Long-term Neutron Background Environment Measured by the Dynamic Albedo of Neutrons (DAN) Instrument onboard Mars Science Laboratory (MSL)

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Introduction:

The Dynamic Albedo of Neutrons (DAN) instrument onboard Mars Science Laboratory (MSL) consists of a pulsed neutron generator (PNG) and the neutron detector/electronics (DE) module. There are two ^{3}He-proportional counters used in the DE module. One counter is surrounded with a Cd shell enclosure and measures epi-thermal neutrons with >0.4 eV. The second detector does not have a Cd shell enclosure and measures both thermal and epi-thermal neutrons.

The main scientific objectives of DAN are two-fold: (1) the primary objective is to measure the bulk hydrogen abundance (in forms of water or hydrated minerals) of the sub-surface and (2) the secondary objective is to measure the background neutron environment at the surface. DAN achieves the first objective by using a pulsed 14 MeV neutron source (ACTIVE mode). Emitted neutrons undergo a series of nuclear interactions with the regolith and lose energy. The DAN DE module then measures the time profile of the neutrons returned from the regolith. Even a small amount of hydrogen, as low as 0.1 weight % in the regolith, can effectively moderate the high energy neutrons [Mitrofanov, et al.,]. The less-moderated (or epi-thermal) neutrons arrive at the detector earlier than the more-moderated (or thermal) neutrons. The shape and magnitude of neutron time profile curves after pulses can be used to estimate the depth distribution of the hydrogen content. When no neutron pulse is used (PASSIVE mode) DAN measures the neutron background environment at the Mars surface. There are two sources of the background neutrons which DAN would measure: one is secondary neutrons generated by galactic cosmic ray (GCR) interactions with atmospheric and surface materials and the other is neutrons from the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) onboard MSL as a power source. The passive mode data for the first 1300 sols of the MSL mission are presented in this paper. A summary of the DAN surface operation is described by [Mitrofanov et al., 2012; Jun et al., 2013.

Neutrons from MMRTG

Plutonium used in the MMRTG undergoes alpha decay and spontaneous fission. Neutrons are generated in these processes, which need to be subtracted from the total counts in order to accurately estimate the “natural” neutrons from GCR interactions with the atmosphere and regolith. Fig. 1 shows the MMRTG neutron count rate measured during a check-up before launch.

GCR-Induced Neutrons

Galactic cosmic rays constitute a major part of the space radiation environment in the solar system. GCRs are very energetic charged particles - protons and atomic nuclei - likely accelerated by vast spheroidal blast waves from supernova explosions that propagate in the interstellar gas [*Jokippi*, 2010]. The accelerated cosmic rays enter the heliosphere on their way to the inner solar system. Typical energies of GCR found near Earth are in the range of 0.1 to 10 GeV/nucleon although extremely high energy of GCRs (> 1 TeV/nucleon) have been observed. All of the naturally occurring atomic nuclei are found in GCR – protons (~87%), alpha particles (~12%), and heavier nuclei (~1%). Because of their high energy, the reaction mechanisms for GCR with matter can be very complex. When the GCR particles enter the Mars system, they interact with the atmosphere first before reaching the surface of Mars. In this process, GCR particles slow down and/or undergo the cascades of nuclear reactions (called spallation and/or fragmentation reactions) producing scores of secondary particles, most notably neutrons, muons, pions, etc. These secondary particles along with the surviving primary GCR particles further interact with the surface materials down to a depth of about 200 g/cm^2 [e.g., *McKinney et al.*, 2006].

DAN Passive Data from the Surface Operation for the First 1300 Sols:

Passive data collected for the first 100 sols of the surface operation show a short- and long-term variability along the traverse. Fig. 2 illustrates the traverse path of the rover from the landing site to the Sol ~1300 location. Fig. 3 shows the MMRTG background-corrected passive data (thermal neutron counts) as a function of sol after landing.

