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An investigation of epithermal neutron fluxes from lunar impact basins

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The article presents the distribution of epithermal neutron fluxes and hydrogen contents in lunar impact basins and mare formations across the entire equatorial lunar surface. A distribution of a suppression factor of epithermal neutron flux in selenographic longitude has been obtained. As a result of the distribution it may be concluded that the suppression factor (a degree of neutron flux reduction relative to a maximum, located near crater Tycho) has the highest value in the near side marine basins. In the same places the largest amount of hydrogen is contained. In contrast, the lower hydrogen contents and, accordingly, the minimum neutron suppression factors correspond to the mare formations and impact basins on the far side. So, suppression of epithermal neutrons is almost completely absent in the mare Moscoviense. Therefore, the corresponding concentration of hydrogen is also rather insignificant there. Additionally, the results presented here indicate that the concentration of hydrogen is a very complicated function of age (maturity) of the lunar surface. This in turn points to the lack of a gradual accumulation of hydrogen with time over a period of several million years or more. Taking into account that the age of the far side impact basins of the Moon is, in general, more than the age of the same near side objects, it is possible to assume indigenous origin of the hydrogen in marine lavas.

Keywords: Lunar hydrogen, impact basins, LEND, LPNS, lunar regolith, epithermal neutrons

1 Introduction

At the present time there are data from two different neutron spectrometers: Lunar Exploration Neutron Detector (LEND) and Lunar Prospector Neutron Spectrometer (LPNS) that cover the entire lunar surface including equatorial regions (Feldman 1998, Mitrofanov 2010b). Currently many efforts are devoted to identify the so-called neutron suppression regions (NSR) of epithermal neutrons (EN) near both lunar poles. Analysis of epithermal neutron fluxes obtained by LPNS from the polar

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areas (especially southern) showed a noticeable excess of hydrogen content compared with its average equatorial value (Feldman 1998, 2001). The authors have shown that polar areas with enhanced abundance of hydrogen continually overlap the so-called permanently shadowed regions (PSR). But the results obtained by collimated sensor of LEND with significantly higher resolution pointed out that NSRs do not coincide with PSRs on both poles (Boyton 2012). At the same time it should be mentioned that the distribution of epithermal neutrons in the equatorial regions still remains relatively unexplored. The authors of LPNS found a moderately good anticorrelation between soil maturity (Lucey 2000) and EN flux. It also points to the lack of a functional connection between the age of surface formations and hydrogen content (Johnson 2002). Finally, in a recent publication of Lawrence (2015) some statistical relationship between the surface maturity and bulk hydrogen abundances has been established. But this applies only to the lunar highlands, namely Feldspathic Highlands Terrane (FHT). It is necessary to say that the distribution of EN flux strongly anticorrelated with hydrogen content. This article shows the results of studies of EN distribution through all large impact basins and marine formations.

2 The distribution of EN suppression factor in selenographic longitude

To quantify the estimation of EN flux through the lunar surface, the so-called suppression factor has been used (Boyton 2012):

$$\delta = \frac{N_{\rm ref} - N_{\rm ex}}{N_{\rm ref}}, \tag{1}$$

where $N_{\rm ex}$ and $N_{\rm ref}$ are testing and reference average count rates of epithermal neutrons respectively. Each of the explored impact basins has been selected as testing areas by turns. As a single reference zone we chose the vicinity of crater Tycho, because it has maximum value of EN count rate. Therefore, a zero value of suppression factor corresponds to the maximum neutron flux and, accordingly, the minimum hydrogen content. This is clearly seen from the neutron flux and concentration of hydrogen at the vicinity of crater Tycho (Fig. 1). Thus, the suppression factors were calculated for impact basins and marine formations around the equatorial surface. More details of the results of calculations can be seen for Mare Imbrium (Fig. 5).

