Lunar water

Ujjal Kumar Sur

Water is one of the most important chemicals on Earth. It makes up over 60% by volume of the human body and covers up 70% of the Earth's surface. The presence of liquid water is thought to be essential to the development of life. The search for evidence of liquid water in other planets and the Moon was considered equivalent to the search for previous life.

Lunar water is water that is present on the surface of the Moon. Liquid water cannot persist on the Moon's surface; water vapour is quickly decomposed by sunlight through a process known as photodissociation[1] and lost to outer space. However, since the lunar mission in the 1960s, scientists have predicted that water-ice can survive in cold, permanently shadowed craters at the Moon's poles and that the surface of the Moon is completely dry. The possibility of ice in the floor of polar lunar craters was first suggested in 1961 by Caltech researchers, Kenneth Watson, Bruce C. Murray and Harrison Brown. Although trace amounts of water was found in lunar rock samples collected by Apollo astronauts, this was assumed to be a result of contamination, and the majority of the lunar surface was generally assumed to be completely dry. The first proposed proof of water-ice on the Moon came in 1994 from the United States military Clementine probe. In an investigation, known as the 'bistatic radar experiment', Clementine used its transmitter to beam radio waves into the dark regions of the south pole of the Moon. Echoes of these waves were detected by large dish antennas of the Deep Space Network on Earth. The magnitude and polarization of these echoes was consistent with an icy rather than rocky surface, but the results were not conclusive.

Three recent papers have challenged this notion. Recently, lunar scientists have carried out infra-red (IR) spectroscopic measurements of the lunar surface from a spacecraft, which can provide unambiguous evidence for the existence of water or hydroxyl ($OH^{\bullet}$) group[2–4]. Study of the lunar samples returned by the Apollo missions revealed none of the water-bearing primary minerals that are common in Earth rocks[5]; instead, all the rocks examined were composed entirely of anhydrous minerals. Some of the rocks in the Moon also contain primary igneous metallic iron, which is susceptible to alteration by water. No such alteration was found. Even in the case of coarse-grained plutonic rocks (which are formed from the cooling of molten rock below the surface), where volatiles in the magma chambers would have had ample opportunity to react with minerals, no hydrous phases were observed. This perceived dryness of the Moon stands in stark contrast to the abundant water found at the Earth's surface and throughout its crust.

Recent reports of a few parts per million water detected in lunar glasses and phosphates with more sensitive methods, suggest that the deep lunar interior may contain much more water than previously assumed[6,7]. However, the spatial pattern of the OH group and other volatiles in volcanic glasses suggests a diffusion profile[6], perhaps established while these erupting glasses lost water in flight through the lunar vacuum following eruption. Calculations of the original water contents suggest water abundances near 0.1% by weight, similar to those of terrestrial mid-ocean ridge basalts, indicating that the deep Moon may be as rich in water as is the deep Earth.

The new spacecraft measurements shift the focus of lunar water from the interior to the surface of the Moon. Infrared spectroscopic measurements from three spacecrafts have precisely detected absorptions near 3 μm on the lunar surface that are almost certainly due to hydroxyl groups or water, or both[2–4]. Three micrometres is the position of the fundamental vibrational absorption of the OH group and so is an extraordinarily sensitive indicator of the presence of water (or hydroxyl group). Preliminary modelling by Sunshine *et al.*[4] suggests a few tenths of a per cent by weight water in the optical surface. All three experiments show that the water-related absorption increases toward the lunar poles, although this observation does not necessarily mean that the concentration of a water-bearing phase increases toward the poles.

In September 2009, India's Chandrayaan-1 detected water on the Moon and hydroxyl absorption lines in reflected sunlight. In November 2009, NASA reported that its LCROSS space probe had detected a significant amount of hydroxyl group in the material thrown up from a south polar crater by an impactor; this may be attributed to water-bearing materials – what appears to be 'near pure crystalline water-ice'. In March 2010, NASA reported that the Mini-SAR radar aboard the Chandrayaan-1 has detected what appears to be ice deposits at the lunar north pole, at least 600 million tonnes in sheets of relatively pure ice a couple of metres thick[8]. The US space agency's (NASA) Mini-SAR experiment found more than 40 small craters containing water-ice. Paul Spudis, Lunar and Planetary Institute in Houston, USA, estimated that there was at least 600 million metric tonnes of water-ice held within these impact craters. According to him, equivalent amount, expressed as rocket fuel, would be enough to launch one space shuttle per day for 2200 years. Temperatures in some of these permanently darkened craters can drop as low as 25 K – colder than the surface of Pluto – allowing water-ice to remain stable.

Water may have been delivered to the Moon over geological timescales by the regular bombardment of water-bearing comets, asteroids and meteoroids or continuously produced *in situ* by the hydrogen ions (protons) of the solar wind impacting oxygen-bearing minerals. The search for the presence of lunar water has attracted considerable attention and motivated several recent lunar missions, largely because of the usefulness of water in rendering long-term lunar habitation feasible.

