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OBSERVATIONS OF LARGE SCALE STEADY MAGNETIC FIELDS IN THE DAYSIDE VENUS IONOSPHERE

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Abstract. Although the dayside ionosphere of Venus is often "field-free" except for fine scale features, large scale, steady ionospheric magnetic fields with magnitudes sometimes exceeding 100 gammas are occasionally observed by the Pioneer Venus Orbiter magnetometer. These fields are mainly horizontal and can assume any angle in the horizontal plane. The orientation of the field may change along the spacecraft trajectory. The field magnitude in the upper ionosphere usually shows a distinct minimum near ~200 km altitude, but the altitude profile is otherwise arbitrary. With few exceptions, the observations of these large scale fields occur when periapsis is at solar zenith angles <50°. The occurrence of large scale fields is often coincident with the observation of high solar wind dynamic pressures by the Pioneer Venus Orbiter plasma analyzer closely following the ionosphere encounter. However, the detection of this phenomenon even during some orbits for which the dynamic pressure is not extraordinarily high suggests that other factors, such as hysteresis effects, must also play a role in determining the occurrence frequency of large scale magnetic fields in the dayside Venus ionosphere.

Introduction

The Pioneer Venus Orbiter, injected into orbit on 4 December 1978, initially probed the dayside ionosphere of Venus at solar zenith angles near 63°. As periapsis moved toward larger solar zenith angles on the succeeding orbits, the fluxgate magnetometer measurements revealed that the dayside ionosphere in the near terminator region generally has a very weak field (≲10 gammas) except in very narrow (≲30 km) regions where the measured field sometimes exceeds 100 gammas (Russell et al., 1979a). These small scale features have been interpreted as helical magnetic bundles or flux ropes by Russell and Elphic (1979). However, during a small fraction of the orbits in this sector, large scale steady fields with magnitudes of up to ~130 gammas and a marked absence of fine scale structure were observed in the ionosphere down to periapsis at an altitude of ~160 km. Periapsis returned to the dayside at approximately orbit 120 and as it moved toward the subsolar region the magnetic field in the ionosphere was found to retain its dichotomous behavior, except that the high ionospheric fields were seen more frequently.

At the present time over 450 orbits of data are available for analysis including 2 complete periapsis traversals of the subsolar region. The purpose of this letter is to report the results of a survey of the currently available ~220 orbits of dayside ionospheric data obtained by the Pioneer Venus fluxgate magnetometer (Russell et al., 1980) which shows the general occurrence patterns and characteristics of the orbits with large scale magnetic fields. Measurements of the solar wind dynamic pressure by the Pioneer Venus plasma analyzer (Wolfe et al., 1980) are used to investigate the relationship between the appearance of these large scale ionospheric fields and solar wind conditions external to the Venus ionosphere.

Observations

The orbit of Pioneer Venus limits in situ observations of the ionosphere to altitudes >150 km and latitudes from about 15°S to 45°N, and provides one ionospheric encounter every ~24 hours (Colin, 1979). For the purpose of the present study of the dayside ionosphere, orbits 1-20, 120-240 and 380-460 were selected because their periapsides occurred at solar zenith angles <90°. The point of entry into the ionosphere was identified using a combination of magnetic field and AC electric field data (F.L. Scarf, personal communication, 1980). The electric field shows an abrupt decrease in noise level at the ionopause, where the plasma density increases sharply (Taylor et al., 1979). The magnetic field, as will be shown, sometimes decreases within the ionopause to ≲10 gamma from values ~50-130 gammas just outside of the ionopause (Elphic et al., 1980).

Figure 1 shows examples of the various states of magnetization of the dayside Venus ionosphere. Three general categories of large-scale field structure are observed: 1) near absence of large-scale field as shown by Fig. 1a (but with many of the small scale structures discussed in detail by Russell et al. 1979, a, b, Russell and Elphic, 1979); 2) a field strength on the order of the field strength at the ionopause (~50-130 gammas) throughout the observable ionosphere, with little or no fine structure as in Fig. 1c; 3) an apparent diamagnetic layer of variable thickness, located in the region between the ionopause and an altitude of ~200 km, with a low altitude layer of high field as in Fig. 1b. The small scale variations may appear in the diamagnetic layer if the field is very weak there. Usually the field structure is the same type on the inbound and outbound legs of the orbit, although on a few orbits two different categories were seen inbound and outbound.

The large scale ionospheric fields are usually oriented nearly parallel to the surface of the planet. The ionospheric field can be directed parallel to the local external field, which has a direction related to the prevailing interplanetary field direction, but can also have an arbitrary orientation which changes along the spacecraft trajectory. More will be said about the field direction below.

