Adv. Space Res. Vol. 7, No. 12, pp. (12)115–(12)118, 1987
Printed in Great Britain. All rights reserved.

0273–1177/87 $0.00 + .50

WAVES ON THE SUBSOLAR IONOPAUSE OF VENUS

C. T. Russell,* R. N. Singh,* J. G. Luhmann,* R. C. Elphic* and L. H. Brace**

Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024, U.S.A.
***Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.*

ABSTRACT

The subsolar ionopause of Venus is expected to be stable to both the Kelvin-Helmholtz and flute instabilities. However, magnetic profiles obtained in the subsolar region indicate that the surface of the ionopause contains large amplitude corrugations, perhaps incipient flux ropes. A possible mechanism for destabilizing the boundary is suggested by the observation that the ion density does not drop abruptly at the ionopause but continues to decrease smoothly into the magnetosheath.

INTRODUCTION

We expect the subsolar ionopause of Venus to be stable to fluid instabilities. The two sources of instability that have been discussed for the ionopause are the Kelvin-Helmholtz instability and the flute instability /1/. The Kelvin-Helmholtz instability is driven by the shear in the plasma velocity across an interface. In the subsolar region the velocity of the magnetosheath and the ionospheric plasmas should be at a minimum and the shear should be minimal. Furthermore, the Kelvin-Helmholtz waves grow as the plasma flows toward the terminators. Even if the subsolar ionopause were unstable to the Kelvin-Helmholtz instability the waves would be small here. So too the flute instability is expected to be inoperative because of the tremendous stabilizing effect of the bouyancy force. The magnetic forces pulling downward on the magnetosheath plasma cannot overcome the bouyancy due to the large difference in mass density between the magnetosheath and ionospheric plasmas.

However, there is clear evidence for instability. First, there is the indirect evidence provided by flux ropes in the Venus ionosphere. The Venus ionosphere has two magnetic states. It is either weakly magnetized and threaded with small scale, highly structured ropes or strongly magnetized with a rather uniform steady field /2/. On a single pass of the Pioneer Venus orbiter regions of both type may be observed but never is the ionosphere completely unmagnetized and devoid of flux ropes. Since Venus has no observable intrinsic magnetic field /3/, and since the magnetic belt is present only for large dynamic pressure /10/, the only two feasible sources for flux ropes are a dynamo acting on seed fields diffusing in from the magnetosheath /4/ or some instability of the ionopause. If flux ropes come from an instability of the ionopause, the subsolar ionopause must be unstable because flux ropes are seen everywhere including the low altitude subsolar ionosphere /5/. In this paper we will examine the direct evidence for instability at the ionopause. We will first study the characteristics of the magnetic fluctuations of the plasma and field at the ionopause and suggest a way that the flute instability can be destabilized.

ORBITAL CONSIDERATIONS

The Pioneer Venus spacecraft was put into orbit about Venus in December 1978. It has a highly elliptic orbit of 24 hour period going out to 12 Venus radii (R_V). Periapsis altitude was maintained at low altitude for about 600 orbits. Then it was allowed to climb. During the first 600 orbits the Pioneer Venus spacecraft passed through the subsolar region in two different periods about orbit 185 and about orbit 410. When periapsis began to climb a few high altitude entries into the subsolar ionosphere were obtained near orbit 635 but most of the passes during this period remained in the magnetosheath. Thus most of our information on the subsolar ionopause must be obtained during only two seasons of Pioneer Venus operation.

