CHONDRULE FORMATION IN RADIATIVE SHOCK

T.V. Ruzmaikina (Lunar and Planetary Laboratory, University of Arizona, Tucson 85721), and **W.H. Ip** (Max-Planck-Institut für Aeronomie, D-3411 Katlenburg-Lindau, Germany)

Introduction The most abundant constituent of most groups of chondrite meteorites are chondrules - those are sub-millimeter to millimeter-sized, spherical-shaped grains, composed of silicates [1]. Physical, mineralogical, and isotopic properties of chondrules strongly indicate that they were formed by rapid melting and resolidification of preexisting solids composed from primitive material. The chondrule precursors were heated to temperature about 1800 K in short high temperature events, followed by cooling with a rate 10^2 to 10^3 K/hr. A significant abundance of chondrules in almost all types of chondrites reveals high efficiency of the energy sources in conversion of precursor material into liquid droplets. Lightning discharges and flayers in the solar nebula [2], and melting of chondrule precursors by the interaction with the gas in an adiabatic accretional shock [3,4] or in the shocks (of unspecified nature) within the solar nebula [5] were discussed as possible mechanisms for chondrule formation.

Summary. In this paper we reconsider heating of chondrule precursors in an accretional shock, i.e. in a shock produced by infalling gas, when it hits the solar nebula. This shock had inevitably developed at the stage of solar nebula formation, and a significant fraction of infalling gas and dust had been reprocessed in this shock [6]. In contract to earlier papers, we took into account cooling of the postshock gas. We took into account cooling by dissociation of hydrogen molecules, rotational cooling by dipole molecules H_2O, OH, CH, CO, HCl, HD (according to [7]), and radiative cooling by small dust particles. We assume that the material has a solar bulk composition and that 0.05% (of the mass) of the condensible elements is concentrated in small dust particles, which include in the gas cooling. For the abundance of dipole molecules, we assume that the bulk of atoms of O and half of C are in a molecular form, and that less abundant elements are equally distributed between different molecules containing them. Other parameters were taken as follows: the mass and angular momentum of protosolar cloud $M_{PC} = 1.1\ \mathrm{M}_\odot$, $J_{PC} = 2 \cdot 10^{52}$ g cm^2 s^{-1}, the surface density of the solar nebula $\Sigma = 10^4\ (R/1\,\mathrm{AU})^{-1}$ g cm^{-2}, and temperature in the solar nebula, far from the shock front, is $T_r = \left(T_{en}^4 + T_{eff}^4\right)^{1/4}$. where $T_{en} = 1200\ (R_{ce}/R_{p\odot})^{1/2}\ (R\,/\,1\,AU)^{-1}$ K, $R_{p\odot}\ (= 3\,R_\odot)$ is the radius of protosun, R_{ce} is the centrifugal radius of infalling material which is ≤ 2 AU in our case, and T_{eff} is a photospheric temperature of viscous disk, which is approximated as $T_{eff} \simeq 475\ (R\,/\,1\,\mathrm{AU})^{-3/4}$ K.

We found that shocked gas cools fast by dipole molecules and small dust particles, and it results in a sharp increase of gas density in the postshock region. Sub-millimeter and larger grains cross the region of cooling and penetrate in cooled and compressed postshock gas. As a result the grains are heated by the drag stronger than in the shock without cooling. This makes possible melting of dust aggregates (chondrule precursors) in the radiative accretional shock during formation of the solar nebula, even when the matter is transparent for the thermal radiation of the aggregates. The maximal radius of region of chondrule formation increases with the density of infalling gas. Clumpy accretion [8,9], and enhancement of density in the vicinity of the centrifugal radius of infalling gas [4,10] could provide the necessary densities of the infalling gas at distances of the asteroid belt.

