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Water on the Moon

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Abstract. After years of thinking the Moon is dry, we now know there are three manifestations in which water appears on the Moon today: 1) Previously hypothesized buried deposits of volatiles at the lunar poles were found at Cabeus crater. There are questions about the origin of such volatiles (i.e., in-falling comets & meteorites, migration of recently formed surficial OH/H_2O, and accumulated release from the interior), but there is no doubt the water is there. 2) Widespread, thinly-distributed, surficial OH (or H_2O) has been clearly detected across all types of lunar terrain. The consensus is that the OH is derived from solar wind, but we do not know how quickly it forms, nor how mobile it is. 3) The amount of water present soon after the Moon formed is now documented in new analyses of lunar materials in volcanic glass beads, apatites and plagioclase feldspars. Apollo era sample analyses were not precise enough to distinguish between indigenous lunar water and terrestrial contamination. Measurements with modern equipment are more precise (both elemental and isotopic), and can better constrain a host of processes (e.g. diffusion, thermal cycling). Scientists around the world are studying lunar water. Ongoing analyses are informing a number of hypotheses and theories about the connection between the Earth and its wet Moon.

Keywords. water, Moon, SSERVI, NLSI, lunar science

1. Introduction

Together with the broader lunar science community, researchers at NASA's Solar System Exploration Research Virtual Institute (SSERVI) and its predecessor, the NASA Lunar Science Institute (NLSI), have made tremendous progress investigating the presence of water on the Moon. This high level summary brings together a number of key discoveries and concepts which would not have been possible without new technologies and the recent cadre of spacecraft sent to the Moon by several countries. Research using data from these missions has added immensely to our understanding of the Moon, from its formation to present day activities. This is an important time in lunar science, where novel techniques are yielding tremendous insights into the Moon's past, in turn shedding light on the history of our own planet.

2. Lunar water in polar cold traps

Despite much discussion to the contrary, the literature supports the theoretical existence of water at the coldest points on the lunar surface, where water is far more stable than the noble gases or other possible constituents of the lunar atmosphere (Watson *et al.* 1961). Possible mechanisms for delivery to the surface include: arrival via impacts, migration of surficial OH or H_2O from lower latitudes to the poles, and internal sources that make their way to the surface. Regardless of how it got there, the presence of water was validated by NASA's Lunar Cratering Observation and Sensing Satellite (LCROSS) mission. LCROSS impacted Cabeus Crater near the lunar south pole, creating a plume that was observed by the shepherding spacecraft (Colaprete *et al.* 2012). A combination of dirty ice grains and more pure ice grains was seen in the ejecta plume up to four minutes after impact (Colaprete *et al.* 2010). LCROSS found water concentrations of 6.3 ± 1.6 percent by mass in Cabeus crater (Strycker *et al.* 2013), although Elphic *et al.* (2011) point out that volatile abundances of 5 wt% or more, distributed uniformly and homogeneously throughout Cabeus do not agree with orbital measurements, suggesting this may be a local, rather than regional, amount of water. LCROSS mission payload details can be found in Ennico *et al.* (2012) and a thorough summary of plume evolution and physical causes in Heldmann *et al.* (2015).

Prior to LCROSS and NASA's continuing Lunar Reconnaissance Orbiter (LRO) mission, launched together in 2009, NASA's Lunar Prospector (LP) Mission mapped the Moon's surface composition and looked for possible deposits of polar ice, measured magnetic and gravity fields, and studied lunar outgassing. Launched in 1998, LP carried a neutron spectrometer that detected hydrogen at both lunar poles. The data indicated that a large quantity of water ice, about 300 million tons, was mixed in the regolith at each pole. LP's neutron spectrometer measured regions where epithermal neutron flux from the surface is suppressed, indicating enhanced hydrogen content (Feldman *et al.* 1998). The Lunar Exploration Neutron Detector instrument on LRO mapped the hydrogen distribution over the lunar surface with spatial resolution of 10 km on the poles, further characterizing the neutron component of the lunar radiation environment (Mitrofanov *et al.* 2010). These missions provided the stepping stones to deeper understanding about the lunar volatile inventory.

3. Surficial OH/water

Launched in 2008, India's Chandrayaan-1 Mission carried the Moon Mineralogy Mapper (M^3), a U.S. instrument which revealed a widespread 2.8-3 μm absorption feature that progressively intensified from about 60 degrees poleward in both directions (Pieters *et al.* 2009, McCord *et al.* 2011). These data indicated OH/H_2O, an unexpected finding given the high daytime temperatures in the mid-latitude regions, and the early Apollo sample sudies that indicated a dry Moon. Fortunately, two additional sources of independent observations were available from NASA's Cassini and EPOXI spacecraft. The Visual and Infrared Mapping Spectrometer (VIMS), carried aboard Cassini, flew past the Moon on its way to Saturn in 1999, and the earlier data were investigated in light of the M^3 discovery. EPOXI had been making numerous close approaches to the Earth-Moon system and was observing the Moon as a calibration source in the same wavelength range. Prompted by the M^3 discovery, EPOXI observed the Moon in June 2009. In both cases, the 3μm lunar spectral signature was observed and confirmed (Clark *et al.* 2009, & Sunshine *et al.* 2009), respectively. Furthermore, the EPOXI observations suggested possible diurnal effects, given the reduction in surficial OH as regions rotate into the Sun.

