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COVER STORY

Lunar surprise

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in New Delhi

One of the payloads of Chandrayaan-1 confirms the presence of water molecules in the moon’s soil and rocks.

NASA/AP

A NASA image of a gibbous moon as seen from above the earth’s atmosphere, captured by an STS-128 crew member on the Space Shuttle Discovery on August 30, 2009. In a gibbous moon more than half the disc is illuminated, but it is not a full moon.

THE moon is bone dry and anhydrous. That was the message the world got following the intensive studies on the lunar samples brought by the American Apollo and the Soviet Luna missions in the early 1970s. Well, practically so. The maiden lunar mission of the Indian Space Research Organisation (ISRO) has overturned that position with one of its main payloads, the Moon Mineralogy Mapper (M^3) of the United States’ National Aeronautics and Space Administration (NASA), finding telltale signs of the presence of hydroxyl (OH) and water (H_2O) molecules on the lunar surface soil and rocks.

The fact that Chandrayaan-1's mission was abruptly and unexpectedly cut short on August 29, after just 312 days in orbit against its design life of two years, does not in any way lessen this achievement. This discovery by M^3 is actually crowning testimony to the quality of data gathered by most of the on-board experiments on Chandrayaan-1 in that short span of time. The M^3 data were obtained in the beginning of February 2009 and the results were published by Principal Investigator Carle Pieters of Brown University and others in the September-end issue of the journal *Science*.

The team also included ISRO scientists J.N. Goswami, Director of the Physical Research Laboratory (PRL), Ahmedabad, and Chandrayaan-1's Principal Scientist; M. Annadurai, Project Director of Chandrayaan-1; and S. Kumar of the National Remote Sensing Agency, Hyderabad. Goswami and Kumar participated in the analysis and interpretation of the M^3 data and Annadurai was responsible for all the mission operations. Significantly, this path-breaking finding has been corroborated by lunar data obtained by two other operational NASA space missions: the comet-probe mission Deep Impact and the mission to Saturn and its satellites.

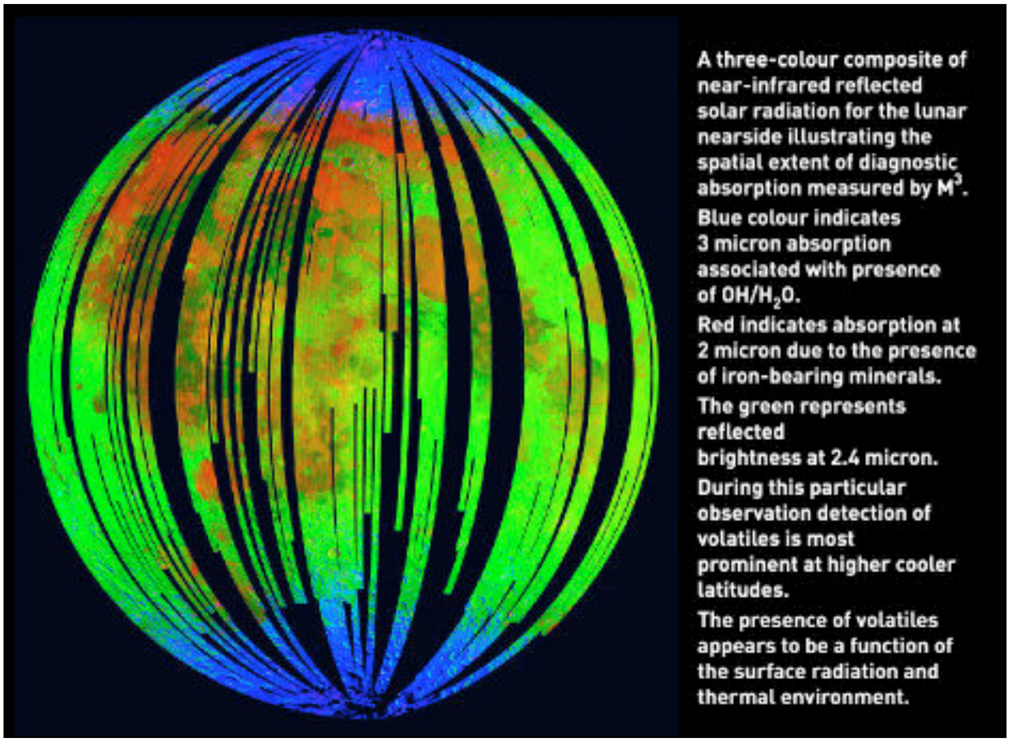
So, have we found water on the moon? "Not yet," says Goswami to be scientifically accurate. "We have not found water either in liquid or solid (ice) form. To say that we have found water is not correct at this stage. What has been detected is the presence of water molecules in extremely minute quantities in surface soil and rock. At best, these would be some hydrated silicates. Of course, if these molecules are there, the possibility [of finding water in its natural forms] always exists."

