

**DISTRIBUTION OF SULFUR ON THE SURFACE OF MARS DETERMINED BY THE 2001 MARS ODYSSEY GAMMA RAY SPECTROMETER.** S. M. McLennan<sup>1</sup>, W. V. Boynton<sup>2</sup>, S. Karunatillake<sup>1</sup>, B. C. Hahn<sup>3</sup>, G. J. Taylor<sup>4</sup> and the Mars Odyssey GRS Team, <sup>1</sup>Department of Geosciences, SUNY at Stony Brook, Stony Brook, NY, 11794-2100, USA ([Scott.McLennan@sunysb.edu](mailto:Scott.McLennan@sunysb.edu); [swalimunidev@notes.cc.sunysb.edu](mailto:swalimunidev@notes.cc.sunysb.edu)), <sup>2</sup>Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, 85721, USA ([wboynton@lpl.arizona.edu](mailto:wboynton@lpl.arizona.edu)), <sup>3</sup>Department of Earth and Planetary Sciences, University of Tennessee, Knoxville, TN, 37996, USA ([hahnbrian@hotmail.com](mailto:hahnbrian@hotmail.com)), <sup>4</sup>Institute of Geophysics and Planetology, University of Hawaii at Manoa, Honolulu, HI, 96822, USA ([gjtaylor@higp.hawaii.edu](mailto:gjtaylor@higp.hawaii.edu)).

**Introduction:** Understanding the global distribution of sulfur on the Martian surface is central to evaluating both the Martian sulfur cycle and the history of aqueous processes on that planet. The sulfur-rich nature of Martian soils and dust has been recognized by each of the Viking, Pathfinder and MER spacecraft and the presence of sulfate minerals in some ancient sedimentary deposits have been recognized by various orbital IR spectrometers. In spite of this, the global distribution of sulfur across Mars has never been fully characterized or quantified.

The 2001 Mars Odyssey gamma ray spectrometer (GRS) experiment has now obtained sufficient data, identified appropriate analytical peaks and developed data reduction approaches sufficient to produce a statistically useful map of the sulfur distribution in the Martian near-surface for low- to mid-latitudes. Here we present these results and discuss geochemical relationships among the large-scale distributions of sulfur and the other highly mobile elements that have been mapped by GRS, hydrogen and chlorine (both recalculated to the same resolution as the sulfur maps).

**Sulfur Map:** Figure 1 is a map of sulfur concentrations in the upper few tens of centimeters (exact interrogation depth for GRS depends on the soil/rock material properties at any given location and peak energy). Concentration data were derived from the 5421 keV capture line [1] smoothed using a boxcar filter with a radius of 25° and binned at 10°X10°. Mapped one sigma uncertainties are in the range of ±0.35-1.0% and, apart from the highest mapped latitudes, are mostly less than ±0.65%. Further details of the GRS data reduction approaches can be found in Ref. [2]. The sulfur map is overlain onto a Mars Orbiter Laser Altimeter (MOLA) shaded relief topographic map.

The Martian near-surface is characterized by elevated sulfur concentrations, varying from <1% to >3% and averaging 1.76% (SO<sub>3</sub>=4.40%). This average concentration is significantly lower than the average sulfur concentration in analyzed soils (SO<sub>3</sub>=6.2%; Ref. [3]), reflecting the relative proportions of soil and bedrock exposed at the Martian surface. Similar to other elements mapped by GRS, sulfur distributions exhibit a near-gaussian distribution planet-wide, with skewness

of 0.33 (mild positive skew) and excess kurtosis of -0.28 (mildly platykurtic). Regions of sulfur enrichment or depletion and major geological features do not overlap visually. On the other hand, there is a broad elevation of sulfur concentrations at low latitudes, notably between about ±20-30°.

**H<sub>2</sub>O – Sulfur Relationships:** Hydrogen (as H<sub>2</sub>O) displays highly scattered but statistically significant correlation with sulfur. There is a notable hemispheric difference in the strength and details of the correlations. Accordingly, on a plot of H<sub>2</sub>O versus S, the southern hemisphere displays a higher correlation coefficient with a steeper slope and lower H<sub>2</sub>O intercept.

We also attempted to evaluate the possibility that elevated hydrogen found at mid-latitudes [2,4,5] might be due in part to the presence of hydrous sulfate minerals, as has been suggested previously by a number of workers. We examined the H-S relationships as a function of latitude. Southerly mid-latitudes (+10° to -30°) represent a contiguous region where near-surface water abundances are elevated and water ice is unstable under near surface conditions across all longitudes [6] and, for this area, a scattered correlation persists (r=0.45, with a standard error of 0.07) with an intercept of 2.7±0.5% H<sub>2</sub>O.

The slope of the H<sub>2</sub>O-S correlation may be interpreted as reflecting structural and/or bound water in near-surface minerals. The average slope, when converted to molecular proportions, is equivalent to an effective average hydration state of 2.4±0.4 for divalent cation sulfates (i.e., Ca-, Mg-, Fe<sup>2+</sup>-sulfates). As higher latitudes are included in the correlation, the implied effective hydration state varies mostly in the range of 2.2-2.8 for divalent sulfates. For Fe<sup>3+</sup>, Al<sup>3+</sup>- or mixed valence sulfates, the effective hydration states implied by the correlation are higher, in the range of about 4-10. For reference, kieserite has a hydration state of one; gypsum, 2; jarosite and alunite, ~3; coquimbite, 9; and bilinite, 22. Accordingly, the H-S relationships are consistent with some variety of sulfate minerals significantly influencing, but not fully explaining, the water content of surficial deposits in regions where ice is expected to be unstable at the surface.

