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Characterizing near-surface elemental layering on Mars using gamma-ray spectroscopy: A proof-of-principle experiment

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ABSTRACT

Gamma-ray spectroscopy investigations characterize the chemical composition of planetary surfaces by measuring element-characteristic gamma rays with energies of ~100 keV to ~9 MeV. Over this energy range, the mean free path of a gamma ray varies from about 1 to 25 cm, therefore gamma-ray measurements sample subsurface composition. Many elements emit gamma rays at multiple, often widely spaced energies, so gamma-ray measurements can in principle also be used to identify depth-dependent variations in subsurface composition. We report results from laboratory measurements and radiation transport modeling designed to demonstrate this capability. The laboratory measurements verified the presence of depth-dependent gamma-ray signatures, and were then used to benchmark radiation transport simulations that were used to model realistic Mars-like scenarios. The models indicate that compositionally distinct subsurface deposits, buried to depths of ~80 cm (125 g/cm^2), can be identified using gamma-ray measurements. Going beyond identification to characterization (burial depth, relative composition of the layers) of the deposits requires knowledge of the vertical and horizontal variability in the water content of the near-surface surface materials, the local Galactic Cosmic Ray environment (magnitude and energy distribution), the depth-dependent neutron flux, gamma-ray production cross sections, and knowledge of the composition and column density of the atmosphere. The results of our experiments and models provided a basis for examining the utility of using orbiter- and lander-based gamma-ray measurements to identify subsurface deposits on Mars.

1. Introduction

A fundamental problem in Mars science is the existence of a near-ubiquitous layer of dust and soils that obscure ancient, underlying materials of scientific interest. In-situ exploration of Mars' surface has revealed the importance of examining subsurface materials in order to reveal the environmental conditions at the ancient surface. The Mars Exploration Rovers (MERs) Spirit and Opportunity provide several examples. The Opportunity rover observed layered bedrock exposed in the walls of Eagle crater [1], some of these layers hosted hematite-rich spherules thought to have formed by aqueous processes in shallow, acidic sea [2]. While traversing the "Home Plate" region of Gusev crater near the Columbia hills, Spirit inadvertently excavated a several-cm-deep trench with its inoperative front wheel (Fig. 1), exhuming light-toned soils that subsequent geochemical analyses revealed to be opaline silica [3]. The presence of opaline silica, along with other contextual evidence from the Home Plate region, led [3] to conclude that materials at this site were chemically altered by hydrothermal processes.

The identification of ancient salty seas and extinct hydrothermal sites are among the most significant discoveries of the MER program. Yet these discoveries were fortuitous; Opportunity's landing in Eagle crater was not planned, and Spirit's discovery of the opaline silica was an accident resulting from the unintentional excavation of subsurface materials by an inoperative wheel. These situations are emblematic of the difficulties associated with studying Mars' dust- and soil-covered surface. These dust and soil veneers, which are distributed globally via aeolian and impact processes, are near homogenous in chemistry [4] and are not necessarily representative of underlying geologic units.

The current solution to the dust and soil problem is twofold; orbital investigations examine dust- and soil-free regions (e.g. craters, highly sloped surfaces) to characterize underlying dust-free materials, and surface-based investigations carry tools (e.g. scoops, brushes and/or drills) that remove these and other weathering surfaces to expose fresh material for direct study. Additionally, rovers travel to outcrops and

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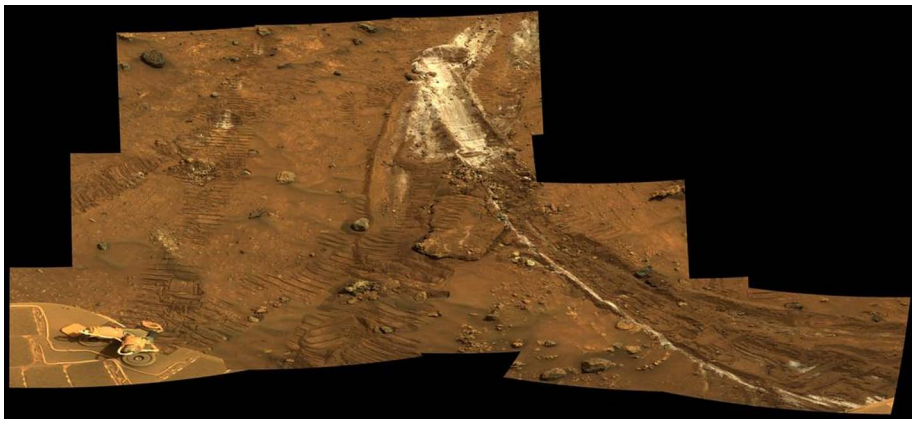

Fig. 1. Light-toned soils, excavated in the "Home Plate" region of Gusev crater by the rover Spirit. This trench was inadvertently dug by Spirit's inoperative front wheel on sol 1182 of its mission. Image credit: NASA/JPL-Caltech/Cornell (http://mars.nasa.gov/multimedia/images/?ImageID=4036).

crater walls, where otherwise buried materials are exposed. While valuable, these approaches do not provide a geographically complete view of the geologic or geochemical properties of subsurface materials.

