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Venus-like interaction of the solar wind with Mars

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Abstract. The magnetometer and electron reflectometer experiment (MAG/ER) on the Mars Global Surveyor (MGS) spacecraft has obtained magnetic field and electron data which indicates that the solar wind interaction with Mars is primarily an ionospheric-atmospheric interaction similar to that at Venus. However, the global-scale electric currents and resulting magnetic fields due to the interaction at Mars are locally interrupted or perturbed over distance scales of several hundred kilometers by the effects of paleomagnetic fields due to crustal remanence. In this paper we compare the Mars-solar wind interaction with the Venus-solar wind interaction by selecting MGS orbits which do not show significant magnetic perturbations due to crustal magnetic anomalies, and demonstrate that a number of phenomena characteristic of the Venus-solar wind interaction are also observable at Mars.

Introduction

The Mars Global Surveyor spacecraft was initially inserted into a highly elliptical orbit with low periapsis (altitudes near 110 km) to achieve orbital modification by aerobraking. Magnetometer and electron reflectometer (MAG/ER) measurements were thus obtained from the solar wind through the bow shock and through the ionosphere. The measurements revealed that Mars does not possess an appreciable global intrinsic magnetic field, although evidence for small-scale crustal magnetic fields of ancient origin due to crustal remanence was found [Acuña et al., 1998; Ness et al., 1999]. The large scale (global) pattern of magnetic fields (and electric currents) was found to resemble that of Venus, implying that the interaction of the solar wind with Mars was an ionospheric-atmospheric interaction similar to that found at Venus, as previously deduced from Phobos-2 results [Riedler et. al., 1989].

The solar wind interaction with a non-magnetic planet has been extensively investigated in the case of Venus by the Pioneer Venus spacecraft, which carried a broad range of plasma diagnostic experiments to measure various ion and electron characteristics as well as vector magnetic fields. In over 14 years of operation in Venus orbit, these parameters were measured over nearly all latitudes and longitudes, for nearly all solar zenith angles (day and night), and for a wide range of solar wind conditions. These exhaustive investigations delineated a number of unique physical mechanisms and spatial features which are characteristic of the Venus-solar wind interaction, and which might be expected to arise as a result of the solar wind interaction with any non-magnetic planet. In this paper, we present the results of a search for such definitive features in the MGS MAG/ER data set, restricting our search to orbits which do not show evidence of magnetic field perturbations from surface crustal anomalies at altitudes of interest. We have also limited our scope to those features in the post-shock sheath, ionosphere and neutral atmosphere which can be directly observed by the MAG/ER instrument, and in doing so, have excluded some characteristic features which perhaps exist at Mars but which require other instrumentation for verification. The specific subset of phenomena included in our search comprises:

(a) magnetic field rotations associated with ionopause crossings
(b) magnetic field rotations associated with detached ion-electron clouds above the ionopause.
(c) magnetic field enhancement associated with post-shock flow stagnation (Magnetic Field Pile-up Boundary)
(d) wave activity between the shock and Magnetic Field Pile-up Boundary
(e) flux-rope formation within low-field ionospheric regions
(f) disappearing nightside ionosphere
(g) nightside ionospheric "holes"

In the following section we further define these features.

(a) Magnetic field rotations at the ionopause

Analysis of high-resolution vector magnetic field data from the Pioneer Venus Orbiter (PVO) spacecraft in conjunction with high-resolution ion spectrometer data obtained by the Orbiter Ion Mass Spectrometer (OIMS) instruments revealed magnetic field rotation in the horizontal plane in coincidence with the thermal ionopause of Venus [Law and Cloutier, 1995]. The thermal ionopause is defined as the region between mainly post-shock proton flow and the photochemical ionosphere of atmospheric composition. These rotations result from the shear in the horizontal flow through the ionopause, with the magnetic field in the ionosphere "weathervaning" away from the sub-flow point. A second rotation occurs in the lower ionosphere which restores the field to the direction outside the ionopause, resulting from ion-neutral collisions which allows magnetic tension to straighten the magnetic field lines. Except in cases where the post-shock flow and magnetic field are nearly parallel, the rotation produced by this shear effect is between 90° and 180°, depending on the intensity of magnetosheath field fluctuations [Law and Cloutier, 1997].

