OBSERVED SEASONAL VARIATIONS OF HYDROGEN ABUNDANCE IN THE SHALLOW SUBSURFACE OF MARTIAN TROPICS AND IMPLICATIONS FOR WATER CYCLE.

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Introduction:

Ground ice is known to be abundant in the very shallow subsurface at high latitude of Mars and slightly deeper at midlatitudes. At low latitudes some modest spatially varying amount of hydrogen is present as a component of hydrated salts or as an unstable, currently sublimating deposits.

Significant amount of information about H distribution in the shallow subsurface came from two neutron detectors onboard Mars Odyssey orbiter, Mars Odyssey Neutron Spectrometer (MONS) [Feldman et al., 2002], and High-Energy Neutron Detector (HEND) [Mitrofanov et al., 2002]. They are based on different measurement approaches, however, they measure the same physical quantity, local neutron flux as a function of neutron energy.

With HEND data, significant seasonal variations of neutron spectra in martian tropics have been reported and interpreted as seasonal changes in ice abundance in the upper 10-30 cm of the surface [Kuzmin et al, 2005, 2007, 2015]. The reported effect is unexpectedly and alarmingly strong, however, potentially explainable. This effect has been neither confirmed nor disproved with MONS data, partly because the MONS data reduction procedure would artificially suppress seasonal variations, if they indeed exist. On the other hand, the reported processing of HEND data ignored the effects of seasonal variations of the atmospheric mass and a number of possible biases. If HEND-detected seasonal ice redistribution [Kuzmin et al, 2005, 2007, 2015] is reliably confirmed, this would have a profound effect on our understanding of the martian surface layer processes and properties; this also would require significant changes in the present widely used global climate models.

I tried to independently analyze both MONS and HEND data to figure out, if the effect reported by Kuzmin et al. is caused by seasonal changes in ice abundance in the shallow subsurface, or it is an observational artefact. Here I present my preliminary results.

Reanalysis of neutron spectrometer data:

The physical mechanism of sensitivity of neutron data to ice in the shallow subsurface is the following. Galactic cosmic rays (GCR) split nuclei in the shallow subsurface; this process released a few high-energy neutrons per split; the neutrons elastically (= without nuclear reactions, with energy conservation) collide with other nuclei and, collision by collision, give part of their energy to them until the energy reduced to typical thermal energy; some neutrons occasionally leak from the surface to space. Light nuclei, and especially the lightest ones, H nuclei, reduce neutron energy more effectively, therefore, if H is more abundant, leaked high-energy neutrons are less abundant.

Neutron detector data are difficult to reduce. Neutron leakage flux depends on GCR flux and spectrum that vary at time scales form hours to decades. In addition, detector sensitivity and rate of background detections also vary in a bizarre way. **Fig. 1** shows the 10 martian year (MY) long history of high-energy neutron fluxes registered by MONS (counts of “category 2 events” in the instrument terminology) averaged over two latitudinal zones (10°N – 30°N, blue, and 10°S – 30°S, red) and over several days long time periods. I carefully removed all data associated with various kinds of irregularities. It is seen that the systematic difference between the zones (lower flux = higher H abundance in the N zone) is tiny in comparison to long-term variations of the detected flux. MONS and HEND teams used data reduction approaches, although different, both based on assumption that there are no variations in true neutron “albedo” in some specific areas. I try to reprocess the data without such assumptions to obtain the most objective information about seasonal flux variations. This work is in progress, and technical details will be reported elsewhere.

My preliminary results suggest that seasonal variations in neutron “albedo” are a real effect. **Fig. 2** (red crosses) presents the ratio of raw fluxes (N zone / S zone) from Fig. 1 for 10 martian years. The scattering is comparable to what would be expected from the pure Poisson noise of individual neutron counts. Individual consecutive measurements in these zones are separated by minutes; within these short intervals, variability of the GCR flux is very minor, while rare sudden jumps in detector gain were filtered out. Systematic seasonal variations of the ratio are clearly seen. Blue line in Fig. 2 shows the least-square fit with a periodic function smoothed down to 4 Fourier harmonics (with periods from 1 MY to ¼ MY). The first two harmonics are well above the noise level (~ 5 “sigma”). To obtain this fit I used the Lomb-Scargle algorithm from [Scargle, 1989] with some errors fixed. My analysis of possible observational biases preliminarily shows that these periodic variations objectively characterize the ratio of neutron “albedo”.

Despite inherently wide field of view of the neutron detectors, seasonal frost does not affect the measurements in Fig. 2, because all seasonal frost is always beyond the Odyssey's horizon in the considered latitude zones. Seasonal variations of atmospheric pressure are known to affect the high-energy neutron flux. On average, the N zone has a lower elevation and hence a thicker atmosphere than the S zone, therefore, variations in atmospheric pressure can potentially have a minor second-order effect on the neutron flux ratio. In **Fig. 3** the single one-year period of the fit curve from Fig. 2 is compared against the seasonal atmospheric pressure curve (orange dots), which is arbitrarily stretched and shifted, and also inverted (upside down) to show the expected signature of the second-order effect on the N/S ratio. It is seen that the pressure effect likely contributes to the observed seasonal variations, but cannot account for the whole signal. (In principle, the pressure effect can be quantitatively obtained from the observations, but this work is still in progress at the abstract submission date). The residual variations of the flux ratio should be attributed to variations in neutron "albedo" of the surface, which suggests variations of H abundance in the upper decimeter(s) of the surface. The observed varied H is almost certainly is in the form of water molecules, therefore the observed variations imply seasonal cyclic transport of H_2O to and from the uppermost decimeters of the surface.

