ACCRETION AND DIFFERENTIATION OF TERRESTRIAL PROTOPLANETARY BODIES AND Hf-W CHRONOMETRY

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Introduction. The extinct $^{182}\mathrm{Hf} - ^{182}\mathrm{W}$ isotope system has been widely applied to date core formation in planetary bodies (e.g., [1]). New Hf-W data for C and H chondrite meteorites [2-4] lead to very rapid accretion and early core formation of asteroids and terrestrial planets: 3 – 4 Ma for the Vesta, <30 Ma and <15 Ma for the Earth and Mars cores formation respectively [2, 3]. According to analytical calculations [5] and computer simulation [6] last stages accretion process of terrestrial planets the value of 100 Ma is preferable. We suggest here other interpretation of new chondritic ratio $^{182}\mathrm{W}/^{184}\mathrm{W}$ and the Solar system initial $^{182}\mathrm{Hf}/^{180}\mathrm{Hf}$: these data tell us about initial differentiation in large terrestrial planetesimals and protoplanets at the stage of large impacts before the end of accretion of terrestrial planets. In this scenario Earth's core and Moon were formed later but before late bombardment stage.

Theory and Estimations. Bodies formation in the preplanetary disk was taking place in several stages (see, e.g. [5, 6]). Dust settling and forming of the first generation of planetesimals with the sizes up to 1000 km continued from 1 to 10 Ma. It is $^{26}\mathrm{Al}$ that could be a source of early heating and relative differentiation of the early bodies. Impacts with velocities surpassed 5 km/sec and differentiation of melted interiors were the main sources of energy for heating and differentiation of bodies of sizes above 1000 km which, according to [5, 6], accumulated at times 10–100 Ma (see Table 1).

Heating of a growing protoplanet of mass M while collisions with bodies of mass $m_i = \mu_i M$ was estimated in [5] as

$\overline{T} = T_0 + 1500\mathrm{K}(R/1500\mathrm{km})^2 f(\mu_i)$,

where $f(\mu_i \to 0) \simeq 2.5\mu_i$, $f(\mu_i \to 1) \simeq 1$. The same order of heating by collisions with great number of the less large bodies $(N m_j \sim m_i)$ $\Delta T_N \sim 1500\mathrm{K} N f(\mu_i/N)(R/1500\mathrm{km})^2$.

For population of largest planetesimals of the radius R the main characteristic times are

1) accumulation time $\tau_a = R/\dot{R} \propto R/(1-aR^2)$;

2) internal heat transfer time $\tau_\kappa = R^2/\mathrm{Nu}\,\kappa$ (Nu is the Nusselt number accounting the impact stirring as well, $\kappa \simeq 10^{-2}\mathrm{cm}^2/\mathrm{sec}$);

3) differentiation time $\tau_d = R/v_d$ (v_d is the differentiation velocity).

Possible $3! = 6$ regimes are determined by relations of the type $\tau_\kappa < \tau_a < \tau_d$, $\tau_a < \tau_\kappa < \tau_d$ and so on. Two of them are the most interested, they are $\tau_d < \tau_\kappa < \tau_a$, $\tau_d < \tau_a < \tau_\kappa$. In these cases the differentiation of enough large (1000–3000 km) protoplanet bodies to core and mantle must be accompanied by the additional heating (see Fig. 1).

With the use of sinking (or sedimentation) equation for the heavy component sinking with the velocity $v_d \propto \exp[-E/R_* T]$ and the heat conduction equation with the source of the form $c\Delta\rho g v_d$, $(g = 4\pi G\overline{\rho}R)$ we get the criterion for a fast development of the differentiation [5, 7]:

a) $c\Delta\rho g v_{d0} h^2 E/(4\mathrm{Nu}\kappa_0 \rho c_p R_* T_{d0}^2) > \gamma_{cr}$, $\gamma_{cr} = 0.88$ — flat layer, $\gamma_{cr} = 2$ — spherical layer,

b) $\theta = E(T - T_{d0})/R_* T_{d0}^2 > \theta_{cr} \simeq 1$.

For characteristic parameters of protoplanets in the terrestrial zone we estimate thickness of the layer where the effective differentiation begins as ≈ 300 km and find that it depends on these parameters variation weakly.

Discussion. The joint analysis of the planet accumulation at the Large Impact stage and their impact heating up to liquidus temperatures points to essential heating and possible differentiation in exothermal regime with selfheating (between catastrophic collisions). Because of this, Hf - W data can be interpreted as evidence for early differentiation and forming of primitive cores and mantles in large preplanet bodies tens of Ma before their final integration into four terrestrial planets. Data on Nb - Zr [8] evidencing for moderately fast accumulation, and Earth's core formation during 70 - 100 Ma, and presence of relict

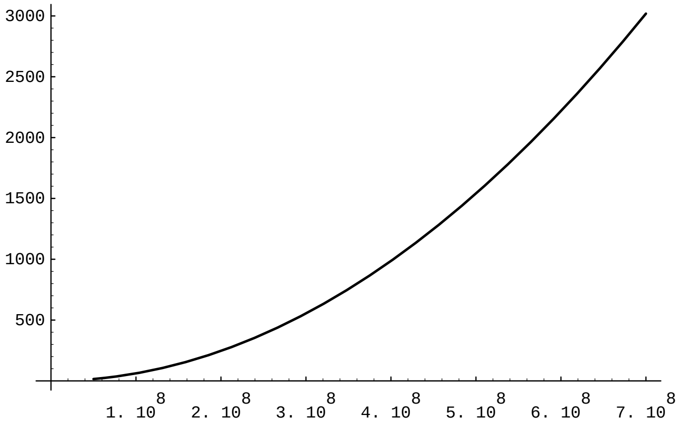

Figure 1: Heating due to gravitation differentiation

detrital terrestrial zircons [9] are not in contradiction with this scenario.

Table 1. Distribution of the large bodies in the feeding zone of the growing Earth

Mass of the growing Earth $m(t)$	$0.7\,m_{\oplus}$	$0.9\,m_{\oplus}$	$0.99\,m_{\oplus}$
The growth time, 10^6 yr	~ 50	~ 80	~ 100
Masses and radii of five largest bodies			
$m_1(g)$	$3.1\,10^{26}$	$1.1\,10^{26}$	$1.2\,10^{25}$
$r_1(km)$	2600	1900	900
$m_2(g)$	$9.0\,10^{25}$	$3.1\,10^{25}$	$3.2\,10^{24}$
$r_2(km)$	1700	1200	570
$m_3(g)$	$5.1\,10^{25}$	$1.8\,10^{25}$	$1.8\,10^{24}$
$r_3(km)$	1400	1000	470
$m_4(g)$	$3.5\,10^{25}$	$1.2\,10^{25}$	$1.2\,10^{24}$
$r_4(km)$	1300	900	420
$m_5(g)$	$2.6\,10^{25}$	$9.0\,10^{24}$	$9.0\,10^{23}$
$r_5(km)$	1200	800	380
Interval of radii (km)	The number of bodies $N(r)$ in the freeding zone		
$500 - 100$	2150	870	127
$100 - 10$	$6.9\,10^5$	$2.8\,10^5$	$4.1\,10^4$
$10 - 1$	$2.2\,10^8$	$8.8\,10^7$	$1.3\,10^7$

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