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SPACE

Moon mystery

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Chandrayaan-1 has come up with a startling discovery on the level of carbon dioxide in the atmosphere on the sunlit side of the moon.

PICTURES: COURTESY ISRO

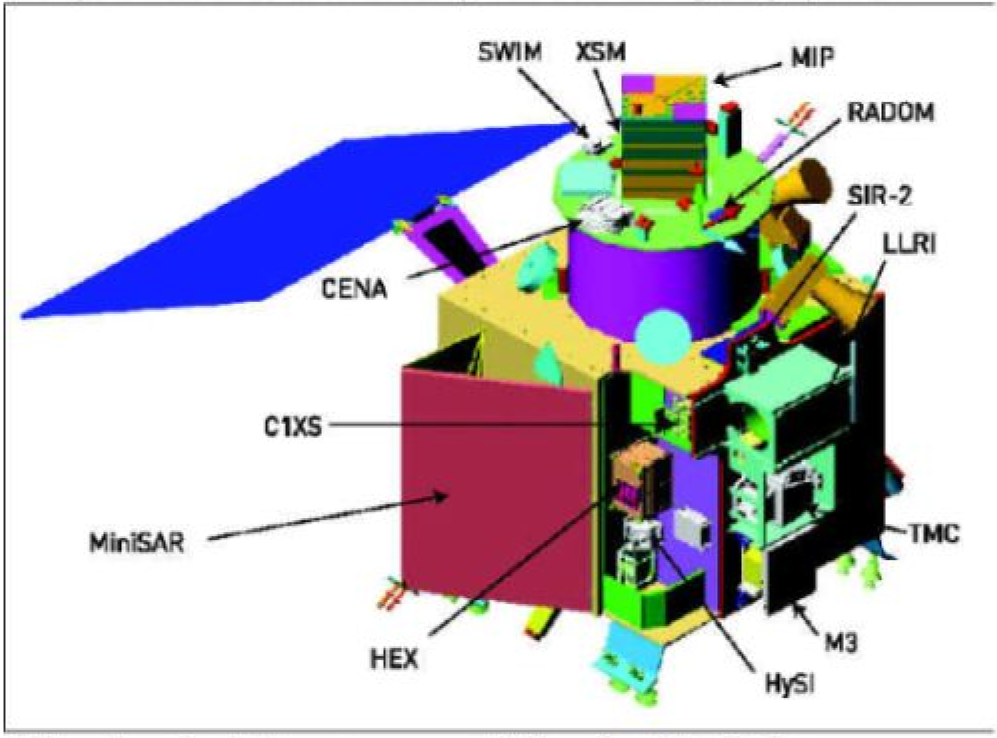
The CHACE payload in its flight configuration.

AFTER the discovery of water on the moon – in the upper layers of its surface and in its atmosphere – Chandrayaan-1, the Indian moon mission, has now come up with another startling result: The atmospheric pressure on the sunlit side of the moon is about 100 times more than that expected from the night-time measurements made by the Apollo missions. This significant increase is substantially because of the presence of carbon dioxide (CO_2) and water in the lunar atmosphere at intriguingly high concentrations.

While there may be an explanation for the water in the lunar atmosphere given the evidence for its presence on the moon from the other experiments on board Chandrayaan-1, the presence of significantly high levels of CO_2 is a mystery. What is required are a confirmation of these levels by future experiments, including the follow-up mission Chandrayaan-2, and a viable explanation for them.

These first-ever set of measurements of the sunlit lunar atmosphere has been published by R. Sridharan and colleagues from the Space Physics Laboratory, Thiruvananthapuram, of the Indian Space Research Organisation (ISRO) in the latest issue of the journal Planetary and Space Science (PSS).

