STUDIES OF THE CONFIGURATION OF THE VENUS IONOSPHERIC MAGNETIC FIELD

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ABSTRACT

The dayside ionospheric magnetic field of Venus has been modelled from two different points of view. The Cloutier et al. electrodynamic model makes specific predictions about the behavior of the global magnetic field configuration that can be compared with those expected from the alternate diffusion/convection model. Although the diffusion/convection model is currently only one-dimensional, it is found that it is consistent with the observations in several areas where the 3-dimensional electrodynamic model is not.

INTRODUCTION

The ionospheric magnetic fields of Venus contain key information about the physics of the solar wind interaction with planetary atmospheres. Following their discovery in the early orbits of the Pioneer Venus mission /1/, these horizontal, typically $\lesssim$100 nT ionospheric fields were found to occur preferentially in the subsolar ionosphere at times when the incident solar wind dynamic pressure was extraordinarily high /2/. These early studies also considered the appearance of the altitude profiles of the ionospheric fields, separating the observations into two classes depending on whether the altitude profile of the field magnitude did or did not exhibit a deep minimum between the ionopause and periapsis altitude at ≅ 150 km. It was subsequently determined that the altitude profiles with the field strength minima had constant characteristics from orbit to orbit /3/. Although the magnitude of the low altitude field maximum depends on the incident solar wind dynamic pressure /2/ and on the solar zenith angle where the observation was made /3/, the minimum and near-periapsis peak field magnitudes are always at nearly the same altitudes of ≅ 190 km and 170 km, respectively. Phillips et al. /4/ corroborated the requirement of extraordinary incident solar wind dynamic pressure for most observed cases of ionospheric magnetization, showing that dynamic pressures sufficient to drive the subsolar ionopause down to an altitude of ≅ 250 km provided a good predictor for its occurrence.

In parallel with the latter studies, several theoretical efforts had begun to interpret the observations in terms of the physics of the solar wind interaction. Prior to the Pioneer Venus mission, Cloutier and Daniell /5/ had developed a model of the solar wind interaction with Venus' ionosphere which Cloutier et al. /6/ later invoked to describe the ionospheric data. This model is based on a calculation which assumes that the solar wind is absorbed by Venus' ionosphere with the result that a potential from the solar wind convection electric field is applied across it. A driven current system is then derived on the assumption that ohmic heating of the ionosphere is minimal. Although this calculation has been criticized for some of its physical assumptions /7,8/, its advantage is that it gave a 3-dimensional or global picture of a predicted ionospheric magnetic field. Moreover, Cloutier et al. /9/ consider that their picture explains the details of the observed field. One of the major features of the Cloutier et al. model is the interpretation of the observed altitude profiles as latitudinal structures sampled along the spacecraft orbit.

An alternate explanation for these fields suggested by Luhmann et al. /10/ and further developed by Cravens et al. /11/ successfully describes the details of the observed altitude profiles from a different physical standpoint. These authors demonstrated that a one-dimensional model in which the ionopause is regarded as a fixed "source" of horizontal magnetic field which both diffuses into the collisional ionosphere and is subject to ionospheric vertical convection can produce field altitude profiles closely resembling those observed. Unlike the Cloutier et al. model, this model does not depend on solar wind electric fields. Instead, the ionosphere behaves like a kinematic dynamo, redistributing the field that has diffused and convected in from the overlying magnetosheath. In particular, Cravens et al. /11/, using a model of the Venus dayside ionosphere to compute the expected ionospheric vertical convection altitude profile, found that it had the behavior required to produce the characteristic field profile maxima and minima. The only effects of the solar wind interaction on this ionosphere model occur in anomalous, high altitude heat sources which have some effect on the pressure gradients /12/. It has been found that whistler damping near the ionopause can explain the electron heating /13/ and that chemical processes can explain the ion heating /12/. The Cravens et al. ionospheric vertical velocity profile was subsequently used by Phillips et al. /4/ to examine the effect of the solar wind dynamic pressure on the appearance of the ionospheric field in the diffusion/convection model. In these studies, the solar wind controls the ionospheric field through its influence on the ionopause height and the ionopause field magnitude. The results agree with observations until the ionopause reaches its minimum altitude of ≅ 220 km and the field becomes strong enough to affect the vertical velocity /11,4/. One limitation of this model is its limited dimensionality which neglects the effects of the horizontal flow in the ionosphere on the redistribution of the field. While this limitation did not appear to prevent satisfactory modelling of the observations, it makes it difficult to envision the global field structure for comparison with both the data and the earlier model. Although horizontal flow can be included in the diffusion/convection model by carrying out the calculations in three-dimensions, this extension is computationally non-trivial. While these developments await, one can examine the observations for patterns of behavior that characterize the 3-dimensional structure of the dayside ionosphere field and thus help to distinguish between the proposed models. The analyses described here focus on the question of whether the observed altitude profiles represent vertical or latitude structure and on the determination of the global ionospheric magnetic field configuration.