HEND data have a better signal-to-noise ratio and more data irregularities; they yield a generally similar result, which again suggests that the observed trend is objective.

The absolute amount of H_2O abundance change cannot be deduced from the data alone without involvement of some modeling of neutron interaction with the surface nuclei. Order of magnitude estimations by Kuzmin et al. [2007, 2015] are equivalent to a few mm equivalent layer of ice coming to and going from a 10 – 30 cm thick surface layer. Application of the same estimation method to MONS data (Fig. 2) gives a part of a mm ice equivalent.

Implications for martian water cycle:

Exchangeable H_2O in the upper decimeters of the surface can be in different physical forms: as ice, brine, molecules adsorbed at the soil particle surfaces, crystalline water. Kuzmin et al. [2007] argued that the observed H variations are due to seasonal accumulation of ice due to vapor exchange with the atmosphere. Straightforward calculations [Kreslavsky, 2022] with LMD Mars Climate Database as a proxy for martian temperature and humidity conditions showed seasonal ice condensation with such a mechanism only above ~30° latitude and seasonal brine-forming deliquescence only above ~40° latitude. Those calculations did not account for slopes; it is likely that on slopes of proper orientation ice formation could potentially occur at lower latitudes. These considerations, however, have two significant caveats. First, the calculations [Kreslavsky, 2022] predict formation of seasonal ice in N in late summer, therefore the iciest season is early fall, significantly earlier than the observed neutron minimum. Similar predicted seasonality is likely for all other H_2O forms (adsorbed and crystalline water), if they are formed due to vapor exchange with the atmosphere. Second, the observed amount of variable H_2O is alarmingly high. For a martian regolith analog and martian conditions, Hudson et al. [2007] obtained diffusion coefficient of H_2O vapor about 4 cm^2s^{-1}. With this diffusion coefficient, the characteristic diffusion time scale through the tens of cm thick regolith layer is several hours. This means that diffusion is not a significant barrier for the seasonal exchange of H_2O, and the amount of exchange is limited by ability of the atmosphere to transport H_2O vapor from polar summer sources to low latitude boundary layer. If exchange of a mm of H_2O equivalent between the surface and the atmosphere indeed occurs, this means that the water cycle in all martial climate models is modeled incorrectly, and significant changes are needed in the models.

Another possible explanation of the observed variability of H abundance is H_2O vapor exchange between shallow and deeper subsurface. The high effective diffusivity of H_2O vapor [Hudson et al. 2007] makes likely movement of large amounts of H_2O. The predicted seasonal phasing of H_2O transport up and down through the seasonal thermal skin is roughly consistent with the observed phase of the annual harmonic in Fig. 2 and 3. The caveat is that shallow ground ice is known not to be stable at those latitudes [e.g., Schorghofer & Aharonson, 2005], therefore the variable shallow ice could only exist if there is a transient ice deeper in the subsurface (meters), which is in the process of ongoing removal. In this case, the presence of variable ice in the upper decimeters again requires a significant flux of H_2O vapor from the shallow subsurface to the atmosphere, which in turn means the need of proper changes in the water cycle modeling.

Conclusions and prospects:

Reanalysis of neutron spectrometer data confirmed seasonal variations of H_2O abundance in the shallow (decimeters) subsurface of Mars. The seasonal changes are likely caused by seasonal vertical redistribution of transient, unstable ice in the subsurface in response to seasonally changing temperature gradients. This process is inevitably associated with seasonal release of H_2O vapor in the atmosphere.

Future work includes accomplishment of the independent neutron data processing and derivation of seasonal atmospheric corrections from the data alone. Theoretical modeling of ice migration in the regolith is needed for better understanding of processes operating in the shallow subsurface of Mars and quantification of atmospheric water sources. Inclusion of regolith vapor sources and sinks is essential in future Mars climate models.

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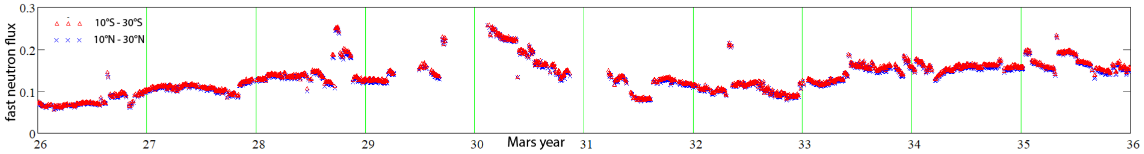

Fig.1

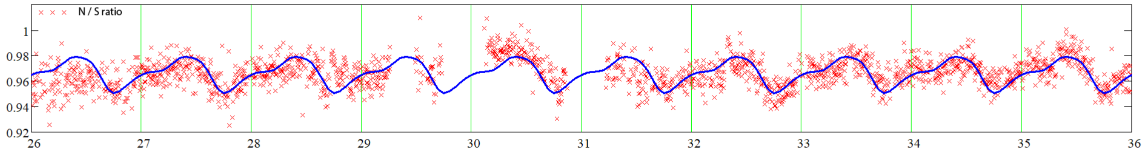

Fig.2

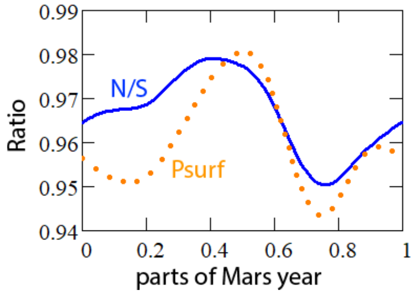

Fig.3