EVOLUTION OF THE TERRESTRIAL PLANETS: ACCRETION, ATMOSPHERE FORMATION AND THERMAL HISTORY; Takafumi Matsui and Yutaka Abe, Geophysical Institute, Faculty of Science, University of Tokyo, Tokyo 113, Japan.

Introduction. Since a large amount of accretional energy was liberated during accretion of the terrestrial planets, the efficiency of retention of accretional energy largely controls the early thermal state. This efficiency is strongly dependent on whether or not a proto-atmosphere is formed and covers the entire surface of a growing planet. We have recently shown that an impact-induced atmosphere likel formed during accretion and, due to the blanketing effect of the atmosphere, the surface temperature increased to a level where the formation of a magma ocean is possible (1). Evolution of an impact-induced atmosphere depends strongly on two parameters: the size of the planet and its distance from the sun (2,3). In this paper, we show that the early evolution of the terrestrial planets can be described by a diagram of energy flux (F_o) versus optical depth (τ_{ir}), on which curves displaying the evolution of surface temperature may be plotted.

Assumptions. The surface temperature of a planet is a function of the energy released at the surface and the optical depth (τ_{ir} for long-wavelength and τ_{vs} for short-wavelength) of the atmosphere: $\alpha T_s^4 = S_o G(\tau_{ir},\tau_{vs})+F_o B(\tau_{ir})$, where σ is the Stefan-Boltzmann constant, T_s is the surface temperature, S_o is the solar flux, F_o is the energy flux at the base of the atmosphere, and G and B represent absorptive and/or scattering features of the atmosphere with respect to short- (visible) and long-wavelength (infrared) radiation. Assuming a water-vapor atmosphere, local thermodynamic equilibrium for long-wavelength radiation, isotropic scattering for short-wavelength radiation, and a two-stream approximation, we can calculate the surface temperature for the given set of S_o, F_o and τ_{ir} (or the mass of the atmosphere).

Earth. Figure 1 shows curves of equal surface temperature for the Earth (S_o = 960 W/m^2). The shaded region represents the greenhouse region. The dotted region is the magma ocean region ($T_s >$ liquidus temperature). The cross-hatched region depicts the range of conditions under which H_2O cannot exist in the gas phase and precipitation takes place. Arrows indicate the mean impact-energy fluxes for various accretion times. This diagram suggests that even if the accretion time is as long as 10^8 years the formation of a magma ocean is possible. We can plot the evolution of surface temperature and the mass of an impact-induced atmosphere for a "standard" Earth model (1) on this diagram.

As the planet grows, the mass of the impact-induced atmosphere increases very rapidly: most of the proto-atmosphere is formed during the growth from 0.2 to 0.4 of the final radius R_o. Therefore, the evolutionary track is almost parallel to the horizontal axis until it crosses the solidus temperature (1500K), after which the track makes a loop. This corresponds to a major stage in the Earth's formation, growth from ~ 0.4 R_o to ~ 0.95 R_o. Since the solubility of water in silicate melt controls the mass of the H_2O atmosphere (1), the mass of the impact-induced atmosphere decreases slightly with an increase in accretional energy flux and the loop maintains a near-constant surface temperature. As the growing planet approaches its final radius, the accretional energy flux decreases rapidly but the mass of the atmosphere stays nearly constant and the evolutionary track becomes nearly parallel to the vertical axis. The evolutionary track enters the region in which water condenses from the gaseous phase, so that the model predicts that a hot ocean is formed. The mass of the hot proto-ocean is about 10^{21} kg. Evolutionary tracks of other models (1) show similar features.

Other terrestrial planets. At the solar distance of Venus, because of higher solar flux (1830 W/m^2), the cross-hatched region becomes very small (in fact almost negligible), which means that the evolutionary tracks (2) never enter the liquid H_2O region. H_2O will be disintegrated into H_2 and O by photodissociation. H_2O may be lost by hydrodynamic escape within 1 b.y. (4).

The liquid H_2O region is much larger at the solar distance of Mars than that of the Earth because S_o (414 W/m^2) is less than half that for the Earth. Therefore, the evolutionary tracks of most Mars models (except for the rapid accretion models, where $\tau_{acc} < 5 \times 10^6$ y) enter the liquid H_2O region at a very early stage in the accretion process and an impact-induced atmosphere is not formed. Because of the greater sensitivity to the input parameters, modelling the early evolution of Mars is much more complicated than for either Venus or the Earth.

Modelling the early evolution of the Moon and Mercury is also complicated because the escape of an impact-induced atmosphere plays an important role in the evolution of the atmosphere (3).

References. (1) T. Matsui and Y. Abe, Nature, in press (1986). (2) T. Matsui and Y. Abe, LPSC XVI, 524-525 (1985). (3) T. Matsui and Y. Abe, in Origin of the Moon, in press (1986). (4) J.F. Kasting and J.B. Pollack, Icarus, 53, 479-508 (1983).

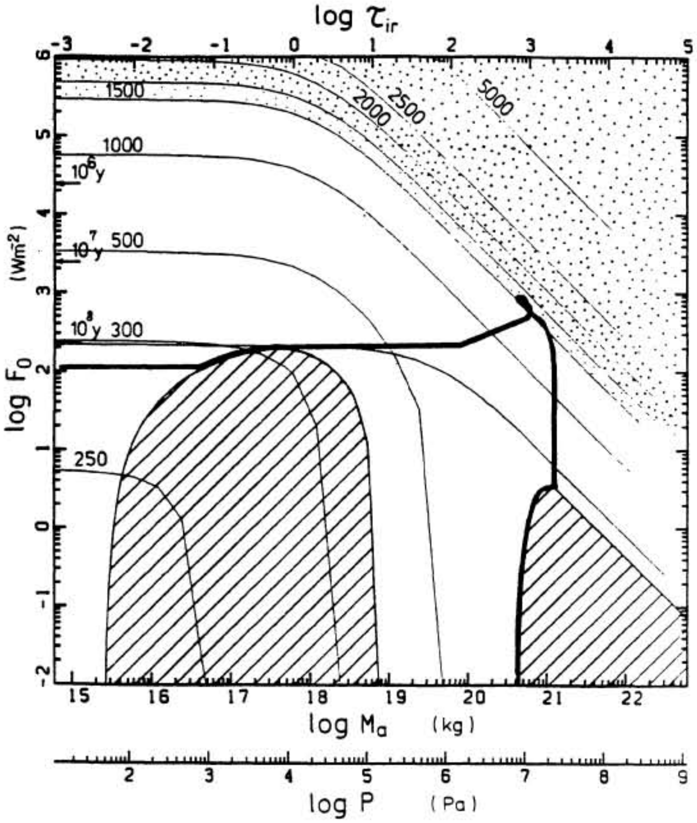

Figure 1. Evolutionary diagram of the standard Earth model.