FORMATION OF THE PLANETS

Chushiro Hayashi
Dept. of Physics, Kyoto University, Kyoto, Japan

A timetable for an evolutionary sequence of processes, which begins with the formation of the solar nebula being nearly in equilibrium and ends with the planetary formation, is presented. Basic features of the processes and grounds for the estimation of time-scales are explained for each of the processes.

1. INTRODUCTION

On the origin of the solar system, a wide variety of theories have so far been presented since the days of Kant and Laplace in the 18th century. Theories have become more and more realistic with time and, at present, we are at a stage of very scientific investigation.

There still remain many fundamental problems to be solved. For example, it is not yet clear to what degree the magnetic force is important in determing the structure of the pre-planetary nebula. The magnetic force will be effective in a collapsing stage of the nebula and also in the outer regions of the nebula after it has settled into equilibrium, i.e., in stages and in regions where the gas is ionized above a certain level by cosmic rays and the solar UV radiation. However, in most of the regions of the nebula where the planets are formed, the ionization degree of the gas is lower than, say, 10^{-15} and the magnetic effect may be neglected compared to the solar gravity and the gas pressure.

Besides the magnetic effect, a variety of solar nebula models have so far been proposed. Here I choose recent three models and indicate their basic differences. First, in Cameron's model (Cameron 1973, DeCampli and Cameron 1979), the mass of the nebula is as large as $2M_\odot$ (including the Sun) and the surface density of the disk is as high as 10^5 g/cm^2. Then, the disk fragments into gaseous protoplanets with mass as large as that of the present Jupiter (see Section 4 for the condition of fragmentation).

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On the other hand, in models of Safronov (1969) and us (Kusaka et al. 1970, Hayashi et al. 1977 and others) the nebular mass is in the range, 0.01-0.04$M_\odot$, and the gas disk is stable against fragmentation. The fragmentation occurs only in a thin dust layer which is formed later as a result of sedimentation of dust grains towards the mid-plane of the gas disk. A basic defference between Safronov and us lies in that we have fully considered the effect of the nebular gas on planetary formation, such as on the growth time of the planets and on the formation of the giant planets.

It is not possible to review here all the topics on planetary formation. Then, I choose to talk mainly about the results of our Kyoto group obtained in these ten years, which are summarized in the following timetable (Table 1) where an evolutionary sequence of many important processes are listed.

Table 1. Main events and time intervals.

Interval	Events and processes
10^4y ---	Collapse of a rotating molecular cloud of about 1 $M_\odot$.
	Formation of a pre-planetary gas disk being in equilibrium.
10^4y ---	Growth and sedimentation of grains to form a dust layer.
	Fragmentation of the dust layer into planetesimals ($\sim 10^{18}$ g).
10^5y ---	Accumulation of planetesimals to protoplanets ($\sim 10^{25}$ g).
	Formation of protoplanets with surrounding gases.
10^6y ---	Radial migration and trap of planetesimals in the Hill sphere.
	Formation of the Earth surrounded by a hot H_2 atmosphere.
10^7y ---	Growth of a Jupiter's core to 10 times the Earth mass.
	Formation of Jupiter with collapsing of its atmosphere.
10^{7-8}y -	Escape of the nebular gas and the Earth's H_2 atmosphere.
	Complete gas escape, formation of present Earth atmosphere.
4×10^9y -	Planetary perturbation and other processes in the absence of gas.
	Present.

There are four processes or stages of special importance in the evolution, as denoted by the thick lines in Table 1, where very drastic changes occur in the physical condition of the solar nebula. These are (1) the collapse of a cloud and the formation of a gas disk which is rotating (in nearly Keplerian motion) around the proto-Sun and is nearly in a state of thermal and dynamical equilibrium under the influence of the solar gravity and radiation, (2) the fragmentation of a thin dust layer due to gravitational instability, (3) the collapse of surrounding H_2 atmospheres onto the protoplanets which have grown above a certain limit (about 10M_E, where M_E being the Earth's mass) and (4) the disappearance of the gas component of the disk due to the solar wind and UV radiation which are expected to be very strong in the T Tauri stage of the Sun.

In stages lying between the above four stages, the change of physical conditions is more continuous and gradual and we may follow the evolution with more precise calculations. Explanation of the processes listed in Table 1 will be given in each of the following sections.