THE DIFFUSION/CONVECTION MODEL AND GLOBAL FIELD CONFIGURATION

The 3-dimensional counterpart of the one-dimensional diffusion/convection equation discussed by Luhmann et al. /10/ and Cravens et al. /11/ is just the dynamo equation

$$\frac{\delta\overline{B}}{\delta t} = \nabla\times(\overline{V}\times\overline{B}) - \nabla\times D(\nabla\times\overline{B})$$

where $\overline{V}$ is the ionospheric velocity field and D is the collisional diffusion coefficient which depends on the electron-neutral and electron-ion collision frequencies, and the ionospheric density.

In the one-dimensional limit which neglects the ionospheric horizontal flow and makes use of the Cravens et al. /11/ vertical velocity model, the solutions of this equation give altitude profiles of the ionospheric magnetic field magnitude in the direction of the overlying magnetosheath field which have their maxima and minima at fixed altitudes but have degrees of magnetization depending on the magnetosheath field magnitude and the ionopause altitude. Since the latter are related by the empirically determined rule that the magnetic

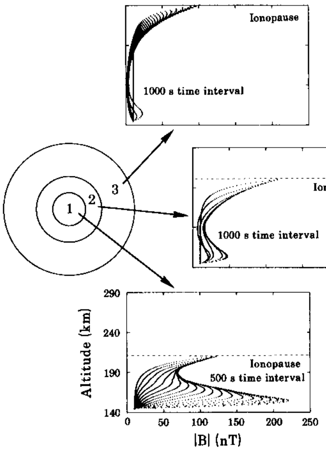
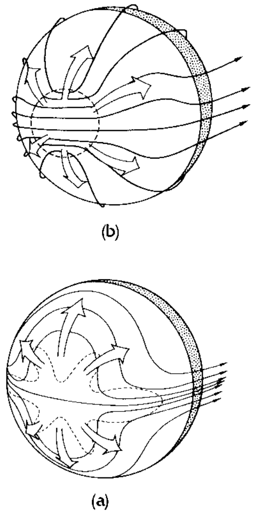


Fig. 1. Illustration of the regions of the dayside Venus ionosphere where various types of altitude profiles of the magnetic field are expected based on the diffusion/convection model. The different model profiles in the insets (from /4/) are determined by the local height of the ionopause which is controlled by the solar zenith angle-dependent component of the incident solar wind dynamic pressure.



(b)

(a)

Fig. 2. Schematic illustrations of magnetic field lines inside the Venus ionosphere (a) based on the model of Cloutier et al. /9/ and (b) the field lines are not on a constant altitude surface, but lie at minimum altitude in the subsolar region and merge with the magnetosheath field in the subsolar region and merge with the magnetosheath field in the flanks. The altitudes of the field lines in (a) are not known.

rotations from the overlying field direction are attributed to the passage of the spacecraft through the dayside sectors between the equator and noon meridian, so it is necessary for us to compare the data with both pictures.

