SURVIVAL OF A PROTOATMOSPHERE THROUGH THE STAGE OF GIANT IMPACTS. H. Genda and Y. Abe, Department of Earth and Planetary Science, The University of Tokyo (7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan; genda@sys.eps.s.u-tokyo.ac.jp, ayutaka@eps.s.u-tokyo.ac.jp).

Introduction: The recent works on the planetary formation show that several tens of Mars-sized protoplanets are formed through a successive accretion of planetesimals in the terrestrial planet region [*e.g.*, 1]. Then, these protoplanets collide each other as their orbit crosses due to gravitational perturbations among them [*e.g.*, 2]. Therefore, it is generally thought that several giant impacts of Mars-sized planet occur at the late stage of the terrestrial planet formation.

Protoplanets would have a protoatmosphere, which is either of an impact-induced atmosphere [*e.g.*, 3], a gravitationally-attracted solar-type atmosphere [*e.g.*, 4], or a mixed atmosphere of them [5, 6]. The giant impacts modify a protoatmosphere in the mechanical aspects and/or thermal aspects. In the mechanical aspects, a large amount of protoatmosphere of the target and impactor planet may be blown-off by the global ground motion exited by a strong shock wave traveling in the planetary interior. If the proto-atmosphere is not completely blown-off by the strong ground motion, the hydrodynamic outflow of the residual protoatmosphere may occur due to the release of enormous impact energy (the thermal aspects). Therefore, giant impacts should have affected the origin and evolution of planetary volatile budget, and especially the quantity and isotopic fractionation of noble gases. In this study, we will focus on the mechanical aspect rather than the thermal one.

There are the previous studies of the atmospheric blow-off by the giant impact in the mechanical aspects [7-9]. These previous studies concluded that almost all protoatmosphere is lost by the strong ground motion (~6km/s at the antipodes) expected for a Mars-sized impact. Therefore, it is generally thought that the present atmosphere of the terrestrial planets derives from volatile-rich planetesimals and/or comets accreted after the final giant impact. However, isotopic fractionation data of noble gases and D/H ratio of the ocean in the present Earth do not support such single source of the terrestrial volatile budget [*e.g.*, 10, 11].

In this study, we re-examine the relations between the ground motion and the amount of the lost protoatmosphere for various types of proto-atmospheres, and estimate the loss fraction of the protoatmosphere by the giant impacts.

Model: We consider a spherically symmetric motion of the ground and the protoatmosphere. We ignored radiative cooling and the effect of ambient nebula gas that may fill the solar system at the stage of giant impacts. We take the initial global ground velocity as a parameter, and calculate the atmospheric motion assuming that the subsequent ground motion obeys ballistic motion.

We considered six cases for the initial proto-atmosphere (see [12] in detail). The protoatmospheres of Case 1-4 imitate the present Earth's ones. Case 5 imitates the degassed atmosphere composed mainly of H_2O during accretion of planetesimals. We adopted that the surface temperature of 1500K and the surface pressure of 10^7Pa [3]. Case 6 imitates a solar-type H_2-He atmosphere formed by gravitational attraction of the nebula gas. We adopted that the surface temperature of 2300K and the surface pressure of 10^7Pa [4].

For each initial protoatmospheric condition we performed the calculations changing the initial velocity of the ground motion from zero to the escape velocity with the stepping of 2% of the escape velocity.

Numerical Results: Figure 1 shows temporal evolution of the atmospheric particle velocity and density distribution for the initial ground velocity u_s = 5.6km/s of case 1. The ground motion induces a shock wave in the atmosphere. The shock front arrives at the top of atmosphere at ~ 3.5 seconds. At that time, the top of the atmosphere is expanding adiabatically, and accelerates up to several ten times of the escape velocity. After 5 seconds, the upper part of the atmosphere, where the density is very low, greatly exceeds the escape velocity, but the lower part of the atmosphere, where the density is relatively high, cannot be accelerated beyond the escape velocity. Thus, the upper part of the atmosphere is finally lost, but the lower part is gravitationally bounded.

Figure 2 shows the initial ground velocity (u_s) and the loss fraction (X_{loss}) of the protoatmosphere for six cases of the initial protoatmosphere. It should be noted that the loss fraction is insensitive to the initial protoatmospheric conditions, and can be approximated by a linear function of u_s, that is,

$$X_{\mathrm{loss}} = \begin{cases} 4/3 \times (u_s/u_e) - 1/3 & \text{for } u_s > 1/4 \times u_e \\ 0 & \text{for } u_s \le 1/4 \times u_e \end{cases}$$

where u_e is the escape velocity. Complete loss occurs only when the initial ground velocity exceeds the escape velocity. Noticeable loss starts at u_s ~ 2km/s, which is roughly corresponding to the criterion for the complete loss derived by Ahrens [7, 8].

