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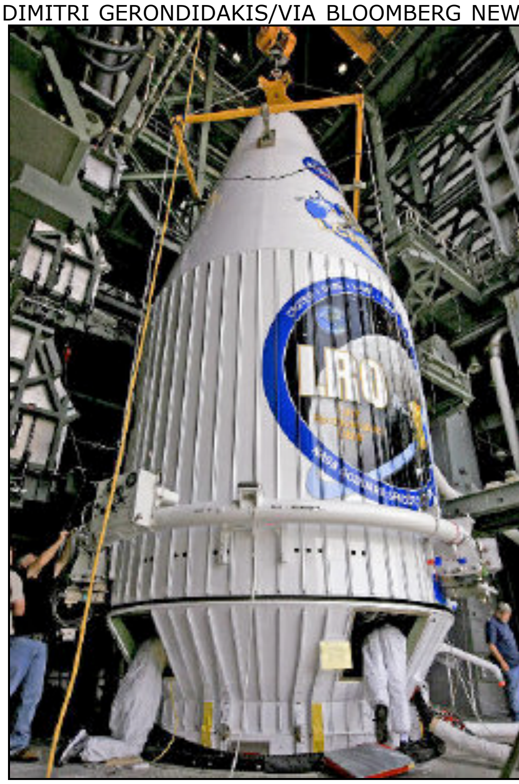
COVER STORY

A settled question?

R. RAMACHANDRAN

The question now is not whether there is water on the moon but how it got there and how much of it is trapped in the moon's polar craters.

DIMITRI GERONDIDAKIS/VIA BLOOMBERG NEWS



Workers attach NASA's Lunar Reconnaissance Orbiter and Lunar Crater Observation Sensing Satellite to an Atlas V rocket inside the mobile service tower at Cape Canaveral, Florida, U.S., on May 28. The LRO, launched on June 18, focusses on the selection of safe landing sites, identification of lunar resources, and the study of how the lunar radiation environment will affect humans. It searches for evidence of water ice on the moon's surface.

THE detection of water ice on the moon by the M^3 (M-cube) experiment aboard the Chandrayaan-1 spacecraft of the Indian Space Research Organisation (ISRO), if further confirmed following detailed analyses, may settle once and for all the 17-year-old controversy over whether the moon harbours water as ice at all. The possibility of ice having accumulated molecule by molecule over geological time scales within the craters at the poles was first suggested in 1961 by Caltech researchers Kenneth Watson, Bruce Murray and Harrison Brown.

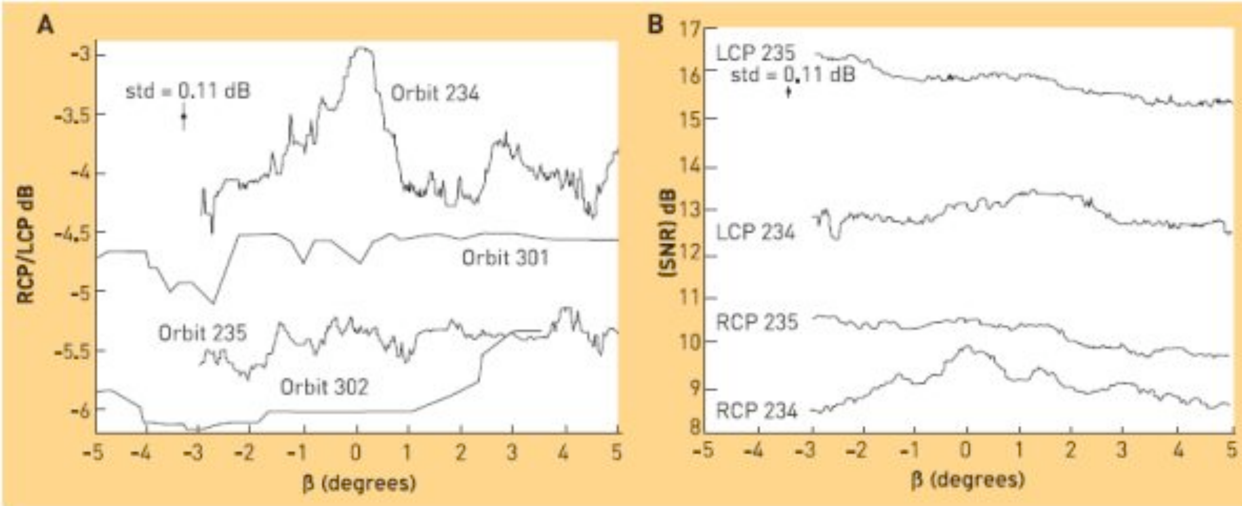
The moon does not have an atmosphere and hence no stable formation of water or ice on it. The moon is regularly bombarded by water-bearing comets, asteroids and meteoroids, which could bring ice molecules and deposit them on it. However, because of the lack of atmosphere, the extreme energy from the sun splits this water into its constituent elements, hydrogen and oxygen, which escape into space. Watson and associates argued that because of the slight axial tilt of the moon's rotation axis of 1.6 degrees to the ecliptic – the plane containing the earth's orbit around the sun and the sun – the crater floors near the poles of the moon would be permanently dark and very cold with temperatures less than -150^{o}C, and this would serve as "cold traps" where water (as ice) would remain stable for thousands of years.

