# The ionosphere of Venus based on pioneer Venus measurements

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**Pioneer Venus Orbiter has been working for well over a decade. Important results have been published by various PIs and group leaders. I have chosen to present a concise outline of some of the important results revealed by these measurements.**

SINCE its injection into Venus orbit on 5 December 1978, the Pioneer Venus Orbiter (PVO) has been exploring the upper atmosphere, ionosphere, and magnetosphere of the planet, with special emphasis on its interactions with the solar wind. The payload includes neutral and ion mass spectrometers to measure the thermosphere and ionosphere composition, a Langmuir probe to measure the electron temperature and density, a retarding potential analyser to measure the ion temperature, density and velocity, a magnetometer, an ac electric field instrument, and a plasma analyser to determine the solar wind density, temperature, and velocity. These instruments are described in detail in a special issue of the *IEEE Transactions on Geoscience and Remote Sensing* (vol. GE-18, no. 1, Jan. 1980).

In the period from December 1978 to August 1980, the periapsis altitude was maintained below about 160 km. Its highly eccentric orbit allowed PVO to transit the low latitude ionosphere and thermosphere once every 24 hours, obtaining quasi-height profiles of the density, composition, and temperature of these regions almost down to the ionosphere electron density peak. The motion of Venus about the Sun permitted periapsis to sweep through all local times once each Venus year (approx. 224 days). When onboard fuel ran low in the summer of 1980, periapsis gradially rose out of the ionosphere, eventually reaching 2300 km in 1986. Periapsis then gradually declined until atmospheric reentry and burnup in October 1992.

The principal ionospheric results of the mission have been reviewed extensively in chapters 23 and 24 in the *Venus Book* (eds. Hunten, Colin, Donahue, and Moroz, University of Arizona Press, Tucson, Arizona, 1983). More recent results have been published in *Space Science Reviews* (1991, 55, 1–4). These findings will not be presented in detail here. Instead, I will only summarize what was reported there, and add a few details that have been uncovered using the more recently obtained high altitude measurements. Figure 1 is a cartoon that illustrates the major features of the Venus ionosphere in the context of solar wind interactions.

## The dayside ionosphere

The dayside ionosphere is produced by photoionization of thermospheric neutrals by solar EUV radiation, the major neutrals being $CO_2$ at altitudes below about 160 km and O above. The major ions are $O_2^+$ below about 180 km and $O^+$ above. Many minor ions are also present, and not all of these are consistent with the current best photochemical models which were adapted from models which work well in explaining the ion composition in the Earth's ionosphere. The main peak of ionization at about 142 km on the dayside appears to be equivalent to the Earth's E region, where the ion production rate is balanced locally by the ion recombination rate. The lighter ions $H^+$ and $He^+$ become major ions only at high altitudes on the nightside. The ionospheric electrons are heated from within by photoelectrons and from above by solar wind interactions at the ionopause, with the latter apparently more important by a factor of 4 or 5. The ions are heated by collisions with the hot ionospheric electrons, but this source is insufficient to fully account for the dayside elevated ion temperatures.

## The ionopause

The dayside ionosphere is bounded above by the ionopause, which is marked by an abrupt gradient in which the electron density falls from about $1 \times 10^4$ cm$^{-3}$ to less than $1 \times 10^2$ cm$^{-3}$. A pressure balance is apparently responsible for fixing the ionopause height. In equilibrium, the magnetic field pressure above the ionopause ($B^2/8\pi$) is balanced by the ionospheric plasma pressure ($nkT_p$) just below, where $T_p = 1/2(T_e + T_i)$. The magnetic field pressure is a proxy for the solar wind dynamic pressure ($1/2\, nmv^2$) which generates the magnetic field by driving currents in the ionosheath and in the ionosphere itself. At high solar

