

# Influence of the lunar ambience on dynamic surface hydration on sunlit regions of the Moon

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## Abstract

The accepted paradigm of a dry Moon has been upset by the recent detection of a wet Moon. EPOXI, NASA's extended mission for the Deep Impact spacecraft, observed and quantified dynamic surface hydration on sunlit regions of the Moon by infrared spectrometry in separate flybys. MIP CHACE, released from ISRO's Chandrayaan-1 spacecraft, detected H<sub>2</sub>O by mass spectrometry in orbit in the sunlit lunar ambience at a partial pressure exceeding Apollo inferences by over two orders of magnitude. Here it is shown CHACE and EPOXI are mutually supportive, suggesting the order of magnitude reported by CHACE is correct. With this confirmation in mind, it is shown the CHACE data imply H<sub>2</sub>O in the lunar ambience impinges upon near equatorial surfaces at an annual average of  $\sim 400 \text{ g m}^{-2} \text{ yr}^{-1}$  by cursory estimate.

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## 1. Introduction

In 2008, the Indian Space Research Organization's (ISRO) Chandrayaan-1 spacecraft released its Moon Impact Probe (MIP) in orbit over the Moon, and the MIP's Chandra's Altitudinal Composition Explorer (CHACE) detected by mass spectrometry a partial pressure of H<sub>2</sub>O (amu = 18)  $p' \sim 8 \times 10^{-8}$  Torr at an altitude  $h \sim 97$  km above  $\sim 20^\circ\text{S } 14^\circ\text{E}$  (Sridharan et al., 2010a,b). The time of day at  $\sim 14^\circ\text{E}$  inferred from ISRO mission data was  $\sim 30^\circ$  past local noon.

From this Wang et al. (2011) inferred a local surface pressure ( $p$ ) and concentration ( $n$ ) of H<sub>2</sub>O molecules of  $\sim 2.7 \times 10^{-5}$  Pa and  $\sim 6 \times 10^9$  molecules  $\text{cm}^{-3}$ . They assumed hydrostatic equilibrium and the validity of the barometric formula and ideal gas law. They estimated the surface temperature as  $T \sim 350$  K.

## 2. Calculations and discussion

### 2.1. H<sub>2</sub>O impingement rate from CHACE data

According to kinetic theory, the impingement rate ( $A$ ) of an ideal gas on the walls of a container is given by:

$$A = \frac{p}{\sqrt{2\pi kTm}} \quad (1)$$

where  $p$  is the pressure,  $k$  is the Boltzmann constant,  $T$  is the absolute temperature, and  $m$  is the mass of the molecule (Chambers et al., 1998). Using the values of  $p$  and  $T$  from Wang et al. (2011), Eq. (1) gives an H<sub>2</sub>O impingement rate per second  $A_{sec} \sim 9 \times 10^{17}$  impingements  $\text{m}^{-2} \text{ s}^{-1}$  at the given lunar surface and time of day, where  $m$  is the mass of the H<sub>2</sub>O molecule.

### 2.2. Consistency of CHACE and EPOXI

Before discussing the impingement rate, the validity of the underlying data must be considered. The CHACE data

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came as a great surprise to contemporary thinking in the art. Put in perspective, the Lunar Atmospheric Composition Explorer Experiment (LACE) deployed by Apollo 17 established a dayside upper limit of  $2 \times 10^7$  H<sub>2</sub>O molecules cm<sup>-3</sup> on the surface at  $\sim 20^\circ\text{N}$  (Hoffman et al., 1973). This is more than two orders of magnitude less than the surface concentration determined for the opposite side of the equator by Wang et al. (2011) using CHACE data. Given this great disparity, it would be helpful to have an independent confirmation of the CHACE data.

