HYDRODYNAMIC ESCAPE FROM DISKS FORMED BY GIANT IMPACTS. Hidenori Genda and Yutaka Abe, Department of Earth and Planetary Science, University of Tokyo, Tokyo 113-0033 (genda@sys.eps.s.u-tokyo.ac.jp, ayutaka@eps.s.u-tokyo.ac.jp).

**Introduction:** According to the giant impact hypothesis, a circumterrestrial disk is generated by an oblique impact of a Mars-sized protoplanet onto the proto-Earth [1-2]. The disk just after the Moon-forming impact is very hot and partially vaporized. We analytically estimate a criterion for the disk escape and its dependence on the physical parameters of the disk. Escape from the disk affects the formation of the Moon by changing the mass and shape of the disk. If escape of gas component selectively occurs, the disk is depleted in volatile components and enriched in refractory components. Thus, the composition of the Moon is affected. Release of latent heat due to condensation of vaporized silicate makes the adiabat nearly isothermal. Since an isothermal gas is not bounded by the gravity of the central planet, silicate vapor possibly escapes from the disk through a hydrodynamic outflow.

**Adiabatic Change of Partially Vaporized Silicate:** The disk is created within several Kepler times or several hours after a giant impact [2]. Therefore, we may treat the disk-formation process as an adiabatic one by ignoring the radiative cooling. For simplicity, we assume that disk material is one component and two phases. The adiabatic changes are given by using the ideal gas law and equations of entropy change and vapor-condensate equilibrium. When we adopt a typical value for partially vaporized silicate (the latent heat for vaporization is $2.0 \times 10^7$ J/kg [3], the specific heat at constant pressure is $1.4$), and for impact-generated disk (the mass fraction of vapor, $X_{0.0}$, and the temperature, $T_{0.0}$, are $0.5$ and $6000$ K, respectively), the adiabat can be approximated by a polytrope ($p \propto \rho^\gamma$, where $p$ and $\rho$ are the pressure and the density) with polytropic exponent $\gamma$ nearly $1.05$. This means that the disk is nearly isothermal, as $\gamma = 1$ means isothermal. It is known that an isothermal atmosphere is not bounded by the gravity of the central planet [4]. Thus, we may expect hydrodynamic outflow from the disk.

**A Criterion for Escape:** We approximate a partially vaporized disk by a polytropic gas with polytropic exponent $\gamma$, and the pressure at the central plane of the disk by a power of distance from the central planet ($p \propto r^{-\alpha}$). The density, the pressure and the temperature are derived from the hydrostatic equations of the disk. If the pressure given by the hydrostatic equations is zero at infinite distance from the central planet, such a disk can be in hydrostatic equilibrium. On the contrary, if the disk has finite pressure at infinite distance, the disk cannot keep a state of hydrostatic equilibrium, because a finite pressure cannot be supported in the distant space. Then, a hydrodynamic outflow occurs so as to satisfy the zero-pressure boundary condition at infinite distance. The criterion for the break down of hydrostatic equilibrium is analytically derived. When $\alpha \leq \gamma/(\gamma - 1)$, the hydrodynamic outflow occurs outside of the critical radius ($r_c$), which is given by the following equation,

$$\frac{r_c}{r_0} = \left(\frac{\gamma - 1}{\gamma}\right)^{\frac{\gamma}{\alpha \gamma - 1}}$$

where $\lambda_{0.0} = \frac{GMm_{0}\lambda}{X_{0.0}kT_{0.0}r_0}$

where $r_0$ and $\lambda_{0.0}$ are the radius of the central planet and the escape parameter, respectively. $G$, $M$, $m$ and $k$ are the gravitational constant, the mass of the central planet, the mass of gas molecule and the Boltzmann constant, respectively. When $M = 6.0 \times 10^{22}$ kg, $r_0 = 6.4 \times 10^6$ m, $m = 5.0 \times 10^{-26}$ kg and $T_{0.0} = 6000$ K [2], $\lambda_{0.0}$ is $55$ for $X_{0.0} = 0.6$. Then, the critical radius is about $3r_0$ (~ the Roche radius). Therefore, in the case of the highly vaporized disk ($X_{0.0} \geq 0.6$), most materials outside of the Roche radius is lost by escape, even if the Moon-forming impact scatters sufficiently large amount of disk materials beyond the Roche radius. Thus, direct accretion of the Moon from the disk materials outside of the Roche radius is only possible for a low temperature disk. Accretion of the Moon after spreading of a compact disk owing to angular momentum transfer following the gravitational instability [5] seems more likely.

**Timescale of Disk Escape:** We estimated the timescale of the escape by non-steady two-dimensional hydrocode based on the CIP (Cubic-Interpolated propagation) [6-7] algorithm. The initial conditions of the disk are $\gamma = 1.05$, $\lambda_{0.0} = 50$ and $q = 2.0$, $3.0$ and $4.0$ ($\Sigma \propto r^q$, where $\Sigma$ is the surface density), which correspond to $\alpha = 3.6$, $4.6$ and $5.6$. The initial disk’s outer edge is $6r_0$. Figure 1 shows the snapshot of spatial density distribution and velocity vectors in the case of $q = 3.0$ at forty days after the start of expansion. Thin and thick arrows indicate subsonic flow and supersonic flow, respectively. The sonic point appears...
about $50r_0$ and moves outward with time. Figure 2 shows the time-evolution of the disk mass in the case of $q = 2.0, 3.0$ and $4.0$. Disks with large $q$ values or extended disks suffer large loss of the total mass. The arrows indicated on the right side of Figure 2 are analytically estimated final mass of the disk on the assumption of complete loss beyond the critical radius ($r_c$). The timescale to reach the half-way to the estimated final mass is from several tens to one hundred days.

The Effect of Cooling: The above numerical simulation does not include the radiative cooling. In reality, temperature drop by cooling will retard the escape. We estimate this effect by numerical simulation of spherically symmetric flow including the radiation and turbulent convection. A spherically symmetric flow is good approximation at large distance ($>20r_0$) from the central planet. We used the Wuchterl’s model [8] for time-dependent turbulent convection. Though the outer region, where the velocity exceeds the escape velocity, cools efficiently, inner region, whose expansion drives the outflow, does not cool and expands adiabatically for the absorption coefficient ($\kappa$) greater than 0.01 [m$^2$kg$^{-1}$]. When 1% of the disk material is condensed as the particles with 1\(\mu\)m radius, the absorption coefficient ($\kappa$) is 2.5 [m$^2$kg$^{-1}$]. Therefore, the assumption of adiabatic flow is valid for our case.

Summary: 1) We analytically derived a criterion for the escape of an impact-generated disk. 2) Escape occurs at the outer side of the disk and the scale of escape greatly depends on the disk’s thermal structure, that is, the temperature and the mass fraction of vapor. 3) The silicate vapor escapes almost adiabatically and the timescale of escape is about one hundred days. 4) When we apply the results to the disk formed by the Moon-forming impact, for the case of highly vaporized disk ($X_{0.0} > 0.6$), the material outside of the Roche radius can escape.