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Water IN and ON the Moon: Recent Discoveries In Orbit And In The Lab

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In recent years, the Moon has been at the center of several international exploratory missions. With the hint of possible water-ice at the poles from the Clementine Mission in 1994, furthered evidenced by the neutron spectrometer data from the Prospector Mission in 1998, the scene was set for a concentrated set of missions by several nations at the beginning of the 21st century. Starting with the ESA-sponsored SMART Mission, with its unique form of propulsion, followed by the JAXA Kaguya Spacecraft, the Chinese Change-1 Mission, the Indian Chandrayaan-1 Orbiter, and the most recent US LRO and LCROSS Missions, the terra-bytes of new scientific data from the Moon have rapidly become over-whelming.

The ***Moon Mineralogy Mapper (M3)*** [1], a NASA-funded reflectance spectrometer on the Chandrayaan-1 Orbiter, ***was the first to discover OH-HOH water over large portions of the Moon.*** PI Carle Pieters [1] was far-sighted enough to insist on extending the spectral range from 0.4 to 3.0 microns. This OH-HOH finding, actually in early 2009, was strongly debated among the M3 team members; however, two on the team are members of other Missions - Cassini [2], and Deep Space [3], with their VIMS and EPOXY instruments, which completely verified this startling discovery of water over most of the Moon. However, the quantities are not much, only 200-1000 ppm. The most surprising discovery is that the presence of this water seems to be a diurnal feature, which has led to the M3 term of **Lunar Dew**, and appeared in Science in September 23, 2009 [1]. More recently, the sister Mission to LRO, the LCROSS impactor - this novel impactor and its trailing instrument package hit into the South Pole Permanently Shadowed Crater (PMS) Cabeus, and effectively threw water-ice and vapors into the exosphere, where they were identified as consisting mainly of water vapor, with minor amounts of methanol, ammonia, and even formaldehyde, but not near as much as was expected (only 1,000-2,000 ppm).

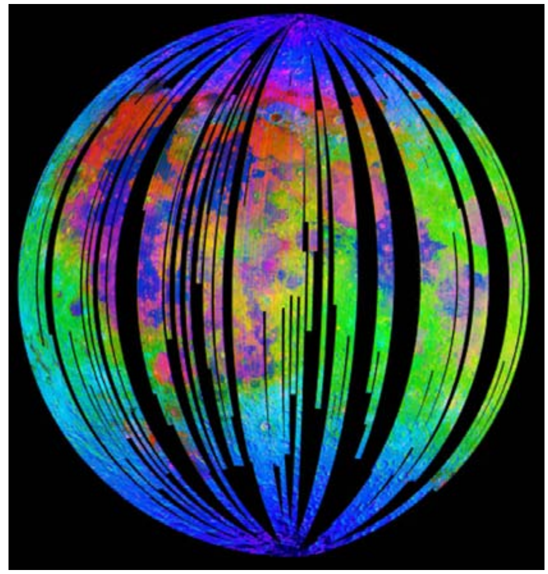

Figure 1. New map of water and hydroxyl on the moon from M3 data [2]. Red = 2-micron pyroxene absorption band depth; green = 2.4-micron apparent reflectance; and blue = absorptions due to water and hydroxyl. In the scheme of color mixing, cyan (light blue) = green + blue; magenta = blue + red; and pink = blue + green + red. Yellow and orange = green plus red. Therefore, **all blue, cyan, magenta and pink areas contain adsorbed water and/or hydroxyl,** while **red, green, yellow and orange contain little to no water or hydroxyl.**

The Moon is no longer dry! The origins for the water ON the Moon are distinctly different, one being the probable result of cometary impacts and subsequent sequestering of this water in the 30-40 K PSCs. But, the ***Lunar Dew*** has an entirely different origin. The major space weathering agents of micrometeorite, solar-wind, cosmic/galactic particle impacts effectively 'activate' the lunar soil by creating myriads of "dangling bonds" on the surface of the soil grains. With the lunar soil consisting of ~45 wt% oxygen, the majority of these unsatisfied bonds are those of oxygen.

One theory is that solar-wind protons [H^+], which constantly impact the lunar crust, but with different flux rates mainly as a function of the Earth's magnetosphere, encounter the dangling $O^=$ and for OH and HOH. Experiments with Apollo soil have demonstrated that such water can indeed be formed by proton bombardment [4]. It is entirely possible that this **Lunar Dew** upon vaporization due to rising diurnal temperatures, could be an additional source for the water-ice captured in the PMCs. These are exogenic sources of lunar water.

For many years, it has been suspected that there might be some endogenic water in some lunar minerals and glasses, but water has not been demonstrated to be due to terrestrial contamination [e.g., 5, 6]. It was only recently that Saal et al. [7] measured 40-45 ppm water in some Apollo volcanic glass beads, reasoning that they contained much more water when initially lofted into the lunar exosphere. This has spurred several teams to intensify their searches for water in lunar phases. It has long been suspected that apatite – $Ca_5(PO_4)_3(F,Cl,X)$ – might have some OH in the X position, as has been recently emphasized [8]. Indeed, two of the teams that Larry Taylor is a member of have just reported finding up to >6,000 ppm (0.6 wt%) H_2O at the Lunar and Planetary Science Conference with Liu et al. [9] and Greenwood et al. [10], along with McCubbin et al. [11]. Papers are about to be published in Science and Nature – Greenwood et al., [12]; Boyce et al. [13].

The study that has produced the most significant data to date is that of Greenwood et al. [10], in which the D/H values of this lunar water in apatite has been determined. Surprisingly, the D/H vales are mostly indicative of an ultimate **cometary source** for this lunar water. One can imagine that shortly after the giant impact of Theia with the Early Earth, there was considerable cometary water impacted into the Earth-Moon system. This water signature was largely camouflaged by the abundant Earth water, but could have had a distinct effect on the dry proto-Moon. The significance of these

findings of lunar water in apatite and glass has major significance for density, viscosity, and phase equilibria of magmatic systems on the Moon [e.g., 14]. It is obvious that these studies are only the beginnings of many forthcoming investigations.

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