To the extent that the ionopause occurs at roughly a fixed altitude (which varies with solar zenith angle SZA), the orbit of Pioneer Venus (which is also a shell in solar pointing ecliptic coordinates) cuts the ionopause along two lines, one outbound and one inbound. Neither of these lines need intersect the subsolar point and in fact neither of

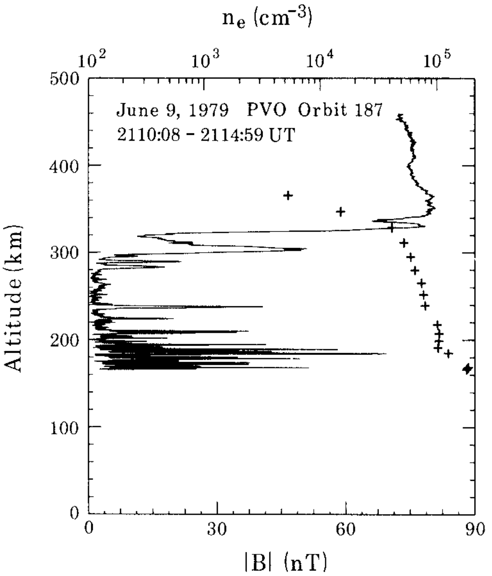

Fig. 1. Altitude profile of magnetic field strength and electron number density outbound on orbit 187, June 9, 1979. Magnetic field data were obtained four times a second on orbits 187 and 189.

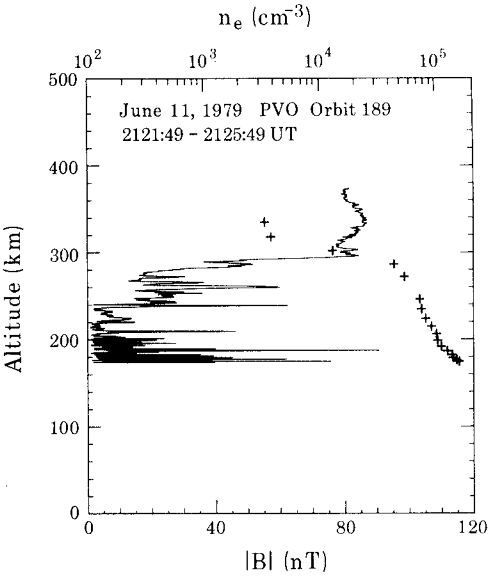

Fig. 2. Altitude profile of magnetic field strength and electron number density outbound on orbit 189, June 11, 1979.

them do. The line of outbound intersections comes closest to the subsolar point. Thus we restrict our attention to outbound ionopause crossings. The solar wind should control the shape of the ionopause and on average the solar wind appears to come from 5 degrees west of the sun because of the motion of Venus perpendicular to the solar wind. The passage through the "subsolar wind" region occurs about 4 orbits after the passage through the subsolar region.

OBSERVATIONS

Fig. 1 shows an altitude profile of the magnetic field and electron density for the outbound pass of Pioneer Venus from periapsis through the ionopause and into the magnetosheath on orbit 187, June 9, 1979. The ionopause crossing occurred at an altitude of 330 km at a solar zenith angle of 6.4^{o}. The equivalent solar-wind zenith angle was 2.9^{o}. At lowest altitudes the magnetic profile shows the thin magnetic structures associated with flux ropes. On the ionopause itself there is also structure. This structure could be due to waves on the ionopause causing it to move back and forth across the spacecraft or it could be structured more akin to flux ropes. We note that the presence of these wave-like structures causes the ionopause transition to spread over 40 km whereas the main current layer is only 10 km thick. The electron density and presumably the ion density too does not change abruptly at the ionopause rather it decreases smoothly as the magnetosheath is entered.

Fig. 2 shows a second example of the magnetic field and electron density for the outbound pass on orbit 189, June 11, 1979. The ionopause was crossed at an altitude of 290 km at a solar zenith angle of 7.7^{o} and a solar wind zenith angle of 2.3^{o}. Again the profile shows flux ropes at lowest altitudes and an ionopause with much structure in the magnetic field. Further the difference between ionopause structure and flux ropes is less distinct in this example, especially in the altitude range from 240 to 280 km.

While the displays of Figs. 1 and 2 provide little help in distinguishing waves on the boundary from the helical structure of flux ropes, the vector components of the magnetic field can help in this regard. Fig. 3 shows the vector components in radial east and north coordinates plotted versus time. Since the ionopause is roughly horizontal, there should be no radial component of the magnetic field to first order. The radial component of the field is small except in the ionopause structures and flux ropes.

