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MAGNETIC FIELD AND PLASMA WAVE OBSERVATIONS IN A PLASMA CLOUD AT VENUS

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Abstract. Pioneer Venus magnetic field and plasma wave data are examined in a particularly clear example of a plasma cloud above the Venus ionosphere. The magnetic configuration is suggestive of acceleration of the plasma cloud by magnetic tension. If the plasma is at rest at the subsolar point, it could be accelerated to ∿90 km/sec by the observed stress at the location of the measurement. This far exceeds the escape velocity and suggests that plasma clouds do form a significant loss mechanism for the Venus ionosphere but do not necessarily indicate that the plasma cloud is detached from the ionosphere proper. The plasma cloud is accompanied by strong plasma wave activity and is significantly hotter than the ionospheric plasma encountered later on the same pass. We estimate a loss rate of the order of 2×10^{25} ions per second during this event. The geometry suggested by these observations is one of a ridge of dense cold plasma starting in the subsolar regions and flowing over the poles of the planet. Thus, these plasma clouds may be the planetary analogue of cometary tail rays.

Introduction

Plasma and magnetic field measurements have revealed the Venus ionopause to be very dynamic, varying in height often dramatically from day to day [Elphic et al., 1980a,b; Brace et al., 1980]. Often multiple ionopause crossings are encountered indicating a wavy structure to the ionosphere [Elphic et al., 1980a; Brace et al., 1980]. At times the outermost of these multiple "ionopause" crossings is at such an altitude that it seems to be detached from the rest of the ionopause [Brace et al., 1981]. If these plasma clouds are moving at the solar wind velocity, or any significant fraction of the solar wind velocity, they represent an important loss mechanism for the Venus ionosphere and ultimately for the Venus atmosphere [Brace et al., 1981].

The solar wind interaction with Venus is thought to be in many ways analogous to the solar wind interaction with comets. Observations of comets are quite complementary to the measurements available at Venus. The cometary data are in the form of global pictures as a function of time, but integrated along the line of sight. The Venus data are local measurements along the satellite trajectory at an instant of time. Comets, as Venus, have a very dynamic interaction with the solar wind. Tail rays form, lengthen, and rotate into the tail. Tails rotate in the solar wind and can become disconnected [cf. Neidner and Brandt, 1978]. If we could identify the analogous phenomena in the Venus measurements we could gain a better understanding of both the Venus and the cometary interaction.

As one step in this investigation we have examined the magnetic field [Russell et al., 1980] and plasma wave [Scarf et al., 1980] data during periods identified with the electron temperature probe [Krehbiel et al., 1980] as plasma clouds. During most of these periods the interplanetary conditions, as judged from the magnetic field records from just before and just after periapsis passage, were quite irregular. However, on one orbit the interplanetary field seemed to be quite steady which allowed us to proceed with an analysis which gives some insight into the geometry of the plasma cloud, the mechanism of formation and the analogy with the cometary interaction.

Interplanetary Data

Magnetic field data and plasma wave data for the 24-hour period surrounding periapsis on Pioneer Venus orbit 601 are shown in Figure 1. The spacecraft enters the distant magnetosheath at about 10 UT on 7/28/80 at a radial distance of 8.5 R_V and 130° SZA. The change in field strength is only partially due to the crossing of the bow shock. The major cause is a large drop in the beta of the solar wind so that the magnetic pressure greatly exceeded the plasma pressure [J.D. Mihalov, personal communication, 1981]. This effect lasted well into the outbound passage of the spacecraft as can be seen in the steadiness of the magnetic field during this period.

The magnitude of the field builds up slowly and then rapidly as the planet is approached. The abrupt decrease in field strength and equally abrupt rise surrounding 1530 UT marks the entry into and exit from the ionosphere. After periapsis passage the field decreases gradually at first and then abruptly at the bow shock. The interplanetary magnetic field is similar in orientation to that observed before periapsis until about 1845 UT when it changes orientation and becomes more irregular.

