GEOPHYSICAL RESEARCH LETTERS, VOL. 8, NO. 5, PAGES 517-520, MAY 1981

OBSERVATIONS OF LARGE SCALE STEADY MAGNETIC FIELDS IN THE NIGHTSIDE VENUS IONOSPHERE AND NEAR WAKE

J.G. Luhmann, R.C. Elphic, C.T. Russell and J.A. Slavin

Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California 90024

J.D. Mihalov

NASA Ames Research Center, Moffett Field, California 94035

Abstract. Pioneer Orbiter Magnetometer observations during the few minutes surrounding nightside periapsis traversals generally show a weak average field of magnitude <10 gammas between ~200 km and the periapsis altitude of ~150 km except when either 1) the local solar wind dynamic pressure is high or 2) the spacecraft is in a ~70° wide solar zenith angle range, which includes the midnight meridian and is centered west of it at ~1 hr local time. Both the direction and magnitude of the low altitude weak field vary irregularly along the orbit on apparent spatial scales of 1-1000 km, the peak value of the field magnitude remaining under ~20 gammas. When the local solar wind dynamic pressure exceeds ~5 × 10^{-8} dynes cm^{-2} average low altitude fields of up to ~40 gammas with a primarily horizontal orientation are observed in the regions adjacent to the terminator. In contrast, within ~35° of the antisolar point where the average magnetic field is typically higher (~10-20 gammas), the field magnitude does not exhibit a similar correlation with incident solar wind dynamic pressure. Moreover, it is found that the radial component may exceed 60% of the total field magnitude. Closer inspection of the data near the antisolar point indicates that the radial fields are frequently related to the observation at higher altitudes of extended regions of radial field that reverse direction along the orbit. These results are consistent with the interpretation that a magnetotail-like feature is sometimes present down to ionospheric altitudes on the nightside of Venus.

Introduction

Since the Pioneer Venus orbiter was injected into orbit on 4 December, 1978, periapsis has drifted across the nightside hemisphere at ~150 km altitude and ~15°N latitude three times, thereby providing several hundred orbits which included nightside ionospheric data. Initial observations of magnetic fields in the Venus nightside ionosphere by the Pioneer Venus Orbiter magnetometer (Russell et al., 1980) were reported by Russell et al. (1979) who suggested that the moderately strong (20-30 gammas) horizontal fields were convected remnants of ionospheric fields induced on the dayside by the solar wind interaction. Here, the results of an analysis of a large sample of these data is presented which reveals more details of the characteristics of the magnetic fields near periapsis when periapsis is on the nightside of the planet. The complementary analysis for the dayside low altitude fields can be found in the recent letter by Luhmann et al. (1980). Some of the data discussed in the present report have been previously examined for evidence of an intrinsic planetary magnetic field by Russell et al. (1980) who placed a very low upper limit on Venus' internal dipole moment. Practically all of the magnetic fields discussed below can therefore be assumed to arise from ionospheric and other external sources.

Observations

The nearly polar, elliptical orbit of Pioneer Venus, which is described in detail elsewhere (Colin et al., 1979) typically intersects the Venus ionosphere between the latitudes of ~60°N and ~50°S (Brace et al., 1980; Elphic et al., 1980). Periapsis, maintained by spacecraft maneuvers at ~150 km altitude (for the first ~500 orbits) drifts across the nightside ionosphere at ~15°N latitude during the course of ~112 24-hour-period orbits. For the purpose of the present study, orbits 19-120 and 467-578 were selected because their periapsides occurred at solar zenith angles >90°. The second periapsis traversal of the nightside ionosphere (orbits 243-355) was not included in the statistical analyses because of the loss of data from many orbits due to a superior conjunction and to dedication of telemetry facilities to the Pioneer Saturn encounter. However, inspection of the available orbits indicates that the average characteristics of these data were consistent with those observed during the other two nightside traversals.

Some representative time series of the magnitude of the magnetic field observed near Venus during orbits with periapsis in the nightside ionosphere are shown in Fig. 1. The dashed lines show the approximate locations of the nightside ionopause, where the plasma density falls to a few electrons cm^{-3} within an altitude interval of ~10's of km (Brace et al., 1980). As the examples in Fig. 1 illustrate, the magnetic field may vary over different time (space) scales throughout the ionosphere, with peak magnitudes typically ≲40 gammas. The statistical analyses of the ionospheric field that are described here utilized the averaged magnitudes and directions observed at altitudes below 200 km. Because this value is nearly the same as the ionospheric field parameter $|\langle\overline{B}\rangle_{per}|$ which was employed in the analogous dayside ionospheric fields study of Luhmann et al. (1980), the present study can be regarded as the complement of the dayside investigation. However, below it will be suggested that the nightside ionospheric fields are sometimes closely related to the magnetic field structure at higher altitudes in a manner that has no dayside analog.

