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Evolution of the Proto-lunar Disk: The Mode of Gravitational Instability and the Physical State of the Moon Forming Material

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The giant impact hypothesis is the most favored one for the origin of the Moon at present. It can account for the major characteristics of the Moon; the large specific angular momentum of the Earth-Moon system and the depletion of iron and volatile elements in the Moon. According to this hypothesis, a partially vaporized, compact disk is formed through the collision of a Mars-sized body with the proto-Earth. Most of the disk material is distributed interior to the Roche radius. The impact-generated disk has high temperature (~ 5000K or higher; Cameron, 1997) and high gas pressure (~ 100bar at the equatorial plane of the disk). Under such condition, the disk consists of the mixture of vaporized gas component and condensate liquid drops (In the following, we call them dust for simplicity.). The Moon forming process is considered as follows: spiral-arm structures are formed through gravitational instability in the disk, and the impact-generated compact disk spreads owing to the gravitational torque by the spiral-arms, then the Moon is formed outside the Roche radius of the Earth by the accretion of disk materials (Ida et al., 1997). There are two possible modes of gravitational instability; one is the instability of the dust-gas mixture (Thompson & Stevenson, 1988), and the other is the instability of the equatorial dust layer formed by the sedimentation in the disk. The former requires cooling of the disk to the critical gas-fraction and the latter requires thinning of the dust layer to the critical thickness. Thus, the onset time of the instability is controlled by cooling for the former and dust sedimentation for the latter.

Thompson & Stevenson (1988) discussed that the disk may evolve in marginally unstable state, in equilibrium between radiative cooling and gravitational energy released during disk evolution. They indicated that the instability of the dust-gas mixture occurs by the decrease of the gas fraction due to the cooling of the disk. This time scale is about 100 years. However, they did not take account of the instability of the dust layer triggered by the separation of dust particles from the gas. Here, we investigate the instability induced by the separation of dust particles from the gas.

In this study, by comparing the time scale for the instability of the dust layer with that for the instability of the dust-gas mixture, we investigate the preferred mode of the instability. Considering the growth of dust particles and the effect of turbulence, we shows that even 1 micrometer-sized dust particles grow to 1 cm-size in 0.01 year and dust sedimentation triggers disk instability in the time scale of 0.01 year. Thus, 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.

When the initial gas fraction is larger than the critical value, dust particles fall to the Earth without inducing the disk instability, where the critical value of the initial gas fraction varies from 0.15 to 0.32 with increasing the disk mass from two to four present Moon mass. If the initial gas fraction is higher than the critical value, 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.

When the initial gas fraction is below the critical value, the accretion of the Moon starts following the instability of the dust layer. In this case, the volatile-poor Moon is formed from dust particles mainly transported from the dust layer, which are early condensate depleted in volatile components. Because the evaporation rate of the disk where the gravitational instability may occur is at most about 30%, sodium and potassium are lost almost completely from dust particles while silicon and magnesium are not. Therefore, the Moon generated by the giant impact is moderately volatile-poor one.