Gamma-ray spectroscopy is uniquely suited to the task of characterizing the elemental composition of materials beneath an optically thick (> mm) layer of dust or soil. Gamma rays sample to depths of order tens of cm (Section 2.2), making them relatively insensitive to the composition of a thin (< 1 cm) surficial layer. In principle, depth-varying composition information is available in gamma-ray spectra, as most elements produce gamma-ray emissions at multiple energies, each of which has a different mean free path within surface materials and therefore samples surface composition to different depth [5].

We designed a laboratory experiment to test the feasibility of using gamma-ray spectroscopy to identify the presence of, and depth to, compositionally distinct subsurface deposits (Section 3). Our experiment adopted the scenario of the opaline silica deposits of Gusev crater as a case study. The results of the experiment served to benchmark Geant4 models that were subsequently extended to demonstrate the usefulness of orbital gamma-ray spectroscopy to investigate this stratigraphic scenario on Mars (Section 4).

2. Gamma-ray spectroscopy

2.1. Gamma-ray production

Planetary gamma rays originate from the decay of naturally radioactive elements (K, Th, and U), as well as the de-excitation of stable (non-radioactive) elements following reactions with energetic particles, primarily galactic-cosmic-ray (CGR) generated neutrons. In the latter scenario, GCRs penetrate a planet's surface to depths of a few meters, along the way liberating neutrons from atomic nuclei via nuclear spallation. As these spallation neutrons travel through surface materials, they can transfer energy to (excite) nuclei via inelastic scattering. Low-energy neutrons can undergo capture reactions, producing new nuclei in excited states. These excited nuclei return to their ground states by shedding energy via the emission of gamma rays at element-characteristic energies. These gamma rays appear as a unique combination of peaks in a gamma-ray energy deposition spectrum (e.g., [6]). The concentration of a given element within the surface is proportional to the total number of events in the respective gamma-ray peaks.

GCRs easily penetrate Mars' thin (~20 g/cm^2) atmosphere, resulting in ubiquitous gamma-ray emissions across the surface. In contrast, Earth's thick (~1000 g/cm^2) atmosphere blocks primary GCRs and therefore GCR-induced gamma-ray emissions are insignificant at the surface. As a consequence, GCR-induced gamma-ray emissions cannot be studied directly in the laboratory, and everything from pre-mission simulations of Gamma-Ray Spectrometer (GRS) measurements to the final analyses of GRS data are carried out using radiation transport codes like MCNPX (e.g. [7]) and Geant4 (e.g. [8]). Using a GCR energy spectrum and model surface composition as an input, these codes simulate the entire process of interest, which includes: 1) GCR-induced interactions, including the liberation of neutrons from atomic nuclei via nuclear spallation, 2) neutron transport within planetary materials, including near-surface materials (e.g. rock) and, if present, an atmosphere, 3) neutron-induced gamma-ray production, and 4) gamma-ray transport within planetary materials (rock and atmosphere), including absorption and scattering. While MCNPX and Geant4 do incorporate laboratory data (e.g. spallation and neutron cross sections), the processes in question occur over many decades in energy and the accuracy of this data varies by element, reaction, and particle (proton, neutron) energy. Experiments designed to benchmark radiation transport codes have revealed an inability to exactly reproduce some aspects of the experimentally measured gamma-ray spectra for both MCNPX [9] and Geant4 [10], and to date no study has explored the ability to derive composition information for layered materials. As a consequence, extending radiation transport modeling to cover the scenario of gamma-ray emissions from layered materials requires some benchmarking to validate the accuracy of the model outputs.

2.2. Gamma-ray transport

Our experiment was designed to test the hypothesis that depth-dependent variations in the subsurface composition of planetary materials can be identified and characterized using gamma-ray measurements. Note that throughout this manuscript we adopt the term "stratigraphy" to describe scenarios wherein vertical layers of compositionally distinct materials are present and measurable. Within the study of geologic stratigraphy, layers of ~5–100 m are termed "strata", and ~cm to ~m scale layers are called horizons. We are sensitive to the latter, and we characterize the chemical, not geological properties of the horizon(s). Finally, note that we assume each horizon has discrete compositional boundaries, as opposed to compositional gradients due to mixing.

Our hypothesis that chemically distinct horizons can be recognized with gamma-ray measurements was founded on the fact that, in the ~0.1–10 MeV energy range, the mean free path (ℓ) of a gamma ray (γ) increases with energy (E_γ). For a material "M", ℓ is calculated as

$$\ell(E_\gamma) = [A_M(E_\gamma)\rho]^{-1} \quad (1)$$

where $A_M(E_\gamma)$ is the energy and material-composition-dependent mass attenuation coefficient (units of cm^2 g^{-1}) and ρ is the material density (units of g cm^{-3}). $A_M(E_\gamma)$ values used in this study were retrieved from the NIST XCOM database [11].

Once a gamma ray undergoes any interaction its energy is no longer characteristic of the element from which it was generated. The gamma rays of interest for gamma-ray spectroscopy are therefore limited to those that traverse the path length t (gamma-ray origin location to the gamma-ray spectrometer) without any interactions. The fractional probability (P_γ) that a gamma ray will traverse a path length t without

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