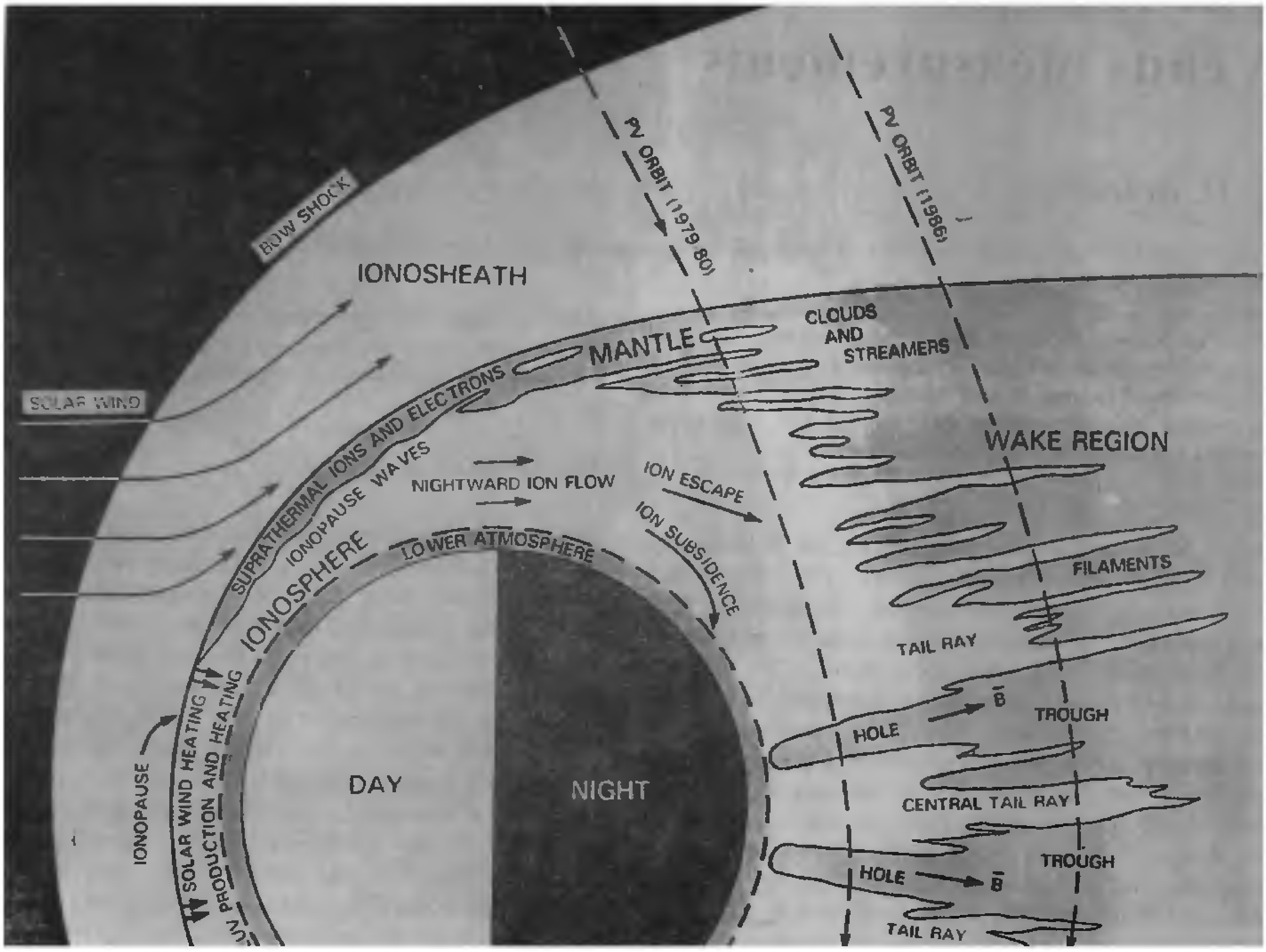

Figure 1. A sketch that illustrates some of the features of the near Venus environment that are described in the text (Note that the dimensions of the ionosphere is enlarged by about a factor of 2.)

wind pressures (high velocities and/or densities) the subsolar ionopause forms at altitudes of the order of 300 km, while at low solar wind pressures it rises to much higher altitudes (up to about 600 km in the subsolar region). The ionopause height increases toward the terminator (where the radial component of the solar wind pressure vanishes), typically reaching altitudes in the range of 700–2500 km at the flanks just beyond the terminator.

The ionopause is not a simple surface. The flow of shocked solar wind plasma over the cold ionospheric plasma appears to generate Kelvin Helmholtz instabilities that in turn produce ionopause surface waves with horizontal scale sizes of the order of $10^3$ km. These waves break near the terminator to form plasma clouds or streamers whose exact configuration cannot be determined, since the *in situ* measurements can only determine their dimensions along the satellite track.

The nightside ionopause is even more complex. The more recent PV data taken at higher altitudes show that these clouds stretch out on the nightside into what may be the equivalent of cometary tail rays and filaments. These rays are now known to extend at least 3000 km downstream from Venus, having typical densities of the order of a few × $10^2$ $cm^{-3}$ with intervening troughs where the density is much lower. Again, the *in situ* measurements can only determine the horizontal dimensions of these features, and thanks to the upward evolution of periapsis, we can follow the changes with distance down the Venus ionotail.

