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Magnetically controlled structures in the ionosphere of Mars

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[1] The ionospheric sounding data obtained by the MARSIS (Mars Advanced Radar for Subsurface and Ionospheric Sounding) instrument on the Mars Express spacecraft show that the dayside ionosphere has considerable structure over regions of strong crustal magnetic fields. This structure is typically seen as a hyperbola-shaped trace in a display of echo intensity versus apparent altitude and time. The hyperbola shapes are consistent with oblique reflections from regions of enhanced electron density that are fixed with respect to Mars. Comparisons with the Cain et al. (2003) model for the crustal magnetic field of Mars show that the apexes of the hyperbolas, which identify the closest approach to the regions of enhanced electron density, usually coincide with regions where the crustal magnetic field is strong and nearly vertical. The electron density enhancements, which extend as much as 50 km above the surrounding ionosphere, are believed to arise from increases in the scale height of the ionosphere, possibly due to heating of the ionosphere by solar wind electrons that reach the base of the ionosphere along the nearly vertical (open) magnetic field lines. Statistical analyses of the apparent altitudes of the apexes of the hyperbolas, as well as analyses of repeated passes over the same region, indicate that the electron density enhancements usually consist of horizontal cylinder-like structures rather than isolated hemispherical structures. In many cases the axes of the cylindrical density structures are aligned with the symmetry axes of adjacent cylindrical magnetic field structures with opposite polarity.

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1. Introduction

[2] The Mars Express spacecraft was launched on 2 June 2003 and entered an elliptical orbit around Mars on 25 December 2003 [*Chicarro et al.*, 2004]. Mars Express carries a low-frequency radar called MARSIS (Mars Advanced Radar for Subsurface and Ionospheric Sounding) that is designed to provide subsurface radar soundings and to study the ionosphere of Mars [*Picardi et al.*, 2004]. Initial reports on the subsurface and ionospheric sounding results from MARSIS were published by *Picardi et al.* [2005] and *Gurnett et al.* [2005]. One of the unanticipated results from the ionospheric sounding was the discovery of oblique echoes from electron density structures that are associated with the crustal magnetic fields of Mars first discovered by the magnetometer aboard the Mars Global Surveyor (MGS) spacecraft [*Acuña et al.*, 1998, 1999; *Ness et al.*,1999; *Connerney et al.*, 1999]. The purpose of this paper is to expand on these early results by studying the location and geometry of the electron density structures and their relationship to the crustal magnetic fields.

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[3] The MARSIS instrument consists of a 40 m tip-to-tip dipole antenna, a 7 m monopole antenna, a radio transmitter, a receiver, and a digital signal processing system. In the ionospheric sounding mode, a quasi-sinusoidal pulse of 91.4 μs duration is transmitted once every 7.86 ms via the dipole antenna. After transmitting the pulse the intensities of any returning echoes are detected in a digital receiver with a 10.9 kHz bandwidth centered on the frequency of the transmitted pulse. The time delay of the echo is determined by sampling the received signal intensities in 80 contiguous 91.4 μs time bins starting at 254 μs and extending to 7.57 ms after the transmitted pulse. After each transmit/receive cycle the frequency of the pulse is advanced in an ascending time order, with a complete scan consisting of 160 quasi-logarithmically spaced frequencies ($\Delta f/f \approx 2\%$) from 100 kHz to 5.5 MHz. A complete scan takes 1.26 s, and the basic sweep cycle is repeated once every 7.54 s. Although the orbit parameters have changed somewhat during the course of the mission, for the time period analyzed in this paper the periapsis altitude was about 275 km, the apoapsis altitude was about 10,100 km, and the period was about 6.75 hours. Ionospheric sounding data are normally collected during periapsis passes, usually starting and ending at an altitude of 1200 km. A typical ionospheric sounding pass lasts about 36 min and provides about 285 frequency scans. Because of gravitational perturbations, the local time and latitude of periapsis evolve rather rapidly. The data analyzed in this

