PINSA, 66, A, No. 5, September 2000, pp. 483-498

THE IONOSPHERE AND UPPER ATMOSPHERE OF VENUS : A REVIEW

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(Received 6 October 1999; Accepted 27 December 1999)

Most of our current knowledge of the upper atmosphere and ionosphere of Venus has come from the various aeronomy experiments on the Pioneer Venus Orbiter (PVO) which was inserted into a highly eccentric orbit around Venus on December 4, 1978. The PVO provided ionospheric data till Oct. 7, 1992 after which it entered the dense atmosphere and incinerated. We now know that Venus has an extended atmosphere with CO_2 dominating in the lower thermosphere and O and He at higher altitudes. The atmosphere is not very sensitive to solar EUV variability with the daytime exospheric temperature changing only by about 60 K over a solar cycle. This weak response has been explained due to very strong 15 μm cooling from CO_2, collisionally excited by oxygen atoms. This cooling approximately balances the EUV and UV heating. And in the upper ionosphere, major ion is O^+ above about 200 km, but lower down O_2^+ dominates and forms the main ionospheric peak around 140 km. The ionosphere responds very strongly to changes in solar activity and solar zenith angle. The planet has no intrinsic magnetic field and therefore the solar wind interacts directly with its ionosphere resulting in a sharp density gradient (called the ionopause), above the top of the ionosphere. Inspite of the long Venus night, a substantial nightside ionosphere exists mainly due to transterminator flow of O^+ from the dayside during solar maximum. During solar minimum, electron precipitation provides an equal or higher contribution to the maintenance.

Key Words: Ionosphere; Upper Atmosphere; Pioneer Venus Orbiter; Ion Composition; Electron Temperature; Ion Temperature; Ionopause; Transterminator Flow; Solar Activity

1 Introduction

Venus is the closest planet to earth and therefore many spacecrafts have visited it since the beginning of the space age. Fig. 1, taken from Mahajan and Kar[1], gives a summary of the various successful planetary missions to Venus in relation to solar activity. The climax reached with the Pioneer Venus (Colin[2]) which consisted of two scientific missions - the orbiter and the multiprobe. The Pioneer Venus Orbiter (PVO) was launched on 20 May, 1978 and was inserted into a highly elliptical orbit on 4 Dec., 1978, having an inclination of 105°, a period of 24 hours and with periapsis at 17°N. The apoapsis was at an altitude of about 72000 km and periapsis was maintained in the vicinity of 150 km for the first two years, after which it rose and then fell due to solar gravitational perturbations, as shown in Fig. 2, taken from Strangeway[3]. Important ionospheric and thermospheric experiments on the PVO were the electron temperature probe, OETP (Krehbiel *et al.*) ion mass spectrometer, OIMS (Taylor *et al.*), retarding potential analyser ORPA (Knudsen *et al.*), and neutral mass spectrometer, ONMS (Niemann *et al.*). The Pioneer Venus multiprobe was launched on 8 August, 1978 and it reached Venus on 9 December, 1978. The Pioneer Venus bus on the multiprobe (PVMB) had a neutral mass spectrometer[8] and an ion mass spectrometer[5], on it.

Excellent reviews, mostly based upon PVO measurements, have periodically appeared in the literature, (1) on the theoretical aspects, especially on energetics by Nagy *et al.*[9], Nagy and Cravens[10], Mahajan[11], (2) on ionosphere structure by Schunk and Nagy[12]; Brace *et al.*[13]; Mahajan and Kar[14], Brace and Kliore[15], Kar[16], Fox and Kliore[17], and (3) on neutral atmosphere by von Zahn *et al.*[18], Kasprazk *et al.*[19]. In this paper, we shall summarize the most important characteristics of the Venus ionosphere, including the latest advances in the areas of (1) neutral atmosphere, (2) ion composition, (3) electron and ion temperatures, (4) ionopause structure and, (5) the maintenance of the nightside ionosphere.

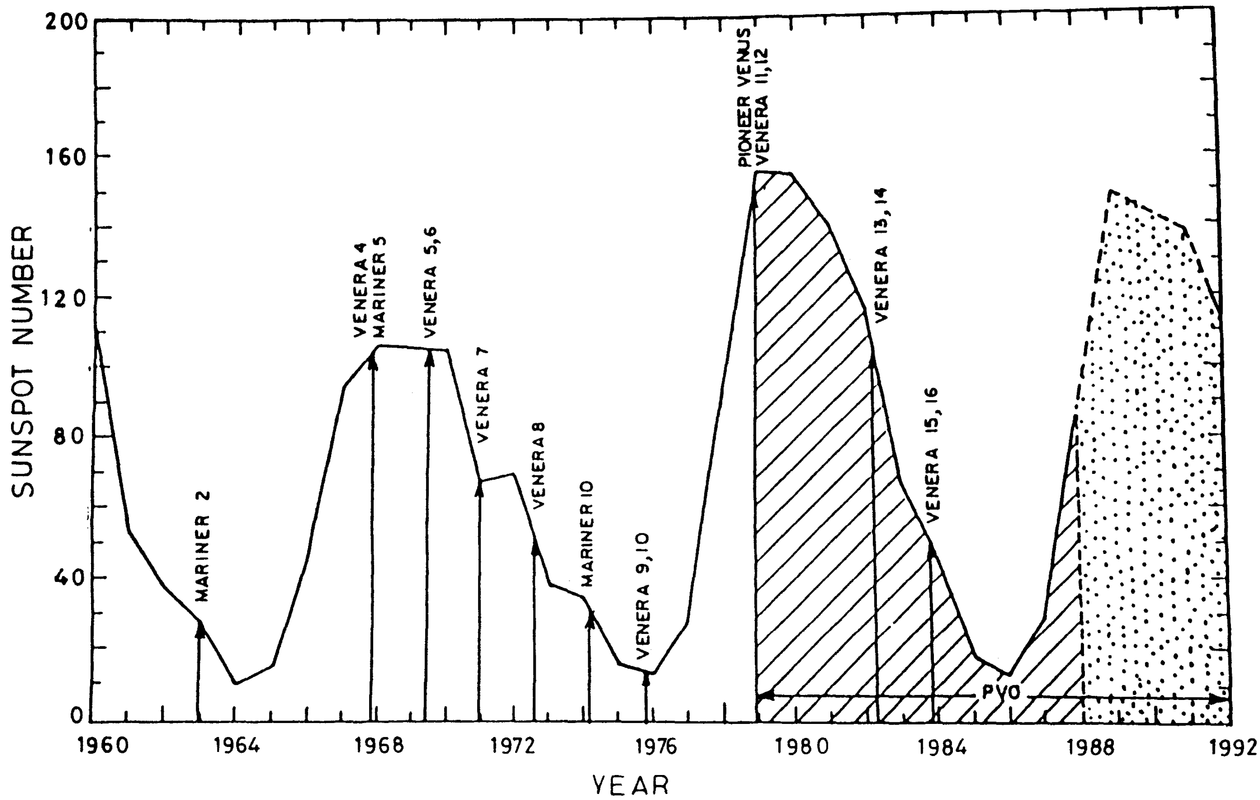

Fig. 1 Solar activity and various planetary missions to Venus[1]

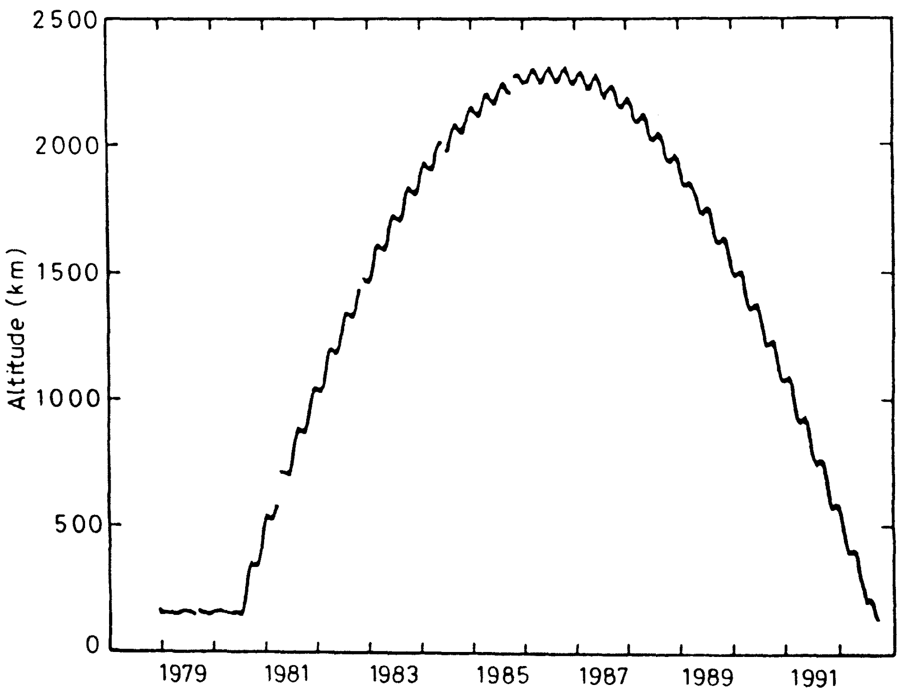

Fig. 2 The PVO periapsis altitude as a function of time. The orbiter entered the atmosphere in late 1992 and burnt[3]

2 Neutral Atmosphere

2.1 Earlier Measurements

Exploration of the outer atmosphere of Venus began in October, 1967 when two spacecrafts, the U.S. flyby Mariner 5 and the Soviet Venera 4 carried UV photometers to Venus. Both the experiments were designed to detect emission features of H at 1216 Å and of O at 1304 Å. No signal was detected at 1304 Å by either of the experiment, but both the photometers measured L_{α} emission. These observations indicated that the atomic hydrogen in the Venusian upper atmosphere is of the same order as in the earth's atmosphere[20,21]. Subsequent measurements on Mariners and Veneras re-confirmed these results. These measurements were complemented by UV spectral observations on rockets to detect emissions from atomic hydrogen and atomic oxygen[22-24]. While atomic oxygen could not be detected on any of the Mariner and Venera missions, both of these constituents were detected on the rocket campaigns.

