THE VENUS ATMOSPHERE AND IONOSPHERE AND THEIR INTERACTION WITH THE SOLAR WIND: AN OVERVIEW

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This chapter summarizes the state of our knowledge of the atmosphere and ionosphere of Venus and their interaction with the solar wind. Its purpose is to set the stage for the chapters that follow. It also briefly identifies the principal gaps in our present knowledge and the measures that might be taken to fill them in.

I. INTRODUCTION: PROPERTIES OF THE ATMOSPHERE

Venus is a very warm, very dry planet with a dense carbon dioxide atmosphere. The average temperature at the mean planetary radius of 6051.5 km is 737 K. The atmosphere there exerts a pressure of 95.0 bar and has a lapse rate of 8.06 K km^{-1}. Its density is 66.47 kg m^{-3}. It consists mainly of CO_2, with a mixing ratio of 0.965±0.008 and of N_2 at 0.035±0.008. The mean molecular weight of this atmosphere is thus 43.33±0.15 kg per mole. The carbon content of the CO_2 per g of planet is $(2.67\pm0.30)\times10^{-5}$ g. This is to be compared with a terrestrial inventory of $(1.5 \text{ to } 4.5)\times10^{-5}$ g g^{-1} of carbon, where the lower figure is crustal carbon, mainly carbonate, and the higher figure includes mantle carbon. A similar exercise for nitrogen would compare (2.49±0.30) μg g^{-1} in the atmosphere of Venus with 0.666 μg g^{-1}, 0.78 μg g^{-1}, and 1 μg g^{-1} in Earth's atmosphere, crust and mantle, respectively. CO_2, which is in the atmosphere of hot, desiccated Venus as a gas, has been converted on Earth, in the presence of abundant water, to carbonate in reaction with rocks such as wollastonite.

II. NONRADIOGENIC NOBLE GASES

This rough parity in carbon and nitrogen, two important constituents of volatile compounds on the two planets, does not extend to other volatiles, such as the nonradiogenic noble gases. The elemental abundances of these gases, the isotopic ratios of ^{20}Ne to ^{22}Ne, ^{36}Ar to ^{38}Ar, and the ratio of abundances on Venus and Earth, normalized to the planetary mass, are shown in Table I.

TABLE I

Elemental Abundances, Isotopic Ratios and Ratios of Abundances on Venus and Earth

Element	Venusian Abundance (ppm)	Venus/Earth Ratio	Isotopes	Sun	Isotopic Ratio Venus	Isotopic Ratio Earth
^{20}Ne	7	21	$^{20}Ne/^{22}Ne$	13	11.8±0.7	10
^{36}Ar	30	70	$^{36}Ar/^{38}Ar$	5.35	5.55±0.6	5.21
Kr	0.0047	3				
Xe	<0.0040	<35				

The abundances of these elements on Venus, Earth and Mars and typical C3V and CI meteorites are shown in Figs. 1 and 2. The great excess in elemental neon and argon on Venus and the very different relative abundance patterns on the three planets have challenged explanation since they were revealed by probe missions in the 1970s. But, recently, remarkable progress has been made in the construction of scenarios for planetary genesis that provide a plausible explanation for these noble gas abundances. These contemplate that, as the planets grew from planetesimals, their interiors received similar endowments of volatiles from their accreting cores. In the late stage of accretion they are supposed to have received an extra surficial contribution of volatiles from icy planetesimals arriving from the outer solar system. Earth and Venus also received a veneer of material rich in carbon and nitrogen during the last stages of accretion. Initially, Earth and Venus are supposed to have had almost identical supplies of the noble gases with relative abundances like solar gases. Neon, an exception, is supposed to have been depleted before the planetary material was formed. The hydrogen-dominated early upper atmospheres of these water-rich planets were driven away in a supersonic blowoff powered by 450-fold enhanced EUV solar radiation. The outflowing hydrogen carried away the noble gases with it. As the strength of the solar EUV radiation decreased, the outflow rate eventually declined to a level at which it could not carry xenon away. From that time on, the Xe abundances remained fixed in the two atmospheres at today's levels. Earth, but not Venus, suffered a singular event: a collision with a giant planetesimal, probably the one that resulted in the formation of the Moon. This impact dramatically eroded the atmosphere, noble gases included. This is supposed to be the reason that terrestrial abundances of noble gases are so low compared to those of Venus. A subsequent period of degassing of Ne, Ar and Kr, but not Xe, from the interior is supposed to have occurred during the final stages of fractionation on Earth, but not on Venus. The entire process took about 300 Myr to complete on Venus. The final abundances of the noble gases are those shown in Figs. 1 and 2. Blowoff fractionates isotopes as well as elements. The fractionation achieved by the model reproduces the terrestrial and Martian abundances very well (Pepin 1991,1995; Jakosky et al. 1994).

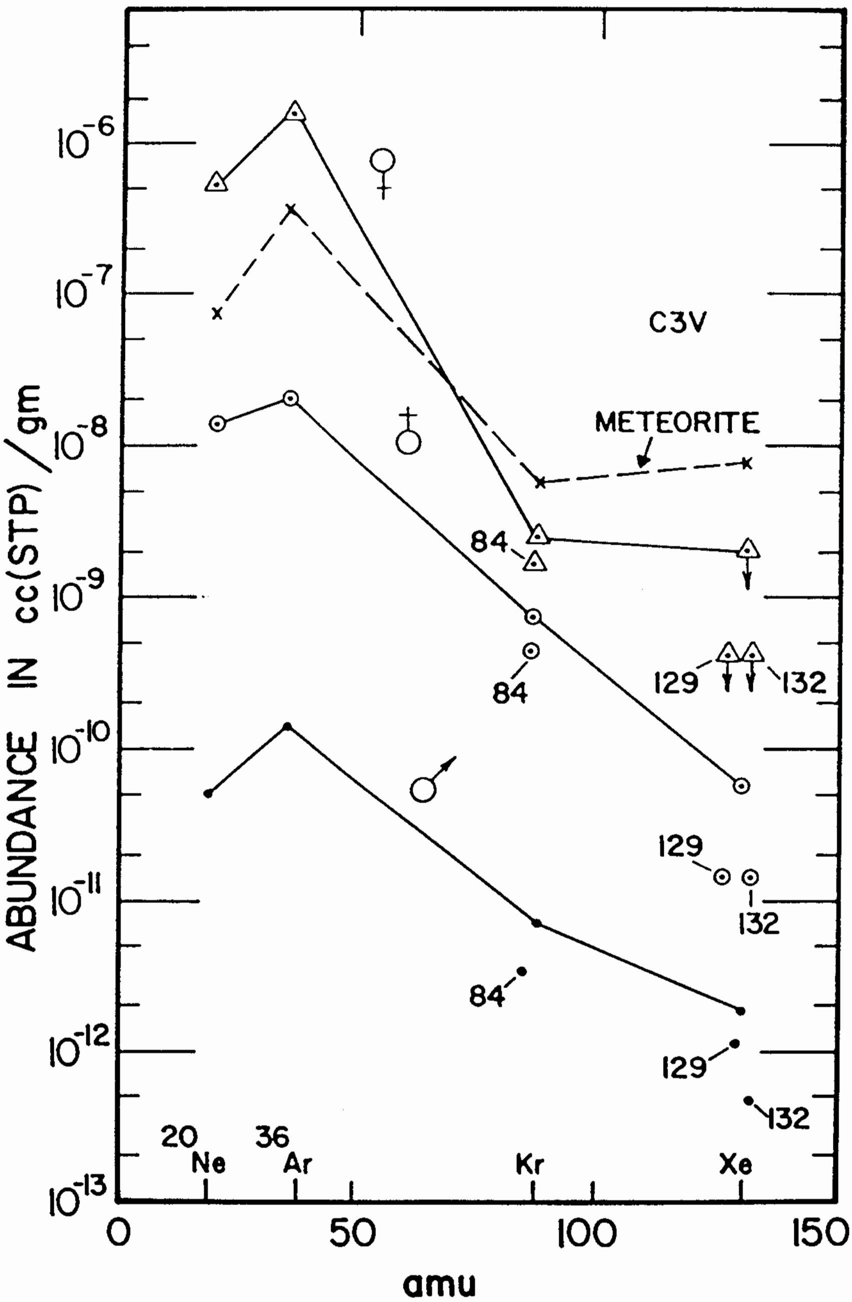


Figure 1. Abundances of noble gases on Venus, Earth, Mars and in a 3CV carbonaceous meteorite (figure from Donahue and Pollack 1983).