2. STRUCTURE OF A GAS DISK

At the end of the collapse, the solar nebula will be heated to relatively high temperatures (say, 2×10^3K in the Earth region) by shock waves and will also be in turbulent motion. This turbulence as well as the magnetic field, if it is strong enough, may have a role of transferring angular momentum outwards. The turbulence will decay in a time of several Keplerian periods and, further, in a time of the order of 10^3 yrs the disk is flattened (i.e., the Helmholtz-Kelvin contraction) and the gas cools to reach a thermally steady state where the heating of the nebular gas by the solar radiation balances with the radiative cooling.

Let us now consider the structure of the equilibrium disk in helio-centric cylindrical coordinates where r and z denote the distance from the Sun and the height from the equatorial plane of the disk, respectively. Under the assumption that the radial displacement of all the dust materials (which form the planets later) during the time from this stage to the present was minimum, Kusaka, Nakano and Hayashi (1970) determined the distribution of the surface density $\rho_s(r)$. For example, they distributed the present Earth's mass uniformly in the region, r=0.85-1.23 AU, and multiplied this by a factor, 300 =(H+He)/(Mg+Si+Fe). Then, from considerations of thermal and dynamical equilibrium, they constructed a disk model where the gas density ρ and the temperature are determined as functions of r and z.

According to this model, the total mass of the gas disk is in the range 0.02-0.04$M_\odot$ and the structure has such features as shown in Table 2, where $z_o(r)$ denotes the half-thickness of the nebula and $\eta(r)$ $(=1-\Omega(g)/\Omega)$ is the deviation of the gas angular velocity $\Omega(g)$ from the Keplerian angular velocity, $\Omega=(GM_\odot/r^3)^{1/2}$, which is due to the existence of a pressure gradient in the r-direction.

Table 2. Structure in regions of the Earth and Jupiter.

r(AU)	z_o(AU)	$T_{z=o}$(K)	$\rho_{z=o}$(g/cm^3)	η
1.0	0.04	230	6×10^{-9}	0.002
5.2	0.33	100	2×10^{-10}	0.004

The radial distribution of the surface gas density is approximated by the form r^{-k} with a constant k lying in the range 1.5-2.0. Adopting, for example, the case of k=2, we plot the surface density of dust mass in Fig. 1, where also the ranges of the present planetary perturbation are indicated. Keeping in mind Bode's law, we may imagine from Fig. 2 how the giant planets were formed in the outer regions and also how the gap in the asteroid region resulted from Jupiter's perturbation.

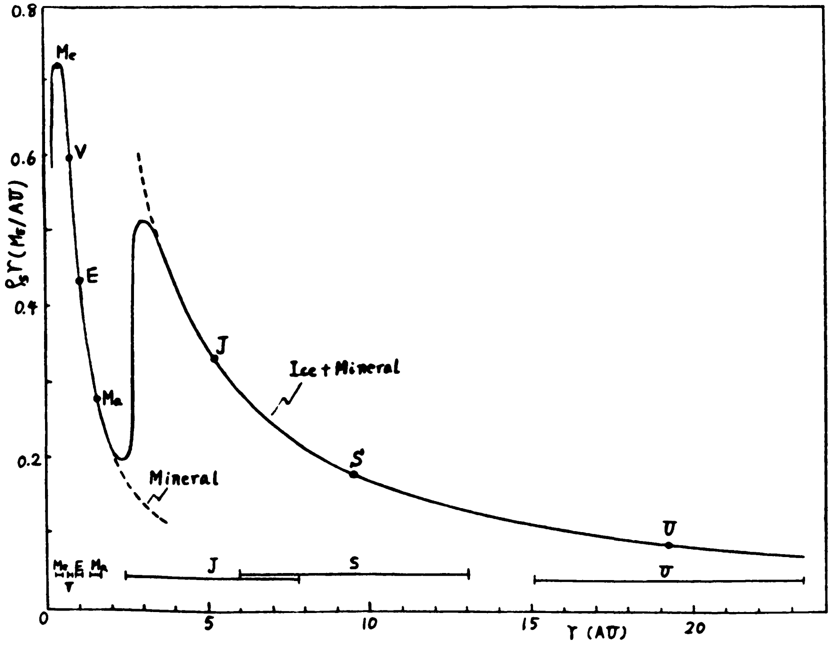

Fig. 1. Distribution of dust mass and ranges of planetary perturbation. The ordinate is the surface density ρ_s of dust mass multiplied by the distance r. The ranges of planetary perturbation, indicated by the segments in the lower region of the diagram, correspond to a ± (7h+ea) where a, e and h are the semi-major axis, the eccentricity and the Hill radius of the present planets.