2.2 Pioneer Venus Measurements

The neutral mass spectrometers on the PVMB and PVO provided the first direct measurement of the neutral composition in the upper atmosphere of Venus. The measurements on the Bus were for the dayside and covered the altitude range from about 700 km down to 130 km. The Bus detected He at an altitude of 700 km and below about 200 km CO_2 became the dominant neutral constituent[25]. However, a really detailed account of neutral composition was provided by the PVO. Early measurements on the ONMS, which were during a period of high solar activity, showed that during the day CO_2 dominated upto 150 km, atomic oxygen from 150 km to 250 km and helium above 250 km. These transitions occurred at somewhat lower altitudes during the night. Fig. 3 shows typical altitude profiles for the important neutral constituents for dayside and nightside conditions and is an update by Kasprazk *et al.*[19] of the earlier measurements by Niemann *et al.*[26] during the solar maximum. It includes H from Brinton *et al.*[27] and from Grebowsky *et al.*[28] and mass density from Keating *et al.*[29]. The ONMS densities were raised by a factor of 1.63 to bring agreement between the satellite drag and neutral mass spectrometer measurements. Fig. 4, again taken from Kasprazk *et al.*[19], shows composition data from the pre-entry

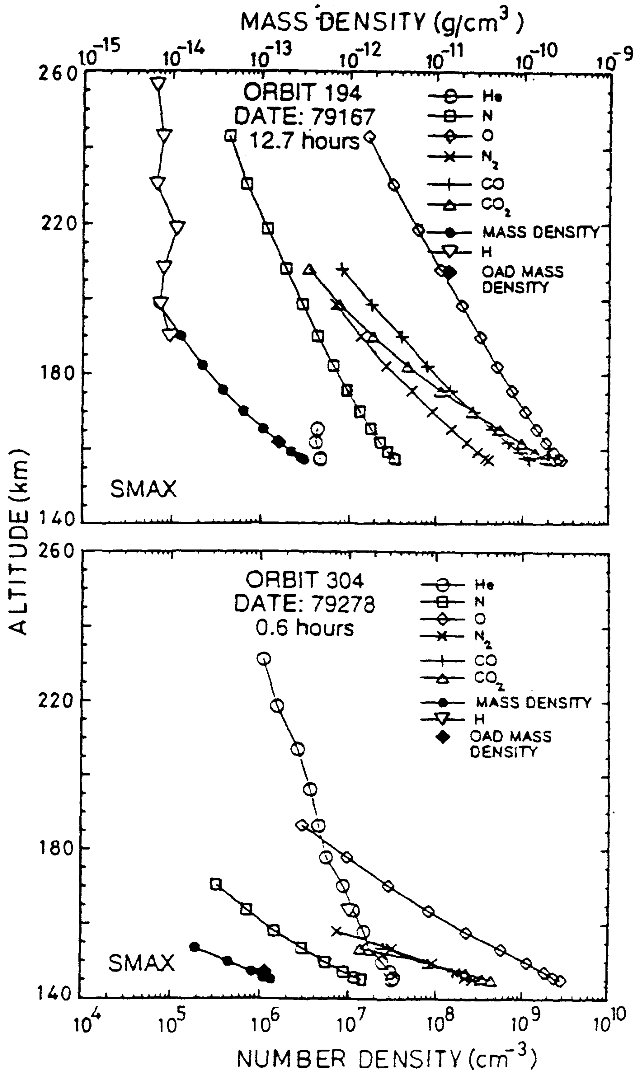

Fig. 3 Neutral composition measurements by ONMS during solar maximum conditions. CO_2 dominates in the lower thermosphere, O and He dominate at higher altitudes[19]

measurements at solar medium conditions for 2.2 hr local solar time. Values of H density have again been taken from Grebowsky *et al.*[28] and for the mass density from Keating and Hsu[30]. No significant change seems to have occurred from solar maximum (Fig. 3) to solar medium (Fig. 4) for nighttime composition and densities. Scale heights of the neutral constituent indicate exospheric temperature of about 300 K during the day and 100 K during the night. The diurnal variations of all species, except H, D and He have maximum near noon with very steep gradients at the terminators, leading to much lower densities on the nightside than on the dayside. The lighter

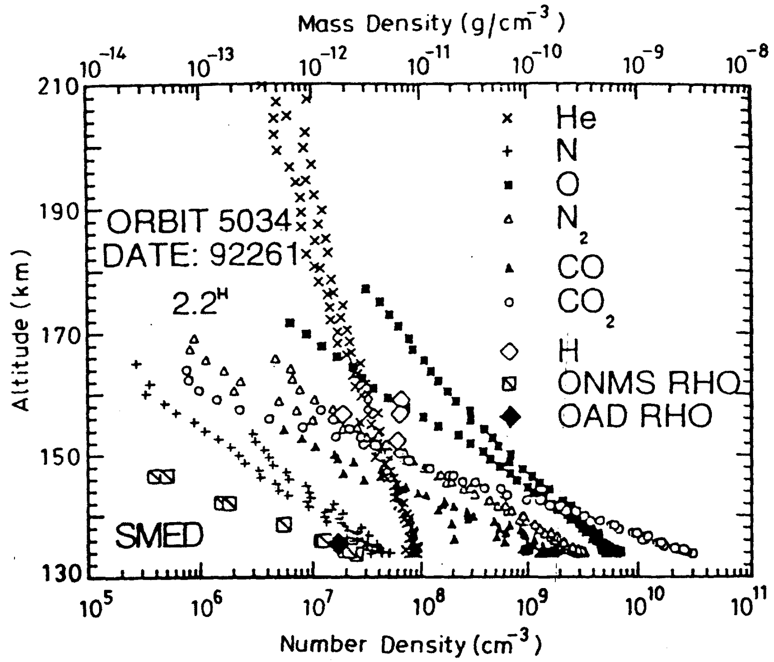

Fig. 4 Pre-entry measurement of neutral composition at medium solar activity conditions. Composition and densities for the nightside have not changed between solar maximum and solar medium[19]

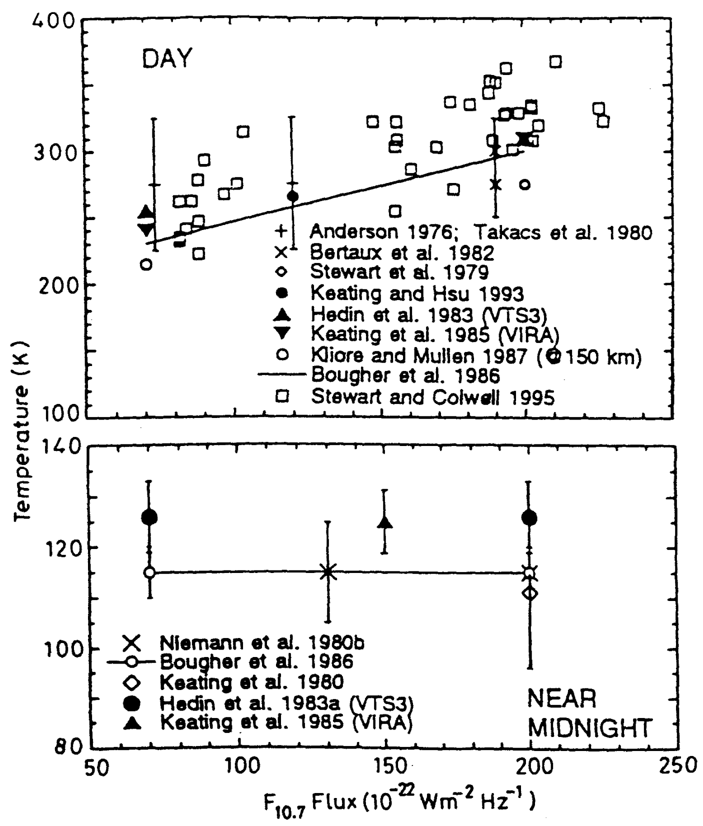

Fig. 5 Dayside and near midnight exospheric temperature measured over a solar cycle. The temperature changed by 60 K for the day and less than 15 K for the night from solar maximum to solar medium (Kasprazk *et al*[19]).

species (viz. H, D and He) have shown predawn bulges which indicate that the upper thermosphere super rotates[31].