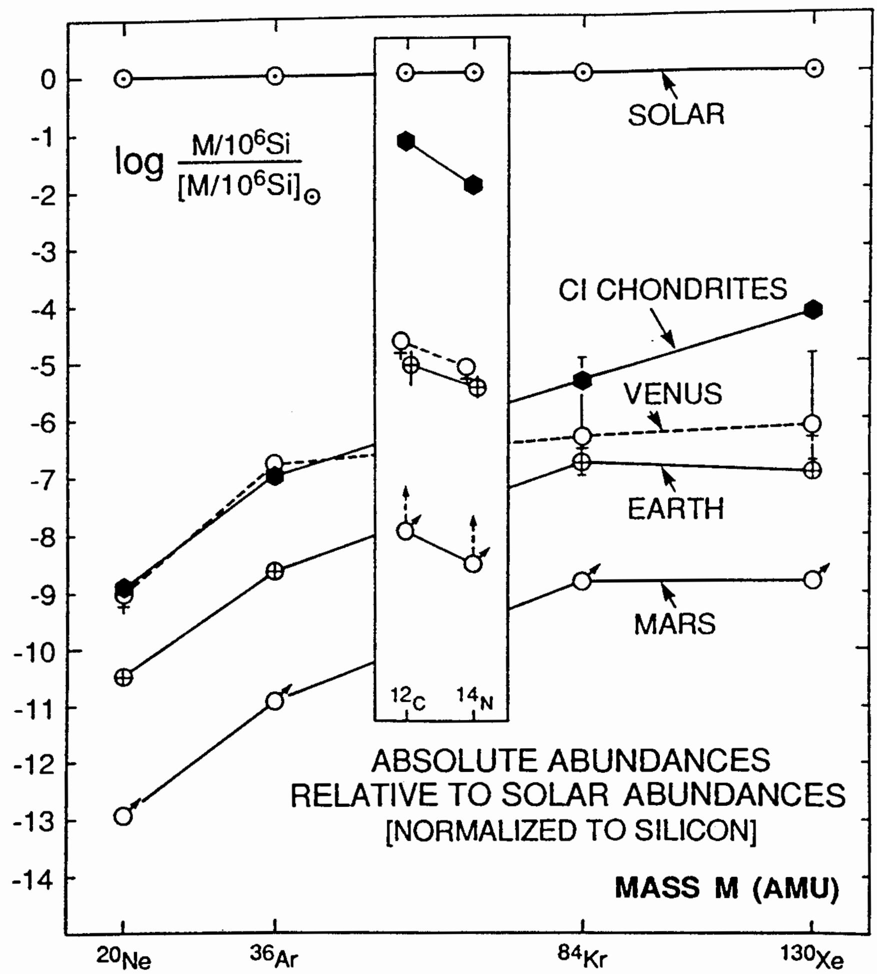


Figure 2. Absolute noble gas, carbon and nitrogen abundances in planetary atmospheres and in CI meteorites relative to the corresponding solar ratios (figure from Pepin 1991).

Crucial for testing this model is a determination of the Xe elemental abundance and a measurement of the Kr and Xe isotopic ratios on Venus with an accuracy in the neighborhood of 5%.

III. RADIOGENIC NOBLE GASES

The radiogenic noble gas ^{40}Ar, whose abundance is 34 ppm v/v, is less abundant by a factor of 4 on Venus than on Earth. Unfortunately, the abundance of radiogenic ^{4}He is uncertain by a factor of 20 (0.6 and 12 ppm), because it has been measured accurately only in the upper atmosphere and extrapolation to the mixed atmosphere is model dependent. There is between 175 to 3700 times as much ^{4}He in the atmosphere of Venus as there is in Earth's atmosphere. However, helium escapes from Earth in the polar wind at a globally average rate of $(3\pm1)\times10^{6}$ cm^{2}s^{-1}. It is in a steady state in which escape and outgassing from the interior are balanced. The amount of ^{4}He outgassed on

Earth during its lifetime turns out to be larger than the amount in the atmosphere of Venus by a factor of at least 3 (perhaps 60). These nonradiogenic noble gas comparisons suggest that outgassing rates on Venus are less than on Earth by a factor of 3 to 4 (Krasnopolsky et al. 1994).

An accurate measurement of the ^{4}He abundance in the mixed atmosphere is required for an adequate understanding of the extent to which Venus has outgassed the radiogenic gases produced in its interior.

IV. WATER

Water is a prototypical volatile that should have been abundant on early Venus if the terrestrial planets were formed from well-mixed primordial nebular material, but is scarcely present at all today. Recently, a consensus has developed that most of the time and in most places the mixing ratio of water vapor below the clouds of Venus is only 30 ppm. The question that begs to be answered is whether this water is mostly the remnant of an early abundant supply of water, most of whose hydrogen has escaped to space, or, instead, consists to a large extent of water that has been introduced comparatively recently by comets or by volcanic outgassing. To answer this question it is necessary, in addition to knowing the present hydrogen abundance, at least to know the degree to which deuterium is enriched in the present water compared to primordial or exogenous water. This ratio (D/H) depends on the amount of hydrogen that has escaped compared to that originally present, because hydrogen escapes more readily from the atmosphere than deuterium does. It is also necessary to know the rate at which hydrogen and deuterium are escaping today. It would be good to be able to model also the rates at which they have escaped in the past. It would also be good to know the strength of cometary and volcanic sources. Although that is difficult, the evidence for volcanism and massive resurfacing events obtained by Magellan may provide some insights. Numerous measurements now firmly fix the deuterium:hydrogen ratio in water on Venus at 150 times that in terrestrial water. Water on Earth, which has scarcely suffered from fractionating escape of hydrogen, is presumably a good sample of primitive water on Venus. The escape fluxes of hydrogen from Venus have been modeled and measured. At most two processes are important. These are, first, escape of fast atoms, which were once fast ions but have exchanged electrons with slow atoms, and, second, escape of ions driven by charge separation electric fields. These processes vary strongly with solar activity. Averaged over the planet and over time, the H escape flux appears to lie between 7×10^6 cm^{-2}s^{-1} and 1.6×10^7 cm^{-2}s^{-1}. The fractionation factor, which measures the relative efficiency of deuterium and hydrogen escape, lies between 0.44 and 0.10. If sources are unimportant, this information is sufficient to determine that the original amount of water on Venus was 260 to 7700 times the amount present today. That is enough water to cover the planet with water 4 to 115 m deep, if it was liquefied. There is an interesting possibility that the water was originally much deeper—say as deep as a full terrestrial ocean—but was lost at such a catastrophic rate that deuterium was exhausted along with hydrogen. This would have been the consequence of vaporization of the water in a "moist" or "runaway" greenhouse atmosphere. Only when the water level reached the equivalent of a few meters would fractionation have begun. If a cometary source of deuterium-poor water is balancing hydrogen escape today, even more early water is required to explain the larger present D/H ratio—between 19.5 and 525 m. There are alternatives to this scenario. One is that hydrogen loss is balanced by volcanic injection of water with a D/H ratio 20 times terrestrial. Another is that a massive outgassing event injected water with a D/H ratio 1.5 times terrestrial within the past billion years. After the event, the atmosphere is supposed to have been 150 times wetter than it is today. Loss of hydrogen belonging to this water would have caused the present enhancement in the D/H ratio (chapter by Donahue et al.).

To provide a robust solution to the problem of the origin of the water on Venus, more information is needed about possible spatial and temporal variation in water abundance today and the strength of present potential endogenous and exogenous sources of water, along with their degree of fractionation.

V. SULFUR

Another important class of volatile substances on Venus are sulfur compounds. The clouds are 75% sulfuric acid, 25% water vapor. SO_2 is abundant—180$\pm$70 ppm below the clouds in 1982 and also in 1992, according to near infrared spectral soundings. But above the clouds SO_2 seems to be quite variable, and to have decreased from 90 ppb to 3 ppb during the lifetime of the Pioneer Venus Orbiter (PVO) mission, according to observations made by the PVO ultraviolet spectrometer. Ultraviolet spectrophotometric observations with the Hubble Space Telescope indicate that its concentration has continued to decline since 1992. This behavior of SO_2 in the upper atmosphere has caused speculation that there was massive volcanic injection of SO_2 into the atmosphere shortly before PVO arrived. But there is a mystery: how can SO_2 vary above the clouds and remain constant below, as this suite of measurements suggests?

Another prominent sulfur species near the surface is carbonyl sulfide OCS. Its abundance decreases from 55 ppm near the surface to 0.5 ppm above 35 km. This variation is probably associated with the increase in CO from 12 ppm at 23 km to 23 ppm at 42 km (and perhaps 39 km ppm at 46 km) because of the removal of CO at the surface in a reaction with pyrite (FeS_2) that produces magnetite (Fe_3O_4) and carbonyl sulfide. H_2S has an abundance of 3 ppm near the surface and begins to disappear at 20 km. Other volatiles found in low concentration are HCl, HF and ethane (C_2H_6) (chapter by Fegley et al.).

One of the imperatives for exploration of Venus is the determination of the redox state of the lower atmosphere and understanding of the chemical interaction between the surface and the atmosphere. Gases that are volatilized near the surface in the lowlands may precipitate and form mineral layers which are conspicuous in radar images on highlands, such as Maxwell Montes. The reality of such processes needs to be established.

VI. THERMAL STRUCTURE

Greenhouse models (Fig. 3) give a reasonable explanation of the high surface temperature and the altitude profile. The atmosphere in these models is convective below 35 to 50 km. There are variations with latitude and local time significantly larger than expected theoretically before the PV and Venera probe missions. Where differences of the order of 0.1 K were expected, contrasts as large as 5 K were found below 10 km increasing to as much as 20 K near 60 km, with evidence for large oscillations. There is, however, no evidence for a *steady* variation in the deep atmosphere at low latitudes. Differences between high and low latitude temperatures are associated with maintenance of cyclostrophic balance of zonal winds at mid latitudes (chapter by Crisp et al.).

