Ionosphere of Venus: First Observations of the Effects of Dynamics on the Dayside Ion Composition

Abstract. *Bennett radio-frequency ion mass spectrometers have returned the first in situ measurements of the Venus dayside ion composition, including evidence of pronounced structural variability resulting from a dynamic interaction with the solar wind. The ionospheric envelope, dominated above 200 kilometers by O^+, responds dramatically to variations in the solar wind pressure, which is observed to compress the thermal ion distributions from heights as great as 1800 kilometers inward to 280 kilometers. At the thermal ion boundary, or ionopause, the ambient ions are swept away by the solar wind, such that a zone of accelerated suprathermal plasma is encountered. At higher altitudes, extending outward on some orbits for thousands of kilometers to the bow shock, energetic ion currents are detected, apparently originating from the shocked solar wind plasma. Within the ionosphere, observations of pass-to-pass differences in the ion scale heights are indicative of the effects of ion convection stimulated by the solar wind interaction.*

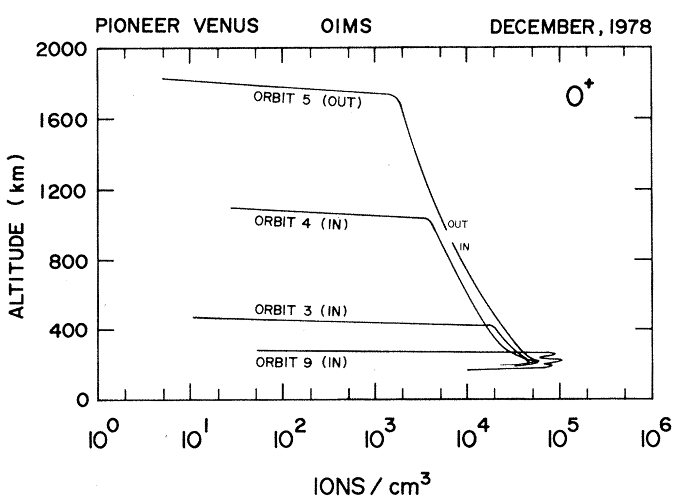
The Bennett radio-frequency ion mass spectrometers on the Pioneer Venus bus and orbiter spacecraft are providing the first detailed in situ measurements of the ion composition of a planetary ionosphere, as discussed in (*1*). We report here some of the preliminary results that illustrate the high degree of variability in the ion distributions resulting from the strong interaction between the solar wind and the thermal ionosphere.

The ion spectrometer design includes a servo-controlled detection system to optimize the individual samples of each ion species, activating automatic adjustments of instrument parameters to account for variations in spacecraft velocity, spacecraft skin potential, and bulk drifts of ionization. Another design feature that facilitates the detection of irregularities is the explore-adapt mode, in which a sequence of 16 possible ion mass (amu) positions are explored during an interval of about 1.6 seconds, followed by adaptively repeated measurements of from one to eight of the most prominent ions detected during the explore cycle. Together, these instrument capabilities permit detection of structural variations with height scales of the order of a few kilometers to a few hundred meters, depending upon the number of ion species being detected within a given height interval. Further details of the instrument functions have been described (*2*).

As was noted in (*1*), the OIMS and BIMS instruments on the orbiter and bus provide detailed profiles of the distributions of thermal, ambient ion composition, at lower altitudes, where the ion distributions are largely decoupled from the solar wind. The degree and altitude extent of this coupling depends on several factors. The height to which the solar wind penetrates above the planet is determined by the balance between the solar wind ram pressure and the plasma pressure exerted by the ionosphere. For strong wind pressures, the solar wind penetrates to relatively low altitudes, while, for reduced wind pressure, the ionosphere expands to relatively high altitudes. This variability is dramatically illustrated in Fig. 1, which shows a comparison of data from OIMS for the dominant ion O^+ for orbits 3, 4, 5, and 9. The extreme compression on orbit 9 is clearly indicative of a large solar wind influx, particularly when compared to that of orbits 4 and 5.

