tional potential (ΔU) for Earth, moon, and Mars are approximately described by the Kaula rule (*15*): $V_\ell^2\ (\Delta U) \simeq A(2\ell + 1)10^{-10}\ell^{-4}$, where A is a constant. Such a power law can be explained by a random distribution of density anomalies (*16*). Mars departs significantly from this rule for the second and third harmonics because of the Tharsis gravity anomaly (*10, 11*). The best fit of the Kaula rule for the Earth harmonics plotted in Fig. 4 shows an excess of gravity in the vicinity of the sixth harmonic. This corresponds to the second harmonic Fourier spectral peak shown in Fig. 3 and can be considered a nonstochastic component, related to, as previously discussed, plate boundaries and regions of enhanced mantle flow. The Venus harmonics are also fairly well described by a Kaula rule; the constant A is about 1.5 times that for Earth, but we do not consider this significant. There is a deficiency of power around the sixth harmonic for Venus and an excess for higher harmonics. If the gravity field of the region of Venus thus far sampled arises from dynamic processes in the mantle, such processes must take on a different planform than for the whole Earth. Certainly, anomalies comparable in magnitude and spacing to the largest dynamically related anomalies on Earth are absent from this portion of Venus. The enhanced Venus spectrum for harmonics greater than eight may indicate a shift to shorter wavelengths for these phenomena. Alternatively, this enhanced portion of the spectrum may indicate an origin from a lithosphere thicker than that of Earth. Further elucidation of the origin of these long-wavelength anomalies must await detailed comparison with the surface tectonics as revealed by radar imagery and altimetry.

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Ionosphere of Venus: First Observations of Day-Night Variations of the Ion Composition

Abstract. *The Bennett radio-frequency ion mass spectrometer on the Pioneer Venus orbiter is returning the first direct composition evidence of the processes responsible for the formation and maintenance of the nightside ionosphere. Early results from predusk through the nightside in the solar zenith angle range 63° (dusk) to 120° (dawn) reveal that, as on the dayside, the lower nightside ionosphere consists of* F_1 *and* F_2 *layers dominated by* O_2^+ *and* O^+*, respectively. Also like the dayside, the nightside composition includes distributions of* NO^+*,* C^+*,* N^+*,* H^+*,* He^+*,* CO_2^+*, and* 28^+ *(a combination of* CO^+ *and* N_2^+*). The surprising abundance of the nightside ionosphere appears to be maintained by the transport of* O^+ *from the dayside, leading also to the formation of* O_2^+ *through charge exchange with* CO_2*. Above the exobase, the upper nightside ionosphere exhibits dramatic variability in apparent response to variations in the solar wind and interplanetary magnetic field, with the ionopause extending to several thousand kilometers on one orbit, followed by the complete removal of thermal ions to altitudes below 200 kilometers on the succeeding orbit, 24 hours later. In the upper ionosphere, considerable structure is evident in many of the nightside ion profiles. Also evident are horizontal ion drifts with velocities up to the order of 1 kilometer per second. Whereas the duskside ionopause is dominated by* O^+*,* H^+ *dominates the topside on the dawnside of the antisolar point, indicating two separate regions for ion depletion in the magnetic tail regions.*

An investigation of the composition of the nightside ionosphere of Venus has been performed with results from the Pioneer Venus orbiter ion mass spectrometer (OIMS) experiment. These results are based on data obtained during the period December 1978 through March 1979. In this period, the location of periapsis (fixed in latitude at 18°N) precessed from a solar zenith angle (SZA) of ~63° at insertion on 5 December 1978, through the highest SZA

