Icarus 299 (2018) 513–537

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Results from the dynamic albedo of neutrons (DAN) passive mode experiment: Yellowknife Bay to Amargosa Valley (Sols 201–753)

C.G. Tate[a,*], J. Moersch[b,a], I. Mitrofanov[c], M. Litvak[c], P. Bellutta[d], W.V. Boynton[e], D. Drake[f], B. Ehresmann[g], F. Fedosov[c], D. Golovin[c], C. Hardgrove[h], K. Harshman[e], D.M. Hassler[g,i], I. Jun[d], A.S. Kozyrev[c], D. Lisov[c], A. Malakhov[c], D.W. Ming[j], M. Mischna[d], M. Mokrousov[c], S. Nikiforov[c], A.B. Sanin[c], R. Starr[k], A. Vostrukhin[c], C. Zeitlin[l]

[a] Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA
[b] Department of Earth and Planetary Sciences, University of Tennessee, Knoxville, TN 37996, USA
[c] Space Research Institute, RAS, Moscow, Russia
[d] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[e] University of Arizona, Tucson, AZ 85721, USA
[f] TechSource, Inc, Los Alamos, NM 87544, USA
[g] Southwest Research Institute, Space Science and Engineering Division, Boulder, CO 80302, USA
[h] School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA
[i] Institut d'Astrophysique Spatiale, Univ. Paris-Sud, Orsay, France
[j] Astromaterials Research and Exploration Science Directorate, NASA Johnson Space Center, Houston, TX, USA
[k] Department of Physics, The Catholic University of America, Washington, DC 20064, USA
[l] Leidos, Exploration and Mission Support, Houston, TX, 77042, USA

ARTICLE INFO

Article history:
Received 2 April 2017
Revised 18 July 2017
Accepted 16 August 2017
Available online 18 August 2017

Keywords:
Mars
Mars, surface
Cosmic rays

ABSTRACT

The Mars Science Laboratory (*Curiosity* rover) Dynamic Albedo of Neutrons (DAN) experiment detects neutrons for the purpose of searching for hydrogen in the shallow subsurface of Mars. DAN has two modes of operation, active and passive. In passive mode, the instrument detects neutrons produced by Galactic Cosmic Ray interactions in the atmosphere and regolith and by the rover's Multi-Mission Radioisotope Thermoelectric Generator. DAN passive data from Yellowknife Bay to Amargosa Valley (sols 201 through 753) are presented and analyzed here. Water equivalent hydrogen (WEH) estimates from this portion of *Curiosity's* traverse range from 0.0 wt. % up to 15.3 wt. %. Typical uncertainties on these WEH estimates are ~0.5 wt. % but in some cases can be as high as ~4.0 wt. % depending on the specific circumstances of a given measurement. Here we also present a new way of reporting results from the passive mode of the experiment, the DAN passive geochemical index (DPGI). This index is sensitive to some key geochemical variations, but it does not require assumptions about the abundances of high thermal neutron absorption cross section elements, which are needed to estimate WEH. DPGI variations in this section of the traverse indicate that the shallow regolith composition is changing on both the local (~meters) and regional (~100 s of meters) scales. This variability is thought to be representative of the diverse composition of source regions for sediments within the crater floor. Kolmogorov-Smirnov Tests on the populations of WEH estimates and DPGI values demonstrate there are statistically significant differences between nearly all of the geologic units investigated along the rover's traverse. We also present updated previous DAN passive results from Bradbury Landing to John Klein that make use of revised DAN active mode results for calibration, however, no qualitative changes in the interpretations made in Tate et al. (2015b) are incurred.

1. Introduction

The Dynamic Albedo of Neutrons experiment (DAN) on the Mars Science Laboratory (MSL) rover *Curiosity* has been operating successfully on the surface of Mars since landing in Gale Crater on August 6th, 2012. In that time, DAN has contributed to the mis-

* Corresponding author.
E-mail address: ctate10@vols.utk.edu (C.G. Tate).

http://dx.doi.org/10.1016/j.icarus.2017.08.022
0019-1035/

sion's success in completing one of its primary mission objectives of finding a habitable environment (Grotzinger et al., 2012, 2014). DAN measurements constrain the bulk composition of the shallow regolith of Gale crater, specifically, the amount of water equivalent hydrogen (WEH) and absorption equivalent chlorine (AEC) (Mitrofanov et al., 2014; Tate et al., 2015b). For a discussion of results from the DAN active experiment, see Mitrofanov et al. (2014, 2016) and Litvak et al. (2014, 2016). Tate et al. (2015b) present DAN passive results and WEH estimates from the start of the surface mission at Bradbury Landing (sol 0 of the mission) to John Klein sol (200), and the present work extends this analysis of DAN passive data to Amargosa Valley (sol 753). Also of interest, Jun et al. (2013) discuss DAN passive measurements in relation to the Martian radiation environment.

In its active mode of operation, the DAN experiment utilizes a pulse neutron generator (PNG) and two ^{3}He proportional counters called the detector element (DE), to constrain the abundance of subsurface hydrogen. The DE detects neutrons via the reaction $n + {}^3He \rightarrow {}^3H + {}^1H + 0.764$ MeV (Batchelor et al., 1955). One of the counters in the DE, known as the counter of total neutrons (CTN), is capable of detecting neutrons over a broad spectrum of energies (<0.1 MeV), however, its detection efficiency above 1 keV is very low (Litvak et al., 2008). The other counter in the DE, known as the counter of epithermal neutrons (CETN), is covered with a thin (1 mm-thick) jacket of cadmium that absorbs neutrons with energies below ~0.4 eV and therefore only counts neutrons with energies above this "Cd cutoff" (Litvak et al., 2008). The count rates in each detector are differenced to produce thermal neutron count rates, which in the context of the DAN instrument refers to neutrons below the Cd cutoff energy.

