THE EVOLUTION OF AN IMPACT-GENERATED PARTIALLY-VAPORIZED CIRCUMPLANETARY DISK. R. Machida[1] and Y. Abe[1], [1]Department of Earth and Planetary Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan (mach@eps.s.u-tokyo.ac.jp)

Introduction: According to the giant impact hypothesis, a partially vaporized disk is formed through the collision of a Mars-sized body with the proto-Earth [1, 2]. Most of the disk material is distributed interior to the Roche radius. Since the impact-generated disk has high temperature (~ 5000 K [3, 4]) and high gas pressure, the disk consists of the mixture of vaporized gas and condensate liquid drops (In the following, we call them dust, for simplicity).

The following moon-forming process is proposed under the assumption of a gas-free disk composed of debris [5]: spiral-arm structures are formed through gravitational instability in the disk, and the disk spreads owing to their gravitational torque, then a single large moon is formed outside the Roche radius of the Earth by the accretion of disk materials.

However, the impact-generated disk is partially vaporized in reality. There are two possible modes of gravitational instability in a partially vaporized disk; one is the instability of the dust-gas mixture [6], and the other is the instability of the equatorial dust layer formed by the sedimentation in the disk. If the dust and gas are coupled firmly, the instability of the dust-gas mixture occurs through the decrease of the gas fraction induced by the radiative cooling of the disk. If the dust sedimentation forms an equatorial dust layer in a shorter time scale than the cooling, the instability of the dust layer may occur. Here, we investigate the latter possibility.

Numerical Simulation: We perform a two-phase fluid numerical simulation for the evolution of the circumplanetary disk.

Approximations and Initial Conditions. We assume a hydrostatically equilibrated axisymmetric disk with uniform temperature T (varies from 4000 K to 6000 K) and initially uniform gas fraction X. Here, we focus on the separation of dust particles from the gas, and neglect the coagulation and evaporation of dust particles. The total mass of the disk, $M_{\rm disk}$, varies from $2M_{\rm moon}$ to $4M_{\rm moon}$, where $M_{\rm moon}$ is the present lunar mass. We approximate the initial surface density of the disk is proportional to the negative power of distance from the Earth, $\Sigma \propto r^{-\alpha}$, where α is a parameter which denotes the compactness of the disk ($\alpha = 1$, 3, and 5).

Model. The dust and gas move with the terminal velocities that are approximately proportional to r_d^2 where r_d is the radius of dust particles [7] as long as the dust particles are smaller than 1 cm. The characteristic size of liquid drops that can hold together inside the Roche radius is restricted to be smaller than approximately 1 cm [6]. If the dust grows through mutual collision during sedimentation, 1 μm-sized dust particles grow to 1 mm-size in typically 10^{-2} year. This time scale is much shorter than that of the dust sedimentation. Hence, we set the initial radius of dust particles 1 mm, and consider the dust growth to the size of 1 cm due to the mutual collisions.

The Kelvin-Helmholtz instability due to difference of the velocities at the dust-rich region and the dust-poor region should occur around the equatorial plane, and prevents the dust settling. The quasi-equilibrium dust distribution [8] will be achieved in the turbulent layer. If sufficient amount of the dust concentrates at the layer, a fully-compacted dust layer with density ρ_{mat}, where ρ_{mat} (~

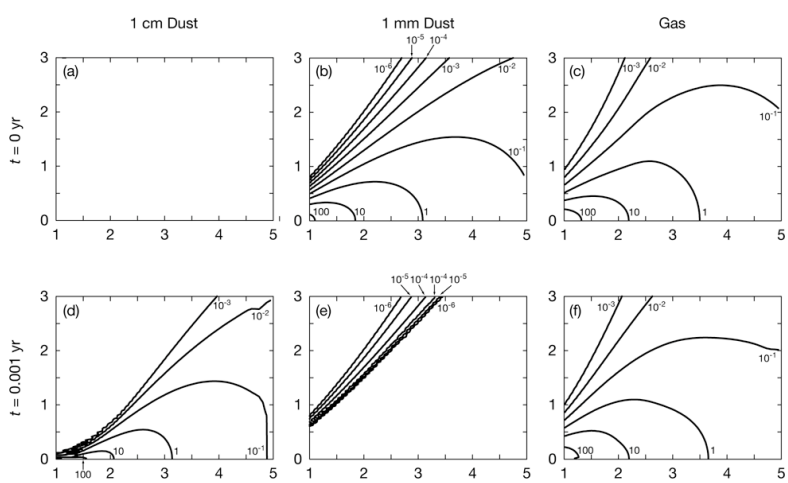

Fig. 1. Snapshots of density distribution of the 1 cm-sized (a, d) and 1 mm-sized (b, e) dust particles and the gas (c, f), where $M_{\rm disk} = 3M_{\rm moon}$, $X = 0.7$, $\alpha = 3$, and $T = 5000$ K. The unit of density is [kg/m^3]. Both axes are normalized by the Earth's radius. Though the gas distribution does not change significantly (c, f), a fully-compacted dust layer is formed at the equatorial plane by the sedimentation of dust particles in a time scale of 10^{-3} year (d). Before the formation of the dust layer, most of the 1 mm-sized dust particles have grown to 1 cm, while only a small part of them remains afloat above the dust layer (e).