Lunar water has two potential origins: water-bearing comets (and other bodies) striking the Moon, and *in situ* production. It has been theorized that the latter may occur when hydrogen ions (protons) in the solar wind chemically combine with the oxygen atoms present in the lunar minerals (oxides, silicates, etc.) to produce small amounts of water trapped in the crystal lattices of the minerals or as hydroxyl groups, potential water precursors. The hydroxyl surface groups (S–OH) formed by the reaction of protons (H^+) with oxygen atoms accessible

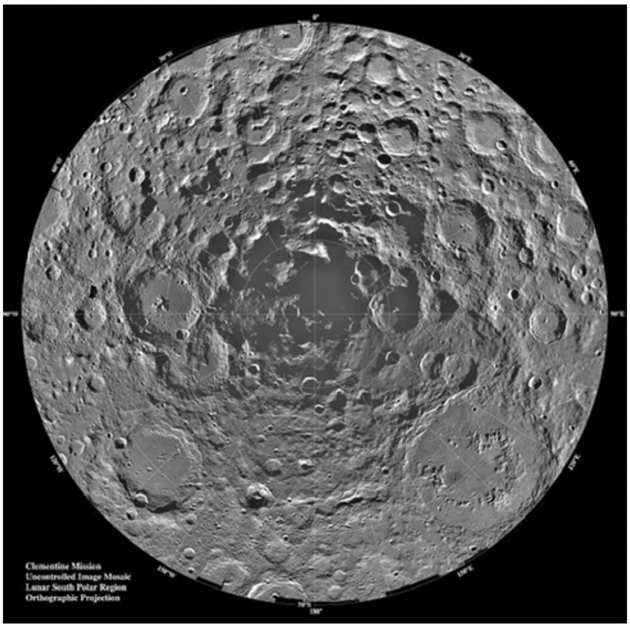

Figure 1. Composite image of the moon's south polar region, captured by NASA's Clementine probe over two lunar days (image courtesy NASA).

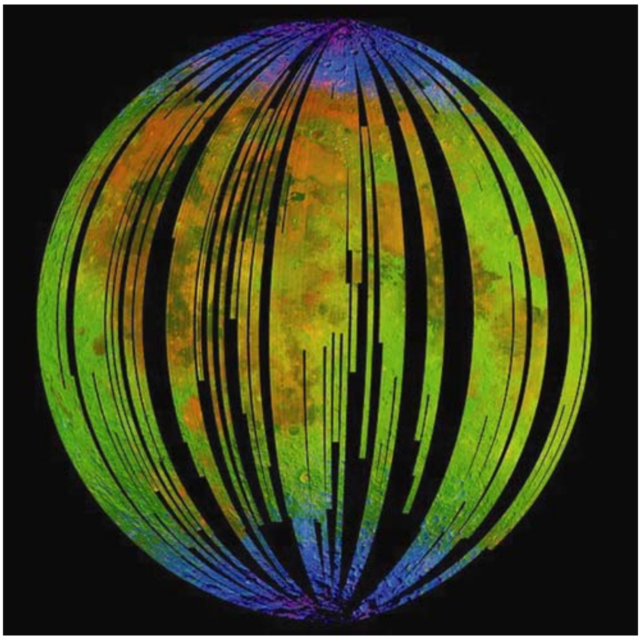

Figure 2. Image of the moon taken by the Moon Mineralogy Mapper (image courtesy NASA).

at the oxide surface (S=O) could further be converted in water molecules (H_2O) adsorbed onto the mineral surface of the oxide. The mass balance of a chemical rearrangement at the oxide surface could be schematically written as

$$2S–OH \rightarrow S{=}O + S + H_2O,$$

or

$$2S–OH \rightarrow S–O–S + H_2O,$$

where S represents the oxide surface.

Figure 1 shows the composite image of the Moon's south polar region, captured by NASA's Clementine probe over two lunar days. Figure 2 shows the image of the Moon taken by the Moon Mineralogy Mapper. Blue colour shows the spectral signature of hydroxide, green the brightness of the surface as measured by reflected IR radiation from the Sun and red shows an iron-bearing mineral called pyroxene.

What is the ultimate source of the water detected? Important continuous sources of water include reduction of lunar divalent iron in minerals to metallic iron by solar-wind hydrogen, producing water, and liberation of water from the impact of interplanetary dust and small meteoroids. Water may also be implanted episodically by large comets or asteroids, but these require a mechanism for retention of water (probably in the form of chemically reacted hydroxyl). These sources must be reconciled with the lack of any obvious evidence of alteration of sampled lunar materials by water.

There may be much 'wetter' regions to be discovered far from the sites that have been sampled to date. It is also possible that rare water-bearing minerals previously observed in lunar samples[9], but argued to be terrestrial contamination[10], might be intrinsic. Perhaps, the most valuable result of these new observations is that water is present in the surface of the Moon, and it is not completely dry.

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Ujjal Kumar Sur is in the Department of Chemistry, Behala College, Kolkata 700 060, India.
e-mail: uksur99@yahoo.co.in