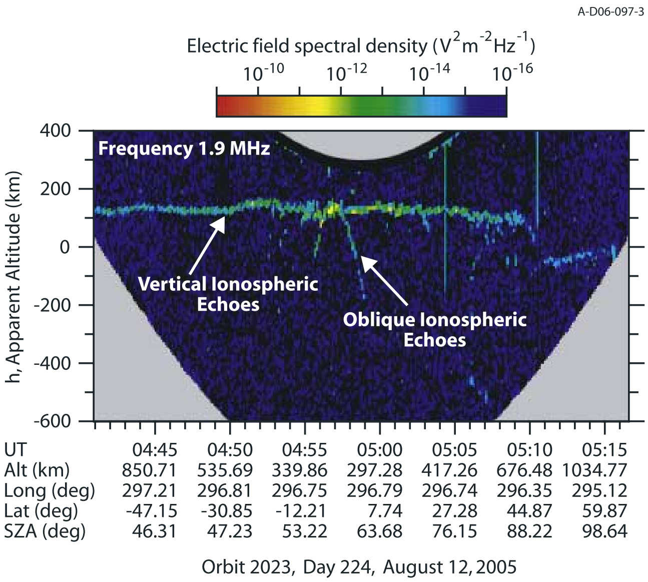

Figure 1. A color-coded radargram that shows echo intensity as a function of apparent altitude and time. The color intensity code is shown at the top of the spectrogram. The coordinates at the bottom of the plot are time (UT), altitude (ALT), west longitude (Long), latitude (Lat), and solar zenith angle (SZA). Note, from the near constancy of the longitude, that the subspacecraft track is very nearly south to north. The horizontal band labeled "vertical ionospheric echoes" at an altitude of about 130 km is the usual vertical echo from the horizontally stratified ionosphere. The downward-facing hyperbola-shaped feature labeled "oblique ionospheric echoes" is due to oblique echoes from a small-scale density structure in the ionosphere.

paper cover the period from 11 July 2005 to 27 January 2006 and are mainly from the dayside of Mars.

[4] Several types of plots are used for analyzing the ionospheric sounding data. One such plot, called a radargram, consists of a color-coded display of the echo intensity at a fixed frequency as a function of apparent altitude, h, and Universal Time, UT. Apparent altitude is the altitude that would be inferred if the echo reflected vertically from directly below the spacecraft, not accounting for dispersion or oblique propagation effects, and is given by $h = z - c(\Delta t/2)$, where z is the altitude of the spacecraft, c is the speed of light and Δt is the time delay of the echo. Dispersion is the frequency-dependent effect the plasma has on the propagation speed of the wave, which otherwise would be the speed of light. Although dispersion corrections are important for computing accurate electron density profiles, for our purpose, which mainly involves identifying the location of density structures, we have ignored these corrections. Because Mars has a nonspherical shape, the altitude, z, is computed relative to the best-fit reference ellipsoid for Mars using the parameters given by *Seidelmann et al.* [2002].

2. Oblique Echoes

[5] A radargram showing the apparent altitude of the ionospheric echoes observed during a typical ionospheric sounding pass is shown in Figure 1. The nearly horizontal line across the spectrogram at an apparent altitude of about 130 km is due to vertical (specular) reflections from the nearly horizontally stratified ionosphere of Mars. Such vertical reflections are a common feature in all of the ionospheric sounding data collected on the dayside of Mars. The altitude at which the echo occurs varies with frequency and is controlled by the electron density profile in the ionosphere. Since the free space electromagnetic mode cannot propagate at frequencies below the electron plasma frequency [*Gurnett and Bhattacharjee*, 2005], for vertical incidence on a horizontally stratified ionosphere, reflection occurs when the electron plasma frequency is equal to the transmitted wave frequency. The electron plasma frequency is given by $f_p = 8980\sqrt{n_e}$ Hz, where n_e is the electron density in cm^{-3}.