The Apollo-Luna message of a bone-dry moon was really not all that unequivocal because traces of water and some hydrous minerals had been seen in some Apollo lunar samples. But, since water molecules were not detected in the bulk of most of the samples, it was presumed that the measurements indicating the presence of water were errors and the water seen was actually contamination from terrestrial water-bearing materials. Also, there was nothing that distinguished lunar water from earthly water. In fact, even 'rust' found in some lunar rock material was attributed to moisture-laden terrestrial air.

Planetary scientists have, however, kept the idea of water on the moon alive by the simple reasoning that both the earth and the moon were born out of similar cosmic material. It, therefore, stands to reason that the moon should also harbour water in some form in its innards. It is known that small quantities of water are regularly introduced into the lunar environment by the bombardment of water-bearing meteoroids, meteoroid dust and comets. Thus, water on the moon can be endogenous or exogenous.

Apollo samples revisited

ISRO



An M^3 image indicating the presence of water on the moon.

In fact, Alberto Saal, also of Brown University, and others revisited the Apollo 15 green and Apollo 17 orange volcanic glass samples last year and detected 20-45 ppm (parts per million) of water in their interior using the advanced Secondary Ion Mass Spectrometry (SIMS) technique. These are believed to be the most primitive materials from the lunar mantle. The very formation of these ancient glass spherules requires that water present in them must be intrinsic to the moon. This discovery by Saal and others triggered a wave of reanalyses of Apollo samples using modern laboratory equipment.

We also know that the sun continuously emits low-energy hydrogen (H) ions, which are nothing but protons, in the form of solar wind. These hydrogen ions freely impact the lunar surface with neither a lunar magnetic field nor a lunar atmosphere to stop them. The number of such H ions hitting the lunar surface is quite high, about 100 million per square centimetre per second. The energy of the solar wind H ions allows them to penetrate the top loose layers of lunar soil and rock, called regolith, by about one tenth of a micrometre where they can pick up oxygen (O) ions to form strongly bonded hydroxyl (OH) molecules. The combination of another solar H ion will result in the formation of water.

But the harsh lunar environment, with the temperatures on the sun-facing surface going up to 125^{o} C, is most likely not to allow the water on or in the lunar *regolith* to survive. The water would simply evaporate under the intense heat of the sun that is beating down on the moon and escape into space. But there is also the possibility that lunar volatiles, including water vapour, can be transported to the much colder polar regions. The lunar polar craters, for instance, are forever hidden from sunlight, and temperatures at the crater floors are estimated to be around -150^{o} C.

Polar 'cold traps'

These permanently shadowed regions are perhaps the coldest regions in the solar system. The water molecules, it is believed, migrate towards these polar 'cold traps' and probably remain frozen there for many years. In fact, some recent lunar missions, such as Clementine in 1994 and Lunar Prospector in 1998, were designed specifically to look for water in these polar regions. These missions did return positive indications but were not unambiguous.

According to the authors of the M^3 paper, more recently it has also been proposed that a few layers of molecular water could be thermodynamically stable or that the OH and H may simply exist as molecules *adsorbed* onto the regolith grains. "It has also been demonstrated experimentally that water can adsorb onto surfaces either physically, retaining its integrity, or chemically (dissociatively) to form OH. Both single and multiple layers of different forms of OH and H_2O have been observed on simple mineral species along with the general temperature range of stability," they point out. "Nevertheless," they add, "historically the moon has been believed to be 'quite dry'." Thus Chandrayaan-1's findings may, as Goswami says, lead to a paradigm shift in our views of the moon.

The M^3's identification of water and OH molecules is based on the characteristic absorption of incident sunlight on the lunar surface by these molecules. M^3 measures the intensity of reflected sunlight from the lunar surface over the wavelength region of 0.7 to 3.0 micrometre (visible and infrared part of the electromagnetic spectrum). This enables the identification of various minerals on the lunar surface with characteristic absorption features at specific wavelengths. If any of the materials exposed on the lunar surface also have OH and H_2O molecules attached to them, additional absorptive features would be seen in the infrared region (2.7-3.2 micrometre).

