The Institute of Space and Astronautical Science
Report No. 675, September 1999

VENUS IONOSPHERE: MAJOR FEATURES

By

K.K. Mahajan* and K.-I. Oyama**

(August 4, 1999)

Abstract: 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 exospheric temperature changing only by about 60 K over a solar cycle. 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 150 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. In spite 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.

1. INTRODUCTION

Venus is the closest planet to earth and therefore many spacecrafts have visited it since the beginning of the space age. Figure 1 gives a summary of the various successful planetary missions to Venus in relation to solar activity. The climax reached with the Pioneer Venus orbiter, PVO (Colin, 1980) which 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 (Figure.2). Excellent reviews, mostly based upon PVO measurements, have periodically appeared in the literature, (1) on theoretical aspects by Nagy et al. (1983); Nagy and Cravens (1997), (2) on ionospheric structure by Schunk and Nagy (1980); Brace et al. (1983a); Mahajan and Kar (1988); Brace and Kliore (1991); Kar (1996); Fox and Kliore (1997); and (3) on neutral atmosphere (von Zahn et al, 1983; Kasprazk et al. (1997) and Bougher et al. (1997). In this report we shall summarize the most

* National Physical Laboratory, New Delhi, India
** Institute of Space and Astronautical Science, Sagamihara, Japan

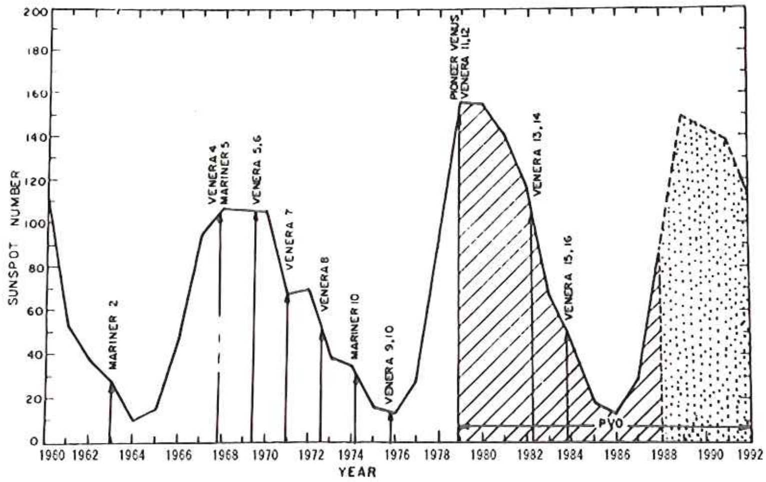


Fig.1: Solar activity and various planetary missions to Venus (from Mahajan and Kar, 1988).

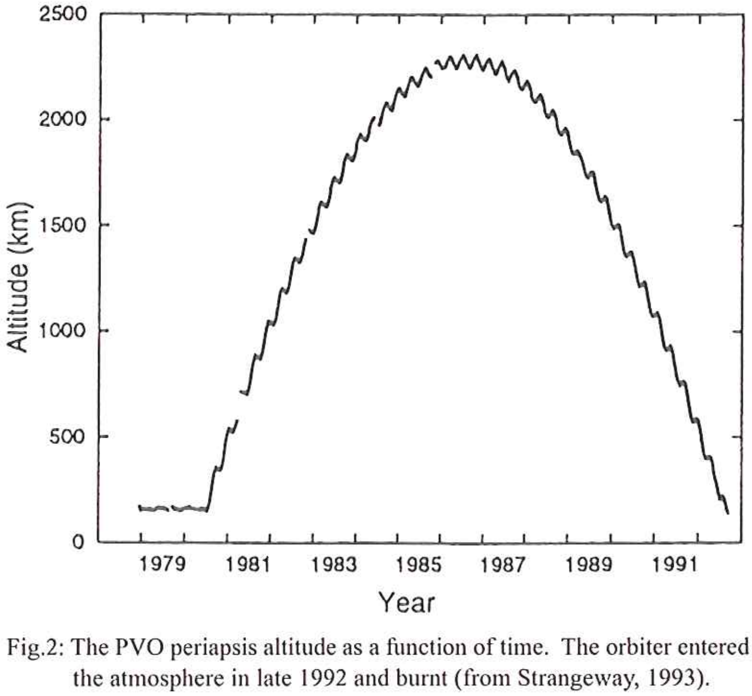


Fig.2: The PVO periapsis altitude as a function of time. The orbiter entered the atmosphere in late 1992 and burnt (from Strangeway, 1993).

important characteristics of the Venus ionosphere, including latest advances in the areas of neutral atmosphere, ion composition, electron densities, electron temperature, solar wind interaction, and the maintenance of nightside ionosphere.

2. NEUTRAL ATMOSPHERE

The first in-situ measurements of the Venus upper neutral atmosphere (above 100 km) were made by the orbiter neutral mass spectrometer, ONMS (Niemann et al., 1980a). During the day, carbon dioxide was

