GEOCHEMICAL ORIGINS OF THE EARTH

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Summary

The Earth formed through accretion of planetesimals in 1–100 million years. Planetesimal impacts induce degassing, melting, and vaporization during accretion. The impact degassing, as well as the gravitational capture of the surrounding solar nebula gas, formed the proto-atmosphere on a growing Earth. The impact of heating and the blanketing effect of the proto-atmosphere resulted in the melting of the growing Earth and the formation of magma ponds or magma oceans. Separation of metallic iron and silicate in the magma ponds or magma oceans lead to the formation of the iron core. Also, this melting resulted in the chemical differentiation of the proto-mantle to some extent. At the last stage of accretion, steam in the proto-atmosphere condensed and formed a proto-ocean.

1. Formation of the Solar System

The present theory of planetary formation was proposed around 1970 with the background of the theory of star formation developed in the 1960s. The theory developed in accordance with the success of planetary exploration in the 1970s. By the early 1980s a “standard model” of planetary formation, which is based upon the accretion of planetesimals, had been generally accepted. Development of radio astronomy enabled the direct observation of young stars with surrounding disks in the late 1980s. On the other hand, difficulties in the standard theory have been brought in light by accumulation of observational and theoretical knowledge. Figure 1 shows the outline of the standard model of planetary formation (See also *The Solar System*).

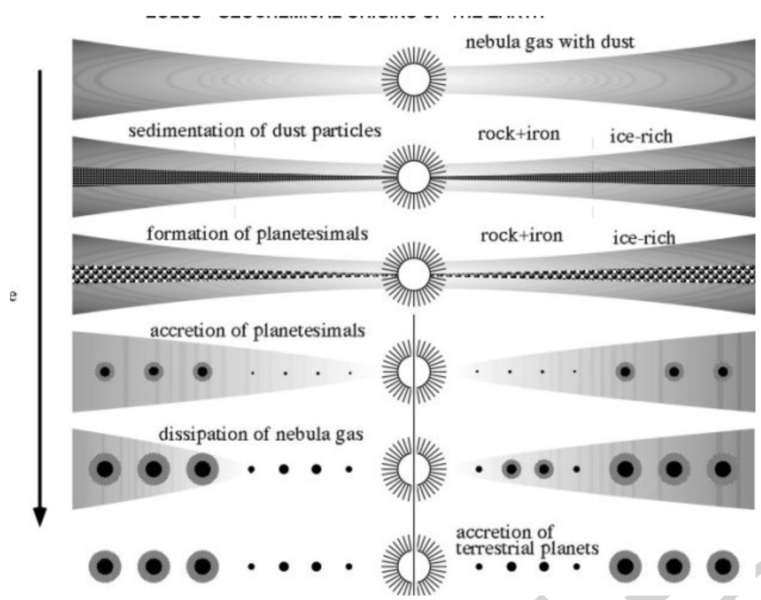

Figure 1.Schematic diagram for planetary formation. A cross-sectional view of the solar nebula is shown. Time goes from the top to the bottom. Top: formation of solar nebula composed of dust-gas mixture. Second: sedimentation of dust to the mid-plane of the disk. Third: formation of planetesimals. Fourth: accretion of planetesimals. Fifth and bottom: the left side shows the case when the dissipation of nebula gas occurs before the formation of terrestrial planets. The right side shows the case when terrestrial planets are formed in the nebula gas.

1.1. Formation of the Protoplanetary Disk

Interstellar molecular clouds are regions in space of high density of hydrogen molecules and low temperatures. The typical density of hydrogen molecules is about $5x10^{-5}$ m^{-3} (cf. the number density of air at the standard temperature and pressure is about $2.5x10^{13}$ m^{-3}). The typical size of a molecular cloud is 10^6~10^7 AU (astronomical unit = mean distance between the Earth and the sun) and mass is about 100 times to 10^5~10^6 times of the mass of the sun (1 $M_{SUN} = 1.99x10^{30}$ kg). Most elements, other than highly volatile materials such as hydrogen, helium, or carbon monoxide, are in solid particles (dusts) of about 1 micrometer size in the cloud. The mass fraction of dust is about 1~2 percent. Heavy elements, which are in the dust, are mostly formed at the last stage of star evolution. The very active young sun may have reprocessed a fraction of elements in the protoplanetary disk.