One of the displays of the magnetic data that Cloutier et al. use to argue in favor of the global ionospheric field configuration in Fig. 2a consists of overlays of the field vectors pressure and plasma pressure become equal within the ionopause current layer /4/, one can create field profiles that should be characteristic of different solar zenith angles for a fixed incident solar wind dynamic pressure. This idea, which is illustrated by Fig. 1, is consistent with the observations of the solar zenith angle dependence of field structure /2/, but gives no information about how the fields at the various solar zenith angles are connected. However, a qualitative description can be drawn from our knowledge of the ionospheric horizontal flow and the diffusion/convection mechanism. Knudsen et al. /14/ have measured an antisolar flow which is generally consistent with a wind driven by the day-to-night ionospheric plasma pressure gradient. In Cloutier et al.'s model, a similar antisolar flow, which in their case is driven by the solar wind electric field, was found to produce an ionospheric magnetic field line pattern which is reproduced here as Fig. 2a. The field in the subsolar region is seen to rotate away from the direction of the overlying magnetosheath field except at the equatorial flanks and near the noon meridian. In the diffusion/convection picture, the high field in the subsolar region lies at low altitudes approximately parallel to the overlying draped magnetosheath field in the subsolar region. The size of the region of magnetization is determined by the maximum solar zenith angle at which the solar wind dynamic pressure forces the ionopause down to ≅ 250 km. Although the true behavior of the field at high solar zenith angles can only be determined with a three-dimensional model, comparisons of the one-dimensional model results with the data suggest that the flux must become widely distributed at large solar zenith angles. The implication for the ionospheric field lines is that they must diverge from the central region as sketched in Fig. 2b. This geometry can be thought of as resulting from flux tubes embedded in the subsolar region whose ends at higher altitudes in the flanks are carried antisunward by the ionospheric convection. Of course, this picture may be somewhat distorted if the ionospheric flow field includes a significant zonal corotation /15/ or if the interplanetary magnetic field is highly variable in orientation or has a large radial component.

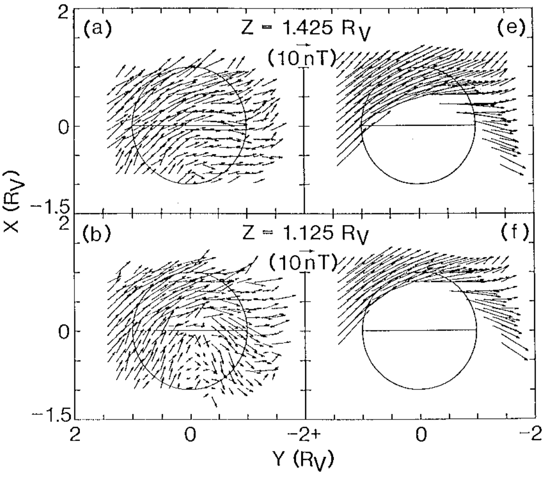


Fig. 3. (a) and (b). Observed draping of the magnetic field near the north "magnetic" pole of Venus, showing the more pronounced draping that occurs within the polar ionosphere as one moves downward along the z (polar) axis. (e) and (f) show gas dynamic magnetosheath model results for comparison. (From /4/).

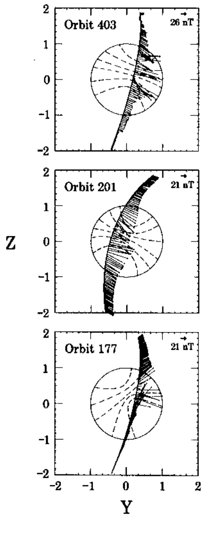


Fig. 4. Field lines analogous to Fig. 2 (b) compared with some observations of the vectors of the ionospheric and magnetosheath fields along the dayside periapsis portion of the Pioneer Venus Orbiter orbit. The projected views are from the sun.

One observation in support of the configuration in Fig. 2b is the vector plot in Fig. 3 from the statistical field study of Phillips et al. /16/ which shows that the average field within the "polar" ionosphere is more severely draped than the overlying magnetosheath field. Another observation in support of this picture is the appearance of a substantial rotation of the ionospheric field from the magnetosheath field direction when the spacecraft samples this field configuration at high latitudes. In the Cloutier et al. model, along the orbit on this draping pattern. As a counter argument, Fig. 4 contains data from several orbits which can contrarily be made to agree with the draping of field lines in Fig. 2b. These orbits are not atypical. However, it is true that some appear more consistent with this picture than others. In view of the variability of the magnetosheath field and consequently the ionospheric field orientations, it is felt that the strongest observational evidence for the configuration in Fig. 2b is that in Fig. 3 from the statistical study of Phillips et al. /16/, as discussed above.