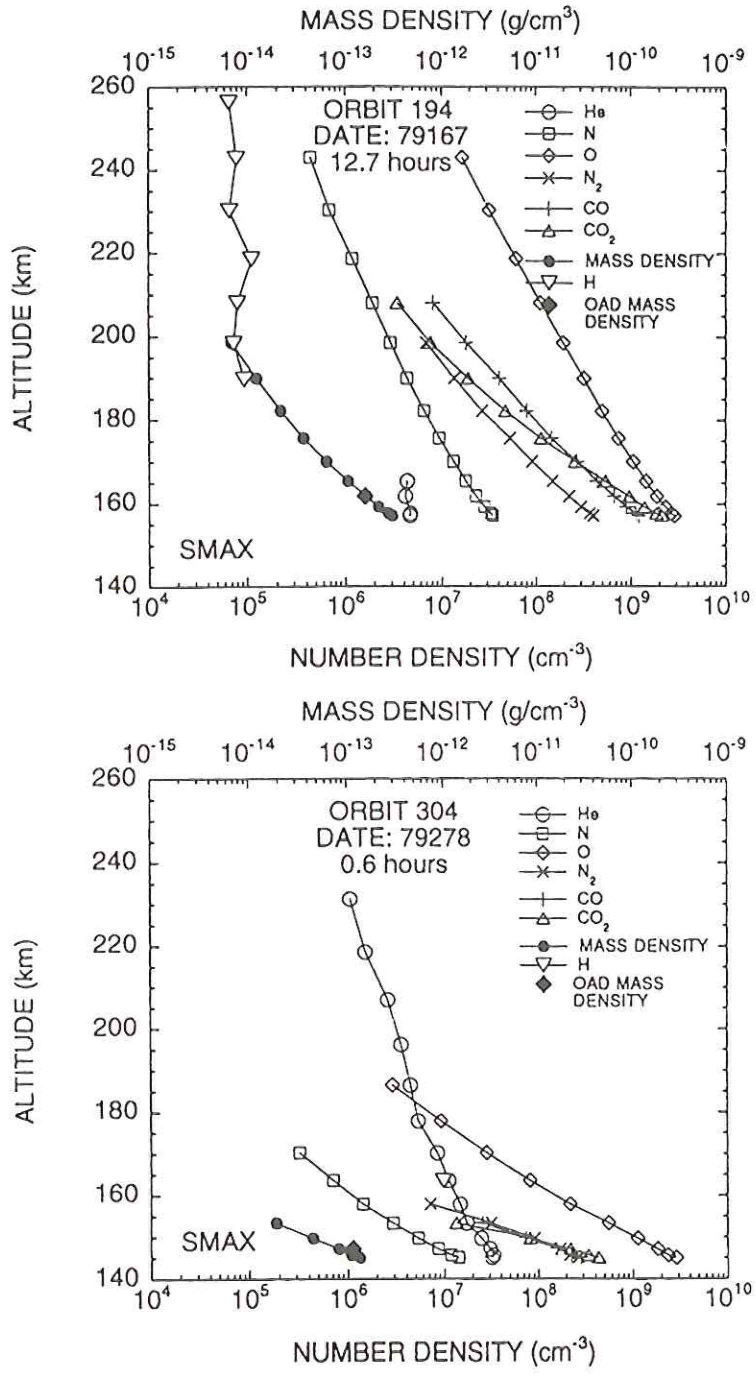


Fig.3: Neutral composition measurements by ONMS during solar maximum conditions. CO_2 dominates in the lower thermosphere, O and He dominate at higher altitudes (from Kasprazk et al., 1997).

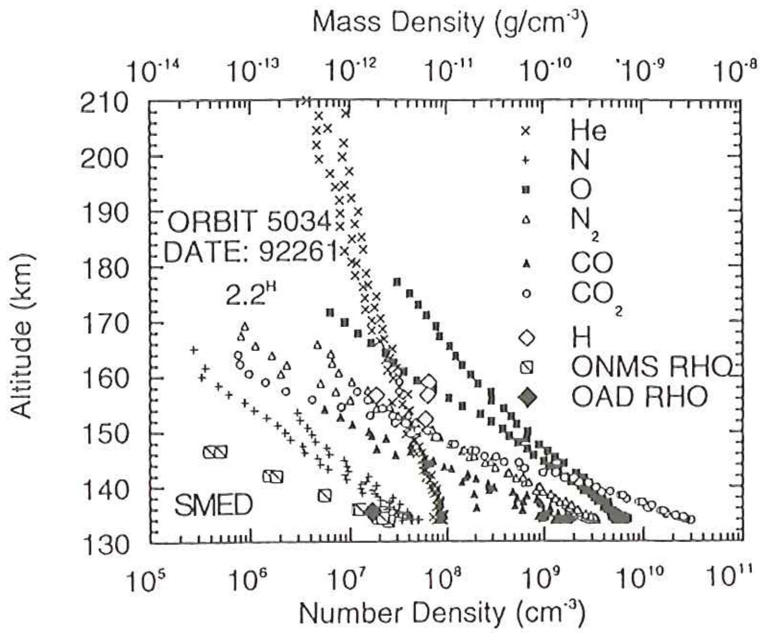


Fig.4: Pre-entry measurement of neutral composition at medium solar activity conditions. Composition and densities for the nightside have not changed between solar maximum and solar medium (from Kasprazk et al., 1997).

found to predominate up to about 150 km, atomic oxygen from 150 km to 250 km and Helium above 250 km. These transitions occur at somewhat lower altitudes during the night. Figure 3 shows typical altitude profiles for the important neutral constituents for dayside and nightside conditions and is an update by Kasprazk et al. (1997) of earlier measurements of Niemann et al. (1980b) during solar maximum. It includes H from Brinton et al. (1980) and Grebowsky et al. (1995) and mass density from Keating et al. (1980). The ONMS densities were raised by a factor of 1.63 to bring agreement between the satellite drag and neutral mass spectrometer measurements. Figure 4 shows the composition data from the pre-entry measurements at solar medium conditions for 2.2 hr local solar time. Values for H density have again been taken from Grebowsky et al. (1995) and for the mass density from Keating and Hsu (1993). No significant change seems to have occurred from solar maximum (Figure.3) to solar medium (Figure.4) for nighttime composition and densities. Scale heights of the neutral constituents 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. Predawn H, He and D bulges have been observed, which indicate that the upper thermosphere superrotates (Mayr et al., 1980).

The PVO data from 1978-1980 has been analyzed by various workers to study the variations due to solar rotation in the upper atmosphere at solar maximum ($F_{10.7}$~200) and a response of 0.14 to 0.19 K/$F_{10.7}$ unit in the global mean temperature has been found (Kasprazk et al., 1997). This is about ten times smaller than seen in the Earth's thermosphere. The ONMS pre-entry data and drag measurement of Magellan orbiter (MGN) and PVO spacecrafts 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 tempera-

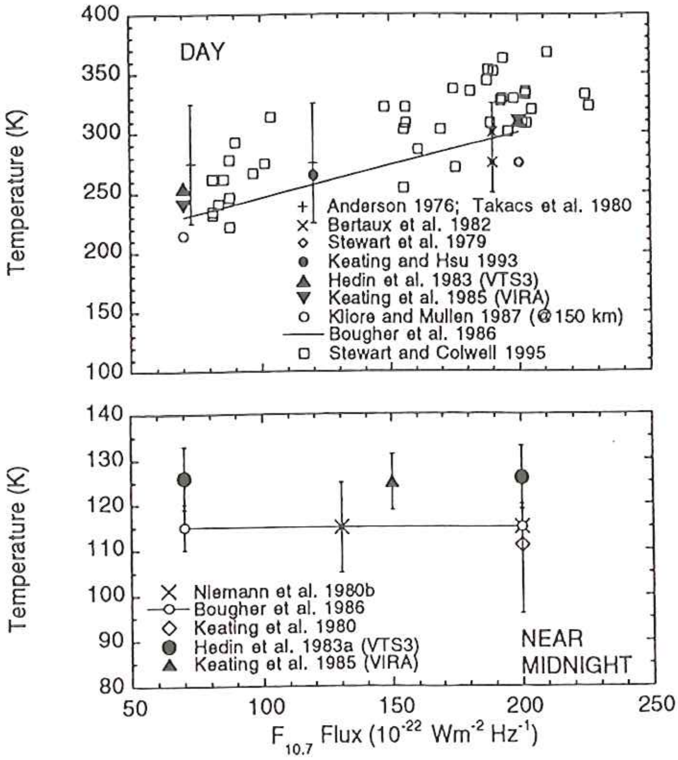


Fig.5: Dayside and near midnight exospheric temperature measured over a solar cycle. The temperature changed by 60 K for the day and less than 15 K for the night from solar maximum to solar medium (from Kasprazk et al., 1997).