Postshock region of cooling. Fig. 1a÷1c shows distribution of gas density in the postshock region for the normal component of infall velocities 15; 18; 21; 24; 27; 30; and 33 km s^{-1}. These velocities are equal to parabolic ones (for 1 $\mathrm{M}_\odot$) at distances 8.73; 6.07; 4.46; 3.41; 2.70; 2.18; and 1.80 AU, respectively. The average densities of the preshocked gas at these distances are $0.61 \cdot 10^{10}$; $0.11 \cdot 10^{11}$; $0.17 \cdot 10^{11}$; $0.25 \cdot 10^{11}$; $0.36 \cdot 10^{11}$; $0.49 \cdot 10^{11}$; $0.65 \cdot 10^{11}$ cm^{-3}, assuming accretion rate $1 \cdot 10^{-5}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$ (Fig. 1a). (For the fragmented accretion, density of clumps could be significantly larger while the average rate of infall is the same.) The density of the infalling gas is assumed 10 times larger (b), and 50 times larger (c) than for the case (a); velocities and the distances are the same.

Grain Heating: Results. Evolution of temperature of 1-mm grains is determined by a balance between their heating due to gas drag and UV radiation from the shock front, and cooling of grains by their thermal radiation. When particles are melted or evaporated, the latent heat of these phase transitions is an additional important sink of energy. We assume, that the region of grain heating is transparent for their thermal radiation. In the cooling postshock region heating of grains by UV-radiation is the same as in an adiabatic shock, with the same parameters, while the postshock region is transparent for UV radiation emitted by the shock front. Figure 2(a-c) shows the evolution of the temperature of 1 mm solid grain in the postshock region with the cooling for the postshock gas density distribution 1(a-c), respectively. Dotted lines are marked the temperature 1600 and 1800 K.

Formation of chondrule precursors. Models of chondrule formation in the accretional shock, associated with formation of the solar nebula, generate a question: as it possible that grains (as big as ~ 1 mm in size, and ~ 1 to a few 10^{-3} g in mass) could be formed before entering the solar nebula. A detailed (both analytical and numerical) consideration of the coagulation of interstellar dust particles in protostellar clouds, seem to, give a positive answer [11]. If the aggregate has a constant density, then $r_d \propto t^2$ for large t. Fractal aggregates with dimensions $D = 2.5, 2.3$, and 2.11, with the initial radii 10^{-5} cm reach 1 cm in $\leq 10 \cdot 10^6$ yrs for the fractals with $D \leq 0.54$, and 1 cm for $D \leq 2.43$. If the initial radius of grains is 10^{-4} cm and 10^{-4} cm, they reach 1mm and 1 cm in 8.0, 2.7, and $0.7 \cdot 10^6$ yrs, respectively. The typical mass of cm-size aggregates is comparable or exceeds that of chondrules. Grain coagulation is also effective in the inner part of infalling envelope, provided that the turbulence is amplified during collapse, because of transference into collapse of a fraction of the kinetic energy of the infall.

References

[1] Grossman, J.N. 1988. Formation of Chondrules. In *Meteorites and the Early Solar System*, (J.F. Kerrige, and M.Sh. Matthews, Eds.), pp.680-696. Univ. of Arizona, Tucson.

[2] Levy E.H. 1988. In *Meteorites and the Early Solar System*, (J.F. Kerrige, and M.Sh. Matthews, Eds.), pp.697-714. Univ. of Arizona, Tucson.

[3] Wood, J. (1984). *Earth Planet. Sci. Lett.*, **70**, 11–26.

[4] Ruzmaikina, T.V. 1990. *Lunar Planet. Sci. XXI*, 1053–1954.

[5] Hood, L.L., and M., Horanyi 1991. *Icarus* **93**, 259–269.

[6] Ruzmaikina, T.V., I.V. Khatuncev, and T.V.Konkina 1993. *Lunar Planet. Sci. XXIV*, 1225–1226.

[7] Hollenbach, D., and McKee, C.F. 1979. *Astrophys. J.,Suppl.*

[8] Graham, J.A. 1992. *Publ. Astron. Soc. Pacific* **104**, 479–488. **41**, 555–592.

[9] Boss, A.P., and J.A. Graham 1993. *Lunar Planet. Sci. XXIV*, 153–154.

[10] Cassen, P.M., and Moosman, A. 1981. *Icarus* **81**, 353–376.

[11] Weidenschilling, S.J., and T.V. Ruzmaikina 1993. *Astrophys. J.*, in press.