MCNP Simulations

First, in order to understand general behavior of DAN passive data under different conditions, especially under different water/chlorine contents, a set of preliminary simulations were carried out using the rover, soil, atmospheric, and GCR models described in Jun et al, [2013]. The results are summarized in Figure 4. A few quick, but important, observations from these simulation results are noteworthy and described in Table 1. Also, we can note that the majority of DAN passive data are from the MMRTG neutrons. It is also shown that the thermal neutron count variations are dependent on many factors: atmospheric column density, surface water/Cl content, and (although not shown here) GCR flux level; and weakly on ground temperature; and that the epithermal neutron count variation is sensitive only to surface water contents.

Discussion and Summary

The DAN active data have been successfully used to estimate the near-surface water and chlorine contents along the rover traverse and the analysis has resulted in several papers by the DAN team members [Mitrofanov et al., 2014; Mitrofanov, et al., 2015; Litvak et al., 2014; Martin-Torres et al., 2015]. The DAN active mode measurements are dependent mainly on soil compositions (especially hydrogen and chlorine contents) and subsurface layering structure. And interpretation of the DAN active data was possible using a library generated by extensive simulations covering different subsurface water/chlorine contents and layering structure. It was also found that estimates by DAN for water distribution are consistent with measurements by Sample Analysis at Mars (SAM) although the sensing volumes between the two instruments are different. DAN provides the active mode data whenever the rover moves to new locations, and the active data are being analyzed almost in real time as soon as the data are downlinked. At the same time, it has to be noted that the PNG itself has a limited lifetime because of the decay of tritium in the target and degradation of "vacuum-ness" in the tube. Note that the DAN/PNG has already passed its formal lifetime as of August 2013, and at this time of proposal writing, is still working but at a lower neutron output.

The DAN passive mode operation does not have such lifetime limitation and the passive measurements are being made almost all sols since landing. The initial use and interpretation of DAN passive mode data is described by Jun et al. [2013]. As noted there, the data from DAN passive measurements can be used to study: (1) the subsurface hydrogen content (in lieu of or in combination with the active data) because the MMRTG neutrons and the GCR neutrons are sensitive to the subsurface water content; (2) the low energy neutron environment at the Martian surface which is a function of the free space GCR environment and solar energetic particles (SEP); (3) the GCR/SEP propagation through the Martian atmosphere by simultaneously measuring the neutron environment in orbit (HEND) and at the surface (DAN); (4) the diurnal variation of the surface neutron environment related to thermal inertia of the subsurface material (e.g., see Tate et al., 2013); and (5) the long term variations of the surface neutron environment in response to the change of the global ambient environment conditions (temperature, column density, GCR flux level, etc.).

In this paper, the DAN passive data are introduced and its long-term variation along the MSL traverse is shown. A few observations are noteworthy:

1. The neutrons from MMRG are the main contributor to the DAN passive measurement.
2. The DAN passive epithermal neutron data do not show much long-term variation (both along the traverse and for different seasons) during the he long-term surface operation of MSL.
3. In the meantime, the DAN passive thermal neutron data show rather strong variations along the rover traverse. We postulate that this is mainly due to the MMRTG neutron response to variations of composition of the near surface materials (soil, regolith, etc.).
4. Possible correlation(s) between the DAN thermal neutrons data and ambient environment conditions (e.g., GCR flux level, atmospheric density, etc.) may be possible based on the extensive MCNP simulation results (Figure 4 and Table 1), and this will be a subject for a separate paper in the near future.

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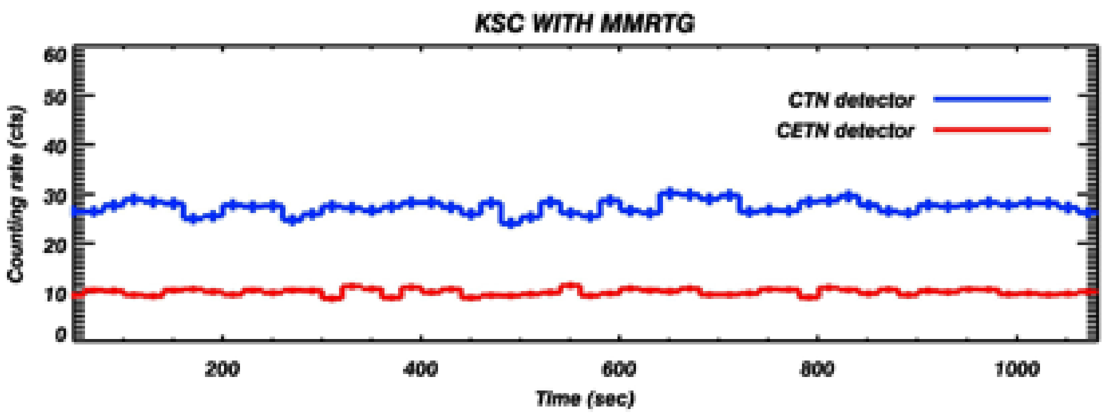

