Identification of Surface Hydrogen Enhancements Within Shackleton Crater at the Moon's South Pole

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Abstract

Enhanced hydrogen abundances have been identified within the Moon's Shackleton Crater using fast neutron data from the Lunar Prospector mission. This enhancement is unique and is the result of a rigorous statistical analysis used to evaluate the spatial distribution of hydrogen at lunar poles.

The fast neutron derived hydrogen concentration is 850±144 ppm H. This is statistically equivalent to the abundance derived independently using epithermal neutrons (888±33 ppm H), implying the hydrogen lies at or near the surface. In contrast, other permanently shadowed regions are likely buried under >10 cm of hydrogen-poor regolith.

Shackleton crater is ~30 K warmer than other South Pole permanent shaded craters, suggesting that thermal processes may control the vertical migration of hydrogen within Shackleton and inhibit hydrogen migration within colder craters.

Comprehensive Analysis

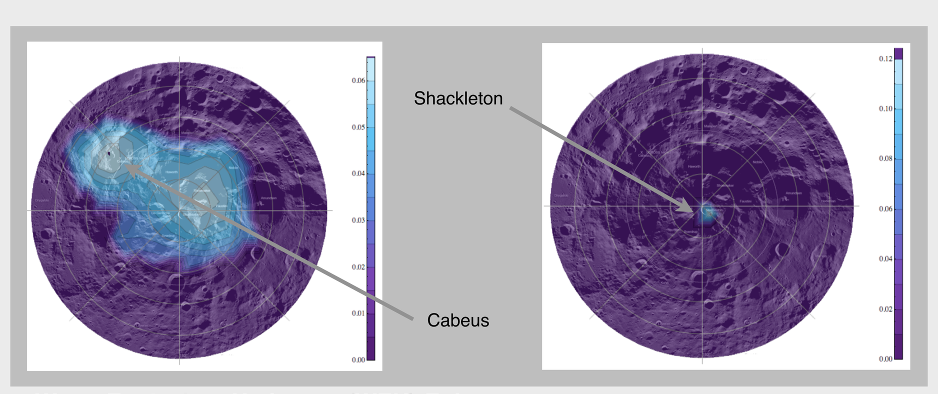
A recent combined analysis of lunar neutron datasets from NASA's *Lunar Prospector* (LP) and *Lunar Reconnaissance Orbiter* (LRO) missions used a robust statistical approach to characterize the abundance distributions of hydrogen at the lunar poles (1, 2).

Observations support a unique feature at ***Shackleton Crater***
Neutron suppression ⇒ hydrogen abundance enhancements (3, 4).

The uniqueness of the signature motivated the extended analysis presented here.

Goals

- **Fast Neutrons**: Revalidate observed deficit → Improved analysis
- **γ-Rays**: Exclude possible alternative (elemental) explanations
- **Thermal Neutrons**: Search for corresponding enhancement
- **H Abundances**: Independently from ***epithermal*** & ***fast*** neutrons
- **Stratigraphy**: Infer from independent H abundances

