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Water and Other Volatiles on the Moon: A Review

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Abstract—This paper presents a review of research findings on the various forms of water on the Moon. First, this is the water of the Moon's interior, which has been detected by sensitive mass spectrometric analysis of basaltic glasses delivered by the Apollo 15 and Apollo 17 missions. The previous concepts that lunar magmas are completely dehydrated have been disproved. Second, this is H_2O and/or OH in a thin layer (a few upper millimeters) of the lunar regolith, which is likely a result of bombardment of the oxygen contained in the lunar regolith with solar wind protons. This form of water is highly unstable and quite easily escapes from the surface, possibly being one of the sources of the water ice reservoirs at the Moon's poles. Third, this is water ice associated with other frozen gases in cold traps at the lunar poles. Its possible sources are impacts of comets and meteorites, the release of gas from the Moon's interior, and solar wind protons. The ice trapped at the lunar polars could be of practical interest for further exploration of the Moon.

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INTRODUCTION

This review is mainly about water on the Moon; however, it will also discuss, although to a lesser extent, the presence of other volatile compounds and organic substances. The research of recent years has completely changed our thinking about the presence of these components on the Moon. It was believed that the latter had been completely dehydrated; it was only the permanently shadowed areas at the lunar poles that had been suspected of having water ice, which could have accumulated in these cold traps via an inflow of water vapors of various origin (Watson et al., 1961). The thinking that the Moon was dry (except for the poles) stemmed from the results of an investigation of the moon rock samples delivered by the American Apollo missions and the Soviet Luna robotic spacecraft missions. Since no H_2O/OH (and CO_2) containing minerals had been found in these samples, researchers came to the conclusion that water and other volatile substances were largely absent from the Moon (see, e.g., Haskin and Warren, 1991).

This feature of the Moon's composition is also consistent with the observed enrichment of lunar rocks in refractory elements, such as Ca and Al. This manifests itself, e.g., in the fact that, compared to terrestrial basalt plagioclase, the plagioclase from lunar mare basalts is highly rich in anorthite components and lunar highlands are abundant in high-calcium anorthosite (see, e.g., Papike et al., 1991; Taylor et al., 1991). The severe depletion of lunar volatiles and enrichment in refractory elements, together with some other features of the Moon's geochemistry, spurred a number of physical models of the Moon's formation. One of them—the giant impact model—assumes that the Moon formed in the near-Earth orbit from hot debris thrown into space when a Mars-sized body collided with the Earth (see, e.g., Hartmann and Davis, 1975; Canup and Asphaug, 2001; Kleine et al., 2009).

The suspicions that the Moon's polar areas have elevated concentrations of hydrogen, most likely in the form of water ice, were confirmed in 1999, when the neutron detector of the American *Lunar Prospector* spacecraft detected a marked decrease in the neutron flux (Feldman et al., 1998; 2000; 2001). The same measurements but with a better spatial resolution have been carried out since the end of 2009 onboard the American *Lunar Reconnaissance Orbiter* spacecraft with the Russian LEND (Lunar Exploration Neutron Detector) neutron detector (see, e.g., Sanin et al., 2010; 2011; Mitrofanov et al., 2010; 2011). The measured results for the neutron flux over the lunar poles and their interpretations will be discussed below.

In 2008–2009, the measurements of the American mapping spectrometer Mineralogy Mapper (M3) onboard the Indian *Chandrayan 1* spacecraft revealed an H_2O/OH absorption feature at 3 μm over almost the entire surface of the Moon (Pieters et al., 2009). This was a surprising discovery; moreover, this band was in the long-wavelength part of this instrument's spectral range, in which the thermal emission of the Moon's surface interferes with measurements. To make sure that the feature was real, researchers reviewed the Moon observation data collected in 1999 with the VIMS optical spectrometer onboard the American *Cassini* spacecraft on its way to the Saturn system (Clark, 2009) and carried out new observations of the Moon with the SIM mapping spectrometer onboard the American *Deep Impact/EPOXI* spacecraft (Sunshine et al., 2009). The results of these spectral

