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Time Scale for the Formation of the Earth and Planets and Its Role in Their Geochemical Evolution

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The duration of the process of formation of the Earth and planets is discussed. A short time scale for formation of the Earth (10^4–10^5 years) has been proposed, not from a consideration of the rate of its growth, but from geochemical and geophysical considerations. On the basis of the dynamics of a swarm of protoplanetary bodies and the process of accretion of the planets, the author has found an accumulation time for 98 percent of the mass of the Earth of 6×10^7–10^8 years and a characteristic time for sweeping out of the protoplanetary cluster (reducing its mass by half) of 10^7 years. It is shown that the shorter accretion time found by Öpik, Cameron, Hallam, and Marcus is related to arbitrary assumptions about the parameters of the model for the swarm (e.g., the relative velocities of the bodies, the cluster density).

The initial mass of the solar nebula is discussed. Models of a massive nebula (two solar masses and more) encounter serious difficulties: an effective mechanism of transfer of the momentum from the central part of the nebula outward, capable of leading to formation of the Sun and removal of half the mass of the nebula from the solar system has not been found. As a consequence of the instability of these models, their evolution can end with the formation, not of a planetary system, but of a binary star. The possibility is demonstrated of obtaining acceptable growth rates for Uranus and Neptune by prolonging the thickening of preplanetary dust in the region of large masses.

The important role of large bodies in the process of formation of the planets is noted. The impacts of such bodies, moving in heliocentric orbits, could have imparted considerable additional energy to the forming Moon, which, together with the energy given off by the joining of a small number of large protomoons, could have led to a high initial temperature of the Moon.

1. In recent years, interest in the time scale of planetary formation has increased considerably, because a close connection has been found between the length of the formation period and initial state of the planets, and, consequently, their subsequent evolution, especially geochemical. A short scale leads to a higher initial temperature of the planet and, in principle, even permits fractionation of the elements in the accretion process.

As a result of two opposing approaches to the problem, two sharply differing scales of the accretion process are now used:

A. In 1945, O. Yu. Schmidt (ref. 1) derived a formula for the growth rate of the planets. The mass of a planet increases in proportion to the geometric cross section of the planet, in proportion to the surface density σ of the solid material remaining in the planet's zone of accretion, and in inverse proportion to the period of revolution P of the planet around the Sun. In 1954, we refined this formula. It was found that the gravity of a planet significantly accelerated its growth. As a consequence of gravitational focusing, the effective collision cross section was larger than the geometric cross section of the planet πr^2, by $1 + V_e^2/V^2$ times, where V_e is the parabolic velocity at the surface of the planet and V is the mean relative velocity of a body in the zone of the planet. Thus,

$$\frac{dm}{dt} = 4\pi r^2 \ (1 + V_e^2/V^2) \frac{\sigma}{P}. \qquad (1)$$

Solid material could not be ejected from the region of the terrestrial group of planets by planetary perturbations, and the initial mass of the region was equal to the current mass of these planets. Therefore, the only unknown quantity in the formula is the velocity of the bodies. The relative velocities of the bodies increased, as a consequence of their gravitational interaction upon approaching a rotating system, and it decreased in inelastic collisions. A comparison of these opposing effects (ref. 2) resulted in finding that the relative velocities of gravitating bodies are proportional to the parabolic velocities at the surface on the largest body in this zone (nucleus of the planet): $V^2 = V_e^2/2\theta = Gm/\theta r$. In the absence of a gas slowing the motion of the bodies and with a distribution of the bodies like the distribution of the mass of the asteroids, this proportionality factor is found to be close to 1/3, which gives a velocity of the body in the zone of the Earth, in the concluding stage of its growth, of about 4 km/s ($\theta \simeq 3-5$). These data permit the growth rate of the planets to be estimated. The radius of the proto-earth increased at practically a constant rate at 20 to 30 cm per year, to half its current value. Then, as the supply of material in the growth zone was exhausted, growth began to slow down. A characteristic time for sweeping out the material of the swarm, i.e., reducing its mass by half, with these values of θ, is 8 to 12 million years, and the time for accumulation of 98 percent of the mass of the Earth is 60 to 100 million years. In a review of the results of the Cambridge Cosmochemical Symposium, Mitler (ref. 3) notes that this scale is in conformance with the observed differences in ages of different types of meteorites, in particular, with the conclusion that the majority of the achondrites are 50 million years older than the chondrites—a figure obtained from a Rb/Sr estimate and confirmed by the Pb/Pb method. Our estimates permit an indeterminacy of half an order of magnitude; therefore, a value of 10^7 years can apparently be considered as the lower limit for the time of growth of the Earth.