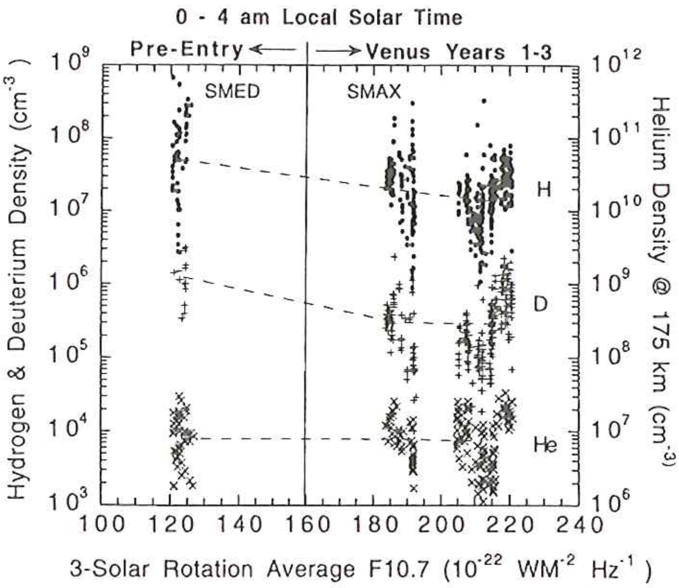


Fig.6: Variation of H, D and He densities with solar activity for local solar time 0 to 4 hr. Densities decrease with increase in solar activity (from Kasprazk et al., 1997).

ture varies by about 60 K for the dayside and by less than 15 K for the night, from solar maximum to solar minimum as can be noted from Figure 5. The weak dayside response has been explained by the CO_2 15 μ m-emission cooling which approximately balances the EUV and UV heating (see Kasprazk et al., 1997 and references therein). In contrast, hydrogen and deuterium densities in the bulge region increase with decrease in solar activity (Figure 6). This has been attributed to the reduction in the exospheric escape of H and D with decreasing solar activity (Hartle et al., 1996).

3. ION COMPOSITION AND ION DENSITIES

The orbiter ion mass spectrometer, OIMS (Taylor et al., 1980a), identified 12 ion species with O_2^+ as the major ion at altitudes below about 200 km, and O^+ at higher altitudes (Taylor et al., 1980b). Figure 7 shows a plot of ion composition measurements from a single PVO passage through the subsolar iono-

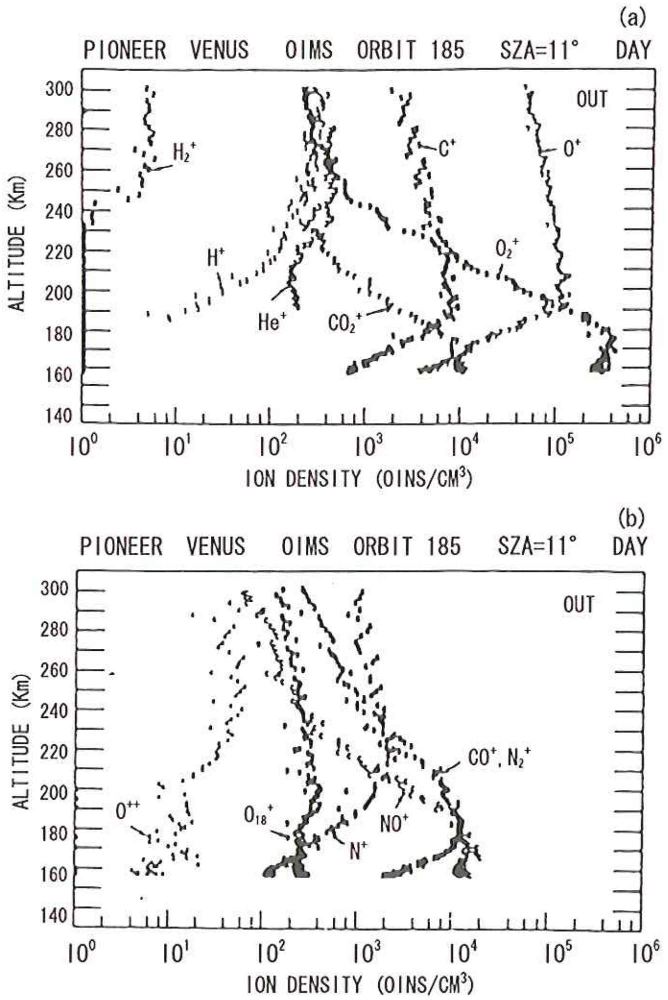


Fig.7: Ion composition measurements from a single PVO passage through the subsolar ionosphere demonstrating that O_2^+ is the dominant ion below 200 km, while O^+ dominates above it (from Taylor et al., 1980b).

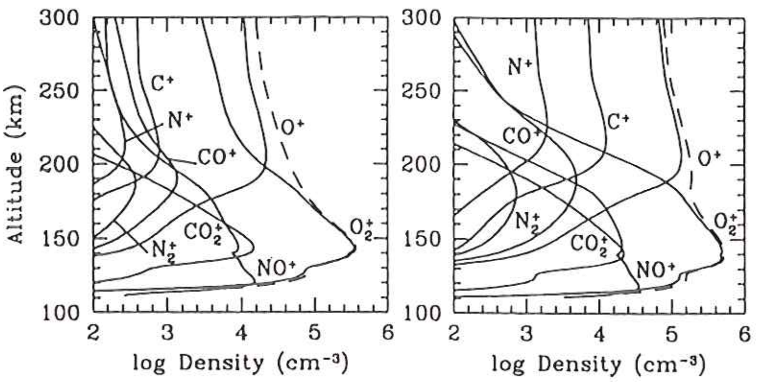


Fig.8: Computed altitude profiles for the major ions (left) for the low solar activity model and (right) for the high solar activity model (from Fox and Kliore, 1997).

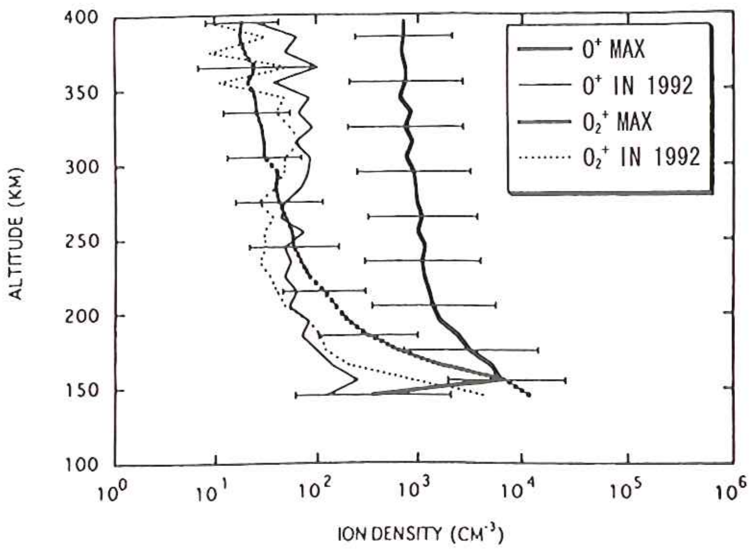


Fig.9: Average altitude profiles of O^+ and O_2^+ during the primary mission of PVO (solar max.) and in 1992 during PVO entry with data from midnight to 04:30 (from Kar et al., 1994).

sphere. The rich but complex variety of ions can be noted. Although CO_2 is the major neutral constituent, CO_2^+ remains a minor ion at low altitudes because of charge exchange of CO_2^+ with O and of O^+ with CO_2. 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. Model calculations have found a reasonable agreement with the experimental measurements (see Fox and Kliore 1997 and references therein). Figure 8 shows computed altitude profiles for the major ions for the low solar-activity and high solar activity models.