Using data from LEND and concentration of hydrogen produced on the basis of LPNS data we calculated the suppression factors for epithermal neutrons and the average hydrogen abundance for 37 investigated objects across the equatorial surface of the Moon (Table 1). The data from this table is presented on the diagrams (Fig. 2). It is clearly seen that the suppression factors δ (LEND) and hydrogen contents (LPNS) are quite well correlated (Fig. 2,a). Meanwhile, the suppression factor has increased values (δ = 0.02–0.06) in longitudes which correspond to the near side (300°–60°), especially in the so-called KREEP zone (Fig. 2,b). In contrast, suppression factors for the far side marine formations like mare Moscoviense and mare Ingenii have significantly lower values ($\delta = 0.003$; 0.019 respectively). This means that the average hydrogen abundance on the near side lunar basins are noticeably higher than on the far side. The maximum concentration of hydrogen (92.1 ppm) has mare Cognitum (long. = 337.10°). In general, as can be seen from the diagram (Fig. 2,b)

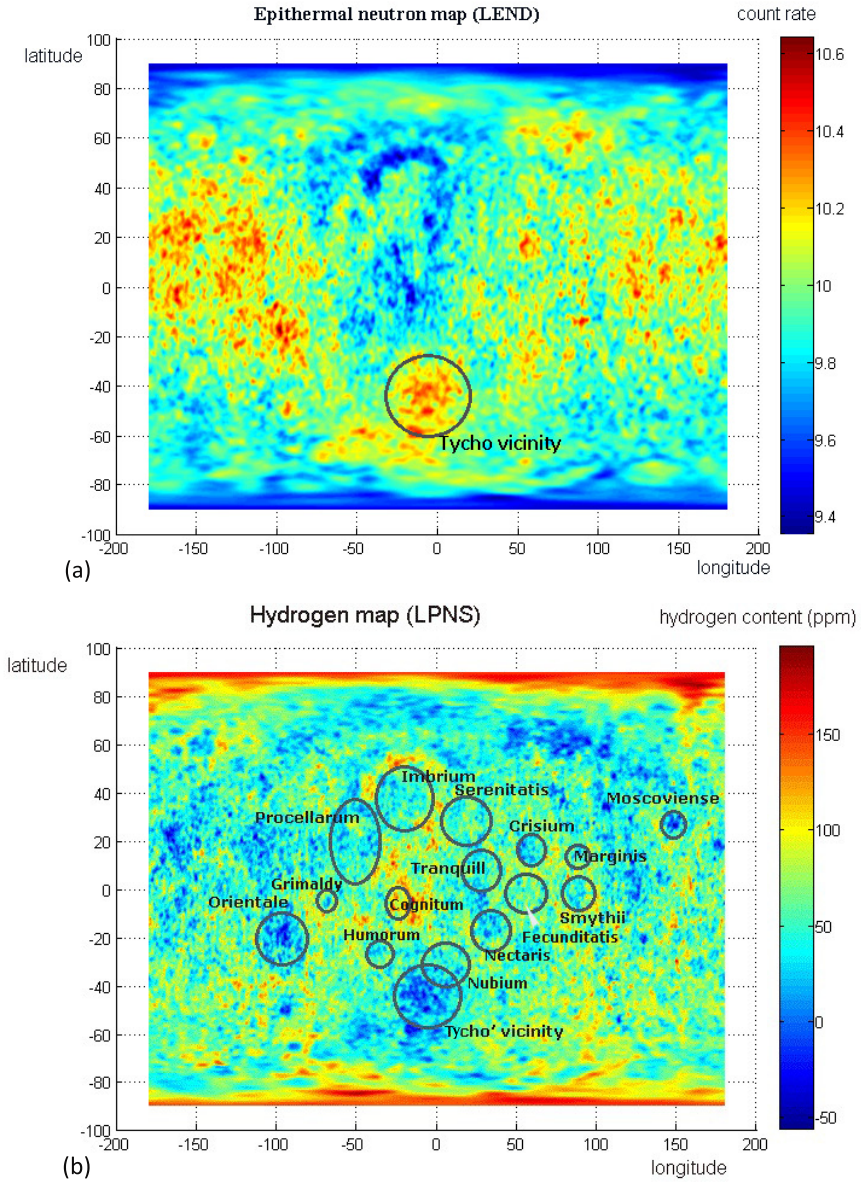


Figure 1 (a) EN flux distribution around the equatorial surface, obtained by LEND omni-directional sensor (Litvak 2012), and (b) global map of hydrogen by LPNS data (Planetary Data System). The data from these two spectrometers are in good agreement. The EN fluxes and concentrations of hydrogen are strongly anticorrelated. Some impact basins are indicated on the hydrogen map.

the suppression factor is quite noticeable, smoothly changes with longitude and has a maximum near zero degrees (sinus Lunicus, sinus Medii, sinus Fidei, palus Patradinis).