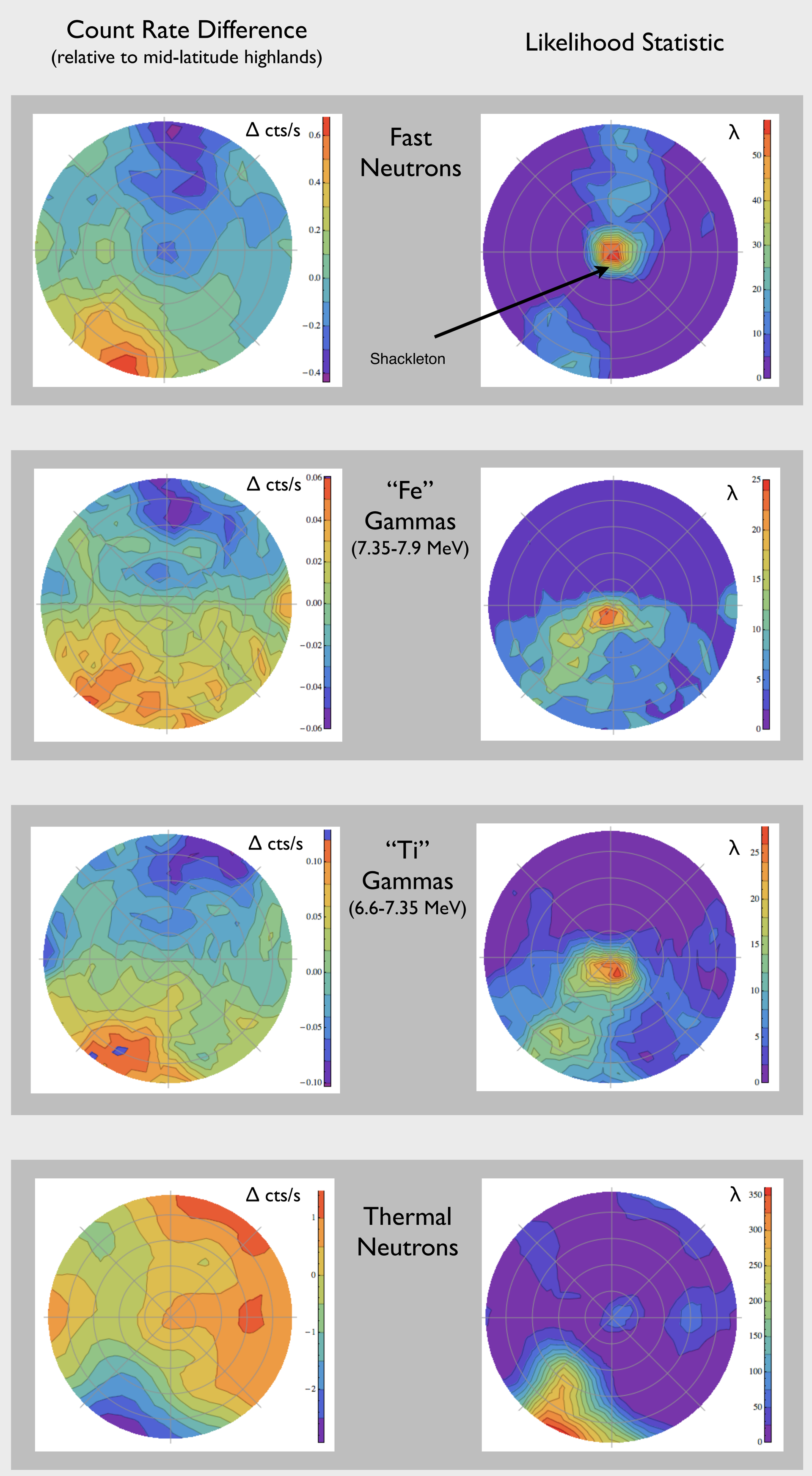


Water Equivalent Hydrogen (WEH) Enhancements. Illustrative examples shown relative to non-polar levels (50 ppm, 0.045% WEH) and given as a percentage by weight. Enhancements shown here have not been corrected using a forward model that addresses instrument response. Spatial distributions are shown overlaid on topographical maps of the Moon made by the Lunar Reconnaissance Orbiter Camera (LROC) at a resolution of 400 m/pixel. An orthographic projection is shown. From (1).

Methodology

Proper determination of statistical significance and confidence intervals are critical for a proper interpretation. A likelihood approach (2) is employed to characterize consistency between acquired neutron data and the desiccated hypothesis, and the resulting statistic (λ) used to determine the statistical significance of neutron observations. The power of this approach is that it formalizes significance determination by incorporating relevant observational details (e.g. exposures) and the inherent statistical uncertainties governing particle detection.

Lunar South Pole



λ≥25 corresponds to 5σ confidence level detection (1 DoF).

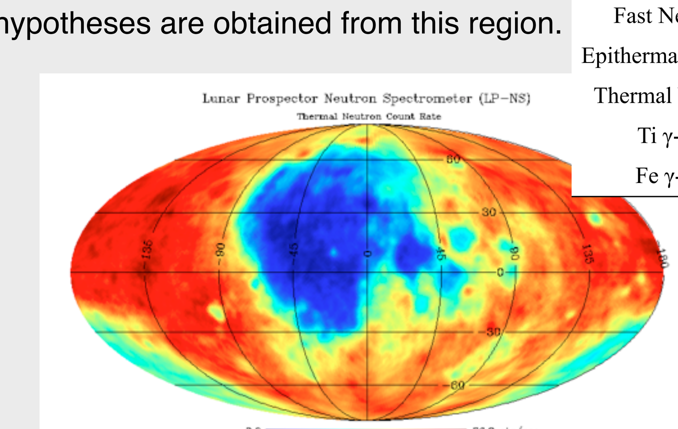
Null Hypothesis

Reservoirs of volatile compounds are unlikely at the lunar mid-latitudes. Mid-latitude highlands mitigate the impact of the mare, rich in elements (Fe, Ti, Gd, Sm) that can influence the count rate of neutrons and γ-rays (5, 6).

