GROWTH OF CONDENSATIONS IN THE PREPLANETARY DISK AND THE PLANETS FORMATION. G.V. Pechernikova and A.V. Vityazev, Institute for Dynamics of Geospheres RAS, 38 Leninsky prosp. (bldg. 1), 119334 Moscow, Russia, pechernikova@idg.chph.ras.ru

Formulation of the problem. Two approaches for explanation of planetary systems were developed in the last two centuries. According to the first of them, planets were accumulated from the solid bodies (Chladni, 1794, Multon-Chamberlin, 1905, Schmidt, 1945, Safronov, 1950-80, Wetherill, 1980-1990, et al). According to the second one, planets were originated from large gas-dust condensations (Kant-Laplace, XVIII c., Berlage-Weizsekker, 1930-50, Eneev-Kozlov, 1975, et al). In the standard scenario of the Solar System formation it is assumed that terrestrial planets were formed from the solid bodies [1-4] after a short condensation stage, but giant-planets were formed from condensations. Recently [5, 6] some geochemical arguments in support for prolongated stage of condensation for terrestrial planets were proposed. Here we attack such a possibility from a dynamical point of view.

Model: Growth of mass of the largest condensations in terrestrial zone. A formal description of evolution of an individual condensation is given in [1, 2]. Here we outline a constitutive part of it. The internal gravitational force of a primary condensation is greater than external forces. Therefore, the condensation starts to contract, until gravitation is balanced by centrifugal force, increasing during contraction. Its velocity of rotation is close to the Keplerian velocity. It has long been noticed that non-central collisions were the only mechanism capable to maintain the planetesimals in rarefied state. The combining of condensations leads to an efficient compression, on the average, irrespective of whether it is a cloud of dust or rotating swarm of debris. Thus, in the case of the combining of two condensations of comparable masses colliding centrally, its mass doubles practically while the angular momentum remains as before: the radius of the condensation decreases twofold while the density increases 16-fold. At tangent collisions the change of angular momentum can even exceed considerably the angular momentum before the collision, maintaining the newly formed condensation in rarefied state, and even leading to the scattering of a substantial part of the matter. Thus, in the condensation system there is a need to describe simultaneously change in number, masses, sizes (densities) and angular moments of colliding, combining and disintegrating condensations in the framework of a self-consisted problem. The description of the set of equations can be found in [2]. Below, a brief account of the corresponding model and results of new calculations are presented.

The mass distribution of preplanetary bodies is usually represented in the form of a simple power law

$$n(m,t)dm = c(t)\, m^{-q} dm, \quad 1 < q < 2, \qquad (1)$$

where the exponent q does not depend on time and is determined by a coagulation equation of the type

$$\frac{dn(m,t)}{dt} = \int_{m_0}^{m/2} A(m', m-m')n(m',t)n(m-m',t)dm' - n(m,t)\int_{m_0}^{M} A(m,m')n(m',t)dm'. \qquad (2)$$

Here, $A(m, m')$ is the coagulation coefficient and m_0 and M are the lower and upper limits of the distribution. The coagulation coefficient $A(m, m')$ is proportional to the frequency of collisions between bodies with masses m and m', having a relative velocity $V(m, m')$ before encounter, and is written as:

$$A = \pi(r+r')^2\left[1+\frac{2G(m+m')}{V^2(r+r')}\right]V,$$

$$V = \sqrt{v^2(m) + v'^2(m')}\,, \qquad (3)$$

where the first three factors determine the cross section for the collision within the framework of the two-body problem. For $A(m, m') \propto m^\alpha + m'^\alpha$ with $0 < \alpha < 2$ a solution of the equation (2) was obtained as $q = 1 + \alpha/2$ [2]. On the assumption that the momentum of a condensation rotation is determined only by its mass, $K \propto m^\gamma$, it was shown in [2] that $q = \bar{\gamma}$ for the massive condensations, the escape velocity from which exceeds V. The rate of growth of a largest condensation is described by the equation [1, 2]:

$$\frac{dm}{dt} = \pi\, l_0^2 \bar{\rho}_d v \approx \frac{8\pi}{3}(1+2\theta)\zeta\, r_0^2 \left(\frac{m_0}{m}\right)^{6-4\bar{\gamma}} \frac{\sigma_d}{P_K}, \qquad (4)$$

where l_0 is the impact parameter, ρ_d and σ_d are the density and the surface density of the solid matter in the feeding zone of the planet respectively, $v = (Gm/\theta r)^{1/2}$ is the average relative velocity of the condensations, r_0 and m_0 are their initial radius and mass, P_K is the period of revolution around the sun, ζ is the coefficient of initial contraction of the condensations ($\zeta \sim 10^{-1}$), θ is a parameter of the order of first units for bodies in the absence of the gas and of the order of ten for bodies moving in the gas (Safronov' parameter) [1, 2].