(b) Magnetic field rotations associated with ion clouds

The analysis of Law and Cloutier [1995] showed that magnetic field rotations in the horizontal plane sometimes

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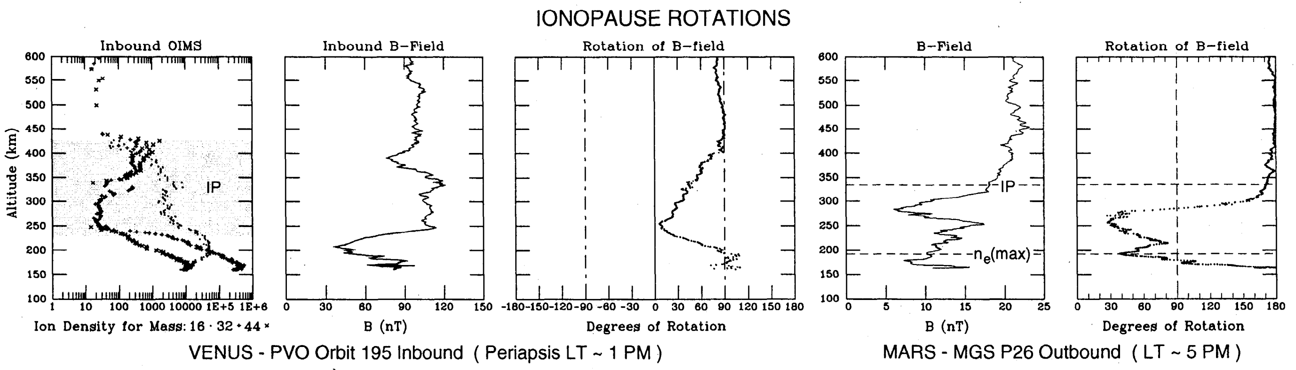

Figure 1. Plots of ionopause magnetic field rotations at Venus and Mars. (left) PVO Orbit 195 inbound pass plots of ions, magnetic field magnitude, and magnetic field rotation within the ionopause region. The angle plotted is between the magnetic field and the axisymmetric antisolar plasma flow velocity. (right) Plot for MGS orbit P26 of magnetic field magnitude and field rotation compared to axisymmetric antisolar plasma flow.

occurred above the thermal ionosphere, and that these events were associated with super-thermal "clouds" of ions which apparently were slower-moving than the surrounding post-shock solar wind flow and caused the same "weathervaning" as the ionospheric plasma.

(c) Magnetic field pile-up boundary

Both Soviet and U.S. experiments have shown that in the post-shock stagnation region of the solar wind interaction with Venus, the magnetic field increases to unexpectedly large magnitudes, resulting in approximate balance between the solar wind dynamic pressure and this "pile-up" magnetic field pressure [Elphic et al., 1980; Brace et al., 1980; Vaisberg et al., 1980]. This result implies that plasma pressure, which should provide most of the total stagnation pressure, is somehow lost.

(d) Wave activity between the shock and pile-up boundary

At Venus, wave activity, apparent in the magnetic field, is usually seen between the shock and the Magnetic Field Pile-up Boundary , with wave activity dying out as the magnetic-field magnitude increases to stagnation pressure. Analysis of the wave characteristics shows a strong peak at the hydrogen ion cyclotron frequency, and the waves appear to be left-circularly-polarized Alfvén waves (electromagnetic ion cyclotron waves).

(e) Flux-rope formation in low-field ionospheric regions

In the dayside ionosphere of Venus, regions below the ionopause where the magnetic field strength is low typically show complex small scale structures of magnetic field in which the field appears to be "wrapped" into helical bundles called flux-ropes [Russell et al., 1979].