Although the major controlling influence on ionopause height is direct solar wind ram pressure, other factors, such as interplanetary magnetic field (IMF) geometry, may strongly affect the coupling with the solar wind. If the IMF is closely aligned with the solar wind flow vector, then the solar wind flux into the ionosphere may be large even though the ram pressure is not relatively large. This was apparently the case for the Mariner 10 encounter with Venus, which provided a weak shock (*3*) and a highly compressed ionosphere (*4*). The observed response of the Venus ionosphere is roughly analogous to the contraction and expansion observed in Earth's plasmasphere (*5*), although for the case of Venus it is the result of the direct solar wind interaction, while for Earth it arises from the solar wind-induced convection in the magnetosphere (*6*).

The independent instruments on the bus and orbiter provide the opportunity to compare the dawn- and duskside ionopause, with the results shown in Fig. 2. Although as indicated, the dawnside ionopause is about 300 km lower than that at dusk measured earlier on orbit 5, this difference will require further analysis before quantitative arguments concerning possible dawn-dusk asymmetries in the thermal ion envelope can be made. In particular, noting the pronounced day-to-day variability observed in the height of the ionopause, it must be emphasized



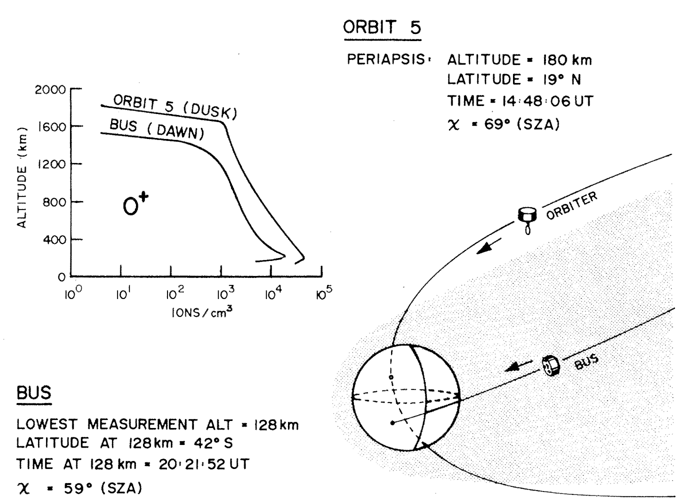


Fig 1 (left). Altitude profiles of O^+, the dominant topside ion, measured by the orbiter ion mass spectrometer (*OIMS*) on four different days. The extreme variability of ionopause height is indicated. Fig. 2 (right). Independent observations of the Venus ionopause at dawn and dusk. Dawnside bus entry occurred on 9 December 1978, approximately 5 hours after the duskside periapsis of orbit 5. Bus and orbiter relative geometries are shown.

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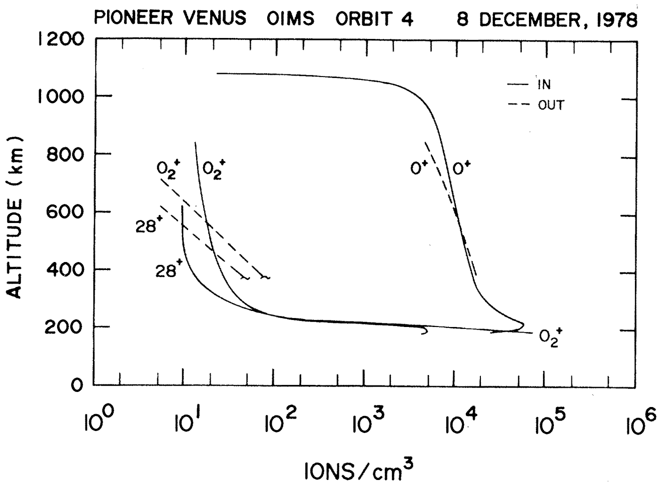