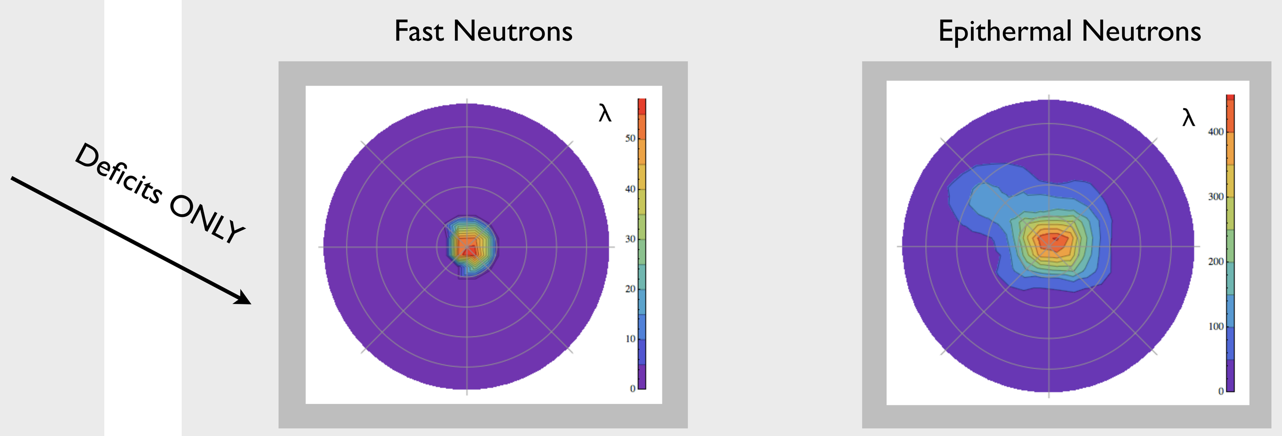
Mid-latitude highlands are defined using thermal neutrons in the latitude band from 20˚ South to 45˚ North, and exclude the mare defined using a procedure outlined in (7).

Following 'Highlands' definition the rates used for null hypotheses are obtained from this region.

	Count Rate (counts/sec)
Fast Neutrons	13.43
Epithermal Neutrons	19.76
Thermal Neutrons	21.41
Ti γ-rays	2.48
Fe γ-rays	1.25

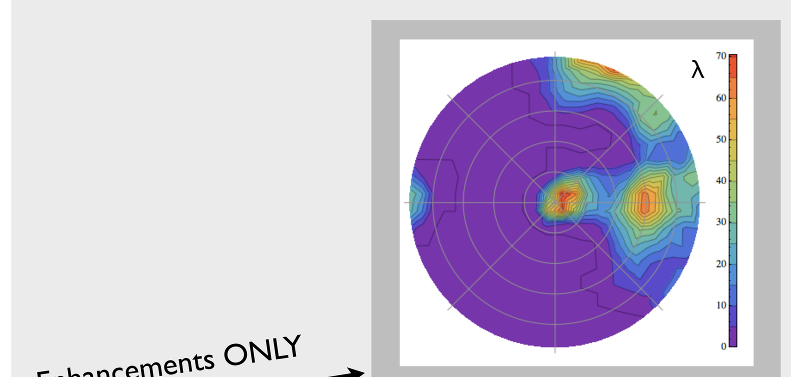


Shackleton Crater



	Shackleton (%)	SPA (%)	Non-SPA (%)
Fast Neutrons	-1.7±0.3	3.1±0.5	2.3±2.7
Thermal Neutrons	2.8±0.2	-8.8±1.5	-9.1±10.2
Ti γ-rays	3.4±0.6	6.6±0.5	2.8±2.1
Fe γ-rays	3.5±0.8	6.1±0.4	2.9±2.3

- Thermal neutrons: enhancement in a region encompassing Shackleton Crater, and a very strong suppression within the SPA.
- Titanium: consistent with South Pole regions (excluding SPA)
- Iron: consistent with South Pole regions (excluding SPA)

