FORMATION OF CHONDRULES AND MATRIX MATERIALS IN THE HETEROGENEOUS SOLAR NEBULA. H. Nagahara, Geol. Inst., Univ. Tokyo, Hongo, Tokyo 113, Japan

New model for origin of chondrules in special relationship to matrix materials is proposed based on conditions obtained in texture reproducing experiments, vaporization and condensation experiments, and petrological observations on chondrites.

Presence of silicate liquids give important clues on physical conditions of the solar nebula. At first, high temperature and high pressure are necessary. Pressure dependence of liquidus curve is small, and then melting temperature for chondrule formation is not largely different from that obtained from texture reproducing experiments at 1 atm. Recent vaporization and condensation experiments succeeded in determining stability limit for silicate liquids. Experimentally determined "triple points" for forsterite, enstatite, and diopside, though they are not triple points in a strict sense for most cases because of presence of temperature interval between solid and liquid, lie at $1x10^{-5}$ bar 1700°C, $2x10^{-6}$ bar 1550°C, and $1x10^{-6}$ bar 1350°C, respectively [1,2]. Temperature varies with mineral species, but pressure range for stability of those three liquids is small. Although chondrule compositions are mixtures of several phases and are not so simple as single minerals, pressure for stability of chondrule liquids should be close to above values, that is, about 10^{-5} to 10^{-6} bar. The triple point moves to higher pressure in the presence of hydrogen (and helium) gas. (H+He)/(Mg+Si+Fe) ratio for the solar abundance is approximately 10^4, and the triple point should lie about 10^{-1} to 10^{-2} atm accordingly. This shows that chondrules could not be formed stably in the solar nebula of the canonical models; such temperature and pressure conditions are not expected in the canonical models. Mysen and Kushiro [3] showed that H/dust ratio is important for stability of liquids. In order to form liquids in the solar nebula, either there was high pressure region or dust was enriched in chondrule forming region. Dust should have been enriched by 2 to 3 orders of magnitude at 10^{-4} atm total pressure compared to average dust distribution based on the relationship between H_2/dust and minimum pressure for liquid stability [2]. Formation of liquid is possible, as a consequence, either at total pressure as high as 10^{-1} to 10^{-2} torr when dust was homogeneously distributed or dust was enriched by 2 to 3 orders when gas was homogeneously distributed. Chondrule formation in a dust enriched region has already been proposed by many investigators. Metastable liquid is easily formed in the experiments but lives only short duration, within a few minutes, so that metastable liquid origin of chondrule melt is implausible because of fairly slow cooling rate.

Experimentally determined cooling rate for chondrule formation also give clues on solar nebula conditions. Most suitable cooling rate is 10^3-1 °/hr during crystallization (at about 1700 to 1200 °C) [3,4], which is too rapid for cooling of entire nebula but is too slow for small particles which cooled by radiation in a nebula with total pressure as low as 10^{-4} atm. Cooling rate estimated for chondrules ranges 3 orders of magnitude, which further requires significantly variable media around chondrules.

Chemical compositions of olivine and pyroxene in chondrules show that they were formed at fO_2 several to ten orders of magnitude higher than that in the canonical solar nebular models. Because oxygen fugacity varies as a square of abundance of ice and/or dust, then ice and/or dust should be enriched to 2 to 3 orders of magnitude compared to the averaged solar nebula. This value is similar to the dust enrichment factor for liquid stability. Ice may be present rather as mantle of silicate dusts, but not as isolated fragments. Accordingly, enrichment of ice results in enrichment of dust in a similar proportion.

Matrix materials of chondrites are fine-grained, rich in Fe-rich olivine at least in ordinary and CV chondrites, and often contain interstellar materials. This suggests that they were formed at fairly low temperatures and oxidizing environment. Although the ratio of chondrules to matrices are variable from chondrite to chondrite and especially from chemical group to group, sum of compositions of chondrules and matrices is constant in chondrites with the same chemical group. This suggests that chondrules and matrices were formed through the same event in an essentially closed system for each chemical group of chondrites which has already been suggested by Anders [5]. Vaporization and recondensation experiments in the olivine solid solution system [6] showed that forsterite, enstatite, silica mineral, iron-bearing pyroxene, fayalitic olivine, and metallic iron condensed successively from an iron-rich gas vaporized under oxidizing condition from magnesian olivine. Based on the results, composition of matrices of ordinary and CV chondrites are estimated to be formed at about 1000 to 800 ^{o}C by rapid cooling of a gas partially vaporized from chondrules.

In order to satisfy above physical conditions, dense and small clouds are required. As mentioned before, metastable formation of chondrule liquids is not implausible, which in turn shows that liquids were stably formed. High temperature (up to about 2000K) and high pressure (up to 10^{-1} bar) and/or dust-ice enrichment (up to three orders of magnitude) can be achieved in a dense cloud near the sun. Though temperature distribution in the solar nebula depends on model and is not fully understood, temperatures are too low for chondrule formation in most part of the solar nebula in the canonical models except for recent Boss's model assuming high viscosity [7]. Temperature was high only near the sun, and hence chondrules were formed when the cloud located near the sun. The cloud necessarily have pressure gradient, which make it possible to form chondrules and matrix materials simultaneously. Chondrules were formed by heating in the inner portion of the cloud because of high pressure, and matrix materials were formed at the outer portion of the cloud because of lower pressure. Moderately rapid cooling rate is achieved in a small dense cloud and cooling rate variation for chondrules were caused by pressure gradient from center to surface of the cloud. Gas formed by partial vaporization from chondrules were quenched to form matrix materials which is enriched in Fe-rich olivine. Chondrules and matrix materials could have common origin and were formed in a closed system; chemical group of chondrites are due to origin in different clouds of which compositional differences had been established during condensation in the early stage of the solar nebula. A similar model was proposed by Hewins [8]. Origin of high temperature by collision of two large bodies may be possible, and in that case the cloud was formed by intensive vaporization.

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