[6] In addition to the vertical echoes, oblique echoes are also frequently observed in the MARSIS ionospheric sounding data [*Gurnett et al.*, 2005]. In a radargram the oblique echoes appear as downward facing hyperbolas. A good example of such an isolated hyperbola-shaped echo trace is shown in Figure 1. The apex of the hyperbola in this case is located at 0457:04 UT. That this hyperbola-shaped trace must be due to oblique propagation is evident from the fact that the apparent altitude of the reflection is well below the main (horizontal) reflecting layer of the ionosphere. Such an echo signature is impossible for a purely vertical reflection, since the wave would have to pass through the region where the wave cannot propagate, i.e., where $f_p > f$. That hyperbola-shaped traces of this type arise from regions that are fixed with respect to Mars has been verified by computing the apparent altitude that would occur if the radar signal reflected from a fixed point in the ionosphere. Figure 2 shows the result of such a computation using the example in Figure 1. The white hyperbola-shaped line was computed by first finding the range, R(t), between the spacecraft and a fixed point target in the ionosphere using the equation

$$R(t) = \left[(x(t) - x_0)^2 + (y(t) - y_0)^2 + (z(t) - z_0)^2\right]^{1/2}, \quad (1)$$

and then computing the apparent altitude using $h = z(t) - R(t)$, where x(t), y(t) and z(t) are the coordinates of the spacecraft at time t in a coordinate system fixed with respect to Mars, and x_o, y_o, and z_o are the coordinates of the target. The best fit was obtained by placing the target in the plane of the orbit immediately below the apex of the hyperbola (latitude = −4.1° and longitude = 296.7°) and then adjusting the altitude so that it agrees with the apparent altitude of the apex (altitude = 140 km). As can be seen, the fit to the observed hyperbola-shape echo trace in the radargram is very good. Other comparable events give similar results, thereby providing strong evidence that the hyperbola-shaped traces originate from structures in the ionosphere that are fixed with respect to the surface of Mars.

3. Relationship Between the Oblique Echoes and the Magnetic Field of Mars

[7] In our initial report on the MARSIS ionospheric sounding results [*Gurnett et al.*, 2005] we showed that oblique echoes of the type shown in Figure 1 tend to occur in regions of strong crustal magnetic fields of the type first discovered by the MGS magnetometer [*Acuña et al.*, 1998,

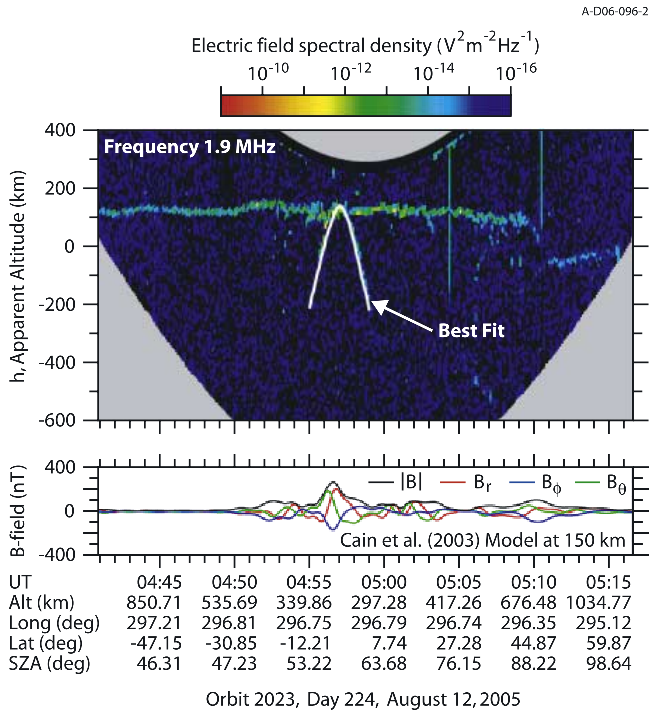

Figure 2. The top panel shows the same radargram as in Figure 3. The white line labeled "best fit" is the apparent altitude computed from a fixed point target located in the orbital plane of the spacecraft at a latitude and longitude that corresponds to the apex of the hyperbola, and at an altitude that corresponds to the apparent altitude of the apex. The bottom panel shows the magnitude and components of the magnetic field computed from the *Cain et al.* [2003] model at an altitude of 150 km. The apex of the best fit hyperbola corresponds almost exactly with a region of strong vertical magnetic field.