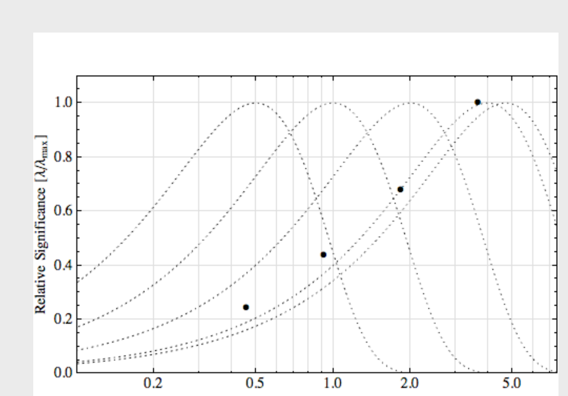


Discussion

Sufficient surficial hydrogen will thermalize fast and epithermal neutrons, possibly producing a detectable enhancement of thermal neutrons, although on its own it is not a unique signature of hydrogen.

Additional simulation and phenomenological studies are required to make a more definitive connection between hydrogen and thermal neutrons to address the potential influence from elemental abundance non-uniformities.

Titanium and Iron gamma-ray count rates are consistent with the South Pole as a whole (excluding SPA, a known special region). ***Elemental abundance enhancements can therefore be excluded*** as an alternative, non-hydrogen hypothesis for the fast neutron signature and the enhanced surficial hydrogen scenario (7).



The significance of the most significant pixel (i.e. Shackleton) as a function of pixel size, along with the expectations for several Gaussian-like features having different spatial extents on the lunar surface.

Data support a characteristic scale size of ~4˚, well matched to the estimated LP-GRS spatial resolution of ~120 km (3.9˚ angular extent) at 30 km altitude (7).

Abundance & Stratigraphy

Hydrogen abundances → directly related to the magnitude of neutron deficits. The conversion process is described elsewhere (1).

Neutron deficits measured in different neutron energy regimes can also be used to infer hydrogen stratigraphy (8-11).

Epithermal Neutrons: probe hydrogen to depths to ~meter
Fast Neutrons: probe hydrogen to depths of ≤10 cm of the surface

In the case of Shackleton the near equality of the two independent neutron-derived concentrations implies the presence of surficial hydrogen (7).

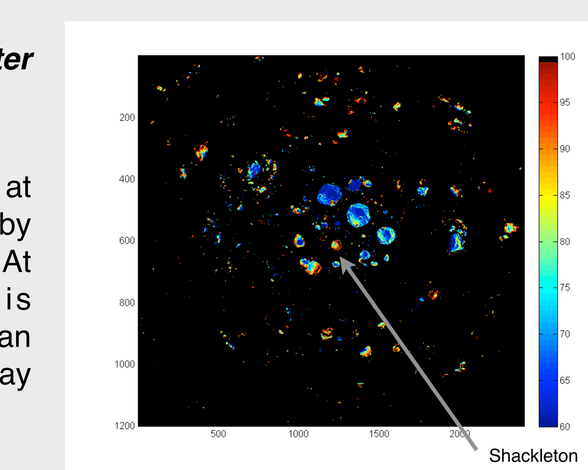
	Deficit (%)	WEH (wt. %)	H Abundance (ppm)
Fast Neutrons	-1.66±0.27	0.72±0.13	850±144
Epithermal Neutrons	-6.30±0.21	0.71±0.03	888±33

To minimize systematics, ONLY Lunar Prospector data has been used for the Shackleton Analyses

Defining Characteristic (?)

What makes it Shackleton Crater special?

Average maximum temperatures at the lunar South Pole, measured by the DIVINER instrument (12). At ~95 K Shackleton Crater is approximately 30 K warmer than 'typical' PSRs, a feature that may be ***its defining characteristic***.



Surficial hydrogen may be connected to temperature via thermally-induced diffusive migration processes may be indicated.

A more definitive understanding of lunar hydrology, and the Shackleton Crater environment in particular, may require the development of comprehensive models, as well as a better understanding of the relationship between temperature and diffusion through regolith motivated by Shackleton's special thermal environment.

This represents the first definitive identification of hydrogen enhancements on the lunar ***surface***, and was possible only because of a comprehensive fast and epithermal neutron detection capability.

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