The PVO data from 1978-1980 has been analyzed by several workers to study the variations due to solar rotation in the upper atmosphere at solar maximum ($F_{10.7} \approx 200$) and a response of 0.14 to 0.19 $K/F_{10.7}$ unit in the global mean temperature has been found[19]. This is about ten times smaller than seen in the Earth's thermosphere. The ONMS pre-entry data and the drag measurement of PVO spacecraft suggest a rather very small change in the dayside and nightside thermosphere density and temperature with solar activity on the long term scale. The exospheric temperature varies by about 60 K for the dayside and by less than 15 K for the nightside from solar maximum to solar minimum, as can be noted from Fig. 5 taken from Kasprazk *et al.*[19]. This weak response has been explained to be due to the very strong 15 µm cooling from CO_2 collisionally excited by oxygen atoms. This cooling approximately balances the EUV and UV heating[32]. Such large cooling efficiencies have indeed been reported by Sharma and Wintersteiner[33]. In contrast, hydrogen and deuterium densities in the bulge region increase with decrease in solar activity as will be clear from Fig. 6 taken from Kasprazk *et al.*[19]. This feature has been attributed by Hartle *et al.*[34] due to the reduction in the exospheric escape of H and D with decreasing solar activity.

3 Ion Composition

There were three instruments aboard the PV mission which measured the ion composition and the total ion concentration. These were (1) ion mass spectrometer, on the Pioneer Venus Bus, BIMS[5]. (2) the ion mass spectrometer, on the Pioneer Venus Orbiter, OIMS[5] and (3) the retarding potential analyzer, on the Pioneer Venus Orbiter, ORPA[6]. The ion mass spectrometers detected and identified a total of 12 ion species with O_2^+ as the major ion at altitudes below 200 km and O^+ at higher altitudes (Taylor *et al.*[35]). Other ions detected were C^+, N^+, H^+, He^+, D^+, NO^+, CO_2^+, O^{++}, O_{18}^+ and mass 27 which may have contributions from both CO^+ and N_2^+. The ORPA measured the concentration of major ions like O_2^+, O^+ and CO_2^+ (Kundsen[36]). Fig. 7, taken from Taylor *et al.*[35], shows a plot of the ion composition measured on a single PVO passage through the subsolar ionosphere. The rich but complex variety of ions can be observed.

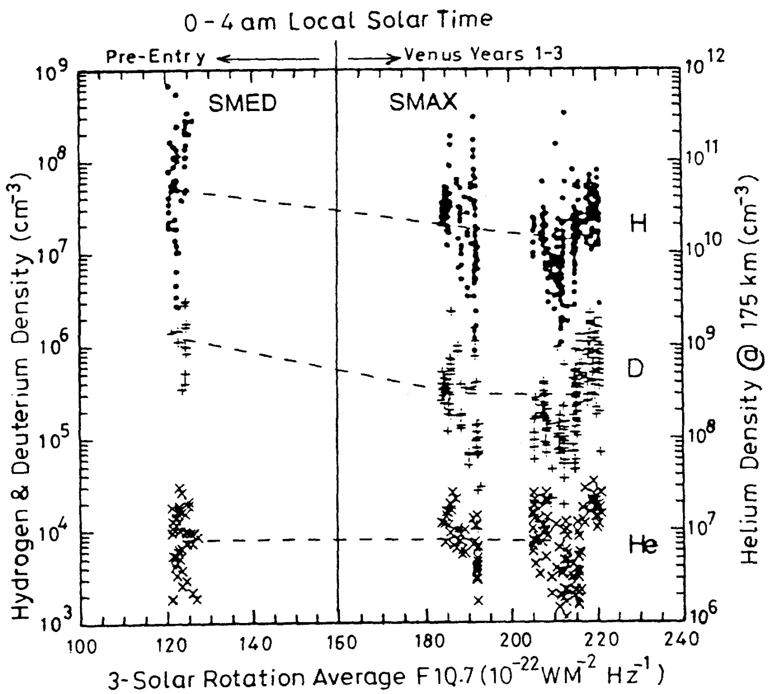

Fig. 6 Variation H, D and He densities with solar activity for local solar time) 0 to 4 hr. Densities decrease with increase in solar activity[19]

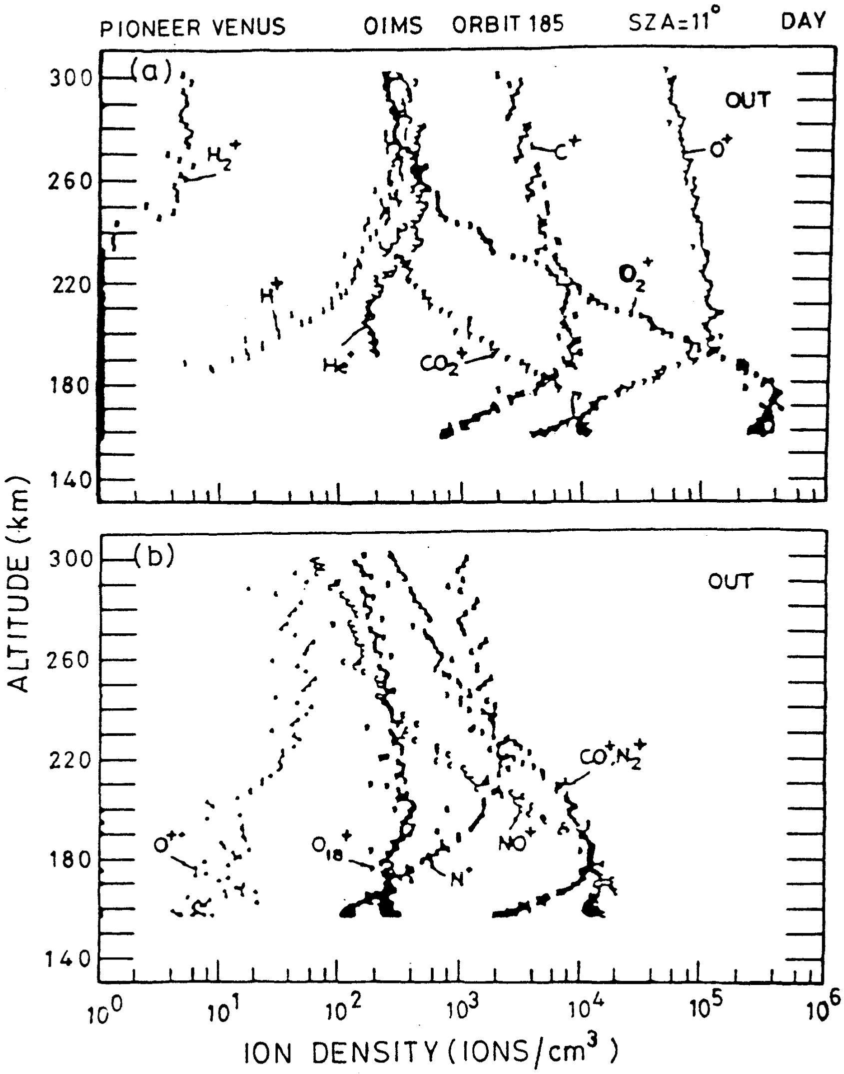

Fig. 7 Ion composition measurements from a single PVO passage through the subsolar ionosphere demonstrating that O_2^+ is the dominant ion below 200 km, while O^+ dominates above it[35]

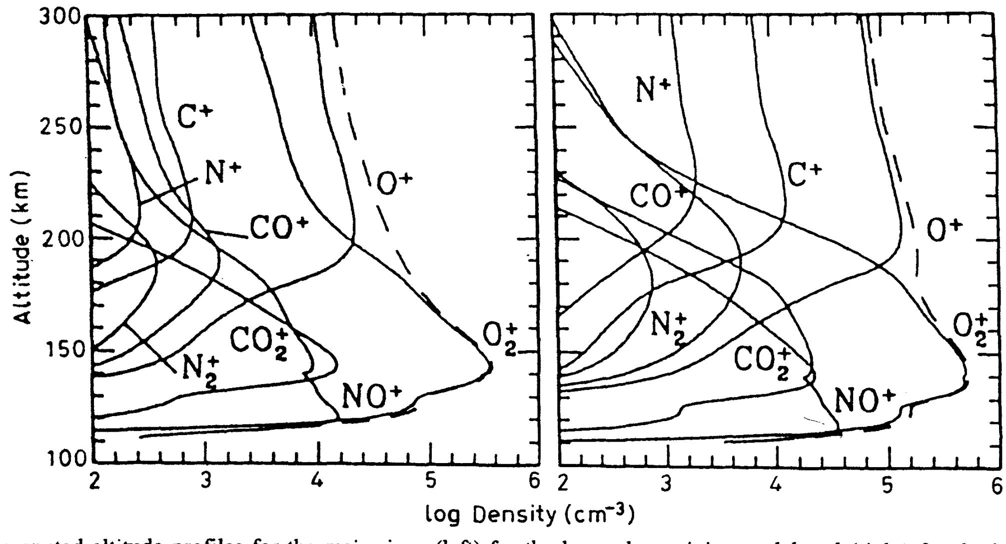

Fig. 8 Computed altitude profiles for the major ions (left) for the low solar activity model and (right) for the high solar activity model[12]

It may be observed that although CO_2 is the major neutral constituent, CO_2^+ remains a minor ion because of charge exchange of CO_2^+ with O and of O^+ with CO_2, as given under:

$CO_2^+ + O \rightarrow O_2^+ + CO$

$O^+ + CO_2 \rightarrow O_2^+ + CO$

The main photochemical ionization layer is due to O_2^+ with a peak density at about 140 km as seen on BIMS. The photochemical and diffusive processes compete to produce an O^+ maximum at about 200 km above which diffusion and bulk transport control the ion distribution.