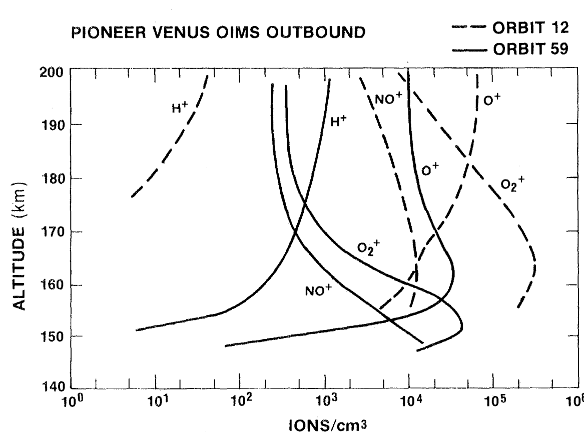

Fig. 1. A comparison of representative ion profiles from orbit 12 (dayside, predusk) and orbit 59 (nightside), with solar zenith angles of 80° and 150°, respectively.

(~165°) on 16 February 1979, to the dawnside (SZA = 100°) on 24 March 1979.

The initial characteristics of the dayside ionosphere observed in the SZA interval of 70° to 90° have been presented (*1*). Relative to the earlier dayside results, perhaps the most significant nightside feature observed to date is the remarkable abundance and extent of the ionization observed deep in the nightside region, in spite of the long Venus night (equivalent to 58 Earth days). As shown in Fig. 1, a comparison of representative dayside ion distributions from orbit 12 (SZA ≃ 80°) with those from the nightside orbit 59 (SZA ≃ 150°) reveals a nightside composition surprisingly similar in several ways to that of the dayside, with the ions O^+ and $O_2{}^+$ forming the nightside F_2 and F_1 layers, respectively, as was the case on the dayside. Both the heights and concentration levels of the peak layers are found to vary relative to the dayside values.

Aside from the obvious similarities, several important differences are noted in the day-night composition results.

First, a general tendency is observed for a depletion of the high-latitude ionosphere (inbound passes: northern hemisphere) relative to lower latitudes (outbound passes: crossing equator, into southern hemisphere). Owing to this relatively greater abundance of low-latitude ionization (*2*), in this report we have concentrated on the equatorial-southern hemisphere observations.

A second day-night variation is a significant increase in the relative role of the light minor ion H^+, with the ratio of H^+/O^+ increasing strongly with SZA, as shown in Fig. 2. At 250 km this ratio increases from about 3×10^{-3} at SZA = 70° to a value approaching unity near SZA = 180°. As the orbit moves dawnward beyond the antisolar point, H^+/O^+ continues to increase, peaking near SZA ≃ 140°, decreasing thereafter. A significant consequence of the asymmetric diurnal variation in the ratio H^+/O^+ is that the nightside ionopause, defined as the high-altitude depletion of the major ion species, is identified by O^+ as the dominant constituent in the dusk to midnight sector and by H^+ as the major topside ion in the midnight to dawn sector.

A third composition change is that of the relative prominence of NO^+ within the group of molecular ions. With increasing SZA, the ratio $NO^+/O_2{}^+$ increases, approaching unity in the F_1 layer, near the antisolar point. The fact that on the nightside NO^+ continues to increase with decreasing altitude after the $O_2{}^+$ distribution peaks near 150 km indicates that NO^+ may be the dominant constitutent of an E-layer, peaking below the orbiter periapsis, and perhaps consistent with the occultation observations of an ionization peak near 140 km (*3*). This compositional change is associated with the fact that whereas all of the molecular ions, including $O_2{}^+$, NO^+, 28^+ ($CO^+ + N_2{}^+$), and $CO_2{}^+$ decrease with increasing SZA, the *relative* diurnal decrease of the other molecular ions exceeds that of NO^+. In particular, in the altitude range 150 to 200 km, the heaviest molecular ion, $CO_2{}^+$, falls on the nightside to concentrations near the limiting sensitivity of the OIMS (about five ions per cubic centimeter).

