observed decrease of O^+ with altitude, we obtain at SZA = 70° the value H/r_0 “ 0.07. The quantity H, and consequently H/r_0, are approximately constant above 400 km. The ratio of 0.07 derived from measured parameters lies midway in the range of values that have been inferred from measurements of the shock position (*6, 7*).

Pressure balance across the ionopause. If we assume that under steady conditions the magnetic field in the vicinity of the ionopause is tangent to the ionopause, we may expect the expression $(B^2/8\pi + p)$ to remain constant as the boundary is traversed (*6, 8*) (B is the local magnetic field strength, and P is the local charged particle pressure). The typical particle pressure at 500 km may be evaluated from Figs. 3 and 4. Inside the ionosphere B is typically (but with significant exceptions) of the order of 1 γ (*9*). Using these values to evaluate the expression in the ionosphere and normalizing, we obtain:

$$\left| \left(\frac{B}{48\ \gamma}\right)^2 + \left(\frac{n}{10^4\ \mathrm{cm}^{-3}}\right)\left(\frac{T_e + T_i}{6500\ \mathrm{K}}\right) \right| \doteq 1 \quad (1)$$

where n is the local plasma density. In passing into the ionopause from below, the thermal concentration decreases toward 10 cm^{-3} and T_e and T_i remain approximately constant. If we assume that no high-temperature particles are present in the boundary region, Eq. 1 requires B to be 48 γ. Russell (*9*) reports that for most of the early orbits B increases to 40 to 60 γ at the ionopause. The magnetic field is typically supplying the bulk of the pressure balance, which implies that particles with shocked solar wind energy do not contribute significantly to the balance at the ionopause at SZA = 70°.

W. C. KNUDSEN
Lockheed Palo Alto Research Laboratory, Palo Alto, California 94304
K. SPENNER
Institut für Physikalische Weltraumsforschung der Fraunhofer Gesellschaft, 78 Freiburg, West Germany
R. C. WHITTEN
NASA Ames Research Center Moffet Field, California 94035
J. R. SPREITER
Stanford University, Stanford, California 94305
K. L. MILLER
Lockheed Palo Alto Research Laboratory
V. NOVAK
Institut für Physikalische Weltraumsforschung der Fraunhofer Gesellschaft

References and Notes

1. L. Colin and C. F. Hall, *Space Sci. Rev.* **20**, 283 (1977).
2. W. C. Knudsen, J. Bakke, K. Spenner, V. Novak, *Space Sci. Instrum.*, in press.
3. R. C. Whitten, *J. Geophys. Res.* **74**, 5623 (1969).
4. R. H. Chen and A. F. Nagy, *ibid.* **83**, 1133 (1978).
5. H. E. Hinteregger, *J. Atmos. Terr. Phys.* **38**, 791 (1976).
6. J. R. Spreiter, A. L. Summers, A. W. Rizzi, *Planet. Space Sci.* **18**, 1281 (1970).
7. C. T. Russell, in *Solar System Plasma Physics*, C. F. Kennel, L. J. Lanzerotti, E. N. Parker, Eds. (North-Holland, New York, in press).
8. C. L. Longmire, *Elementary Plasma Physics* (Interscience, New York, 1963).
9. C. T. Russell, R. C. Elphic, J. A. Slavin, *Science* **203**, 745 (1979).
10. The RPA experiment is supported by NASA through contract NAS2-9481 and by Bundesminister für Forschung and Technologie through contract 01 Do 238 (RV 14-B 28/73). We thank all those whose dedicated efforts made possible the perfectly working RPA.

16 January 1979

Electron Temperatures and Densities in the Venus Ionosphere: Pioneer Venus Orbiter Electron Temperature Probe Results

Abstract. *Altitude profiles of electron temperature and density in the ionosphere of Venus have been obtained by the Pioneer Venus orbiter electron temperature probe. Elevated temperatures observed at times of low solar wind flux exhibit height profiles that are consistent with a model in which less than 5 percent of the solar wind energy is deposited at the ionopause and is conducted downward through an unmagnetized ionosphere to the region below 200 kilometers where electron cooling to the neutral atmosphere proceeds rapidly. When solar wind fluxes are higher, the electron temperatures and densities are highly structured and the ionopause moves to lower altitudes. The ionopause height in the late afternoon sector observed thus far varies so widely from day to day that any height variation with solar zenith angle is not apparent in the observations. In the neighborhood of the ionopause, measurements of plasma temperatures and densities and magnetic field strength indicate that an induced magnetic barrier plays an important role in the pressure transfer between the solar wind and the ionosphere. The bow shock is marked by a distinct increase in electron current collected by the instrument, a feature that provides a convenient identification of the bow shock location.*