From an analysis of the OIMS measurements, Taylor *et al.*[35] identified three distinct ion regions, (i) the bow shock-ionosheath energetic ion layer, (ii) the super thermal ion flow region resulting from the solar wind acceleration of thermal ions in the upper ionosphere-ionopause region and, (iii) the main region of thermal ions. Taylor *et al.* have defined the region between the ambient thermal ionosphere and the region of ion acceleration or super thermal flow as "ionopause". We shall discuss more on this region in a subsequent section.

Model calculations for the dayside have been made by several workers[37,38,34,17] and they have found a reasonable agreement between the theory and the experimental results with the exception of N^+ and CO^+ (and/or N_2^+) where the discrepancies are the largest. Fig. 8, taken from Fox and Kliore[17], shows computed altitude profiles for the major ions for low solar activity and high solar activity models. Fox and Kliore have pointed out that the shoulder near 200 km in the electron density profile at high solar activity is due to the peak in O^+ density profile. According to these authors, this shoulder was incorrectly interpreted by Shinagawa *et al.*[40] as an evidence of magnetised dayside ionosphere.

Large diurnal and solar activity variations have been seen in the ion composition. Fig. 9 taken from Kar *et al.*[41] compares density profiles from important ions for the nightside during solar maximum and solar medium (the pre-entry period). While O^+ changed by a factor of 10, O_2^+ showed a much smaller variation. H^+ and He^+ showed decrease in their concentration during the pre-entry period. These results have been interpreted by Kar *et al.*[41] as an indication of the importance of particle precipitation during solar medium and during solar minimum. We shall discuss this issue in somewhat more detail in our section on the maintenance of nightside ionosphere.

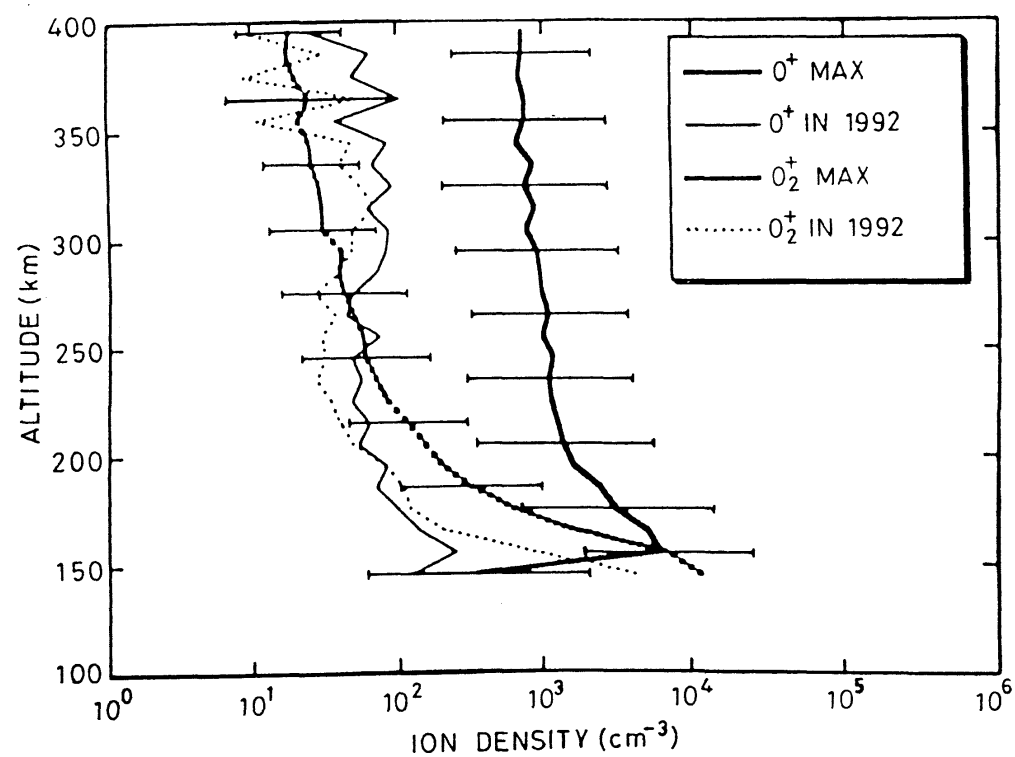

Fig. 9 Average altitude profiles of O^+ and O_2^+ during the primary mission of PVO (solar max.) and in 1992 during PVO entry with data from midnight to 04:30[41]

The ion densities, as mentioned earlier, have also been measured by the ORPA and by the electron temperature probe, OETP and these densities have shown an excellent agreement with the OIMS measurements, except for the O_2^+ bulge at 170 km seen on the OIMS. This disagreement has not yet been settled. Fig. 10, taken from Miller *et al.*[42], shows median ion densities obtained by the ORPA experiment and sorted according to SZA, grouped into 30° intervals during the high solar activity period. A significant control of SZA is evident, but the densities change very little between 0 to 60° (central dayside) and 120 to 180° (central nightside). The OETP data gave similar results[15]. The EUV control on the densities, in terms of solar activity, can be noted from Fig. 11, taken from Knudsen *et al.*[43], which shows electron density profiles from radio occultation measurements during solar maximum and solar minimum. As noted in the OIMS measurements, there is a large decrease in the densities at higher altitudes from solar maximum to solar minimum. This is expected to be so since O^+ is produced mostly by direct ionization of O and lost by reaction with CO_2. Both O and ionizing photon fluxes decrease with decreasing solar activity and the loss due to charge exchange increases with decreasing solar activity. Fox and Kliore[17], from model calculations, have estimated that O^+ density will decrease by about a factor of 6 from solar max. to solar min. The observed densities, however, decreased by more than a factor of 10 during this period.

4 Electron and Ion Temperatures

The OETP instrument measured electron temperature while ORPA measured electron as well as the ion temperatures. A large amount of data has been generated by these instruments and therefore the morphology of the thermal structure of the Venus ionosphere is now well established. Figs. 12(a) and 12(b), taken from Miller *et al.*[42], show median electron and ion temperature profiles measured by the ORPA for various solar zenith angles. It can be seen that the plasma temperatures are significantly higher than the gas temperature

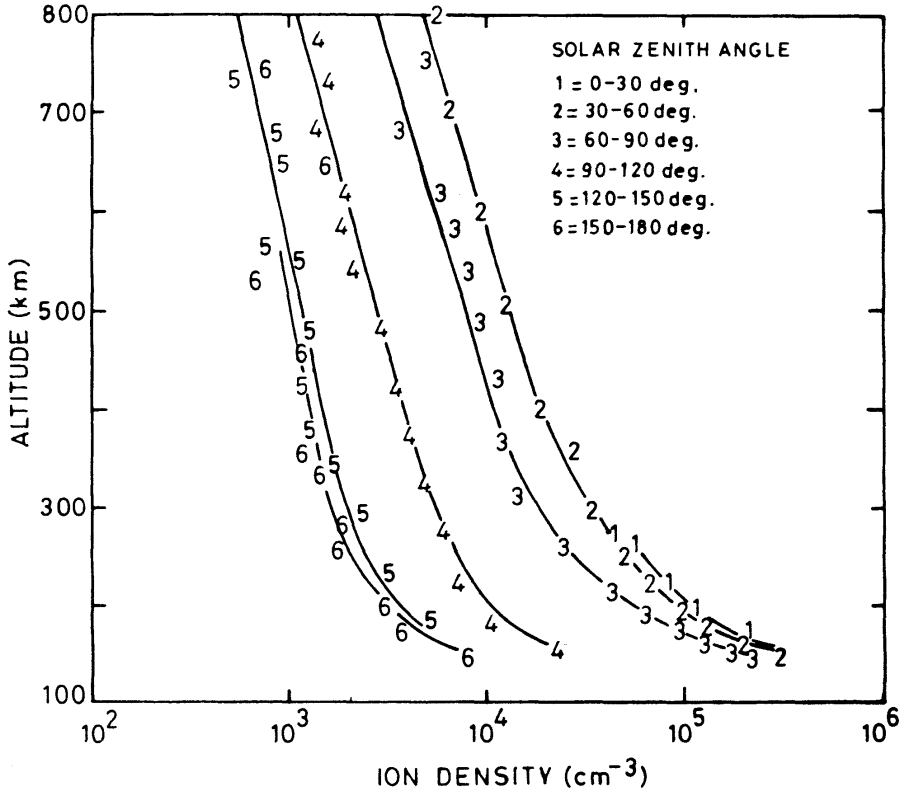

Fig. 10 Median total ion density profiles from ORPA for 30° intervals of SZA. There is little variation of the density between 0° and 60° (central dayside), and 120° to 180° (central nightside), but large changes occur for other values of SZA[42]