Determination of atmospheric structure parameters with high temporal and spatial resolution, horizontally and vertically, is highly desirable but technically all but unachievable because of the hostile environment at low altitudes.

VII. CLOUDS

Clouds cover Venus globally in three layers between 48 and 68 km. Above and below these layers is haze that extends as high as 90 km and as low as 32 (perhaps 10) km. There are three modes of cloud particles whose sizes and number densities are shown in the cartoon of Fig. 4. The large mode particles are found predominantly in the middle cloud layer. They are, perhaps, crystals. Those in the median mode have diameters of 2 μm. Small mode particles pervade the entire region from 30 to 70 km. Infrared soundings, especially from the Galileo spacecraft, have revealed that the cloud opacity evolves rapidly. It appears to vary rapidly in space and time. This behavior suggests high winds and a high level of meteorological activity near the tropopause of Venus. This is a state of affairs quite different than that expected from a dense, slowly moving lower troposphere.

The sulfuric acid which is the principal constituent of the cloud particles is probably produced as a result of the reaction of SO_2, rising from the troposphere, with dissociation products of water that produces SO_3. H_2O and SO_3 then react to make H_2SO_4. H_2SO_4 precipitating from the clouds will be thermally decomposed into SO_3, which is unstable against conversion to SO_2 at low altitudes. Another source of low altitude SO_2 is elemental sulfur, which is created by photolysis of SO_2 above the clouds and descends to levels at which it can be oxidized to SO_2 (chapter by Esposito et al.).

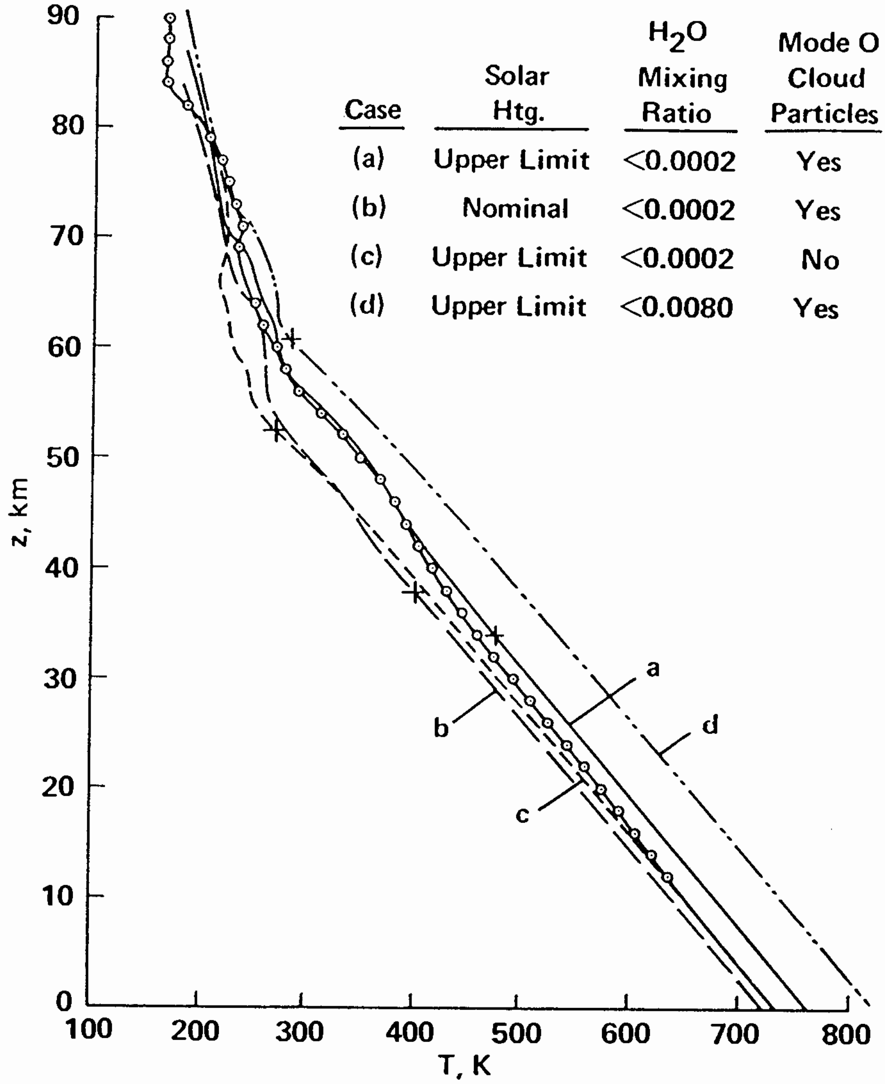


Figure 3. Theoretical greenhouse models. These are radiative, convective equilibrium models, adiabatic below the + symbols and superadiabatic above (figure from Pollack et al. 1980).

Discovering what makes the clouds yellow, confirmation of the cloud chemistry models, explanation of the large variability in cloud opacity and the nature of the mechanism that generates lightning, if it occurs in the clouds, should be the foci of investigations in the future.

VIII. WINDS: LOWER ATMOSPHERE

Zonal wind velocities increase with altitude (Fig. 5). High retrograde speeds of about 100 m s^{-1} are reached near 60 km. The velocity is small near the surface but grows to 10 m s^{-1} at 10 km. Near the subsolar point the atmosphere is neutrally stable from 20 to 30 km and from 50 to 55 km in the clouds. There is a stable layer between 30 and 50 km. This part of the atmosphere may support a regime of deep thermal convection. Recently,

CLOUDS

Layers	z km	μm	n cm^{-3}
Haze	90	<0.5	100
	68		
Upper		2.7-3.2	1-200
	57		
Middle		3.2-3.8	250
	51		
Lower		1.8-32	50
	48		
Haze	(32-10)	< 0.5	> 10^3

3(?) Particle Modes

$H_2SO_4 + ?$

Why Yellow??

Sulfur/$FeCl_3$?

UV markings

$SO_2 + Cl_2$?

Figure 4. Venus cloud structure.

study of the distribution of ground streaks near impact craters in Magellan images has provided rather strong evidence for a Hadley circulation regime below 10 km (chapter by Gierasch et al.).

Our understanding of the dynamics of Venus' atmospheric circulation system is still much too primitive. Measurements with good temporal and spatial resolution and sufficient sensitivity to record very slow atmospheric motions at low altitude are required to repair this deficiency.

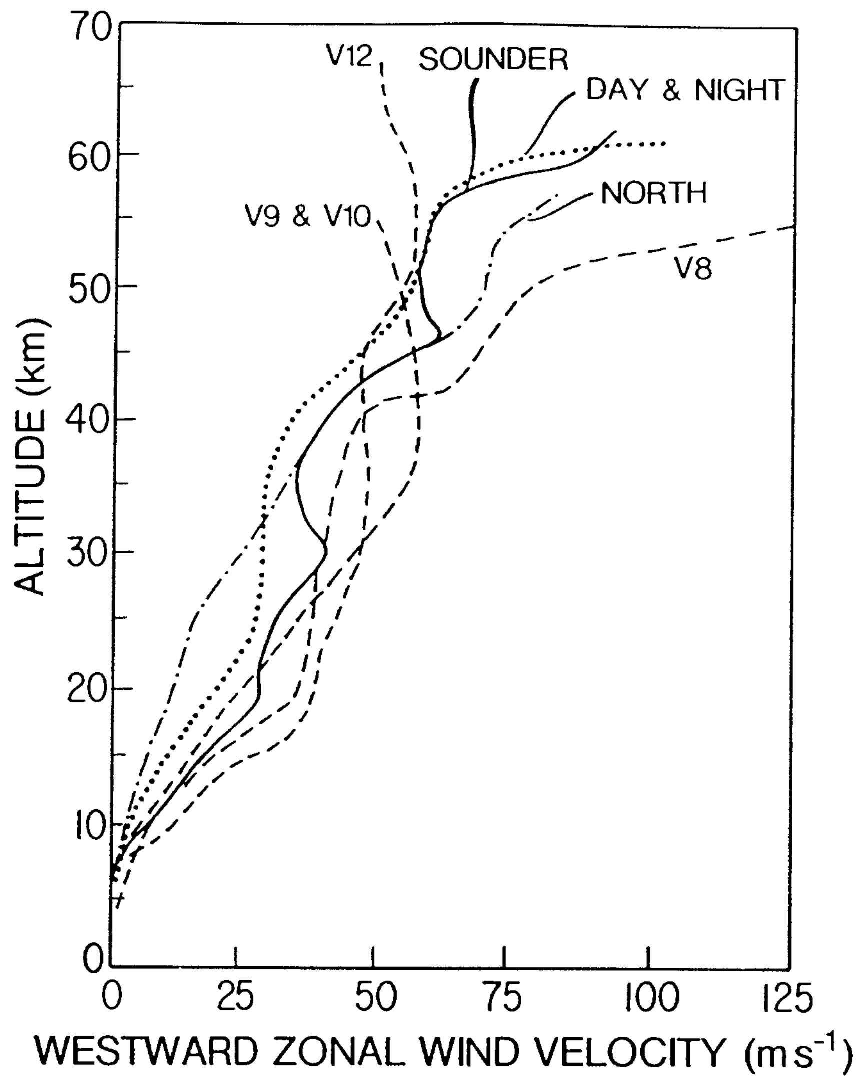


Figure 5. Vertical profiles of east-to-west wind speed from Doppler tracking of Veneras 8, 9, 10 and 12, and interferometric tracking of Pioneer Venus probes (figure from Schubert et al. 1980).