LATITUDE VS. ALTITUDE STRUCTURE

The question of whether the observed minimum in the altitude profiles of the ionospheric field is due to the spacecraft sampling latitude structure or altitude structure can best be answered by examining the data from orbits which pass through the equatorial region of the magnetized ionosphere. In the Cloutier et al. model, one would see no field minima on these occasions, while in the diffusion/convection model, the minima are present everywhere that the ionospheric field is present. Unfortunately, the spacecraft orbit lies in an approximately North-South plane and the interplanetary magnetic field is rarely in that plane. Nevertheless, one case in which a fairly steady North-South ionospheric and magnetosheath magnetic field was observed is shown in Fig. 5. The altitude profile for this orbit shows a well defined minimum in the observed ionospheric field in agreement with the diffusion/convection model.

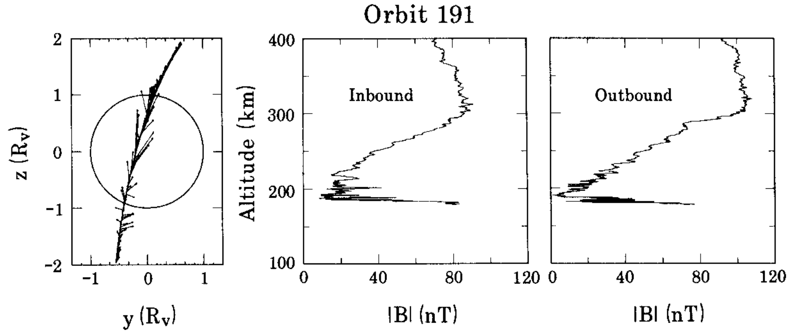


Fig. 5. Behavior of the observed magnetic field during an orbit for which the magnetosheath field draping was primarily north-south or parallel to the spacecraft orbit. The left-hand panel shows the view from the sun of the vectors (analogous to Fig. 4). The two other panels show the "altitude" profiles of the field magnitude observed inbound and outbound.

Of course, the diffusion/convection picture (see Fig. 1) also has latitudinal variability, but it is connected with the solar zenith angle dependence of the ionopause altitude. To further examine the possibility that the ionospheric field occurs in a "belt" rather than throughout an approximately circular region, one can predict the frequency of occurrence of observing an ionospheric field belt of constant latitudinal width and compare it with the statistics of ionospheric field observations in the earlier studies /2/. Figure 6 shows the results for different latitudinal widths of belts with arbitrary orientations with respect to the orbit plane. Although the data fall primarily within the curves for

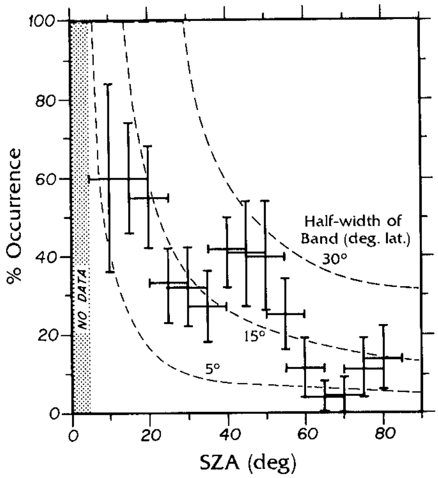


Fig. 6. Occurrence of orbits with magnetized ionospheres as a function of the periapsis solar zenith angle (from /2/). The dashed lines show the expected behavior if the fields occurred in latitudinal bands of various widths.

a 5° and 30° latitudinal belt, the general trend of the data suggests that too few observations of ionospheric fields occur at high solar zenith angles to support the belt geometry. If the ionospheric field lies inside of a given solar zenith angle that depends on incident solar wind pressure, as in the diffusion/convection picture, the observed solar zenith angle distribution of ionospheric fields is largely a result of the distribution of solar wind dynamic pressures for this data set. Since solar wind dynamic pressures at Venus are rarely sufficient to drive the ionopause in the flanks to ≅250 km, the distribution of the data in Fig. 6 can be explained by solar wind properties. However, it should be mentioned that the Cloutier et al. model "belt buckle" geometry would reduce the statistics of observations of a belt in the flanks.