The core of the molecular cloud is the region with a higher density of about $0.02m^{-3}$. The typical size of the core is 10^4 AU, the typical mass is a few times the solar mass, and the typical temperature is 10 K. A protostar is formed by contraction of the core with about one million years time scale. In spite of a very large amount of gravitational energy released during contraction, temperature is kept low because of efficient radiative cooling. As contraction proceeds, the efficiency of radiative transfer gets worse and temperature and pressure rise at the central part of the core. Then, the gravity force and pressure gradient is balanced, and the contraction changes to a quasi equilibrium. Objects at this state are called protostars. Protostars radiate a large amount of energy released by contraction, but we cannot see them in visible light as they are embedded in the molecular cloud core. We see infrared radiation from the surrounding gas and dust.

Stars become visible as gas and dust are lost, either blown away or falling onto them 10^5~10^6 years after their formation. Such stars are called T Tauri type stars. Temperatures of T Tauri type stars are still too cool for nuclear fusion (hydrogen burning). They radiate energy released by their contraction. In spite of low surface temperatures, their luminosity is large because of a large radius. As their contraction proceeds, the central temperature gets high enough for hydrogen to burn. This is the transition to the main sequence stars. It takes about 30 million years in the cases of one-solar-mass stars.

Most T Tauri stars seem to have a circumstellar disk. The size of the disk is estimated about 100 AU, which roughly corresponds to the size of the solar system. We call such disk structures protoplanetary disks. They correspond to the proto-solar nebula, which is postulated in the theory of the solar system formation.

The formation of the protoplanetary disk proceeds contemporaneously with the formation of the central star. Gas and dust in the molecular cloud have non-zero angular momentum around the protostar. Owing to the conservation of the angular momentum, the cloud core spins up as it contracts. Then, gravity balances with the centrifugal force in the direction perpendicular to the spin axis. However, contraction proceeds parallel to the spin axis and forms a disk structure.

Though the disk contains as much as 25–50% of the total mass, some part of it falls onto the star and the other part moves away through the transfer of angular momentum in the disk. Such a falling disk is called an “accretion disk.” Though the mechanism is not well understood, the accretion stops and a low-mass disk remains around the star. The formation of planets occurs after the cessation of disk accretion.

1.2. The Standard Model of Planetary Formation

In the standard model, the initial configuration and state of the nebula are just assumed, because knowledge about star formation is limited. In a disk-like nebula, the solar gravity, gas pressure, and centrifugal force are all balanced. Mass distribution in the nebula is estimated from the present mass distribution in the solar system. One well-known model is given by Hayashi et al (1981) as follows.

$$\Sigma = 1.7\times 10^{3}\left(\frac{a}{1\ \mathrm{AU}}\right)^{-\frac{3}{2}} \quad (\mathrm{g\ cm^{-2}}) \qquad (1)$$

$$\Sigma_d = \begin{cases} 7.1\left(\frac{a}{1\ \mathrm{AU}}\right)^{-\frac{3}{2}} & (\text{for } 0.3\ \mathrm{AU} < a < 2.7\ \mathrm{AU}) \\ 30\left(\frac{a}{1\ \mathrm{AU}}\right)^{-\frac{3}{2}} & (\text{for } 2.7\ \mathrm{AU} < a < 36\ \mathrm{AU}) \end{cases} \quad (\mathrm{g\ cm^{-2}}) \qquad (2)$$

where Σ is the surface density of the disk, which is the mass of the disk integrated in the direction of disk thickness, and a is the distance from the sun. Σ_d is the surface density of solid materials (dust). It changes at 2.7 AU because of condensation of H_2O-ice beyond this limit. Since this model assumes minimum amount of materials for planetary formation, the model is called the minimum-mass Solar nebula model. In this particular model, the total mass of the disk is 1.3% of the solar mass.