EPOXI, NASA's extended mission for the Deep Impact spacecraft, observed and quantified dynamic surface hydration on sunlit regions of the Moon in separate flybys using the High-Resolution Instrument–infrared spectrometer (HRI-IR), and found a smidgen of surface hydration on what appears to be essentially all surfaces of the Moon (Sunshine et al., 2009). This corroborated a similar finding of surface hydration detected by infrared spectrometry with the NASA Moon Mineralogy Mapper (M<sup>3</sup>) onboard Chandrayaan-1 (Pieters et al., 2009). Together this prompted NASA to report for the first time on a similar finding from a decade earlier of surface hydration detected by infrared spectrometry with the Visual and Infrared Mapping Spectrometer (VIMS) on the Cassini spacecraft (Agle and Brown, 2009; Clark, 2009).

Sunshine et al. (2009) estimated the content of adsorbed water at the lunar surface to be  $\sim 0.3$  weight percent using infrared spectrometry, with 30–50% being retained at noon and then returning to morning values by evening. Infrared spectrometry is effective in detecting water and hydroxyl in the top few or top 1–2 mm of the optical surface using OH and H<sub>2</sub>O absorptions near 1.5, 2, and 3  $\mu\text{m}$  (Clark, 2009; Pieters et al., 2009). Meyer (2003) notes the bulk of the lunar regolith has a density of 1.5 g cm<sup>-3</sup>. Thus, at 0.3 weight percent with 30% retention at noon, the top millimeter has lost  $\sim 0.2$  mol m<sup>-2</sup>. This assumes it to be H<sub>2</sub>O as opposed to tightly bound hydroxyl (Kerr, 2009, quoting Pieters). Given an impingement rate  $A_{sec}$  as determined above from the CHACE data, it would take  $\sim 1\frac{1}{2}$  Earth days for this much H<sub>2</sub>O to impinge upon the surface. Since a few Earth days (1 week) are available for this amount to be restored by local evening as the surface cools from its noontime high temperature, the orbital findings of Sridharan et al. (2010a,b) are here found to be consistent with (i.e., in the same ballpark as) the dynamic surface findings of Sunshine et al. (2009).

### 2.3. Surface variation of the impingement rate

Assuming hydrostatic equilibrium and the validity of the barometric formula and ideal gas law, the partial pressure at the lunar surface inferred from CHACE data is derived as  $p = p' e^{mgh/H}$ , where  $p'$  is the partial pressure detected in orbit by CHACE at altitude  $h$ ,  $H = kT/mg$  is the scale height,  $k$  is the Boltzmann constant,  $T$  is the absolute temperature at the surface,  $m$  is the molecular mass, and  $g$  is the acceleration due to gravity at the surface (Wang

et al., 2011). Substituting for  $p$  obtained by this method into Eq. (1), the impingement rate ( $A$ ) at the lunar surface is inferred from CHACE data as:

$$A = \frac{p' e^{mgh/kT}}{\sqrt{2\pi kTm}} \quad (2)$$

Though Sridharan et al. (2010a,b) do not tabulate  $p'$ ,  $m$ ,  $h$ , and  $T$  for multiple coordinates, they provide altitudinal data for latitudes designated as 20.4656°S, 50.51°S, 65.85°S, 80°S, and 88.96°S, and the remaining data can be inferred from their figures and text and by making temperature assumptions. To account for both the latitudinal and longitudinal aspects of the solar zenith angle effect, the cosine model used here to estimate absolute surface temperature is  $T = 120 + 280 \cos(\theta) \cos(90 - \psi)$ , where  $\theta$  is the latitude and  $\psi$  is the phase angle (degrees past local sunrise) as determined by the surface coordinates of the MIP overhead in reference to local time ( $\psi$  at  $\sim 14^\circ\text{E}$  was  $\sim 120^\circ$ ). As noted by Wang et al. (2011), amu = 17 may also include NH<sub>3</sub>, but for the sake of estimates here it is treated as OH only.

In this manner, it is inferred that the impingement rate for H<sub>2</sub>O (amu = 18) rises from  $\sim 20^\circ\text{S}$ ,  $\sim 350$  K to  $\sim 61^\circ\text{S}$ ,  $\sim 240$  K by a factor of  $\sim 1.9$  and decreases thereafter, with  $\sim 20^\circ\text{S}$ ,  $\sim 350$  K and  $\sim 87^\circ\text{S}$ ,  $\sim 130$  K showing roughly the same rates. The impingement rates of the free hydrogen atom (H) (amu = 1) and hydroxyl radical (OH) (amu = 17) may be similarly considered. From  $\sim 20^\circ\text{S}$ ,  $\sim 350$  K to  $\sim 89^\circ\text{S}$ ,  $\sim 125$  K, OH impingement roughly mirrors H<sub>2</sub>O impingement at  $\sim 1/4$  the rate; in contrast, H impingement increases in the poleward direction as a function of decreasing temperature in a nearly linear fashion. See Fig. 1.