3. GROWTH AND SEDIMENTATION OF DUST GRAINS

Old results of Kusaka et al. (1970) have been greatly improved by recent calculations of Nakagawa, Nakazawa and Hayashi (1980), where the disk are divided into 10 layers in the z-direction and the time variation of the mass spectrum of grains in each layer is calculated. The details will be talked by Nakagawa in this session. The result indicates that a thin dust layer, composed mainly of cm-size grains, is formed near the mid-plane of the gas disk in about 5×10^3 yrs. This layer begins to fragment into a number of planetesimals as shown in the following section.

4. FRAGMENTATION OF THE DUST LAYER

Gravitational instability of a thin disk (a homogeneous mixture of dust grains and gas molecules) for a ring-mode variation in the form, $\exp(i\omega t+ikr)$, was studied by Safronov (1969), Hayashi (1972) and Goldreich and Ward (1973). The dispersion relation and the condition for instability are given by

$$\omega^2 = \Omega^2 + c^2k^2 - 2\pi G\rho_s k < 0 \quad \text{(unstable)}, \tag{1}$$

where ρ_s is the surface density of the dust layer and c is the sound velocity given by

$$c^2 = \gamma p/\rho = \gamma(n_m+n_d)kT/(\rho_m+\rho_d) \simeq \gamma n_m kT/\rho_d \; . \tag{2}$$

Here, the subscripts m and d denote gas molecules and dust grains, respectively.

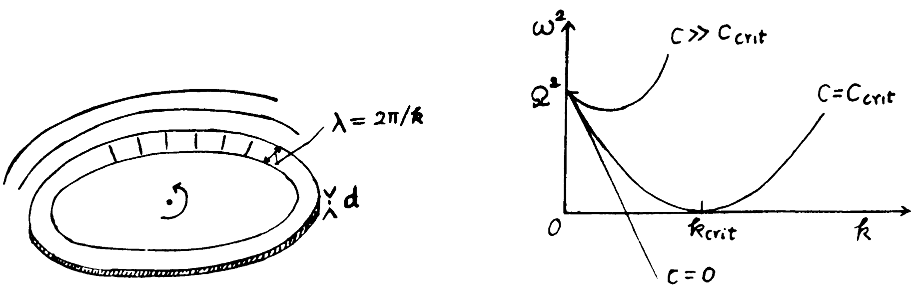

Fig. 2. Ring-mode instability and dispersion relation.

As the sedimentation of grains proceeds, the sound velocity decreases gradually and when it becomes smaller than the critical value, $c_{crit}=\pi G\rho_s/\Omega$, the layer fragments into a large number of rings (Fig. 2) and it is expected that, nearly at the same time, a ring fragments into a number of beads. At a critical stage, where $c=c_{crit}$ and $k=k_{crit}=\Omega^2/\pi G\rho_s$, and at r=1 AU with $\rho_s=20\,g/cm^2$, we have for the size and the mass of a fragment, $\lambda=2\pi/k=7\times10^8$ cm and $m=\rho_s\lambda^2=1\times10^{19}$g, respectively. The thickness and the density of the layer at this stage are about 200 cm and 0.1 g/cm^3, respectively. The total number of the fragments in the whole disk is about 10^{12}.

The above dispersion relation was obtained for the case of one-component fluid. The case of two-component fluid (i.e., gas fluid and dust fluid with mutual frictional interaction) was studied by Hayashi (unpublished). The result indicates that the fragmentation begins at a stage earlier than the above-mentioned critical stage, i.e., at a stage when the density of the dust layer becomes nearly equal to the Roche density ($=2\times10^{-6}g/cm^3$ at r=1 AU) and the layer thickness is about 10^7 cm. At this stage, sedimentation is faster than fragmentation. Then, the final size and mass of a fragment will not be greatly different from the above-mentioned values.

The fragment, formed in the above process, still contains a small amount of gas molecules and shrinks gravitationally to a so-called planetesimal of 10 km size, which is made of sands of silicates containing also ices if r is greater than about 2.7 AU.

5. ACCUMULATION OF PLANETESIMALS TO THE PLANETS

Our final aim for the accumulation process will be to find the time variation of a distribution function f(m; a, e, i; t) (where m is the mass, and a, e and i are the semi-major axis, the eccentricity and inclination, respectively, of a Keplerian orbit around the Sun) for an ensemble of solid bodies with size ranging from planetesimals to the present planets and also to find the time variations of the density and velocity of the gas present in the solar nebula. This is to solve a problem of long-term stochastic irreversible processes occuring in a coupled system of the gas and solid bodies, both of which are under the strong influence of the solar gravity. It will be very difficult, at present, to find a complete solution but we have to know, at least, the relative velocities of colliding planetesimals and also the rate of their radial migration, both of which determine the rate of their accumulation.