Large diurnal and solar activity variations have been seen in the ion composition. Figure 9 compares density profiles for important ions for solar maximum and the pre entry period. While O^+ changed by

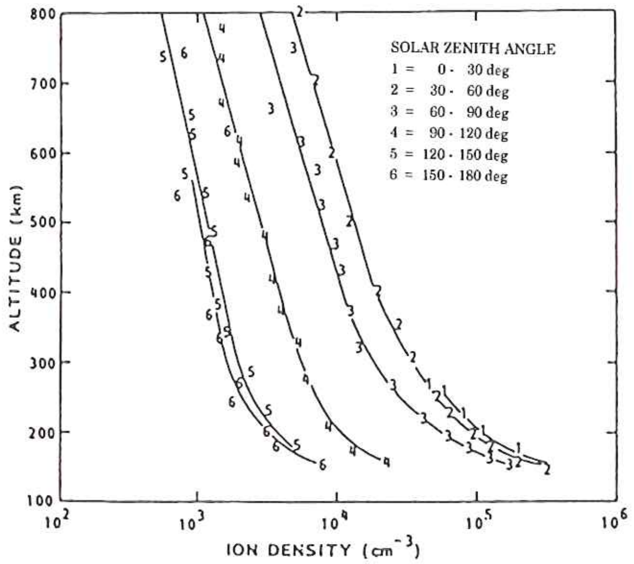


Fig.10: Median total ion density profiles from ORPA fro 30° intervals of SZA: There is little variation of the density between 0° to 60° (central dayside), and 120° to 180° (central nightside), but large changes occur for other values of SZA (from Miller et al., 1980).

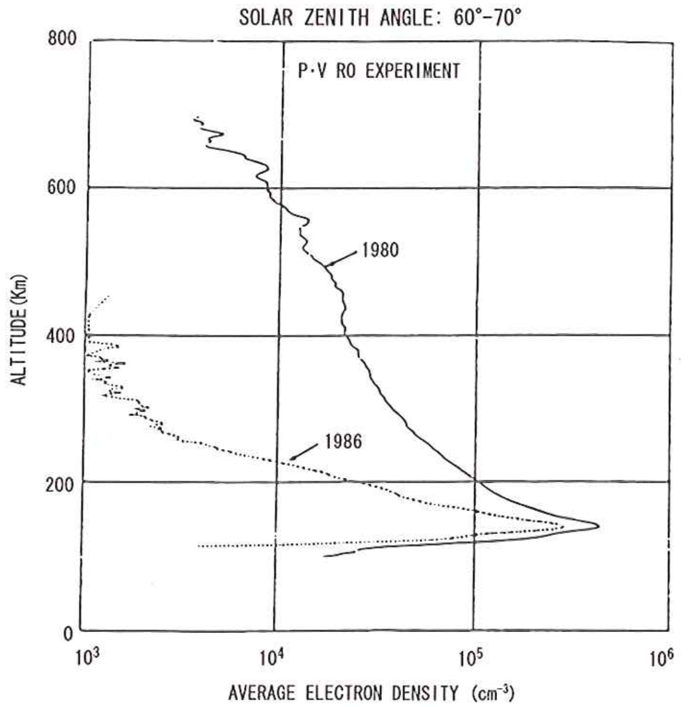


Fig.11: Electron density profiles obtained by PVO radio occultation at solar maximum (1980) and solar minimum (1986). A large depletion in the dayside upper ionosphere at solar minimum can be noted (from Knudsen et al., 1987).

about a factor of 10, O_2^+ showed a much smaller variation. H^+ and He^+ also showed decrease in their concentrations during the pre-entry period (Kar et al., 1994). These results indicate the importance of particle precipitation during solar medium (Kar et al., 1994) and possibly during solar minimum too.

The ion densities have also been measured by the orbiter retarding potential analyzer, ORPA (Knudsen et al., 1980a) and the electron temperature probe, OETP (Krehbiel et al., 1980) which have shown a reasonable agreement with the OIMS measurements. Figure 10 shows median ion densities obtained from the ORPA data and sorted according to SZA, grouped into 30° intervals. A significant control of SZA is evident, but the densities change very little for SZA between 0 to 60° (central dayside) and 120 to 180° (central nightside). The OETP data gave similar results (Brace and Kliore, 1991). The EUV control on the densities, in terms of solar activity, can be noted from Figure 11 which shows electron density profiles obtained from radio occultation measurements during solar maximum and solar minimum.

4. ELECTRON AND ION TEMPERATURES

The OETP instrument measured electron temperature while ORPA measured electron as well as the ion temperatures. Figure 12 shows profiles of median electron and ion temperatures from ORPA and it can be noted that the temperatures change little with SZA. The electron temperatures are about a factor of two

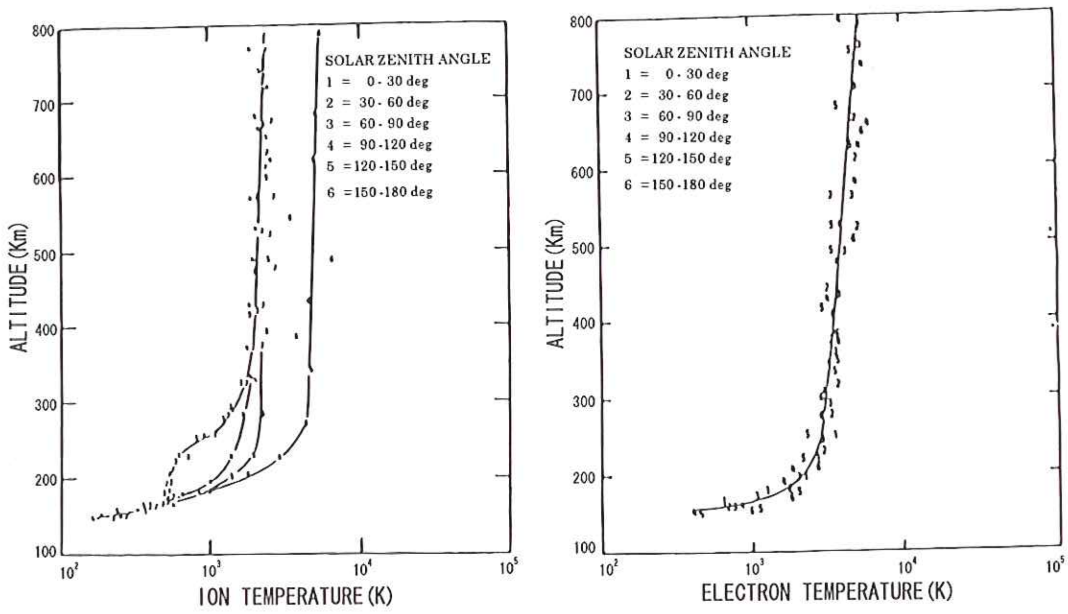


Fig.12: Plasma temperatures as measured by ORPA (a) electron temperatures (b) ion temperatures. There is little diurnal change in the temperatures. Ion temperature is about one half of the electron temperature, except in the antisolar region, where the two are equal (from Miller et al., 1980).