Table 1 The suppression factor δ and hydrogen content H in impact basins and mare formations.

No	Mare	Lat. (deg)	Long. (deg)	δ (%)	Standard error	H (ppm)
1	Anguis	22.6	67.7	2.87	4.2σ	44.9
2	Australe	–38.9	93.0	3.91	31.1σ	73.4
3	Cognitum	–10.5	-22.3	4.76	24.1σ	92.1
4	Crisium	17.0	59.1	1.31	8.05σ	41.5
5	Fecunditatis	–7.8	51.3	2.38	16.8σ	58.5
6	Frigoris	56.0	1.4	4.61	36.2σ	45.7
7	Grimaldi	–5.4	–68.4	2.02	5.49σ	45.9
8	Humboldtianum	56.8	81.5	1.48	6.34σ	8.2
9	Humorum	–24.5	–38.6	3.04	17.7σ	44.0
10	Imbrium	32.8	–15.6	4.24	34.8σ	57.9
11	Ingenii	–33.7	163.5	1.88	9.88σ	40.0
12	Insularum	7.5	–30.9	5.35	35.5σ	88.6
13	Marginis	13.3	86.1	1.90	7.04σ	52.1
14	Moscoviense	27.3	148.1	0.31	1.38σ	37.6
15	Nectaris	–15.2	35.5	2.12	11.4σ	27.4
16	Nubium	–21.3	–16.6	3.55	24.7σ	59.8
17	palus Epidemiarum	–32.0	–28.2	2.77	11.6σ	48.6
18	palus Putredinis	27.4	0.0	5.46	18.3σ	84.8
19	palus Somni	13.7	44.7	3.58	8.5σ	74.6
20	oceanus Procellarum	18.4	–57.4	4.26	36.0σ	56.8
21	Serenitatis	28.0	17.5	3.64	26.5σ	49.9
22	sinus Aestuum	12.2	–6.6	4.15	17.6σ	68.1
23	sinus Amoris	20.0	37.3	3.38	13.2σ	46.2
24	sinus Asperitatis	–3.8	27.4	2.36	11.3σ	22.3
25	sinus Concordiae	11.0	42.5	2.80	7.6σ	63.9
26	sinus Fidei	18.0	2.0	6.36	6.8σ	65.2
27	sinus Honoris	11.7	18.1	4.13	8.0σ	55.3
28	sinus Iridum	44.1	–31.5	3.88	18.1σ	42.4
29	sinus Lunicus	32.3	–2.1	5.44	16.5σ	51.4
30	sinus Medii	1.6	1.0	4.26	16.1σ	57.0
31	sinus Roris	50.3	–50.9	4.13	17.5σ	32.9
32	sinus Successus	1.1	58.5	2.72	5.7σ	58.5
33	Smythii	–1.7	87.0	1.74	8.4σ	39.7
34	Spumans	1.1	65.1	1.68	3.5σ	51.7
35	Tranquillitatis	8.4	30.8	3.20	23.6σ	47.0
36	Undarum	7.5	68.7	3.47	10.9σ	69.0
37	Vaporum	13.3	3.6	3.92	16.7σ	49.3
38	crater Tycho	–43.5	–11.5	0.0	–	3.0