Fig. 1. MMRTG neutron counts measured during the Assembly, Test, Launch Operation (ATLO) at KSC before launch. The CETN detector is surrounded with a Cd enclosure so that it only measures epi-thermal (>0.4 eV) neutrons and the CTN detector measures both thermal and epi-thermal neutrons.

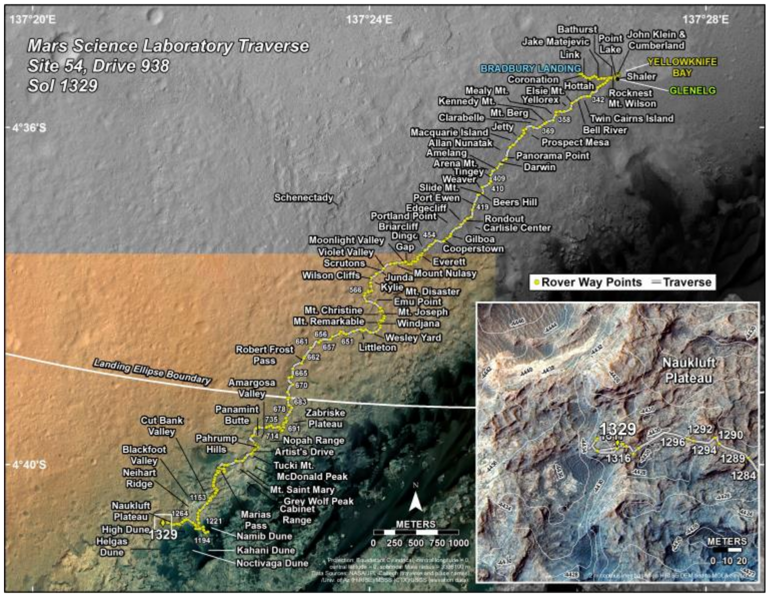

Fig. 2. Rover traverse path through Sol 1329. The total driving distance from the Sol 0 location to the Sol 1329 location is about XXX m.

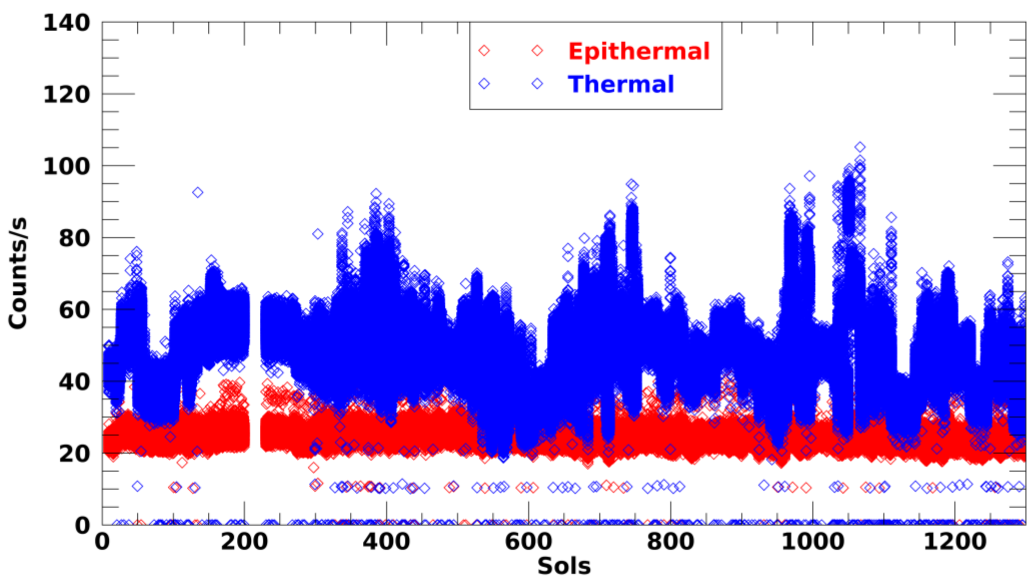

Fig. 3. DAN passive data (thermal neutrons) corrected for the MMRTG neutrons through Sol 1300.

