THERMAL PHYSICS RELEVANT TO THE CONDENSATION OF
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Thermodynamic equilibrium is a very special state that pre-
supposes mechanical, chemical and thermal equilibria. Whereas
space represents an entirely new frontier in thermal physics and
whereas the existence of the various equilibria in colloidal gases
in space has not been demonstrated, we should try to avoid - if at
all possible - the a priori assumption of thermodynamic equilibrium
in studying the condensation of meteoritic material. It has been
demonstrated that the condensation of this material in the "solar
nebula" (if the material did indeed condense in the solar nebula)
is most likely to have taken place in a state of thermal disequilib-
rium with the gas phase kinetic temperature $T_k$ being higher than
the condensed phase ("grains") internal temperature $T_c$ (1).

In the thermal steady state defined above, the effective
saturation vapor pressure of a condensable species is

$$P_e = P_o \left(\frac{T_k}{T_c}\right)^{\frac{1}{2}} \left[\kappa_o(T_C)/\kappa(T_k,T_c)\right]$$

(1)

where $P_o$ is the conventional
vapor pressure at temperature
$T_o$, $\kappa_o(T_C)$ is the sticking
probability of the condensable
molecules at this tempera-
ture, and $\kappa(T_k,T_c)$ is the
sticking probability in
temperature disequilibrium.
It is not possible to estab-
lish a "condensation sequence"
for the various meteoritic
solids without knowing the
values of the parameters $\kappa_o$ and $\kappa$. However, even with
this limitation, we shall be
able to arrive at an impor-
tant conclusion with regard
to the condensation sequence.

The relationship between
$T_k$ and $T_c$ can be established
with some certainty for a
cosmic gas phase of given
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density and temperature. We define this relationship and obtain values of \( T_C \) as a function of \( T_K \) for a wide range of degree of ionization of the gas phase - and for an assumed negligibility of the infrared opacity of the region of condensation (1). These values are shown in Figure 1 where \( N \) is the total gas density, the C's are the thermal accommodation coefficients (subscripts \( m, a, i \) and \( e \) for molecules, atoms, ions and electrons respectively), and \( \gamma_a \) and \( \gamma_i \) are the efficiencies of heat transfer to a grain due to association and recombination of hydrogen on the grain surface.

The above results and other physical arguments can be used together to place upper limits on the total gas pressure in the condensation environment for the cases where the gas is neutral and undissociated ("neutral gas limit") and where the gas is fully ionized ("plasma limit"). In Figure 2 we plot these limits, as also the vapor pressure \( P_e \) and the partial pressure of a selected condensate: metallic iron. The vapor pressures are determined from Eq.(1) for the neutral gas limit \( (T_K \approx 3000 \text{ K}) \) and for two different values of \( \kappa : \kappa = \kappa_0 \) and \( \kappa = 10^{-3} \kappa_0 \). The grain temperature domain in which the vapor pressure \( P_e \) exceeds the partial pressure is forbidden for the condensation environment.

An upper limit \( T_{CO} \) of \( T_C \) thus occurs when the two pressures are equal. Assuming that the abundance of iron relative to hydrogen is \( 10^{-5} \) we find that \( T_{CO} \approx 1250 \text{ K} \) for \( \kappa = \kappa_0 \) and \( T_{CO} \approx 1100 \text{ K} \) for \( \kappa = 10^{-3} \kappa_0 \). The corresponding gas pressures can be read from the figure. Clearly, in a progressively cooling gas, \( T_{CO} \) for a given solid represents the temperature of onset of condensation for that solid. Thus the ordering of \( T_{CO} \) determines the condensation sequence in disequilibrium.

The crucial point to note here is that for a change of \( \kappa \) by three orders of magnitude, \( T_{CO} \) changes by only \( \sim 150 \text{ K} \). This conclusion holds for other solids of interest as well. It is reasonable to assume...
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that in going from the equilibrium to the disequilibrium picture, \( \kappa \) does not change drastically. With this assumption, the ordering of \( T_{co} \) (but not its value) for the various solids will remain unchanged in going from the equilibrium to the disequilibrium situation. We may now argue that the condensation sequence of solids determined on the basis of \( \kappa_{o} \) (i.e. the sequence determined in thermodynamic equilibrium - the Larimer-Grossman type sequence) will be substantially the same as that determined on the basis of \( \kappa \) (i.e. the sequence in thermal disequilibrium), barring of course any effects due to ionization of the condensing species.

On the basis of the formalism outlined above, we can draw certain conclusions about the process of condensation and about a physically reasonable meteorite condensation environment:

1. An agreement between observations in meteorites and the Larimer-Grossman type condensation sequence should not be taken as a proof for equilibrium condensation. The agreement admits of a multiplicity of \( T_{k} - T_{c} \) relationships, including the case \( T_{k} = T_{c} \).

2. The temperature of the gas phase may be inferred from physical grounds to be in the approximate range 3000 - 10,000 K.

3. In this temperature range the upper limit of the total gas density that permits growth of iron grains is about \( 10^{13} - 10^{14} \) cm\(^{-3}\). The corresponding upper limit of the gas pressure is about \( 10^{-5} - 10^{-4} \) atmosphere.

The formalism outlined here can be employed to study in greater detail the condensation of meteoritic solids in thermal disequilibrium.

A concluding remark: The choice between equilibrium and disequilibrium theories lies in the capability of the theories to explain the oddities in the condensation sequence, and not the sequence itself.

REFERENCE