The Pioneer Venus orbiter electron temperature probe (OETP) is designed to measure the thermal structure of the ionosphere of Venus. These data should permit us to better understand the processes by which the ionosphere is heated and cooled. The case of Venus is of particular interest in this regard because of the strong interaction expected between the solar wind and the ionosphere of this weakly magnetized planet. Unlike Earth and Jupiter, whose strong

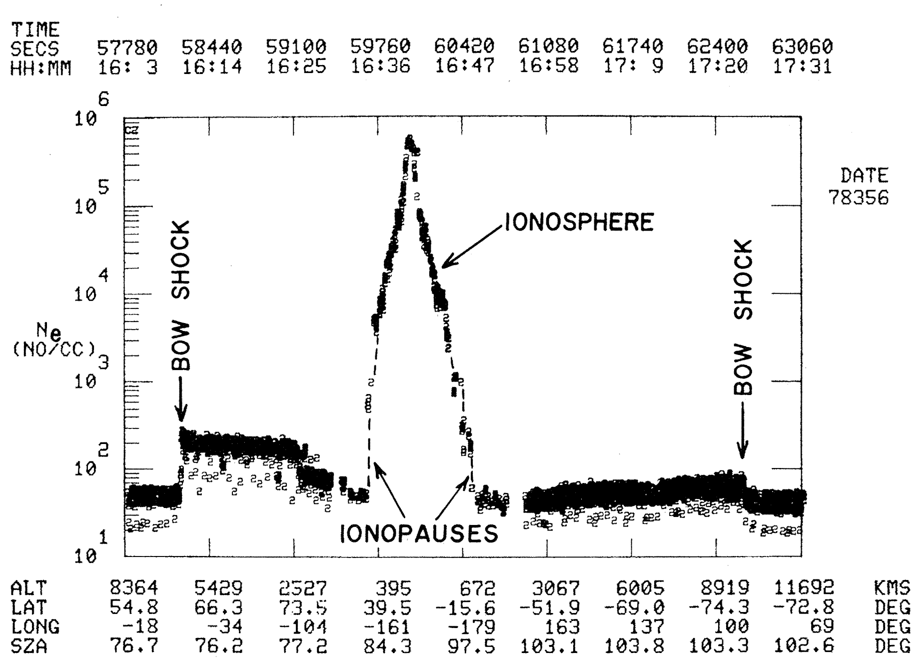


Fig. 1. Onboard OETP measurements of N_e acquired on orbit 18 showing the bow shock and ionosphere signatures. Background densities of about 50 per cubic centimeter are due to spacecraft photoelectrons.

Table 1. Ionopause plasma and magnetic pressures.

Date (year-day)	N_e (cm^{-3})	T_e (K)	$\lvert B \rvert$ (gammas)	$N_e k(T_e + T_i)$* ($N\ m^{-2}$)	$B^2/8\pi$ ($N\ m^{-2}$)
78339	1.4 (4)	4900	62	1.4 (−9)	1.5 (−9)
78340	1.2 (4)	4400	39.5	1.1 (−9)	6.2 (−10)
78341	1.8 (4)	3600	48	1.3 (−9)	9.2 (−10)
78342	7 (3)	5000	32	7.2 (−10)	4.1 (−10)

*T_i assumed equal to $T_e/2$.

