EGU22-3311, updated on 18 Aug 2022
https://doi.org/10.5194/egusphere-egu22-3311
EGU General Assembly 2022

Moon Formation via Streaming Instability

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- The Apollo lunar samples reveal that Earth and the Moon have strikingly similar isotopic ratios, suggesting that these bodies may share the same source materials. This leads to the "standard" giant impact hypothesis, suggesting the Moon formed from a partially vaporized disk that was generated by an impact between the proto-Earth and a Mars-sized impactor. This disk would have had high temperature (~ 4000 K) and vapor mass fraction of ~20 wt %. However, impact simulations indicate that this model does not mix the two bodies well, making it challenging to explain the isotopic similarity. In contrast, more energetic impacts, such as a collision between two half Earth-sized objects, could mix the two bodies well, naturally solving the problem. These impacts would produce much higher disk temperatures (6000-7000K) and higher vapor mass fractions (~80-90 wt%). These energetic models, however, may have a challenge during the Moon accretion phase. Our analyses suggest that km-sized moonlets, which are building blocks of the Moon, would experience strong gas drag from the vapor portion of the disk and fall onto Earth on a very short timescale. This problem could be avoided if large moonlets (>1000 km) form very quickly by the process called streaming instability, which is a large clump formation mechanism due to spontaneous concentration of dust particles followed by gravitational collapse. We investigate this possibility by conducting numerical simulations with the code called Athena. Our 2D and 3D hydrodynamic simulations show that moonlet formation by streaming instability is possible in the Moon-forming disk, but their maximum size is approximately 50 km, which is not large enough to avoid the strong gas drag. This result supports the Moon formation models that produce vapor-poor disks, such as the standard model. We will further discuss implications for moons in the solar system and extrasolar systems (exomoons).