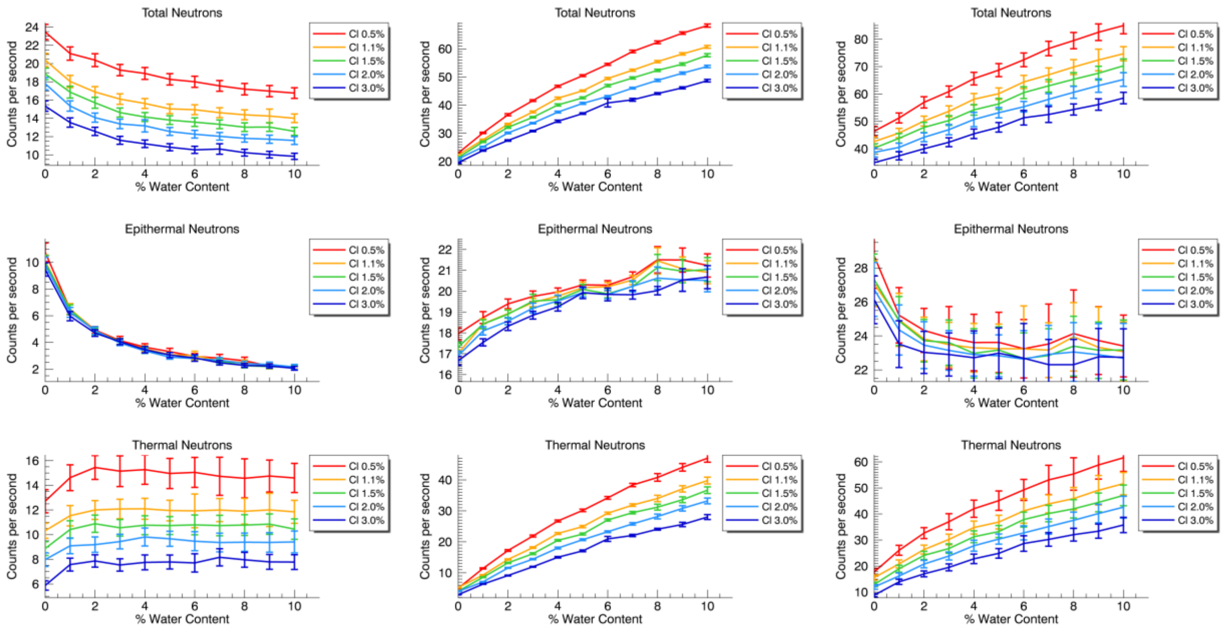

Fig. 4. Variations of the expected DAN passive mode operation count rates based on MCNPX simulations for different water and chlorine contents. The other input parameters used in these preliminary simulations are described in Jun et al. [2013]. The plots in the left are for the expected count rates for GCR-induced neutrons, the plots in the center are for neutrons from MMRTG. The plots in the right are the sums of these two.

Table 1. Observations drawn from Figure 2 for the trend of thermal and epithermal count rates for varying water and chlorine contents. Here the arrows pointing up (or down) indicate that the counts increase (or decrease) as functions of water/chlorine contents.

THERMAL NEUTRONS		
	Counts from GCR	**Counts from MMRTG**
For increasing water content	**Not Sensitive**	**Sensitive** ↑
For increasing Cl content	**Sensitive** ↓	**Sensitive** ↓

EPITHERMAL NEUTRONS		
	Counts from GCR	**Counts from MMRTG**
For increasing water content	**Sensitive** ↓	**Less Sensitive**
For increasing Cl content	**Not Sensitive**	**Not Sensitive**