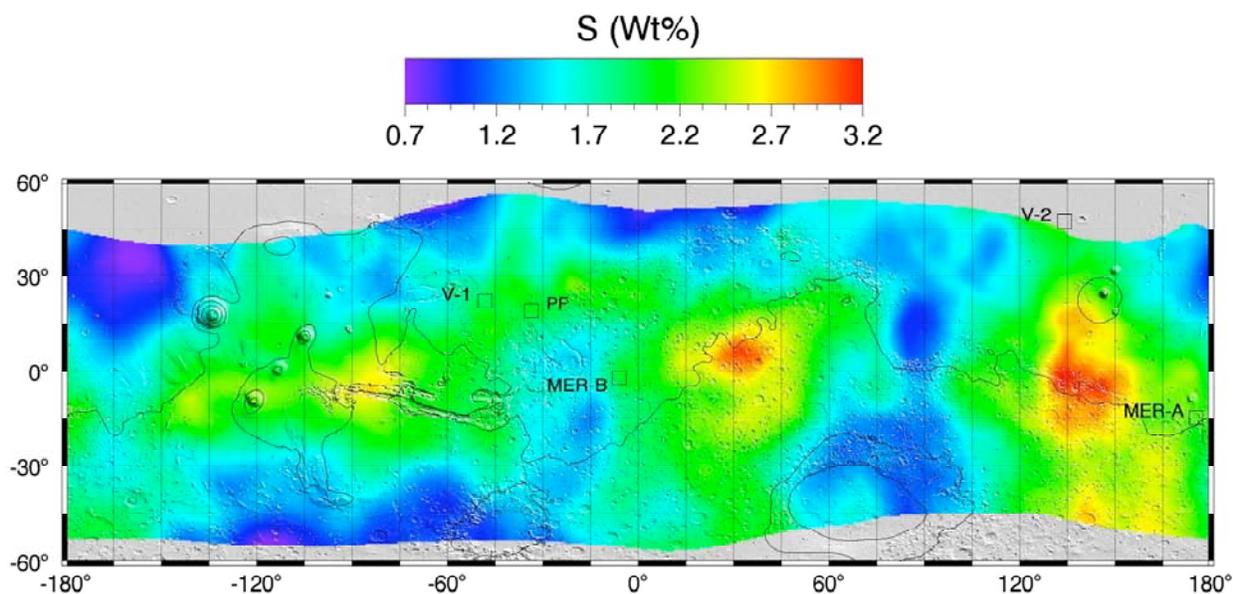
**Chlorine – Sulfur Relationships:** Chlorine also exhibits a scattered but statistically significant correlation with sulfur, with the northern hemisphere being considerably more scattered than the southern hemisphere ( $r=0.31$  vs.  $0.61$ ). Of special interest is the observation that the correlation also has a significant Cl-intercept of about 0.37%, or roughly two-thirds the average Cl concentration in the near surface environment. This value is about a factor of two higher than the intercept observed for a plot of Cl versus S for basaltic soils (Cl-intercept of  $\sim 0.16\%$ ), filtered to exclude anomalous P-, Si-, S- and Fe-rich varieties.

Since igneous rocks have very low S and Cl concentrations compared to the average Martian surface, an intercept of near zero is expected if S and Cl behave coherently during surficial processes. The significant Cl intercept for both soils and the Martian surface on average suggests differential vertical mobility between these elements with Cl being preferentially enriched in the near-surface environment. Such differential upward mobility of Cl may also be evident at much smaller spatial scales as chloride deposits identified by orbital thermal emission spectroscopy [7] and the halite enrichments in surface rinds and veneers on some outcrops at Meridiani Planum [8].

The upward enrichment of Cl at the Martian surface may have astrobiological implications. Tosca et

al. [9] modeled water activity as a function of evaporative concentration for high S/Cl brines derived from aqueous alteration of Martian basalts. Unlike terrestrial seawater, in such brines, halite is among the very last minerals to precipitate, after Mg-sulfate precipitation, at extremely low water activities ( $<0.5$ ). Thus upward preferential mobility and preservation of chlorides on a global scale may suggest persistently low water activity across broad regions of the Martian surface, which in turn may create considerable challenges for biological activity, especially near the surface.

**References:** [1] Evans, L. G. et al. (2008) *LPS XXXIX*, Abstract#1875. [2] Boynton, W. V. et al. (2007) *JGR*, 112, E12S99, doi:10.1029/2007JE002887. [3] Taylor, S. R. and McLennan, S. M. (2009) *Planetary Crusts: Their Composition, Origin and Evolution*. Cambridge Univ. Press, 378pp. [4] Feldman, W. C. et al. (2002) *Science*, 297, 75-78. [5] Feldman, W. C. et al. (2004) *JGR*, 109, E09006, doi:10.1029/2003JE002160. [6] Feldman, W. C. et al. (2004) *GRL*, 31, L16702, doi:10.1029/2004GL020181. [7] Osterloo, M. M. et al. (2008) *Science*, 319, 1651-4. [8] Knoll, A. H. et al. (2008) *JGR*, 113, E06S16, doi:10.1029/2007JE002949. [9] Tosca, N. J. et al. (2008) *Science*, 320, 1204-7.



**Figure 1.** Map of the sulfur concentrations in the upper few tens of centimeters of the Martian surface at low- to mid-latitudes (H-mask) overlain onto a MOLA shaded relief topographic map. Map is based on gamma capture line data smoothed with a boxcar filter using a radius of  $25^\circ$  and binned at  $10^\circ \times 10^\circ$ . Note that there is a broad relative enrichment of sulfur concentrations in the near equatorial latitudes.