Magnetic field draping enhancement at Venus: Evidence for a magnetic pileup boundary

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[1] The absence of a global-scale dynamo-generated magnetic field and the existence of an ionosphere at Venus and Mars caused many to predict that their solar wind interaction would be similar. After Pioneer Venus Orbiter (PVO) observations, it was concluded that the global aspects of the Venusian interaction could be well described by single-fluid models. According to these models, the magnetic field draping should develop progressively from the shock down to the ionopause. A recent study at Mars, where a "Venus-like" interaction was expected, showed that draping is prominent only inside the magnetic pileup boundary (MPB), a well-defined plasma boundary located between the shock and the ionopause first reported at comets, but never at Venus. From an identical analysis on PVO magnetometer data, we report a dramatic enhancement of draping on the dayside of Venus. Then, we deduce the existence of a Venusian counterpart of the Martian and cometary MPB.


1. Introduction

[2] The lack of global-scale dynamo-generated magnetic fields and the existence of well-developed ionospheres at Venus and Mars has led so belief that their interactions are very similar. The most prominent similarities are the formation of a magnetic barrier, where the initial solar wind dynamic pressure upstream from the bow shock is transmitted into the enhanced magnetic pressure on the dayside, and a magnetic tail similar to those of comets. Much of the current understanding of the solar wind interaction with Venus is based on Venus 9, 10, and Pioneer Venus Orbiter (PVO) observations [e.g., Russell and Elgerath, 1983, and references therein]. Most of the literature then concluded that the magnetic aspects of the Venusian interaction could be well described by gas-dynamical or single-fluid MHD models [e.g., Speerle and Shaluba, 1992; Tanaka and Horikawa, 1997]. Nevertheless, Venere observations suggested the existence of additional boundaries between the shock and the ionosphere [Vaittiez and Zelenyi, 1984].

[3] It was unlikely to find a strong intrinsic magnetic field at Mars, a "Venus-type" interaction was then expected [e.g., Lakhmann and Brinte, 1991]. In 1997, Mars Global Surveyor (MGS) magnetic field and superthermal (E < 10 eV) electron (MAGGER) data confirmed the absence of a significant intrinsic magnetic moment [Acuña et al., 1998] and unveiled an unexpected feature that had not been reported at Venus: the magnetic pileup boundary (MPB), a permanent plasma boundary located between the bow shock and the so-called "ionopause" [Wyman et al., 2000]. Figure 1 shows MGS MAG data for a near terminator orbit, between 150 and 500 km altitude (−0.140−0.262 R Mars, arccentric distance). The data are expressed in spherical Mars-centered solar orbital coordinates (MOS). It is elevation angle, θ is the azimuth (φ = sunward), and dB is the magnetic field magnitude. The fourth panel shows the altitude. The bow shock is crossed at 07:34 UTC. A few minutes before, the spacecraft is in the magneotsheath (hereafter, MS), a region characterized by a very turbulent plasma with significant wave activity. The MPB appears as a very sharp discontinuity crossed around 07:02 UTC, at 1180 km altitude (−1.35 R Mars, distance), at −83° solar zenith angle (SZA) and at ~8 a.m. local time (LT). This boundary, reported and characterized for the first time at comets [Neubauer, 1987; Mazelle et al., 1988], represents on the dayside the outer limit of the magnetic pileup region or magnetic barrier region (hereafter MPB). The magnetic field and the plasma undergo drastic changes at the MPB. The MPB is always characterized by a reduction in the magnetic field fluctuations, as depicted here, and a sudden and strong decrease in the suprathermal electron fluxes (not shown here) [Wyman et al., 2000]. The latter is associated to a cooling of the electron distribution system if cold electron density increases with decreasing altitude [Green et al., 1989]. This is consistent with the continuous increase of planetary ions with decreasing altitude [Lundin et al., 1990]. The MPB is also the "place where there is a "switch" from mainly thermal pressure in the MS into suddenly enhanced magnetic pressure. The MPB is characterized by smoothly varying, piled-up fields that form the magnetic barrier on the dayside. In this case, [B] in the barrier peaks at ~43 nT.

[4] The occurrence of the MPB as a distinct plasma boundary, different from the bow shock and the ionopause boundary at Mars and comets has generated many concerns over the difficulty for single-fluid approaches, successful in describing the Venusian interaction, to reproduce the typical MPB signatures. Recently, a

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quantitative study of the 3-D magnetic field topology showed that the sudden enhancement of the magnetic field draping is another characteristic signature of the MPB. In this study, we use the term analysis to establish if this signature is present between the MS and the MPB of Venus, a planet where the MPB has never been reported.