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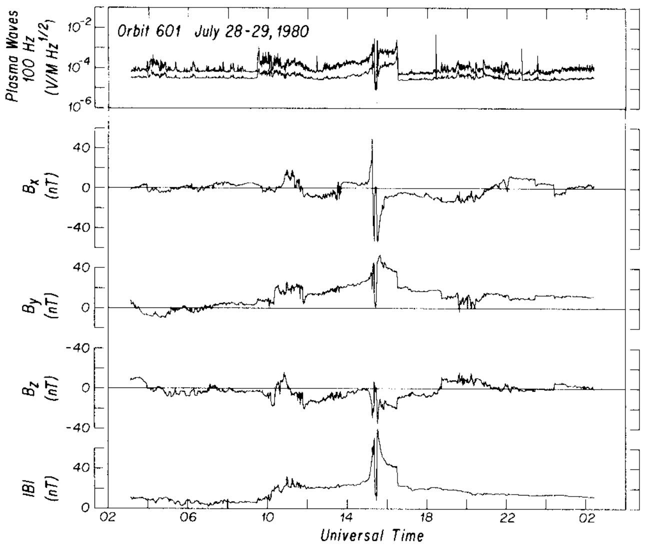

Figure 1. Magnetic field and plasma wave data on Pioneer Venus orbit 601 on July 28, 1980.From top to bottom are the 100 Hz plasma wave amplitudes, the B_x, B_y and B_z solar ecliptic components of the magnetic field and the total magnetic field strength. The sudden rise at ∿1000 UT and subsequent slow decay of the field strength signals the arrival of an interplanetary shock. The enhancement of field around periapsis at ∿1530 UT is the usual signature of the near planet magnetosheath. Multiple crossings of the bow shock are evident after 1100 UT. Outbound from periapsis there is a single abrupt crossing at 1630.

The Plasma Cloud

Figure 2 shows the magnetic field components in solar ecliptic coordinates, the magnetic field magnitude, the plasma wave activity at 100 Hz and the electron number density measured by the Langmuir probe through a plasma cloud on orbit 601 continuing into the ionosphere proper where the electron density increases and the field strength drops. The plasma cloud, centered at about 1517:15 lasts close to 90 seconds. During this period the plasma wave activity at 100 Hz reaches a level close to that seen later at the ionopause and the field strength drops by 20 nT. The plasma wave emissions at higher frequencies (not shown) are also strong; in fact, these higher frequency emissions are much stronger than at the ionopause. The direction of the X-component of the field reverses in the center of the cloud. We examine this variation in detail below but first we examine the implications of the magnitude drop.

The magnetic field in the center of the plasma cloud is depressed 20 nT below an interpolated 60 nT. This drop would be caused by the presence of a plasma with an energy density of 5 kev/cm^3. If we take the electron density measurement in the center of the drop as indicative of the total number of electrons present and assume an equal number of ions we obtain an average energy of 7.2 eV/electron-ion pair. The measured electron temperature in the cloud is 12,500 ^{o}K or close to 1.2 eV. Hence the average ion temperature must be about 6 eV. If these ions are O^+ then the thermal velocity is about 8.5 km/sec, which is, probably not coincidentally, close to the escape velocity. If these ions had been ionized in the flowing magnetosheath they would have a thermal velocity equal to the component of the magnetosheath flow velocity perpendicular to the magnetic field. The fact that this thermal velocity is much less than that expected for a magnetosheath flow indicates that these ions were generated either in the ionosphere or in a region shielded from the magnetosheath flow. We note for comparison that the electron temperature in the cloud is only slightly greater than that observed at a similar density as the ionopause is crossed. However, it is several times greater than that observed well inside the ionosphere.

Magnetic Structure

In Figure 3 we show the magnetic field in solar cylindrical coordinates plotted along the Pioneer Venus trajectory. In this coordinate system the X-coordinate is the solar direction and the ordinate is in the direction perpendicular to the sun-Venus line through the spacecraft. There is a component perpendicular to the page. The reversal of the field in the X-direction at the plasma cloud indicated by the black bar is quite evident in this figure as is the wrapping of the field lines about the planet. This display is perhaps somewhat misleading because it gives the impression of layering of the field and radial structure. This might be expected if the interplanetary magnetic field had recently re-

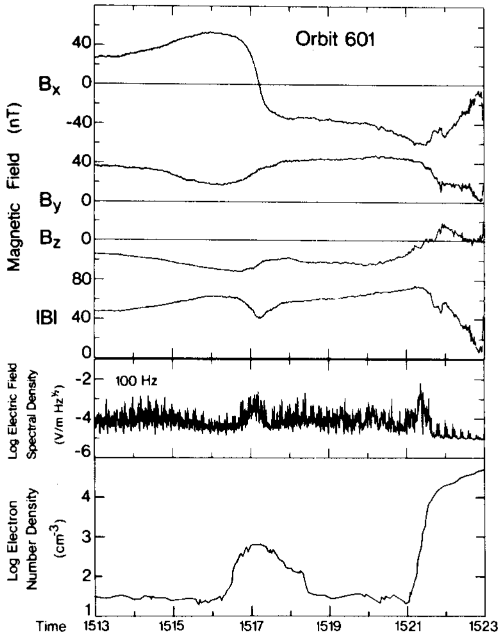

Figure 2. The top four panels show high resolution measurements of the magnetic field components in spacecraft coordinates and the total field. The bottom two panels show the electric field detector activity in the 100 Hz channel and the electron number density measured by the GSFC electron temperature probe. Values equal to or less than about 80 cm^{-3} represent the noise level of the instrument at this time.

versed, leading to a reconnection geometry but the available data suggest a static configuration.