(f) Disappearing nightside ionospheres

The nightside ionosphere of Venus is largely controlled by nightward convection through the terminator of photoions from the dayside, with an inverse correlation with solar wind pressure. At times of high solar wind pressure, the ionopause moves downward toward the exobase, leading to decreased trans-terminator ion transport owing to ion-neutral drag in the higher neutral density [Taylor et al., 1979; Cravens et al.,

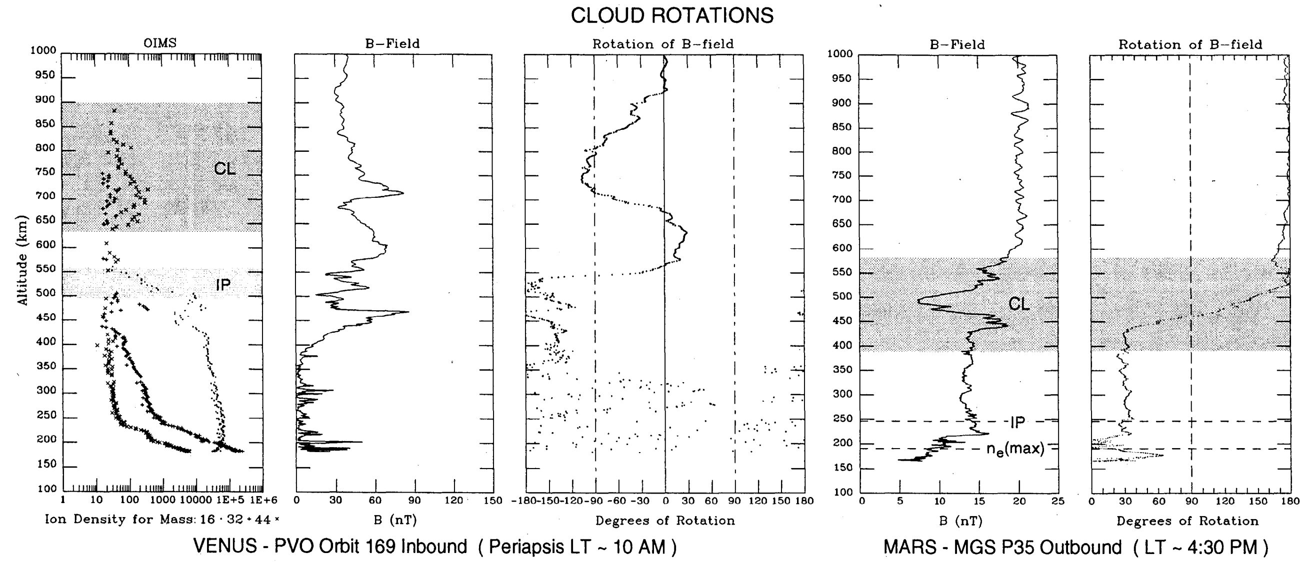

Figure 2. Plots of magnetic field rotations associated with ion "clouds" at Venus and Mars. (left) PVO Orbit 169 inbound pass plots of ions, magnetic field magnitude, and magnetic field rotation. The angle plotted is the variation from the magnetic field orientation at 1000 km. (right) Plot for MGS orbit P35 of magnetic field magnitude and field rotation. The ion cloud feature extends from ~580 km down to 390 km.