Hayashi, Nakazawa and Adachi (1977) studied this problem under the simplifications that (1) all the solid bodies, except for one massive protoplanet under consideration, have the same mass but this mass increases with time and (2) all the gas is in circular motion with velocity as mentioned in Section 2. The orbital motion of solid bodies is treated as composed of regular motion (with e=i=0) and random motion which is proportional to e and i. If we set aside the accumulation process for a moment, the change of orbital motion is determined by three effects: gravitational scattering, gas drag effect and planetary perturbation, as will be explained in the following.

5.1. Gravitational scattering (a large number of two-body encounters).

We use the result of Chandrasekhar on the problem of stellar dynamics by modifying it in order to apply to the case of Keplerian particles under consideration, where the mean random velocity v is given by

$$v^2 \simeq (e^2 + i^2)\, v_k^2. \qquad (3)$$

Here, v_k is the Keplerian velocity in circular motion. Obviously, the mean change in Δt due to scattering is zero, i.e., $\langle\Delta a\rangle=\langle\Delta e\rangle=\langle\Delta i\rangle=0$, but the mean square change in Δt is finite and the diffusion coefficients in the three-dimensional (a, e, i) space are given by

$$\frac{<(\Delta a)^2>}{a^2 \Delta t} \simeq \frac{<(\Delta e)^2>}{\Delta t} \simeq \frac{<(\Delta i)^2>}{\Delta t} \simeq \frac{e^2+i^2}{t_c} \quad , \tag{4}$$

where t_c is the collision time which is related to the cross section σ for two-body scattering, the mass m and the surface number density n_s of solid bodies:

$$t_c = \frac{1}{nv\sigma} \quad , \quad \sigma = \pi\left(\frac{2Gm}{v^2}\right)^2 \ell n\left(\frac{v^2 d}{2Gm}\right) \quad , \quad n = \frac{n_s}{ai} \quad . \tag{5}$$

Here d is the mean separation of solid bodies. By means of Eq.(5), the above diffusion coefficient is written as

$$\frac{e^2+i^2}{t_c} = \frac{1}{\tau_c} \frac{1}{i(e^2+i^2)^{1/2}} \quad , \quad \tau_c = 9 \times 10^{63} (\Omega a^2 n_s m)^{-1} \text{ (c.g.s.).} \tag{6}$$

It is to be noticed that diffusion is very rapid if e and i are small.

5.2. Gas drag effect.

The gas drag effect which changes the orbital elements a, e and i was calculated by Adachi, Hayashi and Nakazawa (1976) and Weidenschilling (1977). The difference in the angular velocity between the gas and a solid body, as mentioned in Section 2, gives rise to a gradual change in a, e and i. The drag force acting on a body is given by

$$F \simeq \pi r_b^2 \rho v^2 \quad , \quad v \simeq (e + i + \eta) v_K \quad , \tag{7}$$

where r_b is the radius of a solid body, v is the relative velocity between the gas and the body, and η is a small quantity as shown in Table 2. Calculations with perturbation method give

$$\frac{1}{a}\frac{da}{dt} \simeq -\frac{2}{\tau_g} (e + i + \eta) (\eta + e^2) \quad , \tag{8}$$

$$\frac{1}{e}\frac{de}{dt} \simeq \frac{1}{i}\frac{di}{dt} \simeq -\frac{e+i+\eta}{\tau_g} \quad , \quad \tau_g = 7 \frac{m^{1/3}}{\rho v_k} \text{ (c.g.s.)} \; . \tag{9}$$

It is to be noticed that the rate of decrease of a (i.e., the rate of radial migration) is much smaller than those of e and i and that all the rates are sensitive to the values of e, i and η.

5.3. Effect of planetary perturbation.

This effect is important only in the neighborhood of a protoplanet (i.e., if the distance from a planet is smaller than about seven times the Hill radius). The excitation of random motion of a solid body due to this effect was estimated by Hayashi et al. (1977) by means of numerical calculation of the orbits in the frame of the Restricted Three-Body Problem.

