Investigations of the effect of material mixing on the spatial distributions of water ice and volatiles in the lunar polar regions. Masatoshi Hirabayashi[1], Emily S. Costello[2], Ariel N. Deutsch[3], Kevin M. Cannon[4], Kris A. Zacny[5], Ya Huei Huang[6], Essam Heggy[7,8], Bradley J. Thomson[9], [1]Auburn University, Auburn, AL, thirabayashi@auburn.edu, [2]University of Hawai'i, Honolulu, HI, ecostello@higp.hawaii.edu, [3]Brown University, Providence, RI, ariel_deutsch@brown.edu, [4]Colorado School of Mines, Golden, CO, cannon@mines.edu, [5]Honeybee Robotics, Altadena, CA, kazacny@honeybeerobotics.com, [6]MIT, Cambridge, MA, yahuei@mit.edu, [7]University of Southern California, LA, CA, heggy@usc.edu, [8]NASA JPL, Caltech, Pasadena, CA, [9]University of Tennessee, Knoxville, TN, bthomso1@utk.edu.

Executive summary

This white paper addresses science questions for the critical roles of impact-induced material mixing processes in the redistribution of water ice in surface and subsurface layers on the Moon. We recommend the Artemis III mission conduct drill core sampling and ground-penetrating radar sounding to assess the magnitude of mixing processes of lunar regolith and water ice on both small and large scales. This white paper is complementary to Cannon and Deutsch [1], who argued the science significance of the 3D stratigraphy of icy regolith deposits in the south polar regions on the Moon.

Background

Water and volatiles have been measured on the lunar surface by the current state-of-the-art remote sensing technologies [2-7]. Surface water and volatiles are mainly situated in the permanently shadowed regions (PSRs) around the lunar poles, where direct sunlight does not reach [e.g., 2-7]. In PSRs, the surface temperatures are low so that water and volatiles can be cold trapped as ice. The origin of water ice on the Moon is still unknown, and ice may have originated from various processes [8] including impacts of comets and asteroids, the release of gas from the interior such as volcanic activities [9], and material collisions with solar protons. Such processes may cause surface water molecules to be transported from some region where the surface temperature is higher than the sublimation temperature and be eventually cold trapped in PSRs. Water molecules are likely to be initially accumulated on the top surface layer. However, as the lunar surface is bombarded continuously by meteoroid impacts of various sizes, it results in a mixture of surface and subsurface materials due to excavation and redistribution by impacts [10-11]. The mixed zone gradually spreads towards deeper layers, and this process may widely distribute water ice. Such mixing processes have occurred through the entire history of the Moon, and regolith layers with redistributed water ice in the lunar polar regions would be a record of the origin and evolution of water ice, as well as that of life and the Earth-Moon system. Furthermore, understanding how water ice has been processed over time is critical for the future utilization of lunar resources.

Physical processes of water ice redistribution

There are two key impact-mixing mechanisms that strongly infer the redistribution of water ice in surface and subsurface layers. First, impact-driven regolith mixing may be strongly dependent on geological processes, such as the distribution of impact craters and ejecta covering [10]. Larger craters can mix materials in wider areas, although the emplacement number is small. On the other hand, smaller craters can affect more limited areas although they are much more numerous. The variation in the cratering mixing capability correlates with the local area and the surrounding regions, resulting in a strong heterogeneity in the mixing zones. This mechanism implies that observations of regolith mixing on both small and large scales can provide detailed local geologic processes. Second, regolith mixing on a small scale is strongly influenced by secondary cratering, a cratering process made by collisions of ejected materials from meteoroid impact craters [11]. Many ejected fragments are retained by lunar gravity and re-impact the surface. This process enhances the mixing depth over time. The mixing depth may reach 1 - 2 m over 1 Ga on the Moon, and thus in this region, water ice would be highly mixed with lunar regolith [11]. This prediction was consistent with a recent numerical study, which also predicted the water ice existence down to depths of ~ 1 m [12]. Therefore, accelerated by secondary impact events, top surface layer may have experienced a much faster mixing rate than subsurface layers.

Suggested investigations

We recommend that the Artemis III mission conduct drill core sampling and ground-penetrating radar sounding at multiple locations to investigate material-mixing processes that have redistributed water ice on the lunar surface.

We recommend PSRs or partially illuminated regions in or around older craters (> 3.5 Ga) as a potential investigation site. As predicted by recent remote sensing studies [e.g., 5-7], PSRs are the major regions that potentially host water ice. However, as PSRs are often situated inside complex craters, they may not easily be accessible. In this case, partially illuminated regions outside craters hosting PSRs would also be potential investigation sites. These regions surround high crater rims and exhibit relatively flat terrains. Such locations may not be as cold as PSRs but cold enough that subsurface layers can host water ice; recent studies showed that if the surface temperature is 120 K above the sublimation temperature, water ice can be stable below 40 cm depth [13]. The regions satisfying this condition extend beyond PSR-hosting craters. Furthermore, older craters can have had more time to accumulate more water ice than younger craters. More comets and asteroids have bombarded the Moon before 3.5 Ga ago, such as Late Accretion and Late Heavy Bombardment. Mare basalt-forming eruptions began to wane after ~ 3.5 Ga [9]. Solar protons constantly reach the lunar surface over time. Thus, craters older than 3.5 Ga should have experienced more of these processes than younger craters. Currently, 12 complex craters that may host surface water ice, including Haworth, Shoemaker, and Faustini, are considered to be older than 3.5 Ga [14-15].

We suggest measuring the spatial (vertical and lateral) distribution of water ice on both small and large scales. Potential investigation techniques include drill core sampling for a small-scale mixing structure and ground-penetrating radar sounding for a large-scale mixing structure.

1. ***Drill sampling:*** We recommend sampling materials down to ~3 m depth at multiple locations; materials sampled from deeper depths more likely reflect older impacts, therefore, older ice [16]. We note that if the investigation site is partially illuminated, the top surface region may host less water ice [11-12]. Necessary drill core technologies have been developed and improved over 50 years. The Apollo 15-17 missions obtained regolith cores down to 3 m depth [17]. The Luna 24 sample return mission captured a 2 m core [18]. The technology of an automated coring auger drilling system such as PVEx [19] has been under development, which will expand the drilling capability for subsurface explorations.
2. ***Radar sounding:*** We suggest bistatic and monostatic low frequency radar sounding measurements to identify the mixing of regolith and water ice down to 300 m depth. This recommendation is consistent with [1]. From the locations of water-hosting complex craters, the cumulative ejecta thickness from these craters may reach 200 m – 300 m around the lunar south pole. Because water ice can influence radio wave propagations, a proper design of very high frequency sounders will provide higher resolution and wider area coverage. The technology has been used on multiple space exploration missions [20-21]. Craters smaller than 5 km in diameter are considered to provide optimal dielectric setups to assess ice presence in subsurface layers [21].

References:

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