shock crossing. The bow shock shape in Fig. 4 is the shape calculated by Spreiter *et al.* (4) for $H/r_0 = 0.25$, where H is the local atmospheric scale height and r_0 is the distance from the ionopause nose to the center of Venus. Also, an upstream sonic Mach number of 8 and a ratio of specific heats of 5/3 were assumed. A shape associated with $H/r_0 \sim 0.3$ would seem to be most representative of the measured bow shock locations, although they undoubtedly have been observed over a wide range of upstream sonic and Alfvén Mach numbers and solar wind pressures. The associated ionopause locations would imply a much thicker ionosphere (4) than the one observed, but inclusion of magnetohydrodynamic effects can result in lower-altitude ionopause surfaces (5). Another feature not included in the calculations would be effects of a possible thick ionopause boundary layer (3, 4, 6).

Observations in the ionosphere near periapsis were obtained by the plasma analyzer in its low-energy ion mode. Figure 5 shows the low-energy ion spectrum obtained between 0 and 40 V at ~ 1500 UT on 11 December during orbit 7 when the spacecraft was at an altitude of ~ 310 km. The first peak in the spectrum occurs at ~ 8 V and the maximum of the broader second peak occurs at ~ 15 V. Because of the measured angle of incidence, we interpret these data as indicating nonflowing ions apparently impinging from a direction along the ram velocity vector of the spacecraft. The ram speed at this time was ~ 9.7 km/sec so that the peak in the spectrum at ~ 8 V is consistent with an ion of mass 16, such as O^+, as indicated by the arrow in Fig. 5. Several ions could give rise to the second peak, and the mass positions of CO^+, O_2^+, and CO_2^+ ions expected at this altitude in the Venus ionosphere (7) are shown in Fig. 5.

The electron data obtained thus far are incomplete. However, preliminary results indicate the presence in the ionosheath of high-temperature electrons with typical energies in the range 50 to 100 eV. These observations seem consistent with heating of the solar wind electrons across the bow shock.

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Ionosphere of Venus: First Observations of the Dayside Ion Composition Near Dawn and Dusk

Abstract. *The first in situ measurements of the composition of the ionosphere of Venus are provided by independent Bennett radio-frequency ion mass spectrometers on the Pioneer Venus bus and orbiter spacecraft, exploring the dawn and duskside regions, respectively. An extensive composition of ion species, rich in oxygen, nitrogen, and carbon chemistry is identified. The dominant topside ion is* O^+, *with* C^+, N^+, H^+, *and* He^+ *as prominent secondary ions. In the lower ionosphere, the ionization peak or* F_1 *layer near 150 kilometers reaches a concentration of about* 5×10^5 *ions per cubic centimeter, and is composed of the dominant molecular ion,* O_2^+, *with* NO^+, CO^+, *and* CO_2^+, *constituting less than 10 percent of the total. Below the* O^+ *peak near 200 kilometers, the ions exhibit scale heights consistent with a neutral gas temperature of about 180 K near the terminator. In the upper ionosphere, scale heights of all species reflect the effects of plasma transport, which lifts the composition upward to the often abrupt ionopause, or thermal ion boundary, which is observed to vary in height between 250 to 1800 kilometers, in response to solar wind dynamics.*

Bennett radio-frequency (rf) ion mass spectrometers carried by the Pioneer Venus bus and orbiter spacecraft are providing the first detailed in situ measurements of the dayside ion composition. The orbiter instrument began returning daily profiles of the planetary ionosphere starting on 5 December 1978, with an initial periapsis of 379 km at 17.0°N latitude, solar zenith angle (χ) of 63°, and an orbital inclination of 105°. The orbit geometry is such that inbound passes approach periapsis from the north, with an orbit plane precession of about 1.5° per day toward the dusk terminator. On 9 December, the bus instrument obtained a single profile of the dawnside ionosphere, providing measurements down to about 128 km ($\chi = 59°$; 42°S latitude), below which instrument performance degraded rapidly because of the impact with the dense neutral atmosphere.

The identical bus and orbiter instruments (BIMS and OIMS, respectively) (1) are designed to provide detailed measurements of the concentration and variability of as many as 16 possible ion species, selected originally as the most probable constituents from theoretical considerations. As the instrument explores for, and detects the presence of, a given species, an in-flight analysis is made of each ion measurement to account for the effects of spacecraft velocity, skin charge, and bulk ion drift. This analysis also permits the recovery of suprathermal ion characteristics induced by the interaction of the solar wind and the ionosphere. The instrument operating modes are automatically sequenced to alternately explore, then adapt to, repeated measurements of prominent ions. The temporal and spatial sampling resolution for a given ion thus varies, according to the number and relative abundance of species detected. In general, prominent ions are measured at a rate of about once per second, corresponding to a height resolution of a few kilometers between successive samples.