IX. WINDS: UPPER ATMOSPHERE

Gases in the upper atmosphere of Venus above 95 km (in the thermosphere and cryosphere) are driven in a strong flow from the dayside hemisphere to the nightside (Fig. 6). Here the gas descends and returns to the other hemisphere below 95 km. This circulation, which is different from that existing on Earth, and that believed to exist on Mars, is a consequence of the very slow retrograde rotation of Venus. Prolonged solar heating in one hemisphere and CO_2 in the other cause a great temperature contrast. Although radiative cooling keeps the temperature in the dayside thermosphere far below that of Earth, 300 K versus 1000 to 2000 K (Fig. 7), the night side has no thermosphere at all. Above 150 km the temperature drops below 100 K at night. This temperature contrast between the two hemispheres sets up a strong pressure gradient that drives the strong subsolar-antisolar circulation (chapter by Bougher et al.). Density, temperature and pressure change very rapidly near the terminator.

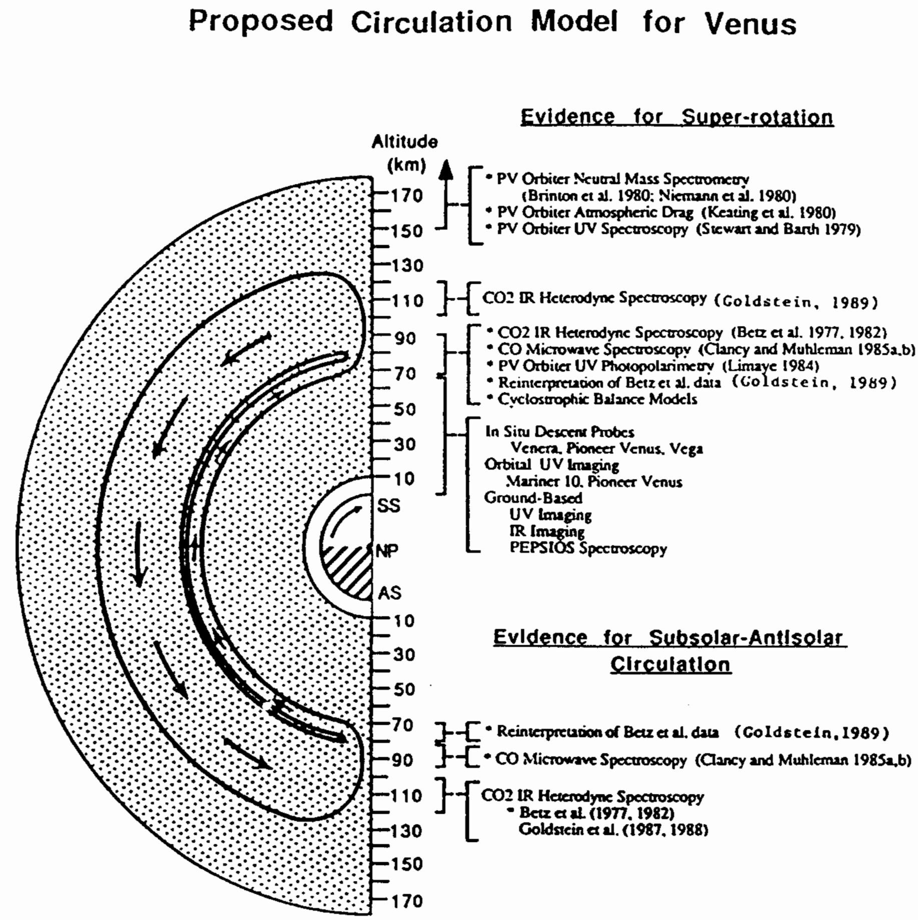


Figure 6. Dynamical regions of Venus' mesosphere and thermosphere (figure from Goldstein 1989).

The circulation is rather more complicated than a simple axially symmetric one. The temperature minimum on the night side is displaced toward the morning sector where there is also a maximum in the brightness of the airglow and a great bulge in the density of the light gases: hydrogen, deuterium and helium. This asymmetry may be due to a westward superrotation of the atmosphere with wind speeds greater than 50 m s^{-1} or the consequence of gravity wave breaking and production of drag which is larger at the morning terminator than at the evening terminator. The light species bulge on the night side is a consequence of the great scale height of these light gases which are dragged along by the dominant heavy gases. The circulation must be divergence free for the principal constituents, but such a circulation would lead to a net inflow of the light gases on the night side above 95 km, if not compensated for by a large asymmetry in density.

There is very little change in the temperature or density of the thermo-

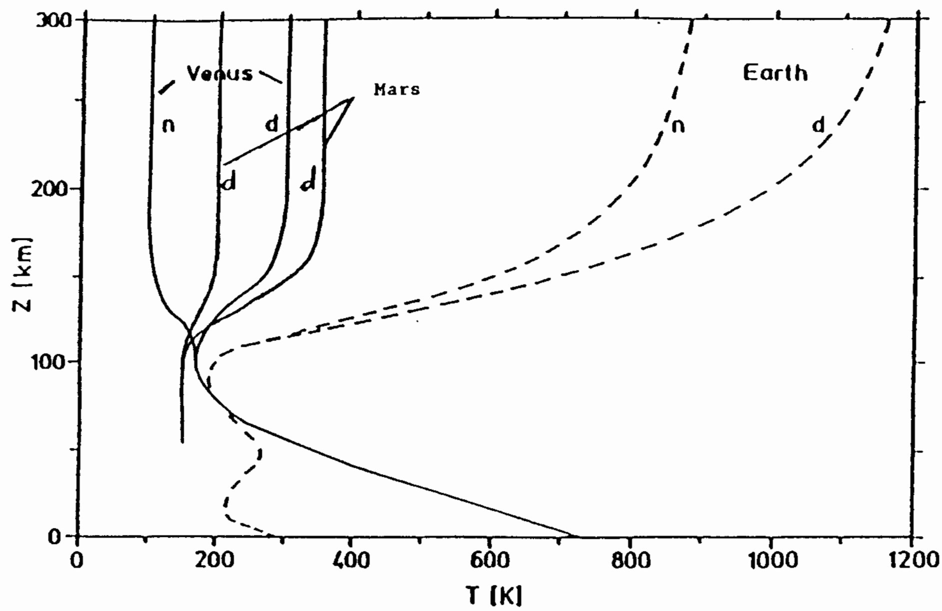


Figure 7. Temperatures of the neutral atmospheres of Earth, Venus and Mars (figure from Fox and Bougher 1991).

sphere and cryosphere with solar activity. This is less true for the short-term changes due, for example, to solar rotation and more so for the long term, solar cycle variations. The reason appears to be the balance between ultraviolet heating and CO_2 15-μm emission cooling (Bougher et al. 1994; chapter by Kasprzak et al.). The CO_2 emission is produced in a bending mode produced by collisions with atomic oxygen. As solar activity increases, so does the oxygen density, the collision rate and consequent CO_2 15-μm cooling (chapter by Bougher et al.).

X. THERMOSPHERIC COMPOSITION

At the homopause, where thorough mixing of different constituents weakens, and molecular diffusion begins to dominate, gases of different mass begin to assume their individual scale heights. The homopause is located somewhere between 130 and 145 km, depending on the gas species and the circulation model chosen. The number densities of the various species found in the thermosphere between 100 km and 200 km on the night side and day side are shown in Fig. 8. The atmosphere of Venus (at high and low altitude) is remarkable for the low concentration of the dissociation products of CO_2. O, CO, and a potential product of atomic oxygen recombination, CO_2 are very low in abundance. (Straightforward recombination of CO and O to reform CO_2 is a very slow process. Nevertheless, CO_2 dominates O_2 in the lower atmosphere.) This anomaly requires that O and CO be removed rapidly from the thermosphere and recombined efficiently in the middle atmosphere, presumably by a catalytic cycle. On Mars, which also has a CO_2-dominated atmosphere, the cycle involves products of water dissociation. Because of the low abundance of water on Venus, especially above the clouds, the same cycle will probably not work there. Instead, chlorine may be involved in chemistry of the CO_2 recombination process on Venus.

The upper atmosphere of Venus, like that of Earth and Mars, is the source of a great variety of airglow emissions. Solar resonance radiation excites hydrogen and oxygen. In the case of hydrogen, Lyman-α resonance radiation from the atmosphere has been observed by instruments carried on a number of spacecraft. Analysis of this spectral data provides the only source of information about atomic hydrogen above the escape level (200 km). Near the subsolar point the observations require a large upward flux of hydrogen in the lower thermosphere. This flow supports the inter-hemispherical thermospheric circulation pattern, already discussed. Strong emission bands of CO, O_2, CO^+, CO_2^+, O_2^+ and NO are seen in the nightglow, as well as emission lines of C, O, He, and their ions (chapter by Kasprzak et al.).