The temperature of the disk can be estimated by assuming that the disk is transparent and the temperature of gas is the same as those of the dust particles. Temperature is given by radiative equilibrium between the solar irradiation and infrared emission from a dust particle.

$$T = 280\left(\frac{L}{L_{SUN}}\right)^{\frac{1}{4}}\left(\frac{a}{1\mathrm{AU}}\right)^{\frac{1}{2}} K \qquad (3)$$

where L_{SUN} is the solar luminosity $3.9\mathrm{x}10^{26}$W. Pressure at the midplane of the disk is given by the force balance of pressure gradient and gravity,

$$p(0) = 1.4\left(a/1\mathrm{AU}\right)^{-13/4}\ (\mathrm{Pa}) \qquad (4)$$

Since dust particles are not supported by gas pressure, dust gradually falls onto the mid-plane of the disk. Dust particles grow during the sedimentation process because of mutual collision. If dusts stick together at every collision, sedimentation time is about $2\mathrm{x}10^3$ years and dust grows up to 1 cm~20 cm size at 1 AU. Sedimentation takes a long time at a large distance from the sun.

As the sedimentation proceeds, the thickness of the dust layer decreases. When the thickness of the dust layer gets thinner than a critical value, mutual gravity of dust particles becomes large enough to lead to gravitational fragmentation of the dust layer. This forms gravitationally bounded dust blobs, called “planetesimals.” The estimated mass of planetesimals is about 10^{15} kg and their compressed size is about 10 km at 1 AU. The planetesimals are the building blocks of planets. Unfortunately, however, no sample of planetesimals can be obtained and their properties are unknown. Beyond 2.7 AU from the sun, the planetesimals are made of ice. Cometary nuclei may be fossils of icy planetesimals formed in the distant part of the solar system.

Gravitational instability occurs only when the thickness of the dust layer gets extremely thin (~700 km at 1 AU). However, the motion of gas may disturb the sedimentation of dust particles. Some researchers think that the planetesimals are not formed by the gravitational instability but by other processes such as sticking growth of dust particles.
In any event, accretion of planets proceeds through mutual gravitational interaction of 10^{10} planetesimals orbiting around the sun. In the following, just a qualitative account of the accretion process is given. If we consider randomly moving planetesimals and ignore collisional fragmentation, the growth rate of planetesimals is given by the product of collision cross section σ_{col}, spatial density ρ_p, and relative velocity v of planetesimals. The collision cross section is larger than the geometric cross section because of gravitational attraction. For simplicity, we consider only 2-bodies interaction

between a protoplanet (larger planetesimal) and a planetesimal, and we assume that the planetesimal is much smaller than the protoplanet. The relative velocities of planetesimals are approximately given by the thickness of the region h where planetesimals exist (different from the thickness of the gas disk) divided by the Kepler period τ_K. The spatial density ρ_p corresponds to the dust surface density Σ_d divided by the thickness h. Then, approximate growth rate is given by

$$M\overset{\prime}{Y} \approx \pi R^2 \left(1+\frac{v_e^2}{v^2}\right)\frac{\sum_d}{\tau_K} \qquad (5)$$

In spite of simplification, the formula describes the qualitative nature of the accretion process.

First, the larger growth rate is the result of the shorter Kepler period and the larger surface density. The Kepler period increases with the 1.5th power of the distance from the sun. In the Hayashi model, the surface density decreases with 1.5th power of the distance from the sun. Thus, accretion time increases with the 3rd power of the distance. Therefore, very long accretion time is required for the distant planets. It is well known that the theoretical estimate of the accretion time of Neptune is too long and may exceed the age of the solar system. This problem is not resolved yet.