B. A few years ago, the hypothesis of a considerably faster accretion of the planets became widespread. It did not arise initially from a consideration of the accretion process. Ringwood (ref. 4) approached it from geochemical considerations based on the idea of a hot initial state of the Earth. Hanks and Anderson (ref. 5) saw, in the idea of rapid accretion, the possibility of accelerating formation of the core of the Earth, and Turekian and Clark (ref. 6) and then Anderson and Hanks (ref. 7) saw the possibility of deriving a hypothesis of nonuniform accretion of the Earth. The last authors named above assumed the accumulation time of the Earth to be 50 thousand years. Such a rapid accretion would lead to a hot, almost molten initial state of the Earth. However, no estimates of accretion times which would reinforce this point of view were made by the authors. Such estimates began to appear somewhat later. They should be dwelt on in greater detail.

The problem was analyzed in greatest detail by Öpik (ref. 8). The characteristic time he found for sweeping out the Earth's swarm is an e-fold decrease in its mass, $\tau_e = 50\,000$ years, which corresponds to the time for reducing the mass of the swarm by half, $\tau_2 = 35\,000$ years, i.e., 2.5 orders of magnitude less than the value of 10^7 years we found. Öpik himself called this the *minimum* time. He did not determine the relative velocities of the bodies, and took the lowest value permissible from his point of view, 3/4 km/s, for the numerical estimate. In this case, he had to adopt a highly artificial model, to concentrate all the solid material of the zone in a thin, narrow ring around the orbit of the Earth, 0.2 AU wide, that encompasses only one-third of the supply zone of the Earth. If he had considered a more likely model, in which the bodies were distributed over the entire zone of the Earth and had sufficient velocity to be able to fall to Earth, the time for sweeping out the swarm and, correspondingly, the time of the growth of the Earth would have increased by almost two orders of magnitude. At slower velocities of the bodies, they could only move from the outer parts of the zone to the vicinity of the Earth by diffusion. However, diffusion is a still slower process, and takes over 10^8 years.

Accretion of the preplanetary bodies also is considered in the recently published work of Hallam and Marcus (ref. 9). In it, an accretion time of the Earth $\tau_+ = 200\,000$ years. However, it was obtained with an unrealistically high density of solid material in the zone of the Earth $\rho = 2 \times 10^{-9}$ g/cm^3, taken ad hoc for a model similar to that of Cameron. Our model leads to $\rho = 4 \times 10^{-12}$ g/cm^3. With such a density, the growth time of the Earth would coincide with our value of 10^8 years.

The shortest time for accretion of the Earth (less than 10^4 years) has been obtained by Cameron (refs. 10 and 11). This is only partially connected with the high mass of the solar nebula adopted in the model of Cameron. The principal cause of very rapid growth of the planets in Cameron's model is that he proposes their accretion in an unrestrictedly flattening layer of particles, with a thickness much less than the diameter of the planet. However, first, this extremely high degree of flattening of the layer is physically impossible, because of gravitational perturbations by the massive protoplanets (ref. 12). Second, the model is internally contradictory: strong flattening means low relative velocities of the bodies and small eccentricities of their orbits. Under such conditions, a planet might gather material located only in a very narrow zone along its orbit, i.e., only a small fraction of the material located in its zone. Expansion of the supply zone takes place only in proportion to increase in the velocities of the body and, correspondingly, should take more and more time.