The Loss Fraction by the Giant Impact: We will estimate the actual loss fraction for the giant impact by using the above results. In connection with the origin of the Moon, several researchers have performed the direct simulations of Mars-sized impact onto the Earth-sized planet, using SPH (smoothed particle hydrodynamics) code. According to Cameron's simulation [13], which has been referred in Chen and Ahrens [9], the ground velocity at the antipodes becomes about 6 km/s. When we apply this velocity to our results, the loss fraction becomes about 30%. Therefore, most of the protoatmosphere survives the giant impact. On the case of the large planetary impact, the antipodal velocity is generally greater than the globally averaged velocity [*e.g.*, 14]. It makes the loss fraction smaller than 30%. According to the latest SPH simulations [15], the globally averaged velocity is 4-5 km/s in the case of head-on collision of 0.1 and 0.9 Earth's mass with the escape velocity. Therefore, when we adopt this velocity, the loss fraction becomes 10-20%. In either case, we conclude that most of the protoatmosphere survives the giant impact.

References: [1] Kokubo, E. and Ida, S. (1998) *Icarus*, 131, 171-178. [2] Chambers, J. E. and Wetherill, G. W. (1998) *Icarus*, 136, 304-327. [3] Abe, Y. and Matsui, T. (1986) *J. Geophys. Res.* (Suppl.), 91, 291-302. [4] Mizuno, H. et al. (1982) *Planet. Space Sci.*, 30, 765-771. [5] Abe, Y. et al. (2000) In *Origin of the Earth and Moon*, 413-433. [6] Abe, Y. et al. (2002) *Geochim. Cosmochim. Acta*, 66, A5 (abstr.). [7] Ahrens, T. J. (1990) In *Origin of the Earth*, 211-227. [8] Ahrens, T. J. (1993) *Annu. Rev. Earth Planet. Sci.*, 21, 525-555. [9] Chen, G. Q. and Ahrens, T. J. (1997) *Phys. Earth Planet. Inter.*, 100, 21-26. [10] Owen, T. C., and Bar-Nun, A. (2000) In *Origin of the Earth and Moon*, 459-471. [11] Zahnle, K. (1993) In *Protostars and planets III*, 1305-1338. [12] Genda, H. and Abe, Y. (2002) *Icarus*, submitted. [13] Cameron, A. G. W. (1992) *Lunar Planet. Sci.*, XXIII, 199-200 (abstr.). [14] Watts, A. et al. (1991) *Icarus*, 93, 159-168. [15] Asphaug, E. and Agnor, C. (2002), personal communication.

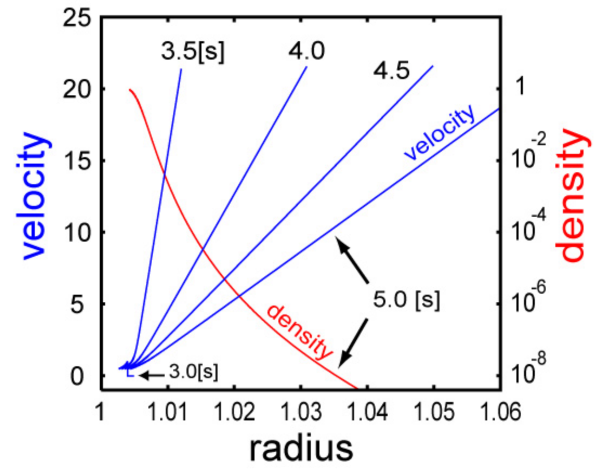

Figure 1. Temporal evolution of the atmospheric particle velocity and density distribution for the initial ground velocity u_s = 5.6km/s of case 1. The particle velocity is normalized by the local escape velocity. The density is normalized by the values at the bottom of the initial protoatmosphere. The value of the horizontal axis is normalized by the initial planetary radius.

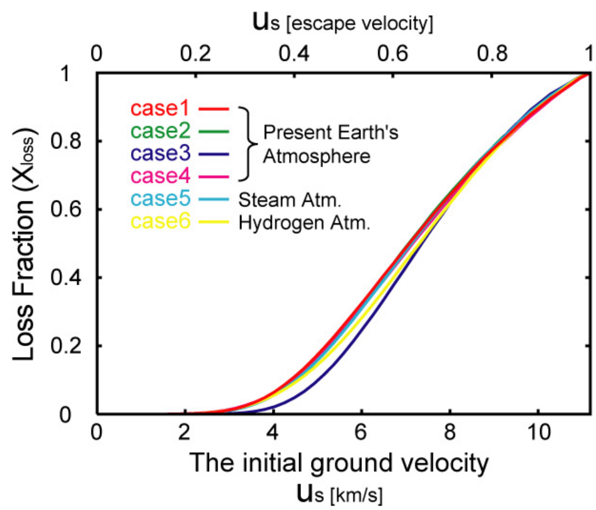

Figure 2. The relations between the initial ground velocity, u_s, and the final loss fraction, X_{loss}. The loss fraction is defined by the mass fraction of the atmosphere whose particle velocity exceeds the local escape velocity after 100000 seconds.