1999; *Ness et al.*, 1999; *Connerney et al.*, 1999]. In this section we will examine the relationship to the magnetic field in more detail. The bottom panel of Figure 2 shows the magnetic field magnitude |B|, and the radial B_r, southward B_θ, and eastward B_φ, components of the magnetic field computed from the *Cain et al.* [2003] magnetic field model at an altitude of 150 km. As can be seen the apex of the hyperbola at 0457:04 UT is centered almost exactly over a region with a strong radial (vertical) magnetic field, in agreement with our earlier results. The current model for the origin of the oblique echoes is that they originate from bulges in the ionosphere that are associated with regions of open (nearly vertical) magnetic field lines. The geometry involved is illustrated in Figure 3. The basic idea for the origin of the bulges is that hot solar wind electrons, which have access to the base of the ionosphere along the nearly vertical open magnetic field lines, heat the ionosphere and thereby cause the ionosphere to expand upward due to the increase in the scale height. This idea was first suggested by *Ness et al.* [2000] based on comparisons with radio occultation data, and has since been further developed by *Mitchell et al.* [2001] and *Krymskii et al.* [2002, 2003, 2004].

[8] Although the oblique echoes in Figure 1 appear to originate from a single isolated magnetic field structure, the echo patterns are in most cases more complicated. Figure 4 shows another south-to-north periapsis pass that went over almost the same region of Mars as in Figure 1 about 6 days earlier, but shifted eastward in longitude by about 2 degrees. As one can see, the small 2 degree shift in longitude makes a big difference in the number and pattern of oblique echoes that are observed. Only one hyperbola-shaped echo trace was observed in Figure 1, whereas at least four were observed in Figure 4. Note that the apex of the hyperbola at 0107:09 UT in Figure 4 occurs at almost the same latitude as the apex of the hyperbola at 0457:04 UT in Figure 1 ($-5.0°$ versus $-3.8°$). By comparing the magnetic signatures for the two passes, it is apparent that these two hyperbola-shaped traces arise from the same crustal magnetic field structure extended east-west over several degrees in longitude. It is also apparent in Figure 4 that the oblique echo pattern is not always symmetrical with respect to the apex of the hyperbola. Oblique echoes consisting of a fraction or half of a hyperbola are quite common, with the dominant part oriented either to the right or left of the apex with about equal probability. Of 163 clearly defined hyperbola-shaped traces that have been identified in the course of this study, 68 were nearly symmetric full hyperbolas, and the rest were either partial or half hyperbolas. Usually, the apparent altitude of the apex extends noticeably above the surrounding ionosphere, in agreement with the interpretation that the echoes are due to an upward bulge in the ionosphere, near or directly below the spacecraft.

[9] To estimate the vertical amplitude of the density bulges we have measured the difference, Δh, between the apparent altitude of the apex and the apparent altitude of the surrounding ionosphere for all of the 163 events described above. A plot of the number of events as a function of Δh is shown in Figure 5 for a frequency of 1.8 MHz. If we ignore the outlying points at $\Delta h = -100$ km, -76 km, and +100 km, the root-mean-square (rms) value of Δh is 19.2 km