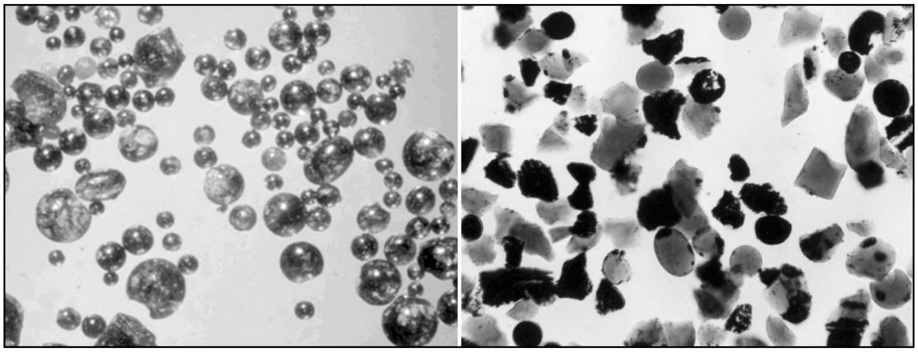

Fig. 1. Beads of the Apollo 15 (left) and Apollo 17 (right) green and orange glass through a microscope. The field of view of each image is 1 × 1.5 mm. Photo: NASA.

measurements and their interpretations will be discussed below.

Lastly, in 2008–2009 researchers reported detecting traces of water and some other volatiles by secondary ion mass spectrometry in the supposedly pyroclastic green and orange glasses from the samples delivered by *Apollo 15* and *17* (Saal et al., 2008; Friedman et al., 2009; Hauri et al., 2009), and in 2010–2011 traces of OH were discovered in apatite contained in lunar mare basalts (Greenwood et al., 2010; 2011a; 2011b; McCubbin et al., 2010a; 2010b; Liu et al., 2010).

Thus, it is clear now that water (H_2O and/or OH) is indeed present on the Moon and is found in three very different reservoirs, which will be briefly described in the following order: (1) H_2O and other volatiles in the lunar magmatic systems; (2) H_2O and/or OH in a thin (the first millimeters) layer on the most part of the Moon's surface; and (3) H_2O and other volatiles trapped in the regolith at the Moon's poles. These three types of water are also referred to as the Moon's interior water or juvenile water, surface water, and buried water, respectively.

WATER AND OTHER VOLATILES IN THE LUNAR MAGMATIC SYSTEMS

As said above, the lack of H_2O and CO_2 containing minerals in moon rocks delivered to the Earth made scientists believe that the lunar magmatic systems and, hence, the Moon as a whole were devoid of volatiles. There were numerous attempts to measure the content of these components in various samples including the Apollo 15 and Apollo 17 green and orange glasses (see, e.g., Epstein and Taylor, 1973; Friedman et al., 1972; Kaplan and Petrowski, 1971; Gibson and Moore, 1973; Gibson, 1977). Those were not localized measurements; they measured the bulk content in the samples.

The discovered very low concentrations of hydrogen (approximately 0.1–1 ppm) and partly carbon were interpreted as implanted solar wind components, and the traces of molecular water were thought to be terrestrial (laboratory) contamination.

In 1978, the study by Akhmanova et al. (1978) was published, which reported that several samples of the lunar regolith core taken by *Luna 24* were analyzed by IR spectrometry to discover a water content of approximately 0.1 wt % (1000 ppm) provided that the sensitivity of the method was 0.01 wt %. The authors did not reject the possibility that the discovered content could have been a result of contamination during the transportation or storage and picking up the probes for analysis, but they drew the reader's attention to the fact that the previously studied Luna 16, Luna 20, Apollo 11, and Apollo 12 samples were found to contain no traces of water, probably as a result of the lower (by a factor of two to three) sensitivity of the instruments used in those studies. Other researchers of lunar regolith paid no attention to this work by Akhmanova et al. (1978).

In 2008, the study by Saal et al. (2008) was published, which described the results of the investigation of volatiles and a number of rock-forming and rare elements in the Apollo 15 very low-titanium and low-titanium green glasses (sample 15427) and Apollo 17 high-titanium orange glasses (sample 74220) (Fig. 1).

The Apollo 15 green glasses and Apollo 17 orange glasses are beads (or their fragments) a few fractions of a millimeter in diameter. They are considered to be pyroclastic volcanic deposits formed as a result of picrite basalt lava fountaining (Delano, 1986; Delano et al., 1994; Shearer et al., 2006). The evidence for their pyroclastic origin is based on the spherical shape of the particles they are composed of, which requires droplets of liquid lava to solidify in free flight in combination with some features of their chemical composition. The latter include, in particular, chemical homogeneity with respect to the content of nonvolatile elements (e.g., Ti, Al, Cr, Fe, Mn, Mg, Ca, and REE) and correlation between the content of volatile and medium volatile elements (e.g., C, N, F, Na, S, Cl, Zn, Cd, Pb, and Bi) on the surface of the grains and those captured into gas bubbles inside the grains. The surface of the particles of the green and orange glass beads is highly enriched in Zn, Pb, F, and other medium volatile elements, which is explained by the