5.4. Interplay of the effects of scattering and gas drag.

From Eqs.(4), (6) and (9) the mean values of e and i of an ensemble of solid bodies are found to change with time as

$$\frac{1}{e^2}\frac{de^2}{dt} = \frac{1}{\tau_c}\frac{1}{e^2 i(e^2+i^2)^{1/2}} - \frac{e+i+\eta}{\tau_g}\ , \qquad (10)$$

$$\frac{1}{i^2}\frac{di^2}{dt} = \frac{1}{\tau_c}\frac{1}{i^3(e^2+i^2)^{1/2}} - \frac{e+i+\eta}{\tau_g}\ . \qquad (11)$$

It is found from the above equations that in a relatively short period of time ($\simeq$ several times 10^4 yrs) both e and i attain equilibrium values given by

$$e \simeq i \simeq 1\times10^{-13}\ (a n_s m/\rho)^{1/5}\ m^{4/15}\ \text{(c.g.s.)}. \qquad (12)$$

Using the values of n_s and ρ in the model of Kusaka et al., we found that the equilibrium values of e and i at r=1 AU are 0.0004 (for $m=10^{18}$g), 0.003 (for 10^{21}g) and 0.014 (for 10^{24}g).

Putting these values of e and i into the equations for a, i.e., Eqs. (4), (6) and (8) we can estimate the time of radial migration which is composed of the two processes, i.e., (1) in-and out-wards diffusion ($a \rightarrow a/2$ or $2a$) due to the scattering effect and (2) inflow ($a \rightarrow a/2$) due to the gas drag effect. It will be seen that the interplay of scattering and gas drag shortens the migration time considerably compared to the case where only one of the two effects is present. The migration time for the case of, for example, $m=10^{21}$g is given in Table 3.

Table 3. Equilibrium values of e and i and time of radial migration.

	$e \simeq i$	Diffusion time	Inflow time
Earth region	0.003	1×10^{9}y	8×10^{6}y
Jupiter region	0.006	1×10^{10}y	2×10^{8}y .

Considering the change of m with time, we estimated the growth time of the planets (see Section 7). This growth time depends essentially

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on the above migration rate for solid bodies lying in regions distant from a protoplanet under consideration.

The above statistical treatment of the many-body problem was refined and extended (to the case where solid bodies has a mass spectrum of the form of the power law, m^{-k} dm) by Nakagawa (1978). He generalized the theory of Brownian motion to the case of non-isotropic velocity distribution and succeeded to find a self-consistent solution to the Fokker-Planck equation. Furthermore, Nakagawa calculated the accumulation of planetesimals and the change of the mass spectrum in very early stages where the mass increases from 10^{18} to 10^{22}g and the accumulation is due mainly to sticking of two bodies in direct collisions. He used the sticking cross section of the form,

$$\sigma = \pi \; (r + r')^2 \; \{ \; 1 + \frac{2G(m + m')}{|\vec{v} - \vec{v}\,'|^2 (r + r')} \} \quad , \tag{13}$$

where the magnitude of the relative velocity, $\vec{v}-\vec{v}\,'$, is known from the distribution function obtained by him. He has neglected the time required for radial migration since the migration over a short distance is very rapid. The result shows that, if the accumulation starts from bodies with a same mass, 1×10^{18}g, the mass spectrum tends to have a form of $m^{-1.5}$ in a period of 3×10^{4} yrs (see Fig. 3). The largest body in this spectrum is expected to grow to a protoplanet with mass of about 10^{25}g (as described in the next section) in about 10^5 yrs.

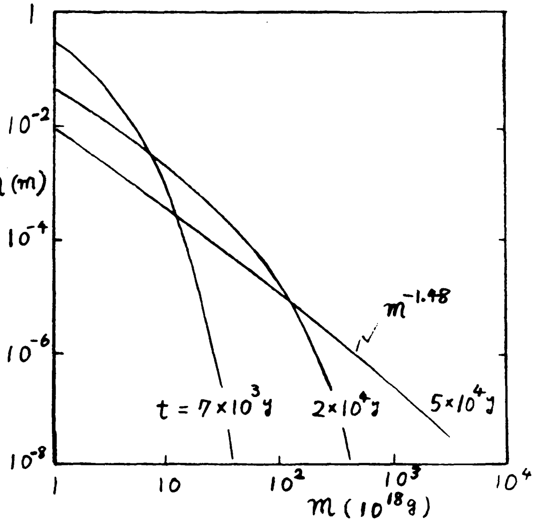

Fig. 3. Time variation of the mass spectrum of planetesimals in the Earth region. The ordinate denotes the number of planetesimals with mass between m and m+dm. At time t=0, all the planetesimals have the same mass, 1×10^{18} g.

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6. CAPTURE OF PLANETESIMALS IN THE HILL SPHERE OF A PROTOPLANET

The radius h of the Hill sphere, i.e., the sphere of gravitational influence of a protoplanet (with mass M and distance a from the Sun) is given by $h=a(M/3M_\odot)^{1/3}$. When M becomes greater than 10^{25} g, the escape velocity at the surface of the protoplanet becomes greater than the sound velocity of the nebular gas. Then, with M increasing, the nebular gas is attracted more and more towards the protoplanet and a surrounding atmosphere is formed. The gas density in the interior of the Hill sphere becomes higher than in the external regions. Consequently, the kinetic energy of a planetesimal which entered the Hill sphere is, more or less, dissipated by the gas drag effect and it tends to be trapped within the Hill sphere.