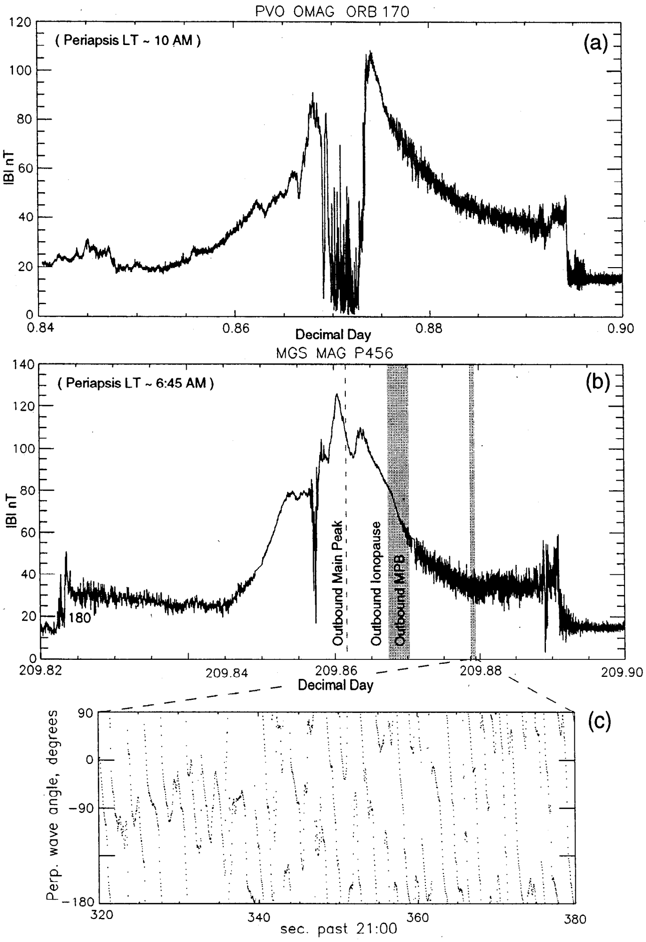

Figure 3. (a) Magnetic field time series data for PVO Orbit 170. Wave activity on the outbound pass is seen from the bow shock at .894 to .875, very close to the peak of the Magnetic Field Pile-up Boundary . (b) Magnetic field time series data for MGS P456. Like in panel (a), wave activity on the outbound pass is seen from the bow shock to part way through the Magnetic Field Pile-up Boundary . (c) A 1 minute period is selected from the post shock region of P456 as indicated by the shaded region in (b). The angle of the wave magnetic field in the plane perpendicular to the mean field direction is plotted from the high resolution 32/s data. A decreasing angle indicates left handed circular polarization of the wave field. The left-handed polarization is found at both Mars and Venus everywhere the magnetic field magnitude shows that waves are present in the post-shock region. In this example, the frequency of the waves is approximately that of the local proton gyrofrequency.

1982]. Under these circumstances, the nightside ionosphere is either very sparse or non-existent, which has been referred to in the literature as a "disappearing" nightside ionosphere.

(g) Nightside ionospheric holes

Transits of the nightside ionosphere of Venus by the PVO spacecraft revealed distinctive spatial structures in ionospheric content and magnetic fields which were repeatedly evident. These structures, called ionospheric holes, were regions of depleted ion density in which the normally horizontal nightside magnetic field turned tailward, with ionospheric plasma pressure outside the hole in balance with the pressure of the tailward magnetic field inside. The depletion of ionization within the holes is believed to be caused by outward plasma escape [Brace et al., 1982].

Mars Global Surveyor Data

A search of low dayside periapsis orbits of the MGS spacecraft and elimination of those orbits showing clear evidence of crustal magnetic perturbations led to numerous examples of both ionopause magnetic rotations and rotations associated with detached plasma clouds. Typical examples of ionopause rotations at Venus and Mars are shown in Figure 1 for PVO orbit 195 inbound and MGS P26 outbound. Also shown in the MGS data are the locations of the ionopause (IP) and main ionospheric peak (n_e(max)) inferred from the electron reflectometer. The ionopause is marked by a sharp decrease in electron fluxes for energies >100 eV. In the Venus and Mars examples shown, the low altitude rotations restoring the field to the external field direction are clearly seen. The rotations of the magnetic field at Venus and Mars associated with high altitude plasma clouds are shown in Figure 2 for PVO orbit 169 inbound and MGS P35 outbound. The cloud is seen in the shaded OIMS ion density data for PVO while the shaded region (labeled CL) on the MGS plots show cloud extent determined from the electron reflectometer.

In an examination of magnetic field variations between the shock and ionopause, numerous orbits of MGS exhibited a Magnetic Field Pile-up Boundary somewhat similar to that at Venus. It should be noted, however, that the sharpness of the boundary at Venus is generally not as great as observed at Mars or at comets. In Figure 3a, magnetometer (OMAG) data are shown for PVO orbit 170. The outbound portion of this orbit clearly shows the low altitude magnetic field buildup, the region of increased wave activity between the Magnetic Field Pile-up Boundary and the shock, and the shock itself. Analysis of the wave activity for this orbit showed a strong peak at the hydrogen ion cyclotron frequency with left circularly polarized waves. In panel (b) we show magnetometer data for MGS orbit P456. Although the large field magnitude near periapsis and the sharp drop in field magnitude just prior to periapsis are evidence of a crustal field anomaly near periapsis, the higher altitude data appear unaffected, and the similarity with Venus is clearly seen. Analysis of the wave characteristics in the shaded region of panel (b) revealed left-handed circular polarization. In panel (c) we plot the angle of the transverse component of the magnetic field in the plane perpendicular to the average field direction which illustrates the left-handed circular field rotation. A Fourier transform of that interval showed a peak at the local proton gyrofrequency.