3 Some possible causes for uneven suppressions of EN in selenographic longitude

How can this distribution of suppression of EN in longitude be explained? It is believed that in addition to hydrogen, which slows down the neutrons, there are

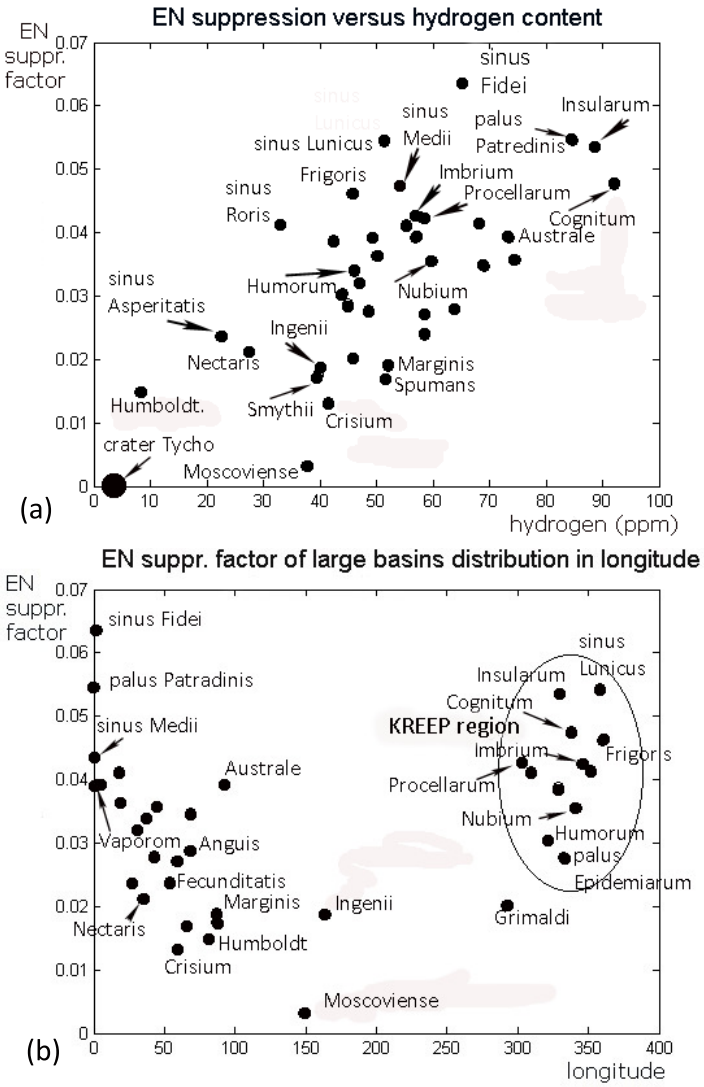


Figure 2 (a) Relation between EN suppression factor δ (LEND) and hydrogen content (LPNS); (b) longitude distribution of δ for impact basins and other marine formations.

elements that absorb them. It is assumed that such elements include iron, thorium and rare earth elements (samarium and gadolinium). It is supposed also that on the near side of the Moon, wherein the contents of these elements are increased, they have a decisive influence on the suppression of epithermal neutrons (Elphic 2000, Lawrence 2015). However, the evidence that these elements cause EN suppression in general does not exist. As an example we give a plot of δ versus the iron content for the same impact basins (Fig. 3). The plot shows the absence of noticeable correlation. Therefore, we can conclude that iron content does not affect the EN flux in impact