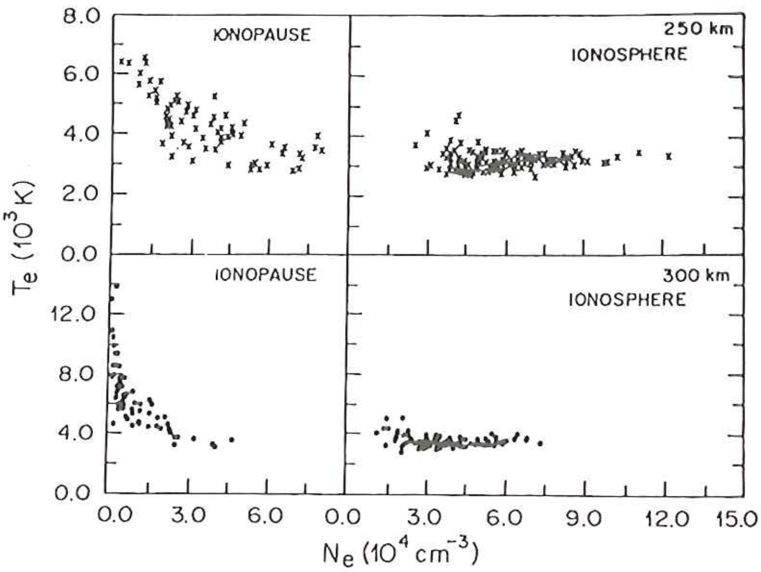


Fig.13: Inverse correlation between the electron temperature and density in the ionopause region. The temprature in the main ionosphere remains nearly constant, while most of the variability is due to variations in the ionopause region (from Mahajan et al., 1994).

higher than the ion temperatures, except for the antisolar region where the two are nearly equal. The observed temperatures have been explained by assuming adhoc topside heat fluxes or by reducing the thermal conductivity due to magnetic field fluctuations (see Nagy and Cravens, 1997, and references therein). Although one sees a large variability in the electron temperatures, most of this variability is in the ionopause region and follows changes in electron densities (Mahajan et al., 1994) as can be seen in Figure 13.

5. SOLAR WIND INTERACTION

Venus ionosphere acts as an obstacle to the solar wind, and Figure 14 gives a schematic representation of this interaction. The solar wind dynamic pressure, P_{sw}, 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 solar wind pressure. As this pressure increases, a higher ionospheric pressure is needed to balance and the 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 P_{sw} decreases in proportion to $\cos^2 \chi$(χ=SZA). The effect of P_{sw} and SZA on ionopause altitude has been studied by several workers (e.g. Brace et al., 1980, 1983a). Figure 15 shows plots of plasma and magnetic pressure for three orbits with varying solar wind conditions: (a) low (b) moderate and (c) extremely high, P_{sw} more than maximum plasma pressure. Time from periapsis on the x-axis provides the altitude of measurement.

The ionopause altitude falls rapidly with increasing P_{sw} but levels off above about 4 nPa (Brace et al.,

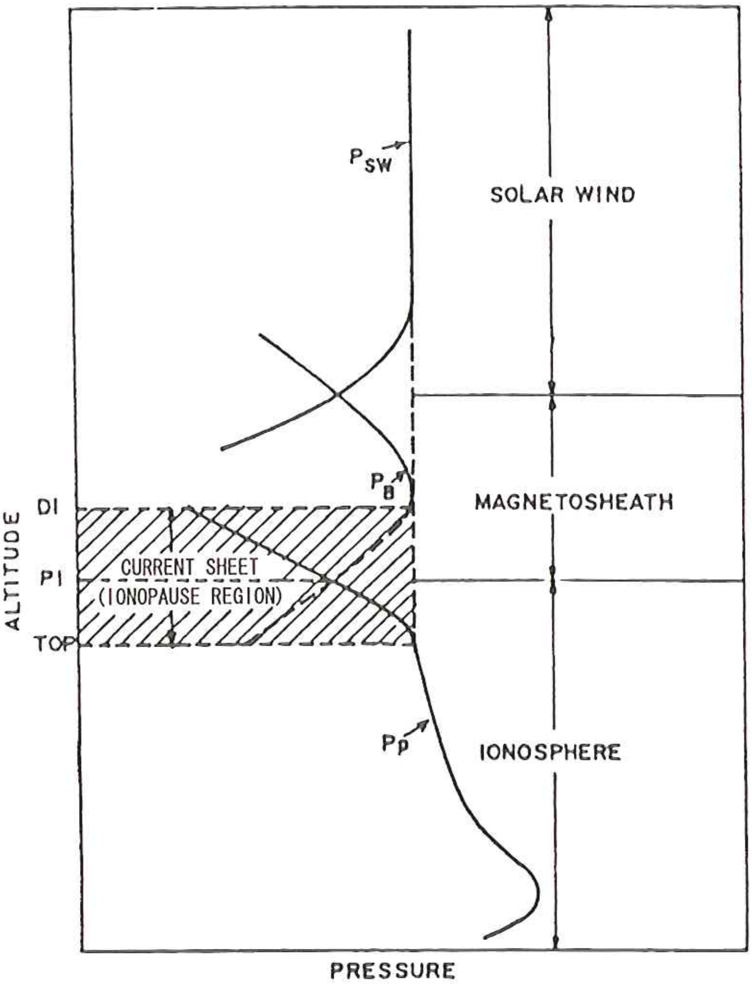


Fig.14: A schematic of solar wind interaction at Venus showing the three major regions, namely the solar wind region, the magnetosheath and the ionosphere. The region of the steep plasma gradient (above the top of the ionosphere) is the ionopause (from Mahajan, 1995).

1980). This saturation has been explained by Mahajan et al. (1989) due to the ionopause being driven so deeply into the thermosphere that photo-ion production loads down the solar wind interaction (i.e. the 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, as will be evident from Figure 16. It can be noted that at low P_{sw}, ionopause tracks the plasma pressure while at high P_{sw} it tracks the neutral gas pressure.