The mechanism of CO_2 recombination needs to be established. This requires composition measurements capable of identifying potential participants in catalytic recombination cycles in the middle atmosphere.

XI. IONOSPHERE

The ionosphere (Fig. 9) is produced primarily by solar EUV ionization of CO_2 on the day side of the planet. But CO_2^+, like its counterpart on Earth, N_2^+, is a minor species in the ionosphere. O_2^+ is the dominant ion up to about 200 km where O^+ becomes ascendant. The dominance of O_2^+ in the lower ionosphere is a consequence of the high reaction rate of CO_2^+ with O and O^+ with CO_2, both of which produce O_2^+.

The existence of a sometimes robust ionosphere at night is an anomaly. Given the slow rotation rate of the atmosphere, the night is long, and solar EUV absent long enough for the ions created in daylight to recombine. However, during solar maximum the dense ionosphere holds the solar wind well away from the planet. The daytime ionosphere is extensive (Fig. 9) and there is a large flux of O^+ ions across the terminator to the night side. These are the ions that maintain the night side ionosphere during times of high solar activity. During solar maximum, even minor ions such as H^+ and He^+ owe their existence at night (at least in large part) to charge exchange between O^+ and neutral H and He.

However, it is also clear that there are fluxes of energetic electrons on the night side large enough to create a significant amount of ionization under suitable conditions. Such conditions prevail during solar minimum when the ionopause moves close to the planet (Fig. 10). The spectacular compression of the ionosphere that is produced is illustrated by the electron density profiles obtained by the radio occultation observations at solar minimum in 1986. Transport of O^+ virtually terminates. The population of nighttime ions is

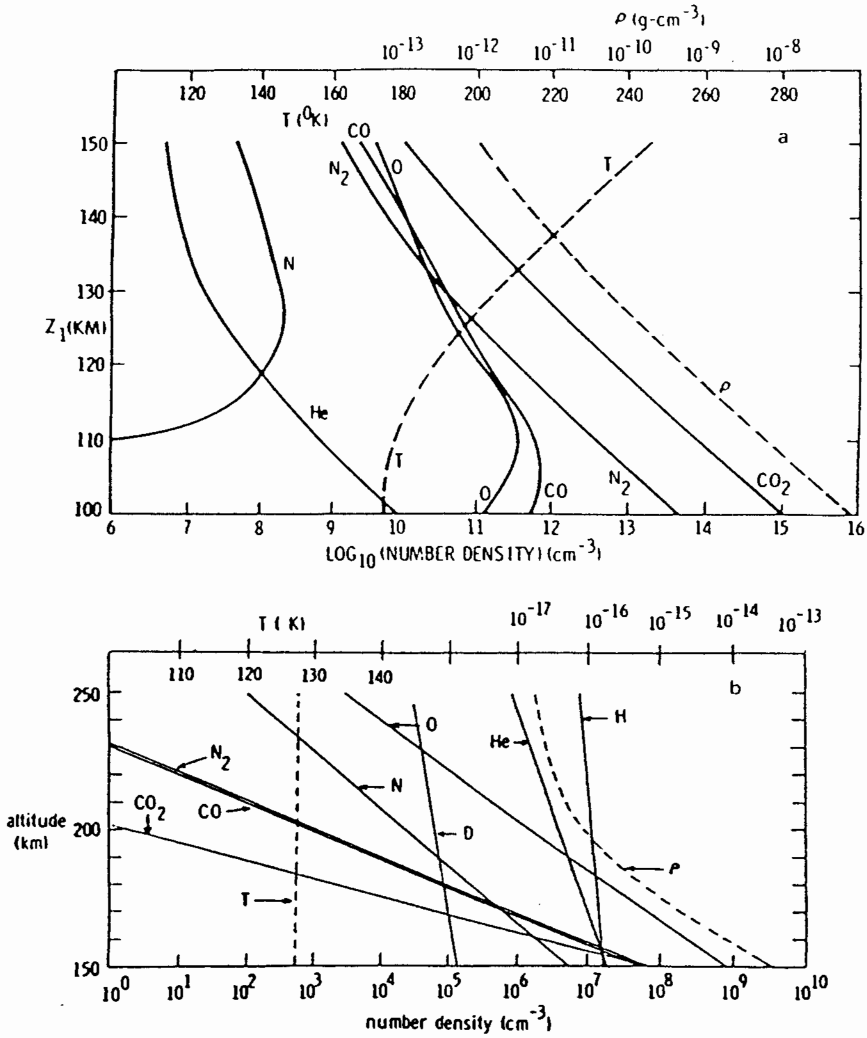
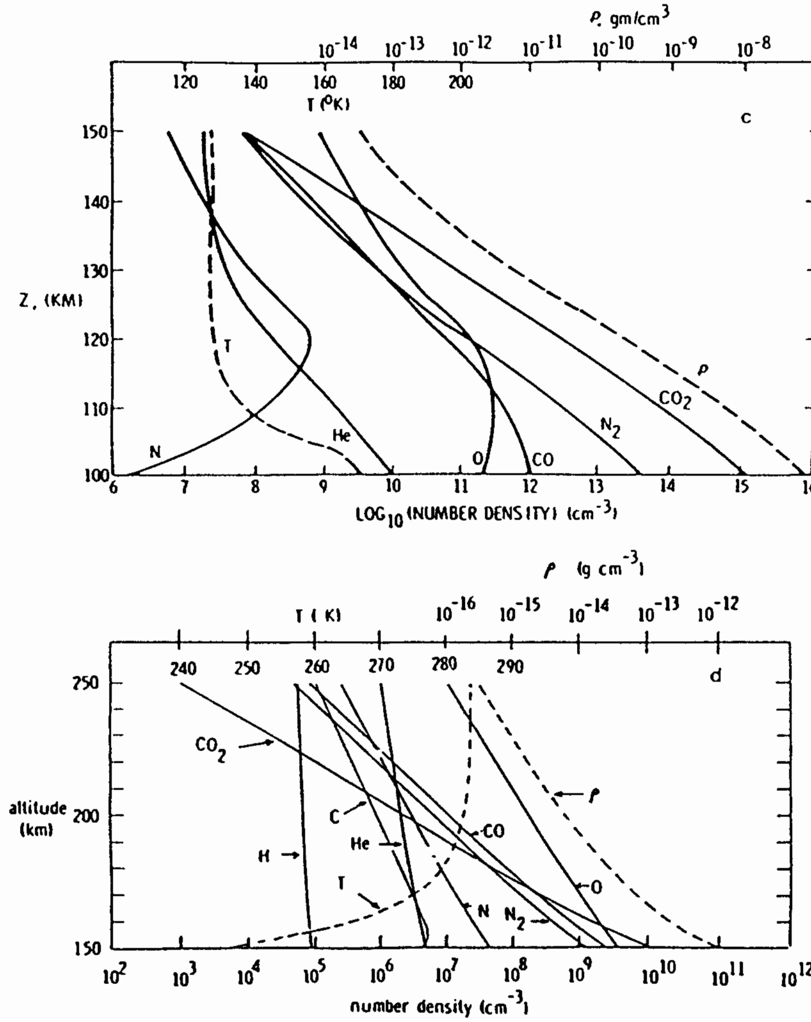


Figure 8. Neutral number densities from the VIRA model (a,b) day side; (c,d) night side (figure from Keating et al. 1985).

drastically reduced (Figs. 11, 12 and 13). Ionization by electrons with energies probably in the neighborhood of 1 keV then dominates at night.

The nightside ionosphere is by no means a region where ion densities vary slowly in space and time. The cartoon of Fig. 14 (Brace and Kliore 1991) illustrates the rich spectrum of temporal and spatial variations that occurs. Sometimes holes in the ionosphere are found extending to the lowest altitudes that have been explored. Filaments or rays extend far into regions called the ionotail and magnetotail. Detached clouds and streamers also populate these regions. All of these features, apparently, vary rapidly. Here some ions, such as O^+ have been observed to be traveling away from the planet with sufficient velocity to escape from the atmosphere into space (chapters by Fox et al. and



by Nagy et al.).

Despite the wealth of data acquired by the PVO mission, the difficult task of distinguishing spatial from temporal variations needs to be finished.

