THE MAGNETOSPHERE OF VENUS:
EVIDENCE FOR A BOUNDARY LAYER AND A MAGNETOTAIL

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Abstract. A detailed examination of Mariner 5 magnetic field data reveals evidence for a boundary layer beginning in the dayside ionosphere, and a magnetotail much like the terrestrial magnetotail in accord with Venera measurements.

A recent re-examination of the magnetic field data of Dolginov et al. (1969) obtained during the Venera-4 entry into the upper atmosphere of Venus has led to the suggestion that Venus could have planetary dipole moment of moderate size, up to 6.5x10^{22} Gauss-cm^3, insufficient to stand off the solar wind flow by itself, yet large enough to play an important role in the solar wind interaction (Russell, 1976a). If Venus does have an intrinsic field, then one would expect that the weak planetary field would be stretched by the viscous drag of the solar wind in the form of a long tail in the antisolar direction. Mariner 5 passed behind the planet during its flyby of Venus. Although it did not pass into the optical shadow or geometric wake of the planet, it did pass close enough to the sun-planet line (1.38 Venus radii, Ry, at a distance 2.0 Ry behind Venus) that entry into a magnetotail might be expected. Although an unambiguous identification of a Venus magnetotail has never been reported, early studies of the Mariner 5 magnetic field and plasma data (cf. Bridge et al., 1969) give this as one possible explanation of the data. It is the purpose of this paper to re-examine these data in the light of the re-examination of the Venera data and in the context of what we now know of the interaction of the solar wind with the earth.

High Resolution Magnetic Field Data

Figure 1 shows the vector measurements of the magnetic field during the Mariner 5 encounter, in a solar cylindrical coordinate system with X towards the sun, p perpendicular to the planet-sun line through the point of observation and q completing the right-handed orthogonal set, counter-clockwise about C. The encounter period has been divided into four phenomenological regions: magnetosheath, boundary layer, tail, and upstream waves. We first discuss how these regions were chosen, then where these regions are located with respect to the planet and finally some further supporting evidence. It is not our purpose to discuss in detail bow shock associated phenomena and upstream waves in this report.

The first planet-associated feature during the encounter period the bow shock crossing, occurred 156 minutes before closest approach. This feature is evidenced by the sudden field increase in Figure 1 and the drop in velocity and rise in number density observed by the plasma analyzer (Bridge et al., 1967). For the next 58 minutes, the magnitude and direction of the field remain rather constant. We have labelled this period magnetosheath in analogy with the terrestrial magnetosheath. Then, 98 minutes prior to encounter, the field strength drops and the field becomes more turbulent. While this could be a temporal change, we obtain a consistent picture by interpreting it as a spatial boundary. The direction of the X-component of the field is opposite that expected for a magnetosheath field. Rizzi (1971) has pointed out that the characteristic through this point intersects the ionopause close to the terminator, suggesting that the region interior to this discontinuity was a turbulent boundary layer in which the flow was affected by interaction with the ionosphere.

Finally, 56 minutes prior to encounter, we identify the entry into the magnetotail. This identification is based on, first, the direction of the field. In this region, the field is directed away from the planet as would be expected for an observation in the northern lobe of the Venus tail where Mariner 5 is located, given the polarity of the dipole moment implied by the Venera 4 data (Russell, 1976a). The field is flaring out from the planet as would be expected. This can be seen clearly in Figure 2 which shows the Mariner 5 trajectory in the X-p plane and the projection of the field in this plane. Note especially how the tail field parallels the ionopause identified by the Mariner 5 and Venera 4 magnetopause crossings. Further, the tail field opposes the external field seen both before and after entry. This opposition can be explained only by a planetary field, or coincidental reversals in sign of the B_X component of the magnetosheath magnetic field. Further, although the entries and exits from the tail are somewhat ambiguous if we examine |B|, B_X, or B_0, the entries are defined quite precisely by B_0, for the B_0 component in the tail is considerably smaller than in the surrounding magnetosheath and boundary layer regions. The smallness of this component is inconsistent with an interplanetary or magnetosheath source. It is consistent only with field lines rooted in the planet. We note that within the region labelled boundary layer in Figure 1, the period from E-80 to E-70 has many of the attributes of the region we
Figure 1. Mariner 5 magnetic field measurements during Venus encounter in solar cylindrical coordinates: X along planet-sun line; \( \rho \) radially outwards from planet-sun line through Mariner 5 position; \( \theta \) anti-clockwise about \( X \). Abbreviations are used for the magnetopause, MP, the double magnetopause crossings, DMP, the boundary layer, BL, the magnetosheath, MS, the shock, S, and the upstream waves, UW.

have identified as magnetotail. However, the \( B_\theta \) component is not as close to zero at this time as after E-56.

The second method of identification is the spectrum of fluctuations. The region identified as magnetotail is somewhat quieter than the boundary layer region. The large amplitude low frequency (periods \( \approx 1 \) minute) oscillations appear to be multiple magnetopause crossing. This interpretation is supported by minimum variance analysis which shows that the direction of minimum variance, the "normal" to the boundary is in the direction expected geometrically.

Exit from the magnetotail is taken to be the point at which the field begins to wrap around the tail as evidenced by the increase in \( B_\theta \). Exit from the boundary layer region is taken to be the region of sudden increase in the field strength two minutes after encounter. This is the same criterion as used to define the initial entry into the boundary layer from the magnetosheath. We have drawn the line identifying the bow shock at 10 minutes after encounter. At this point and thereafter the field strength regularly falls back to its upstream value. This region we tentatively identify as the upstream wave region.