A representation of Chandrayaan-1 showing its payload



HySI	Hyper Spectral Imager
M3	Moon Mineralogy Mapper
TMC	Terrain Mapping Camera
LLRI	Lunar Laser Ranging Instrument
SIR-2	Near Infra Red Spectrometer
RADOM	Radiation Dose Monitor
MIP	Moon Impact Probe

XSM	X-ray Solar Monitor
SWIM	Solar Wind Monitor
CENA	Chandrayaan-1 Energetic Neutrals Analyser
C1XS	Chandrayaan-1 X-ray Spectrometer
MiniSAR	Mini Synthetic Aperture Radar
HEX	High Energy X-ray Spectrometer

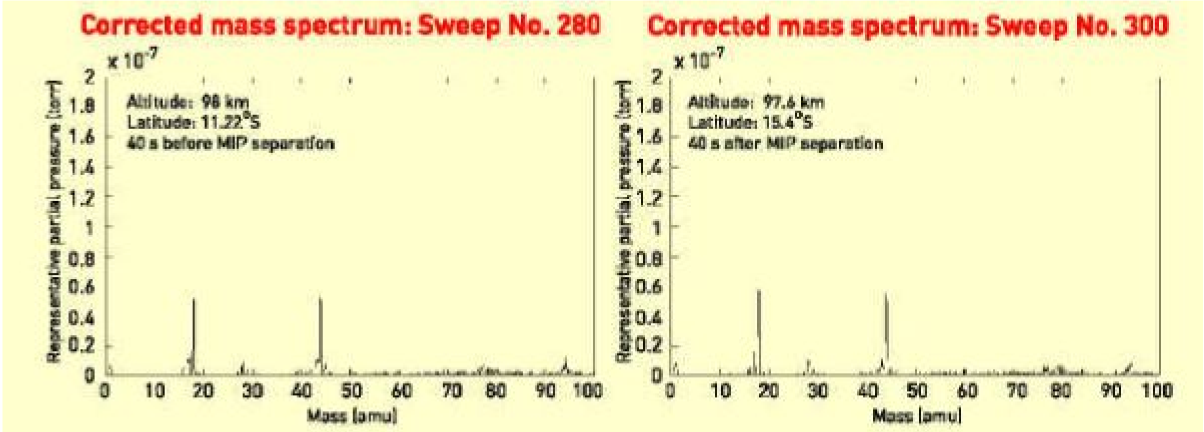
This puzzling discovery comes from one of the experiments on the Moon Impact Probe (MIP), the 35-kilogram sub-satellite that rode piggyback on Chandrayaan-1 and was made to crash on a spot near the lunar south pole. The relevant data were produced by the instrument called Chandra's Altitudinal Composition Explorer (CHACE). It was a combination of a mass spectrometer, which sampled the lunar atmosphere and determined its composition, and an ionisation pressure gauge (generally used for vacuum conditions), which measured the total atmospheric pressure.

It was CHACE that first detected water as a component of the moon's atmosphere even before the Moon Mineralogy Mapper (M3) – one of the experiments of the National Aeronautics and Space Administration (NASA) of the United States aboard Chandrayaan-1 – found its signatures in the top few millimetres of the lunar regolith, the loose, heterogeneous layers of the surface. However, being a one-shot experiment, CHACE's direct detection of water needed corroboration. This came initially from the M3, on the basis of near-infrared absorption spectroscopy, and later from MiniSAR (Mini Synthetic Aperture Radar), which detected water in the form of ice in the permanently shadowed craters near the lunar north pole by measuring the polarisation of the reflected radar waves that were beamed at the polar region from the on board S-band radar. Sridharan and co. claim that the abundance of water in the atmosphere correlates well with the surface water-ice data of the M3.

To recall, Chandrayaan-1 was captured by lunar gravity on November 8, 2008, and was brought down to a stable orbit at an altitude of about 100 km on November 12. The stand-alone MIP, which was perched on the main spacecraft like a top hat, carried three experiments – a radar altimeter, a moon-imaging system and the extremely sensitive mass spectrometer CHACE. The MIP was released on November 14 and was directed to impact the south pole region, near the Shackleton crater. The probe was also spun up to 82 rpm to make it spin-stabilised after its separation. During the separation, a solid motor was fired to provide a small de-boost velocity to make the MIP's orbit suboptimal so that it would crash on the surface (instead of going around with the orbiter after separation). The separation occurred when the MIP was at 13.3 ^{o}S 14^{o}E in the 98-km-high orbit. Following an oblique flight track lasting 24 minutes, the MIP impacted to self-destruction at a designated point very close to the south pole at 89^{o}S 30^{o}W. During its descent, CHACE obtained data on the neutral composition of the atmosphere.