Thus, in all cases, arguments in favor of a short scale of growth of the planets may disclose arbitrary assumptions, whose elimination also leads to lengthening the scale.

Mizutani et al. (ref. 13) discussed the rate of accretion of the Moon in an isolated protolunar cloud. The authors calculate the density of the cloud and the velocities of the particles, at which rapid accretion of the Moon takes place (in less than 10^3 years) and the outer part of the Moon turns out to be molten. They consider this melting to be a necessary requirement from geochemical and geophysical data. However, the physical model of the initial cloud analyzed by the authors is very indefinite, and its suitability is not substantiated. Such estimates would made sense only if the protolunar cloud itself could have formed very quickly, significantly more rapidly than the Moon then formed from it. However, assuming that the Moon was formed in a circum-Earth swarm of particles encompassing the Earth during the entire time of its growth, we must conclude that the replenishment time of the cluster and the accretion time of the Moon was 10^7 to 10^8 years.

2. Our concepts of the nature of the physical, chemical, and mechanical processes in the solar nebula and the protoplanetary cloud essentially depend on the initial model of the nebula. In particular, the P–T conditions of condensation of the solid particles that determine the chemical composition of the planets, as well as the rate of accumulation of the planets, depend heavily on the mass of the nebula. In recent years the massive solar nebula model of Cameron (refs. 10 and 11), double the mass of the Sun, has become widespread. In this model, the amount of solid material in the zone of the Earth turns out to be approximately 20 times the mass of the Earth. This would give a 20-fold acceleration in growth of the Earth. However, there are very important problems in the description of this model, which do not permit it to be considered to be internally consistent. The most serious of them are the following:

A. The problem of evolution of the extended rotating gas-dust nebula into a star (Sun), with simultaneous removal of half the mass of the nebula beyond the solar system, has not been solved. Estimates have shown that all of the previously proposed mechanisms for transfer or momentum from the central region of the nebula outward are extremely ineffective and are not capable of leading to formation of the Sun. There is no basis for expecting that the new, still little-studied method of "meridional circulation," proposed by Cameron only in qualitative form, will prove to be more effective (ref. 14). On the contrary, there are serious doubts, both as to the possibility of effective transfer of momentum from the inside to the outside by means of this mechanism, and as to the possibility of the very existence of a large-scale circulation in highly flattened systems. Moreover, the possibility is not excluded that evolution of a nebula, with such a large momentum as that in the model of Cameron, can culminate in formation, not of a planetary system, but of a binary star.

B. The problem of how to remove more than 90 percent of the solid material from the region of the terrestrial group of planets has not been solved. Existing data testify against the possibility of this removal. Radial displacement of bodies due to their being slowed down by the gas ends quite early, because of the rapid growth of the mass of the bodies. Interaction of the bodies among themselves cannot give them significant velocities and leads to ejection of a considerable fraction of all the bodies from the zone of the terrestrial group of planets (as occurred in the region of the giant planets).

Recently, Levin (ref. 15) proposed a new model of a massive solar nebula. The author sees the principal difficulty of the problem as slow growth of the outer planets. With an initial amount of solid material in the zone of Uranus and Neptune equal to the modern mass of these planets, the time of their growth, according to formula (1), turns out to be on the order of 10^{11} years (ref. 16). The assumption of a large initial mass of the outer sections of the nebula, as well as that the main loss of gas took place by means of thermal dissipation, accompanying a significant approach to the Sun of the residue (jet effect), led Levin to the conclusion of very large initial (post-collapse) dimensions of the nebula (200–300 AU). He assumes the total mass of the nebula, including the protosun, to be 3–4 solar masses, i.e., 1.5–2 times larger than in the model of Cameron. In order to eliminate difficulty B. of the model of Cameron, he takes a considerably smaller density of nebula material (and, correspondingly, total mass) in the region of the terrestrial group of planets, than in the model of Cameron (a slower increase in density toward the center of the nebula).