In the analysis of the dayside ionospheric fields it was found that during about 70% of the orbits the average magnetic field in the altitude range between ~150 km and ~200 km was less than 10

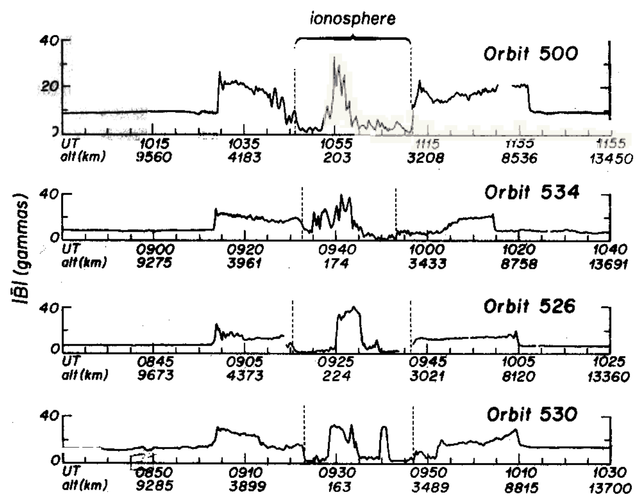

Figure 1. Typical time series of the magnitude of the magnetic field observed along the Pioneer Venus orbit when periapsis occurred at night. The time resolution of this plot is 1 minute. Direction of field in the ionosphere is irregular during orbits 500 and 534 and nearly radial during orbits 526 and 530 (see text).

Paper number 1L0391.
0094-8276/81/001L-0391$01.00

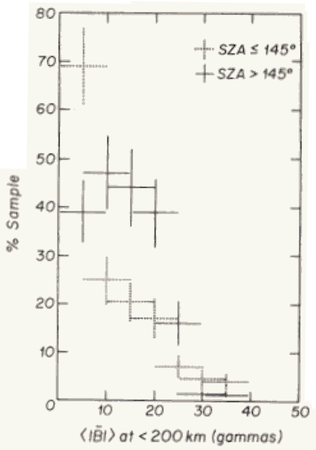

Figure 2. Distribution of field magnitude observed between ~150 and 200 km on the nightside of Venus.

gammas. During the remaining 30% of the orbits the average magnitude of this field was substantially greater, sometimes reaching ~130 gammas (Luhmann et al., 1980). Figure 2 shows the statistics of the average field for the nightside ionosphere. Because it was apparent, at first glance, that the field near the antisolar point was different from the typical field closer to the terminators, the nightside data were divided into the two solar zenith angle ranges indicated. The distribution of magnitudes for the near-terminator sectors resembles the distribution for the dayside ionosphere. The field magnitude is generally ≲10 gammas, but there is a tail on the distribution from the occasional occurrence of fields of up to ~35 gammas. Although the high fields on the nightside are ~8 times smaller than the maximum fields observed in the dayside ionosphere, the similar behavior of the distribution of magnitudes suggests a dayside-like behavior of the nightside fields near the terminator. This similarity will also be seen in other analyses. In contrast, the distribution of field magnitudes for the region within 35° of the antisolar point (see Fig. 2) shows that field strengths over 10 gammas are typical in this sector.

The distribution of the occurrence of high dayside ionospheric fields in solar zenith angle (SZA) peaked around the subsolar point. An analogous distribution for nightside average fields >10 gammas is shown in Fig. 3. From Fig. 3 it is apparent that these extraordinarily high nightside fields are observed most frequently in the offset (with respect to the antisolar point) solar zenith angle range 160°E <SZA<130°W where E and W denote directions east and west of the midnight meridian, respectively. Accordingly, the data were again separated into two sets, this time consisting of orbits

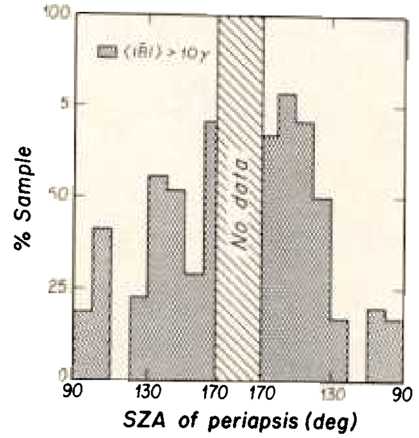

Figure 3. Solar zenith angle distribution of high (>10γ) field observations near periapsis. East and west are in the sense of Earth's, here measured with respect to the midnight meridian.

