

TEMPORAL AND SPATIAL VARIABILITY OF LUNAR HYDRATION AS OBSERVED BY THE DEEP IMPACT, PART II: THE SOUTH POLE. S. Protopapa¹, J. M. Sunshine¹, T. L. Farnham¹, L. M. Feaga¹, M. F. A'Hearn¹ ¹University of Maryland, College Park, MD 20742, USA.

Introduction: The discovery of hydroxyl [OH] and/or water [H₂O] widely distributed on the lunar surface [1,2,3], outside of the permanently shadowed polar regions, adds significant evidence that the Moon is not completely devolatilized as had previously been assumed [4,5]. Lunar surface hydration is most likely an exogenic process, resulting from solar wind protons interacting with oxygen-rich minerals in the regolith [6]. We present a quantitative analysis of the lunar hydration using recalibrated Deep Impact (DI) flyby observations of the Moon, including those over the South Pole that have not previously been analyzed, in order to investigate the mechanisms responsible for the formation, retention, and disruption of OH and/or H₂O across the lunar surface.

Deep Impact lunar data: On Nov 4, 2010, the DI flyby spacecraft [7] successfully encountered comet 103P/Hartley 2 [8], employing two multi-spectral imager and a 1.04 – 4.83 μm infrared spectrometer (HRI-IR). During the cruise phase to Hartley 2, various instrument calibrations were conducted using observations of the Moon obtained during a series of Earth gravitational assists. The analysis of the DI HRI-IR lunar data turned out to be fundamental, not only for calibration purposes, but also to undeniably confirm the presence of hydroxyl [OH] and/or water [H₂O] on the surface of the Moon [2], complementing the results by Pieters *et al.* [1] and Clark [3].

Previous work: Sunshine *et al.* [2], through analysis of DI data covering the equatorial and the northern polar regions of the Moon, demonstrated that lunar surface hydration varies with local time of day, with the entire lunar surface hydrated during at least part of the lunar day, and that hydration is mainly controlled by instantaneous temperature. Evidence of changes in the shape of the overall 3-μm absorption with time of day were also seen, suggesting differential loss of H₂O vs. OH and thus multiple rates and possibly multiple mechanisms for diurnal hydration cycling. However, unambiguous detection of H₂O was not possible given the signal-to-noise ratio (SNR) of the data.

New calibration: Recognizing the importance of the lunar data and the desire to deconvolve OH and H₂O, the DI team acquired a series of >6500 observations to collect spectra of calibration stars specifically to support an improved absolute calibration of the DI lunar data. The new calibration [9] not only improves the absolute flux, but also the shape of the spectral energy distribution and thus the shape of the absorption bands. This results in better temperature and

OH/H₂O content determination. Moreover, the updated calibration enhances the SNR, which helps to uniquely identify the presence of absorption bands (*e.g.*, OH vs H₂O). This improved calibration has now been applied to all DI lunar data, including those presented in the previous work by Sunshine *et al.* [2].

South pole DI data: DI observations of the Lunar South Pole were acquired after the study done by Sunshine *et al.* [2] and are presented here for the first time. These observations include spatially resolved scans separated by one-quarter of a lunar day (Fig. 1). Specifically, three sets of data were acquired at seven-day intervals, during which the Moon rotated by ~90°. These spatially resolved scans of the southern polar regions allow us to study the variability of lunar hydration with respect to local time. It is therefore possible to compare the same location on the Moon at different local times and thus under different insolation conditions. Furthermore, it is possible to investigate whether both mare and highland terrains present the same diurnal hydration cycle or not.

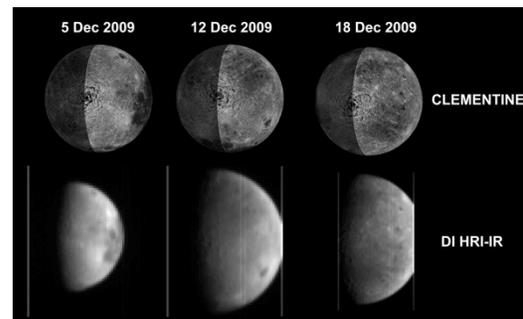


Figure 1: Three sets of observations, separated by one-quarter of a lunar day, acquired by DI over the South Pole of the Moon. The bottom row shows examples of DI HRI-IR spatially resolved scans (resolution ranging from 30 to 70 km/pixel), while the top row shows Clementine maps in the same orientation.

In addition to the spatially resolved scans, integrated chord measurements were obtained by rapidly scanning the spectrometer slit lengthwise across the southern hemisphere of the Moon, such that every pixel along the slit crosses the lunar disk along the same chord (Fig. 2). Two mid-latitude chords (on the morning and evening sides) and one at the south pole (noon at the limb) are available on Dec 12, while two additional chords (on the morning and afternoon sides) were acquired on Dec 5. With the complete DI lunar data set, which covers the equatorial and northern and southern polar regions, it is possible to investigate

changes of the hydration content with respect to composition and instantaneous surface temperature. The chords, which have much higher SNR than the spatially resolved images, will help us compare averages in the morning to those from the evening in either hemisphere, and to search for variations between northern and southern averages.