The solar wind is the likely hydroxylation source as it is composed of protons and electrons streaming at 400 km/sec, with temperatures near 10^5K. Recent work in this area reveals the complexities involved in these processes, as the solar wind can both create and destroy OH/water on the lunar surface (Dyar *et al.* 2010, Farrell *et al.* 2015). Investigations of the mobility of H on the surface (Farrell *et al.* 2013), plus the complex nature of solar wind H-implantation (Farrell *et al.* 2015) and OH formation processes proposed by Poston *et al.* (2012), are leading to greater understanding of the origin and evolution of OH (and possibly H_2O) on the lunar surface. One interesting result from modeling efforts is that defect properties of a crystal have as much (or more) control on retention in an exposed regolith as temperature and/or solar wind flux. Solar wind impacts rough up the surface, possibly removing existing H or OH, but that in turn enables new H or OH implantation to occur more readily (Farrell *et al.* 2015). Furthermore, the lunar surface is oxide-rich (SiO_2, TiO_2, FeO_2), and defects in these materials are especially important in this process (Starukhina 2006, Dyar *et al.* 2010). The irregular and damaged fine-grained lunar soil traps solar wind protons and forms OH. Depending on how aligned or isolated the defects are at any given time, they will either form a channel that allows enhanced diffusion, or trap the incoming particle. As the physics of these studies apply to other airless bodies, the creation and destruction of lunar OH holds considerable promise to understanding bodies beyond the Moon.

4. Water from deep within the Moon

New analyses of Apollo samples have detected magmatic water in lunar volcanic glasses of pyroclastic origin that are substantially higher than earlier studies (Saal *et al.* 2008, Saal *et al.* 2013, Hauri *et al.* 2011). These volcanic glasses were analyzed using microbeam methods with either SIMS or FTIR techniques which were not available when the samples were brought to Earth decades ago. The Saal and Hauri team found melt inclusions from which they could extract pre-eruptive magmatic lunar water. Trapped within olivine crystals before volcanic eruption, these melt inclusions did not experience significant post-eruptive degassing. Prior to these studies, published direct measurements of water in lunar volcanic glasses did not exceed 50 parts per million. Hauri *et al.* (2011) reported the lunar melt inclusions contain 615 to 1410 ppm water and high correlated amounts of fluorine (50 to 78 ppm), sulfur (612 to 877 ppm), and chlorine (1.5 to 3.0 ppm). These volatile contents are very similar to those in primitive terrestrial mid-ocean ridge basalts and indicate that some parts of the lunar interior contain as much water as the upper mantle of the Earth. Studies of water in other lunar materials such as apatites and plagioclase feldspars (see Hauri *et al.* 2015 for references), plus the volcanic rock results, have provided a new and critical constraint upon the high-temperature models previously used to explain the formation and evolution of the Moon.

The Moon likely formed from a giant impact collision (Hartmann & Davis 1975) between a roughly Mars-sized object and the proto-Earth (Canup 2004). The extreme depletion of volatiles in lunar volcanic rocks from early Apollo studies had been taken as evidence of pervasive degassing after that energetic giant impact. More recent models can explain the Earth-Moon angular momentum and early thermal history of the Moon (Cameron & Benz 1991, Canup & Asphaug 2001, Canup 2012, Cuk & Stewart 2012), but they predict melting and partial vaporization of the material that enters the proto-lunar orbit, which makes it difficult to explain the newly measured abundance of volatiles in the lunar interior. However, Nakajima & Stevenson (2015) have shown that even protolunar material vaporized by such an impact may remain gravitationally bound to the Earth and avoid escape. Latest models suggest that in the absence of escape, the Moon's observed volatile depletion could be produced during the last stages of its assembly when volatile-rich material is preferentially accreted by the Earth instead of the Moon (Canup *et al.* 2015). These models also predict that the inner, earlier formed portions of the Moon could be volatile rich, reflecting the composition of a potentially water-rich early Earth and/or giant impactor. Zircons as old as 4,325 Ma provide evidence for the presence of liquid water near the surface of the Earth within 230 Ma of Earth's accretion. This observation is consistent with the conclusion that either the Earth had significant amounts of water before the giant impact, or the material that accreted after the giant impact (but before 4.3 Ga) was rich in volatiles.

5. Summary

Much of the paradigm-shifting work reported here was enabled by the cross-disciplinary work carried out by researchers around the world analyzing the abundance of data from the latest space missions. Our understanding of the Moon has changed significantly in the past few years. We now know there is water on the Moon; we see multiple contributors–some from long ago and some from present day. The Moon retains OH and water, as evidenced by material excavated from permanently shadowed regions, spectroscopic signatures on the surface, and water in lunar samples (a reminder that sample return is a gift to our future selves). The ability to process 40 year old, well-preserved, samples with new technology has enabled us to learn far more than we could originally glean from the Apollo samples. We have learned that the space environment also plays an important role in retention and/or creation of water on the surface–a process likely happening on other airless bodies. In addition, lunar resources may be key to future lunar bases and interplanetary refueling depots, given that all forms of hydrogen are useful for in situ resource utilization. The multidisciplinary teams within SSERVI are focused primarily on science questions needed for future exploration. The search for answers at the edge of our understanding will continue to benefit from the multi-institutional and international research enabled by NASA's virtual institutes.

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