Of the sample of ~220 dayside orbits, approximately 70% of the dayside ionosphere encounters appeared as the example in Fig. 1a, 15% as in Fig. 1b, and 15% as in Fig. 1c, although it will be shown later that these percentages actually depend on the range of solar zenith angles being considered. The separation of the latter two types of events was made somewhat ambiguous by the fact that a continuum of diamagnetic layer strengths is observed, and that the deep and shallow field minima are often seen on contiguous orbits; the occurrence of a deep minimum usually follows an orbit showing a shallow minimum configuration on these occasions. However, the events that appeared as in Fig. 1b (i.e., having shallow field minima) are characterized by a field strength and direction similar to that of the field at altitudes above the ionopause, while the field in low altitude layers like that appearing in Fig. 1c (i.e., having deep field minima) is generally rotated with respect to the field direction above the ionopause. Hence, these two types of observations were treated as separate categories. In the present analysis, a

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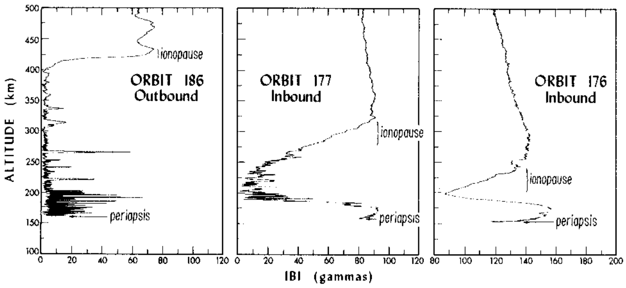

Figure 1. (a) Altitude profile of the magnetic field magnitude observed in the dayside Venus ionosphere showing the "field-free" configuration with small scale structure. This plot represents ~7 minutes of data.

(b) Same as (a) showing the "magnetized" ionosphere field configuration.

(c) Same as (a) showing the presence of a strongly diamagnetic effect in a layer between the ionopause and ~200 km. Note that the |B| scale for (c) begins at 80γ.

quantitative distinction between orbits with large scale and with small scale field structure was made on the basis of the value of the magnitude of the average vector field $\langle \underline{B} \rangle_{per}$ and the average standard deviation of the field magnitude $\langle \sigma \rangle$ observed during the 160 s surrounding periapsis. This time interval corresponds to an altitude range of ~50 km. The frequency distributions of the value of $\langle \underline{B} \rangle_{per}$ for the sample subsets with $\langle \sigma \rangle \geq \langle \underline{B} \rangle_{per}$ and $\langle \sigma \rangle < \langle \underline{B} \rangle_{per}$ are shown by the histograms in Fig. 2. This figure indicates that ionosphere encounters with $\langle \sigma \rangle < \langle \underline{B} \rangle_{per}$ generally had $\langle \underline{B} \rangle_{per}$ magnitudes >10 gammas. The encounters with $\langle \sigma \rangle < \langle \underline{B} \rangle_{per}$ were selected for further analysis of the large scale ionospheric field, thus effectively excluding cases like that shown in Fig. 1a. The distinction between the encounters with weak and strong diamagnetism (e.g., Figs. 1b and 1c, respectively) was made on the basis of the ratio of the magnitude of the ionospheric field minimum to the magnitude of the field maximum above the ionopause. Ratios < 50% were considered diamagnetic layer cases.

The distribution in solar zenith angle (SZA) of all orbits with large scale fields near periapsis is given in Fig. 3. It is evident from this distribution that the large scale fields are generally observed at SZAs < 50°, infrequently observed in the interval 50° < SZA < 70°, and practically never seen at SZA > 70°. The three exceptions at SZA ~79° occurred during orbits 9-11, which will be discussed in more detail later.

The physical factors which determine whether a large scale field is present in the ionosphere appear to be connected with the properties of the ionopause and with conditions in the incident interplanetary plasma. These connections, which are probably interdependent if the ionopause field indeed consists of piled-up interplanetary field (Russell et al., 1979b), are manifested by the occurrence of large scale fields whenever the ionopause field and local solar wind dynamic pressure is extraordinarily large. For example, Fig. 4 shows the relationship between the magnitude of the large-scale circumperiapsis field, defined above, and the maximum magnetic pressure of the field observed just above the outbound ionopause (outbound parameters were used for comparison with $\langle \underline{B} \rangle_{per}$ because the time elapsed between periapsis and the outbound ionopause