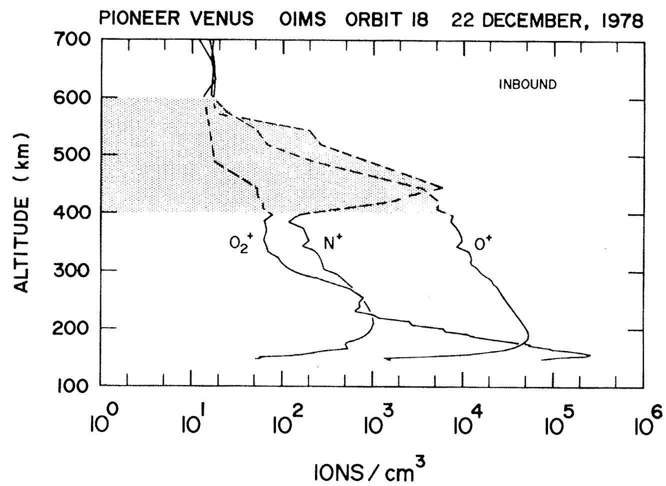

Fig. 3 (left). Comparison of inbound and outbound ion density profiles for orbit 4, indicating the effect of upward transport on the molecular ion distributions measured on the inbound leg. Upward ion motion is associated with increase in ionopause height from ~500 km on orbit 3 (Fig. 1) to ~1100 km on orbit 4. Fig. 4 (right). Ion profiles of O^+, N^+, and O_2^+ observed in three ionospheric regions: the relatively quiescent region below 400 km, a region of onset of acceleration of thermal plasma to suprathermal energies (400 to 600 km), marking the thermal ionopause, and above 600 km, a region of streaming solar wind plasma.

that even during the 5 hours between the two boundary crossings, a modification of the solar wind pressure or geometry (or both) may have occurred, which might explain an apparent further compression of the ion envelope subsequent to the orbiter observation.

In contrast to the relatively smooth distributions of the ions observed during quiescent ionospheric conditions (*1*), the ion composition exhibits several types of irregularities indicative of dynamical coupling with the solar wind during more disturbed times. On 13 December 1978, prior to the periapsis of orbit 9, a large increase in solar wind velocity, from 345 to 630 km/sec, occurred (*7*), leading to the drastically compressed ionosphere exhibited in Fig. 1. Within the compressed envelope, which is driven inward almost to the F_1 layer, considerable structure is evident, including evidence of stratification in the distribution of O^+ (also noted in O_2^+ and other ions).

The stratifications in the ion distributions sometimes observed below the ionopause may be the result of changing ionospheric convection patterns driven by the solar wind. The electric field induced within the ionosphere by the solar wind should cause $E \times B$ "drifts" (E, electric field; B, magnetic field) of ionization at velocities ranging from about 100 km/sec or more near the ionopause to a few meters per second just above the ionization peak (*8*). Under steady-state solar wind conditions, this convection pattern should be largely horizontal, except near the subsolar point. However, variations in solar wind pressure on a time scale of minutes may cause height variations in the convection pattern along flow lines, corresponding to small vertical convection components, which could lead to vertical structure in the ion distributions.

Further indirect evidence for vertical plasma convection components may be seen in Fig. 3, which compares inbound and outbound distributions of several ion species for orbit 4. The inbound data exhibit much steeper distributions of CO_2^+ and O_2^+ than the outbound measurements, while the N^+ and O^+ distributions are only slightly steeper. This behavior is qualitatively consistent with a small vertical component associated with largely horizontal convection. In effect, a flow line moving nearly horizontally through the lower ionosphere descends because of solar wind compression, and picks up a sample ion distribution which has a mixture of heavy and light ions characteristic of the unperturbed equilibrium distribution at that altitude. As the flow line rises in consequence to relaxing solar wind pressure, it carries with it the sample from lower altitudes, which is now relatively rich in heavier ions compared to lighter ions, at the new altitude. Initial calculations indicate that a vertical velocity of the order of 100 m/sec would be required to explain the observed inbound to outbound variation in the orbit 4 ion profiles. The presence of vertical transport inferred from orbit 4 is qualitatively consistent with the observed upward expansion of the ionosphere between orbits 3 and 4 (Fig. 1). Since the predicted convection velocities (*8*) over the altitude range of 400 to 800 km may be of the order of 1 to 10 km/sec, the predominant flow would be horizontal.