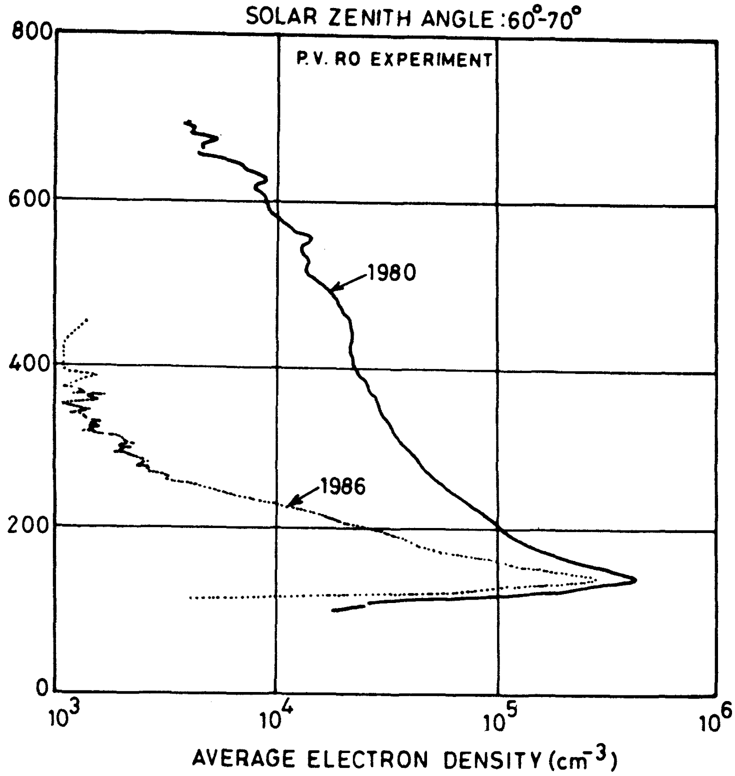

Fig. 11 Electron density profiles obtained by PVO radio occultation at solar maximum (1980) and solar minimum (1986). A large depletion in the dayside upper ionosphere at solar maximum (1980) and solar minimum can be noted[43].

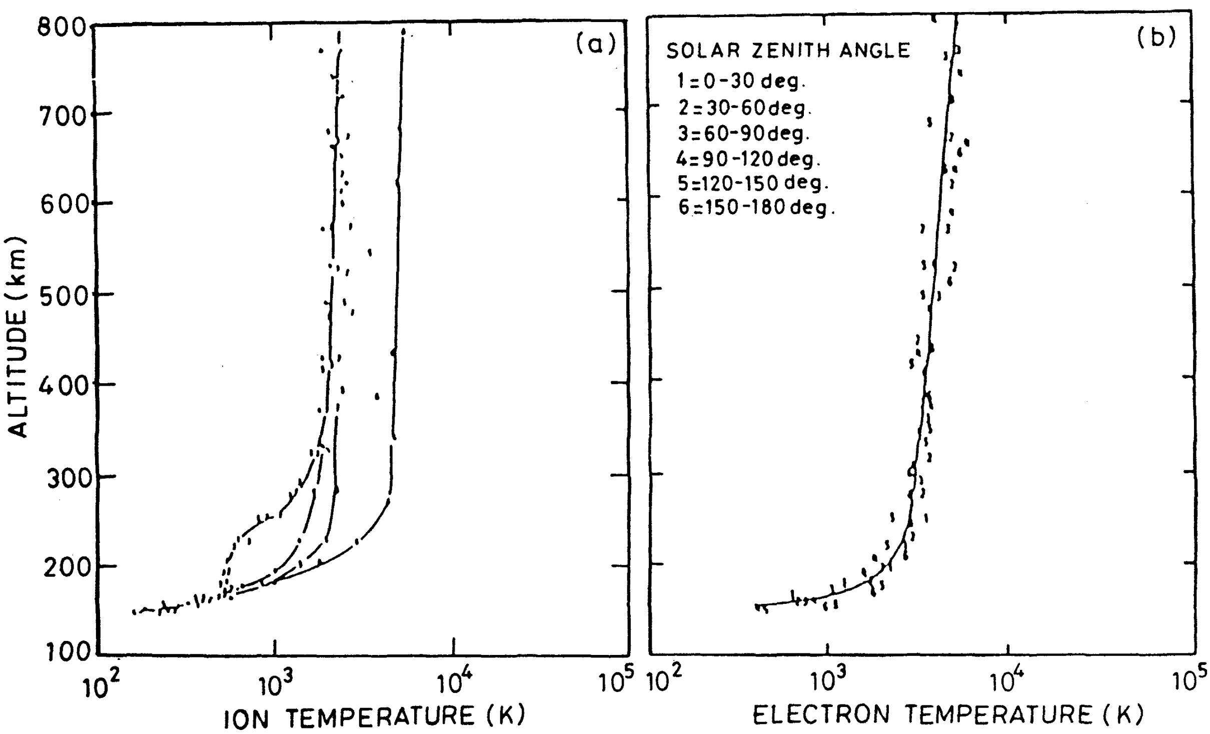

Fig. 12 Plasma temperatures as measured by ORPA (a) electron temperatures (b) ion temperatures. There is little diurnal change in the temperatures. Ion temperature is about one half of the electron temperature, except in the antisolar region, where the two are equal[42].

(which is about 300 K during the day and about 100 K during the night in the upper ionosphere). Further the temperatures change little with SZA. The electron temperatures are about a factor of two higher than the ion temperature, except for the anti solar region where the two are nearly equal. The ORPA measurements of Te are in agreement with the OETP measurements[15].

Heat balance calculations by several workers required topside electron and ion heat fluxes of the order of 5×10^{10} ev $cm^{-2}s^{-1}$ for electrons and 7×10^{7} ev $cm^{-2}s^{-1}$ for the ions to explain the observed plasma temperatures. Since the source of these high fluxes was ad hoc and thus debatable, Cravens *et al.*[44] and Knudsen *et al.*[45] found that introduction of a quasi-horizontal magnetic field could eliminate or reduce the magnitude of external heat source (the horizontal field reduced the thermal conductivity). Since the magnetic field in the Venus ionosphere was found to be highly variable and turbulent[46] Cravens *et al.*[47] used a rather realistic model of magnetic field that included fluctuations. These authors could nearly match the observed Te profiles by using a magnetic field strength of 10 γ and a mean free path of 3 km for the photoelectrons due to fluctuating magnetic field. However, the calculated ion temperatures were found to be independent of the mean free path.

Hoegy *et al.*[48] observed that in the absence of heat sources and sinks (i.e. during the nighttime), the heat flow is constant and the effect of the magnetic field fluctuations can be considered by averaging this term over the measured fluctuations of the dip angles. From an analysis of 30 orbits, they obtained an "effective" dip angle of 2.5° in contrast to the average dip angle of 19.3° corresponding to the same 30 orbits. The reduced effective dip angle decreased the desired heat flow by two orders of magnitude compared to the one needed when the average dip angle was used. It is quite clear therefore that one does not need any ad hoc heat source for explaining the observed plasma temperatures. Indeed the observed fluctuating magnetic fields (which reduce the thermal conductivity) can explain the observed temperatures with EUV as the only heat source.

Another area of interest in the Venus ionosphere has been the orbit-to-orbit variability often noted in the Te measurements. Elphic *et al.*[49] concluded that while the solar rotation-related changes in EUV tracked changes in the electron densities below 200 km rather well, the electron temperature, on the other hand, showed little response to these EUV fluctuations. Mahajan *et al.*[50] identified two distinct regions in the Venus Te profile (1) the region below the ionopause, called the main ionosphere and (2) the region in the sharp Ne gradient i.e (in the ionopause) Mahajan *et al.*[50] concluded that Te at any fixed altitude in the main ionosphere does not vary from one orbit to the next. The major variations in Te is in the ionopause region and are related to changes in the electron density, as will be clear from Fig. 13. Dobe *et al.*[51] have related some of the changes in Te to ionospheric magnetic field.

The near constancy of Te in the main ionosphere, inspite of significant changes in EUV due to solar rotation[49], is a surprising result. Brace and Kliore[15] have, however, correctly explained it as due to opposing changes in the electron cooling rate caused by solar EUV driven increases in Ne. The Te response to changes in Ne in the ionopause region further supports the theory that Venus Te is controlled by EUV heating alone and the steep rise in Te in the ionopause region is related to the steepfall in the Ne. Earlier, some authors[15], had interpreted the sharp rise in Te at the ionopause as an evidence of solar wind heating.

5 Ionopause Structure

Venus ionosphere acts as an obstacle to the solar wind and Fig. 14 taken from Mahajan[52] gives a schematic representation of this interaction. The solar wind dynamic pressure, Psw, is converted to magnetic pressure P_B, in the barrier and this in turn is balanced by the ionospheric thermal pressure, P_p. This balance occurs at the ionopause, the region which is marked by a steep gradient in plasma density at the top of the ionosphere. The density here changes by a factor of about 100. The ionopause height adjusts to the dynamic pressure of the solar wind. As this pressure increases, a higher ionosphere pressure is needed to balance and consequently ionopause moves to a lower altitude, where the thermal pressure is higher and *vice versa.* For the same reason, the ionopause altitude increases with SZA, because effective Psw decreases in proportion to $\mathrm{Cos}^2\chi$ (χ = SZA). The effect of Psw and SZA on the ionopause altitude has been studied by several workers[53,13,35]. Fig. 15, again taken from Mahajan[52], shows plots of plasma and magnetic pressure for three orbits with varying