The data, according to the PSS paper, had an unprecedented altitudinal resolution of about 250 metres and a latitude resolution of about 0.1^{o}. While the mass spectrometer's entire mass range of 1-100 atomic mass units (amu) was scanned in four seconds with a mass resolution that was better than 1 amu, the ionisation (pressure) gauge had the sensitivity to detect pressures less than 10^{-13} torr, which is about one ten-thousandth of a trillionth of one atmospheric pressure (760 torr is one atmospheric pressure; 1 amu is the mass of a proton, or hydrogen atom (H), 2 amu that of the hydrogen molecule (H_2), 18 amu that of H_2O, 44 amu that of CO_2, and so on).

GRAPHS: COURTESY ISRO


Corrected mass spectrum: Sweep No. 280

Corrected mass spectrum: Sweep No. 300

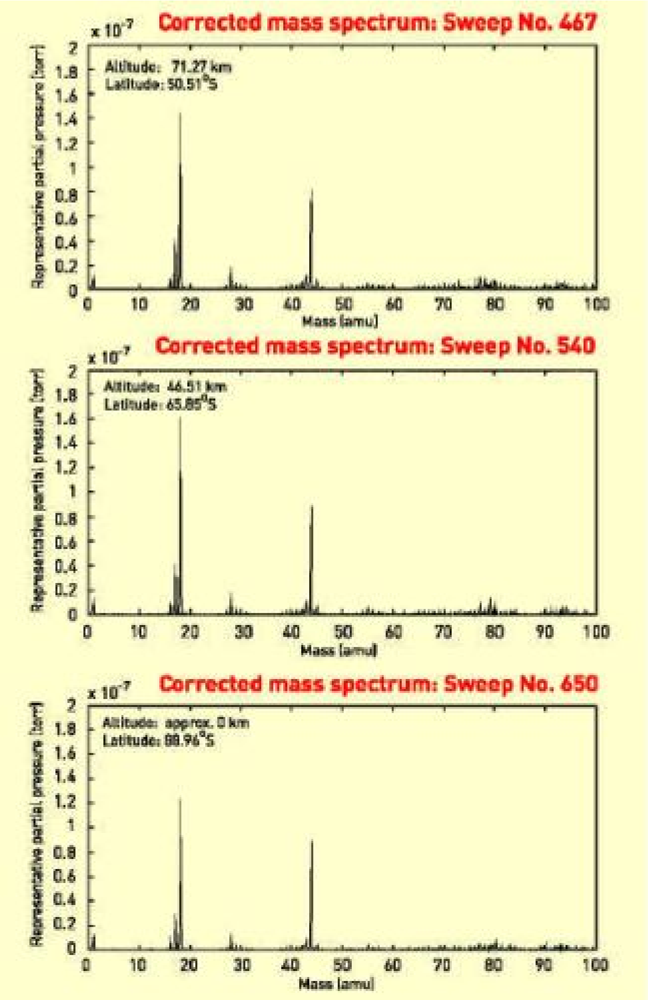
THE SPECTRA FROM CHACE 40 seconds before and after MIP separation. A comparison shows that outgassing had no effect on them.

An important consideration in the operation of CHACE was that it typically takes about 20 minutes for the instrument to warm up and for the ion source filament current to stabilise. To measure actual number densities, it is essential to ensure current stabilisation. So, the instrument had been switched on 20 minutes before the release of the MIP, when the spacecraft was at a latitude of 40°N, and the instrument had stabilised when the spacecraft reached 20°S. In all, 650 spectra of the atmosphere were obtained.

Having CHACE as part of the MIP, an add-on sub-satellite, had its obvious limitations. There was a severe constraint on the availability of power to this module because of which proper calibration of the instrument in lunar orbit could not be carried out (which will be discussed later), and adequate sampling of the atmosphere at different altitudes and latitudes was also not possible as it was a one-shot experiment. These could have been better provided for if such an instrument had been conceived of as part of the originally planned mission (*Frontline*, December 19, 2008). The limitations notwithstanding, CHACE has thrown up some interesting results, which raise more questions than they answer. The most important of which is whether these signals, in the absence of adequate calibration, are artefacts of the experiment or are genuine ones from the lunar atmosphere. If it is the latter, then the understanding of the lunar atmosphere is a good deal less than what Apollo data had led scientists to believe.

The lunar atmosphere is actually very tenuous, with a total mass of only about a few tonnes as compared to the earth's five quadrillion tonnes (5×10^{15} t). Given the moon's low gravity, gases in its atmosphere are easily lost to space. Therefore, light atoms such as hydrogen and helium escape into space in just a few hours when they receive sufficient energy from solar heating. Heavier atoms take longer but will ultimately be ionised by solar (ultraviolet, or UV) radiation and these ions will be swept away from the moon by the solar wind. This process, it is believed, takes a few months.