The structure centered at 2113:25 is particularly interesting. Looking at the time profile of the total field it appears as if one could explain the structure with a boundary motion of an otherwise static ionopause. However although there is a large component of the magnetosheath field in the N-direction, there is zero component in this direction in this structure. Secondly, there is a very striking signature in the B_R component. One would expect there to be a B_R fluctuation if there was a wave in the boundary but it would have the same period as the fluctuation in the total field. In fact, the B_R fluctuation has

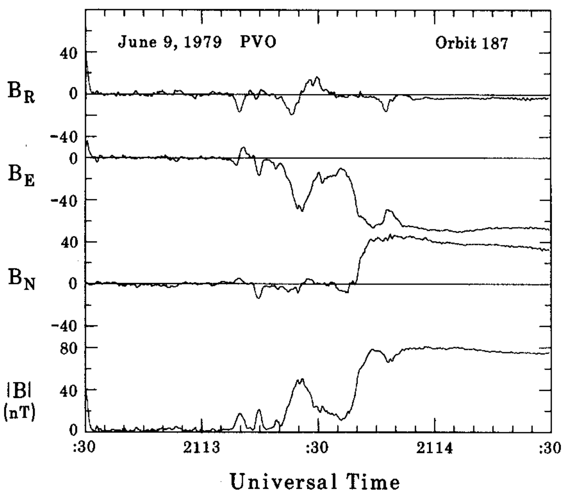

Fig. 3. Time series of vector magnetic field in radial, east and north components for two minutes on the outbound pass of orbit 187.

twice the period of the B_E or total B fluctuation. In other words as the total field rises and falls the radial component rises, falls, goes to a negative value and returns to zero. This is the classic signature of a flux rope /6/. The oscillation centered at 2113:45 also has a small radial anomaly so it appears this field too is being wound up around an axis. It appears that we are seeing the formation of flux ropes at the ionopause.

Fig. 4 shows the radial east and north components of the magnetic field during our second example, on Orbit 189. There are no features that can be explained as simple waves on the ionopause. The main "ionopause" oscillation at 2124:45 has a B_R signature of a flux rope and the other structures at 2124:05, 2124:25, 2124:30, 2124:37 all have directions quite different from that of the magnetosheath magnetic field and many of them have quite significant radial components of the magnetic field. Again, it appears that we are observing an altitude profile of the flux rope forming process.

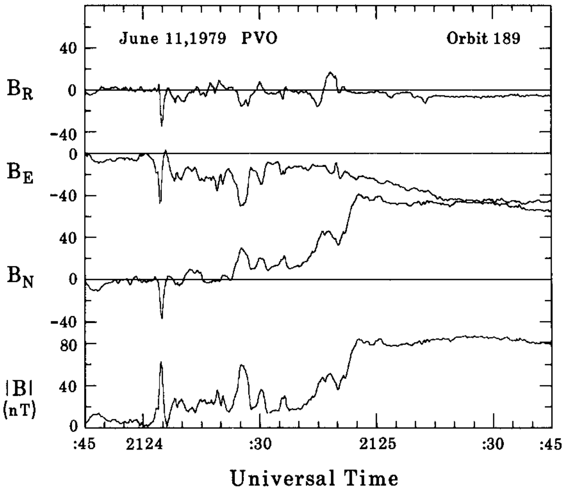

Fig. 4. Time series of vector magnetic field in radial, east and north components for two minutes on the outbound pass of orbit 189.

