Can Chondrules Form from a Gas of Solar Composition?

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Chemical composition and petrological texture of individual chondrules as observed by many investigators indicate melting and rapid cooling, as well as relationships with elemental vapor pressures. What would the properties of a dusty gas have to be so that chondrules with the observed properties could form by sudden heating and cooling in a turbulent gas as, for example, in the bow shocks of collisions with larger objects?

GENERAL REMARKS

Chondrules, by definition, are solidified spherical droplets of molten minerals and other substances that occur in meteorites. With the exception of chondrules occurring in enstatite meteorites, chondrules always contain oxidized iron. Therefore, at temperatures above their melting point, they could not have been in equilibrium with a gas containing hydrogen in solar proportions. Oxidized iron may only form below 800° K and in a very tenuous gas, only as a fine dust. Over sufficiently long periods of time, the fine dust particles may agglomerate to produce objects the size of chondrules. In a second high temperature stage, the dust particles must then have been melted to form the chondrules present in meteorites.

It is important to keep in mind that, because of the near constancy of the isotopic composition of the elements, the various genetic components (in particular, the S and R components) must have mixed in a nearly perfect manner before condensates formed out of the primeval gas cloud. It may be mentioned here that oxygen isotopes are a special case: The relatively large non-mass-dependent fractionation of ^{16}O from the heavy oxygen isotopes ^{17}O and ^{18}O (Clayton *et al.*, 1973) can now be understood in the light of the laboratory experiments by Thiemens and Heidenreich (1983). These experiments show that the ratios of the oxygen isotopes in extraterrestrial matter may be the result of photochemical and charged particle reactions. The time at which such fractionation could have occurred is obviously that of the loss of the gases before and during the second high temperature stage.

OBSERVATIONS

In order to explain the presence of both metal and oxidized iron, one must assume that the second high temperature stage must have been either sudden and brief or it must have occurred after nearly all the hydrogen had separated from the condensed particles. In the first case, the hydrogen must not have had enough time to react with the iron oxide to give metal and water. In the second case, a sufficiently large fraction of hydrogen must have left before the second hot period had started, so that only a fraction of the iron was reduced to metal (Herndon and Suess, 1977). No doubt a separation of condensed matter from the gases must have occurred at some time, but no theory is available that would allow us to quantitatively determine the conditions under which this has occurred.

OXIDATION AND EQUILIBRATION

It is not clear yet whether a relatively simple history of typical chondrules can be assumed, *viz.*, condensation at low temperatures from a homogeneous well-mixed gas and subsequent melting of the condensates during a second high temperature stage, or a more complex history involving intermediate parent bodies. However, in either case, it must be assumed that the state of oxidation of the condensate was established by the processes during the second high temperature stage, which one would assume should have led to homogeneous matter and finally to the formation of "equilibrated" chondrites. Inhomogeneous conditions in a highly turbulent gas, however, obviously could have led to the formation of chondrules of varying states of oxidation and to "unequilibrated" chondrites. Some of these appear to have been subjected finally to metamorphic processes and to an "equilibration" of their constituents.

There are, of course, many other ways by which objects with the properties of chondrules could have formed, such as spraying of a melt, collisions, lightning, etc. These possibilities have been discussed extensively in the literature on this subject. In fact, it is quite possible that one of these ways, and not the one we are suggesting, was actually the way in which the chondrules formed. Nevertheless, in order to decide what could and what could not have happened, a more quantitative analysis of the processes assumed by us has been carried out by one of us (W.B.T.). We start out with hot solar matter, completely gaseous so that perfect mixing of genetic components is possible. Then, with decreasing temperature, a fraction of $\sim 10^{-3}$ parts per mass will form dust particles.

SHOCK HEATING

Let us explore the possibility that a pulse of a secondary heating was produced by a strong shock in the gas-dust mixture. There are many possibilities as to how such a shock can be produced. Let us assume that it is produced by the passing of a solid body (meteorite to asteroid size) through the gas at a velocity of 10 km/sec. The post-shock temperature is then of the order of $50\,V^2$°K, where V is the velocity in km/sec, for a gas primarily of molecular hydrogen. If the initial gas density is $n \simeq 10^{16}\text{cm}^{-3}$, grains that are a few microns in size will be heated almost immediately, but will not reach the temperature of the post-shock gas; instead, heat loss by radiation will hold the temperature T_D of the dust at a much lower value:

$$T_D = 122\,[10^{-16} n\, M_G^{-1/2}]^{1/2}\, T_G^{3/8},$$

where M_G is the molecular weight of the gas, n its density, and T_G its temperature, while the dust grain is assumed to have unit emissivity. For $T_G = 5000°K$, $T_D = 2000°K$, and although the grain remains cooler than the gas, most metals will melt. Since momentum and energy transfer occur at the same high rate, the dust (if of micron size) is swept along with the gas.

CONCLUSIONS AND DISCUSSION

After the shock is past, the gas will cool adiabatically as it reexpands, and its temperature will drop by a factor of 4, carrying the gas temperature with it; however, at this point, cooling becomes much slower and is determined by the radiation loss of the grains. If ~0.1% of the mass is in dust and micron-size grains, the temperature drops below the melting point in a few minutes.

Thus, small dust grains could easily undergo a secondary melting process in a modest shock; however, for the conditions we have considered, collisions between molten grains will be very rare events and coalescence of molten droplets unlikely, unless the dust is already somewhat aggregated.

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