Because of the rate at which atoms escape from the moon's atmosphere, there must be a continuous replenishment of its constituents through structural and dynamical processes to maintain the tenuous atmosphere. The thermal source driven by the large temperature difference between lunar night and day – the average night temperature is about -150°C and the day temperature about +120°C – in a diurnal cycle (of about 29.5 earth days) forms a significant input to the lunar atmosphere. This causes a high degree of adsorption (adhesion of molecules to the surface) of atmospheric gases during the night and heavy desorption during the day. Sources for the constituent gases and particles also include capture of particles from the solar wind and material delivered by impacting comets, meteorites and interplanetary dust, and perhaps even transit of giant interstellar molecular clouds.



A SET OF sample spectra obtained during the mission.

Since the lunar atmosphere is so thin, it is difficult to detect and measure. The difficulty in measuring the composition of the native lunar atmosphere also arises from the fact that its low mass makes it extremely fragile. The gas release during the landing and take-off of a lunar module injects about 10-20 tonnes of non-native gases into the lunar atmosphere, which is comparable to its total mass. This naturally severely perturbs and completely transforms the atmosphere for a time, which, it is believed, can last from weeks to months. Debris from earlier missions, in the form of chunks of material left on the lunar surface, can continuously contaminate the atmosphere through outgassing, especially if they happen to be on the sunlit portion of the moon. Similar outgassing can also occur when any spacecraft enters the ultra-high vacuum (UHV) lunar atmosphere, and more so if this occurs on the dayside. Until the launch of Chandrayaan-1, the only reliable measurements of the lunar atmosphere, both for baseline pressure and composition, were the partial sampling of the night-time atmosphere by the Apollo mission instruments, in particular Apollo 17's Lunar Atmospheric Composition Experiment (LACE), which, like CHACE, was a mass spectrometer measurement. Because of their limited ranges, however, these instruments got saturated by contamination right from sunrise, believed to be because of outgassing from space modules and the detector. The heavy daytime desorption (of gases adsorbed during the night) from the lunar surface owing to the large day-night temperature difference could have also contributed to the saturation of the instruments.

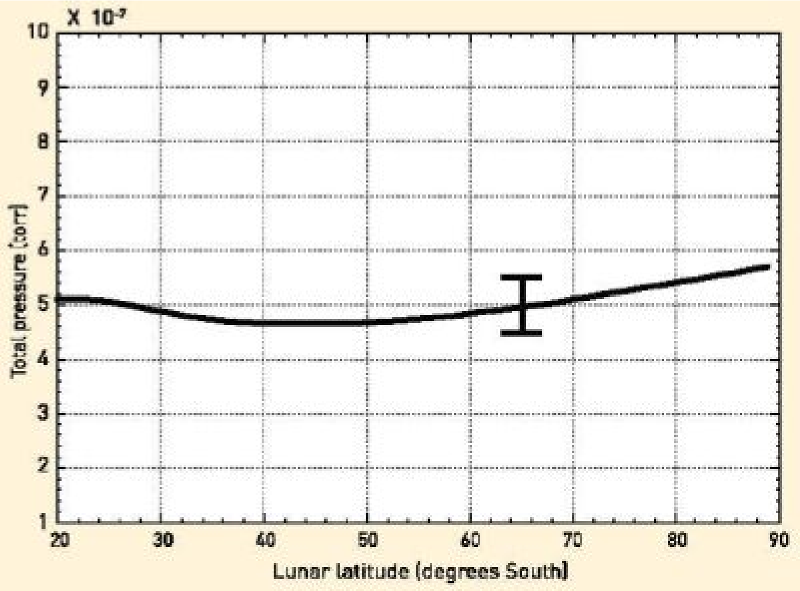
While there was no ambiguity in the values for the night-time atmosphere, there has been a major gap in scientists' understanding of the daytime atmosphere. Thus, measurements made by CHACE, which provide the first data on the daytime lunar atmosphere, are a step towards filling that gap. But the key question, as mentioned before, is whether these measurements reflect the native lunar atmosphere or are artefacts of spacecraft-instrument outgassing. Sridharan and co. argue that the data indeed are signatures of the native atmosphere.