DISCUSSION

These observations suggest that the subsolar ionopause is a source of flux ropes despite the fact that bouyancy forces are expected to stabilize the ionopause against the sinking of flux tubes /1/. The means by which the subsolar ionopause may defeat this stabilizing influence of bouyancy is as follows. First, magnetic field is convected to the subsolar region by the solar wind. In the subsolar region the plasma moves very slowly and the density on these magnetosheath field lines builds up through photoionization of the oxygen exosphere in the same way that ions are formed in the Venus ionosphere. In the Venus ionosphere newly created ions are transported either horizontally or vertically downward to recombine. In the magnetosheath new ions are convected away by the solar wind electric field. The observation that density smoothly changes across the ionopause suggests that the loss rate in and near the ionopause due to solar wind convection is not large. If the density builds up to near ionospheric densities, then the fact that the magnetosheath plasma is magnetized allows the plasma to sink. The curved field lines add an additional downward force on the plasma which overcomes bouyancy. The twist in the field occurs because as the flux tube floats in near equilibrium it is being rotated by the velocity shear which varies along the length of the flux tube. When the flux tube is well inside the ionosphere it should soon become as dense as the ionospheric plasma and sink due to the magnetic curvature forces. High resolution studies of the electron density might be quite revealing in determining how steep these various gradients are and we plan to pursue these in the future. Further, the mechanism proposed herein seems to be a natural candidate for a computer simulation. We urge it be done.

Earlier work on the formation of the low altitude belt of magnetic field /7,8,9,10/ concentrated on the diffusive entry of the field and transport of a low amplitude steady component. However, it is possible that flux ropes could act in the same way to transport magnetic flux from the ionopause to low altitudes. This low altitude flux, however, would be highly twisted. On occasion one observes highly twisted magnetic fields on the upper edge of the low altitude belt. Perhaps these twisted fields represent newly added flux, which then unravels as it dissipates at low altitudes. On the other hand, it is clear from the smooth field profile from ionopause to low altitude belt on many days of high-pressure solar wind that the diffusive entry mechanism is present and significant.

CONCLUSIONS

The vector components of the magnetic field observed at the subsolar ionopause suggests that flux ropes are forming on the subsolar ionopause and convecting downward. Simultaneous electron density profiles show that magnetosheath field lines are heavily mass loaded. We hypothesize that the magnetic forces are sufficient to overcome the stabilizing effect of the bouyancy of the slightly more dense ionospheric plasma.

ACKNOWLEDGMENTS

This work was supported by the National Aeronautics and Space Administration under NASA research contract NAS2-12383.

REFERENCES

1. R.C. Elphic and A.I. Ershkovich, On the stability of the ionopause of Venus, J. Geophys. Res., 89, 997-1002, 1984.

2. J.G. Luhmann, R.C. Elphic, C.T. Russell, J.D. Mihalov and J.H. Wolfe, Observations of large-scale steady magnetic fields in the dayside Venus ionosphere, Geophys. Res. Lett., 7, 917-920, 1980.

3. C.T. Russell, R.C. Elphic, J.G. Luhmann and J.A. Slavin, On the search for an intrinsic magnetic field at Venus, Proc. Lunar Planet. Sci. Conf. 11th, 1897-1906, 1980.

4. J.G. Luhmann and R.C. Elphic, On the dynamo generation of flux ropes in the Venus ionosphere, J. Geophys. Res., 90, 12047-12056, 1985.

5. R.C. Elphic and C.T.Russell, Global characteristics of magnetic flux ropes in the Venus ionosphere, J. Geophys. Res., 88, 2993-3003, 1983.

6. R.C. Elphic and C.T. Russell, Magnetic flux ropes in the Venus ionosphere: Observations and models, J. Geophys. Res., 88, 58-72, 1983.

7. C.T. Russell, J.G. Luhmann and R.C. Elphic, The properties of the low altitude magnetic belt in the Venus ionosphere, Adv. Space Res., 2, #10, 13-16, 1983.

8. J.G. Luhmann, C.T. Russell and R.C. Elphic, Times scales for the decay of induced large-scale fields in the Venus ionosphere, J. Geophys. Res., 89, 362, 1984.

9. T.E. Cravens, H. Shinagawa and A.F. Nagy, The evolution of large-scale magnetic fields in the ionosphere of Venus, Geophys. Res. Lett., 11, 267, 1984.

10. J.L. Phillips, J.G. Luhmann and C.T. Russell, Growth and maintenance of large-scale magnetic fields in the dayside Venus ionosphere, J. Geophys. Res., 89, 10676-10684, 1984.