is turbulent viscosity, or that plus other sources of viscosity which can be included within the modelling. The primitive solar nebula is formed at the center of a collapsing interstellar gas cloud fragment, and it is probable that the internal transport time scales for energy, angular momentum, and mass within the bulk of the nebula become adjusted to comparability with the infall time scale (about 10^5 years) throughout the bulk of the nebula through the establishment of a steady-state mass distribution within the nebula (the only alternative is the unlikely condition that the internal time scales should be longer than the infall time scale). Subject to these approximations the nebula evolves in the expected way: mass flows outward near the outer edge and inward near the center; angular momentum flows always outward; and the gravitational energy which is released flows outward and is also locally dissipated. This dissipation is responsible for heating the nebula; throughout the infall period the mass of the sun grows and the temperature in any region of planetary formation (by which we mean at a variable radial distance at which the specific angular momentum is conserved) will continually increase.

The interstellar gas infalling into the solar nebula contains condensed matter in the form of interstellar grains, initially at very low temperatures (5 to 10K). As such grains move into warmer regions of the gas, the more volatile constituents evaporate. Turbulent motions within the gas actually cause a diffusion of the grains, as has recently been emphasized by Morfill (4), so that layers of molecules of intermediate volatility are likely to condense and again evaporate as the grains diffuse. However, when a parcel of the gas moves into a region with a temperature above about 1800K, the grains will become completely evaporated. We refer to the surface within the nebula containing critical combinations of temperature and pressure at which this total evaporation occurs as 'the total evaporation front'.

In the outer part of the nebula, when a parcel of gas moves in such a way as to undergo expansion with cooling, there are always large numbers of grains present which can act as condensation centers for any vapors that become supersaturated. However, in the inner solar nebula within the total evaporation front, no nucleation centers are present. Such centers can only be created by statistical fluctuations in molecular clustering within the gas, and this generally requires a high degree of supersaturation, as Blander and Katz have long argued (5).

At pressures below $10^{-2.7}$ bars, according to equilibrium theory, the first condensate should be corundum (Al_2O_3), and above this pressure (to $10^{0.06}$ bars) hibonite ($CaAl_{12}O_{19}$) should be the first condensate. In the lower pressure range, hibonite should condense only a few degrees below corundum (6).

We have applied a modification of classical nucleation theory due to Salpeter (7) to estimate the degree of supersaturation needed to create condensation centers when a parcel of gas moves through the total evaporation front toward lower temperatures. Using surface work functions appropriate to crystalline solids, the formal result is that the gas must become supercooled by several hundred degrees Kelvin in order to form condensation centers. On the other hand, surface work functions appropriate to liquids suggest that a supercooling of less than half this amount would be required. Although the absolute values for the degree of supercooling may vary, the ratio of the degree of supercooling for solids relative to liquids of the same composition is constant at about 2.0. We do not interpret this as indicating that liquids would actually condense, but rather that the condensation product would be a chemically complex mixture (we may call this an amorphous solid) with surface properties somewhat like those of liquids. In any case, it appears that the temperature difference between the equilibrium condensation thresholds for corundum and hibonite is small compared to the supercooling required. In practice it is likely that hibonite would thus be the first condensate down to quite low pressures.

Because of the great difficulty in creating new condensation centers, the rate of center creation will be small if the gas is moving fairly slowly and thus not expanding very rapidly. This means that a condensation center, once formed, will feed from a considerable region of the surrounding gas and can thus grow to a substantial size. We suggest that many of the chondrules

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and high temperature inclusions can be formed by condensation processes in the vicinity of the total evaporation front, from which they diffuse to fill the rest of the primitive solar nebula by turbulent transport.

The total evaporation front is a surface perpendicular to the midplane of the nebula at the midplane. With increasing growth of the central sun, the front moves outward within the nebula until it approaches the radial position of Mercury. At higher elevations away from midplane, the front curves inward toward smaller radial distances, overlying part of the midplane where temperatures are too high for condensates to exist.

There is a conceptual difference between the condensation events in these two regions of the total evaporation front:

(1) At the midplane, condensation occurs when a parcel of gas moves radially outward past the total evaporation front. One would expect chondrules formed here to feed from the entire condensation sequence of the less volatile elements, since the component of the gravitational force perpendicular to the central plane of the nebula is very small and the condensates will drift only slowly relative to the gas.

(2) When a parcel of gas moves upward across the total evaporation front, the perpendicular gravitational acceleration is much larger, and the more refractory condensate will fall downwards, although not necessarily across the front. This will prevent the lower temperature condensates from condensing on it, and this may be a way of forming high temperature inclusions. Higher up from the midplane, additional condensation centers must be formed from gas now depleted in the most refractory elements, so that a different nucleation chemistry would prevail. Some types of chondrules may be formed this way.

In reality, conditions are likely to be considerably more complicated than in the above simple-minded classification. However, it does appear possible that very large amounts of mass can be processed into chondrules and inclusions in this way, since turbulent transport within the primitive solar nebula should involve local shearing motions much faster than the bulk drift velocity of the gas toward the center of the nebula. Condensed bodies in the millimeter size range will move quite readily with the gas wherever there are turbulent motions, which should diffusively distribute them throughout the bulk of the primitive solar nebula. The turbulent motions can also easily sweep these small bodies to large distances away from midplane. Thin rims of materials of intermediate volatility may be deposited on these bodies in the course of the diffusion.

At a later stage in the development of the solar nebula, when the gas is sufficiently depleted that turbulent motions are no longer driven, it is possible for material particles to sediment toward the midplane of the nebula. The rate of sedimentation is a function of particle size, with the larger particles falling more quickly toward midplane. When the central midplane mass density of condensed matter is high enough, Goldreich-Ward instabilties can take place forming bodies of asteroidal size (8). We suggest that these instabilities take place at a time when the bulk of the chondrules and inclusions have precipitated, but only a much smaller fraction of the more finely-divided material produced from the interstellar grains has reached the midplane region. In such a situation the mass ratio of chondrules to matrix material should be high in most asteroids and hence also in the meteorites derived from them.

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