As the paper notes, contamination due to outgassing from the surroundings, including the spacecraft and the detector, cannot be avoided totally, especially for measurements pertaining to water vapour and related species “as they are inherently embedded in the basic materials used in the fabrication of the measuring device itself”. But the important difference between the measurements made by the Apollo missions and Chandrayaan-1 is that while all the earlier measurements were from the landing sites, CHACE was a one-shot measurement. The authors argue that the instrument parameters, including outgassing, if any, would have remained constant during the short flight, thus enabling measurement of species of the native lunar atmosphere against this background.

To characterise the outgassing of materials that were used in the manufacture of the spacecraft, samples of the materials were baked at a temperature of 250°C and tested at the UHV conditions of 10^{-8} to 10^{-9} torr. The characteristic signature peaks under laboratory conditions were identified and recorded. The exposure of the probe to deep space vacuum during its three-week journey to the moon would also have reduced outgassing effects, the scientists argue. But, as the paper points out, the spectrometer ion source was switched on only after the spacecraft entered the lunar environment and had reached about a 98-km-high circular lunar orbit. Switching on the instrument involves ramping of the current and associated heating of the instrument, which can cause outgassing.

Unfortunately, as the MIP was an add-on experiment, power constraints forced it to be operated only on batteries, and this prevented operation in the switched-on mode en route to the moon. As the authors point out, sample spectra of deep space would have provided baseline data relating to deep space and outgassing species from the satellite system. Also, five orbits prior to release, the system was run on full operational mode for about 10 minutes for a health check of all the MIP instruments, which included switching on of the ion source of CHACE.

During this period, the instrument collected data on total pressure and the atmospheric composition of species from 39^{o}N to 9^{o}N along the 20.8^{o}>E meridian. Similarly, though the MIP was released at 13.3^{o}S, CHACE stabilised only at 20^{o}S, which means data for this initial descent phase, with CHACE not yet stable, also must have been recorded. For some reason these (during rehearsal and initial mission phase) data, which can provide a useful basis for comparison, have not been published. However, according to Sridharan, these data have been used to study the relative composition at different stages by looking at ratios of abundances when instrument-related parameters, including outgassing effects, would cancel themselves out. Rehearsal and early mission phase ratios compare very well, he points out.



LATITUDINAL VARIATION OF total atmospheric pressure on the sunlit side of the moon.

But, more significantly, running this rehearsal mode over 20 minutes would have allowed the instrument to reach stability and enabled its in-orbit calibration, which was not done, again because of power constraints. “Only limited time of operation was possible,” says Sridharan. “Even the short rehearsal duration was a bonus for us,” he adds. Since baseline data could not be obtained, contamination due to outgassing of the spacecraft has remained an open question.

However, the authors have argued that spectra taken with stabilised full-mode operation before and after the release of the MIP, during the brief de-boost phase and at different stages of its flight to the lunar surface, suggest that spacecraft outgassing effects were minimal. The authors point out that though one would normally expect a spurt of outgassing from the instrument the moment it is switched on, no such effect was seen. Further, they argue that the geometry and orientation of CHACE was such that it avoided any outgassing species getting directly sampled by the instrument. They point out that as the spacecraft velocity of 1.6 km/s was much greater than the thermal velocity, gas particles could not have entered CHACE. The series spectra published in the paper, including before and after separation and during the de-boost firing, would seem to support the authors' claims.