Figure 4 shows the orthogonal projection in which the radial component has been suppressed and only the east-west and north-south components plotted along the trajectory in solar ecliptic longitude and latitude. Two black bars are plotted along the trajectory indicating the plasma cloud and the entry into the ionosphere. We note that rotations of the field are observed at both entries. The spatial symmetry of this suggests that the observed magnetic structure may be a static structure through which the spacecraft moved horizontally. If the magnetic field lines of the shocked solar wind became slowed in their motion across the front of the ionosphere we would expect them to bend about a line perpendicular to the solar wind and the Y-Z component of the interplanetary magnetic field and through the center of the planet. This line and the solar wind direction define a plane which intersects the ionopause along the dashed line in Figure 4. The intersection of this plane with the dawn-dusk terminator has been labeled the "magnetic pole". The determination of this point is uncertain due to the uncertainty in the direction of the IMF at the time of observation. The bar on the "magnetic pole" reflects this uncertainty.

We note that the field lines bend through this magnetic meridian and that it passes through the plasma cloud. The magnetic meridian also nearly bisects the angle between the pre-cloud and post-cloud field as it should. A magnetic meridian further north would be a better bisector and would also pass through the cloud and intersect the "magnetic pole" as defined by our uncertainty in the IMF. The magnetic structure thus suggests the existence of a stationary field pattern in which plasma is being "gathered" by the magnetic field. Presumably this plasma has been created on the magnetosheath field lines closer to the subsolar regions by charge exchange and/or photoionization. This additional mass slows the flow in this region while the flow in other regions on the same line maintains its rapid rate. Thus the field line bends. We know of no reason for this plasma to become detached from the planet in a time stationary situation so we envision this pattern to be present everywhere along the magnetic meridian with decreasing altitude.

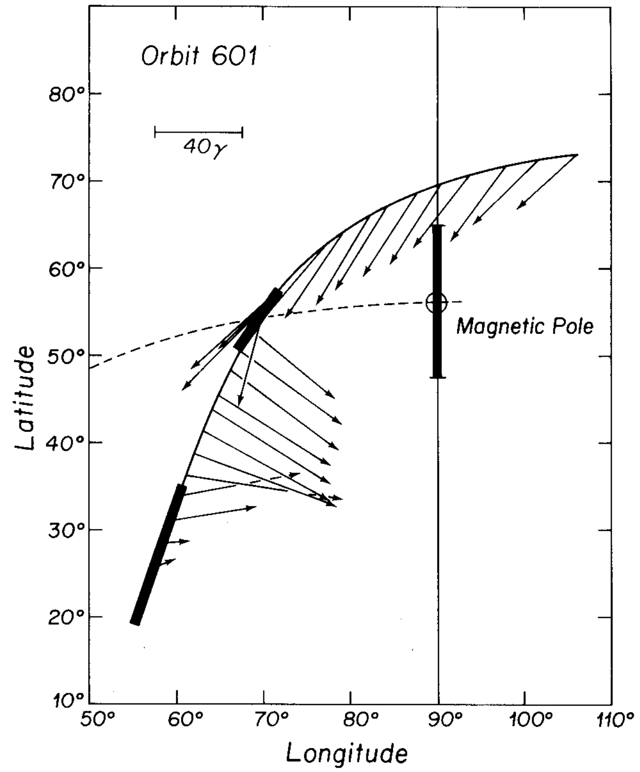

Figure 4. The east-west and north-south components of the magnetic field plotted on a solar ecliptic latitude and longitude map. The dashed line joins the subsolar point and the "magnetic pole". The location of the "magnetic pole" is the intersection with the dawn-dusk plane of the plane containing the solar direction and the planetary center which is perpendicular to the projection of the interplanetary magnetic field in the Y-Z solar ecliptic plane. This is the expected bending line of mass-loaded magnetosheath field lines. The northern heavy bar indicates the location of the plasma cloud. The southern heavy bar indicates the entry into the ionosphere.