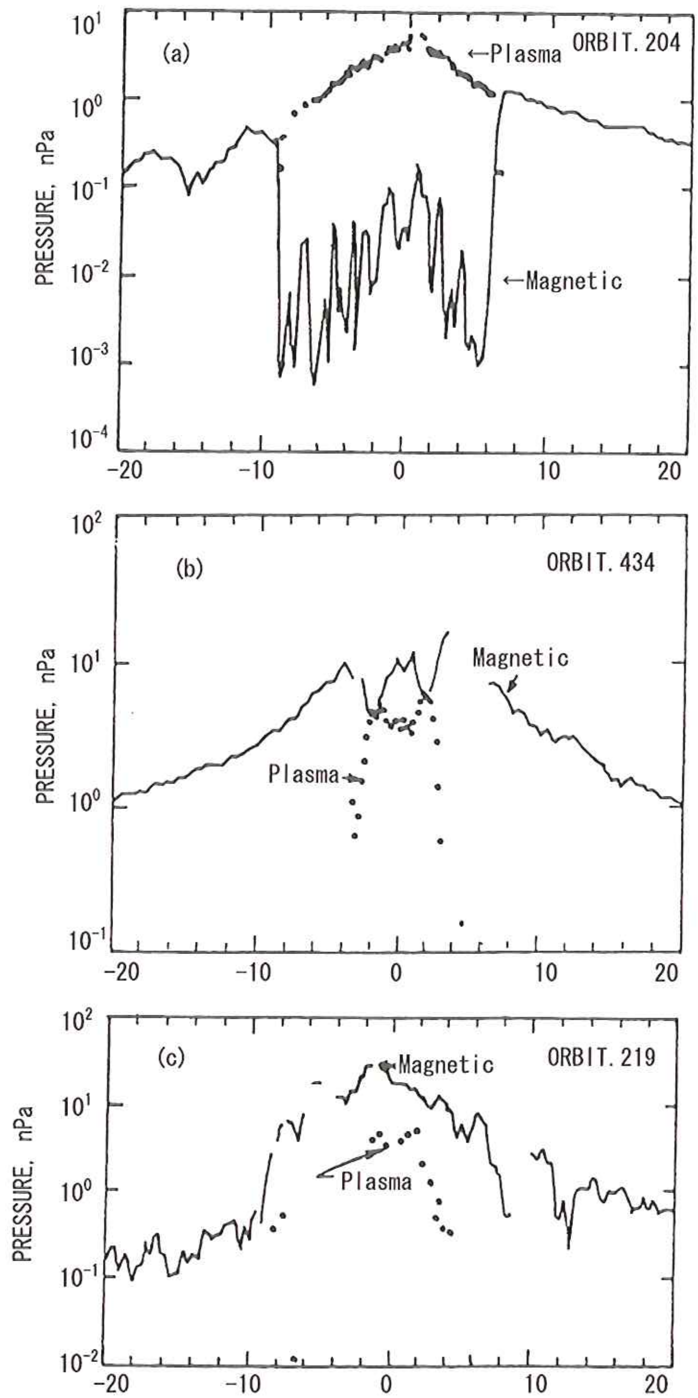


Fig.15: Plots of plasma and magnetic pressure as the PVO enters and leaves the ionosphere, for (a) low P_{sw} (b) moderate P_{sw} and (c) for P_{sw} > maximum plasma pressure (from Mahajan, 1995).

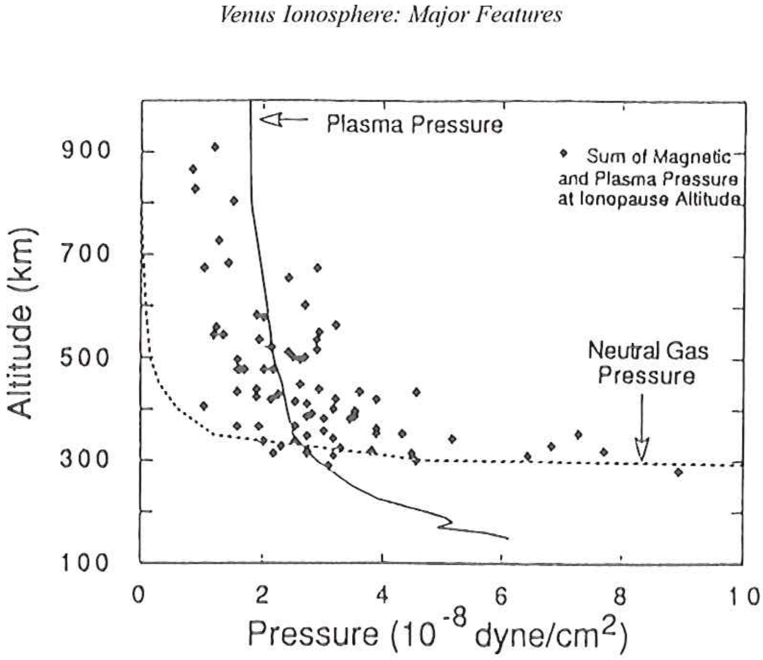
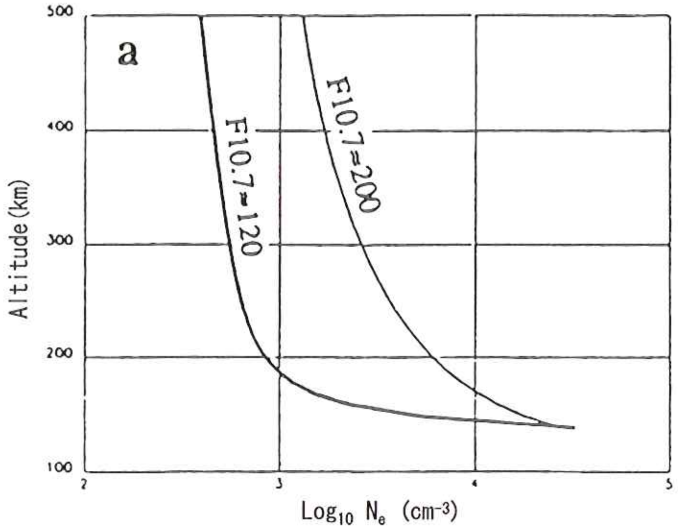


Fig.16: A plot of ionopause altitude versus P_{sw}. Also plotted are model values of plasma and neutral pressure. At low P_{sw}, ionopause tracks the plasma pressure but at higher values it tracks the neutral pressure (from Mahajan et al., 1989).

6. NIGHTSIDE IONOSPHERE

In spite of long Venus night (58 earth days), there is a remarkable abundance of ions on the nightside featuring the same constituents as on the dayside, though with much lower concentration levels (Taylor et al., 1980b). There is a strong solar activity effect which was earlier seen in the radio occultation measurements (Knudsen et al., 1987) and has been reconfirmed from the PVO pre-entry measurements from all the aeronomy experiments (Theis and Brace, 1993; Kar et al., 1994; Spenner et al., 1995, 1996). Figure 17 shows a comparison of nighttime electron densities and temperatures obtained by the OETP during the pre-entry period and during the solar maximum. While the densities decreased during the entry, the temperatures increased (Theis and Brace, 1993). Further, a large variability in the densities has been observed and Figure.18 highlights this variability. It can be noted that the densities can vary by two orders of magnitude during the nightside.