An example of the resolution provided in the ion measurements is given in Fig. 1, in which all samples of each of three prominent ions (O^+, O_2^+, and H^+) are plotted. To facilitate the data processing, smooth profiles have been constructed as a best fit to the measurements, and such profiles are used in the further illustrations in this and in (2). The spread in the raw data points reflects instrument sampling adjustments as well as natural variations, and thus subsequent detailed

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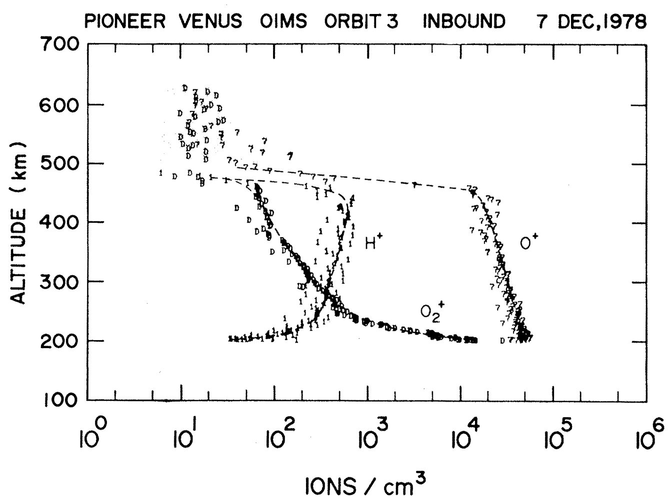
analysis will yield considerably more information on structural variability, which cannot yet be presented in detail.

The duskside height distribution of the ion composition measured by the OIMS on 9 December, about 5 hours prior to the bus BIMS entry on the dawnside, is shown in Fig. 2. These distributions illustrate many of the important features in the first analysis of the early data.

To date, a total of 11 ion species have been positively detected, including O^+, O_2^+, NO^+, CO_2^+, C^+, N^+, H^+, He^+, $^{18}O^+$, O^{2+}, and mass 28, which may have contribution from both CO^+ and N_2^+. In addition to the species listed we have tentative evidence of trace amounts of H_2^+, OH^+, Fe^+, and Mg^+, although further analysis will be required to verify these ions. Our identification of trace amounts of OH^+ and H_2^+, if substantiated, would also imply the presence of H_2 in the Venus atmosphere (*3*). It is emphasized that in several cases the final association of ion currents at a given atomic mass unit (amu) position with specific species is not yet complete. For example, although the 28^+ peak could be identified as either N_2^+ or CO^+, or a combination of both, it appears from photochemical arguments that most of this mass peak is due to CO^+.

The observed concentration of C^+ appears somewhat puzzling in view of the low concentrations of C predicted by theory (*4*). However, C^+ can also be produced by charge transfer between He^+ and CO, which have been measured by the ion and neutral mass spectrometers, respectively (*5*). To obtain the observed C^+ concentration, a CO/CO_2 ratio somewhat greater than indicated at present seems to be required. In addition, the determination of possible contributions of doubly ionized species (such as Mg^{2+} and Si^{2+} to the measurements of 12 and 14 amu) has not yet been examined. Singly charged metallic ions would have long lifetimes in the ionosphere of Venus and have been considered as possible constituents of the nightside ionosphere (*6*). A significant number of these ions might become doubly charged during the long Venus day.

The main photochemical ionization layer (generally referred to as an ionospheric F_1 layer) is dominated by O_2^+ ions, produced by the charge transfer reactions, $CO_2^+ + O \rightarrow O_2^+ + CO$, and $O^+ + CO_2 \rightarrow O_2^+ + CO$ involving the predominant neutral molecular and atomic species in this altitude region. At about 200 km, O^+ reaches a maximum as the result of competing processes of photochemistry and diffusion. This causes a feature in the total plasma density distri-