The DAN passive mode of operation does not make use of the PNG, but rather relies on signal from two lower-intensity, continuous sources of neutrons: the MSL Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), which produces neutrons as a byproduct of its plutonium fuel decay, and galactic cosmic rays (GCR), which spallate neutrons through nuclear interactions in the atmosphere and subsurface. The DE detects the leakage flux of neutrons, which is used (along with models of the bulk geochemical composition) to infer the water equivalent hydrogen (WEH) content of the shallow regolith. WEH refers to the amount of water that would be present if all of the hydrogen were bound in water. Although DAN is the first neutron remote sensing experiment on the surface of Mars, the High Energy Neutron Detector (HEND) (Mitrofanov et al., 2002) and Neutron Spectrometer (NS) onboard Mars Odyssey (Feldman et al., 2002) have produced global maps of WEH from orbit. As will be discussed, there are salient differences between the analysis of neutron remote sensing data acquired from orbit versus those acquired by DAN on the surface including the spatial footprint, the contribution of neutrons from the MMRTG, and the associated characteristics of the epithermal neutron population (Tate et al., 2015b).

After leaving John Klein, *Curiosity* drove a long distance (just under 9 km) to reach the lower units of Aeolis Mons (Mount Sharp), a primary mission goal, along a path referred to as the Rapid Traverse Route (RTR), seen in Fig. 1 (Grotzinger et al., 2015). On sol 753, *Curiosity* reached the proximal edge of the Pahrump Hills from within Amargosa Valley (Grotzinger et al., 2015). This is the location of an exposed contact between the Bradbury group (Aeolis Palus) and the lower units of Mount Sharp, specifically the Murray formation, which represent different depositional environments (Grotzinger et al., 2015). The MSL Science Team's focus on arriving at Pahrump Hills as quickly as possible resulted in fewer in-depth, multi-experiment investigations at waypoints along the traverse than in the preceding portion of the mission. Nevertheless, because the traverse took a long time and only a few geologic units observed in orbital data sets were crossed along the RTR, these units were well-sampled and characterized by *Curiosity's* payload. The units investigated with DAN passive measurements during this portion of the traverse were (as mapped by Calef et al. (2013)) the Smooth Hummocky Unit, the Bedded, Fractured Unit, the Eolian Unit, the Striated Light-toned Unit, and the Rugged Unit. In addition to presenting the first analyses of DAN passive results from Yellowknife Bay to Amargosa Valley, we also present an update of DAN passive results from Bradbury Landing to John Klein that make use of revised DAN active mode results for calibration, though no qualitative changes in the interpretations of Tate et al. (2015b) are incurred.

2. Methods

The DAN passive data analysis methods used here are the same as those described in Tate et al. (2015b), but with the addition of new DAN active calibration sites from the additional sols investigated. We have also applied corrections to the thermal neutron count rate data to account for changes in the geometry of the MMRTG and DAN DE relationship to the ground. As stated in Tate et al. (2015b), this is typically a small effect on WEH estimates and the methods used are described in the appendix to this manuscript. Our approach is to model the Martian neutron leakage flux and the DAN detectors' response to it using different WEH abundances, and then compare these model results to DAN passive data in order to find the best compositional fit. We model the Martian neutron leakage flux in the vicinity of the DAN detectors using the Monte Carlo Neutron Particle eXtended code (MCNPX) (McKinney et al., 2006) for transport and interactions of high energy protons and neutrons. We independently model the neutrons sourced from the MMRTG and those sourced from the GCR in order to understand the different contributions to the final neutron leakage flux and to simplify individual computational processes.

The GCR component of the model is further broken down into two scales; a global-scale model that includes the bulk of the atmosphere and a local-scale model, in the near vicinity of the rover that includes atmosphere, regolith, a rover mass model, and DAN DE. This is necessary because the volumes of the DAN detectors are extremely small compared to the volume of Mars and its atmosphere. A single model combining both scales would result in very poor statistics for predicted neutron count rates in the DAN detectors. The global-scale model includes transport and interactions of primary GCR protons and resulting secondary particles that can contribute to the neutron flux, specifically keeping track of the energy and directional distributions of the particles in question. The flux of particles exiting the lower boundary of the global-scale model are used as the particle source for the local-scale model. This model provides an estimate of the GCR-sourced neutron leakage flux at the DAN detectors and their response. The model that estimates the neutron leakage flux due to the presence of the MMRTG utilizes the same geometry as the GCR local-scale model described above, however this model uses the MMRTG neutron spectrum as its source. A full description of the MCNPX models utilized can be found in Tate et al. (2015b) and a description of the MMRTG source and rover mass model can be found in Jun et al. (2013).

The WEH abundance in the regolith can be systematically varied within these models in order to build a library of model results to compare to the data. The regolith within the model is assumed to be homogenous in composition both vertically and laterally. While more complicated geometries can be modeled, we compare to the simplest assumptions to obtain a bulk regolith composition because DAN passive measurements lack sufficient free parameters to differentiate between simple and complicated geometries. All of our models use the same "background" composition meant to represent the Martian regolith, but with varying amounts of hydrogen (WEH) and AEC. Following the convention