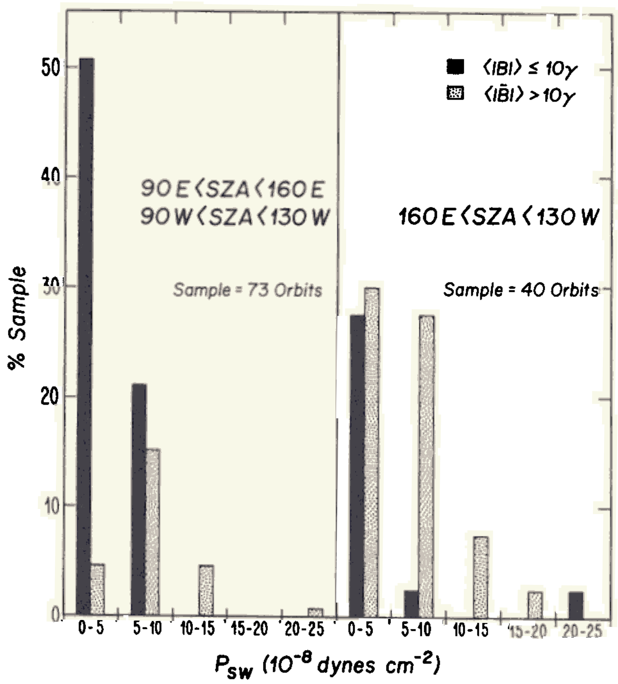

Figure 4. Occurrence frequencies of high and low field observations for various values of solar wind dynamic pressure measured on outbound leg of orbit.

with periapsis SZA within the aforementioned interval and the other comprised of the remainder of the nightside periapsis orbits.

Using the above division of the data, the relationship of nightside high field (>10 gammas) occurrence to solar wind dynamic pressure as observed by the on-board plasma analyzer (Intriligator et al., 1980) just exterior to the outbound bow shock was investigated. Figure 4 shows the histograms for high and low field occurrence at various solar wind dynamic pressures. The histograms of Fig. 4a, for the SZA intervals adjacent to the terminator, appear very similar to the histograms obtained in the dayside fields study; both indicate that high ionospheric fields are correlated with extraordinarily high (≥5 × 10^{-8} dynes cm^{-2}) incident solar wind dynamic pressure. On the other hand, as illustrated by Fig. 4b, the more common high fields observed in the antisolar interval 160°E<SZA<130°W occur for lower solar wind dynamic pressures than near the terminator. Another feature of the nightside high fields which is not observed on the dayside becomes apparent when the average orientations of the near-periapsis fields are examined. Figure 5 shows the fraction of the total field in the radial component for all nightside SZA values. The high dayside ionospheric fields are

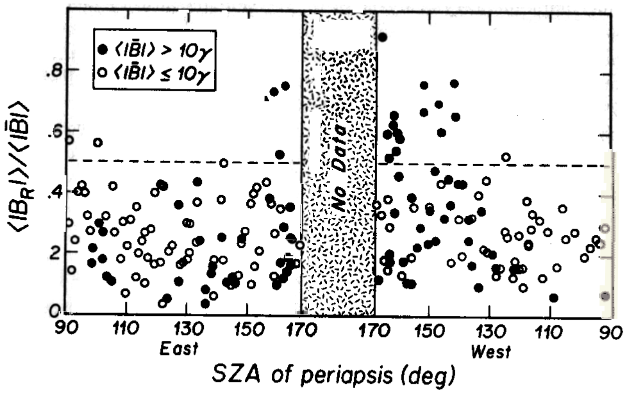

Figure 5. Fractional contribution of radial field to average between ~150 and 200 km as a function of solar zenith angle.