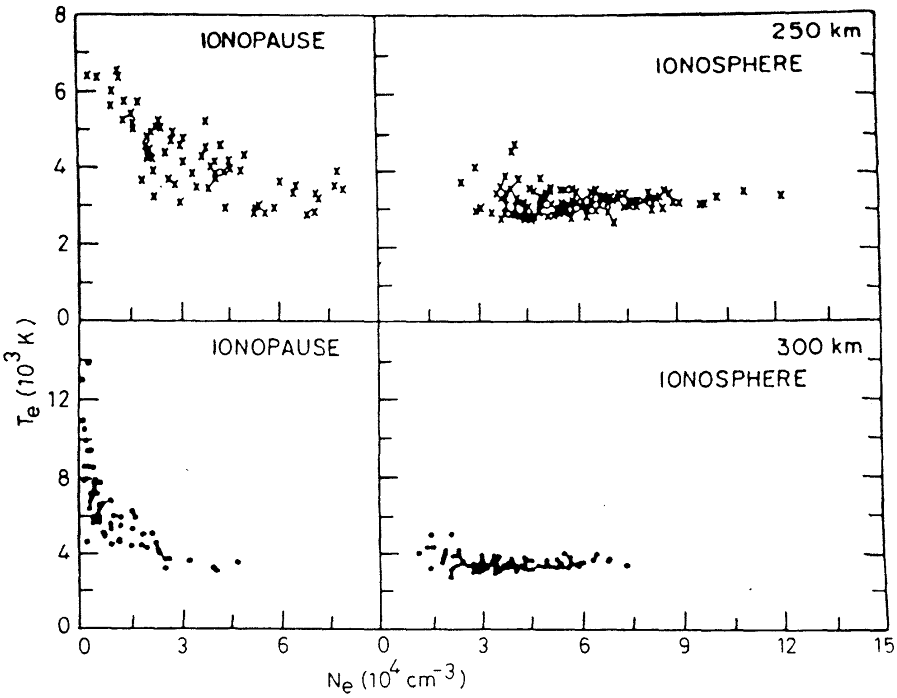

Fig. 13 Inverse correlation between the electron temperature and density in the ionopause region. The temperature in the main ionosphere remains nearly constant, while most of the variability is due to variations in the ionopause region[50].

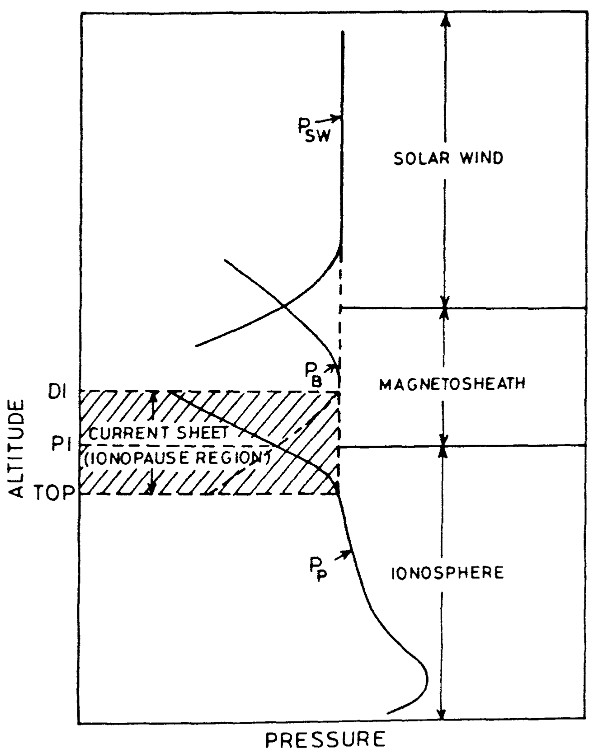

Fig. 14 A schematic of solar wind interaction at Venus showing the three major regions, namely the solar wind region, the magnetosheath and the ionosphere. The region of the steep plasma gradient (above the top of the ionosphere) is the ionopause[52].

solar wind conditions, (a) low, (b) moderate and (c) extremely high, Psw, more than the maximum plasma pressure. Time from periapsis on the x-axis provides the altitude measurement.

Although the ionopause altitude falls rapidly with increasing Psw, it levels off above about 4 n Pa[53]. This saturation has been explained by Mahajan *et al*[54] due to the fact that ionopause is driven so deeply into the thermosphere that photo-ion production loads down the solar wind interaction (i.e. photoionization of the neutral atmosphere replenishes the plasma that is swept away by the solar wind). In this process the height of the ionopause follows the height of the ionizable species, atomic oxygen. This is quite evident from Fig. 16, taken from Mahajan *et al.*[54], which shows a scatter plot of ionopause altitude versus Psw (sum of magnetic and plasma pressure at the ionopause altitude). It can be noted that at low Psw, ionopause tracks the plasma pressure while at high Psw it tracks the neutral gas pressure.

6 Nightside Ionosphere

Inspite of long Venus night (58 earth days), there is a remarkable abundance of ions on the nightside

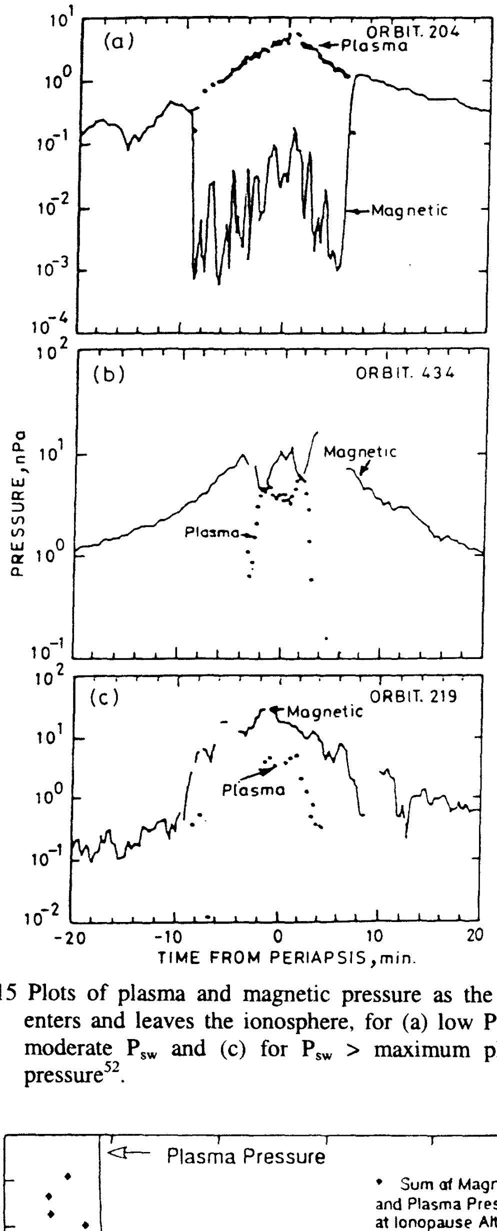

Fig. 15 Plots of plasma and magnetic pressure as the PVO enters and leaves the ionosphere, for (a) low P_{sw} (b) moderate P_{sw} and (c) for P_{sw} > maximum plasma pressure[52].

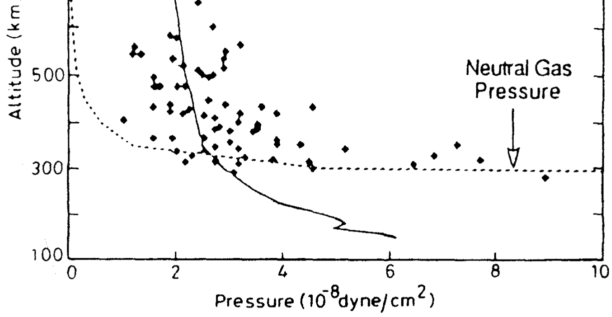

Fig. 16 A plot of ionopause altitude versus P_{sw}. Also plotted are model values of plasma and neutral pressure. At low P_{sw} ionopause tracks the plasma pressure but at higher values it tracks the neutral pressure[54].

featuring the same constituents of ions on the nightside as on the dayside, though with much lower concentration levels[35]. There is a strong solar activity effect which was earlier seen in the radio occultation measurements (Knudsen *et al.*[43]) and has been reconfirmed from the PVO pre-entry measurements from all the ionospheric experiments (viz Theis and Brace[55], from the OETP; Kar *et al.*[41], from the OIMS; Spenner *et al.*[56,57], from the ORPA). Fig. 17, taken from Theis and Brace[55], shows a comparison of nighttime electron densities and temperature obtained by the OETP during the pre-entry period and during the solar maximum. While the densities decreased during the entry, temperatures increased. Further, a large variability in the densities has been observed and Fig. 18, taken from Spenner *et al.*[56], highlights this

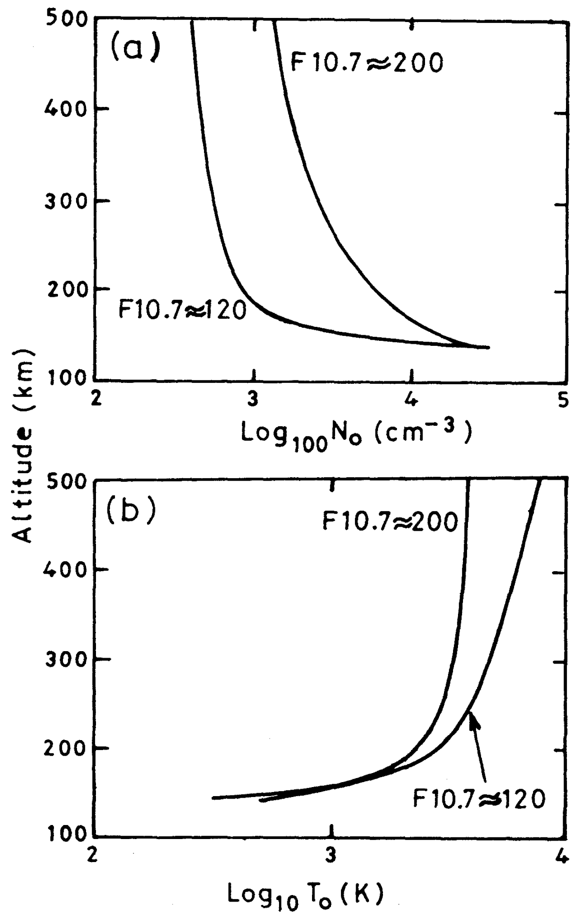

Fig. 17 Comparison of electron densities and temperatures measured by the OETP instrument during the pre-entry period ($F_{10.7}$ ~ 120) and solar maximum ($F_{10.7}$ ~ 200). While the densities decreased, the temperatures increased during the pre-entry period[55].