M^3 found absorption features near 2.8 micrometre and 3.0 micrometre, characteristic of OH and H_2O molecules, for the first time. These molecules are in all likelihood attached to silicate material found in feldspathic rocks. These features were apparently evident in several areas even in the first set of data returned by Chandrayaan-1. The primary source of these molecules, the authors conclude, appears to be the interaction of solar wind H ions with abundant oxygen present in the lunar surface soil and rock.

Absorption occurs as solar radiation passes through randomly oriented particles in the upper 1 to 2 mm of the soil and the reflectance spectra would exhibit the combined absorptions from all particles. Therefore, since reflection is a near-surface phenomenon, such studies can provide information on the mineral composition of the upper few millimetres of the lunar surface. What is significant in M^3's finding is that the absorption features are widely distributed, including in sunlit areas. They are observed systematically across the moon and appear strongest at cooler higher latitudes and at several fresh feldspathic craters.

However, the distribution over the entire moon is yet to be firmly established, points out Goswami. This is because a component of emitted thermal radiation often occurs with the reflected radiation in M^3's measurements. In sunlit areas, where temperatures exceed 100° C, this emitted thermal (infrared) radiation may mask the absorption features of these molecules, particularly if they are weak in some regions. However, as one moves towards the cooler higher latitudes, the signals are much better, says the M^3 paper.

The team has also developed an interactive procedure to measure and remove this thermal emission component. "The pattern seen in M^3 data," says the paper, "may indicate increasingly strong OH/H_2O absorptions with latitudes, but we cannot eliminate the possibility that the 3-micrometre [absorption] feature is present at lower latitudes but is masked by a minor thermal component beyond 2.6 micrometre."

Abundance estimate

Making some specific assumptions about the physical form in which OH and H_2O occur and the location of the hydrates, a model for abundance estimates it to be about 770 ppm, which means about 0.8 g per kg of lunar surface material. But this value is dependent on particle size and the total abundance of hydrated material in the bulk upper regolith. M^3 data suggest a minor hydrated phase, or a hydration process occurs on the lunar surface. This also may mean that there are hydrated silicates on the lunar surface that were not sampled by the Apollo and Luna missions. "These unsampled phases," say the authors, "might be endogenic to the moon and freshly exposed by craters in ancient highland [cratered] terrain, or they may form during an impact event by a water-bearing comet or asteroid."

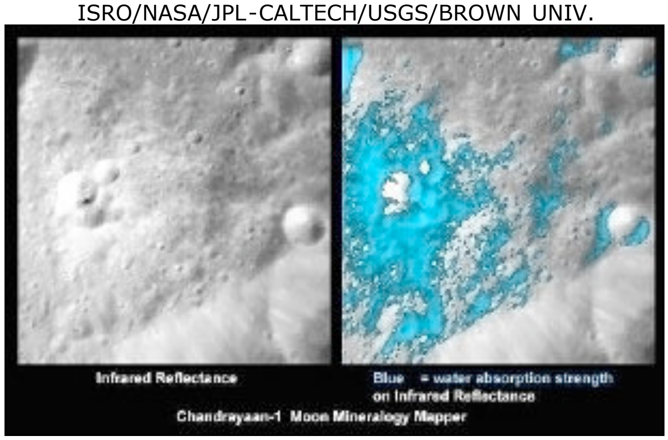
Compared with the absorption features measured by M^3, which originate from the upper few millimetres of the surface, the Lunar Prospector (L.P.) data, which detected hydrogen ions by neutron spectrometer measurements, represent the upper 50 cm or so of the regolith. Further, comparing data of the two from the 113-km Goldschmidt crater, while M^3 data exhibited a prominent 3-micrometre absorption, the L.P. data exhibited distinctly low H abundance. This, according to the authors of the M^3 paper, suggests that the hydrated materials observed by M^3 do not occur at depth and that the M^3 detection of OH/H_2O molecules is distinctly surface-correlated. "Thus," say the authors, "surficial processes involving the solar wind are the most likely explanation for our observations."

Following this identification of OH/H_2O, NASA's Deep Impact mission and the Cassini-Huygens spacecraft, which carry instruments that go beyond 3.0 micrometre, provided an opportunity for an independent confirmation of the results. Results of these independent observations, too, were included in the same issue of *Science*.

Deep Impact was launched in 2005 to explore the Comet Tempel 1, which it did in 2006. It is now in orbit with an extended mission to study extra-planetary objects, including Comet Hartley 2 in 2010. The Principal Investigator of Deep Impact, Jessica Sunshine, is also a member of the M^3 team. In the light of Chandrayaan-1's findings, the Deep Impact team was requested to study the moon when it would fly by the earth-moon system in June 2009. Deep Impact swung by the moon on June 2 and 9 and obtained the relevant data. The team observed both equatorial and polar data.