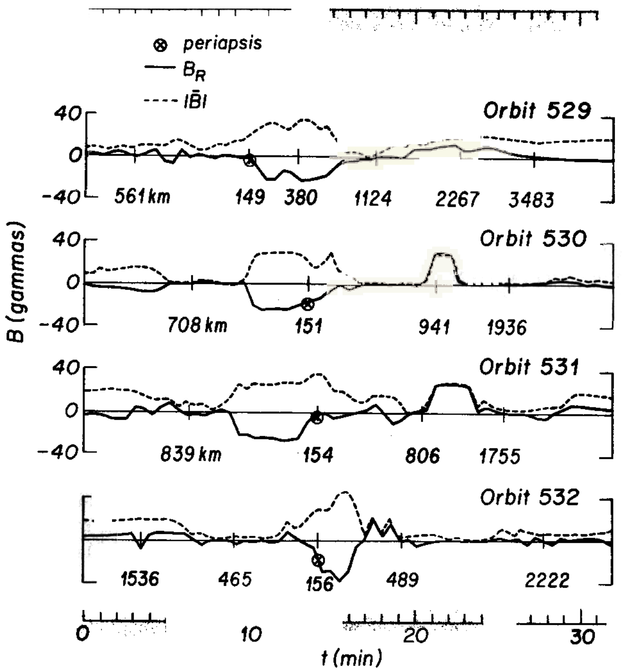

Figure 6. Time series of some orbits with high radial field components near periapsis.

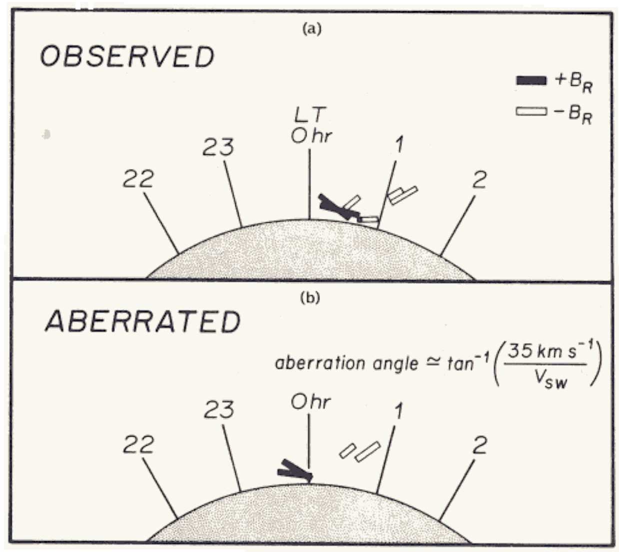

Figure 8. a) Local time plot of the data of Fig. 7.
b) Subset of the data of Fig. 7a rotated by the appropriate aberration angles α.

practically horizontal everywhere. As illustrated in Fig. 5 the high nightside ionospheric fields in the regions near the terminator are also mostly horizontal, but the fields in the antisolar region 160°E<SZA<130°W sometimes exhibit substantial ($\gtrsim$60%) radial components.

It is found that the subset of high field orbits with high radial field components is characterized by time series profiles such as those shown in the two lower panels of Fig. 1 and in more detail in Fig. 6, where 32 s averages of the magnetic field data for several consecutive orbits are shown to emphasize the large scale structure. Here a region of negative radial field followed by a region of positive radial field is observed at altitudes $\lesssim$2500 km. For the orbits shown the field is almost completely radial, although this is not always the case. The regions of opposing field may be contiguous, as on orbit 532, or separated by an interval of low field as on orbits 530 and 531. Sometimes one or two radial field intervals of the same sign are observed or the sign reversal may be opposite to that illustrated. The locations of the orbit segments where the observations of radial fields for the series of consecutive orbits 529-532 were obtained are shown in projection against the dark hemisphere of Venus in Fig. 7. Another view is shown in Fig. 8a which gives the local time projection of these data.