7. FORMATION OF THE PROTO-EARTH AND THE CORE OF JUPITER

The rate of further growth of a protoplanet is determined mainly by the rate of radial migration of planetesimals from distant regions and by the probability of their trap inside the Hill sphere. Hayashi et al. (1977) estimated that the Earth takes about 10^6 yrs to grow to the present mass, 1 M_E, and that a core of Jupiter (made of rocky and ice materials) of 10 M_E is formed in about 10^7 yrs.

8. PRIMORDIAL ATMOSPHERE OF THE EARTH

The structure of an atmosphere (in hydrostatic and thermal equilibrium) surrounding the proto-Earth was calculated by Hayashi, Nakazawa and Mizuno (1979). Boundary conditions are that the gas density ρ and temperature T take the nebular values at the surface of the Hill sphere. The opacity of the gas for thermal radiation is expressed in the form

$$\kappa(\rho, T) = \kappa_m + \kappa_g \ , \qquad \kappa_m = \kappa_{H_2} + \kappa_{H_2O} \simeq 100\,\rho \ (\text{c.g.s.}), \tag{14}$$

where κ_m is the opacity due to molecular absorption and scattering and κ_g is that due to dust grains. The value of κ_g is considered as a parameter which lies in the range between 1 cm^2g^{-1} (the interstellar value) and 10^{-5} cm^2g^{-1} (for which κ_g can be neglected compared to κ_m). At the bottom of the atmosphere there is a release of gravitational energy of accreting planetesimals and the resulting energy outflow (i.e. the luminosity) in the atmosphere is givn by $L=GM\dot{M}/R$, where $\dot{M}$ is the mass accretion rate which is taken to be $1M_E/10^6$ yrs, M and R being the mass and radius of the proto-Earth composed of rocky and metallic materials.

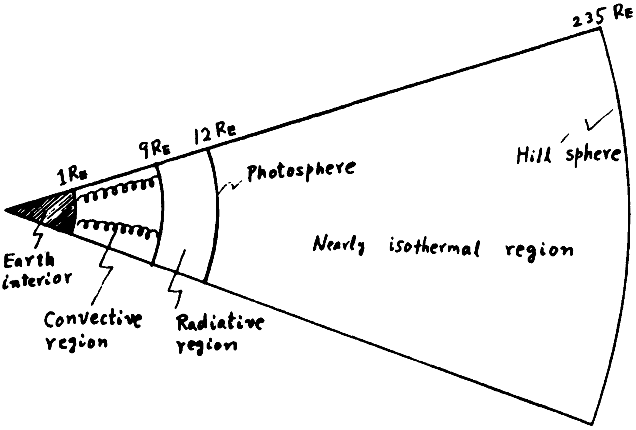

Fig. 4. Primordial Earth's atmosphere at a stage of $M/M_E=1$. The present Earth's radius is denoted by R_E.

The results of our calculations for a case of $\kappa_g=1\times10^{-4}$ cm^2g^{-1} are given in Table 4, where the subscript b denotes the bottom of the atmosphere. The atmosphere consists of radiative and convective regions (see Fig. 4).

Table 4. Structure of the primordial Earth's atmosphere.

M/M_E	T_b(K)	ρ_b(gcm^{-3})	p_b(atom.)	M_{gas}/M	L(erg/s)
0.1	690	1.4×10^{-4}	3.5	0.014	2.5×10^{24}
0.5	2590	2.2×10^{-3}	203	0.018	2.6×10^{25}
1.0	4100	6.1×10^{-3}	890	0.027	1.1×10^{26}

The existence of such a hot and dense atmosphere has two important effects, (1) melting of rocky and metallic materials in the Earth's interior which leads to the formation of the present core-mantle structure and (2) disolution of volatile gases into rocky materials as pointed out by Mizuno, Nakazawa and Hayashi (1980). It is well-known that the present atmosphere of the Earth is formed as a result of degassing from the interior and it is generally believed that this formation occured within a period of less than 5×10^8 yrs after the Earth grew to the present mass. Then, we have to consider that the primordial atmosphere was dissipated into outer space within the above period of time (see Section 10.1).

9. INSTABILITY OF ATMOSPHERES AND FORMATION OF THE GIANT PLANETS

The Earth stops its growth at a time when $M=1M_E$ because of the exhaustion of accreting planetesimals. How about the giant planets?