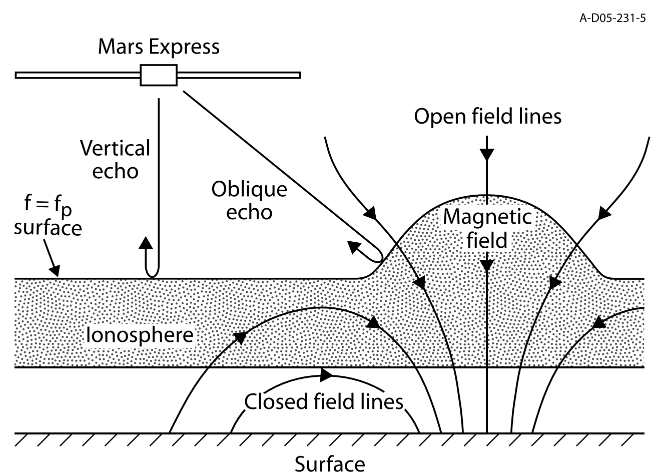

Figure 3. A sketch of the ionospheric density structure that is thought to be responsible for the oblique ionospheric echoes detected by MARSIS. As the spacecraft approaches the bulge two echoes are detected, a vertical echo from the horizontally stratified ionosphere and an oblique echo from the bulge. It is easily demonstrated that a hyperbola-shaped echo trace is generated in a radargram by the temporal variation of the range to the reflection point as the spacecraft passes over the bulge.

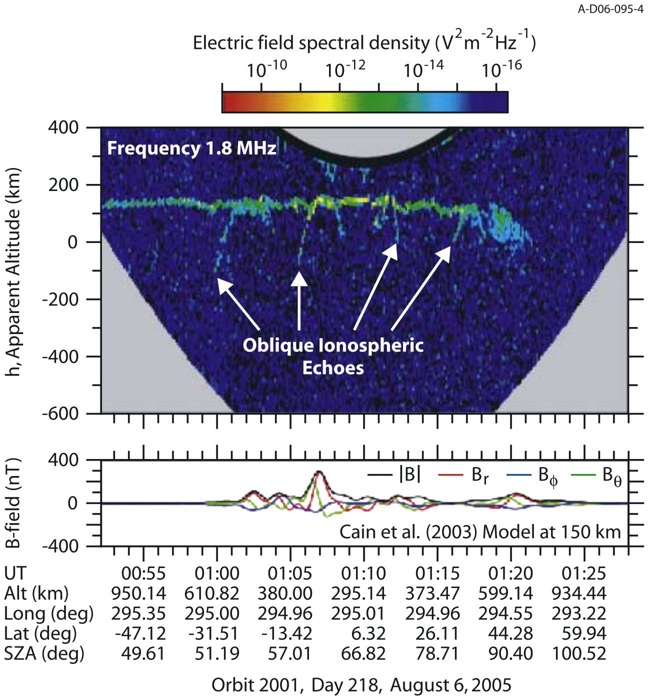

Figure 4. A series of four hyperbola-shaped echo traces observed for a south-to-north pass over the same general region as in Figure 2, but 6 days earlier. Although the spacecraft surface track is shifted only 2° eastward, the pattern of oblique echoes is quite different, even though the crustal magnetic field signatures are very similar. The one common feature appears to be the hyperbola-shaped echo at 0107:09 UT, which correspond closely with the hyperbola-shaped echo at 0457:04 UT in Figure 1. Both of these oblique echoes are associated with the same strong longitudinally extended magnetic field structure.

and the maximum value is 50 km. These measurements show that the bulges are small compared to the range to the spacecraft, which at 1.8 MHz varies from a minimum of about 100 km to sometimes as much as 1000 km. Although the bulges are small compared to the range to the spacecraft, they are nevertheless substantial when compared to the scale height of the ionosphere, which is typically about 25 km on the dayside of Mars. The small size of the bulges relative to the range to the spacecraft explains why the simple point target model described in the previous section gives a good fit to the hyperbolic shape of the echo trace. It is worth noting from Figure 5 that there are only nine cases out of 163 for which the apex of the hyperbola is below the surrounding ionosphere. Among these, seven are just slightly below (Δh = −2 to −6 km) and only two are considerably below (Δh = −76 km and −100 km). Isotropic reflection from a random horizontal distribution of small quasi-hemispherical reflectors would give a large number of negative Δh values due to the fact that the spacecraft would rarely pass directly over the reflector. Since negative Δh values are seldom seen, their near absence implies that the density structures cannot be idealized as small hemispherical structures. The simplest density structure that would account for the near absence of negative Δh values would be a small horizontal cylindrically shaped structure. For specular reflection from a horizontal downward facing half-cylinder the normal incidence point at closest approach would always be in the plane of the orbit (i.e., directly below the spacecraft), which would explain why Δh is almost never negative. That a substantial number of event occur at or near Δh = 0 implies that even very small structures, with radii less than the range resolution (which is about 10 km), can produce strong oblique echoes.

