CONDENSATION AND ACCRETION OF CORUNDUM AND CORUNDUM-HIBONITE GRAINS IN THE SOLAR NEBURA. T. M. Nakamura[1], N. Sugiura[1], M. Kimura[2], A. Miyazaki[1], and A. N. Krot[3], [1]Department of Earth and Planetary Science, Graduated School of Science, University of Tokyo, Tokyo 113-0033, Japan. (takahiro@eps.s.u-tokyo.ac.jp), [2]Faculty of Science, Ibaraki University, Mito 310-8512, Japan. [3]Hawai'i Institute of Geophysics and Planetology, School of Ocean and Earth Science and Technology, University of Hawai'i at Manoa, Honolulu, HI 96822, USA.

Introduction: Equilibrium condensation calculations for a cooling solar gas at total pressure < 10^{-2} atm show that corundum (Al_2O_3) should be the first major condensate [1]. With continued cooling, corundum is predicted to react with the nebular gas to form hibonite ($CaAl_{12}O_{19}$). Replacement of corundum by hibonite has been described in several refractory inclusions from carbonaceous chondrites [1,2]. Condensation processes in the solar nebula may be elucidated from detailed studies of corundum-hibonite grains, however, corundum-bearing CAIs are exceptionally rare [e.g., 1-3]. Recently, we have reported a discovery of 43 corundum grains (1-11 μm in size) and 5 corundum-hibonite grains (4-7 μm in size) of solar nebula origin in matrix of the mineralogically pristine (unaltered and unmetamorphosed), ungrouped carbonaceous chondrite Acfer 094 [4]. Some of the corundum and corundum-hibonite grains occur as aggregates. Six aggregates, each consisting of 2 to 6 corundum grains, were found (Fig. 1). One of the aggregates consists of three corundum-hibonite grains. The corundum and corundum-hibonite grains in an aggregate have similar sizes. The remaining corundum and corundum-hibonite grains are isolated.

Here we discuss constraints on the condensation and accretion environment of corundum and corundum-hibonite grains in the solar nebula.

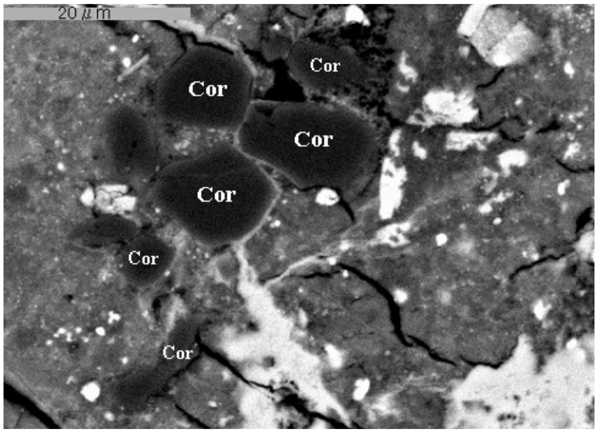

Fig. 1. Backscatered electron image of an aggregate of six corundum (cor) grains in matrix of Acfer 094.

Cooling timescale and condensation temperature according to homogeneous nucleation theory: Based on the homogeneous nucleation theory [5] and the observed size range of the corundum grains in the Acfer 094 matrix, we can estimate cooling time of a solar nebula region at total pressure of 10^{-3} to 10^{-6} atm where these grains could have originated (Fig. 2). The equilibrium condensation temperature and the condensation temperature estimated by the homogeneous nucleation theory are given in Table 1.

min./pressure	10^{-6} (atm)	10^{-5} (atm)	10^{-4} (atm)	10^{-3} (atm)
corundum*	1577	1639	1705	1777
hibonite*	1485	1562	1647	1743
1 μm**	1509	1571	1638	1710
10 μm**	1520	1582	1647	1720

Table 1. *Equilibrium condensation temperature (K) of corundum and hibonite [6]. **Condensation temperature (K) of a corundum grain 1 μm and 10 μm in size based on the homogeneous nucleation theory. At total pressure of 10^{-4} (atm) or 10^{-3} (atm), corundum grains 1-10 μm in size cannot be formed because their condensation temperature based the homogeneous nucleation is lower than the equilibrium condensation temperature of hibonite.

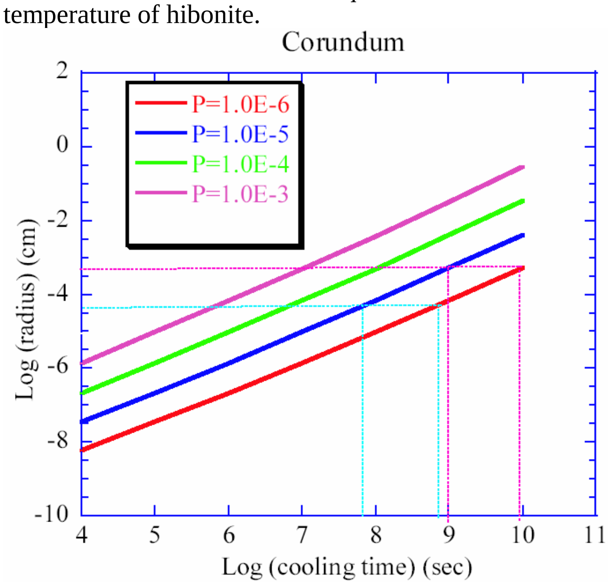

Fig. 2. Cooling time of the solar nebula gas *vs.* radius of corundum grains at total pressure ranging fom 10^{-3} to 10^{-6} atm [5].