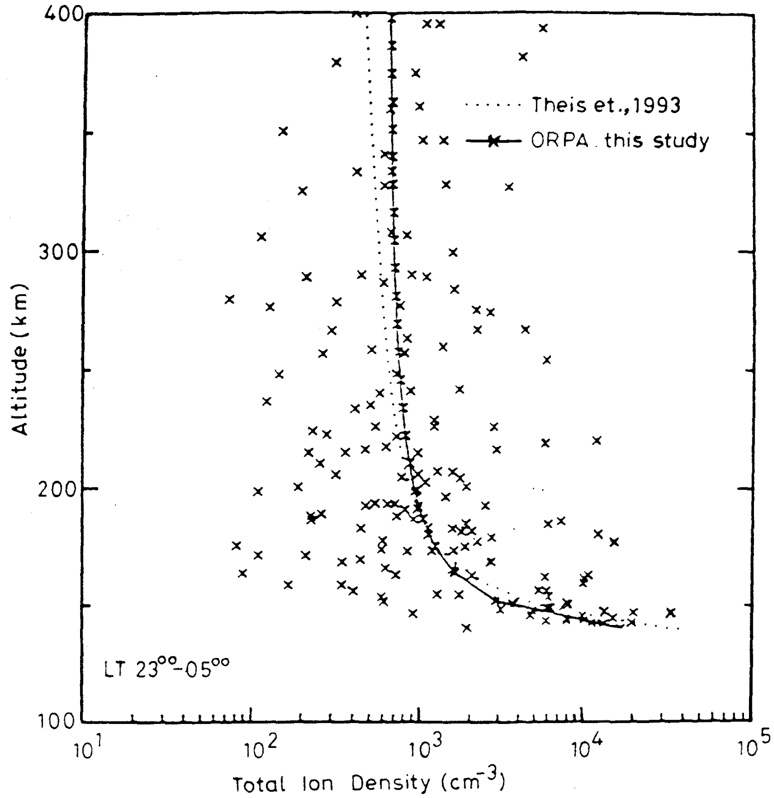

Fig. 18 Nightside electron density values measured during the entry period by ORPA. Large variability in the density can be noted[56].

variability by showing the density values measured by the ORPA during the entry period. In view of this large variability, any average or medium density profile will have a limited utility only.

A question of major concern is the maintenance of the nightside ionosphere. Due to electron-ion recombination processes, no ion is expected to survive during the long Venus night. Two potential explanations have been offered for the maintenance of the nightside ionosphere, (1) precipitation of supra-thermal electrons and (2) transport of atomic ions from the dayside. The supra-thermal electrons have indeed been observed in the nightside of Venus by retarding potential analyzers carried by Veneras 9 and 10 during solar minimum[58] and by the PVO during solar maximum[59]. These supra-thermal electrons are believed to be shocked solar wind electrons moving into the ionosphere from the tail region. The integral fluxes of these supra-thermal electrons during the solar minimum were found to be sufficient to produce the observed peak ion density within a factor of two. The integral fluxes measured by the ORPA in the Venus wake during solar maximum were slightly larger than the Venera measurements but were within the error bars of the two experiments.

The ORPA experiment on the PVO provided the first experimental evidence of antisunward flow, mostly of atomic ions from the subsolar region to about 150° SZA on the nightside. Although these flow velocities were rather small at the subsolar region, these became supersonic at high altitudes near the terminator. Velocities as high as 5 km/s have indeed been observed. These high flow velocities occur because of the large plasma pressure gradients between the day and the nightside. Fig. 19, taken from Miller and Whitten[61] gives the average ionospheric velocity field as measured by the ORPA. The measured velocities very successfully explain the existence of the nightside ionosphere during the solar maximum. Spenner *et al.*[59], for example, demonstrated that downward fluxes of O^+ of the order of 10^8 $cm^{-2}s^{-1}$ could produce the observed nightside O_2^+ peak density through the reaction $O^+ + CO_2 \rightarrow O_2^+ + CO$. The total flux of O^+ across the terminator, estimated by Knudsen and Miller[62] from values of

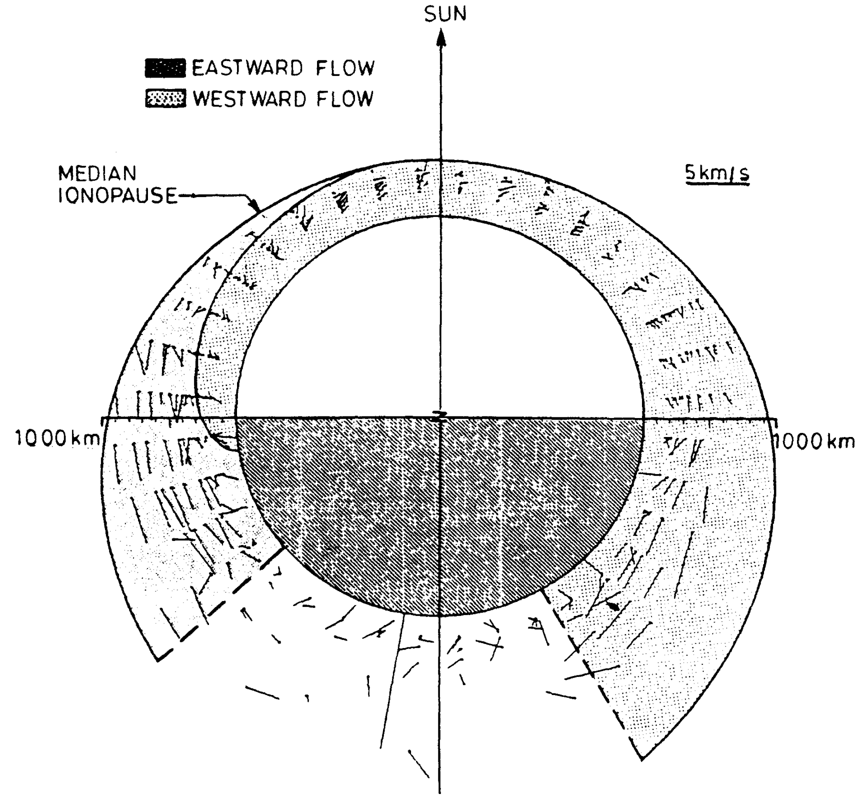

Fig. 19 Average O^+ velocity as measured by the ORPA instrument. Large velocities at the terminators are responsible for the maintenance of the nightside ionosphere[61].

terminator densities and velocities, indeed gave an O^+ downward flux of the same order.

During the solar minimum, the terminator ionopause is likely to move down to very low altitudes (≈ 250 km) and therefore Knudsen *et al.*[43] correctly predicted that there would be a sharp reduction of plasma transport from the dayside to the nightside during solar minimum. Knudsen *et al.* had further inferred that particle precipitation would then be the dominant source for the Venus nightside ionosphere. Kar *et al.*[41] compared the ion composition measurements during solar maximum and with those during solar medium (pre-entry period) and found that O^+ concentration decreased drastically from solar maximum to solar medium. This observation was in conformity with the argument that O^+ flux across the terminator would drastically reduce during solar minimum[43]. Kar *et al* in addition, found that the O_2^+ peak densities were only slightly reduced from solar maximum conditions. According to Kar *et al.*[41]. this result gave a clear evidence for electron impact ionization to be the dominant source for the nightside ionosphere during solar medium, as well as solar minimum. Fox and Kliore[17], however, have cautioned that estimation of the relative importance of ion precipitation and plasma transport by comparing the high and low solar activity ion densities at the peak and those substantially above the peak is not in order. They have given several reasons in support of their concern, (1) the determination of the magnitude of an ionization source needs a knowledge of neutral density profiles which indeed show a large variability in the nightside, (2) the two processes do not produce peaks at the same altitude and, (3) for a weak nightside ionosphere, diffusion, in addition to chemistry, might play an important role. From the above, it is quite clear that although precipitation contributes significantly for the maintenance of the nightside ionosphere during solar minimum, the role of transport from the dayside may not be insignificant, especially in explaining the orbit to orbit variability because the precipitation component has been found to be nearly constant.

7 Other Features

The nightside Venus ionosphere has, in addition, exhibited some important small scale spatial structures like the plasma clouds[63] post-terminator waves[64] antisolar-region waves[48], ionosphere holes[53,65] and ionotail[66]. We have not discussed these features in this review and reader is advised to consult the original papers on these subjects. In addition, there are other topics which are intimately connected with the Venus ionosphere and include; solar wind interaction[67]. ionosphere magnetic fields[68], plasma waves[69] Venus lightning[70]), upper atmosphere dynamics[71]. We have not discussed these topics too and reader is advised to consult the latest reviews cited above.