The existence of the nightside ionosphere has been explained on the basis of transterminator flow of O^+ ions from the dayside (e.g. Knudsen et al., 1980b, Fox and Kliore, 1997 and references therein). This flow occurs because of the large plasma pressure gradient between the day and the nightside and has been confirmed by the ORPA instrument which has measured anti-sunward velocities of about 5 km/s at high altitudes in the terminator region (Miller and Whitten, 1991 and references therein). Figure 19 gives the average ionospheric velocity field as measured by the ORPA. The measured velocities very successfully explain the existence of the nightside ionosphere. Contribution of electron precipitation in the maintenance of the nightside ionosphere is estimated to be in the range 20 to 30% during solar maximum. According to Fox and Kliore (1997) the solar cycle response, the solar zenith angle behavior and the overall variability can not be accounted for by electron precipitation as the major ion source. Spenner et al. (1996)



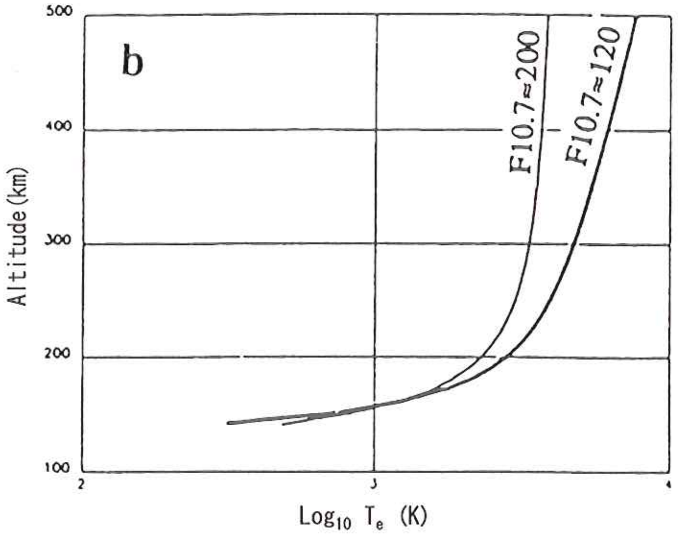


Fig.17: Comparison of electron densities and temperatures measured by the OETP instrument during the pre-entry period ($FF_{10.7}$~120) and solar maximum ($F_{10.7}$~200). While the densities decreased, the temperatures increased during the pre-entry period (from Theis and Brace, 1993).

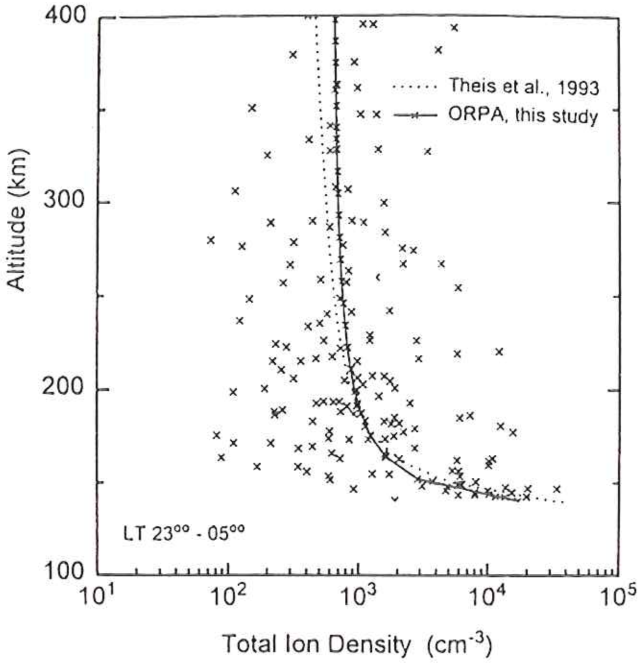


Fig.18: Nightside electron density values measured during the entry period by ORPA. Large variability in the density can be noted (from Spenner et al., 1995).

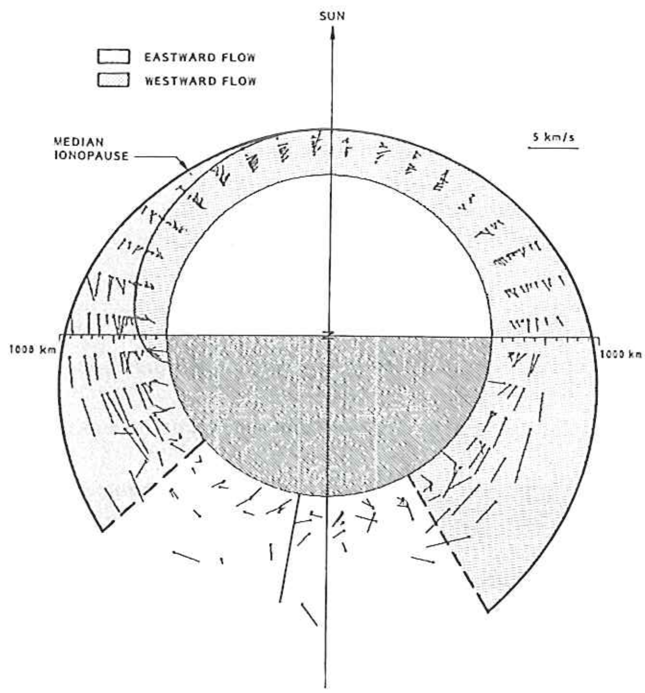


Fig.19: Average O^+ velocity as measured by the ORPA instrument. Large velocities at the terminators are responsible for the maintenance of the nightside ionosphere (from Miller and Whitten, 1991).

conclude equal contributions by transterminator flow and electron precipitation for the maintenance of the nightside ionosphere during medium solar activity. Kar et al. (1994), on the other hand, have concluded electron precipitation as the major ion source during the solar medium and thus the solar minimum too.

7. OTHER FEATURES

The nightside Venus ionosphere has, in addition, exhibited some important small scale spatial structures like the plasma clouds (Brace et al., 1982a) , post-terminator waves (Brace et al., 1983b), antisolar-region waves (Hoegy et al., 1990), ionospheric holes (Brace et al., 1980, 1982b), and ionotail (Brace et al., 1987; Brace and Kliore 1991 and references therein). We have not discussed these features in this report 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 (e.g. Luhmann et al., 1997 and references therein), ionospheric magnetic fields (e.g. Cravens et al., 1997 and references therein), plasma waves (e.g. Huba and Strangeway, 1997 and references therein), Venus lightning (e.g. Grebowsky et al., 1997 and references therein), and upper atmosphere dynamics (e.g. Bougher et al., 1997 and references therein). We have not discussed these topics too and reader is advised to consult the reviews cited above.

ACKNOWLEDGMENT

K. K. Mahajan was a visiting professor at the Institute of Space and Astronautical Science during the progress of this work. He is grateful to ISAS for hospitality and facilities.

REFERENCES

Brace, L.H., Kilometric-sized waves in electron denstity in the Verusian nightside ionosphere; *Geophys. Res. Lett.*, **20**, 2759, 1993.

Brace, L.H., and A.J. Kliore, The structure of the Venus ionosphere, *Space Sci. Rev.*, **55**, 81, 1991.

Brace, L.H., et al., The dynamic behavior of the Venus ionopshere to solar wind interaction, *J. Geophys. Res.*, **85**, 7663, 1980.