XII. ESCAPE OF HYDROGEN AND OXYGEN

It has already been mentioned that escape of hydrogen and deuterium from the planet occurs mainly from the light atom and light ion bulge in the dawn sector of the night side. Because of the large decrease in H^+ density there at solar minimum and because both dominant loss processes involve hydrogen ions, the escape flux decreases sharply as solar activity declines. This results in a significant increase in the population of hydrogen in the bulge at times of

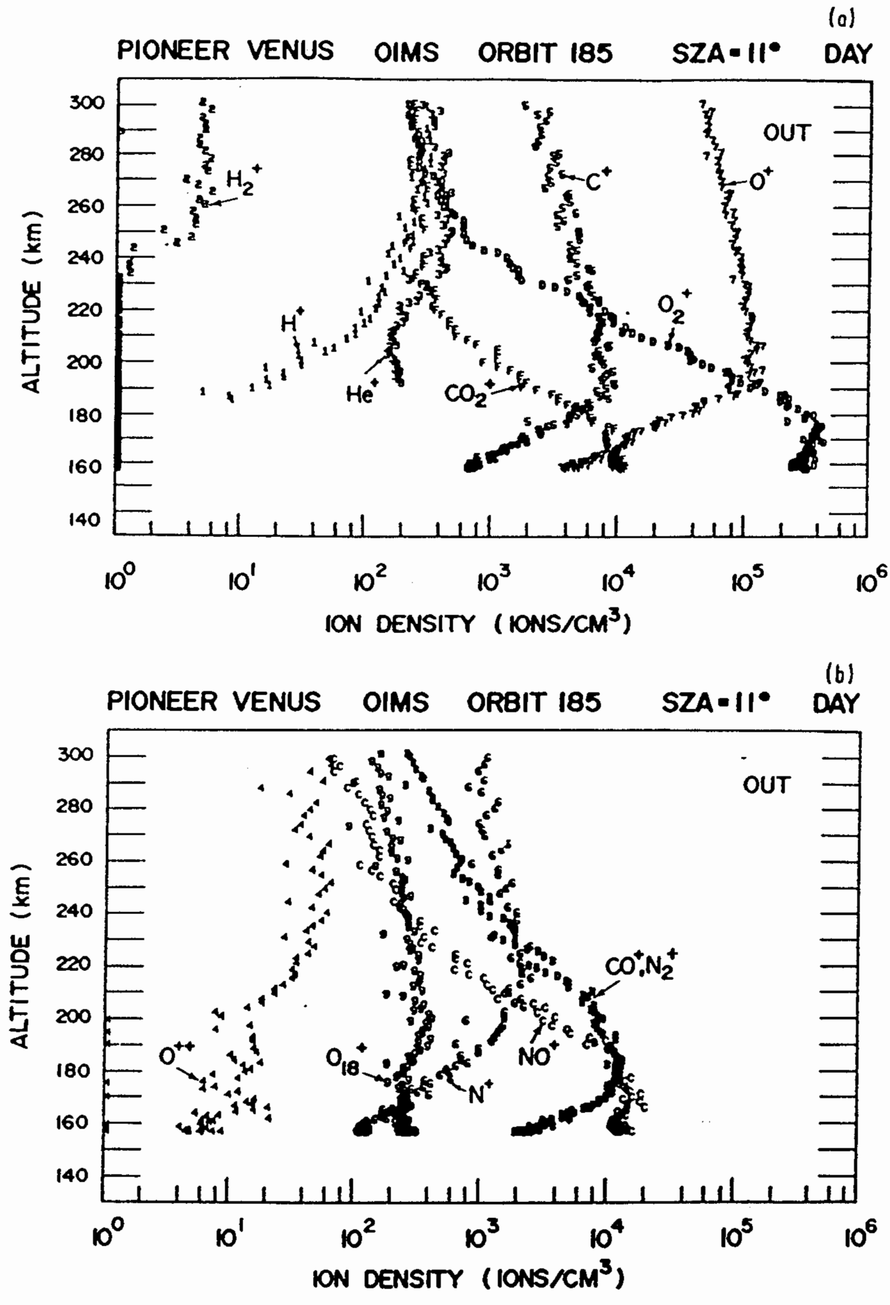


Figure 9. Ion composition in the subsolar region (figure from Brace and Kliore 1991).

low solar activity. Such an increase does not occur for the light gas helium, which does not escape in significant amounts (chapter by Donahue et al.).

Atomic oxygen is being lost by the planet at a rate comparable to that of the hydrogen loss rate. Approximately 90% of the O^+ ions created by photoionization above the ionopause are picked up by the solar wind. The gyroradius of their orbits in the solar wind is so small that, instead of flowing away freely, they re-impact the upper atmosphere. When they do so they

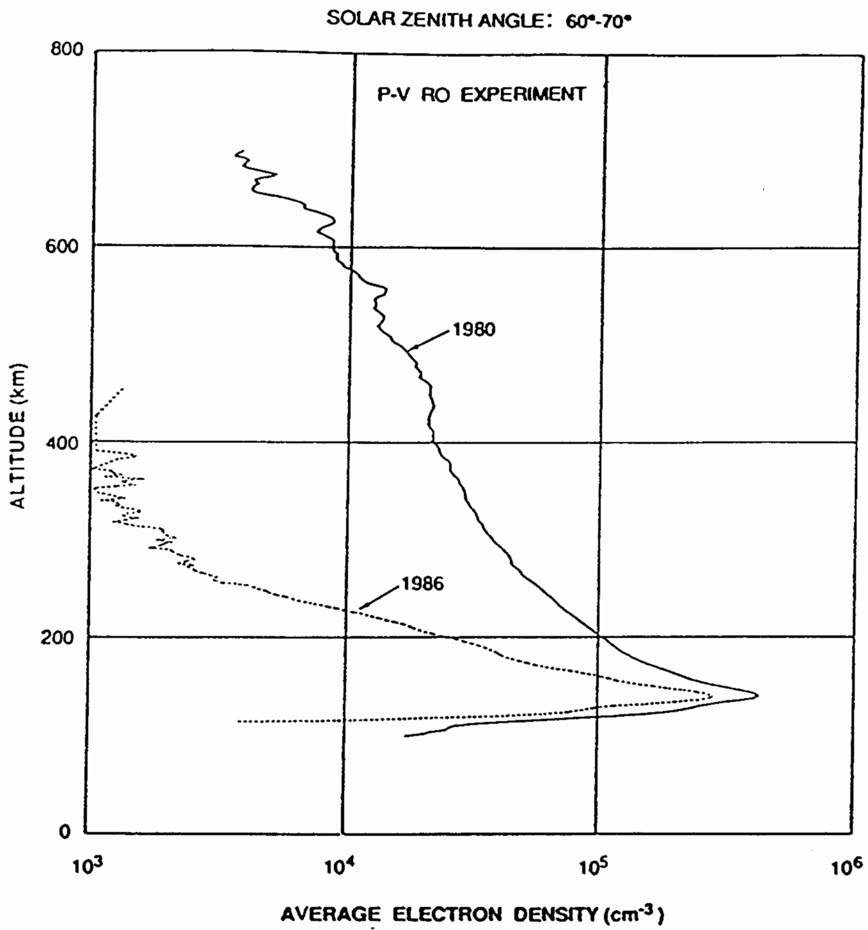


Figure 10. Electron density profiles under solar maximum and solar minimum conditions (figure from Brace and Kliore 1991).

collide with oxygen atoms, many of which attain escape velocity. This "sputtering" of oxygen produces a planet-wide escape flux of 6×10^6 cm^{-2}s^{-1}. Thus, oxygen may be accompanying hydrogen away from the planet at a rate sufficient to prevent a change in its redox state, precluding the need to dispose of the oxygen by processes such as oxidation of the crust (see the chapter by Donahue et al.).

In our knowledge of the upper atmosphere, the most glaring gap is due to our comparative ignorance of the properties of the atmosphere between the cloud tops and 115 km. As on Earth, this is an ignorosphere. But it is a very important region because it is where the mixed undissociated atmosphere is coupled to the chemically active thermosphere above. It is also the region where the return flow of circulation in the upper atmosphere occurs.

XIII. LIGHTNING

In the terrestrial atmosphere, lightning, the common term for the electrical discharge of large potential differences in clouds, occurs in three quite distinct

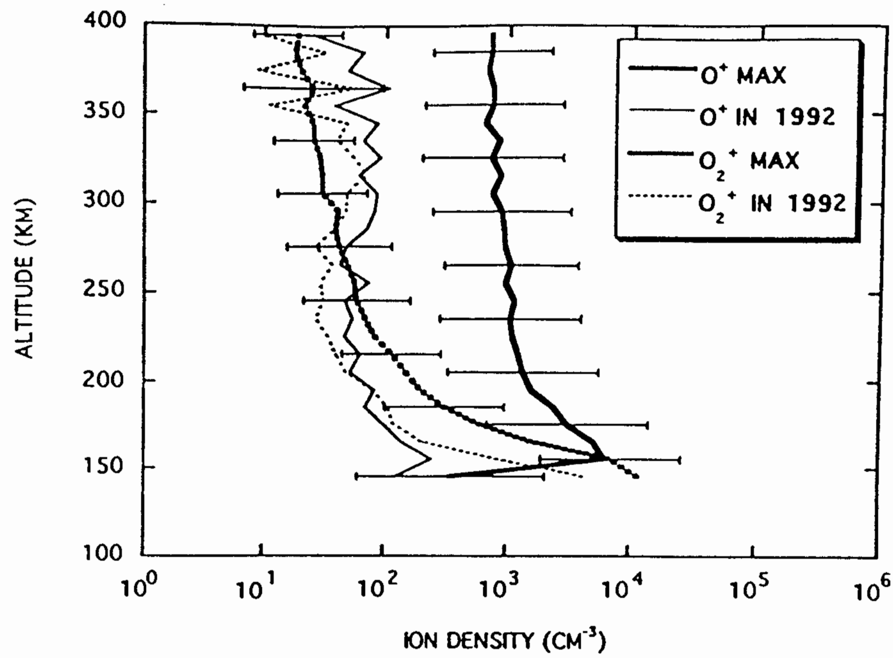


Figure 11. Solar cycle variation of major ions (figure from Kar et al. 1994).