Second, slow relative velocity compared with the escape velocity results in a large collision cross section and large growth rate. The relative velocities of planetesimals are controlled by gravitational interaction among planetesimals and protoplanets. If the relative velocity is kept at a small value independent of the escape velocity of the protoplanet, the collision cross section increases with the growth of the protoplanet. Then, one large protoplanet will grow quickly and many planetesimals will remain small. Such a situation is called “runaway growth.” On the other hand, if the relative velocity increases with the increase of the escape velocity, smaller planetesimals also grow. This is called “orderly growth.” Recent theories and numerical simulations indicate that runaway growth does occur. In the inner solar system, many Mars-sized protoplanets are formed within one million years through runaway accretion. Then the growth rate slows down as the planetesimals are depleted in the feeding zone, the region from which protoplanets collect the material.

Later, the gravitational force between them disturbs the orbits of protoplanets. This leads to mutual collision of protoplanets and further growth. Such collisions of Mars-sized bodies are sometimes called “giant impacts.” Since large eccentricity is required for collisions among protoplanets, some damping mechanism is required to reduce the eccentricities of planets to the present values. However, the damping mechanism is not well understood yet. In any event, the terrestrial planets are thought to be formed in two stages: the runaway accretion stage and the giant impact stage.

The early solar system contained a large amount of solar composition gas, which is lost at present. If a protoplanet grows in the gas, it will gravitationally attract the solar composition atmosphere. If the mass of the protoplanet exceeds about 10 times of the Earth’s mass, the attracted atmosphere collapses owing to its gravity. Jovian planets are thought to be formed in this way. Jupiter has a ~10-Earth-mass “core” probably made of rock and ice surrounded by 300-Earth mass hydrogen–helium gas envelope. Such a structure indicates its formation in the nebula gas. Saturn contains less gas than Jupiter. Uranus and Neptune contain less gas than Saturn. These planets may be formed during the dissipation of the nebula gas. Observations of young stars suggest the lifetime of the gas nebula to be in the order of 10^7 years.

The dissipation mechanism is unknown. Strong solar wind and/or ultraviolet radiation during the T Tauri stage of the sun was a rather popular theory of the mechanism. However, recent observations suggest that strong radiation is accompanied by disk accretion and it fades out before the formation of planets. As alternative mechanisms, the dissipation through viscous transfer of angular momentum due to turbulent motion in the nebula, or transfer of angular momentum due to asymmetric-arm-like structures formed by gravitational perturbation are proposed.

1.3. Age of the Solar System

The oldest material of known age in the solar system is CAI (Calcium–Aluminum-rich Inclusion) in carbonaceous chondrites. Their age of 4.566 Ga is the minimum estimate of the age of the solar system as CAIs are thought to be formed in the protoplanetary disk. The age of the oldest meteorite is 4.5627 Ga, which indicates the formation of small bodies (planetesimals) started within 3 million years of the formation of the disk. The age of the oldest meteorite that records a melting event is 4.5578 Ga, suggesting the igneous activity in planetesimals started within 5 million years of disk formation. The formation age of the Earth is still controversial. An old crustal rock on the moon gives the minimum age of the moon as about 4.5 Ga. This suggests the formation of terrestrial planets occurred within about 100 million years of the formation of the protoplanetary disk.

The evidence of extinct nuclei, the radioactive nuclei that existed in the early solar system but lost at present, may suggest that the interval between the synthesis of elements and the formation of the solar system is very short. However, recent studies suggest a possibility that some extinct nuclei were formed in the solar system owing to vigorous activity of the young sun.

2. Formation of the Earth

The formation and early evolution processes of the Earth are affected by:

1. composition of the Earth-forming material,
2. whether or not the solar composition gas existed around the Earth during accretion, and
3. accretion time, size, and impact velocity of planetesimals.