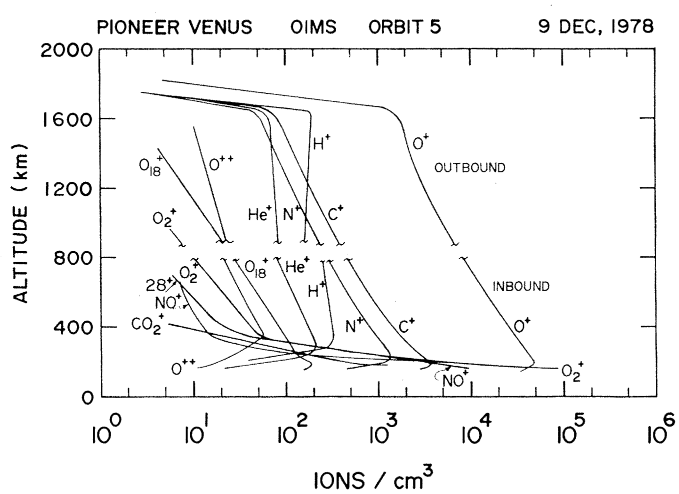
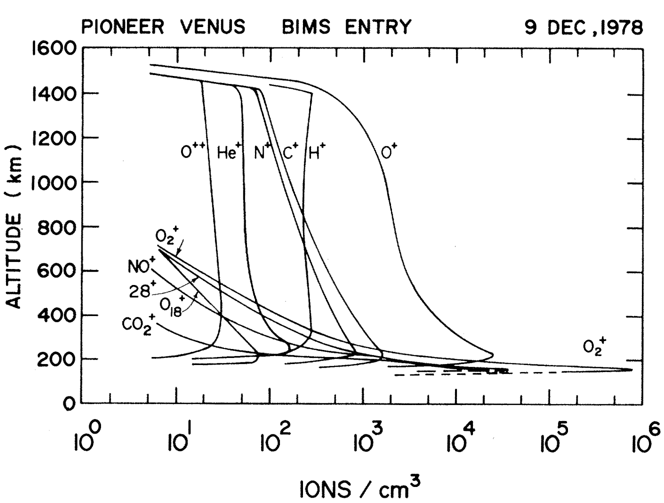


Fig. 1 (left). Representative altitude profiles of three ions measured by the orbiter ion mass spectrometer. The ionopause is marked by the sharp gradient in O^+ at 500 km; above this altitude is a shaded region populated by suprathermal ions. Fig. 2 (right). Ion composition measured by the OIMS on the duskside of Venus approximately 5 hours prior to the bus entry on the dawnside. The high ionopause indicates relatively low solar wind pressure at this time. Inbound and outbound profiles are combined to accommodate gaps in data coverage. At periapsis, $\chi = 69°$.



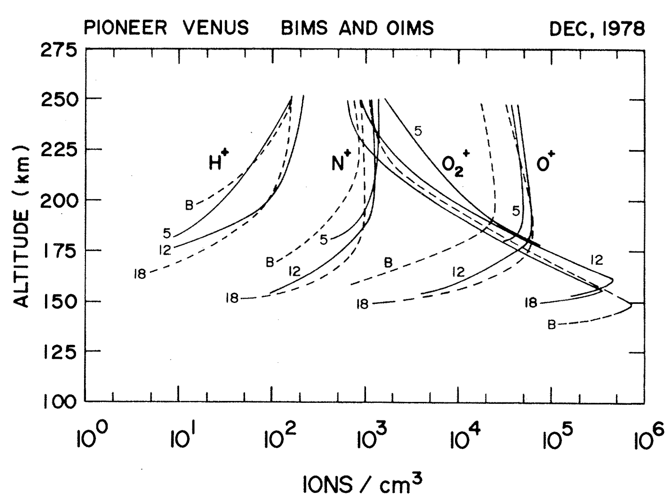


Fig. 3 (left). Ion composition measured by the bus ion mass spectrometer during entry near dawn local time. Measurements were made to an altitude of 128 km ($\chi = 59°$), below the ionospheric O_2^+ peak. Fig. 4 (right). Height profiles of selected constituents in the lower ionosphere as measured during bus entry (*B*) and on orbits 5, 12, and 18. The solar zenith angle at periapsis increased from approximately 69° to 90° between orbits 5 and 18, and was 59° for the bus.

bution previously referred to as an F_2 Ledge (*7*). The observed concentrations of O^+ require an O/CO_2 ratio similar to the one first suggested by Bauer and Hartle (*7*), implying that O begins to predominate over CO_2 above 150 km. Actual neutral composition measurements with the orbiter neutral mass spectrometer confirm this contention (*5*). Above this ledge, O^+ continues to be the dominant ionic constituent in the Venus ionosphere, as is seen in all currently available data (throughout the range $\chi = 60°$ to 90°; nightside data have not yet been processed). Above about 200 km, the distributions of all ions are controlled by plasma transport, including ionospheric convection induced by solar wind interaction (*7, 8*). In the example of Fig. 2, the steepness of the ion profiles appears to be the result of a combination of the observed ratio of electron temperature to ion temperature (*9*), and the strong gradients in plasma temperature (*10*) affecting the polarization field, which controls the diffusion of minor ions (*11*).