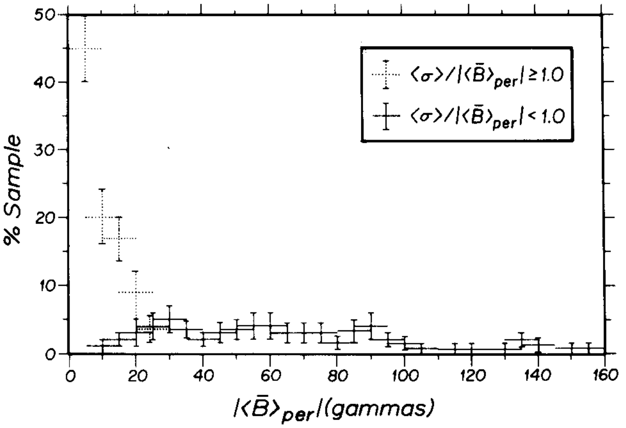

Figure 2. Frequency of occurrence of average magnetic field magnitudes near periapsis for orbits with highly structured ($\langle \sigma \rangle / \langle \underline{B} \rangle_{per}$ ≥ 1.0) and relatively unstructured ($\langle \sigma \rangle / \langle \underline{B} \rangle_{per} < 1.0$) low altitude fields. The data sample is weighted in favor of SZAs < 50°.

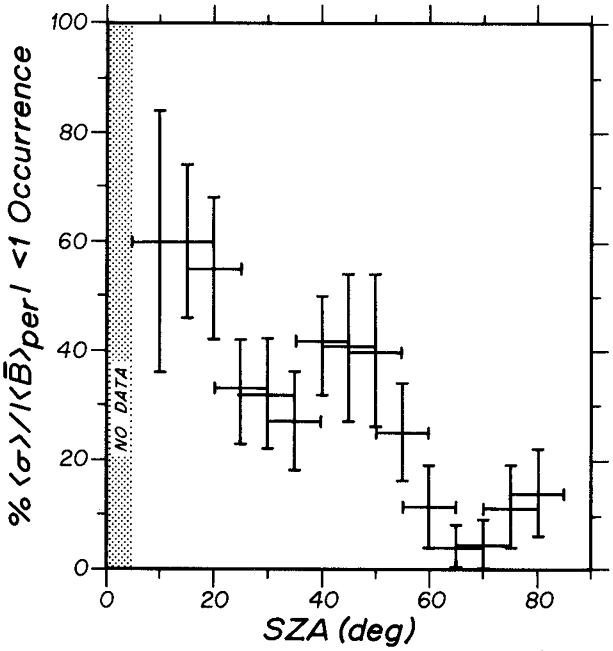

Figure 3. Frequency distribution of orbits with $\langle \sigma \rangle / \langle \underline{B} \rangle_{per} > 1.0$ vs. solar zenith angle at periapsis.

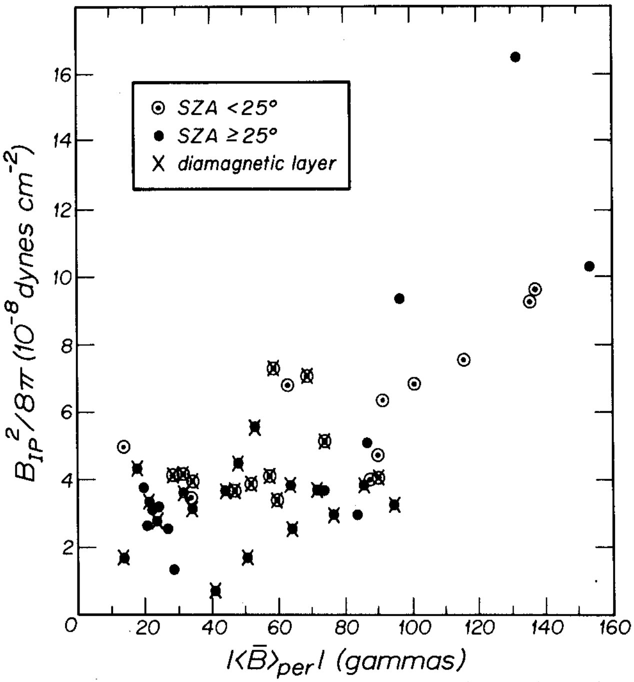

Figure 4. Maximum magnetic field pressure $B_{IP}^2/8\pi$ exterior to the outbound ionopause vs. $|\langle \underline{B} \rangle_{per}|$.