The density δ of the condensations during their collisional evolution increases as

$$\delta = (m/m_0)^{10-6\bar{\gamma}}\delta_0 \qquad (5)$$

from the density δ_0 of the condensation just after its initial contraction. When δ increases up to ~1 g/cm^3 condensations become solid bodies. Denoting $m/M_\oplus = z^3$, where $M_\oplus$ is the mass of the Earth, and taking into account that $\sigma_d(t)$ decreases from its initial value σ_0 due to depletion of the material as

$$\sigma_d(t) = \sigma_0\,[1 - (m/M_\oplus)^{2/3}], \qquad (6)$$

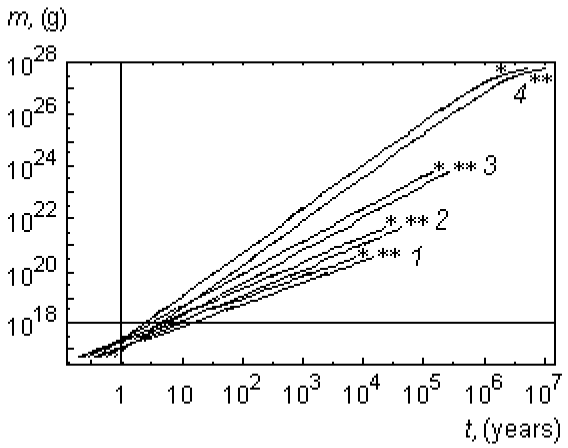
we pass to variable z in Eqs. (4-6). Then, an increase of δ and the time of growth of the condensation from the mass m_0 to $m=z^3M_\oplus$ are described by the following expressions:

$$\delta=\left(\frac{z}{z_0}\right)^{3(10-6\bar{\gamma})}\delta_0, \qquad (7)$$

$$t=\frac{1}{B}\int_{z_0}^{z}\frac{z^{2-3(4\bar{\gamma}-6)}}{1-z^2}dz,\ B=\frac{0.2\pi(1+2\theta)}{9}\left(\frac{M_\oplus}{m_0}\right)^{4\bar{\gamma}-7}. \qquad (8)$$

We set $z_0 = (m_0/M_\oplus)^{1/3}$ and $\delta_0 = 10^{-5}$ g/cm^3, $m_0 = 5\cdot10^{16}$ g for the terrestrial zone. From (7) we find the value z_{max} of conversion of condensations into solid bodies for the values of $\bar{\gamma}$ determined for massive condensations. Then, inserting z_{max} in Eq. (8), we estimate the time t_{max} for corresponding increases of mass from m_0 to $m_{max}= z^3_{max} M_\oplus$.

Results. In Figure and Table we illustrate our estimates of the duration of the evolution of condensations and the corresponding increase in their mass, first obtained with taking into consideration of depletion effects.



Growth of the mass m(t) of a massive condensation in the terrestrial zone depending on parameters γ and θ (see Table). The curves calculated at $\theta = 10$ are marked by *, ones calculated at $\theta = 5$ are marked by **.

Curve	1**	1*	2**	2*
θ	5	10	5	10
t_{max}, 10^3 yrs	15	8	44	23
γ	1.45		1.50	
m_{max}, g	3.5 10^{20}		5 10^{21}	
Curve	3**	3*	4**	4*
θ	5	10	5	10
t_{max}, 10^3 yrs	280	150	(*a*) 11800	(*a*) 6200
γ	1.55		1.60	
m_{max}, g	7 10^{23}		5.8 10^{27}	

(a) At γ = 1.6 the mass growth is calculated up to $m = 0.97\ M_\oplus$, in this case the density remained < 1, (δ = 0.266 g/cm^3).

Discussion. Largest condensations in the zone of terrestrial planets can grow up to 0.1 of their modern masses. These results are obtained within a "mean-field" approximation and for some plausible values of parameters of presolar disk and condensations. One can see from Figure and Table, that protoearth "density' can be < 1g/cm^3 when γ ≈ 1.6 with accumulation time ~ 10 Myr. We don't take into account the fluctuations. It seems likely that **a system of solid bodies and system of condensations in the preplanetary disk existed contemporaneously.** The earlier (first Myr after CAI) formation of differentiated (10-1000km) bodies (as indicated by cosmochemical and isotopic data [7]) doesn't contradict the existence of condensations and giant rubble-piles at one time. The latest stage of accumulation due to an exhaust-effect must lasted about 100 Myr [1-4, 8-11] in accordance with U-Pb and I-Pu-Xe data.

Conclusion. So, synthesis of two approaches which were contrasted during a long time first offers a clear explanation of a whole complex of dynamic and cosmochemical data.

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