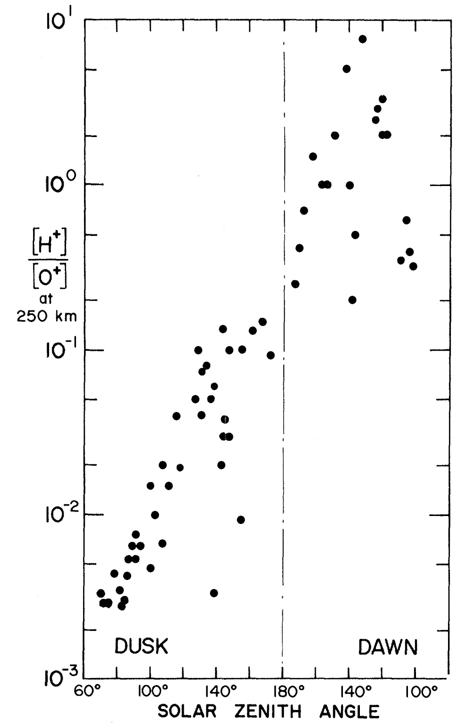

Fig. 2. The variation of $[H^+]/[O^+]$ observed at 250 km, as a function of SZA. Note that this ratio peaks asymmetrically in the dawn sector near 140°, and is declining rapidly at 100°, the position of latest available data.

Another outstanding feature of the nightside ionosphere is the dynamic variability of the upper region, above about 160 km. Although the nightside ionization occasionally reaches conditions of relative calm resembling equilibrium conditions, such as in the case of orbit 59 shown in Fig. 1, the nightside ion distributions are at other times drastically reduced in concentration and highly structured in time and space. An example of this extreme variability is given in Fig. 3, in which the distributions of representative ions are plotted for three different states of ionospheric stability. As exhibited by the profiles obtained on orbits 55, 59, and 60, the ionosphere may be observed to be in the extreme states of: (i) reduced, barely detectable thermal ionization down to about 160 km; (ii) well established ionization, with features similar to the dayside but with generally reduced concentrations (for example, orbit 59 of Fig. 1); and (iii) transition in which the concentration of the dominant ion O^+ decreases to values between 10^2 and 10^3 ions per cubic centimeter with highly variable space and time characteristics.

Further evidence of the nature of the variability is given in Fig. 4, which shows that within the spacing of successive orbits (24 hours), a well-established nightside ionosphere (orbit 54) may be depleted such that thermal ions are barely detected, in this case down to an altitude of 160 km. In the case of orbit 54, the profile of the dominant ion O^+ indicates a substantial ionospheric envelope extending to approximately 1000 km where the pronounced increase in structure in the profile indicates the intersection of the outbound leg of the orbit with a zone of streaming plasma accelerated to high velocities by interaction with the solar wind. In the intermediate region between the lower ionosphere and the ionopause, pronounced structures in the ion distributions are frequently observed. Associated with such structural irregularities is

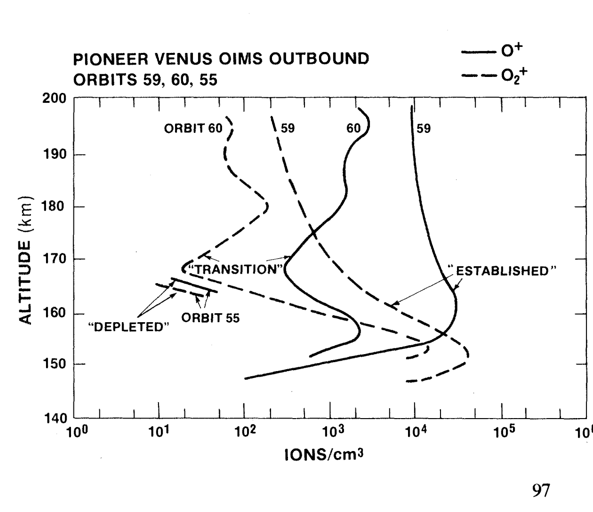

Fig. 3. Profiles of O^+ and $O_2{}^+$ for orbits 59, 60, and 55, exhibiting ionospheric conditions identified as "established," "transition," and "depleted," respectively.