The slow accumulation of water since the origin of the solar system, a time span of billion years, would have resulted in vast quantities of ice at the polar craters.

Lunar rock samples collected mainly from the equatorial latitudes and returned by the Apollo missions, however, were "bone dry", drier than any terrestrial sample. Apollo missions remained at near-equatorial latitudes because of operational and safety considerations. This implied that the moon had no indigenous water and that tonnes of water delivered by the impacting comets did not alter the lunar samples from lower latitudes. But a paper in 1979 by James Arnold of the University of California kept the idea of ice on the moon alive, despite the growing scepticism among planetary scientists. He showed that the arguments of Watson and others were valid and also that water elsewhere on the moon, if not lost by photo-dissociation, would also migrate to the cold polar traps. He suggested a Lunar Polar Orbiter (LPO) mission with a gamma-ray spectrometer to look specifically at the poles. Detection of gamma-rays emitted by hydrogen would be evidence for the presence of water ice at the poles. However, the LPO never materialised, given the other priorities of the National Aeronautics and Space Administration (NASA).

(What we are talking of is water on the lunar surface, down to few metres of lunar soil that is visible and perhaps accessible. We are not talking of water in the interiors of the moon. The bulk moon may or may not contain water. Earlier work on lunar samples from the Apollo and Luna missions concluded that the moon is highly deficient in highly volatile elements relative to the earth, particularly hydrogen, thus making it anhydrous and dry. However, work reported last year by Alberto Saal and others on volcanic glass spherules in these samples using advanced Secondary Ion Mass Spectrometry (SIMS) techniques suggests that bulk moon is not entirely depleted of water.)

Clementine experiment



In the Clementine bistatic radar experiment, two orbits of radar data were taken; orbit 234 passed directly over south polar darkness; the control orbit 235 was over similar terrain that receives sunlight. An enhancement of CPR was seen in orbit 234 data, centred around zero-phase (b=0), over the dark region, but not over the sunlit region (orbit 235), even though both are highland terrains. This relation was interpreted to be caused by the presence of ice in the dark areas near the south pole.

In the 1980s, United States President Ronald Reagan launched the Strategic Defence Initiative (SDI), or Star Wars, which included the development of technologies for defence against ballistic missiles. The launch of small satellites capable of locating and intercepting missiles in space, the so-called 'Brilliant Pebbles' system, was part of this missile defence system. In the early 1990s, the Clementine programme built and launched a small satellite to the moon, a spacecraft derived from the Brilliant Pebbles concept. In 1994, the Clementine spacecraft orbited the moon for 71 days. Although it did not carry any instrument to look for lunar ice, an experiment was improvised to do this. The mission team carried out a "bistatic" radar experiment, wherein the transmitter and the receiver are in different places and not co-located as is usual. The spacecraft beamed radio waves on to the polar crater and the echoes were received on the earth to see if they had distinctive signatures for ice. The reflected signals from the dark regions of the south pole of the moon (the Shackleton Crater) were found to have a high Circular Polarisation Ratio (CPR).

In the Clementine experiment, Right Circularly Polarised (RCP) radio waves and the reception on the earth would pick up RCP and Left Circularly Polarised (LCP) signals. The ratio of the power received in these two channels is called CPR. A dry surface in the crater would have a CPR of less than one, but an icy surface, such as the icy satellites of Jupiter, will have a CPR greater than one. This is because ice is a radio-transparent medium and the waves penetrate and scatter and are reflected multiple times and returned such that some of the reflected waves received would have the same polarisation as they had when they were sent.

