Re-Assessment of "Water on the Moon" after LCROSS.

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The LCROSS Mission has produced information about the possible presence of water in a permanently shaded regions of the Moon. Without the opportunity to have a controlled impact into a sun-lite site on the Moon, the LCROSS information must be carefully evaluated. The Apollo samples have provided a large amount of information on the nature of lunar hydrogen, water and other volatiles and this information must be considered in any interpretation of the observed data from the LCROSS and other lunar missions.

The possible occurrence of water on the Moon has been the cause of much speculation since the first telescopic lunar maps were drawn in the middle of the 17th century. The names of Mare Tranquillitatis, Imbrium, Procellarum etc. were applied to the immense basins thought to be dried-up seas. The lunar surface has been subjected to the infall of meteoroids and comets throughout its history. Watson et al. [1] and Arnold [2] argued that the H_2O and volatiles from the impactors would be stable and thus sublimate into the permanently shadowed regions of the Moon because of the low-temperatures prevailing there. The solar wind has irradiated surface materials and left a record along with the cosmic radiation history.

Many of the early Apollo investigators were disappointed because there were no sediments or hydrated minerals in the samples and even the basalts were formed under conditions of extreme dryness. It was recognized that the moon's surface was constantly bathed in solar wind, predominantly H (ca 10^8 atoms/cm^2/sec) and other elements, most significantly C, N, O and the noble gases, He through Xe. As a result, lunar soils and breccias with a high actual or latent surface areas can contain up to 1cm^3/gram H and all the other relevant elements in the expected relative solar abundances.

The ability of the solar wind to be involved in chemically modifying the lunar surface is manifestly apparent in that high temperature heating of soils and breccias released water. Other species such as CH_4 and higher hydrocarbons were shown to be produced by release using isotopically labeled acids. Some solar wind C is incorporated into metallic iron derived by reduction processes which could include preferential solar wind sputtering and selective impact deposition. An Apollo 17 mass spectrometer detected species cycling through the lunar atmosphere. It showed increased abundance of ions at masses 15, 16, 17, 18, 28, 40, 44 immediately post-dawn of the lunar day compared with the night-detected species are similar to LCROSS's data [12]. Impact temperatures associated with the event were ~500°K [12] similar to those needed to release low-temperature adsorbed volatiles from lunar samples [8].

Lunar soil samples, from lower latitudes, demonstrated hydrogen enrichment produced by the solar wind [3-5]. But none of the samples from nine separate locations (six Apollo sites and three Luna sites) provided evidence for trapped volatiles. None of the sampling sites investigated were near enough to the polar regions of the Moon to act as traps for CHON containing molecules and all of them experienced temperatures of ca 140°C during the lunar day/night cycle.

The lunar regolith constitutes the upper tens of meters of the surface materials in the lunar highlands and in the oldest lunar maria (~3.8 Ga). At the Apollo 11 site, the regolith appears to be only about six meters deep [6]. The origin of the regolith is bombardment by meteoroids of all sizes, materials are degraded and reconstructed and grains are continuously buried and re-exposed during 'lunar gardening' during which grain surfaces are continuously bathed in the solar wind flux of atomic particles from the corona of the Sun. High energy solar wind ions, largely H and He but with significant C and N and noble gases as well, stream continuously from the sun. The flux of ions impacting the Moon per unit area varies with the quantity ejected from the sun and because of interactions with the Earth's magnetosphere. Principal component of the solar wind is H; its deuterium abundance is vanishingly small. The solar-wind isotopic ratio D/H is at least three orders of magnitude less than the terrestrial value of 1.5 x 10^{-4}) [5]. The 2nd most abundant component of the solar wind is He, with an isotopic ratio of ^{3}He/^{4}He = 4 x 10^{-4}. This ratio is substantially higher than the terrestrial atmosphere's He (1.4 x 10^{-6}), which has been modified by addition of ^{4}He from the radioactive decay of U- and Th-series elements within the Earth. O, C, and N occur in the solar wind at concentrations two orders of magnitude less than that of He. An amorphous layer equivalent to the depth of penetration of solar wind ions is seen at the surface on lunar soil minerals. During thermal degassing of lunar soils, C is liberated as CO, CO_2 and CH_4 over different temperature intervals and H is released as H_2, OH and H_2O.

The H abundances with lunar regolith depth is not well understood. The H concentrations observed in lunar cores reflected the maturity of the lunar soils and mineralogy of the cores [4]. Within the Apollo 17 Shorty Crater core the concentrations of H stayed essentially the same, 2 to 3 ppm for a depth between 10 and 58 cm below the surface. The 3-meter Apollo 17 deep drill core showed H concentrations ranging from 5 ppm for a very immature soil horizon up to 65 to 70 ppm for mature soil horizons. The <20 μm grain size separates from several mature soil horizons in a core showed the greatest H concentrations of any lunar materials analyzed to date. These concentrations ranged from 269 to 306 ppm and are approximately ten times the H concentrations for typical lunar soils. H is concentrated within the finest grain size fractions and is present at depth within the lunar regolith [4]. C concentrations, as reflected by the existence of methane and the C associated with superparamagnetic iron, denoted as C_{hyd}, also varies with particle size, the finest grains being greater enriched in both species as are the glassy agglutinates and microbreccias produced by welding together and aggregating the finest grains [6]