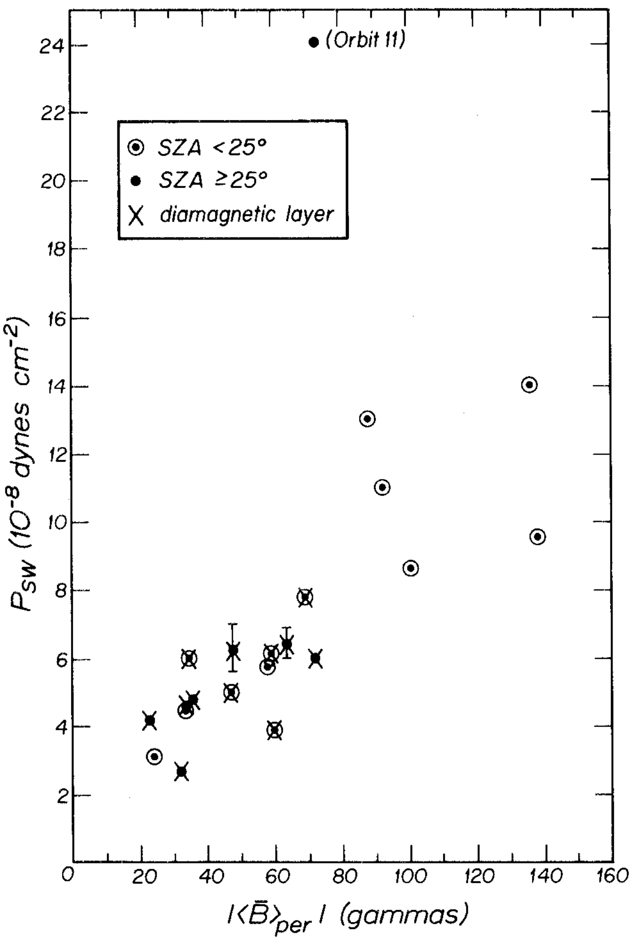

Figure 5. Solar wind dynamic pressure P_{sw} exterior to the outbound bow shock vs. $|\langle \underline{B}\rangle_{per}|$.

crossing is much less than the corresponding inbound interval, and also because the SZA of the outbound leg is closer to the SZA of periapsis). In Fig. 5 the periapsis field strength is similarly compared with the magnitude of the solar wind proton dynamic pressure observed just outside of the outbound bow shock by the onboard energetic plasma analyzer (Intriligator et al., 1980). The dynamic pressure was available for about 40 of the orbits in the sample. It is useful to point out here that dynamic pressures $\sim 3\times10^{-8}$ dynes cm^{-2} are typical at Venus (Wolfe et al., 1979). And that the contribution of helium to the dynamic pressure is typically~20%. The outstanding features of Figs. 4 and 5 are the tendencies for nondiamagnetic, high ionospheric fields to occur preferentially at low solar zenith angles in conjunction with large ionopause and solar wind pressures. Further information about the solar wind effect is given by the histograms on Fig. 6, which show the frequency distributions of the three categories of ionospheric fields for a sample of 40 orbits as a function of solar wind dynamic pressure. Because the orbits for which solar wind pressure was determined were mostly at SZAs <50°, the sample is weighted in favor of small solar zenith angles. Evidently the average dynamic pressures for the orbits with large scale fields are at least 3 times the pressures for the "field-free" orbits.

Discussion

The data suggest that the magnetic field in the ionosphere of Venus generally has two possible states: one practically unmagnetized with small scale (<30 km) regions of field magnitude ≲100 gammas embedded, and one magnetized in a horizontal direction. The figures described above show that the frequency of occurrence of these two states depends on solar zenith angle; the magnetized state occurs more frequently at solar zenith angles <50°. In particular, Fig. 5 indicates that the presence of large ($>8\times10^{-8}$ dynes cm^{-2}) solar wind dynamic pressure is always accompanied by the occurrence of a large scale field in the ionosphere, but large scale fields can also be present when the dynamic pressure is typical ($\sim3\times10^{-8}$ dynes cm^{-2}). The latter cases generally show a strong diamagnetic effect in the upper ionosphere.

The apparent bimodal behavior of the ionospheric field and its solar zenith angle dependence, together with the solar wind pressure correlation, can be made consistent with several explanations; however, a particularly attractive alternative invokes a belt of horizontal magnetic field through the subsolar point. The belt may form when the solar wind dynamic pressure is high enough to force interplanetary magnetic flux into the ionosphere, or when the diamagnetic currents flowing in the ionosphere become insufficient to cancel out the increased external field. If the latitudinal width of the belt is largest at small solar zenith angles, and the belt as a whole grows in area as solar wind pressure increases, the observation of large scale fields at high solar zenith angles (orbits 9-11, SZAs≃79°) on the