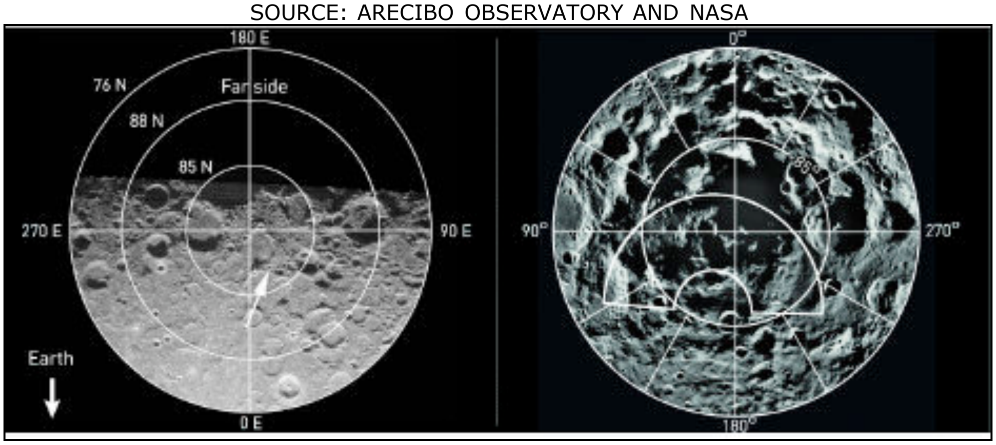
Bistatic experiments can observe reflected waves at different phase angles between the transmitted and reflected waves. This phase dependence of the reflected light is akin to the bright reflection seen from red plastic reflectors placed at road kerbs at certain angles when several internal planes in the transparent plastic align so that there is a very bright reflection. Such a phenomenon, called the Coherent Backscatter Opposition Effect (BOE), is also seen from the moon in both visible and radio wavelengths.

Lunar Prospector

In 1998, NASA sent Lunar Prospector, which carried an instrument designed to measure neutrons emitted from the moon. The energy of neutrons emitted from the poles of the moon suggested that the there was "excess" hydrogen there because medium-energy neutrons are strongly absorbed by hydrogen. However, it does not tell us in what form the hydrogen is present. The LP team estimated that if the presence of hydrogen indicated the presence of ice, the total quantity of surface water ice might be about three billion (giga) tonnes.

Meanwhile, radio astronomers on the earth began to question the Clementine and LP results. Images taken with the giant Arecibo radio telescope, a facility of the National Science Foundation (NSF) operated by Cornell University in Puerto Rico, found radar reflections with high CPR even in sunlit areas of the lunar surface. Since ice is not stable in sunlight, it was inferred that all the observed CPR was caused by surface roughness and that if any ice existed at the poles, it would be in a highly disseminated form which the radar mapping could not see.

SOURCE: ARECIBO OBSERVATORY AND NASA



An earth-based radar image of the north pole of the moon, showing the position of the Erlanger crater (indicated with an arrow). The crater floors near the poles are permanently dark and very cold. (Right) In the Clementine experiment, the reflected signals from the south pole indicated the presence of material with a high CPR.

Rough surfaces can have many corner reflectors. When a radio wave strikes such a rock face (which changes RCP to LCP) and then bounces over to another reflector face which changes LCP back into RCP, the double (and multiple reflections) can create high CPR, which would be similar to high CPR from icy surfaces. A more detailed, high-resolution mapping by the Arecibo research group has only reconfirmed earlier data. A press release issued in 2006 after the most recent work said: "Ice, it turns out, is hard to come up there."

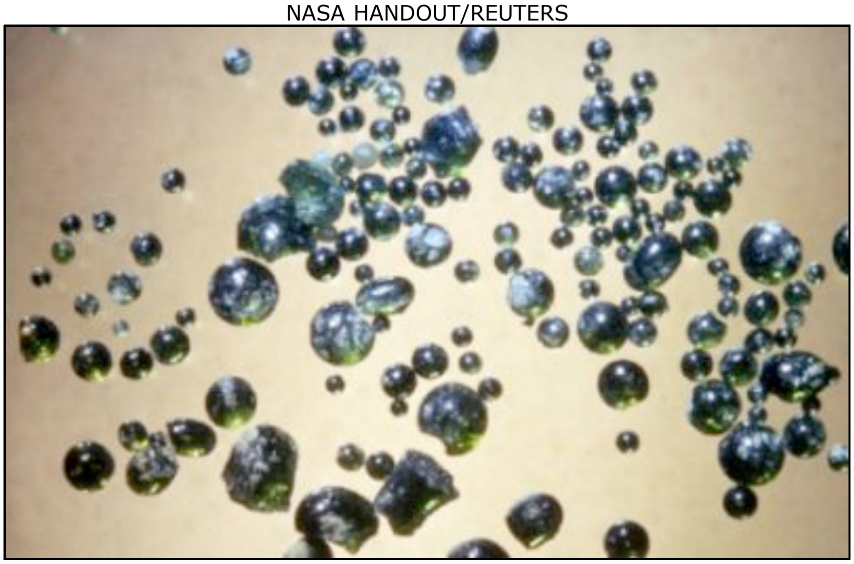
According to Paul Spudis of the Lunar and Planetary Institute, Houston, Texas, who is the principal investigator of the Mini-SAR experiment on Chandrayaan-1 and was deputy science team leader of the Clementine mission, the bistatic mode could distinguish between the two high CPR results. He points out that the Clementine mission measured CPR over two orbits of the lunar south pole, one over an area of polar darkness (orbit 234; see plot) and the other over a nominally sunlit zone near the pole (orbit 235). In the former, the CPR enhancement is symmetric about a high peak at zero phase angle (looking straight into the dark region) whereas in the latter, high CPR values from the sunlit region is more or less uniform about the zero phase angle.