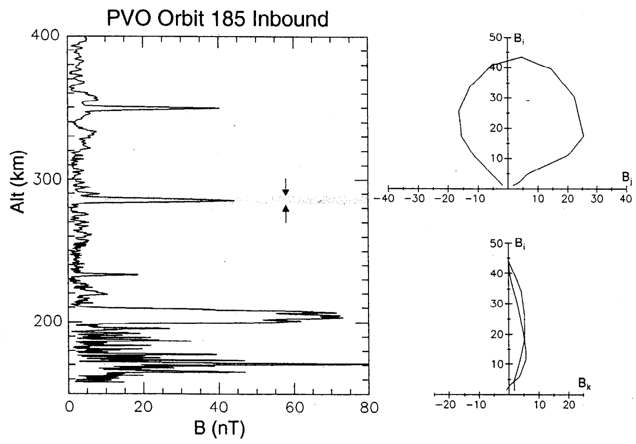

Figure 4. Hodogram of the magnetic field variation through a magnetic flux rope in the Venus ionosphere expressed in principal axis coordinates. The example shown is from the inbound pass of PVO Orbit 185. The highlighted rope is located near 290 km altitude and a solar zenith angle of 33° (after Elphic and Russell, 1983).

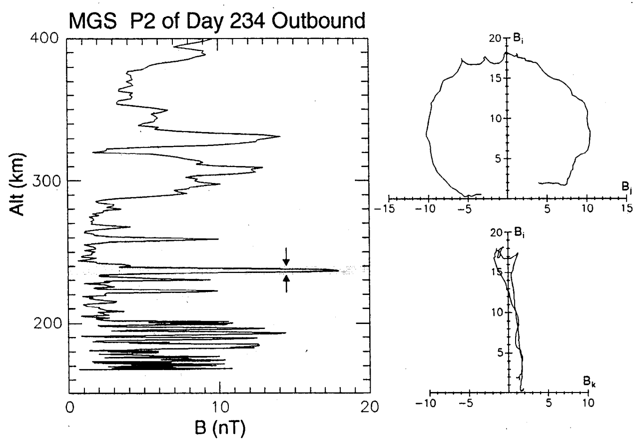

Figure 5. Hodogram of the magnetic field variation through a magnetic flux rope in the Mars ionosphere expressed in principal axis coordinates. The example shown is from the second periapsis outbound pass of day 234, 1998. The highlighted rope is located near 240 km altitude and a solar zenith angle of 78°.

A further search was conducted for cases of relatively low magnetic field magnitude within the Martian ionosphere, with particular emphasis on cases showing narrow spatial features with relatively strong localized fields compared to the low background. In Figure 4 we give an example of a flux-rope at Venus, shown by the shaded region of the plot of magnetic field magnitude with altitude for PVO orbit 185 inbound. The hodograms, or plots of transverse magnetic components against each other, are shown in the two panels to the right in Figure 4, taken from Elphic and Russell (1983). Similarly, Figure 5 shows MGS plots of field magnitude vs. altitude for periapsis 2 of day 234, 1998, with hodograms for the shaded region between 230 and 240 km shown on the right. This structure clearly shows the helical characteristics of a flux rope as defined by Elphic and Russell.

The search for disappearing nightside ionosphere and nightside ionospheric holes has been hampered by lack of orbital coverage on the nightside in the altitude range and local time range where these phenomena might be expected, and their identification must probably wait until better orbital coverage of the nightside ionosphere is obtained.

Summary and Conclusions

On the basis of the successful search for Venus-like features considered diagnostic of the solar wind interaction with a non-magnetic planet, we may conclude that the solar wind interaction with Mars is indeed Venus-like over global scales, and even on small scales, Venus-like features are found when the effects of local crustal magnetic anomalies are not present. We therefore expect that continued observations by MGS, with extension of the spatial coverage to include all latitudes and local times over larger altitude ranges, will reveal other Venus-like phenomena such as nightside ionospheric holes and disappearing night-side ionosphere. In addition, we expect that some phenomena unique to Mars may be found as a result of the more complicated effects of crustal magnetic fields superimposed on the global Venus-like pattern of fields and currents, and look forward to the challenge of identifying and understanding them.

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