[10] To illustrate the spatial relationship between the oblique echoes and the crustal magnetic field, Figure 6 shows a longitude/latitude map that compares the oblique echo observations with the regions where the magnetic field of Mars is nearly vertical. The red dots show the subspacecraft positions of the apexes for all of the 163 hyperbolas used in this study. The black dots show the regions where the angle between the magnetic field and the local vertical is less than 20 degrees at an altitude of 150 km using the *Cain et al.* [2003] magnetic field model. In order to emphasize the regions of strong magnetic field, points are plotted only if the magnetic field strength is greater than 150 nT at an altitude of 150 km. As can be seen the oblique echoes are almost all in the southern hemisphere, where the crustal magnetic fields are the strongest. Many of the red dots are located either on top of or very close to the black dots, especially in regions where the black dots merge into an extended linear feature. These linear features in the vertical magnetic field tend to occur between adjacent horizontal cylinder-shaped magnetic field structures of opposite polarity of the type discussed by *Mitchell et al.* [2001]. This relationship suggests that the cylinder-shaped density structures described in the previous paragraph are closely associated with the cylinder-shaped magnetic structures that are a common feature of the crustal magnetic field of Mars.

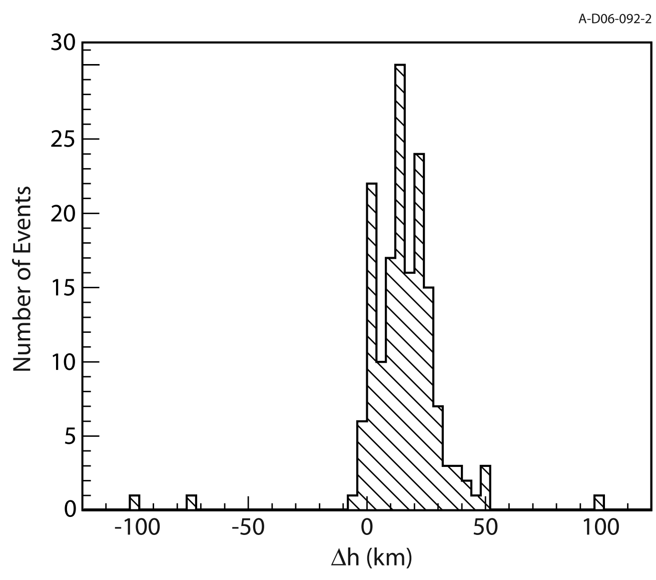

Figure 5. A histogram of the number of hyperbola-shaped echoes as a function of the difference, Δh, between the apparent altitude at the apex of the hyperbola and the apparent altitude of the surrounding ionosphere. The near absence of negative Δh values indicates that in almost every case the spacecraft passed almost directly over the closest approach point to the bulge. Such a result is not possible for a random distribution of hemispherical-shaped bulges and suggests that the bulges must have a horizontally extended cylindrical shape.