2.1. The Composition of the Earth-Forming Materials

There are no samples of the planetesimals that formed the Earth. The composition of the Earth-forming materials is estimated from the composition of meteorites and the average composition of the Earth. It seems natural that the Earth-forming materials were heterogeneous, because the present Earth has both a reducing metallic core and oxidizing oceans and atmosphere.

A simple but powerful model is a 2-components model, which considers a reducing component A, which lacks volatile components and contains iron as oxide and also contains all components in the same proportion as meteorites, and an oxidizing component B, which contains iron as oxide and also contains all components in the same proportion to the meteorites. Since the isotope system of the Earth does not fit any meteorite groups, we should not consider that either A nor B component corresponds to a particular group of meteorites. The present mantle can be approximated by 85:15 mixture of A and B components.

If the composition of the planetesimals accreted to the Earth is roughly constant throughout the accretion, this is homogeneous accretion. If the composition changes during accretion, this is heterogeneous accretion. It is not clear whether the Earth accreted homogeneously or heterogeneously. In the most popular model of heterogeneous accretion, the accretion of the Earth-forming material changed from reducing A-component to oxidizing and volatile-rich B-component. In particular, there is an idea that volatile-rich carbonaceous-chondrite-like or comet-like materials were accreted to the Earth at the last stage of accretion. This is called as the “late veneer” hypothesis. The Earth was likely to have collected nearby planetesimals first and distant planetesimals later. Therefore, if the planetesimals at 1 AU are depleted in volatile components owing to the short distance from the sun, heterogeneous accretion is likely because volatile components are supplied by distant planetesimals. However, it is not clear whether the planetesimals at 1 AU are volatile-depleted or not. If the planetesimals contain volatile components and oxidized materials, the accretion proceeds more or less homogeneously. Therefore, the choice of either accretion model is purely a matter of assumption at present.

2.2. Nebular Gas

It is clear that the Jovian planets are formed in the gas disk. However, whether the terrestrial planets were formed in the gas nebula is uncertain. At present, two extreme models exist for the formation of the terrestrial planets. In one extreme model, the formation of the terrestrial planets is completed before the dissipation of the gaseous nebula. In the other extreme model, the formation of terrestrial planets proceeds in essentially gas-free space. If the lifetime of the gas nebula were in the order of 10 million years, the nebula gas would be likely to be lost after the end of runaway growth and before the completion of the accretion. In reality, the gas nebula would exist at the early stages of planetary formation, but it would be lost before the completion of planetary formation.

2.3. Size and Velocity of Planetesimals and Accretion Time

If planetesimals are formed by gravitational instability, the initial mass is about 10^{15} kg around 1 AU. Since it changes because of collisional growth and fragmentation, it is not easy to estimate the planetesimal mass at the last stage of accretion. During runaway growth, namely, the growth stage up to the Mars-size, the planetesimals are likely to remain small. However, the size of impacting planetesimals during the growth from the Mars-size to the Earth-size is not well understood. Several giant impacts of Moon- or Mars-size bodies occur every 100 million years.

During the runaway accretion stage eccentricity of planetesimals is small and the relative velocity is at most the escape velocity of the proto-Earth. Then, taking into the effect of Earth's gravity, the impact velocity is about $\sqrt{2}$ times that of the escape velocity from the proto-Earth. Thus, the estimated impact velocity is 11 kms^{-1}~15 kms^{-1} at the final stage of accretion. It is roughly proportional to the radius of the proto-Earth. On the other hand, after the end of accretion, the impactors (comets and near-Earth asteroids) have a large eccentricity. The impact velocities of those bodies are characterized by the orbital velocity of the Earth 30 kms^{-1}. Thus, the impact velocity is much larger after the end of accretion.

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Biographical Sketch

Professor **Yutaka Abe,** is an associate professor of Earth and Planetary Science at the University of Tokyo since 1992. Born on June 16, 1959, in Tokyo, Japan. He got his DSc (Geophysics) from the University of Tokyo in 1987. He served as a research fellow of the Japan Society of Promotion of Science

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