### 2.4. Annual H<sub>2</sub>O impingement

For a cursory estimate, assuming the H<sub>2</sub>O impingement rate per second  $A_{sec}$  inferred at  $\sim 20^\circ\text{S}$ ,  $\sim 350$  K is roughly maintained on average for the bulk of the sunlit period

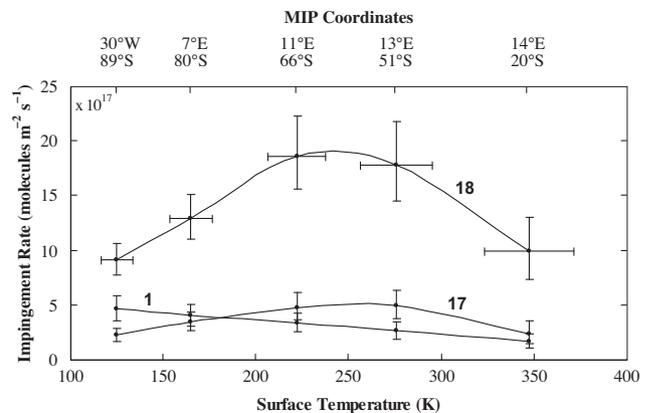


Fig. 1. Impingement rates at the lunar surface inferred from CHACE for amu = 1, 17, and 18 species.

over the course of the year, the corresponding yearly rate  $A_{yr} \sim 1.4 \times 10^{25}$  impingements  $\text{m}^{-2} \text{yr}^{-1}$  translates into an annual impingement of  $\sim 400 \text{ g m}^{-2} \text{yr}^{-1}$  of  $\text{H}_2\text{O}$  at the lunar surface along latitude  $\sim 20^\circ\text{S}$ . To examine the validity of this assumption, recall from Eq. (1) the dependence of  $A$  on pressure. It is seen from Fig. 7 of Sridharan et al. (2010b) that the partial pressure of  $\text{H}_2\text{O}$  ( $\text{amu} = 18$ ) is maintained over the latitude range of  $20^\circ\text{S}$  to  $85^\circ\text{S}$  at not less than its value at  $20^\circ\text{S}$ . Water molecules frozen to the surface on the dark side will be desorbed within a few degrees longitude from the sunrise terminator (Hoffman et al., 1972), as is supported by Apollo 17 surface temperature data at  $\sim 20^\circ\text{N}$  (Langseth et al., 1973, Fig. 9–9), and the situation will be similar on the opposite side of the equator at  $\sim 20^\circ\text{S}$ . Thus, since impingement will largely persist throughout the sunlit period until the surface is cold enough to trap molecules, the assumption appears valid for a cursory estimate.

For a more rigorous estimate, having plotted impingement rates as a function of surface temperature from the CHACE data (Fig. 1), changes in local time over the sunlit period of the day are mapped into changes in surface temperature for a given latitude, and the corresponding impingement rates are averaged over each unit change in time, whereby annual impingement is obtained by multiplying the average of such averages by the annual sunlit period. Noting that the time spent at given temperatures varies with latitude over the sunlit day, impingement rates are thus factored by the time spent at their respective temperatures. This approximation neglects spatial heterogeneity of surface deposits and soil properties, such that the same impingement rate is attributed to the same temperature for all surfaces. In the estimates here, a  $10^\circ$  change in phase angle is used as the unit change in time for taking averages.