Another expected feature of convection within the ionosphere, driven by the solar wind interaction, is the acceleration of heavy ions to higher energies than those of light ions, producing a characteristic nonthermal distribution (*9*). A photoion of mass m and charge $+q$ will be accelerated by the local electric field $\bar{E}$ to a maximum energy $W_0 = 2a_c qE$, where a_c is the gyration radius of the ion in a magnetic field $\bar{B}$.

$$(a_c = mv_\perp/qB,\ v_\perp = E/B)$$

Hence,

$$W_0 = 2m\ (E^2/B^2)$$

Thus, although all ions will drift at the same average speed (E/B), the ions will gyrate about their respective guiding centers with an energy that varies directly with their mass.

In our initial analysis of the ion measurements for evidence of ion drifts, we have qualitatively identified on several orbits the presence of strong horizontal drift near the ionopause. Such an effect is illustrated in Fig. 4 for the inbound portion of orbit 18. In Fig. 4 the ionopause is indicated by the O^+ distribution, which shows a smooth variation below the thermal ion boundary, observed near an altitude of 450 km. Heavy ions such as O_2^+ also exhibit smooth variations below the ionopause, but lighter ions, such as N^+, display a sharp anomalous enhancement starting near 380 km and continuing up to and through the O^+ signature of the ionopause. This enhancement is apparently the result of detection of O^+ ions accelerated by the solar wind flow near the ionopause, and shifted to appear at the detection potentials otherwise expected for ambient thermal ions of N^+. Above this region, which extends to about 600 km, a region of energetic plasma is encountered. In this region, the flowing plasma is observed simply as an energetic ion current level, which on some orbits is observed to extend outward for thousands of kilometers beyond the ionopause to the bow shock, and is attributed to shocked solar wind plasma. In the region of the shaded portion of Fig. 4 and higher in the energetic plasma region, the profiles shown for O^+, O_2^+, and N^+ are not directly representative of thermal ion concentrations, and require further analysis.

Additional observations of dynamic response are indicated within the ion composition results. Some features not necessarily associated with the solar wind interaction include tentative evidence of (i) an apparent increase in the ratio He^+/H^+ approaching the terminator, which may reflect transport of He to the nightside, and (ii) a stratification signature in the lower ionosphere which may identify the location of the exobase. With the increasing body of data becoming available, we anticipate the opportunity to obtain a detailed picture of dynamic responses throughout the ionosphere of Venus.

