DIURNAL VARIATIONS IN MSL DAN PASSIVE MEASUREMENTS WITH ATMOSPHERIC PRESSURE AND SOIL TEMPERATURE.

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Introduction: The Dynamic Albedo of Neutrons experiment (DAN) on the Mars Science Laboratory (MSL) rover *Curiosity* is designed to detect neutrons for the purpose of sensing hydrogen within the subsurface of Mars [1,2]. DAN is capable of detecting neutrons through the use of two He-3 proportional counters, one of which is unshielded and the other shielded with cadmium, which absorbs neutrons with energies below the Cd cutoff of ~0.4 eV [2]. DAN has two modes of operation: an active mode that makes use of a pulsed neutron generator (PNG), and a passive mode, in which the PNG is not used [1,2]. There are multiple sources of neutrons for DAN to detect. One is derived from galactic cosmic rays (GCR). As these energetic particles propagate through the tenuous Martian atmosphere, some will interact with nuclei in the atmosphere producing secondary free neutrons through spallation, along with other particles [3]. The majority of initial GCR protons, however, will reach the surface of the planet and penetrate the subsurface up to a depth of ~1 meter, where they will interact with the nuclei of soil constituents and also produce neutrons through spallation [4]. A separate source is the MSL Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), which produces energetic neutrons as a product of the decay of plutonium-238. These neutrons, along with the GCR-induced neutrons (both from the atmosphere and the subsurface), will move throughout the subsurface and interact with the constituents of the soil through both elastic and nonelastic scattering, which will have the effect of moderating the energies of these neutrons [3]. Some neutrons escape from the surface, providing a leakage flux that the DAN He-3 proportional counters can measure. The energy spectrum of these neutrons is directly dependent on the amount of hydrogen in the subsurface. A higher hydrogen content will lead to more moderation and thus more low energy (thermalized) neutrons. The local environment, however, may also have an effect on this spectrum.

The Rover Environmental Monitoring Station (REMS) on *Curiosity* measures (among other things) the local atmospheric pressure and the ground surface temperature near the rover [4]. The purpose of the work presented here is to explore possible correlations between DAN passive mode measurements and the REMS pressure and temperature measurements and to understand the physical reasons for any such correlations through modeling.

Diurnal Variations: DAN passive data have been taken at many locations and times of day throughout the mission. At sites where data were accumulated over several sols while the rover was stopped, thermal and epithermal neutron count rates (Figures 1 and 2) were observed to undergo weak but repeatable diurnal variations. Also, the count rate of epithermal neutrons was observed to be inversely correlated with the count rate of thermal neutrons, which is unsurprising, as it is the epithermal neutrons that are moderated to become thermal neutrons.

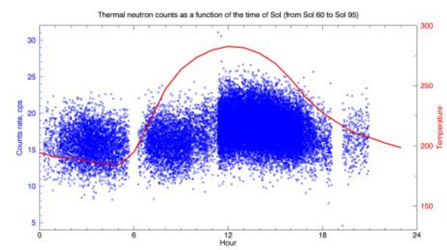

Fig. 1. DAN passive measurements of thermal neutrons (blue points) corresponding to a location known as Rocknest from sol 60 to 95. Overlayed is REMS mean temperaturedata (red curve) from the same location and time period.

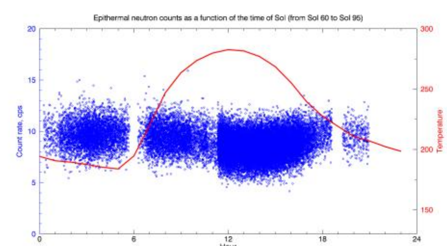

Fig. 2. Dan passive measurements of epithermal neutrons (blue points), corresponding to the same time and location as in Figrue 1. Overlayed is REMS mean temperature data from the same location and time period.