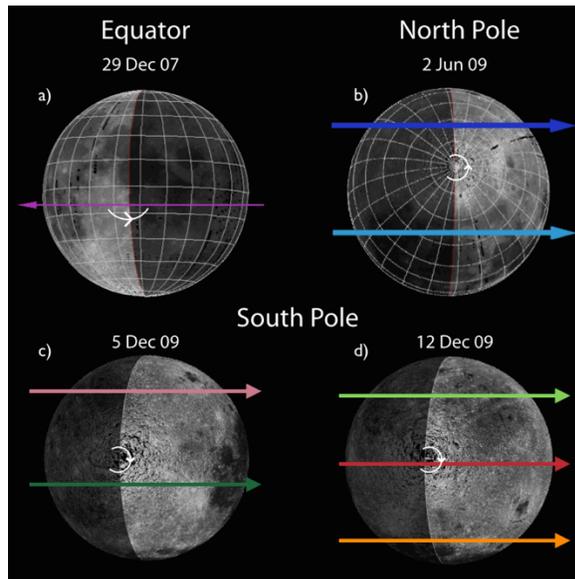


Figure 2: DI HRI-IR chord measurements of the Moon. *Top panels:* From Sunshine *et al.* [2]. The locations of the equatorial (panel a, purple arrow) and the two northern hemisphere chords, one on the morning side (b, cyan) and the other on the evening side (b, blue) plotted over a 750-nm Clementine basemap. *Bottom panels:* Panels c and d display the location of the chords obtained when the spacecraft was looking down on the southern hemisphere.

For example it is possible to compare the South Pole Aitken basin (light green chord in Fig. 2, panel d) with anorthositic regions at the North Pole observed at similar latitude and instantaneous temperatures (similar local times). This analysis will help us understand how temperature and composition factor into the hydration distribution across the lunar surface.

The DI HRI-IR integrated spectroscopic measurements of the Moon of the northern and southern hemisphere are shown in Fig. 3. The spectra show, in addition to the 3- μ m absorption band characteristic of OH and/or H₂O bearing materials, an underlying continuum composed of scattered solar radiation at short wavelengths ($\lambda \leq 2.5\mu\text{m}$) and a thermal contribution due to the surface temperature at longer wavelength. As expected, variations in the thermal component are observed between the different chords. To correctly interpret the 3- μ m absorption band and determine the hydration content, it is necessary to convert radiance into reflectivity [10-12], without altering the shape and depth of the 3- μ m feature. This is possible only after

performing a robust continuum modeling which consists of simultaneously fitting the scattered and thermal components of the spectra [13]. Note that the DI HRI-IR instrument simultaneously covers the full width of the 3- μ m absorption band and the lunar thermal component (Fig. 3), in contrast to the Chandrayaan-1 M³ and VIMS, which only cover up to 3 μ m and 3.4 μ m, respectively. This allows us to use the long wavelength radiance data, where the thermal dominates, to disentangle the contributions of the scattered and thermal components at 3 μ m.

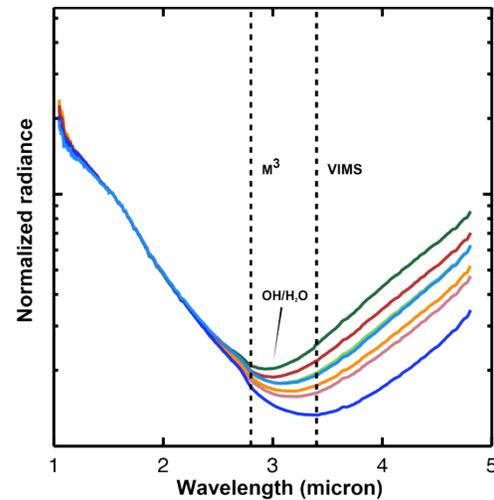


Figure 3: High signal-to-noise ratio HRI-IR radiance spectra of the average response along the northern and southern chords of the Moon. Colors correspond to the chords shown in Fig. 2.

Summary: The DI measurements represent a unique data set. Because of their spatial, wavelength, and temporal coverage, these data allow us to investigate possible correlations between the water content and instantaneous surface temperature, composition, and local time. We will present a comprehensive characterization of the OH and H₂O content across the surface of the Moon focusing on the identification of the mechanisms that control the hydration rate of change.

References: [1] Pieters *et al.* (2009), *Science*, 326, 568. [2] Sunshine *et al.* (2009), *Science*, 326, 565. [3] Clark (2009), *Science*, 326, 562. [4] Jolliff *et al.* (2006), *Reviews in Mineralogy and Geochemistry*, 60, 721. [5] Lucey (2009), *Science*, 326, 531. [6] McCord *et al.* (2011), *JGR Planets*, 116, 0. [7] A'Hearn *et al.* (2011), *Science*, 332, 1396. [8] A'Hearn (2005), *Science*, 310, 258. [9] Klaasen *et al.* (2013), *Icarus*, 225, 643. [10] Pieters *et al.* (1988), *LPSC*, 19. [11] Bandfield *et al.* (2016), *LPSC*, 47. [12] Li and Milliken (2016), *LPSC*, 47. [13] Protopapa *et al.* (2014), *Icarus*, 238, 191.

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