In this manner, annual  $\text{H}_2\text{O}$  impingement is inferred to be  $\sim 700 \text{ g m}^{-2} \text{yr}^{-1}$  along  $\sim 40^\circ\text{S}$ , with a maximum rate of  $\sim 780 \text{ g m}^{-2} \text{yr}^{-1}$  along  $\sim 57^\circ\text{S}$ ; by extrapolating impingement rates for higher surface temperatures not covered by CHACE, the annual rate along  $\sim 20^\circ\text{S}$  is inferred to be on the order of  $\sim 6 \times 10^2 \text{ g m}^{-2} \text{yr}^{-1}$  ( $\sim 50\%$  more than the cursory estimate). The impingement rates of other species may be considered similarly. The total amount of hydrogen impinging annually from  $\text{amu} = 1, 17,$  and  $18$ , expressed as an  $\text{H}_2\text{O}$  equivalent, is inferred to be  $\sim 860 \text{ g m}^{-2} \text{yr}^{-1}$  along  $\sim 40^\circ\text{S}$ , with a maximum rate of  $\sim 960 \text{ g m}^{-2} \text{yr}^{-1}$  along  $\sim 58^\circ\text{S}$ . See Fig. 2.

Since the CHACE data was collected in a one-shot affair at whatever the local times and coordinates were when the MIP passed overhead, the data of Fig. 1 are specific to the given coordinates at their instant (local time) surface temperatures. But by treating the data of Fig. 1 as valid for all latitudes as a function of temperature only, which neglects spatial heterogeneity, Fig. 2 attempts to relate latitude to cumulative impingement, which will be of aid to future exploration by predicting sites of maximum annual impingement.

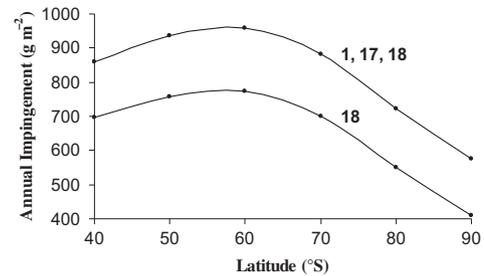


Fig. 2. Annual hydrogen impingement at the lunar surface inferred from CHACE along designated latitudes for  $\text{amu} = 18$  and combined  $\text{amu} = 1, 17,$  and  $18$  species, expressed as an  $\text{H}_2\text{O}$  equivalent. The lower latitudes are neglected because CHACE did not provide partial pressure data for surface temperatures greater than  $\sim 350 \text{ K}$ .

## 2.5. Questions for discussion

How does one justify so large an  $\text{OH}/\text{H}_2\text{O}$  retention capacity as 30–50% at noontime high temperatures as observed by EPOXI for the lunar surface? The flux of solar wind protons in space near the Moon has been estimated as  $\sim 4 \times 10^{14}$  protons  $\text{m}^{-2} \text{s}^{-1}$  (Zeller and Ronca, 1968). This is in the ballpark of  $\sim 10^3$  less than a moisture impingement rate on the order of  $A_{sec}$  as calculated above, as needed to explain the afternoon restoration of the noontime hydration losses observed by EPOXI. So even accepting the likelihood of unaccounted sources of water-group species, the bulk of impingement may therefore be attributed to reflux between moisture desorption and re-adsorption, such that the drying effect of desorption is limited by the watering effect of impingement. The largeness of the noontime retention capacity is thus interpreted to be partly an apparent observation due to moisture reflux, without which the drying would proceed to near completion. It follows that the percent retained at noontime would be expected to increase with increasing baseline moisture content.

EPOXI found greater noontime hydration losses in the mare basalts (70%) than in the highlands (50%), but both terrain types were inferred to return to similar morning/evening values of moisture content (Sunshine et al., 2009). This suggests the influence of temperature on retention capacity largely overshadows that of soil properties at low temperatures, so that comparable steady-state baseline values are achieved based on temperature during the cool portion of the sunlit day.

How does the impingement rate relate to models of  $\text{H}_2\text{O}$  accretion in polar cold traps? Modeling should take into account a warming effect of species impinging with a distribution of energies derived from warmer surfaces, their angles of approach, and the impingement shadows caused by obstacles blocking their paths. This may resolve the paradox of the hydrogen signal being weaker in some permanently shadowed regions near the lunar south pole but comparatively stronger in some surrounding sunlit areas at similar latitudes, as inferred by the Lunar Exploration Neutron Detector (LEND) on the Lunar Reconnaissance Orbiter (LRO) spacecraft (Mitrofanov et al., 2010).