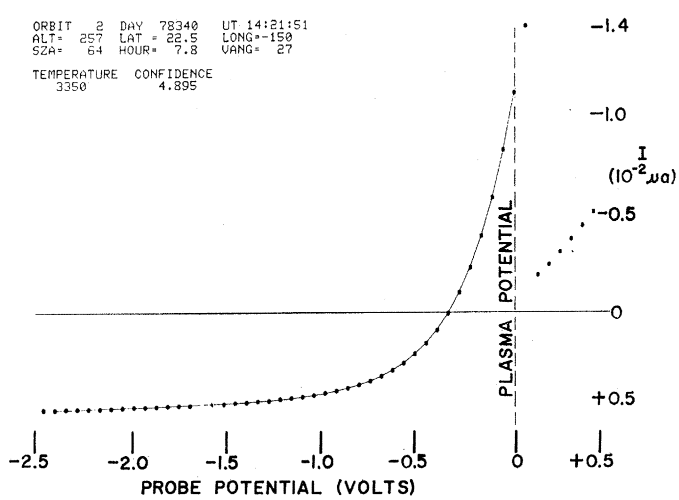
intrinsic magnetic fields stand off the solar wind at great distances, Venus appears to use its ionosphere to divert the solar wind. We present here some of the early OETP measurements at Venus which illustrate these effects, and we speculate on what they tell us about the processes involved in solar wind–ionosphere interactions. Because the data are incomplete, the analysis is preliminary, and the orbital ephemerides are unrefined at this writing, these results must be considered preliminary.

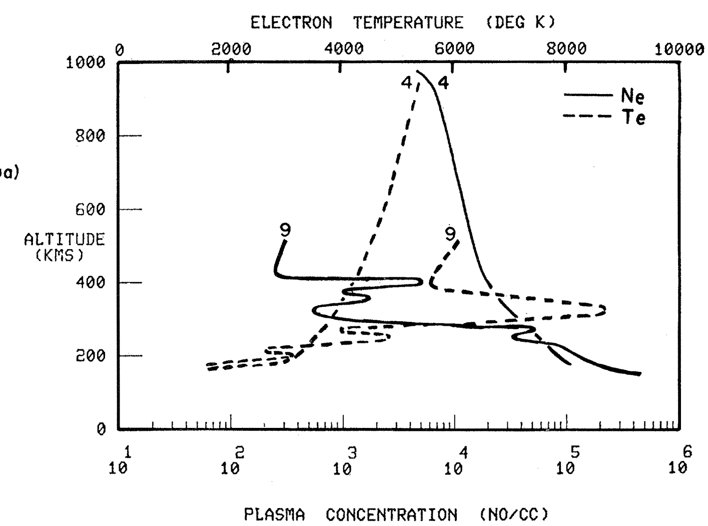
The OETP instrument measures the electron temperature (T_e) and density (N_e) along the path of the Pioneer Venus orbiter through the ionosphere. An outline of the instrument operation is given elsewhere (*1*). The theory of its operation is covered by Brace *et al.* [see (*2*)].

The sampling geometry of the orbiter at Venus is illustrated in figure 3 of Colin (*3*). Periapsis was initially 27° from the evening terminator. The motion of Venus about the sun caused periapsis to approach the terminator at the rate of 1.6° per day. During the inbound orbits the orbiter enters the ionosphere at high latitudes, and during the outbound orbits it exits the ionosphere just south of the equator. Periapsis remains at 18°N latitude at altitudes in the vicinity of 150 km.

The instrument performs a crude onboard processing of the Langmuir probe volt-ampere characteristics to provide values of T_e at intervals of about 1 second and N_e at intervals of about 2 seconds, depending upon the total spacecraft bit rate used. Figure 1 is a computer graphics plot of the N_e processed onboard for orbit 18 taken on 22 December 1978. A dashed line is added where needed to interpolate through regions not fully resolved by the measurements. Bow shock and ionopause crossings are clearly evident. The background of about 50 per cubic centimeter outside the bow shocks represents photoelectrons from the spacecraft itself. It is not clear at this time whether the electron enhancement between the bow shock and the ionopause represents a real population of magnetosheath electrons or is caused by changes in the photoelectron background itself. Planned correlations with data from Pioneer Venus instruments may explain this magnetosheath signature.