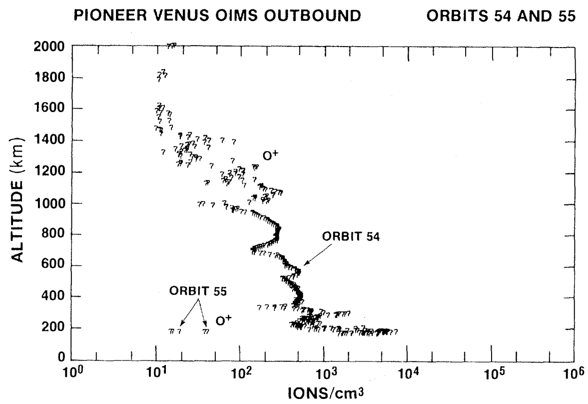

Fig. 4. Extreme contrast in nightside ionospheric content encountered on successive orbits, separated by 24 hours.

evidence of the presence of strong and variable ion flow velocities, which may range from hundreds of meters per second to several kilometers per second. Such variable ion flows are sometimes superimposed on a general trend of increasing ion flow velocity detected as the satellite moves outward from the planet, approaching the solar wind region. The detection of these ion flows by the OIMS is one-dimensional, along the axis of the instrument.

Maintenance of the nightside ionization. The foregoing characteristics provide important clues for understanding the processes of formation and maintenance of the nightside ionosphere. The fact that (i) an extensive ionosphere is sometimes observed, similar in composition to that of the dayside, and (ii) horizontal ion drifts with velocities up to the order of kilometers per second are observed in the upper ionosphere, above the exobase, prompts the view that substantial nightside ionization may be supplied directly by way of transport from the dayside.

The composition and maintenance of the main nightside ion peak has been a controversial issue (*4–6*) ever since the first radio occultation measurements were made from Mariner 5 (*7*). Because of the rapid disassociative recombination rate for molecular ions, their simple transport from day to night was generally ruled out as the source (in view of the unrealistically large horizontal flow velocity required) while impact ionization of the neutral atmosphere by energetic electrons of solar wind origin was considered the most likely source for the main layer (*6*). From the observed concentrations of O^+, O_2^+, and CO_2 (*8*) it is now apparent that a significant source mechanism for maintaining the nightside O_2^+ layer is through the reaction $O^+ + CO_2 \rightarrow O_2^+ + CO$, where the copious supply of O^+ found on the dayside is transported above the exobase in sufficient quantity to the nightside where it diffuses downward. A preliminary estimate for the flow velocity of O^+ at the terminator, required to maintain the O_2^+ layer at night, yields a value of the order of 100 m/sec. This represents only a minimum value for the O^+ velocity since significant additional ion flow is required to supply the ionosphere above the exobase. This is consistent with electrodynamic calculations by Cloutier and Daniell (*9*) which predict ion flows ranging from 100 m/sec near the exobase to several hundred kilometers per second at higher altitudes. Thus, while we are not now taking a stand on the question of the possible contributions of energetic particle ionization, it seems clear that bulk transport of dayside ionization is sufficient to produce the observed nightside ionization.

Above the neutral exobase, where the ionospheric plasma flows freely in response to electrodynamic forces induced by the solar wind, the ion concentrations decrease with increasing SZA, while remaining in approximately the same proportion, with the exception of NO^+ and H^+. Since chemical loss is negligible in this region, this behavior must be explained by strong day-to-night plasma convection, where even modification of the ion profiles by vertical diffusion is weak. In this case, conservation of ion flow along a flow tube implies that the product of the cross-sectional area of the flow tube times the velocity increases since the ion density decreases, indicating an expansive flow or an increasing velocity, or both, as the ionosphere is convected from the dayside to the nightside. This flow region, of course, is highly dynamic and structured, wherein the flow tubes are expected to expand and contract and experience transverse motion in response to the solar wind. Such dynamic behavior in its extreme is the case (see Fig. 3) where the ionosphere is completely swept away by the solar wind.