Acknowledgement

The Author (KKM) was a visiting Professor at the Institute of Space and Astronautical Science, Sagamihara, Japan during the progress of this work. The author (KKM) is grateful to ISAS for hospitality and facilities.

References

1 K K Mahajan and J Kar *Space Sci Rev* **47** (1988) 303
2 L Colin *J Geophys Res* **85** (1980) 7575
3 R J Strangeway *Geophys Res Lett* **20** (1993) 2715
4 J P Krehbiel, L H Brace, R F Theis, J R Cutler, W H Pinkus and R B Kaplan *IEEE Trans Geosci Remote Sens* **GE-18** (1980) 49
5 H A Taylor Jr, H C Brinton, T C G Wagner, B H Blackwell and G R Cordier, *IEEE Trans Geosci Remote Sens* **GE-18** (1980a) 44
6 W C Knudsen, K Spenner, J Bakke and V Novak *IEEE Trans Geosci Remote Sens* **GE-18** (1980a) 49
7 H B Niemann, J R Booth, J E Cooley, R E Hartle, W T Kasprzak, N W Spencer, S H Way, D M Hunten and G R Carignan *IEEE Trans Geosci Remote Sens* **GE-18** (1980a) 60
8 H J Hoffman, K Pelka, U von Zahn, D Krankowsky and D Linkert *IEEE Trans Geosci Remote Sens* **GE-18** (1980) 122
9 A F Nagy, T E Cravens and T I Gombosi, *Venus* Univ. of Arizona Press Tucson Arizona (1983) p 241
10 A F Nagy and T E Cravens *Venus II* Univ of Arizona Press Tucson Arizona p 189
11 K K Mahajan *Proc Indian natn Sci Acad* **64A**, (1998) 377
12 R W Schunk and A F Nagy *Rev Geophys Space Phys* **18** (1980) 813
13 L H Brace, H A Taylor Jr, T I Gombosi, A J Kliore, W C Knudsen and A F Nagy *Venus* Univ of Arizona Press Tucson Arizona (1983a) p 779
14 K K Mahajan and J Kar *Space Sci Rev* **47** (1988) 303
15 L H Brace and A J Kliore *Space Sci Rev* **55** (1991) 81
16 J Kar *Space Sci Rev* **77** (1996) 193
17 J L Fox and A J Kliore *Venus 2* Univ of Arizona Press Tucson Arizona p 161
18 U von Zahn, S Kumar, H B Niemann and R Prinn *Venus* Univ of Arizona Press Tucson Arizona (1983) p 299
19 W T Kasprazk, G M Keating, N C Hsu, A I F Stewart, W B Colwell and S W Bougher *Venus II* Univ of Arizona Press Tucson Arizona (1997) p 225
20 C A Barth, J B Pearce, K K Helly, L Wallace and W G Fastie *Science* **158** (1967) 1675
21 V G Kurt, S B Dostovalow and E K Sheffer *J Atmos Sci* **25** (1968) 668
22 H W Moos, W G Fustie and M Bottema *Astrophys J* **155** (1969) 887
23 H W Moos and G J Rottman *Astrophys J* **169** (1971) L127
24 L Wallace, F E Stuarts, R H Nagel and K D Larson *Astrophys J* **168** (1971)L29
25 U von Zahn, D Krankowsky, K Mauersberger, A O Nier and D M Hunten *Science* **203** (1971) 768
26 H B Niemann, W T Kasprazk, A E Hedin, D M Hunten and N W Spencer *J Geophys Res* **85** (1980) 7817
27 H C Brinton, H A Taylor Jr, H B Niemann, H G Mayr, T E Cravens and D F Strobel *Geophys Res Lett* **7** (1980) 865
28 J M Grebowsky, W T Kasprazk, R E Hartle and T M Donahue *Adv Space Res* **17**(11) (1995) 191
29 G M Keating, J Y Nicholson III and L R Lake *J Geophys Res* **85** (1980) 7941
30 G M Keating and N C Hsu *Geophys Res Lett* **20** (1993) 2751
31 H G Mayr, I Harris, H B Niemann, H C Brinton, N W Spencer, H A Taylor Jr, R E Hartle, W R Hoegy and D M Hunten *J Geophys Res* **85** (1980) 7841
32 G M Keating and S W Bougher *J Geophys Res* **97**(1992) 4189
33 R D Sharma and P P Wintersteiner *Geophys Res Lett* **17** (1990) 2201
34 R E Hartle, T M Donahue, J M Grebowsky and H G Mayr *J Geophys Res* **101** (1996) 4525
35 H A Taylor Jr, H C Brinton, S J Bauer, R E Hartle, P A Cloutier and R E Daniell Jr *J Geophys Res* **85** (1980b) 7765
36 W C Knudsen, K Spenner, K L Miller and V Novak *J Geophys Res* **85** (1980b) 7803
37 A F Nagy, T E Cravens, R H Chen, H A Taylor Jr, L H Brace and H C Brinton *Science* **205** (1979) 107
38 T E Cravens, S L Crawford, A F Nagy and T I Gombosi *J Geophys Res* **88** (1983) 5595
39 T Shimazaki, R C Whitten, H T Woodward, W C Knudsen and K L Miller *Icaras* **60** (1984) 654
40 H Shinagawa, J Kim, A F Nagy and T E Cravens *J Geophys Res* **96** (1991) 11083
41 J Kar, R E Hartle, J M Grebowsky, W T Kasprazk, T M Donahue and P A Cloutier *J Geophys Res* **99** (1994) 11351
42 K L Miller, W C Knudsen, K Spenner, R C Whitten and V Novak *J Geophys Res* **85** (1980) 7759
43 W C Knudsen, A J Kliore and R C Whitten *J Geophys Res* **92** (1987) 13391
44 T E Cravens, A F Nagy, L H Brace, R H Chen and W C Knudsen *Geophys Res Lett* **6** (1979) 341
45 W C Knudsen, K Spenner, R C Whitten, J R Spreiter, K L Miller and V Novak *Science* **205** (1979) 105

46 C T Russell, R C Elphic and J A Slavin *Science* **203** (1979) 745
47 T E Cravens, T I Gombosi, J U Kozyra and A F Nagy *J Geophys Res* **85** (1980) 7778
48 W R Hoegy, L H Brace, W T Kasprazk and C T Russell *J Geophys Res* **95** (1990) 4085
49 R C Elphic, L H Brace, R F Theis and C T Russell *Geophys Res Lett* **11** (1984) 124
50 K K Mahajan, S Ghosh, R Paul and W R Hoegy *Geophys Res Lett* **21** (1994) 77
51 Z Dobe, A F Nagy, L H Brace, T E Cravens and J G Luhmann *Geophys Res Lett* **20** (1993) 1523
52 K K Mahajan *Indian J Rad Space Phys* **24** (1995) 269
53 L H Brace, R F Theis, W R Hoegy, J H Wolfe, J D Mihalov, C T Russell, R C Elphic and A F Nagy *J Geophys Res* **85** (1980) 7663
54 K K Mahajan, H G Mayr, L H Brace and P A Cloutier *Geophys Res Lett* **16** (1989) 759
55 R F Theis and L H Brace *Geophys Res Lett* **20** (1993) 2719
56 K Spenner, W C Knudsen and W Lotze *J Geophys Res* **100** (1995) 14499
57 K Spenner, W C Knudsen and W Lotze *J Geophys Res* **101** (1996) 4557
58 K I Gringauz, M I Verigin, T K Breus and T I Gombosi *J Geophys Res* **84** (1979) 2123
59 K Spenner, W C Knudsen, R C Whitten, P F Michelson, K L Miller and V Novak *J Geophys Res* **86** (1981) 9170
60 W C Knudsen and K L Miller *J Geophys Res* **90** (1985) 2697
61 K L Miller and R C Whitten *Space Sci Rev* **55** (1991) 165
62 W C Knudsen and K L Miller *J Geophys Res* **97** (1992) 17165
63 L H Brace, R F Theis and W R Hoegy *Planet Space Sci* **30** (1982a) 29
64 L H Brace, R C Elphic, S A Curtis and C T Russell *Geophys Res Lett* **10** (1983b) 1116
65 L H Brace, R F Theis, H G Mayr, S A Curtis and J G Luhmann *J Geophys Res* **87** (1982b) 199
66 L H Brace, W T Kasprazk, H A Taylor Jr, R F Theis, C T Russell, A Barnes, J D Mihalov and D M Hunten *J Geophys Res* **92** (1987) 15
67 J G Luhmann, S H Brecht, J R Spreiter, S S Stahara, R S Steinolfson and A F Nagy *Venus II* Univ of Arizona Press Tucson Arizona (1997) p 33
68 T E Cravens, H Shinagawa and J G Luhmann *Venus II* Univ of Arizona Press Tucson Arizona (1997) p 61
69 J D Huba and R J Strangeway in *Venus II* Univ of Arizona Press Tucson Arizona p 95
70 J M Grebowsky, R J Strangeway and D M Hunten *Venus II* Univ of Arizona Press Tucson Arizona (1995) p 125
71 S W Bougher, M J Alexander and H G Mayr *Venus II* Univ of Arizona Press Tucson Arizona (1997) p 259