From the strength of the CPR enhancement, the Clementine group estimated that ice was mixed with regolith dirt and was present in a deposit about two metres thick with a concentration of 1.5 wt. per cent, averaged over hundreds of square kilometres.

However, because of the limited period of the Clementine mission, this experiment could not be repeated. Also, since the mission was not optimised for this experiment, the resolution was poor – about 300 km across. "Given the size of the Clementine resolution," Spudis wrote recently, "the observed CPR enhancement could be explained by the same area of high CPR observed in ground-based radar images of the crater Shackleton. The controversy is not whether an area of high CPR exists in the permanently shadowed interior of Shackleton crater, but over what is causing the high CPR signature."

On the other hand, the Prospector, which was a spinning spacecraft and was able to look in all directions, albeit with a limited resolution of 30-40 km, sampled the upper 40 cm of the lunar surface. Unlike the Clementine and the earth-based radar experiments, it looked directly into the dark crater of the moon. It found strong absorption of medium-energy neutrons at both poles, roughly in similar concentrations of about 200 ppm. Curiously, the Lunar Prospector found that the uppermost layers of the soil are depleted in hydrogen, down to about 10 cm below the surface. Thus, ice seems to be present between 10 cm and 3 m below the surface. "Such a depletion," says Spudis, "suggests a non-solar wind origin for the polar hydrogen, as hydrogen implanted by solar wind would be expected to be high in the upper layers of the surface." But these LP results have also been doubted. It has been argued that the reduction in neutrons is caused by the presence of another light element like sulphur.

NASA HANDOUT/REUTERS



Green glass spherules collected from the Apollo 15 landing site at Hadley Rille on the moon are shown in this undated handout photo. Scientists using a new kind of spectrograph have found evidence of water on the moon, contained in tiny volcanic glass beads collected by astronauts who landed on the moon nearly 40 years ago. These samples represent volcanic deposits formed early in the moon's geologic history.

The recent Japanese lunar mission Kaguya (Selene) also failed to detect the presence of water ice inside the Shackleton Crater in its imaging with the on-board Terrain Camera, a 10-m resolution stereo camera. The crater was faintly lit by sunlight scattered from the upper inner wall near the rim for imaging to be done. "However," the Kaguya team's paper on October 23, 2008, in the journal *Science* noted, "the derived albedo indicates that exposed relatively pure water-ice deposits are lacked on the [crater] floor at the TC's spatial resolution. Water-ice may be disseminated and mixed with soil at a few area per cent [which does not affect the surface brightness] or may not exist at all."

"No single piece of evidence for lunar ice is decisive, but I think the preponderance of evidence indicates that water ice exists in permanently dark areas near the poles," wrote Spudis. "However, its origin and the process associated with its deposition are unclear. The ice could be of cometary, meteoric or solar wind origin; each would have interesting implications for its composition.... Whatever the source, polar ice is a useful resource for future lunar inhabitants."

Recent evidence

The recent evidence, in the form of characteristic absorption lines of OH and water (H-O-H) in the near infrared, as seen by NASA's specifically designed M-cube experiment on board Chandrayaan-1, and corroborated by the evidence from the data of Cassini-Huygens Spacecraft to Saturn during its moon fly-by in 1999 and the Deep Impact (EPOXI) spacecraft targeted to fly by comet 103P/Hartley 2 in November 2010 during its recent passage near the moon, may be more conclusive than the earlier observations. In fact, the M-cube mapping has found water and hydroxyl molecules at diverse non-polar areas including sunlit regions of the moon's surface, but the polar crater regions showed much stronger signals.

But does it resolve the controversy? Perhaps it is too early to say, but, on the face of it, the recent evidence seems more definitive. Again, these observations do not say anything about the origins of water on the moon. However, since these are based on surface absorption, the water molecules detected are interpreted to be endogenous rather than being deposited through cometary or meteoroid impacts. They have been probably produced by hydrogen ions from the sun (solar wind) impacting the surface and interacting with oxygen in the soil. These results have received further confirmation from the initial results of NASA's Lunar Reconnaissance Orbiter (LRO) launched on June 18. So the question now is not whether there is water on the moon but how it got there and how much of it is trapped in those polar craters.