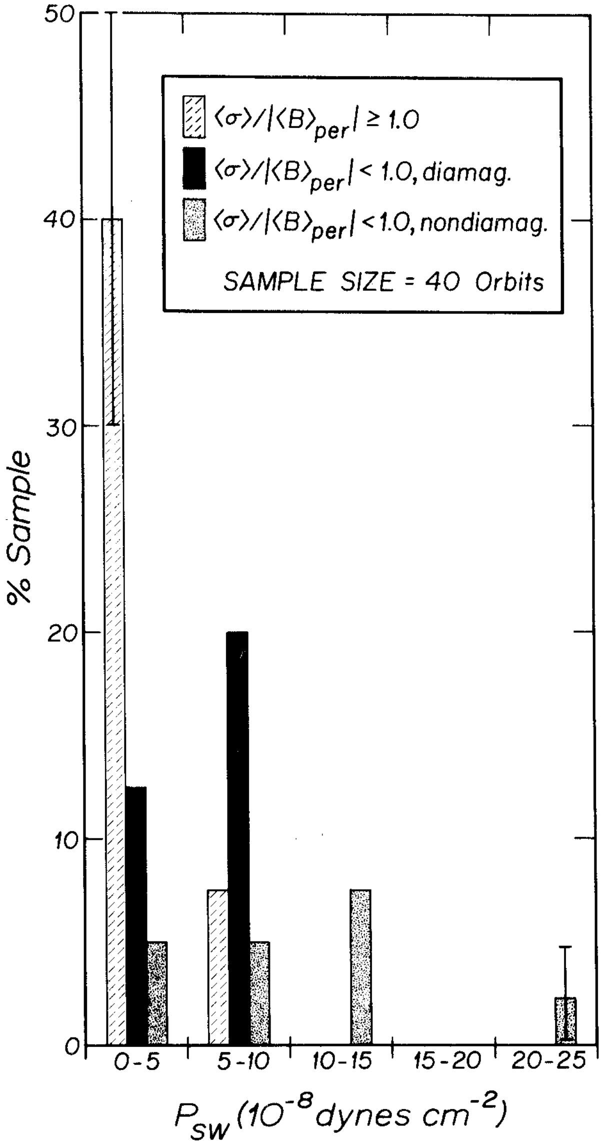

Figure 6. Distribution of the observations of the three categories of large scale ionospheric fields according to the value of the solar wind dynamic pressure observed on the outbound leg.

occasion of several exceptional solar wind enhancements (dynamic pressure>37×10^{-8} dynes cm^{-2} on orbit 9 pre-encounter dropping to 14×10^{-8} dynes cm^{-2} post-encounter; on orbit 11 corresponding values 22 and 24×10^{-8} dynes cm^{-2}) can be understood. Further support for this picture of the ionospheric magnetic field structure is found in the consideration of the magnetic latitudes of the observed ionospheric fields. If the magnetic equator is defined as the great circle that passes through the subsolar point and lies in a plane parallel to the magnetic vector, the magnetic latitude can be measured relative to that equator. Magnetic latitudes <45° are inferred for the observed regions of large scale field. The model is also in qualitative accord with the theory of Cloutier and Daniell (1979) who predicted that the magnetic field in the ionosphere of Venus would be restricted to a latitude band. Finally, in the context of this model the layered field configurations may be explained as the transition phase between the impressed field state and the field-free state following the withdrawal of the enhanced solar wind pressure. Of course, all of these interpretations are subject to the usual difficulty of distinguishing spatial and temporal effects.

Summary

The large scale nearly horizontal magnetic field observed by the Pioneer Venus Orbiter magnetometer in the dayside ionosphere of Venus at solar zenith angles <50° is weak (≲10 gammas) with small scale (<30 km) structure, during about 70% of the encounters analyzed, but has average magnitudes near periapsis of up to ~130 gammas the rest of the time. Large scale fields are generally not observed at SZAs >50°. The orientation of the large scale fields appears to be related to the prevailing direction of the field in the region of piled-up interplanetary field outside of the ionopause unless a high altitude layer of strongly diamagnetic current is present. The latter occurrences sometimes follow orbits during which nearly uniform high fields are observed, suggesting a possible evolutionary relationship between the two configurations. The large scale field is always present at SZAs <50° when the current value of the solar wind dynamic pressure is >8×10^{-8} dynes cm^{-2}. The diamagnetic layer is weak or absent on these latter occasions. In summary, it is apparent from the Pioneer Venus Orbiter observations that large scale horizontal magnetic fields with magnitudes of ~10-130 gammas and a field minimum near ~200 km altitude are a common feature of the dayside Venus ionosphere at solar zenith angles <50°, and that they appear to be related to the passage of solar wind plasma with enhanced dynamic pressure.

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