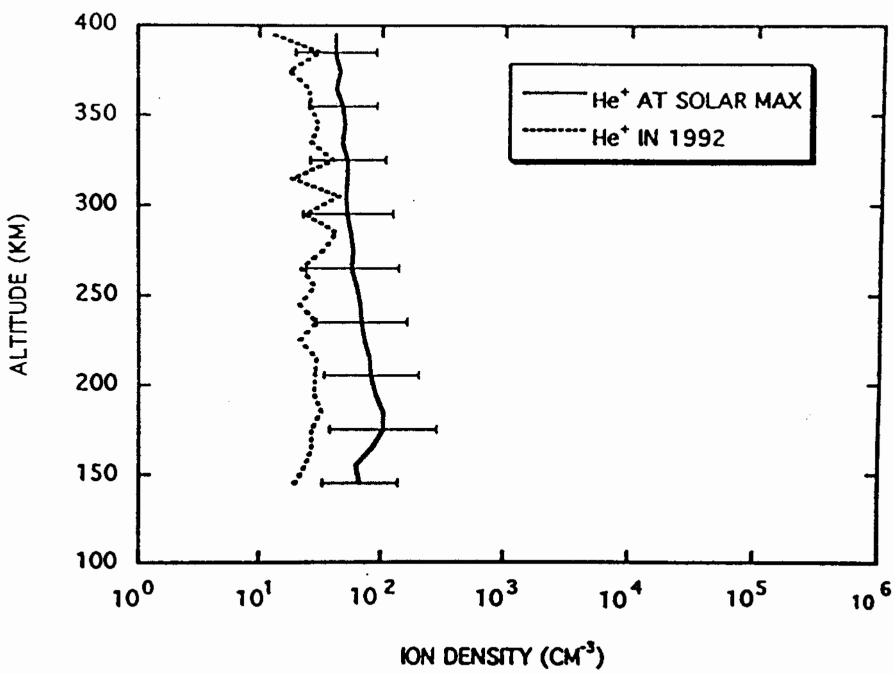


Figure 12. Solar cycle variation of ionized helium (figure from Kar et al. 1994).

ways. The most familiar discharge is from cloud to ground because it is the most readily discernible by the groundbased observer and the most dangerous to humans and machines. On Earth discharges within clouds (cloud-to-cloud) occur twice as often but are less well studied. A third type of discharge, extending upwards toward the ionosphere, has only been recognized recently and is only beginning to be explored. Of the three lightning discharge processes, we expect the latter two to predominate in ridding clouds on Venus of

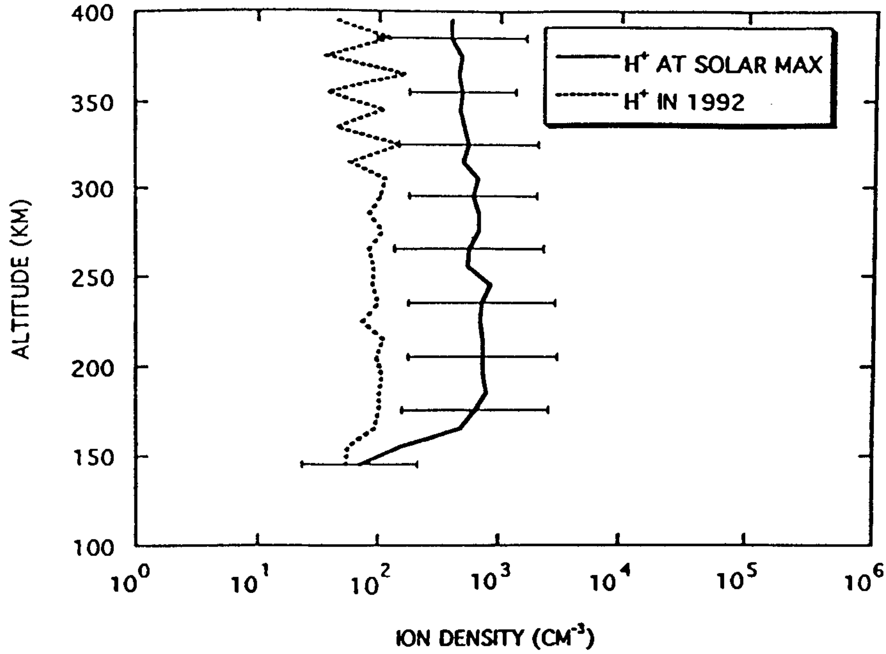


Figure 13. Solar cycle variation of ionized hydrogen (figure from Kar et al. 1994).

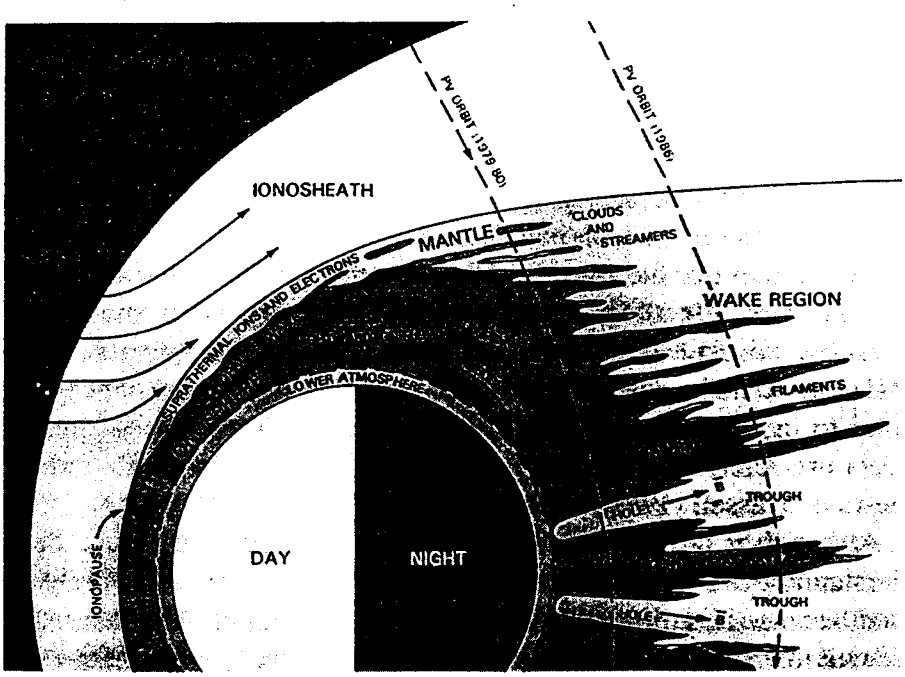


Figure 14. A cartoon representing the complex global configuration of the ionosphere of Venus. Radial scale expanded by a factor of two above the planet's surface (figure from Brace and Kliore 1991).

any build up of electrical potential because of the height of the clouds above the ground and the relative proximity of the ionosphere. The charging of terrestrial clouds is poorly understood even today but is generally believed to result from differential charging of small and large particles and the differential transport of these particles. Terrestrial dust clouds as well as water clouds are found to charge and abruptly discharge sometimes with catastrophic effects (such as in grain elevator explosions). Venus' clouds too have a range of particle sizes and are in a state of constant agitation.

Terrestrial cloud-to-ground lightning produces a column of superheated air that radiates in the visible and expands supersonically to produce the sound waves known as thunder. This column of superheated air also enables chemical reactions to occur that would not take place under standard temperature and pressure conditions. The importance of such processes in a planetary atmosphere depends on the rate of lightning occurrence (on Earth, about 100 s^{-1} worldwide) and is a subject of much debate.

Lightning on Venus has been studied with a variety of techniques and on a variety of missions as illustrated in Fig. 15. The Venera 9 spectrometer apparently detected a lightning storm optically. The Venera 11 through 14 landers detected the impulsive electromagnetic signals in the VLF frequency range associated with terrestrial lightning. Pioneer Venus detected VLF signals in the ionosphere of Venus that could be propagating from the atmosphere below in the expected whistler mode. It also detected VLF signals with similar impulsive characteristics but that could not have reached PVO through electromagnetic propagation. Investigators on PVO further conducted an optical search using scattered light in the star sensor and found no evidence for optical pulses above background. However, there were not many data available for this study and the majority of the data were obtained over the morning sector where the VLF search suggested low occurrence rates for lightning. Nevertheless, some took this evidence, plus their expectation of low lightning occurrence rates due the low mass loading of the clouds, to indicate that lightning was a very infrequent phenomenon. This opinion eased somewhat when the Galileo plasma wave receiver observed electromagnetic radiation at about 1 MHz that could be due to lightning. It eased even more when optical signals similar to lightning were observed from Earth-based telescopes. Interested readers are referred to the review chapter by Grebowsky et al. and to the reviews by Russell (1991,1993).