How does impingement relate to the persistence of H<sub>2</sub>O? There are a variety of aqueous mechanisms by which the free hydrogen atom (H<sup>•</sup>) and hydroxyl radical (•OH) may combine to form H<sub>2</sub>O (Buxton et al., 1988). In theory, once H<sub>2</sub>O levels are elevated enough to form a sheen on the lunar surface, the photodissociation products of H<sub>2</sub>O (H<sup>•</sup>, •OH) may be able to “heal” to form H<sub>2</sub>O via aqueous mechanisms. In the sense of a net mechanism, when H<sup>•</sup> and •OH radicals impinge upon the lunar surface and are linked by an aqueous network, O–H bonds may hop around from one H<sub>2</sub>O structure to another until successors of the H<sup>•</sup> and •OH radicals that initiated the hopping are eliminated by meeting to form H<sub>2</sub>O. Though speculative, such a mechanism is drawn by analogy to the Grotthuss mechanism, in which protons enjoy elevated rates of diffusion by hopping around from one H<sub>2</sub>O structure to another (Agmon, 1995).

Which is more useful in estimating water collection rates, the impingement rate or the concentration (number density)? The surface concentration ( $n$ ) according to the method of Wang et al. (2011) is related to the impingement rate ( $A$ ) of Eq. (1) as  $n = A\sqrt{2\pi m/kT}$  by the ideal gas law. Collection at the surface is best estimated by the impingement rate and collection by a spacecraft is best estimated by the concentration being swept out. However, the concentration as it is being swept out by the path of the spacecraft amounts to an impingement rate:

$$A' = n'v_s + n'\frac{\bar{v}}{4} \quad (3)$$

where  $n'$  is the number density of molecules being swept out,  $v_s$  is the velocity of the spacecraft, and  $\bar{v}$  is the mean molecular speed due to thermal energy; the first term is the ram contribution to the impingement rate and the remaining term is the thermal contribution. For example, a spacecraft encountering an average H<sub>2</sub>O number density of  $\sim 5 \times 10^9$  molecules cm<sup>-3</sup> as it traverses the sunlit lunar ambience at a velocity of  $\sim 1.7$  km s<sup>-1</sup> in a circular orbit 11 km in altitude will sweep out  $\sim 4$  kg of H<sub>2</sub>O per year per square meter normal to its trajectory.

What could explain the dry versus wet lunar findings of the past and present (Lucey, 2009)? There may be temporal and spatial heterogeneity in the concentration of exogenous water-group species impinging upon the Moon from space. If so, it could be a costly mistake to miss the opportunity to collect water during the present period of wetness before the next period of intense dryness sets in.

### 2.6. Future work

There remains a wealth of data to digest by considering trends in impingement rates and concentrations at the lunar surface among species detected by orbital mass spectrometry. Accurate determination of surface temperature will improve calculation of impingement rates and concentrations. Partial pressure data covering the full spectrum of surface temperatures will improve calculation of

annual/diurnal impingement for the full spectrum of latitudes. Comparison of data for different surface locations at the same temperatures will facilitate analysis of surface deposits and soil properties. Quantitative analysis to model moisture proportions in the lunar soil versus ambience as a function of global moisture content awaits development.

### 3. Conclusions

The orbital H<sub>2</sub>O detected by CHACE is supported by the temporal variations in surface hydration detected by EPOXI. Even near the equator, substantial amounts of water substance are available for collection on sunlit lunar surfaces in the form of H<sub>2</sub>O and other water species impinging from above. This would seem more attractive than mining water frozen at the poles or wringing small remnants of adsorbed water out of the soil. At any rate, the data indicate a major water resource which is renewable and impinges on essentially all surfaces of the Moon.

### Acknowledgment

The author invented and has rights to a patent pending method of obtaining water on the Moon by harvesting ambient moisture as it impinges on the surface; the teaching also extends to spacecraft harvesting ambient moisture in space.

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