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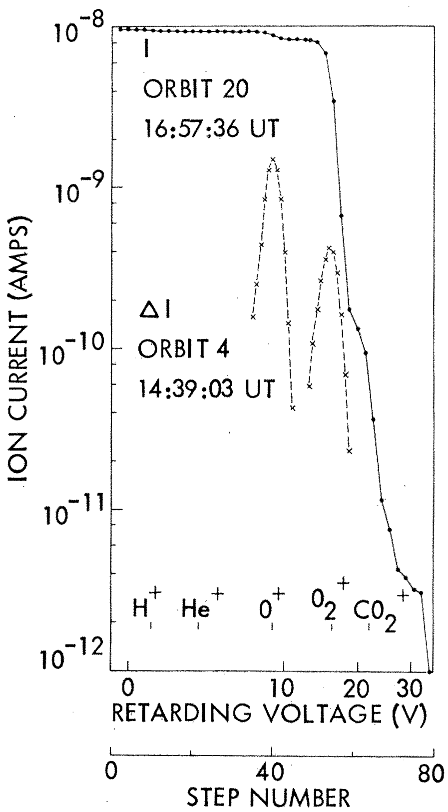
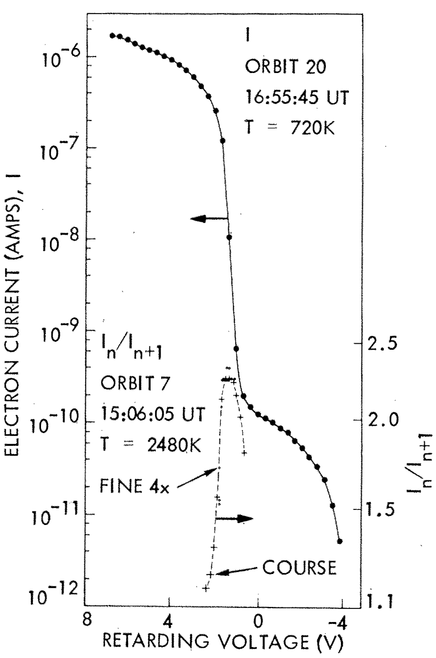
Thermal Structure and Major Ion Composition of the Venus Ionosphere: First RPA Results from Venus Orbiter

Abstract. *Thermal plasma quantities measured by the retarding potential analyzer (RPA) are, together with companion Pioneer Venus measurements, the first in situ measurements of the Venus ionosphere. High ionospheric ion and electron temperatures imply significant solar wind heating of the ionosphere. Comparison of the measured altitude profiles of the dominant ions with an initial model indicates that the ionosphere is close to diffusive equilibrium. The ionopause height was observed to vary from 400 to 1000 kilometers in early orbits. The ionospheric particle pressure at the ionopause is apparently balanced at a solar zenith angle of about 70° by the magnetic field pressure with little contribution from energetic solar wind particles. The measured ratio of ionospheric scale height to ionopause radius is consistent with that inferred from previously measured bow shock positions.*

The Pioneer Venus orbiter was inserted into a highly eccentric orbit on 4 December 1978, with an apoapsis of 66,000 km (*1*). Every 24 hours the spacecraft passes into the ionosphere for approximately 10 minutes, during which time the following data were obtained.

The primary ionospheric quantities, ion temperature (T_i), total and major ion concentrations, ion bulk velocity, electron temperature (T_e), and suprathermal electron energy distribution, are being





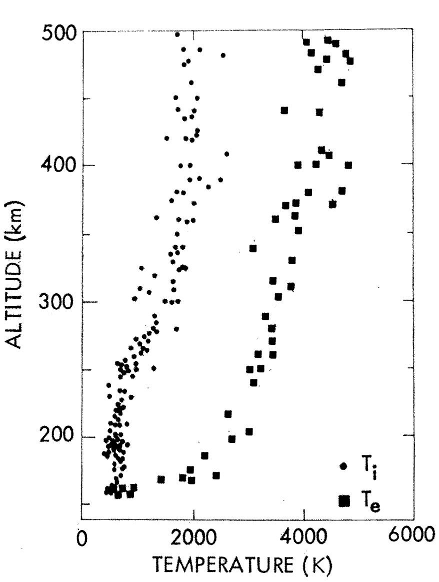


Fig. 1 (above). Ion-retarding curve I during orbit 20 indicating O^+, O_2^+, and CO_2^+ as dominant ions; current differences between successive steps ΔI during orbit 4 showing the two dominant ion species O^+ and O_2^+. Fig. 2 (top right). Complete electron retarding curve I transmitted during orbit 20 and current ratios from successive steps I_n/I_{n+1} around the strongest decrease of the semilogarithmic characteristic during orbit 7 near periapsis. Fig. 3 (bottom right). Electron temperature (T_e) and ion temperature (T_i) profiles measured during six of the first ten orbits.

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