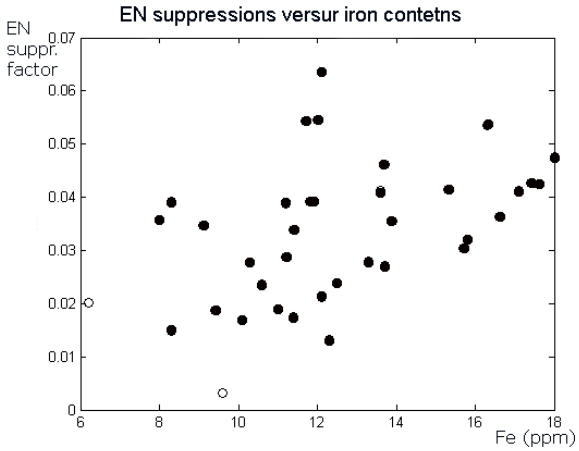


Figure 3 The plot of EN suppressions versus iron contents (Planetary Data System).

basins, at least. Also, there is no direct evidence of influence of rare earth elements on epithermal neutrons in the surface layer (regolith) of the Moon. In this way, exactly the hydrogen content can be an overwhelming factor and, consequently, the main cause of variation of EN in the equatorial regions.

For proper understanding of the nature of origin of bulk hydrogen it is necessary to trace the dependence of suppression factor on the age of surface formations. For representation the age in the form of numerical coefficients the so-called maturity indexes are used (Lucey 2000, Shevchenko 2003).

Here, we present a relation of hydrogen contents from the spectropolarimetric maturity index (Shevchenko 2003) for different points of the near side, especially crater formations (Fig. 4). In this plot there is no visible correlation between maturity and hydrogen contents (neutron flux). At least it could be a very complex relation.

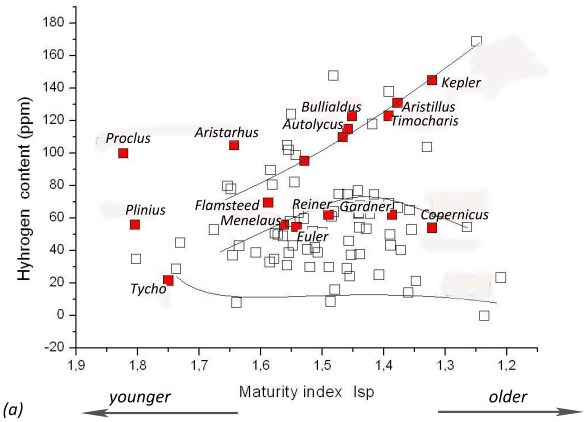


Figure 4 Concentration of hydrogen C_H versus spectropolarimetric maturity index $I_{\rm sp}$ (Shevchenko 2003, Planetary Data System).

If so, the solar wind is unlikely to be a source of successive accumulation of hydrogen (protons) with the age of surface in the top layer of regolith.