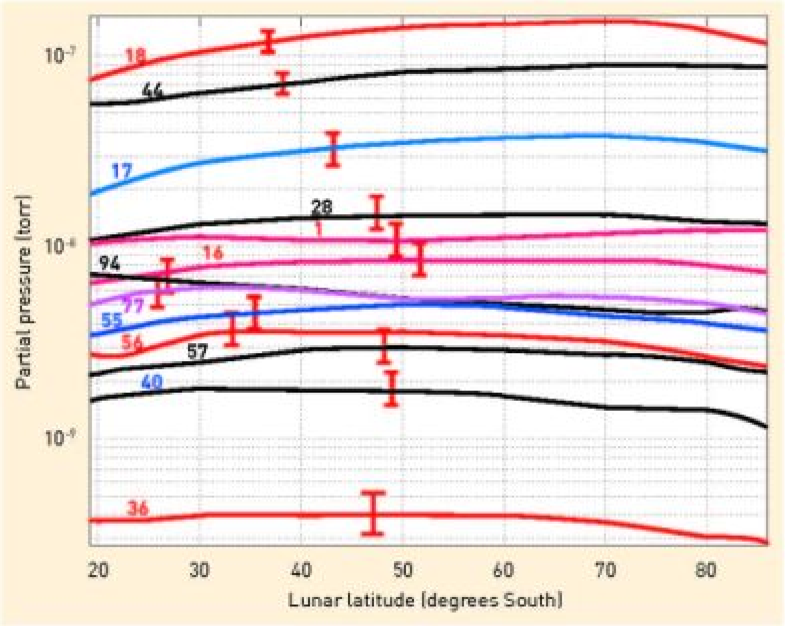
A striking result of the spectra taken during the 24-minute descent is the presence in significant quantities of a large number of species in the mass range of 1 to 100 amu. The most dominant species correspond to 18, 44 and 28 amu, which are water, CO_2 and nitrogen (N_2) or carbon monoxide (CO) respectively. (The plots actually show partial pressures of species that constitute more than 1 per cent of the total. In a mixture of gases such as the atmosphere, the total pressure is the sum of the partial pressures of each individual gas in the mixture.)

The first results from CHACE were published by Sridharan and co. in March, and these pertained to the detection of water in the sunlit lunar atmosphere, providing "direct" evidence of water on the moon. By comparing the water abundance profiles determined by the two experiments, it was shown that the results of CHACE actually complemented the discovery made by the M3. While the M3 data showed a monotonous increase of water/ice signatures in the lunar regolith from 43^{o}S towards the south pole, as would be the case if there were large icy deposits in the cold traps at the pole, CHACE data showed peaking around $60\text{-}70^{o}$S and then a decline towards the pole. This would be consistent if CHACE was actually measuring lunar water vapour from the sublimation of ice, which would decline closer to the icy deposits at the pole.

Though the spectra published in March did show a significant peak at 44 amu as well, the authors chose not to identify it as CO_2 and discuss the finding, which they have done now. Here they point out that in none of the laboratory calibration studies was 44 amu seen as one of the dominant species. While the CO_2:H_2O abundance ratio during tests was always less than 0.1, during the initial stabilisation phase (in the northern hemisphere) it went up as high as 7, according to the paper. The authors, therefore, conclude that the CO_2 detected by CHACE is of lunar origin.

Further, as the figure is a ratio, it would mean that CO_2 seems to be the most abundant species in the lunar atmosphere of the north! In the southern hemisphere, as the plots show, the abundances are comparable. About 95 per cent of the composition is due to H_2O and CO_2, according to Sridharan. The authors also argue that about 40 per cent of the abundance of the 28 amu species could be nitrogen. In 1962, E.J. Oepik predicted CO_2 dominance in the sunlit lunar atmosphere. The findings reported by Sridharan and co. would then be the first direct experimental confirmation of that.

The total pressure on the sunlit side measured by the ionisation gauge showed that it was nearly constant at about 5×10^{-7} torr throughout the latitude range from 20^{o}S to the poles, which is about 100 times the upper limit on daytime pressures inferred from Apollo data, which were on the night-time pressures. A pressure of 10^{-7} torr corresponds to a number density of about 10^{9} particles/cm^{3} (cubic centimetres). If the data pertain to the native lunar atmosphere, CHACE has provided evidence for the first time that compared with the night-time densities of 10^{5} particles/cm^{3}, daytime densities are about four orders of magnitude more. The graph on the facing page shows the latitude-altitude variation of the partial pressures of the various constituent species.



LATITUDINAL VARIATION OF some significant species as measured by CHACE.

Though the constancy of the pressure across latitudes is intuitively not obvious, the authors say that in the case of the thin lunar atmosphere, with the boundary layer close to the surface, the latitudinal variation of temperature (from $+120^{o}$C at the equator to -120^{o}C at the poles) compensates for the altitudinal variation of the pressure as the MIP descended from its release at 98 km. "Since the surface temperature shows a very steep gradient as one moves towards the poles from the equator, the atmosphere would shrink and when such shrinking is compensated for by the altitude one would see nearly a constant pressure. And this has been verified by modelling the surface temperature profile," says Sridharan.