Boundary Locations

Figure 2 shows the trajectories of Mariner 5 and Venera 4 in the solar cylindrical coordinate system. One minute averages of the Mariner 5 field projected into the spacecraft-planet-sun plane are shown every 10 minutes. Representative field values from Venera 4, in the solar equatorial \( X-Y \) plane, are shown along the Venera 4 trajectory. These data have been corrected for possible spacecraft fields by adjusting the baselines so that the Venera 4 and Mariner 5 data obtained simultaneously in the solar wind are in accord.

The crossings from the magnetosheath into the boundary layer are marked with solid circles. The identification of these crossings in the Mariner 5 data has been discussed above. There is a very similar transition in the Venera 4 data. This transition has been called current layer 1 by Russell (1976a). We see that, after correcting for the apparent spacecraft field, the field strength drops upon passing through the current layer similar to the Mariner 5 behavior. However, the field strength then recovers as the planet is approached. If we follow the Mariner 5 boundary layer entry and exit with the Venera 4 entry, a natural extension is to the dayside ionopause. Although we cannot prove this is the proper extension from the present limited data, this extension is the natural geometric extrapolation, and suggests that the near terminator ionopause causes an additional perturbation in the magnetosheath flow. Interactions such as charge exchange (cf. Wallis and Ong, 1975) and photo-ionization leading to mass pick up (Cloutier et al., 1969) should occur throughout the dayside ionosphere, and should present no additional near terminator perturbation. The decrease in field strength in the boundary layer suggests the perturbation is a rarefaction wave. Such a wave could be associated with expansion of the flow onto streamlines depleted by the ionospheric interaction. Another possibility is that this region is modified by the reconnection of the magnetosheath and planetary fields. Russell (1976b) has suggested that during the Mariner 10 encounter very little solar wind was deflected, except perhaps near the terminator regions. In such a case we would expect the bow shock to occur close to the outer edge of the boundary.
layer. This point is plotted with an S in Figure 2 and indeed it is just outside the boundary layer.

If we sketch the boundary of the tail we obtain a similar boundary but much closer to the planet. The Venera 4 tail encounter is taken to be the current trajectory of Venera 4. The opposite direction of the Venera 4 field suggests the Venera 4 bus entered the atmosphere south of the magnetic equator but we cannot check this because we do not have the three-dimensional trajectory of Venera 4. The Venera 9 measurements are known to have been taken in the southern hemisphere and point towards the sun as expected. Finally, we have indicated two prominent double crossings of the magnetopause by dashed lines in Figure 1 and X in Figure 2. These are similar to transient entries into the magnetosheath seen in the outer magnetosphere (cf. Kaufman and Konrad, 1973) and is presumably due to surface waves on the magnetopause induced by changes in the solar wind.

Discussion and Conclusions

Above we have seen evidence for two distinct phenomena of the solar-wind-Venus interaction: one quite different from the terrestrial analog and one quite similar. The Venus boundary layer is quite different than at the earth, since the terrestrial magnetosheath has little opportunity to pick up ionospheric particles or charge-exchange with the geocorona. We are not the first to postulate the existence of a boundary layer at Venus. Spreiter et al. (1970) suggested that Mariner 5 entered a boundary layer. Vaisberg and Bogdanov (1974) also made suggestion in support of their Mar's measurements, and Perez de Tejada and Dryer (1976) have treated a theoretical two-dimensional analog of such a boundary layer. However, our present re-examination of the Mariner 5 and Venera 4 data permits us to define the location of the boundary layer more precisely than in previous work. Rizzi (1971) suggested that perhaps the boundary layer lay anti-sunward of a characteristic which intersects the ionosphere. Our work suggests that this is probably the case and that the characteristic intersects the dayside ionosphere.

Since the boundary layer is more turbulent and has a lower field strength than the normal magnetosheath we would identify this region with the disturbed region of Lepping and Behannon (1970), and the magnetosheath of Whang et al. (1974) observed in the downstream passage of Mariner 10. We believe what we have identified as normal magnetosheath is equivalent to the quiet region of Lepping and Behannon and the pseudo-magnetosphere of Whang et al.

If the entry into the boundary layer is marked by a characteristic, not a streamline, then this boundary layer is expanding into the flow. This expanding wave could be a rarefaction wave, even though a magnetotail exists preventing post-planetary closure of the flow. If a significant fraction of the solar wind is absorbed by the ionosphere as proposed by Russell (1976b), the presence of such a wave might be observed as a rarefaction wave, even though a magnetotail exists preventing post-planetary closure of the flow. If a significant fraction of the solar wind is absorbed by the ionosphere as proposed by Russell (1976b), the presence of such a wave might be observed as a rarefaction wave, even though a magnetotail exists preventing post-planetary closure of the flow. If a significant fraction of the solar wind is absorbed by the ionosphere as proposed by Russell (1976b), the presence of such a wave might be observed as a rarefaction wave, even though a magnetotail exists preventing post-planetary closure of the flow. If a significant fraction of the solar wind is absorbed by the ionosphere as proposed by Russell (1976b), the presence of such a wave might be observed as a rarefaction wave, even though a magnetotail exists preventing post-planetary closure of the flow. If a significant fraction of the solar wind is absorbed by the ionosphere as proposed by Russell (1976b), the presence of such a wave might be observed as a rarefaction wave, even though a magnetotail exists preventing post-planetary closure of the flow. If a significant fraction of the solar wind is absorbed by the ionosphere as proposed by Russell (1976b), the presence of such a wave might be observed as a rarefaction wave, even though a magnetotail exists preventing post-planetary closure of the flow. If a significant fraction of the solar wind is absorbed by the ionosphere as proposed by Russell (1976b), the presence of such a wave might be observed as a rarefaction wave.

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