3000 kg/m^3) is the material density of dust particles, is formed, and becomes gravitationally unstable at the region $r > 1.67R_E$ [9], where R_E is the Earth's radius.

Results: Figure 1 shows snapshots of the evolution of the dust and gas density distributions for the case $M_{\rm disk} = 3M_{\rm moon}$, $X = 0.7$, $\alpha = 3$, and $T = 5000$ K. Though the gas distribution does not change significantly, a fully-compacted dust layer is formed at the equatorial plane by the sedimentation of dust particles in a time scale of 10^{-3} year, which is much shorter than the cooling time scale of 100 years [6]. Hence, the instability of the dust layer likely occurs before the instability of the dust-gas mixture. Therefore, the preferred mode of the instability is that of the equatorial dust layer. While the gas fraction is below the critical value, the onset time of the gravitational instability is about 10^{-3} year (Fig. 2). The critical value of X is about 0.7, which is insensitive to T, $M_{\rm disk}$, α (not shown here). If the initial gas fraction exceeds the critical value, the gravitational instability never takes place, and the most of dust particles should fall onto the Earth much faster than the radiative cooling of the disk. Thus gravitational instability never occurs in a gas-rich disk.

Discussion: In the following, we discuss the effects not considered in our numerical simulation such as the radiative cooling of the disk, and the hydrodynamic escape. Finally, we propose a general scenario for the evolution of the circumplanetary disk.

Hydrodynamic Escape. Genda & Abe [10] discuss the hydrodynamic outflow from a hot disk outside the critical dissipation radius. After the moon formation, most of the dust layer is wiped out from the leftover disk by the moon tide. As a result, the critical dissipation radius is located slightly inside the Roche radius, and the gas-rich disk outside the critical dissipation radius dissipates in typically 100 days.

Radiative Cooling. Figure 1e implies that considerable amount of 1 mm-sized (or even smaller, in real situation) dust particles remains afloat far above the equatorial plane around the original disk margin even after the onset of the gravitational instability. Even if all the small dust particles were 1 mm-sized, the time scale for radiative cooling is about 10 years. The time scale for the radiative cooling obtained here seems compatible with that of [6].

Overall Evolution of Circumplanetary Disk. The onset of the gravitational instability is controlled mainly by the initial gas fraction of the circumplanetary disk.

When the initial gas fraction is larger than the critical value, dust particles fall to the Earth without inducing the disk instability. As a consequence, the disk is likely kept at high gas fraction, and neither the gravitational instability of the dust layer nor that of the dust-gas mixture is possible. Therefore no moon formation occurs.

When the initial gas fraction is below the critical value, the accretion of the moon starts following the instability of the dust layer. The dust layer spreads owing to the gravitational torque by the spiral-arms, and a single moon is formed outside the Roche radius of the Earth in about 1 month [5]. In the region outside the Roche radius, the leftover disk dissipates through the hydrodynamic outflow and hardly captured by the moon. As the gas-rich disk inside the Roche radius cools in the time scale of 100 years, volatile components condense into dusts. Most of them should fall onto the Earth, because the leftover disk should have high gas fraction. Consequently, the gravitational instability never occurs again in such a gas-rich leftover disk. Therefore, the resultant moon is a volatile-poor one composed mainly of the initial condensate transported from the dust layer.

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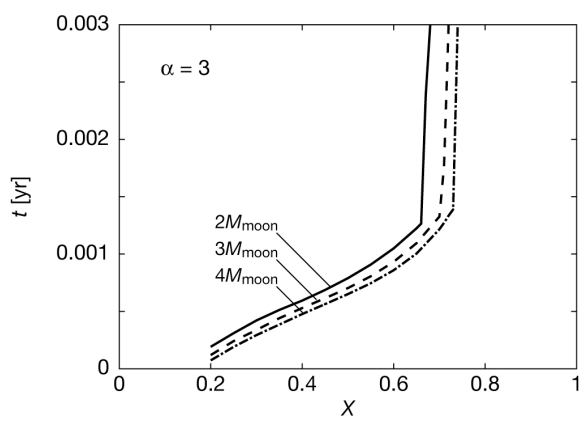

Fig. 2. The onset time of outward mass transport for the cases of $\alpha = 1$, 3, and 5. The mass of the disk $M_{\rm disk} = 3M_{\rm moon}$, and $T = 5000$ K.