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It is well-known that the mass of an interstellar isothermal cloud surrounded by a gas with constant pressure is limited (this is due to a kind of Jeans' instability). For the same reason, when the mass of a surrounding atmosphere becomes comparable to that of a protoplanet (being called a core, for simplicity), the self-gravity of the atmosphere becomes important and the atmosphere begins to collapse onto the planet because of gravitational instability.

The above problem was first studied by Perri and Cameron (1974) under the assumption of a wholly-adiabatic temperature gradient and they found that the critical core mass for the onset of instability is as large as 70 M_E for the case of Jupiter. Mizuno, Nakazawa and Hayashi (1978) studied the same problem but with a different model of the solar nebula and different treatments of boundary conditions and opacities. Very recently, Mizuno (1980) calculated the atmospheric structure in the same manner (but including self-gravity) as described in Section 8 and found that, for the growth rate $\dot{M}=10\times M_E/10^7$ yrs, the critical core mass lies in the range between $2M_E$ (for $\kappa_g=10^{-5}\,cm^2g^{-1}$) and $10M_E$ (for $\kappa_g=1\,cm^2g^{-1}$) for all the protoplanets of the solar system. Then, we have to consider that after the collapse of the atmosphere a considerable amount of the surrounding nebular gas is further accreted onto the planets to form the present giant planets.

10. ESCAPE OF THE NEBULAR GAS AND THE EARTH PRIMORDIAL ATMOSPHERE

It is required that the solar nebula is dissipated into outer space after the formation of the present Jupiter but befoer the formation of the present Earth's atmosphere. Then, the time of escape of the solar nebula (as shown in Table 1) should be in the range between 1×10^7 and 5×10^8 yrs.

10.1 Escape of the Earth's atmosphere.

First, we consider the escape of the Earth's atmosphere which occurs after the dissipation of the solar nebula. Sekiya, Nakazawa and Hayashi (1980) studied the effects of the solar radiation (EUV as well as visible) which is incident on the rotating Earth. They calculated the spherically-Symmetric steady outflow of a gas which starts with very small velocity from the photosphere of the atmosphere (which has a structure as described in Section 8), taking into accounts the effects of (1) cooling of a gas due to adiabatic expansion (2) heating due to absorption of the solar EUV and visible radiation and (3) cooling due to emission of radiation from dust grains and molecules. The outer boundary condition for the gas flow is that the flow should pass through a sonic point, i.e., a well-known condition for a gas outflowing into free space.

The results of calculations show that, if the flux of the solar EUV radiation during the stage considered (i.e. the T Tauri stage of the proto-Sun) is greater by a factor of 10^3 than the present value, the main constituents (H and He) of the atmosphere escape in about 1×10^8 yrs. Furthermore, almost all of heavy atoms such as Kr and Xe can also escape owing to the drag of outflowing H_2 molecules and He atoms. Then, as to the abundance of the rare gas elements, there is no contradiction between the existence of the primordial atmosphere and the composition of the present Earth's atmosphere.

10.2 Escape of the solar nebula.

The effect of strong solar wind on the escape of the nebula was studied by Horedt (1978) and Elmegreen (1978). The above results of Sekiya et al. indicate that more than 10 percent of the absorbed EUV energy is converted into the kinetic energy of the outflow. By means of such energy considerations, let us here estimate the escape time of the solar nebula as a whole. For the model of Kusaka et al., gravitational binding energy of the solar nebula is given by

$$E = -\int \frac{GM_\odot}{2r} \rho_s \, 2\pi r dr = -8.3 \times 10^{43} \text{ erg}. \tag{15}$$

Then, the escape time of the nebula due to the irradiation of the solar wind is given by

$$t_{es} = \frac{-E}{\eta L_W \Omega/4\pi} = 3\times10^6 \frac{0.1}{\eta} \frac{10^{-2}L_\odot}{L_W} \frac{0.25}{\Omega/4\pi} \text{ yrs}, \tag{16}$$

where η is the efficienty of conversion of wind energy, L_W is the solar wind luminosity (or the particle luminosity) and Ω is the heliocentric solid angle subtended by a whole wind-aborbing surface layer of the nebula.

The value of $\Omega/4\pi$ is in the range 0.2-0.3 in the model of Kusaka et al. and probably we have $\eta \lesssim 0.1$. The particle luminosity of T Tauri stars is not well-known at present but probably it does not exceed 1/100 of the total luminosity (i.e., $\sim 1L_\odot$). Then, with η=0.1 we have $t_{es} > 3\times10^6$ yrs, corresponding to $L_W < 10^{-2}L_\odot$. This time-scale is consistent with our result (see Section 7) that the Earth and Jupiter are both formed during stages where the nebular gas is still existing.