Two other analyses which provide tests of the general nature of the ionospheric field structure concern the requirement of a low local ionopause altitude to produce a magnetized ionosphere and the global distribution of the magnetized ionospheres for various incident solar wind pressures. Figure 7 shows the location of magnetized ionosphere orbits in a plot of ionopause altitude vs. solar zenith angle. It is seen here that, for all solar zenith angles, a low ionopause altitude is a requirement for the occurrence of a magnetized ionosphere. Of course, the ionopause is not 'local' in the sense that it is observed some distance from periapsis, but we know from previous studies /4/ that the ionopause everywhere has a minimum altitude of ≅220 km and that if it is low at the outbound ionopause, it is likely to be low ≅10° away above the periapsis point. The diffusion/convection model requires a low local ionopause for the appearance of an ionospheric field. Figure 8 describes where the magnetized ionospheres occur on a plot of solar wind dynamic pressure vs. solar zenith angle. The curve shows the solar zenith angle where the ionopause would be forced down to 250 km if one makes the standard approximation that the normal to the ionopause surface projected along the Venus-sun axis is given by the cosine of the solar zenith angle squared. In other words, this curve shows the approximate high solar zenith angle limit of the magnetized regions in Fig. 1. Except for the region of overlap at the boundary of magnetized and unmagnetized cases (note that the curve of $\cos^2$SZA is not appropriate near the terminator), the data seem to divide themselves in this display in a manner that is consistent with Fig. 1. Some of the scatter in this plot can be attributed to the use of solar wind observations 30 minutes before periapsis when the spacecraft was last upstream, while some will be produced by the fact that it takes finite time for the ionospheric field to grow and to decay /10,11, 14/. However, the magnetized ionospheres are generally observed within a solar zenith angle boundary determined by the incident solar wind pressure at which the local ionosphere is forced to an altitude of ≤250 km.

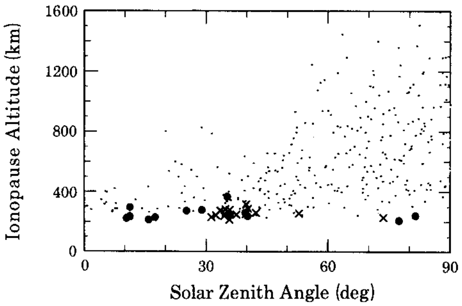


Fig. 7. Locations of the magnetized ionosphere observations (O) as a function of the nearest measurement of the upstream solar wind dynamic pressure (typically within ≅30 min. of the ionospheric observation) and the solar zenith angle of periapsis. The "unmagnetized" cases are shown by a (-) sign. If the condition for a magnetized ionosphere was the location of the local ionopause at 250 km altitude, the O's should fall above the solid line and the -'s below it.

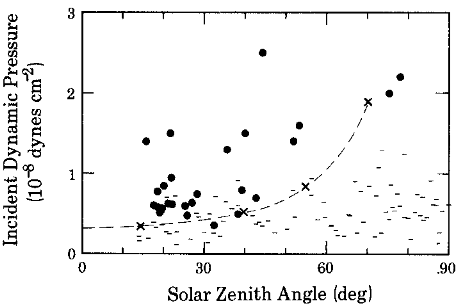


Fig. 8. Altitudes of the ionopause measured at various solar zenith angles. The O's mark inbound ionopauses and the X's mark outbound ionopauses for orbits during which ionospheric fields were observed.

CONCLUSIONS

It has been shown above that certain observed global properties of the magnetized dayside ionosphere of Venus are consistent with the diffusion/convection model for its generation. The magnetized ionosphere of Venus is generally found at solar zenith angles where the local ionopause has been forced to altitudes $\lesssim$250 km by the incident solar wind dynamic pressure. The altitude profiles of the field magnitude consistently show minima near ≅190 km in agreement with the predictions of the one-dimensional diffusion/convection model of the ionospheric field. The ionospheric field draping geometry suggests that the field may diverge from the subsolar regions where magnetization is most pronounced because of the lower local ionopause height and the stronger overlying magnetosheath magnetic field. This latter picture can be thought of as resulting from the "mass loading" of magnetosheath flux tubes that have penetrated the ionosphere at low solar zenith angles. Further evaluation of the ionospheric field configuration will result from comparisons of the data with a fully three-dimensional diffusion/convection model.

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