Spatial Variability of the Martian Crustal Magnetic Field

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Introduction: Although the planet Mars no longer possesses an internal dynamo, its crustal rocks retain strong remanent magnetization thought to have been induced by an ancient core-sourced field. The field as a whole is inconsistent with induction from a single dipolar source, although previous studies have attempted to isolate individual magnetic anomalies to deduce paleopolar orientations. The strength and distribution of the observed crustal field is extremely heterogeneous. The strongest anomalies are found in the Terra Cimmeria region of the southern hemisphere, where large, correlated structures form several east-west trending lineations of alternating polarity 1. While several areas of the planet appear to have been demagnetized, including large impact basins and the Tharsis volcanic province, the distribution of the field is generally poorly correlated with surface geologic structures. However, beyond the spatial pattern of crustal magnetization, the magnetic power spectrum can provide information about the nature of the source and crustal evolution.

Methods: In the absence of free currents and time variability, it is possible to represent an internal magnetic field in terms of a scalar potential. We have primarily used the potential model of [2] to spherical harmonic degree and order 90, although we have evaluated other published models as well. As is typical in magnetic analyses, we use the definition of the magnetic power spectrum $\hat{S}_l$ (at the reference radius) derived by [3],

$$\hat{S}_l = (l+1)\sum_m \left[(g_l^m)^2 + (h_l^m)^2\right]$$

where $[g_l^m, h_l^m]$ represent the Gauss coefficients of the magnetic potential.

Previous studies have used the power spectrum of the Martian field to estimate the approximate depth of magnetic anomalies on Mars [4, 5]. We extend this approach by employing the spatiospectral localization technique of [6, 7] to isolate the magnetic power spectra of specific areas of the Martian surface. This procedure applies a series of optimally concentrated, bandlimited “Slepian” windowing functions to the data in a manner analogous to 1-D multitaper analysis. Most importantly, this method allows us to look beyond the strongly magnetized Terra Cimmeria region, which dominates the global power spectrum. Localized spectral estimates, along with their calculated variances, allow us to examine the significance of observed variations between distinct regions of the planet, and to evaluate the validity of analyses which operate on the whole sphere. To map the varying spectral properties of the planet, we chose a localization window taking the form of a circular cap with a radius of 20°. We then slide this window in intervals of 10° in latitude and longitude, resulting in several hundred local power spectral estimates of the field.

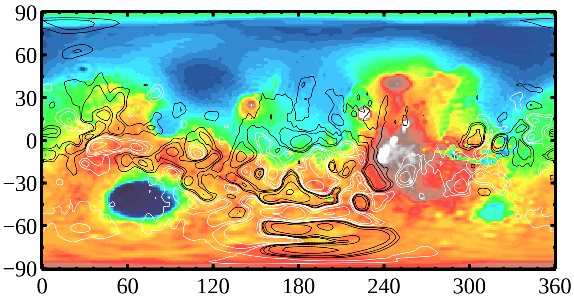

Figure 1: Contour map of the martian radial magnetic field on MOLA topography, after [1].

Approximate strengths and depths of the magnetic sources are calculated for tiled windows on the planet using a random dipolar source model derived by [4]. This idealized model assumes an ensemble of randomly oriented, dipolar magnetic sources scattered on a spherical shell, and takes the form,

$$\{S_l\} = A_x l(l+1/2)(l+1)(r_x/a)^{2l+1}$$

where A_x represents an amplitude term proportional to the mean squared moment of the dipolar sources, while r_x and a represent the magnetized shell and planetary radii, respectively. Although a variety of models may be used to fit the observed spectra, this simple log-linear case allows us to easily parameterize the regional diversity of the Martian field.