Discussion

As mentioned in the conclusions of the earlier study by Luhmann et al. (1980), one interpretation that is consistent with the observed

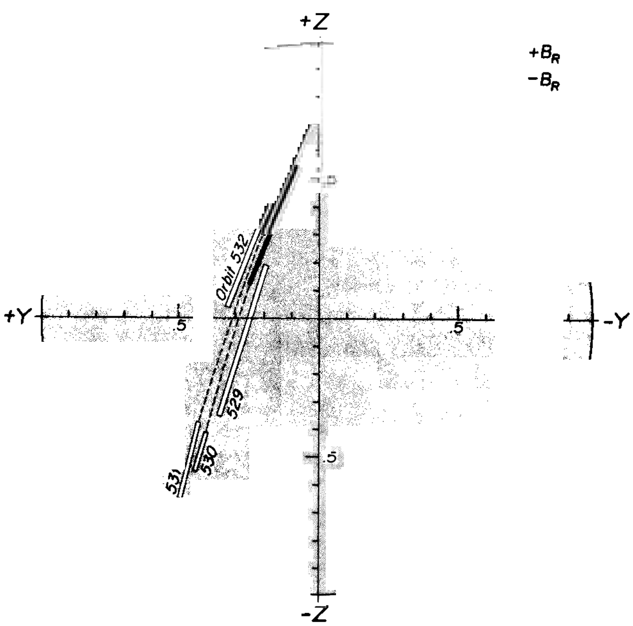

Figure 7. Projected locations of the orbit segments where the radial fields shown in Fig. 6 were observed on the dark side of Venus.

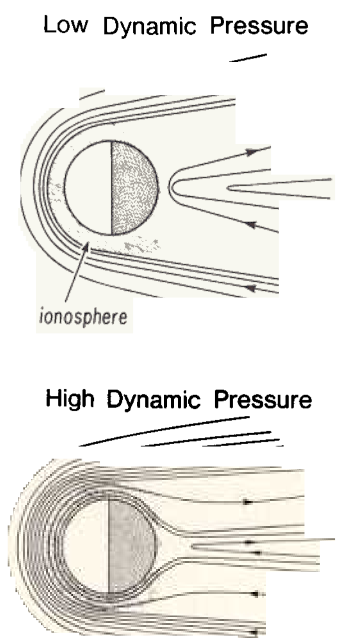

Figure 9. Suggested magnetic field configuration in the plane of symmetry which would be consistent with observations near Venus. The tail current sheet is normal to the plane shown.

geometry of the large-scale magnetic fields in the dayside ionosphere of Venus is that the ionospheric field lines form a belt across the dayside hemisphere. Outside of the ionosphere, in the 'sheath' region; the field consists of interplanetary field lines that are piled up in front of the dayside ionosphere. The manner in which these various field structures connect to the nightside ionosphere and wake region determines the results of the present study.

It is expected that the captured field lines will somehow slip over or through the ionosphere due to the magnetic stress caused by the convecting remainder of the field line. However, the slippage is evidently slow enough to produce a magnetic wake (Russell et al., 1979) out to distances $\gtrsim 11$ Venus radii. The magnetic wake appears to be magnetotail-like, with at least two lobes of opposing (sunward and antisunward) field separated by a current sheet (Russell et al., 1980c). The two lobes are produced by the folding of the captured field and the field of the current sheet on the surface where the tail fields of opposing direction come into contact. This geometry is essentially the same as that proposed by Alfvén (1957) for the formation of comet tails.

The data presented here, where radial fields of alternating sign were observed at low altitudes and in the nightside ionosphere, suggests that the antiparallel magnetotail fields can terminate very close to the planet. Some configurations (in the plane of symmetry) of the combined magnetic fields of the diverted solar wind, ionosphere and tail current sheet which are consistent with the observations are sketched in Fig. 9. For conditions of low solar wind dynamic pressure the ionosphere is field-free (with small scale structure having apparent dimensions $\lesssim 100$ km) except near the low altitude edge of the tail current sheet. For conditions of high solar wind dynamic pressure horizontal fields are present inside of the ionosphere and across the terminator. These ionospheric fields probably merge with the low altitude tail structure in the nightside ionosphere. Within this framework, the locations of the radial field observations shown in Figs. 7 and 8a with respect to the antisolar point can be explained. The average interplanetary field and ionosheath field directions during the period of observations represented was consistently east to west as seen by the dayside hemisphere. This orientation would be expected to produce a tail lobe that was antisunward east of the midnight meridian and sunward west of midnight. Figure 7 shows that the signs of the radial fields are in the proper sense, but the plane of reversal, presumably a north-south plane, is displaced to the west of the midnight meridian. Another view of this behavior is seen in Fig. 8a. An explanation of the apparent aberration from midnight is that the orbital motion of the planet at ~35 km s^{-1} normal to the (radial) solar wind velocity should deflect the axis of the magnetotail from the antisunward direction. The data can be approximately adjusted for this effect by rotating the points eastward by the angle $\alpha = \tan^{-1}(35/V_{SW})$ where V_{SW} is the solar wind velocity in km s^{-1} measured by the plasma analyzer just outside of the outbound bow shock. The results of such a correction for a subset of the data of Fig. 8a are shown in Fig. 8b where the sign reversal is now seen to be located near the midnight meridian.

