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ジャイアントインパクト直後の月形成に伴う元素分別

ELEMENTAL FRACTIONATION DURING RAPID ACCRETION OF THE MOON TRIGGERED BY A GIANT IMPACT

 # 阿部　豊 [1]，Kevin　Zahnle [2]，橋元　明彦 [3]

Yutaka Abe [1], Kevin Zahnle [2], Akihiko Hashimoto [3]

[1] 東大・理・地球惑星物理，[2] NASA Ames Research Center，[3] 北大・理・地球惑星

[1] Earth Planetary Phys., Univ. Tokyo, [2] NASA Ames Research Center, [3] Earth and Planetary Sci., Hokkaido Univ

最近のN 体計算によると、ジャイアントインパクト後の月形成はわずか１月程度で起こる。短期間の集積では、解放される重力エネルギーで材料物質が蒸発し、その結果生成されるシリケイト大気は月重力を振り切って散逸すると期待される。本研究では、H, O, C, S, Mg, Si, Fe, Ca, Al, Na, Ti, N の12元素、272 主の化学種を考慮したPHEQ を用いて平衡蒸発を計算し、シリケイト大気の構造と散逸について推定した。Na などの揮発性元素は集積の初期段階以外には月に保持できず、大部分が失われること、また、Mg, Si, Fe も部分的に蒸発するために相対的に　Ca やAlに富んだ平均組成になることが示された。

Recently, Ida et al. made an N-body simulation of lunar accretion from a proto-lunar disk formed by a giant impact. One of their important conclusions is that the accretion time of the Moon is as short as one month. The energy of accretion always exceeds the gravitational binding energy of newly arriving matter. Hence, without an energy sink, the accreting body is thermally unstable. For the Earth and other planets, radiation acts as the sink. However, in such a short accretion time, the Moon cannot radiate the accretional energy. Even radiating at a silicate cloudtop temperature of roughly 2000K, it would take more than 100 years to radiatively cool the Moon. The plausible alternative heat sinks are latent heat of vaporization and thermal escape of the gas to space, because the scale height at 2000 K (of order 300 km) is a significant fraction of the lunar radius.

The early stages of lunar (or "lunatesimal") growth release relatively little energy and can occur simply by heating the material, especially if the accreting material is originally cold. However, the material is unlikely to be cold, because the disk itself is hot and its cooling time is long, while the lunar accretion time is very short. Therefore the Moon is likely to accrete condensed material just after it condenses. Accordingly, the newly accreted material will be on the verge of vaporization and will have very little heat capacity to spare. Therefore the immediate heat sink is the latent heat of vaporization. Most of the vapor will escape from the Moon, because the thermal energy in the gas can be used to drive escape. However, vaporization is generally incomplete. The latent heat of vaporization exceeds the energy of accretion. Viewed globally, the accretional energy is about half the energy required to vaporize the entire Moon. Thus, to first approximation, half of the Moon-forming material can be vaporized and lost during accretion. During this process, we would expect preferential loss of relatively volatile elements. Escape will retard the rate of accretion.

To test these ideas, we computed detailed models of the thermal state of the Moon during accretion. We pay special attention to the structure of the silicate atmosphere and its loss rate by calculating the chemical species at equilibrium. We used the PHEQ program which includes 12 elements (H, O, C, S, Mg, Si, Fe, Ca, Al, Na, Ti, N) and 272 compounds (including ionic compounds). Because of the large heats of vaporization and ionization, the adiabatic atmosphere is nearly isothermal and massive escape is expected. The pressure of the atmosphere is determined by the balance between vaporization of accreting material and escape. If the accretion time is one month, a 0.3 bar atmosphere is expected. Elemental fractionation depends strongly on the temperature of the accreting material. The initial temperature of the material can be estimated from the condition of gravitational instability in the proto-lunar disk. As shown by Ida et al., accretion starts when gravitational instability spreads the disk beyond the Roche limit. The instability occurs when more than 99% of the material condenses. At this point, all of Ca, Al, Si, Mg, Fe, and 95% of Na (probably K also) are in condensed phases. If the Moon is formed from the accretion of such material, volatile elements such as Na and K are retained in the Moon only atearly in accretion. At later times, K and Na are lost, and a fraction of the Mg, Si and Fe are lost. However, refractory elements such as Ca and Al are retained and so achieve a mild degree of superabundance.