2. Comparing MGS and PVO Observations

Figures 1 and 2 compare MGS and PVO magnetic field data for two typical [B] dayside profiles found in these two datasets. Figure 1b displays PVO magnetometer (OMAG) data between 360 and 6460 km altitude (1.06 and 2.07 R\(_E\) distance). The coordinate system of the VSO, defined in an equivalent way as the MSO. Downstream from the bow shock, the magnetic field in the MS also displays large amplitude wave activity both in direction and magnitude. As in Figure 1a, the outer edge of the MPB (dash lines) crossed near the subsolar point (∼18° SZA) at ∼660 km altitude (∼1.11 R\(_E\) distance) appears well defined as a sharp jump in [B] (a factor of 2.5 in a ∼100 km altitude range) followed by a decay in the magnetic field fluctuations, particularly obvious in the angles. This kind of profile is associated to a mainly axial interplanetary magnetic field (IMF) [Phillips and McComas, 1991]. Important changes in the electron plasma also occur in the barrier: the initial magnetosheath’s suprathermal electron spectrum evolves into a cooler ionospheric-type shape. This region is referred to as the mantle by Spooner et al. [1980]. The peak [B] value in the MPB for this orbit is ∼47 nT.

Figure 2a shows MGS MAG data for an orbit near the noon-midnight plane, between 460 and 3200 km altitude (i.e., 1.14 and 1.94 R\(_E\) distance). In this case, the gradient of [B] at the Martian MPB is not so strong as in Figure 1a. However, the signature in the angles φ and θ and the suprathermal electron data (not shown here), are sufficient to locate the boundary at ∼1300 km altitude (∼1.38 R\(_E\) distance) at ∼35° SZA and ∼10° m. LT. The dashed lines that identify the MPB make the MS and the MPB easily discernible. A similar profile is depicted in Figure 2b for Venus between 210 and 6800 km altitude (from 1.03 to 2.12 R\(_E\) distance). The highest value of [B] in the MPB is ∼33 nT in Figure 2a and ∼75 nT in Figure 2b. Figure 2b corresponds to an orbit under largely transverse IMF conditions. The transition between the MS and the MPB at Venus is rather smooth in [B], but a change of regime can be inferred from the behavior of φ and θ, despite their smaller variability in comparison with Figure 2a. A dash line at 735 km altitude (1.12 R\(_E\) distance) and ∼50° SZA illustrates this change. The Martian ionospheric boundary and the Venus ionopause are located right below the barrier in both figures.

3. Study of the Magnetic Field Draping

To study the evolution of the magnetic field draping we use a very simple method which has been explicitly

Figure 2. a) MGS/MAG data for a ∼10 a.m. LT orbit. b) PVO/OMAG data for an orbit without a strong [B]-jump at the entry into the MPB (see text for details).
described by Bertucci et al. [2003]. It employs an “aberrated” Venus-centered Ecliptic System (r, y, z) that differs from the VSO (x, y, z) system in a 5°-rotation around the z-axis. According to this method, if a spacecraft moves through the 3-D magnetic field structure in a draped configuration, any variation measured in $B_{d}$ (direction antiparallel to the incoming solar wind) will be accompanied by a variation of the transverse magnetic field $B_{t}$ such that its radial cylindrical component $B_{r}$ will be correlated to $B_{d}$ [see also Jurabevich et al., 1994]. This result is valid as long as there are no discontinuities or strong fluctuations in the solar wind during the crossing. In single-third considerations [e.g., Spreiter and Stahara, 1992], draping is expected to evolve regularly from bow shock down to the ionopause. In such a case, a clear $B_{d} \sim B_{t}$ correlation should be found everywhere.

[s] We studied the dependence between $B_{d}$ and $B_{t}$ using high-resolution PVO/OMAG data for the orbits in Figures 1b and 2b. For orbit 183 we analyzed two intervals (A and B) surrounding the place where the magnetic barrier begins to form. Figure 3 shows $B_{d}$ versus $B_{t}$ in interval A (736–1088 km altitude) and B (492–725 km altitude). In region A, the correlation is very poor ($r = 0.35$), indicating that draping there is undetected. However, in region B, the $B_{d} \sim B_{t}$ correlation ($r = 0.91$) shows clearly that draping becomes strong as soon as the MPF is entered. In Figure 2b, $B_{t}$ increases regularly from the MS to the MPF. We examined four intervals labeled A, B, C, and D in function of decreasing altitude (Figure 4). Region A is located in the magnetopause “proper” (3304–4046 km altitude), whereas region B (1722–1822 km altitude) is located deeper in the MS, close to the MPF. Region D is clearly inside the MPF proper (432–741 km altitude), in the so-called plasma mantle, and adjacent to the region C (721–1046 km altitude). A comparison of the linear regression coefficients in regions A ($r = 0.00$), B ($r = 0.41$), C ($r = 0.49$), and D ($r = 0.97$) shows again that a very strong enhancement of draping occurs between C and D. Furthermore, the regression line slopes in the MS, which have no physical meaning because of their low $r$ values, always differ from those in the MPF. The enhancement of the draping has been observed in various PVO orbits. The two cases analyzed here are representative examples of the results gained for other orbits.