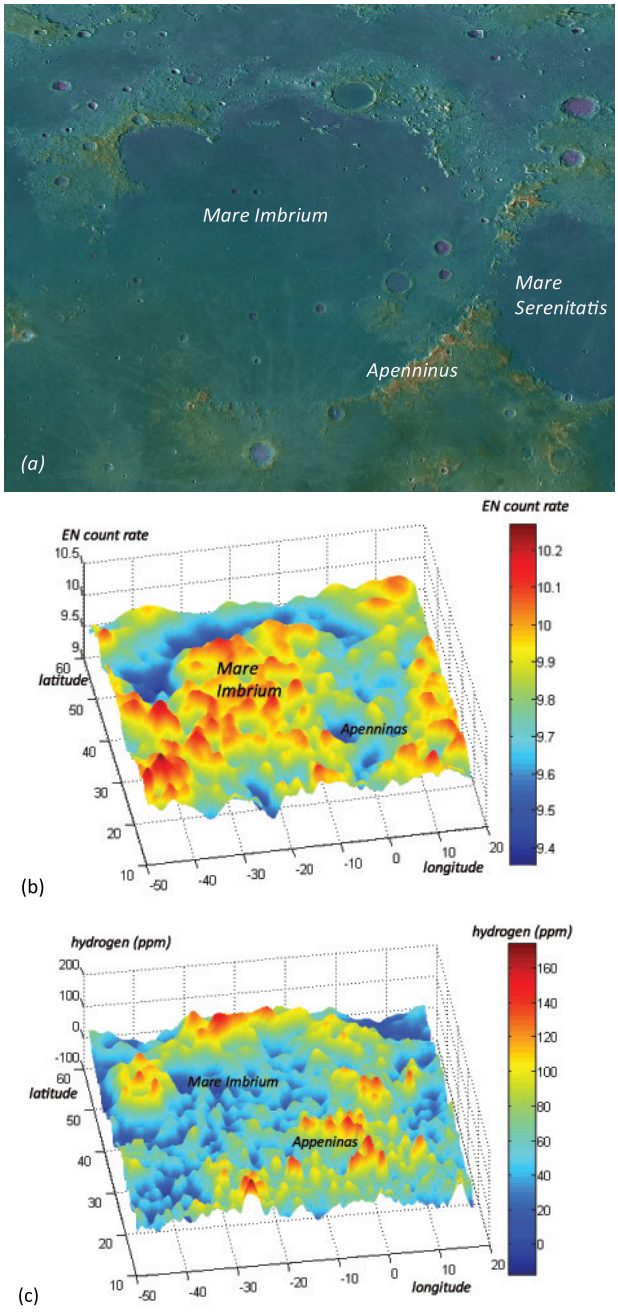


Figure 5 (a) Location of mare Imbrium; (b) distribution of EN and (c) hydrogen content (ppm) in the same region.

In addition, the age of marine lavas, located on the far side slightly exceed the age of near side lavas in general. Indeed, the ages of basaltic lava of mare Imbrium (giant impact basin on the near side) are in the range of 3.57–2.01 Ga (Hiesinger 2000). This corresponds to the Eratosthenian and Imbrian periods. The youngest, copernican lava (1.2 Ga) was found in oceanus Procellarum (the biggest basin of the Moon, located on the near side). While, the age of far side basaltic lava is a little bit older. So, the mare Moscoviense has lava deposits within the age range from 3.5 to 2.6 Ga (Morota 2009). Thus, based on the age of mare lavas it should be assumed that the basalts of the far side mare must have a higher concentration of hydrogen due to the longer exposure time under the solar wind. However, as we can see, there is a quite opposite picture. A recent publication of Lawrence (2015) also indicates the lack of correlation between epithermal neutron flux and OMAT maturity index (Lucey 2000), if we consider marine and Feldspathic Highlands Terrane (FHT) areas together. But the authors argue that the weak correlation nevertheless exists for FHT separately from marine lavas.

A cometary source of the origin of equatorial hydrogen apparently could not be considered seriously. Therefore, the second possibility of the origin of enhanced concentration of equatorial lunar hydrogen is indigenous lunar volatiles (Saal 2008). Currently, there are some studies that prove the presence of hydrogen-containing compounds in the lunar mantle. The recent publication of R. Tartese (2013) states about 1500–30000 ppm hydroxyl in apatite from basalt samples with a high content of titanium and 500–15000 ppm OH with the low content. These results indicate that the lunar mantle may contain up to 1800 ppm of hydrogen. Thus, the near side melted basalts can include hydrogen, which is the cause of the EN suppression.

4 Summary

To summarize we make the following points:

1) In impact basins there is a rather noticeable relation of average hydrogen contents from the selenographic longitude. Moreover, on the near side of the Moon the average hydrogen concentration (∼50–90 ppm) is more than on the far side (∼30–50 ppm).

2) The lack of correlation between maturity (exposure age) of the lunar regolith and hydrogen abundance indicates a weak influence of solar wind protons on average hydrogen concentration.

3) It is possible that the dependence of concentration of hydrogen from selenographic longitude points to indigenous origin of hydrogen compounds.

4) The increased concentration of volatile compounds in the lunar mantle may indicate the possible joint formation of Earth–Moon system. In the case of further accumulation of information about high content of volatile compounds (including water) in lunar interior, it is possible that the origin scenario of the Moon as a consequence of collision of a planetary body with Earth can be reviewed.

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