This model of a massive solar nebula meets with the same serious difficulty A., seen in the model of Cameron; no effective mechanism is known for transfer of momentum from the inside to the outside, which would lead to formation of the Sun. In addition, having a greater extent and lower concentration toward the center, this model of the nebula is still less stable, with respect to decay into a binary system, than the model of Cameron.

We also cannot agree with the opinion of Levin, that such a model of a massive nebula is necessary for solution of the problem of growth of Uranus and Neptune. The process of accumulation of the giant planets was very complicated, and it requires more comprehensive and thorough analysis.

Theoretically, there are three possibilities of reducing the growth time of the outer planets: (1) increase in initial mass of solid material in this region; (2) decrease in relative velocities of the bodies at the stage preceding their ejection from the solar system; and (3) lengthening of the concentration stage in regions of large masses.

It is known that the giant planets ejected a considerable amount of solids from the solar system in the process of growing. The initial mass of solid material in the region of the outer planets could have been much greater than their present mass. However, it is important to determine precisely how much solid material was ejected. According to our estimates, the amount of solid material ejected by a planet is an order of magnitude more than the material absorbed by it. This corresponds to a comparatively small mass of the protoplanetary cloud (0.1–0.15 M.) and to formation of the planets at almost the same distances from the sun as they now are. However, this does not completely insure the growth of Uranus and Neptune in 4.6×10^9 years.

The possibility of accelerating the process of accretion, by means of lower relative velocities of the bodies, i.e., through an increase in parameter θ in (1), is not clear now, although it is not excluded. The velocities could have been less, for example, because of the great inelasticity of collisions of the bodies and particles of ice (a more intensive disintegration) than in collisions of silicate bodies in the region of the terrestrial group of planets.

There is still another feature of formation of the outer planets, to which insufficient attention was given earlier. According to modern conceptions (refs. 2 and 17), the initial evolution of the preplanetary cloud, with a high degree of probability, should have consisted of a flattening of a dust layer, the generation of gravitational instabilities in it, and formation of numerous dust concentrations. Conditions for gravitational instability were most favorable in the region of the giant planets. In the zones of Uranus and Neptune, the critical value of the velocities of particles of the dust layer ($v < v_{cr}$ is necessary for instability) was quite large. In table 1 are presented the values, assumed in our model, of the initial surface density of solid material (P_0) in the zones of various planets, v_{cr} values, initial masses of dust concentrations m_o in fractions of the mass of the planet m_p, their initial densities ρ_0, masses m_b, at which condensation should stop in solid bodies with $\rho \sim 1$–3 g/cm^3, and the time for decrease of the mass of the cluster by half τ_2 in the concluding stage ($m \rightarrow m_p$).

Table 1.—*Values of Initial Surface Density of Solid Material*

Zone of Planet	σ_o (g/cm^2)	v_{cr} (cm/s)	m_o/m_p	ρ_o (g/cm^2)	n_e/m_p	τ_2 (years)
Mercury	1.5	0.4	10^{-15}	5×10^{-5}	10^{-13}	6×10^6
Venus						
Earth	10	11	10^{-11}	3×10^{-6}	10^{-9}	10^7
Mars						
Jupiter	20	270	4×10^{-9}	2×10^{-8}	10^{-5}	10^6
Saturn						
Uranus	4	380	2×10^{-6}	4×10^{-10}	10^{-2}	2×10^8
Neptune	3	560	10^{-5}	10^{-10}	10^{-1}	3×10^8