Timescale of accretion and relative velocities between corundum grains: Observations show that some of the corundum grains exist as aggregates and the sizes of the constituent grains in an aggregate are similar. Here, we assume solar nebula was not chemically fractionated and cooling rate of nebula gas was steady. Then, we examine if formation of corundum aggregates can be explained reasonably.

The presence of hibonite-free corundum aggregates suggests that corundum grains must collide each other before formation of hibonite. We assume that growth of hibonite is controled by diffusion of Ca in corundum. The diffusion coefficient of Ca^{2+} in corundum is assumed to be slightly larger than that of oxygen [7]. Since hibonite was not detectable on the corundum grains in the hibonite-free corundum aggregates, we assume that the hibonite layer is less than 0.1 μm in thickness. Using equation $x = \sqrt{Dt}$, timescale of hibonite formation can be estimated (Table 2).

Table 2. Timescale (sec) of hibonite formation by replacement of corundum.

size/pressure	10^{-6} (atm)	10^{-5} (atm)	10^{-4} (atm)	10^{-3} (atm)
1 μm	4.70×10^{8}	6.39×10^{7}	-	-
10 μm	3.48×10^{8}	4.84×10^{7}	-	-

We define accretion timescale $t_{ac} = 1 / n\sigma\Delta V$, where n is the number density of dust grains, σ is the collisional cross section, and ΔV is the relative velocity. The number density is expressed as $n = \zeta\rho_g / \bar{m}$, where ζ is the mass fraction of dust grains, ρ_g is gas density and $\bar{m}$ is the mean mass of the grains. The collisional cross section is expressed as $\sigma = \pi\bar{r}^2$, where $\bar{r}$ is the mean radius of the dust grains. The accretion timescale has to be shorter than the hibonite formation timescale. From this requirement, relative velocity (V_{req}) between corundum grains needed for formation of corundum aggregates was estimated.

Relative velocities in the solar nebula are produced by the following mechanisms: (V_1) thermal Brownian motion [9], (V_2) sedimentation owing to the vertical component of the solar gravity [9], and (V_3) turbulent motion [10]. An additional requirement is that the relative velocity has to be small enough that two grains stick to each other upon impact: $V_4 \equiv$ velocity upper limit for sticking [8].

We calculated relative velocities between grains of slightly (20%) different size at a radial distance 0.06 AU from the Sun. Relative velocities due to Brownian motion (V_1), sedimentation (V_2) and turbulent motion (V_3) and V_4 are smaller than the velocity required (V_{req}) for formation of corundum aggregates at a steady cooling rate in the nominal solar nebula (Fig. 3).

Therefore, our theoretical consideration suggests that formation of corundum aggregates is not possible in the nominal solar nebula that cools at a steady rate. Either the nebula was chemically fractionated (Ca-poor) or the nebula stayed at a temperature between condensation temperature of corundum and formation temperature of hibonite for a long time.

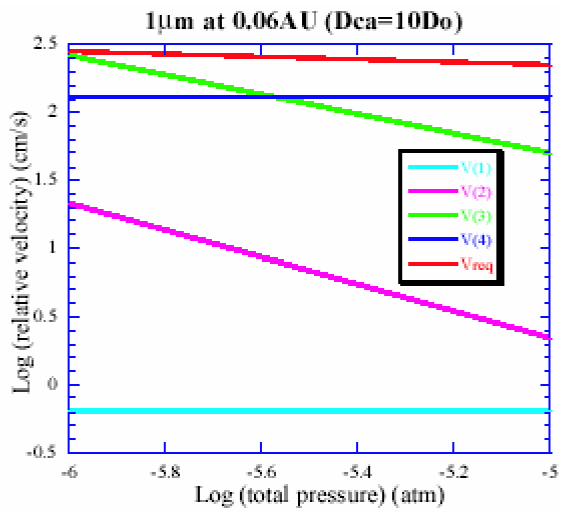

Fig. 3. Relative velocity of a corundum grain 1 μm in size at radial distance 0.06 AU from the Sun.

References: [1] Simon S. B. et al. (2002) *Meteorit. Planet. Sci.* 37, 533-548. [2] Krot A. N. et al. (2001) *Meteorit. Planet. Sci.* 36, A105. [3] Krot A. N. et al. (2004) *GCA* 68, 2167-2184. [4] Nakamura T. M. et al. (2005) *LPS XXXVI*, #1249. [5] Kozasa and Hasegawa (1987) *Progress of Theoretical Physics* 77, 1402-1410. [6] Yoneda S. and Grossman L. (1995) *GCA* 59, 3413-3444. [7] Heuer and Lagrelof (1999) *Phil. Magaz. Lett.* 79, 619-627. [8] Chokshi et al. (1993) *Astrophys. J*, 407, 806-819. [9] Nakagawa et al. (1981) *Icarus* 45, 517-528. [10] Weidenschilling S. J. (1984) *Icarus* 60, 553-567.