The diurnal changes in composition, involving both H^+ and NO^+, also provide clues for the nightside maintenance. In the case of NO^+, the surprising nightside abundance of this ion is as yet unexplained. As has been recognized in the terrestrial ionosphere, however, chemical reaction rates responsible for the production of NO^+ are significantly enhanced under conditions of flow (*10*). While this process may in part be responsible for the observed relative enhancement in NO^+, it is apparently not sufficient to explain the observed concentrations, and this problem will require further study.

In the case of H^+, there are at least two mechanisms contributing to the increase in the concentration ratio $[H^+]/[O^+]$ with SZA on the nightside, both resulting from lateral transport of O^+ from the dayside. One involves the charge exchange equilibrium mechanism between neutral and ionized species of H and O operative below the exobase, where the ratio $[H^+]/[O^+] \propto [H]/[O]$, involving downward diffusion of O^+. On the nightside, the light constituent H is expected to increase with SZA because of a combination of day-to-night advection and exospheric return flow (*11*). The concentration of H is also expected to reach a maximum in the morning sector as a result of atmospheric rotation. Furthermore, preliminary observations of O by the orbiter neutral mass spectrometer have revealed that O decreases with increasing SZA on the nightside, reaching a minimum value near the antisolar point (*8*). Thus, $[H]/[O]$ increases with SZA in the dusk sector and is consistent with the increasing trend in $[H^+]/[O^+]$ there (even though O^+ continues to be the dominant topside ion at dusk). A second mechanism takes place just above the exobase, where the charge exchange equilibrium breaks down and the production rate for H^+ by $O^+ + H \rightarrow H^+ + O$ is expected to exceed its loss rate by $H^+ + O \rightarrow O^+ + H$. This occurs principally because the scale height for O^+ exceeds that for O and because H^+ diffuses upward rapidly, avoiding its O sink. In this case, as O^+ and H^+ flow across the nightside, we expect this mechanism to contribute to an increase in the ratio of $[H^+]/[O^+]$ along a flow tube since more H^+ is added to the flowing plasma than is lost.

We cannot now distinguish which mechanism is most important because of the lack of quantitative detail on the flow geometry and the charge exchange process. In the height region where charge exchange equilibrium becomes well established, the H^+ densities are low and approach the limits of instrument sensitivity. Thus, a definitive measure of the H density ratio awaits further statistical analysis. However, we give a preliminary estimate of the night-to-day H density ratio of the order of 10.

The further buildup of H^+ toward the dawnside, where it becomes the dominant topside ion, sets up a situation that has similarities to the polar wind on Earth, where the light ion H^+ is propelled upward away from the planet by the polarization electric field produced in the presence of the heavier ion O^+. If H^+ is to escape in this manner to form a "tail wind" on Venus, it must occur in a region which presents the least resistance or back pressure. This may actually be the case in the postmidnight region where H^+/O^+ reaches a maximum and where the ionopause is observed to exhibit some of its highest elevations on the nightside; that is, the dawnside plasma bulge previously identified by Brace *et al.* (*2*). This is a likely region for H^+ to escape along open magnetic flux tubes because the higher H^+ can extend the more likely it is to merge with the magnetic flux tubes that are directed antisunward (down the tail). Similarly, on the duskside, where O^+ is the dominant constituent in the dusk plasma bulge, a tail wind of O^+ may be present that would be accelerated upward by the polarization electric field it experiences in the presence of O_2^+. Altogether, we may expect O^+ to escape down the tail predominately from the duskside while H^+ escapes predominately from the dawnside.