To permit ground correction for simplifying assumptions made in designing the onboard processing circuitry, the instrument also stores and returns raw data from some of the volt-ampere characteristics. Several of these curves are taken per minute, the number depending upon the available bit rate. Figure 2 is an example of one such "stored curve," which was recorded at 257 km near peri-





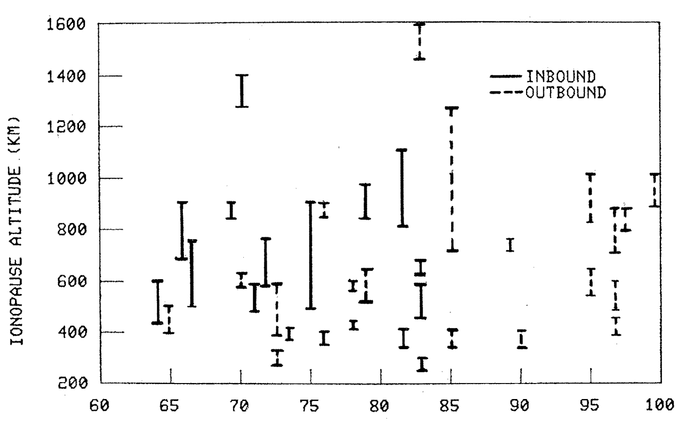


Fig. 2 (top left). Computer plot of a typical stored volt-ampere curve used for calibration of onboard processed temperatures. The points represent the raw currents. The solid line represents a theoretical fit of the exponential region which defines T_e. The discontinuity just to the right of the plasma potential (dashed line) represents an automatic decade downrange adjustment that the electrometer performs when its output reaches full scale. Fig. 3 (above). Height profiles of N_e and T_e for orbits 4 and 9 show the contrast between low and high solar wind conditions. Orbit 9 occurred 44 hours after a class 2B solar flare which produced enhanced solar wind fluxes. This resulted in a compressed ionosphere with large wavelike irregular structure, features that are observed on many orbits. Fig. 4 (bottom left). The height of the ionopause observed on both inbound and outbound passages. The vertical extent of the ionopause region is indicated by the bars. Day-to-day variations in height tend to mask any solar zenith angle (*SZA*) effects that may have been present in this interval.

apsis on orbit 2. The ground analysis derives T_e by fitting a theoretical function to the points measured within the exponential portion of the curve (*2*); N_e is derived from the amplitude of the electron current collected when a fixed positive potential is applied after each curve is obtained (not shown in Fig. 2).

Although the spacecraft travels both horizontally and vertically through the ionosphere, its horizontal uniformity and the eccentricity of the orbit are probably sufficient to permit us to view the measurements in terms of altitude structure. Thus, after the onboard temperatures are normalized to those derived by computer fitting of stored curves, the inbound measurements from two orbits were plotted against altitude in Fig. 3. These orbits were selected to illustrate the ionosphere response to both quiet and disturbed solar wind conditions. Orbit 4 corresponded to a nominal solar wind pressure of 1.9×10^{-8} dyne cm^{-2}, and orbit 9 occurred after a solar flare when the solar wind pressure was 1.8×10^{-7} dyne cm^{-2} (*4*).

The smooth profiles of orbit 4 suggest that during times of low solar wind pressure direct solar wind heating may be taking place only at the top of the ionosphere. The T_e profile is consistent with the deposition of an energy of 3×10^{10} eV cm^{-2} sec^{-1} at the ionopause, with vertical heat conduction maintaining the steep gradients of T_e observed throughout the ionosphere. This profile is similar to the theoretical ones calculated by Chen and Nagy (*5*) and Cravens *et al.* (*6*), which assumed that the ionosphere contains no magnetic field. Since the quiet solar wind energy flux at Venus is probably about 10^{12} eV cm^{-2} sec^{-1}, the observed T_e could be maintained if less than 5 percent of this energy is coupled to the ionosphere. Russell (*7*) has estimated that 29 percent of the solar wind energy may be absorbed by Venus at times. The more disturbed profiles of orbit 9 illustrate the havoc that was wrought upon the ionosphere by intense solar winds that followed a solar flare on 11 December. The ionopause moved inward, and wavelike structure was evident in both the T_e and N_e profiles.

The various mechanisms for solar wind–ionosphere interactions were reviewed by Michel (*8*), and more recently by Bauer (*9*). Most such mechanisms involve a magnetic field induced at the ionopause by compression of solar wind magnetic fields or by currents flowing in the ionosphere itself. Thus it may be instructive to compare the static magnetic field pressure from Pioneer Venus orbiter magnetometer measurements (*10*) with the static plasma pressures calculated for OETP measurements. In Table 1 we show the calculated plasma pressure at the inner edge of the ionopause, $N_e k\ (T_e + T_i)$, and the magnetic pressure, $B^2/8\pi$, just outside the ionopause for four inbound crossings; B (the local magnetic field strength), N_e, and T_e were measured, and the ion temperature (T_i) was assumed equal to one-half of T_e (*11*). It is clear that the magnetic pressure balanced the ionospheric pressure within a factor of 2, thus suggesting that the induced magnetic field plays an important role in the transfer of solar wind pressure to the ionosphere.