4. Discussion

[s] The results show that an unexpected and drastic change in the 3-D magnetic field topology on the dayside takes place across a very thin layer or boundary near the outer edge of the Venusian MPF. As soon as this boundary (we can temporarily call it “draping boundary”) is crossed, the magnetic field suddenly becomes organized and strongly draped. This sudden enhancement of draping seems to be independent from the IMF orientation upstream from the bow shock, and it is not necessarily associated to a strong jump on $B_{d}$ between the MS and the MPF since it occurs even if $B_{d}$ varies smoothly there.

[s] An identical signature was reported at the MPB of comets and Mars [Jurabevich et al., 1994; Bertucci et al., 2003], a boundary where drastic changes occur in every plasma parameter, namely in the solar wind ion dynamics. At Mars and comets, it is evident that the magnetic field lines intercepted at the MPB location on the dayside and on the nightside (magnetotail boundary) are topologically connected [Fagen et al., 2000]. At Venus, Saunders and Russell [1986] affirmed that the field lines at the magnetic tail boundary (they called it “magnetopause”) close on the dayside well above the ionopause. Slavin et al. [1989] further showed how the tail boundary structure and the plasma observed in the Venus tail appear to be controlled by the upstream IMF direction. All these considerations strongly imply that, despite the difference in the spacecrafts’ payload concerning ion measurements, this “draping boundary” is in fact the Venusian equivalent of the MPB.
and therefore the dayside counterpart of the magnetic tail boundary, as suggested by Yermak and Zatsepin [1984]. This is sustained by the similarities between the suprathermal electron plasma properties on each side of the Martian and cometary MFs [Pier et al., 2000; Citterio et al., 2000; Masselli et al., 1989] and of the outer edge of the plasma boundary [Vernier et al., 1983]. In a recent paper, Phillips and McComas [1991] stated: "the connection of the magnetotail to the near-planet interaction region is not yet well understood.

[11] Zhang et al. [1991] defined the upper limit of the Venerian MF as the surface where the magnetic pressure equals the half of the solar wind dynamic pressure upstream from the bow shock adjusted for the barrier normal angle. They fitted a second order polynomial to the distribution of the altitudes of these so-defined upper limits for many orbits as a function of SZA. Thus, Altitude = 0.16 × (SZA) - 0.55 × SZA + 4.98. This predicts a ~500 km altitude at the subsolar point and a ~1700 km altitude at the terminator. The mean altitude and SZA of the boundary between the two dashed lines within region B in Figure 1b are 657 km and 18°, while the fit predicts 540 km for the same SZA. For 50° SZA, the predicted value for the altitude is 471 km, while the altitude of the lower separating region C and D in Figure 2b is 735 km. Thus, the observed boundary altitudes are fully consistent with the fit predictions, considering the dispersion of Zhang et al., data. Therefore, the MF upper boundary, defined from [11] values, coincides with the place where a real and dramatic change in the magnetic field 3-D topography occurs.

[12] Although many studies have had success in reproducing the magnetotail, as suggested by Kivelson and Zatsepin [1984], the agreement is restricted to the MF. No single-fluid model can reproduce such a localized enhancement of damping since no limit restrains other than the impenetrable inner boundary can be introduced. A necessary condition is the dissipation rate into the MF implying a change in the 3-D field topology. This could be done by using, e.g., 3-D multifluid or 3-D hybrid simulations including a realistic solar wind-magnetosphere interaction (see, e.g., Sauer and Deluca, 2000 and Moore et al., 1991).

5. Conclusions

[11] The enhancement of draping is a common feature for Mars Venus and comets. At Mars and comets, it occurs at the MPB, the dayside counterpart of the magnetic tail boundary. At Venus, this feature happens also across a boundary topologically connected to the Venerian magnetic tail boundary. This is induced from the compatibility between the dayside and the expected altitude for the tail boundary dayside counterpart [Sanowar and Basu, 1996]. The identification of this "draping boundary" with the MF is evident and it is supported by the similarities between the changes in the suprathermal electron spectra apertured at Venus, Mars and comets. Further work will include a statistical study on this feature and a detailed comparison between PVG and MGS electron data in equivalent regions. A study on the local properties of the MF as it was done for the magnetotail current vector [Slavin et al., 1989] is also needed. Hopefully, Venera Express will give a more complete description of the plasma near this boundary to better understand its nature.

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