Soil composition, particularly the amount of water and the amount of high thermal neutron absorption cross section elements such as chlorine and iron, is the most important factor in determining the thermal neutron flux at the DAN detectors [2,6]. However, for measurements such as those shown in Figure 1 and Figure 2, the composition is unchanging and thus something else must be the cause of the observed variation. We hypothesize that atmospheric pressure and/or soil temperature variations could be the cause of the neutron flux variations. Atmospheric pressure variations change the atmospheric column density. This affects the proportion of GCR-sourced neutrons that are produced in the atmosphere versus those that are produced in the surface. Likewise, changes in soil temperature will change the exact energy distribution of thermalized neutrons, with higher temperatures shifting the higher-energy tail of the distribution further into the energy region blocked by the detector's Cd shield. Figure 1 suggests a *direct* correlation between surface temperature and thermal neutron counts - the opposite of what might be expected if higher temperatures were causing more neutrons to be blocked by the Cd shield. However the REMS temperature sensor is an infrared detector that measures radiative temperature from the top few microns of the surface. The neutrons detected by DAN, on the other hand, come from a sensing volume that extends several tens of cm into the surface. We hypothesize that the reason DAN thermal counts are directly correlated with surface temperature is because of the phase lag of diurnal temperature variations at depth. A thermophysically-homogeneous subsurface would have a phase lag of π radians at π diurnal thermal skin depths below the surface, or ~8.5 cm deep for a surface of loose sand-sized particles [7], and a bit deeper for a surface containing a mix of sand and larger clasts. Thus, the direct correlation between DAN thermal neutron counts and REMS surface temperature is easily explained if the centroid of the DAN thermal neutron sensing depth is close to π diurnal thermal skin depths. Effects due to atmospheric column density changes would experience no such phenomena as the atmosphere responds rapidly to such events and thus are expected to occur in near real time. Both pressure and temperature change diurnally [5] and thus we have created a model in which their effects can be explored through Monte Carlo methods to discern the extent to which the DAN measurements could be affected.

Monte-Carlo Methods: We use the Monte Carlo Neutral Particle-Extended (MCNPX) software package [8], which models the transport and interactions of GCR protons and the neutrons they produce, to examine the effects of diurnal variations in atmospheric pressure and soil temperature on the neutron energy spectrum and corresponding count rates in the DAN detectors. The model consists of 3 steps, which are needed in order to obtain reasonable counting statistics within the small volume of the DAN detectors. The first step simulates the Martian atmosphere and the GCR proton transport down to a plane 3 meters above the Martian surface. Protons and neutrons are accounted for in terms of their energy and angular distributions. The flux of these particles though the plane above the surface is taken as the starting point for a smaller-scale simulation, that transports the particles throughout the subsurface near the rover. This simulation includes a MSL rover mass model with the DAN detectors ~75 cm above the ground [2] to include the effects of the rover itself on the final neutron flux. The third and final step is to model the contribution to the neutron flux from the MMRTG. This is the same simulation as in the second step, except that the neutron source comes from the MMRTG with an appropriate energy spectrum. These results from the second and third steps are combined to get the total neutron leakage flux incident upon the DAN detectors. Atmospheric pressure and ground temperature inputs are varied independently to examine their separate effects on the neutron counts. For example, atmospheric pressure is examined over a range of values, while ground temperature is held constant. Upon modeling different temperature profiles of the subsurface, it will be possible to back calculate the effective temperature that a specific DAN measurement was sensitive to, which can then be compared to actual thermal models to verify the depth at which this temperature is consistent with the temperature wave.

Interpretations/Conclusions: DAN passive measurements show diurnal variations that are possibly attributed to changes in atmospheric pressure and soil temperature. Analysis using the model outlined above will give insight into the extent that the DAN measurements could be affected and the plausibility of these changes in explaining the actual measurement variation and the observed correlations/anticorrelations with environmental data. Initial results suggest that variation in soil temperature leads to a larger observable effect than changes in atmospheric pressure; however, thorough modeling is ongoing and results will be presented. Simulation trends will be compared to DAN passive data from Mars along with comparisons with REMS environmental data from the first 90 sols of the mission. Ultimately, we may be able to use the phase shift between DAN-inferred subsurface temperatures and REMS surface temperatures to infer the bulk thermal inertia of the subsurface in places the rover has acquired sufficient diurnal coverage with DAN measurements.

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