In the upper region, the interface between the thermal ionosphere and the solar wind, "the ionopause," is observed as a relatively abrupt cutoff in concentration of thermal ions. At this boundary, the ions are "swept away" by the high velocity, postshock solar wind, which in the snapshot of Fig. 2 has penetrated to a height of about 1800 km. Within the interaction region (shaded in Fig. 1) the solar wind picks up the ambient ionization, producing a streaming, energized plasma which is detected by the spectrometer as a variable, suprathermal flux. During relatively quiet solar wind conditions, the thermal ionopause is rather well defined, as in the two examples shown. Under more disturbed conditions, the structure of the thermal ion boundary becomes more complex, as discussed in (*2*). During the first 2 weeks of orbiter operation, the height of the ionopause defined by the thermal ionic constituents is observed to respond dramatically to variations in the solar wind, with the position of the boundary shifting by hundreds of kilometers from day to day.

The near-simultaneous sampling of the lower ionosphere by the OIMS and the BIMS provides the first opportunity to test theoretical concepts of the behavior of the dawn and dusk regions under similar conditions. The bus trajectory penetrated the atmosphere to impact, providing the deepest penetration of the F_1 layer, and the profiles of ion composition detected (Fig. 3) during bus entry confirm the higher altitude evidence from the orbiter that O_2^+ is indeed the dominant constituent of this layer. Qualitatively, although the solar zenith angle for the bus entry was about 10° lower than for orbit 5, the snapshots of the ion composition obtained by the BIMS and OIMS are rather similar. Some differences, such as the height of the ionopause and the distributions of some of the minor ions, require further interpretation. As for the observed difference in the ionopause height, it is probably also significant that 5 hours did in fact elapse between the two traversals of the ionosphere. As was noted (*2*), it is entirely possible that solar wind variations of the time scale of a few hours may result in appreciable variation in the distribution of the thermal plasma. The lower (F_1) region should, however, be relatively unaffected by these short-term variations at higher altitudes. Accordingly, a direct comparison is made between the bus and orbiter results in the region below 200 km. In Fig. 4, the height distributions of O^+, O_2^+, N^+, and H^+ are presented for the bus entry, and the companion orbit 5, as well as for two later orbits obtained on the duskside, at progressively higher zenith angles.

From the analysis of the data of Fig. 4, the height (h_m) and value of the ionization maximum (N_m) follow the expected zenith angle dependence of a Chapman photochemical equilibrium layer, that is

$$h_m \propto H \ln \sec\chi, \text{ and } N_m \propto (\cos\chi)^{1/2}$$

where H is the neutral gas scale height (*11*). Below about 180 km, the densities of all ion species are controlled mainly by photochemical processes. Height distributions therefore reflect the behavior of the neutral atmosphere and can be used to estimate the neutral gas temperature. For example, O^+ ions, produced by photoionization of O and lost by a charge transfer reaction with CO_2, lead to a photochemical equilibrium distribution (160 km $< h <$ 200 km) such that

$$[O^+] \propto [O]/[CO_2] \propto \exp z/H(28)$$

that is, these ions *increase* with altitude (z is a relative height parameter) according to a scale height corresponding to an effective particle mass of 28 amu. Similarly, for N^+ ions

$$[N^+] \propto [N_2]/[CO_2] \propto \exp z/H(16)$$

Appropriate photochemical relationships can also be derived for CO_2^+ and O_2^+ which *decrease* with altitude. From these scale heights, the neutral gas temperatures for various zenith angles were calculated. The results are in reasonably good agreement with values derived from the orbiter neutral mass spectrometer at the terminator and with the bus neutral mass spectrometer and orbiter airglow results for lower zenith angles (*5, 12*). Although the neutral gas temperatures derived from the various ions are not always exactly the same, the averages show an increasing trend from a low temperature $T \sim 180 \pm 20$ K near the terminator to $T \sim 280 \pm 30$ K at a zenith angle of 59° for the bus.

This report allows us to highlight only some of the most salient features seen within the experimental data obtained to date. Each new orbit adds to this body of data, which will, in time, enable us to provide a more definitive picture of the photochemistry and dynamics of the Venus ionosphere (*13*).

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13. A number of investigations relating to the photochemistry and dynamics of the Venus ionosphere based on measurements of ion and neutral composition and plasma temperatures are under way and will be reported later.

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