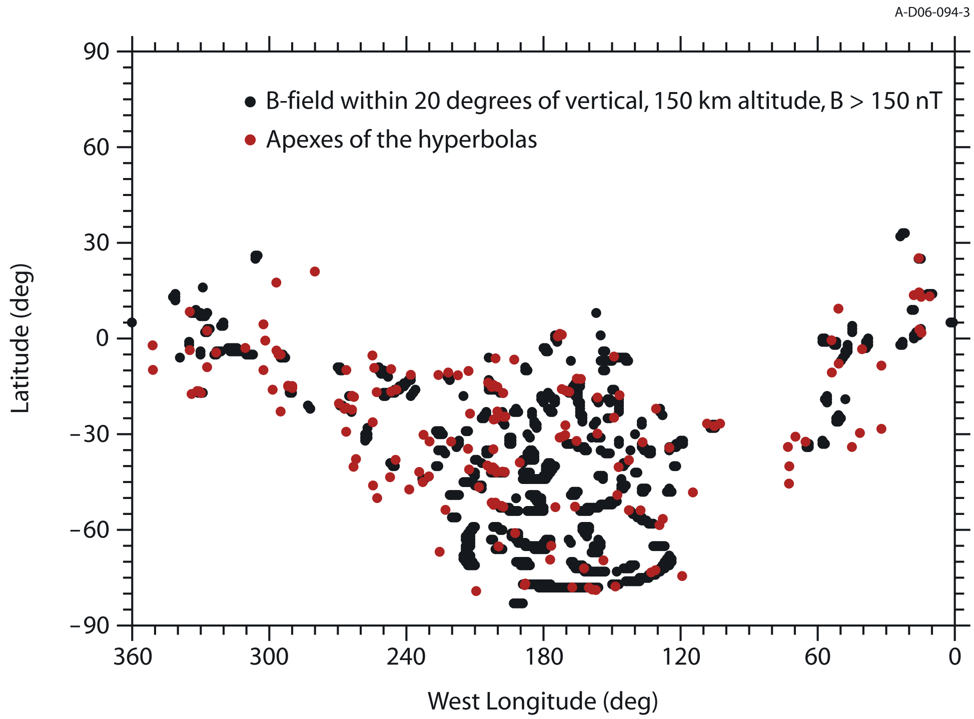

Figure 6. A latitude-longitude map of Mars showing the relationship between the origin of the oblique echoes and the magnetic field of Mars. The red dots show the positions of the sub-spacecraft point for the apexes of 163 hyperbolas of the type illustrated in Figures 1 and 3. The black dots show the locations on Mars where the magnetic field strength is greater than 150 nT and oriented within 20 degrees of vertical. The magnetic field was computed using the *Cain et al.* [2003] model at an altitude of 150 km.

[11] As can be seen in Figure 6, there are also many cases where there is no obvious relationship between isolated red and black dots. Although the orbital coverage is reasonably good down to a scale of a few degrees in latitude and longitude, we have confirmed that some of the isolated black dots occur in regions where the spacecraft did not pass directly overhead and, therefore, may not have been in the proper position to observe specular reflections from those regions. As shown by our earlier comparison of Figure 1 and 4, a shift of only 2 degrees in the longitude can make a significant difference in the occurrence of oblique echoes from a given region. This high sensitivity to the spacecraft orbital trajectory provides further evidence that at least some of the oblique echoes come from structures that require a precise geometrical alignment for the reflected signal to return to the spacecraft. The isolated red dots present another problem. It is clear from Figure 6 that oblique echoes sometimes occur from regions that have no obvious magnetic field signature. A good example occurs at 0117:18 UT in Figure 4, where there is a clearly defined full hyperbola-shaped trace in the radargram, but no obvious magnetic structure that can be associated with this echo. Approximately 20% of the oblique echoes in Figure 6 fall into this category. At present we have no clear understanding of the origin of these echoes. One possibility is there are magnetic structures that are either too small or not adequately represented by the *Cain et al.* [2003] model. It is also possible that they have a completely different origin.