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Initial Observations of the Nightside Ionosphere of Venus from Pioneer Venus Orbiter Radio Occultations

Abstract. *Pioneer Venus orbiter dual-frequency radio occultation measurements have produced many electron density profiles of the nightside ionosphere of Venus. Thirty-six of these profiles, measured at solar zenith angles (χ) from 90.6° to 163.5°, are discussed here. In the "deep" nightside ionosphere (χ > 110°), the structure and magnitude of the ionization peak are highly variable; the mean peak electron density is 16,700 ± 7,200 (standard deviation) per cubic centimeter. In contrast, the altitude of the peak remains fairly constant with a mean of 142.2 ± 4.1 kilometers, virtually identical to the altitude of the main peak of the dayside terminator ionosphere. The variations in the peak ionization are not directly related to contemporal variations in the solar wind speed. It is shown that electron density distributions similar to those observed in both magnitude and structure can be produced by the precipitation on the nightside of Venus of electron fluxes of about 10^8 per square centimeter per second with energies less than 100 electron volts. This mechanism could very likely be responsible for the maintenance of the persistent nightside ionosphere of Venus, although transport processes may also be important.*

The first results of the Pioneer Venus orbiter radio occultation experiment, which described the nature of the polar ionosphere of Venus near the terminator, have been published (*1*). These earlier measurements were made near the terminator at solar zenith angles (χ) ranging from 86.0° to 93.0°. The results reported here were obtained from measurements taken on the nightside of Ve-

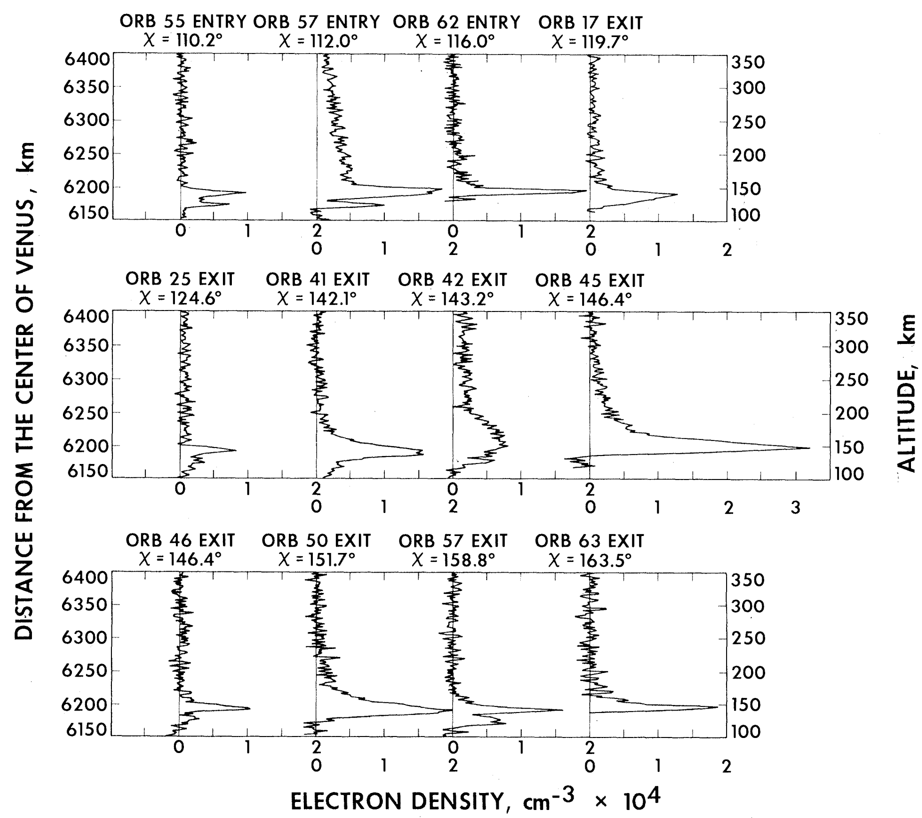

Fig. 1. Electron density profiles in the nightside ionosphere of Venus at solar zenith angles greater than 110°. The electron density scales are linear and extend to 2×10^4 cm^{-3}.