The two orders of magnitude higher daytime lunar atmospheric pressure is owing essentially to the nearly 100 times higher partial pressures of H_2O and CO_2 more than any other species because they dominate the daytime atmospheric composition. Therefore, the abundance of H_2O and CO_2 as seen by CHACE needs to be explained if it really pertains to the native lunar atmosphere. The formation of water itself has a plausible explanation in terms of protons in the solar wind interacting with the regolith to release oxygen, which in turn can react with incoming hydrogen atoms to form water. And, as regards its observed abundance in the atmosphere, Sridharan and co. argue that it correlates well with the M3 data of water on the surface. But there is no immediate explanation for the high abundance of CO_2.

Sridharan believes that the origin could be meteoritic but suggests that more such intensive measurements by future experiments are required. Apparently, some ballpark estimates have been made in the past by modellers. "Meteorites may deliver carbon, but the question is, how does it get converted to CO_2, and secondly, how does a heavy species like CO_2 get transported around to be so pervasive?" asks J.N. Goswami, Director of the Physical Research Laboratory (PRL) of the ISRO and principal scientist of the Chandrayaan-1 mission. "Meteorites are expected to have CO_2 and H_2O in addition to several elemental compositions," says Sridharan.

“In addition, even if carbon is made available, the oxygen released from the lunar lattice could react with it to form CO_2 the way water is hypothesised to get formed. The large thermal cycle would assist these sort of reactions, and over the years CO_2 would build up. Though CO_2 from each meteoritic event is likely to be heavily localised, the activity had been all over the moon,” he adds.

“The detection of carbon dioxide in the lunar atmosphere is very exciting,” said Bernard Foing, lead project scientist for the SMART-1 (Small Missions for Advanced Research in Technology) mission at the European Space Agency. “This discovery comes from a very sensitive instrument and methodical analysis. We need now to elucidate the origin for these exospheric compounds, either from interaction of solar wind with the surface or from outgassing of impact deposits from comets or asteroids”. According to Foing, CO_2 has been detected in comets by infrared observations.

There are scientists who are sceptical of the finding, too. “This is a controversial paper,” said Kurt Retherford of Southwest Research Institute (SwRI) and one of the scientists involved with NASA's Lunar Reconnaissance Orbiter, currently orbiting the moon and which will begin to study the lunar atmosphere in its extension phase in 2011 and after. “It is unfortunate that more time calibrating the instrument response was not technically feasible. The extraordinary claims seem only tentatively supported by the data, with several inconsistencies not addressed sufficiently. The likelihood that instrumental and spacecraft outgassing explains much of the signal seems higher than the concluded abundances of water and carbon dioxide, despite the authors' arguments against this explanation. I look forward to improved experiments on the recently announced Chandryaan-2 mission,” Retherford said in an e-mail to *Frontline*.

“This paper presents very intriguing (though puzzling) results, since the pressure measured is more than just two orders of magnitude larger than expected,” said Randy Gladstone, also of SwRI and also involved with the LRO mission. “It seems to me that the measurements were more plausibly sampling a cloud of species that had earlier outgassed from the spacecraft but were still travelling along with it. In any case, some of the implications of these results are easily tested and are quite startling. If the moon has an atmosphere of 10^{-7} torr of water, then UV sunlight shining on it will produce about 3×10^{28} hydrogen atoms per second, similar to a fairly active comet. Also, since the lifetime of water with respect to photodissociation in the lunar atmosphere is only about 28 hours, if the measured amount of 10^{-7} torr pressure is in steady state, then I estimate that ice must be sublimating at a rate of ¾ tonnes per second in order to maintain that level, equivalent to a 1-cm thick layer of ice lost every 4,000 years or so. I suppose there are lots of other quick checks like this that could be made to see if these results make sense. Perhaps Chandrayaan-2 will be able to verify these results,” he added.

Indeed, given these surprising results from CHACE, Chandrayaan-2 will carry an identical experiment but with more time for calibration and other checks, Goswami said. “The Scientific Context for the Exploration of the Moon”, a 2007 report of the U.S.' National Research Council, observed, “Significant gaps remain in the understanding of the lunar atmosphere system, especially the three-dimensional flows and nature of constituents through the atmosphere…the dynamic system exists, but there is no predictive understanding of its behaviour.”

CHACE's controversial data clearly indicate that, and this may get resolved with future experiments such as the LRO and Chandrayaan-2.

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