Because of the limitations of *in situ* measurements in resolving three-dimensional surfaces, we can only say that the ionopause on both the dayside and nightside is a highly complex surface. Its configuration and behaviour can be described conceptually, based on the PVO data. In Figure 1, I have attempted to depict its configuration and some of its related features like the surface waves, plasma clouds, streamers, tail rays, filaments, holes and troughs.

## The nightside ionosphere

The nightside ionosphere is much more dynamic than the dayside. In the absence of an intrinsic planetary magnetic field, the ions and electrons produced on the dayside are free to flow nightward. Some of this flow subsides to participate in chemical reactions which form the nightside ionosphere. Some of the ions, particularly those that pass the terminator at higher altitude, apparently are accelerated tailward to escape the planet. Measurements of the ion flow velocities near the terminator suggest that the main peak of the nightside ionosphere could be produced entirely by nightward flow, although the precipitation of energetic electrons or ions from the Venus magnetotail may also contribute. Superthermal electrons (order of 10's of eV) are seen throughout the nightside ionosphere, but it is not yet clear what role they play in maintaining the ionosphere, if any. The ion temperature is 2 or 3 times higher in the nightside than in the dayside. Some of this enhancement may be due to the reconvergent flow of ions into the antisolar region. The average electron temperature does not change much from day to night, but the temperature is more highly structured spatially at night for reasons that have not been discovered. The electrons are actually cooler than the ions at night.

A particularly dominant feature of the nightside is the ionospheric holes, or density depletions, that penetrate deeply into the ionosphere in the anti-solar region. They often, and perhaps always, occur in north-south pairs. (If east-west pairing was also occurring, such pairs would not be seen in a single PVO passage because of its near polar orbit.) A strong quasi-radial magnetic field permeates the ionospheric holes and severely limits the transport of ions and electrons from the surrounding ionosphere, thus maintaining low densities in the holes. The ion loss processes operating in the holes have not been identified, although ion recombination and ion pickup by the convecting magnetic field have been suggested. The edges of the holes are populated by superthermal ions (order of 1 eV) and are marked by strong changes in the magnetic field direction that are taken to indicate the presence of a current sheet in the edges of the holes. Superthermal electrons with typical energies of the order of a few eV also predominate in the holes when the cold plasma density falls below perhaps $30\ \text{cm}^{-3}$. It is not clear whether these hot electrons are simply photoelectrons that have been transported from the dayside or are of magnetotail origin. They could also be ionospheric electrons that have been heated by locally generated electric fields associated with the current sheets in the edges of the holes. The nightside ions are heated by an unknown process at altitudes above several hundred km, with temperatures or energies of the order of 1 eV. The electrons remain relatively cool, with temperatures of less than 1 eV except in the holes and troughs where their temperature is much higher.

## Solar activity effects

Since the ionosphere is produced by solar EUV radiation, solar cycle effects are expected to be very large. Unfortunately, *in situ* measurements in the lower ionosphere are only available from the period prior to 1981; i.e., near solar maximum. The only information we have on the solar cycle response of the ionosphere comes from the electron density profiles obtained from the radio occultation data. These data were unaffected by the rise of periapsis.

The profiles obtained during the solar minimum of 1986 show that the electron density on the dayside is lower than the solar minimum values by a factor of 1.5 at the peak and by a much larger factor at higher altitudes. The lower dayside densities reduce the reservoir which supplies the nightward ion flow, so local ion production in the nightside ionosphere may be relatively more important at solar minimum. When periapsis returned to the ionosphere in the fall of 1992, the solar activity was much lower and these data, when fully analysed should make it possible to examine the related changes in ion composition and ionospheric temperature.

## Summary

Although much has been learned in this early exploration of the Venus ionosphere, many questions remain. Some of these will be answered by the Pioneer Venus data obtained at entry (Fall 1992). Others can only be resolved by later missions, perhaps employing circular orbits to better resolve the global structure of the ionosphere and its dynamic and rapid responses to solar wind variations. More sophisticated instrumentation will also be required to obtain improved energy, mass, and spatial resolution in the ions measurements, greater dynamic range in the electron energy and density measurements, and better plasma wave measurements. But these are matters that, it now appears, must await planetary researchers of the next century.