[12] To quantify the statistical relationship between oblique echoes and the magnetic field orientation, Figure 7 shows the number of oblique echoes per unit solid angle, dN/($2\pi \sin\theta\, d\theta$), as a function of the tilt angle θ, between the magnetic field and local vertical (or $180° - \theta$ if the angle is greater than 90°). The plot obviously has a large concentra-

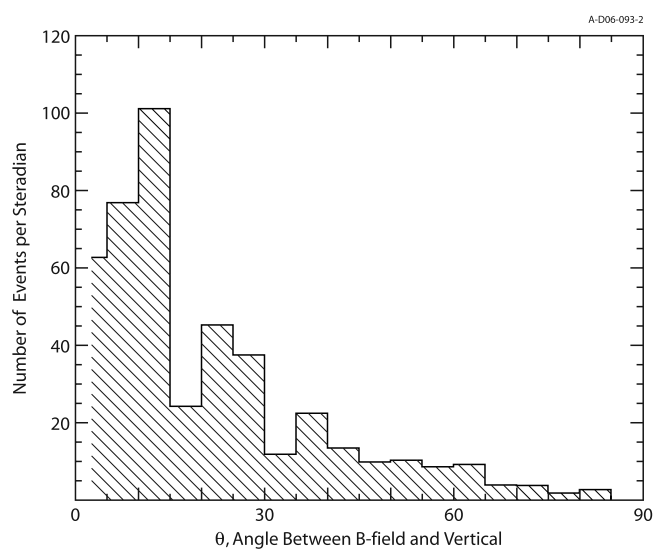

Figure 7. The number of hyperbola-shaped oblique echoes as a function of the angle, θ between the magnetic field and the vertical (or $180° - \theta$ if θ is greater than 90°) evaluated at the apexes of the hyperbolas. This plot shows that oblique echoes tend to originate from regions where the magnetic field is nearly vertical.

tion of events at small angles, less than about 30°, confirming that the oblique echoes originate from regions where the magnetic field is nearly vertical. It also shows that there is a small, but nonzero, number of events for which the tilt angle is near 90°. We do not know how these events might fit into the solar wind heating model. We also investigated the possibility that the occurrence of oblique echoes might depend on the upward or downward direction of the magnetic field. Of the 163 events studied, 69 of the events occur at locations where the magnetic field vector is directed downward into Mars, and 94 of them occur where the magnetic field is upward out of Mars. Since the standard deviation for this number of samples is 13, the two numbers differ by only a little more one standard deviation from the expected median value for a random distribution. Thus there is no evidence to suggest that the occurrence of oblique echoes is related to the upward or downward direction of the crustal magnetic field.

4. Conclusion

[13] In this paper we have carried out a detailed investigation of the oblique echoes detected from the ionosphere of Mars by the radar sounder on the Mars Express spacecraft. These echoes appear as hyperbola-shaped features on a radargram display of echo strength as a function of apparent range and time. The hyperbola shape can be accounted for if it is assumed that the echo arises from an upward bulge in the ionosphere that is fixed with respect to Mars. The apex of the hyperbola, which identifies the point of closest approach as the spacecraft passes over the bulge, often coincides with a region of strong vertical crustal magnetic field. The average r.m.s. vertical displacement of the bulges is 19 km, and the peak displacement can be as much as 50 km above the surrounding ionosphere. Evidence was presented that the bulges often have an elongated horizontal cylindrical geometry rather than a hemispherical geometry. In some cases the cylindrical density bulges are clearly associated with regions of vertical magnetic field that lie between adjacent horizontal cylindrical magnetic field structures of opposite polarity of the type discussed by *Acuña et al.* [1998, 1999], *Ness et al.* [1999], *Connerney et al.* [1999], *Mitchell et al.* [2001] and *Connerney et al.* [2005]. On the basis of previous suggestions by *Ness et al.* [2000], *Mitchell et al.* [2001], *Krymskii et al.* [2002, 2003, 2004] and others, it is believed that the bulges are produced by ionospheric heating caused by solar wind electrons that reach the base of the ionosphere along vertical (open) magnetic field lines that extend outward into the solar wind.

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