Results: For most regions of Mars, the random dipole shell model is adequate to explain the localized power spectrum. Overall, we obtain a wide range of depth estimates across the planet, which are generally shallower than that estimated for the whole sphere. Depth estimates range from -10 to 65 (±10) km relative to the mean MOLA elevation within each cap. These estimates are in comparison to an estimated depth of 40 km for the planet as a whole, relative to the mean planetary radius. The greatest calculated depths coincide with the strongly magnetized Cimmeria region, although much of the southern highland terrain exhibits greater than average depths. Shallower depths are primarily found in the northern lowlands and in the region around the Hellas and Argyre impact basins. Figure 2 shows representative spectra from the greatest

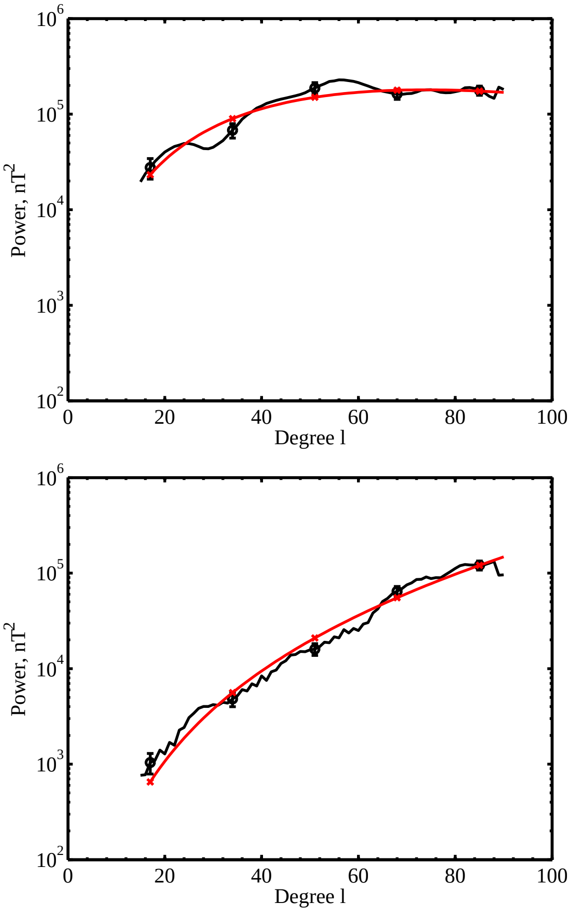

Figure 2: Representative magnetic power spectra from the deepest and shallowest calculated source depths beneath the martian surface. Power spectra are shown in white, while our best-fitting model is shown in red. 1-σ error bars are shown for representative, uncorrelated harmonic degrees.

and smallest observed magnetic source depths, demonstrating the wide differences in spectral slopes observed for different regions of the planet. As is also exemplified by these two cases, our calculated amplitude parameters are generally positively correlated with depths.

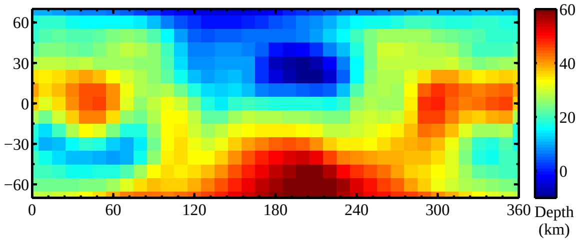

Figure 3: Map of modeled magnetic source depths assuming a shell of randomly oriented dipoles. In general, shallower depths are observed in the northern lowlands, while deeper sources are found in the south, with the deepest occurring in the strongly magnetized Terra Cimmeria region.

Interpretations: The observed variability in modeled magnetic spectra reveal a number of interesting trends, with implications for the origin and nature of the crustal field. Spatial variations in source shell depth generally correlate well with global maps of crustal thickness (Figure 3). This may be an indication that much of the crust contributes to the magnetism rather than, for instance, a magnetized layer of constant thickness, as might be expected if surficial processes were responsible for emplacement of the magnetic carriers. The correlation of source strength with depth is also consistent with the hypothesis that sources modeled at greater depths generally arise from thicker magnetized layers. One location where the correlation between crustal thickness and magnetic source depth breaks down is in the Tharsis volcanic region. This may be evidence of a locally steeper thermal gradient at the time of formation, raising the depth to the relevant Curie isotherm. Modeled negative depths, although within error of the surface, require more analysis and may be an indication of the limits of a random source model, or the magnetic potential model itself at high degrees. The spatiospectral localization technique demonstrates a high degree of variability in magnetic source properties across the Martian surface, which is not captured in a whole-sphere analysis. These findings contribute a new method by which to interrogate the early evolution of the martian crust and deep interior.

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