Finally it should be pointed out that other observations by the Pioneer Venus Orbiter have lead to similar conclusions about the magnetic field geometry (i.e. see Taylor et al., 1980, Brace et al., 1980). Moreover, elements of the above picture obtained from the magnetometer data are present in the theoretical models of the Venus-solar wind interaction proposed by Johnson and Midgely (1967), Eroshenko (1979), Cloutier and Daniell (1979), and Johnson and Hanson (1979), among others, and in the results of the laboratory simulations by Dubinin et al. (1980). What remains to be formulated is an integrated model which can describe the sheath, ionospheric, and wake fields together for a variety of solar wind conditions.

Acknowledgments

The invaluable assistance of G. McLean, H. Herbert, M.F. Garcia and D.J. Kleim in the processing and analysis of the data is gratefully acknowledged. The authors also benefited from discussions with L.H. Brace, F.L. Scarf and P.A. Cloutier. This research was supported by NASA Contract NAS 2-9491.

References

Alfvén, H., On the theory of Comet tails, Tellus, IX, 92, 1957.

Brace, L.H., R.F. Theis, W.R. Hoegy, J.H. Wolfe, J.D. Mihalov, C.T. Russell, R.C. Elphic and A.F. Nagy, The dynamic behavior of the Venus ionosphere in response to solar wind interactions, J. Geophys. Res., *85*, 7663, 1980.

Colin, L., Encounter with Venus: an update, Science, *205*, 44, 1979.

Cloutier, D.A. and R.E. Daniell, Jr., An electrodynamic model of the solar wind interaction with the ionospheres of Mars and Venus, Planet. Space Sci., *27*, 1111, 1979.

Dubinin, E.M., P.L. Israelovich, I.M. Podgorny, and S.I. Shkolinikova, Laboratory model of the induced magnetosphere and its comparison with the spacecraft measurements near Venus, Rep #587, Acad. of Sciences USSR Space Research Institute, 1980.

Elphic, R.C., C.T. Russell, J.A. Slavin and L.H. Brace, Observations of the dayside ionopause and ionosphere of Venus, J. Geophys. Res., *85*, 7697, 1980.

Eroshenko, E.G., Unipolar induction effects in the magnetic tail of Venus, Cosmic Res., *17*, 77, 1979.

Intriligator, D.S., J.H. Wolfe, and J.D. Mihalov, The Pioneer Venus Orbiter plasma analyzer experiment, IEEE Trans. on Geoscience and Remote Sensing, GE-18, *39*, 1980.

Johnson, F.S., and J.E. Midgely, Induced magnetosphere of Venus, Space Res., *9*, 760, 1969.

Johnson, F.S., and W.B. Hanson, A new concept for the daytime magnetosphere of Venus, Geophys. Res. Letters, *7*, 581, 1979.

Luhmann, J.G., 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. Letters, *7*, 917, 1980.

Russell, C.T., R.C. Elphic, J. Slavin, Initial Pioneer Venus Magnetic Field Results: Nightside Observations, Science, *205*, 114, 1979.

Russell, C.T., R.C. Snare, J.D. Means and R.C. Elphic, Pioneer Venus Orbiter fluxgate magnetometer, IEEE Trans. on Geoscience and Remote Sensing, GE-18, 32, 1980a.

Russell, C.T., R.C. Elphic and J.A. Slavin, Limits on the possible intrinsic magnetic field of Venus, J. Geophys. Res., *85*, 8319, 1980b.

Russell, C.T., R.C. Elphic, J.G. Luhmann, J.A. Slavin, The magnetotail of Venus: Pioneer Venus observations, EOS Trans. American Geophys. Union, *61*, 1019, 1980c.

Taylor, H.A., Jr., H.C. Brinton, S.J. Bauer, R.E. Hartle, P.A. Cloutier, and R.E. Daniell, Jr., Global observations of the composition and dynamics of the isonosphere of Venus: implications for the solar wind interaction, J. Geophys. Res., *85*, 7765, 1980.

(Received February 3, 1981;
accepted February 26, 1981.)