Large variations in ionopause height and shape have been noted during the 3-week period for which we now have data. Figure 4 records the ionopause heights as a function of solar zenith angle for all orbits available at this writing. The bars indicate the thickness of the ionopause, with the top of the bar indicating the N_e background and the bottom of the bar indicating the knee at the top of the ionosphere. The height of the ionopause varied from 250 to 1000 km, and its thickness varied from a few kilometers to many hundreds of kilometers. The height variation of the ionopause with solar zenith angle, if any, was smaller than the day-to-day variation observed. The behavior was equally variable inbound and outbound. The apparent lack of ionopause height variation with solar zenith angle is perhaps surprising, as the ionopause had been expected to rise near the terminator where solar wind flow is tangential to the ionosphere, thus exerting reduced pressure (*12*).

L. H. BRACE, R. F. THEIS
J. P. KREHBIEL
NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771
A. F. NAGY, T. M. DONAHUE
Department of Atmospheric and Oceanic Science, University of Michigan, Ann Arbor 48104
M. B. MCELROY
Center for Earth and Planetary Physics, Harvard University, Cambridge, Massachusetts 02138
A. PEDERSEN
European Space Research and Technology Center, Noordwijk, Netherlands

References and Notes

1. L. Colin, *Space Sci. Rev.* **20**, 451 (1977).
2. L. H. Brace, R. F. Theis, A. Dalgarno, *Radio Sci.* **8**, 341 (1973).
3. L. Colin, *Science* **203**, 743 (1979).
4. J. Wolfe, personal communication.
5. R. H. Chen and A. F. Nagy, *J. Geophys. Res.* **83**, 1133 (1978).
6. T. E. Cravens, A. F. Nagy, R. H. Chen, A. I. Stewart, *Geophys. Res. Lett.* **5**, 613 (1978).
7. C. T. Russell, *J. Geophys. Res.* **83**, 625 (1977).
8. F. C. Michel, *Rev. Geophys. Space Phys.* **9**, 427 (1971).
9. S. J. Bauer, in *NASA Spec. Publ. SP-397* (1976), p. 47.
10. C. Russell, R. C. Elphic, J. A. Slavin, *Science* **203**, 745 (1979).
11. W. Knudsen, K. Spenner, R. C. Whitten, J. R. Spreiter, K. L. Miller, V. Novak, *ibid.*, p. 757.
12. J. R. Spreiter, A. L. Summers, A. W. Rizzi, *Planet. Space Sci.* **18**, 1281 (1970).
13. We thank W. R. Hoegy for his programs used for the analysis of volt-ampere characteristics.

16 January 1979

The Polar Ionosphere of Venus Near the Terminator from Early Pioneer Venus Orbiter Radio Occultations

Abstract. *Fourteen profiles of electron density in the ionosphere of Venus were obtained by the dual-frequency radio occultation method with the Pioneer Venus orbiter between 5 and 30 December 1978. The solar zenith angles for these measurements were between about 85° and 92°, and the latitudes ranged from about 81° to 88° (ecliptic north). In addition to the expected decrease in peak electron density from about 1.5×10^5 to 0.5×10^5 per cubic centimeter with increasing solar zenith angle, a region of almost constant electron density above about 250 kilometers was observed. The ionopause height varies from about 300 to 700 kilometers and seems to be influenced by diurnal changes in solar wind conditions. The structures of the profiles are consistent with models in which O_2^+ dominates near the ionization peak and is replaced by O^+ at higher altitudes.*

The Pioneer Venus orbiter mission, described elsewhere in this issue (*1*), provides an opportunity for the observation of approximately 80 consecutive radio occultations. These observations will eventually provide the means for determining temporal and spatial trends in the ionospheric and atmospheric structure of Venus from the comparisons of profiles derived from adjacent occultations.

Four separate types of measurements can be derived from the analysis of the downlink S- and X-band radio signals from the orbiter: (i) the frequency of each of the two signals is precisely recorded, yielding changes in the Doppler

0036-8075/79/0223-0765$00.50/0