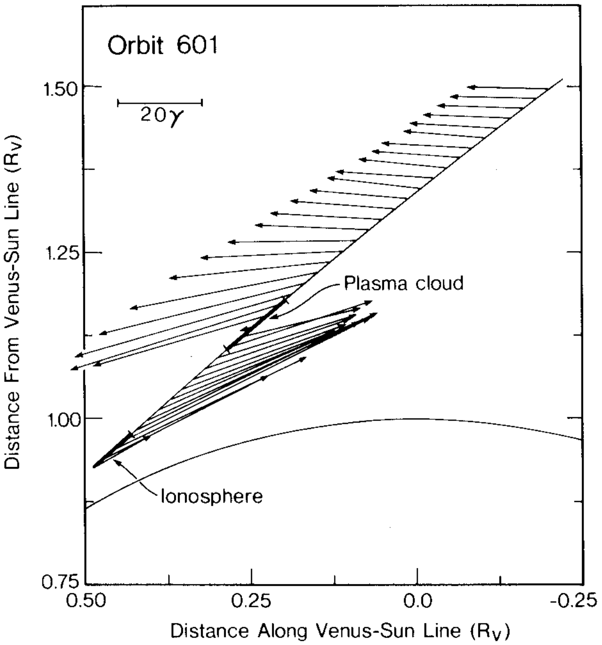

Figure 3. The magnetic field in solar cylindrical coordinates plotted along the trajectory through the plasma cloud (heavy bar). Here the abscissa is the Venus-sun line and the ordinate the distance from the Venus-sun line through the spacecraft.

Discussion and Conclusions

The magnetic configuration shown in Figure 4 is that of a magnetic slingshot. The 60 nT of flow-aligned and 40 nT of cross flow field would apply a Maxwell stress of about 4×10^{-8} dynes/cm^{-2} to the plasma. If we approximate the plasma cloud with a vertical slab 3^{o} thick (300 km) and if we assume the plasma is singly ionized oxygen it should be accelerated at a rate of 0.7 km sec^{-2}. While this is a much greater acceleration than that of gravity, it still takes 130 seconds to accelerate the plasma from the rest assumed to be at the subsolar point, through an angle of one radian. At this point, it would have a velocity of only 90 km/sec, much less than the solar wind velocity but well above the escape velocity. If we assume that the cloud is 500 km in height, i.e., extends from the point of observation down to the ionopause altitude, and that there is a similar cloud in the south, we obtain a loss rate of 2 x 10^{25} ions per second which is much less than Brace et al.'s [1981] experimental upper limit, but still quite significant. We note that if we assume the acceleration is zero at the subsolar point and linearly increases to the observation point, the transit time increases to almost 230 sec and the velocity decreases to 80 km/sec.

To determine if this is a significant loss mechanism for the Venus ionosphere on the longer term we would need to know if this is a frequent occurrence at Venus. Indeed Brace et al. [1981] report that plasma clouds are a frequent occurrence and, in fact, we have seen this geometrical field structure at other plasma clouds. Yet we must emphasize that the conditions observed here were rather special. The encounter was after a decrease in the beta of the solar wind and the interplanetary magnetic field was strong and steady.

This feature of the solar wind-Venus interaction has important consequences for our understanding of the cometary interaction. This feature suggests that in steady-state the cometary solar wind interaction, which is more significantly controlled by mass-loading effects, should be far from cylindrically symmetric. There are also implications for the cometary phenomenon of tail rays which may be the cometary manifestation of the development of the Venus plasma cloud. In particular, since the ridge of high density plasma observed here is apparently moving with much greater speed than the escape velocity it should lead to a formation of a tail streamer far behind the planet. We note that most plasma clouds observed by Brace et al. [1981] are well downstream of the terminator. Since our observations followed by just a few hours an apparent sudden decrease in solar wind beta, the cloud may be a transient phenomenon despite the quasi-static condition of the magnetic field. Comet streamers too are not static features. Further pursuit of the temporal nature of these clouds awaits examination of many additional examples.

In summary our examination of this one event has shown the cloud to be accompanied by a particular configuration of the magnetic field which could lead to the acceleration of the plasma to escape velocity. The plasma in the cloud appears to be hotter than in the ionosphere but much cooler than the solar wind and is accompanied by plasma wave activity similar in spectrum and amplitude to that seen at the ionopause. In combination the magnetic field and plasma data suggest a dayside density ridge connected to a cold plasma streamer behind Venus.

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