11. FORMATION OF THE SATELLITES

As metioned in Section 6, the growth of the protoplanets is due to the accretion of planetesimals which, after entering the Hill sphere, gradually lose their kinetic energies (in interaction with gas molecules which fill the interior of the Hill sphere) until they reach the surface of the protoplanets. If the gas density in the Hill sphere is too high, planetesimals cannot survive as orbiting bodies but soon fall onto the planets. On the other hand, if the gas density and, then, the gas drag effect are too small, planetesimals cannot be trapped into bound orbits around the planets. Therefore, it is probable that the satellites are the remainder of planetesimals (already grown to their present masses) which are trapped in the Hill sphere at stages where the nebular gas is escaping and the gas density is decreasing to an appropriate level. In order to clarify this situation, the orbital motion of a planetesimal in the presence of a gas in the Hill sphere (in the Restricted Three-Body Problem) is now being computed by Nishida and by Komuro of our group.

12. CONCLUSION

It is very obvious that any theory of planetary formation should be self-consistent in itself and also should be tested by direct comparison with observations. In this respect, to promote the study of the origin of the solar system, collaborations of researches in very different fields of science, such as astrophysics, physics, chemistry, geology, geophysics and mineralogy, are indispensable.

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DISCUSSION

Cameron: Did your calculations obtain differential velocities between grains that are low enough that the grains stick, and therefore accumulate rather than fragment, on collision?

Hayashi: Since gas friction is present, the relative velocities between grains are small enough.

Schatzman: If you apply McCrea's theory of formation of planetesimals (fall toward the equatorial plane, viscous drag, growth of dust particles by capture), you get planetesimals of about 1 meter in diameter which reach the equatorial plane in a very short time. What is the situation in the presence of turbulence?

Hayashi: We solved the growth and sedimentation equation by precise numerical computations, the details of which will be talked about by Nakagawa later in this session. That is, we obtained the mass spectrum as a function of t and z (height from the equatorial plane). The maximum size of a grain is about 1 cm. In our theory, a dust layer composed of these grains and gas molecules fragments into a number of planetesimals with masses of the order of 10^{18} g. We consider a situation where turbulence has already decayed.

Schatzman: Which rule did you use to determine the properties of the turbulence in the gaseous disc?

Hayashi: We investigated the density and pressure distributions as functions of r and z. The solar wind produces turbulent eddies only in the very outer layers of the disk where the gas pressure is very small.

Kippenhahn: Just a small objection to the chairman's remarks. Dr. Schatzman, you indicate that, in the case of rotation, sheer means a deviation from solid body rotation. In my review paper tomorrow I hope I can convince you that this is not the case.

Sugimoto: You treated the statistical mechanics of the planetesimals in a box and in a, e, and i coordinates. However, energy is fed into the system from the change in a, i.e. from the change in the gravitational force between a planetesimal and the sun. In this sense the system is thermodynamically open. Is a kind of Boltzmann distribution expected to be realized even in such an open system?

Hayashi: The Boltzmann distribution function in our case, namely, in the presence of a gravitational field, does depend on time, as was shown, for example, by Nakagawa (1978). We did not consider the planetesimals to be confined in a box.

Tayler: How much larger than the present radius of the sun is its radius when the planetesimals begin to form?

Hayashi: If we use, for example, the result of Ezer and Cameron (1965) for the pre-main-sequence evolution, the sun has a radius of about 10 $R_\odot$ when the planetesimals begin to form.

Durisen: Recent theoretical and observational work suggests that processes important for understanding the present dynamics and structure of Saturn's rings are similar to those which occurred in the planetesimal disk. These include gravitational scattering, interparticle collisions, collective gravitational effects, and perturbations by satellites. Observations of the rings can afford a direct test of theoretical models for such processes against a real system.

Hayashi: I agree with you completely.

Aizu: How about the angular momentum in your model?

Hayashi: I suppose that, at a stage when the collapse of the nebula is stopped by centrifugal forces, the nebula is oscillating both in the *r*- and *z*-directions. These oscillations, together with the magnetic force, if this force is strong enough, give rise to transfer of angular momentum outwards.

Bodenheimer: What are the main arguments in favor of the low-mass solar nebula that you use as opposed to the high-mass nebula of Cameron?

Hayashi: It will not be easy to form the planets of terrestrial type, all the satellites, and also cometary objects if we start only from the giant protoplanets.