Bustin and Gibson [4] showed that the <20μm grain size fractions were enriched by approximately a factor of 3 over the value obtained for the bulk soils consistent with a large proportion of the H from the solar wind. The <20 μm size fractions contained upwards of 107 to 146 ppm hydrogen. The <20μm size fraction for a soil breccia contained 176 ppm H. H appears to be enriched in soils with greater Ti concentrations. [3] noted that ilmenite grains retain helium

readily. The finest size fractions contained the greatest concentrations of helium. [4] found H concentrations in highland soils noticeably lower than would have been predicted from maturity data. The average H concentrations in 8 Apollo 16 bulk surface soils was only 28 ppm compared to 39 ppm for 23 bulk mare surface soils. Although 6 of the Apollo 16 bulk surface soils were classified as mature according to there I_s/FeO values, their average was only 34 ppm, considerably lower than the average of 54 ppm for all other mature surface soils. C_{hyd}/FeO, that is abundance of superparamagnetic (finely-divided) iron, is clearly related to both maturity and geochemical abundance of ferrous iron in the source rocks. This identifies an exposure mechanism as being responsible for finely-divided iron production. This mechanism may be solar wind sputtering or selective deposition. The measured total C abundance of lunar soils can be reconciled by a model that takes into consideration their mineralogy FeO abundance and the different penetration depths for the solar wind into different minerals [6].

Two lunar soils and one rock displayed unusual concentrations of volatiles reflecting their possible histories. Apollo 16 soil 61221, a subsurface soil with abnormally coarse grain size from Plum crater, had H concentrations of 3 ppm. This soil contained only 6% agglutinates and had an I_s/FeO value of 9.2 [7]. 61221 soil contained an unusual concentration of adsorbed gases [8]. Those adsorbed gases included H_2O, CO, CO_2, HCN, and NH_3 and were suggested to be of cometary origin on the basis of their gas release patterns. These gases are identical to some of the species identied on the LCROSS mission [12] and might have cometary species derived from a volatile impactor and had become adsorbed because of the cool trap beneath the surface. Apollo 17 soil 74220, the orange soil of volcanic origin contained an abundance of surface condensed volatiles [9]. This was an extremely immature soils with only 2 % agglutinates and an I_s/FeO maturity index of 1 [7]. Apollo 16 breccia 66095 (Rusty rock) showed a very unusual concentration of volatiles along with the multivalent characteristics of the element iron [11].

Even before the Apollo program, it had been proposed that there might be a readily available source of water on the Moon. As the large number of impact craters on the moon testifies, it has been subjected, throughout its long history, to an intense bombardment. Some of the impactors might have been comets, dirty snowballs, or carbonaceous chondrites, primitive meteorites known to contain up to 10 wt % bound H_2O and 3-5 wt % C and its compounds. It was suggested that these objects, on impact, would volatilize. The gas phases would condense out in lunar cold regions [1,2]. Indeed because there is a 1.5^o inclination between the Moon's spin axis and its orbital plane around the Sun, there are places near the lunar poles, particularly inside craters and under boulders, that have never been exposed to direct sunlight. They remain at temperatures lower than -220°C, at which everything except H and He would be frozen out.

The Clementine spacecraft in 1996 tested the ice deposits hypothesis by bouncing radar signals off the lunar poles; the results indicated the existence of ice. A similar experiment had already been successfully performed for Mercury. Mercury is much closer to the Sun and with equatorial surface temperatures in the region of 430°C, and yet it shows the possible existence of ice. Nevertheless, the Clementine results have been challenged because attempts to repeat the ground-based observations performed for Mercury, using the Arecibo radio telescope dish, have failed.

Additional support for the ice hypothesis comes from Lunar Prospector's neutron spectrometer, an instrument that is able to detect the occurrence of H remotely. Prospector found that not only were there H concentrations of ca 1500 +/- 800 wppm within 2° latitude of the lunar poles (most noticeable in the south polar Aitken basin and the crater Shackleton) but H abundances increased threefold when the areas of permanent shadow were targeted. Whilst the neutron spectrometer results from Mars have been largely accepted to infer H_2O, they have not been universally endorsed for the Moon. It has been speculated that there could be other H- and C-rich organic carriers from comets. If true, these might be of even greater scientific interest than water because of the exobiological significance.

The current state of knowledge concerning water on the Moon is that there is a considerable weight of circumstantial evidence summarized as follows: the conditions for trapping H_2O and other volatiles (permanently shaded and hence very cold locations) exist, sources of the species of interest are available (cometary, meteorite impacts and solar wind synthesis) and observations have been made that can be interpreted, but not unambiguously, in favor of ice deposits. The Apollo 17 mass spectrometer demonstrated that cold trapping of volatiles is feasible. Data from the Chandrayaan orbiter with its M^3 mapper [14] and the LRO instruments suggest detectable amounts of water in the form of H and/or OH are present in shadowed regions of the moon and other regions. The detected molecules may represent solar wind derived species similar to those detected in the returned lunar samples. Undoubtedly an appropriately equipped lunar reconnaissance orbiter, with a flight path over the poles will improve the knowledge base but definitive proof of the existence of water/ice etc. awaits the first suitably instrumented lander(s) such as the proposed Lunar Beagle Lander [13].

Because of the wide variety of volatiles present within lunar regolith materials and before any interpretation of polar volatiles seen by the LCROSS mission can be properly made, information available within the returned sample collection must be considered. Perhaps the volatiles seen by the LRO/LCROSS mission might be identical to lunar volatiles within "ordinary lunar equatorial materials". Until the control experiment of having an impactor strike an equatorially site is carried out, caution must be taken when intrepretating the results from the LCROSS mission.

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