The concentration stage was short in the region of the terrestrial group of planets, and it did not play a significant role in the accretion process. According to our estimate the concentrations as a result of their compression on combining, converted to normal bodies ($\rho \sim 1$g/cm^3) after an increase in their initial masses by approximately 2 orders of magnitude (from 10^{-11} to 10^{-9} earth mass). The situation turns out to be completely different in the region of outer planets. The initial masses of the concentrations are inversely proportional to the sixth power of the distance from the Sun, and were only 5 orders of magnitude less than the mass of Neptune in the zone of Neptune. On the other hand, the initial densities of the concentrations (on the order of the Roche density) in the zone of Neptune were 3×10^4 less than in the zone of Earth, and therefore, to convert them into a body required an increase in their initial mass, not by two orders of magnitude as in the zone of the Earth, but by four orders of magnitude. Consequently, the preplanetary material concentration of Neptune could remain quite a long time, until its mass reached approximately a tenth of mass of Neptune (this idea was expressed by Vityazev). Having greater dimensions than a normal body, it swept up the surrounding material considerably more quickly. We have estimated the growth time of Neptune under these conditions, on the assumption of moderate relative velocities of the bodies ($\theta = 5$). The initial mass of solid material in the zone of Neptune was assumed to be ten times the mass of Neptune. The density of the protoplanetary body was assumed to be monotonically increasing (according to the power law), with increase in its mass up to $\rho = 1$, with a mass of one tenth the mass of Neptune. The time for growth of Neptune to 98 percent of its modern mass turned out to be not over 2 billion years. This is an acceptable result and demonstrates that the possibilities still have not been exhausted of solving the problem of growth of the outer planets, without going to a model of a massive nebula. The difficulties of the latter appear to us to be considerably more serious, which forces us to prefer physical, chemical, and mechanical investigations using a model of the solar nebula with a mass of $\sim 1.1 M_{\odot}$ and, correspondingly, a preplanetary cloud, with a mass of $\sim 0.1 M_{\odot}$.

3. The explanation of the large role of large bodies in the process of planetary formation has led to significant corrections in the conceptions of the initial state of the planets. Theoretical research conducted at the Institute of the Physics of the Earth, USSR Academy of Sciences (refs. 2 and 17), has shown that the distribution of mass of the preplanetary bodies, established in the accretion process, can be approximated by an inverse power law $n(m) = cm^{-q}$, at $q \sim 11/6$, i.e., by a law similar to the law describing the distribution of the mass of the asteroids, meteorites incident on the Earth, and bodies forming lunar craters. Bodies hundreds of kilometers in diameter made up a considerable fraction of the mass of all bodies forming the planets. The dimensions of the largest bodies falling onto the planets were estimated from the inclinations of the axis of rotation of the planets, which was created by the infall of large bodies. The impact energy of these bodies was released at considerable depths, and an appreciable part of it did not radiate into space. The layers of the upper mantle, at depths of about 500 km, underwent the greatest impact heating ($\simeq$ 1500° C).

The largest bodies created large-scale thermal irregularities in the upper mantle. Their extensive regions of impact, with diameters up to 1000 km, became hundreds of degrees hotter than the surroundings at the very start. The basic processes of the early evolution of the Earth are connected with the development of these irregularities (ref. 18). Partial melting took place in these irregularities in the first billion years, and two competing and oppositely directed processes, convection and differentiation, were started. These processes should have led to formation of the core of the Earth and the crust of the Earth. However, they are extremely complicated, and they still have been studied little.

There is a basis for considering that large bodies played an important part in the formation of the Moon as well. The source of the early heating of the Moon is quite an important question at the present time. Efforts to explain this heating by formation of the Moon at a distance closer to the Sun or by its extremely rapid accumulation are clearly unjustified. Formation of the Moon from a small number of large protomoons (ref. 19) gives a more suitable source, but for melting of the outer layer of the Moon, one of these bodies alone is inadequate because of the comparative low relative velocities of the protomoons. Bodies close to the Earth had considerably higher velocities when they were in heliocentric orbits at distances of 15–20 Earth radii; the velocities of bodies of the Earth zone reached 6 km/s. The energy of their impacts was 6–7 times greater than the gravitational energy on the surface of the Moon. The impact regions underwent severe heating and, possibly, melting. Wetherill (ref. 20) relates the "lunar cataclysm" ending about 4 billion years ago, with the impact onto the Moon of bodies from the region of the asteroids and even of the giant planets. The impact energies of such bodies were still greater.

Thus, the impacts of large bodies moving in heliocentric orbits were a significant additional preplanetary source for heating the forming Moon. This source deserves careful quantitative analysis.

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