Deep Impact confirmation

ISRO/NASA/JPL-CALTECH/USGS/BROWN UNIV.



These images show a very young lunar crater on the side of the moon that faces away from the earth. The image at left shows brightness at shorter infrared wavelengths. The one on the right shows the distribution of water-rich minerals (light blue) around a small crater.

"The Deep Impact observations of the moon not only unequivocally confirm the presence of OH/H_2O on the lunar surface but also reveal that the entire lunar surface is hydrated during at least some portions of the lunar day," says the paper of Sunshine and others, which was published alongside the M^3 paper. Based on the temporal variations observed over the lunar diurnal cycle, they point out that the hydration process is a dynamic one driven by solar radiation, and water is in the process of dynamic and rapid migration across the lunar surface.

Their findings are also thus consistent with the concept of solar wind interactions with the lunar surface as the source of these molecules. They also find that even though there is the possibility of photo-dissociation of H_2O by solar photons, an equilibrium situation prevails during the day, necessitating a constant source. They also make a new point that all areas of the moon, regardless of their composition, exhibit similar maximum hydration during the night and the short time-scale loss and recovery of OH/H_2O completes entirely within daylight hours.

Their estimate of abundance is <0.5 per cent, as against M^3's 0.1 per cent. "The relatively low abundances suggest that lunar hydration is a surface phenomenon," the authors say.

Similarly, Roger Clark of the U.S. Geological Survey, the Principal Investigator of Cassini and a member of the M^3 team, was encouraged to go back to the archives and look at the 1999 data when the spacecraft had a fly-by of the moon, for calibration purposes. Analysis of the Cassini data, which too has been published by *Science* together with the other two, has revealed clear signatures of absorption features of both OH and H_2O on the lunar surface. Clark argues in favour of comet as the source OH and H_2O for the abundances measured. "But such cometary impacts are sporadic and it is not entirely clear how water molecules released after the impact will be disbursed and preserved in the moon," points out Goswami.

According to Clark's calculation, about 10 trillion kg of water must have been delivered to the lunar surface by comets over the last two billion years or 0.5 kg/sq m. If this amount is distributed uniformly in the top millimetre of the surface, it would be about 50 per cent abundance. Impact gardening would bury and mix the water in the top couple of metres, diluting the average abundance to about 500 ppm, Clark argues. But he also admits of the other possibilities, including endogenic ancient water, as the source of H_2O and OH molecules detected by the Cassini instrument.

As the editorial comment by P.G. Lucey of Hawaii Institute of Geology and Palaeontology in *Science* pointed out, the unambiguous infrared 3-micrometre absorption measurements by the three spacecraft have shifted the focus of lunar water from the interior to the surface of the moon. "However," as Goswami points out, "whether the distribution of water molecules percolate below the lunar surface due to impact-induced mixing of top layers of the lunar surface (gardening) cannot be established from the M^3 data. We also need to know more precisely the source and origin of the water and OH molecules, their abundances in different types of lunar soils and rocks, their spatial and vertical extent, their pole-ward migration when released from the lunar surface and the possibility of their storage in the upper few metres of the regolith."

As Lucey has pointed out, all these have to be reconciled with the lack of any obvious evidence of any alteration of sampled lunar materials by water.

Further analyses from Chandrayaan-1 and other lunar missions will hopefully provide the answers. In fact, it is reliably learnt that NASA's Mini-SAR instrument, which was specifically on Chandrayaan-1 to look for water, gathered data from both the poles before the spacecraft's life ended prematurely and analyses are going on. Since NASA's recently launched Lunar Reconnaissance Orbiter (LRO) carries an instrument similar to the Mini-SAR, a unique coordinated bistatic experiment was attempted by Chandrayaan-1 and the LRO when they were about 20 km away from each other. The idea was to study the poles, the 'cold traps', by bouncing off radio waves from the polar region so that the reflected waves are received by the LRO. Unfortunately, the experiment did not succeed. But the LRO, on its own, will be gathering polar data during the course of its mission. Further, its partner satellite, the Lunar Crater Observation and Sensing Satellite (LCROSS), will be crashing the last stage of a launch vehicle into the polar cold trap, thereby lofting the crater soil into visibility for study by spacecraft and ground-based observations.

There may also be wetter regions to be discovered far from the sites that have been sampled. But even with the new data already obtained, the presence of "water" on the moon or a "wet" moon does indicate a significant revival of lunar research. Future lunar revisits and further exploration plans by planetary scientists around the world are also very much on the cards.

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