Brace, L.H., et al., Plasma clouds above the ionopause of Venus and their implications, *Planet. Space Sci.*, **30**, 29, 1982a.

Brace, L.H., et al., Holes in the nightside ionsophere of Venus, *J. Geophys. Res.*, **87**, 199, 1982b.

Brace, L.H., et al., The ionosphere of Venus: Observations and their interpretation, *Venus*, The Univ. of Arizona Press, 779-840, 1983a.

Brace, L.H., et al., Wave structure in the Venus ionosphere downstream of the terminator, *Geophys. Res. Lett.*, **10**, 1116, 1983b.

Brace, L.H., et al., The ionotail of Venus: Its configuration, and evidence for ion escape, *J. Geophys. Res.*, **92**, 15, 1987.

Bougher, S.W., et al., Upper atmosphere dynamics: Global circulation and gravity waves, *Venus II*, The Univ. of Arizona Press, 259-291, 1997.

Brinton, H.C., et al., Venus nighttime hydrogen bulge, *Geophys. Res. Lett.*, **7**, 865, 1980.

Colin, The Pioneer Venus program, *J. Geophys. Res.*, **85**, 7575, 1980.

Cravens, T.E., et al., Magnetohydrodynamic processes: Magnetic fields in the iono sphere of Venus; *Venus II*, The Univ. of Arizona Press, 61-93, 1997.

Donahue, T.M., et al., Ion/neutral escape of hydrogen and deuterium: Evolution of water, *Venus II*, The Univ. of Arizona Press, 385-414, 1997.

Fox, J.L., and A.J. Kliore, Ionosphere: Solar cycle variations, *Venus II*, The Univ. of Arizona Press, 161-188, 1997.

Grebowsky, J.M., et al., A new look at Venus thermosphere H distribution, *Adv., Space Res.*, **17**, #11, 191, 1995.

Grebowsky, J.M., et al., Evidence for Venus lightning, *Venus II*, The Univ. of Arizona Press, 125-157, 1997.
Hartle, R.E., et al., Hydrogen and deuterium in the thermosphere of Venus; Solar cycle variations and escape, *J. Geophys. Res.*, **101**, 4525, 1996.
Hoegy, W.R., et al., Small-scale plasma, magnetic and neutral density fluctuations in the nightside ionosphere, *J. Geophys. Res.*, **95**, 4085, 1990.
Huba, J.D., and R.J. Strangeway, Plasma wave phenomena at Venus, *Venus II*, The Univ. of Arizona Press, 95-124, 1997.
Kar, J., Recent advances in planetary ionospheres, *Space Sci. Rev.*, **77**, 193, 1996.
Kar, J., et al., Evidence of electron impact ionization on the nightside of Venus from PVO/IMS measurements near solar minimum, *J. Geophys. Res.*, **99**, 11351, 1994.
Kasprzak, W.T., et al., Solar activity behavior of the thermosphere, *Venus II*, The Univ. of Arizona Press, 225-257, 1997.
Keating, G.M., and N.C. Hsu, The Venus atmospheric response to solar cycle variations, *Geophys. Res. Lett.*, **20**, 2751, 1993.
Keating, G.M., et al., Venus upper atmosphere structure, *J. Geophys. Res.*, **85**, 7941, 1980.
Knudsen, W.C., et al., Pioneer-Venus orbiter planar retarding potential analyzer experiment, *IEEE Trans. Geosci. Remote Sens.* **GE-18**, 49, 1980a.
Knudsen, W.C., et al., Transport of ionospheric O^+ ions across the Venus terminator and implications, *J. Geophys. Res.*, **85**, 7803, 1980b.
Knudsen, W.C., et al., Solar cycle changes in the ionization sources of the nightside Venus ionosphere, *J. Geophys. Res.*, **92**, 13391, 1987.
Krehbiel, J.P., et al., Pioneer Venus orbiter electron temperature probe, *IEEE Trans. Geosci. Remote Sensing*, **GE-18**, 49, 1980.
Luhmann, J.G., et al., Global models of the solar wind interaction with Venus, *Venus II*, The Univ. of Arizona Press, 33-59, 1997.
Mahajan, K.K., and J. Kar, Planetary ionospheres, *Space Sci. Rev.*, **47**, 303, 1988.
Mahajan, K.K., et al., On the lower altitude limit of the Venusian ionopause, *Geophys. Res. Lett.*, **16**, 759, 1989.
Mahajan, K.K., et al., Variability of dayside electron temperature, *Geophys. Res. Lett.*, **21**, 77, 1994.
Mahajan, K.K., Planetary ionospheres: The Venus ionopause, *Ind. J. Rad. Space Phys.*, **24**, 269, 1995.
Miller, K.L., and R.C. Whitten, Ion dynamics in the Venus ionosphere, *Space Sci. Rev.*, **55**, 165, 1991.
Miller, K.L., et al., Solar zenith angle dependence of ionospheric ion and electron temperaures and density at Venus, *J. Geophys. Res.*, **85**, 7759, 1980.
Nagy, A.F., and T.E. Cravens, Ionosphere: Energetics, *Venus II*, The Univ. of Arizona Press, 189-223, 1997.
Nagy, A.F., et al., Basic theory and model calculations of the Venus ionosphere, *Venus*, The Univ. of Arizona Press, 841-872, 1983.
Niemann, H.B., et al., Pioneer Venus orbiter neutral gas mass spectrometer experiment, *IEEE Trans. Geosci. Remote Sens.*, **GE-18**, 60, 1980a.
Niemann, H.B., et al., Mass spectrometric measurements of the neutral gas composition of the thermosphere and exosphere of Venus, *J. Geophys. Res.*, **85**, 7817, 1980b.
Schunk, R.W., and A.F. Nagy, Ionospheres of the terrestrial planets, *Rev. Geophys. Space Phys.*, **18**, 813, 1980.
Spenner, K., et al., Ion density temperature and composition of the Venus nightside ionosphere during a period of moderate solar activity: Implications for maintaining the central nightside, *J. Geophys. Res.*, **100**, 14499, 1995.
Spenner, K., et al., Suprathermal electron fluxes in the Venus nightside ionosphere at moderate and high solar activity, *J. Geophys. Res.*, **101**, 4557, 1996.
Strangeway, R.J., The Pioneer Venus orbiter entry phase, *Geophys. Res. Lett.*, **20**, 2715, 1993.
Taylor, H.A., Jr., et al., Bennett ion mass spectrometer on the Pioneer Venus bus and orbiter, *IEEE Trans. Geosci. Remote Sens.*, **GE-18**, 44, 1980a.
Taylor, H.A., Jr., et al., Global observations of the composition and dynamics of the ionosphere of Venus: Implications for the polar wind interaction, *J. Geophys. Res.*, **85**, 7765, 1980b.
Theis, R.F., and L.H. Brace, Solar cycle variations of electron desnity and temperature in the Venusian nightside ionosphere, *Geophys. Res. Lett.*, **20**, 2719, 1993.
von Zahn, U., et al., Composition of the Venus atmosphere, *Venus*, The Univ. of Arizona Press, 299-430, 1983.