Although it now seems clear that lightning occurs on Venus, detailed understanding is lacking. In particular, the rate of occurrence is poorly determined because it is difficult to determine the rate with present data sets over the daylit ionosphere. We also do not know the relative occurrence rates of the different possible discharge paths, and in what levels of the clouds lightning occurs. More radio frequency data at frequencies above 1 MHz are needed to measure the dayside rate.

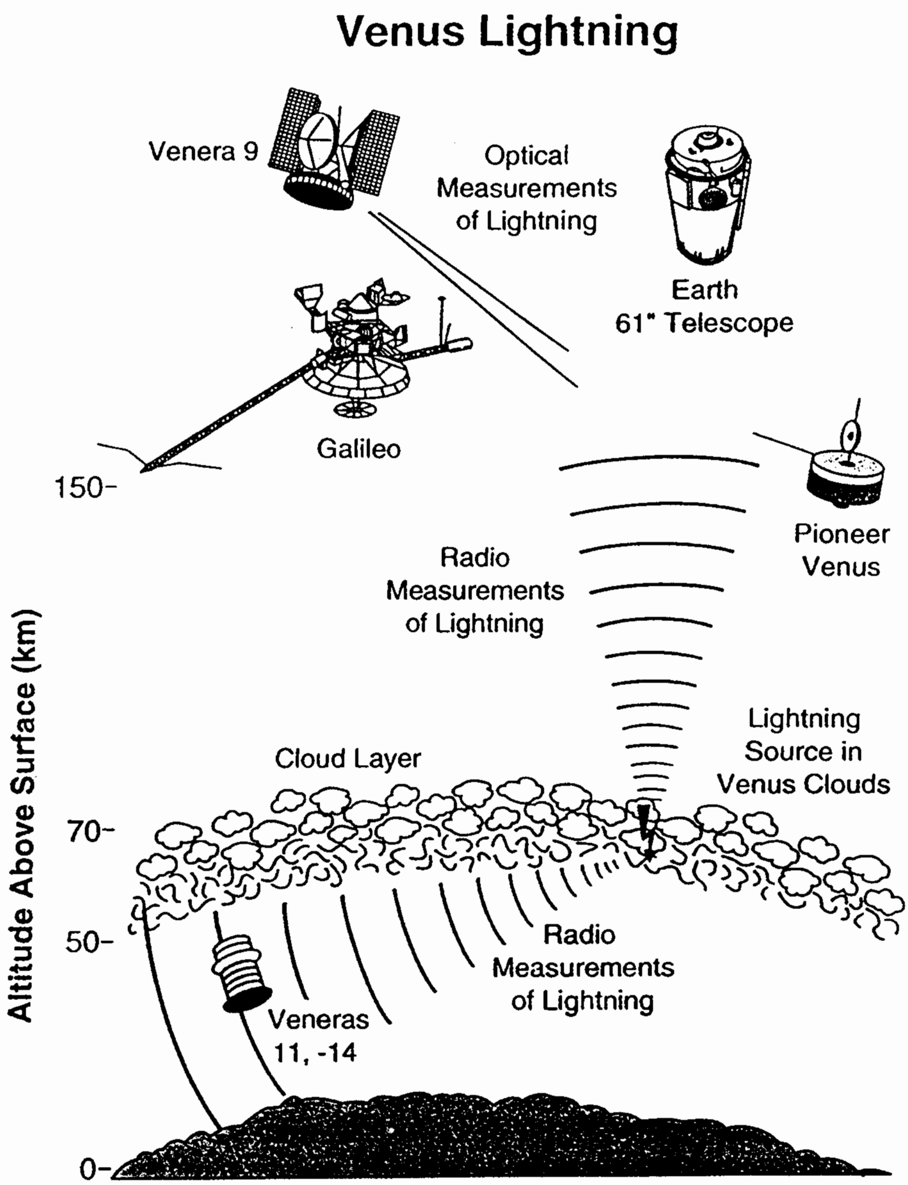


Figure 15. Schematic illustration of the observation of lightning on Venus with flyby, orbiter, and lander spacecraft as well as the 61-inch Earth-based telescope.

XIV. PLANETARY MAGNETIC FIELD

Venus is unique among the planets in that it has no detectable dynamo-driven or remanent magnetic field. (The Martian and lunar dynamos are no longer active, but evidence exists from meteorites and lunar samples that those two bodies have remanent magnetism, presumably induced by ancient dynamos.) Magnetic dynamos occur whenever the interior of a rotating planet has an electrically conducting region that is vigorously stirred by convection. Tiny Mercury has a dynamo believed to operate in a fluid shell on the outside of a relatively large solid inner core. The terrestrial dynamo operates in a fluid core with a small (by volume) inner core whose solidification is thought to provide much of the energy for generation of the magnetic field. Jupiter and Saturn have dynamos in their metallic hydrogen cores and Uranus and Neptune have dynamos thought to be generated in salt water layers at intermediate depths. Successive studies with Mariner 2 and 5, Venera 4, 9 and 10, and Pioneer Venus leave little doubt that the intrinsic field of the planet is far below that of these other planets (Russell et al. 1980; Phillips and Russell 1987). The lack of an intrinsic field at Venus suggests that the solid inner core expected to form in a terrestrial planet is not now condensing. The absence of any seismic data from the various landers that have reached the surface, leaves us almost completely in the dark about the interior of Venus.

The high surface temperatures approach or exceed the temperatures that allow most common planetary minerals to be magnetized. Thus, unlike the surfaces of Mars and the Moon, we do not expect the surface of Venus to be magnetized, and indeed there is no evidence for such magnetization at Venus.

The complete absence of a planetary magnetic field results in a much different interaction of the planet with the solar wind for all planets but Mars. As illustrated in Fig. 16, the magnetized solar wind flow is deflected by the planetary ionosphere (at Venus and also at Mars) at an altitude that permits direct interaction of the solar wind flow and the upper reaches of the planetary exosphere. Hence, a drizzle of atmosphere is continually lost as photoionization, charge exchange and impact ionization expose the exospheric particles to the solar wind electric field and acceleration to velocities far beyond that needed for escape. Sputtering of the atmosphere by these exospheric ions enhances the escape rate. However, the present day rates of escape related to the solar wind interaction are thought to be much less than those needed for the evolution of the atmosphere implied by the isotopic record.

To date no mission has addressed the chemical composition of the escaping ions nor do we have a reliable estimate of the total flux being lost and how this is controlled by the solar wind. This remains for future missions. We also underscore the need for long-term seismic measurements on the surface of Venus to probe the workings of the planetary interior.

XV. IONOSPHERIC MAGNETIZATION

The ionosphere of Venus can be found in two extreme magnetic states. At solar maximum when the solar EUV flux is strong, the ionosphere extends to high altitudes at times of low solar wind dynamic pressure. When such conditions occur the rate of classical diffusion of magnetic flux into the ionosphere is very low and to first order the ionosphere becomes nearly magnetic field-free. At the other extreme when the ionosphere is weak and the solar wind strong, a condition more frequently encountered at solar minimum, magnetic field rapidly diffuses into the ionosphere from the magnetic layer (magnetic barrier) on the inside of the magnetosheath. This magnetic flux is carried to low altitudes by the circulation of the ionosphere and deposited there. (Because

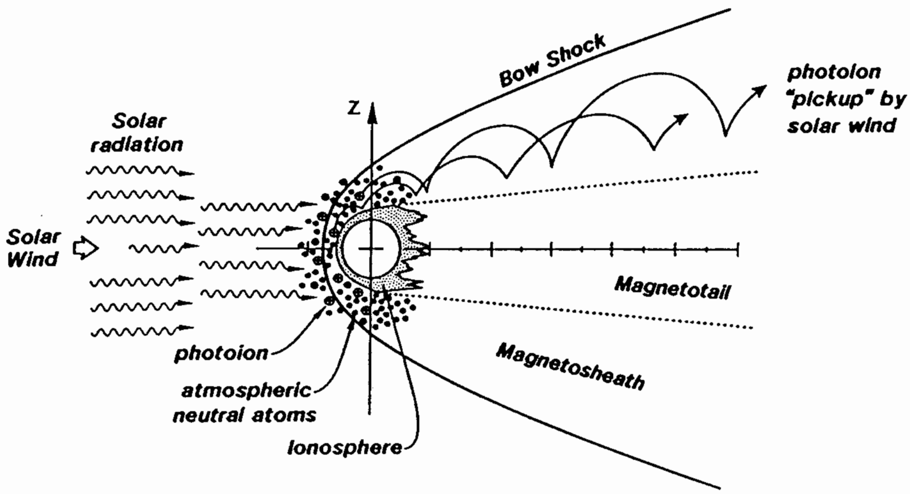


Figure 16. The formation of the ionosphere of Venus and the loss of ions by solar wind pickup (Luhmann 1995). The neutral atmosphere at low altitudes is ionized by the solar ultraviolet and extreme ultraviolet radiation. The neutral atmosphere that extends above the ionopause into the magnetosheath and solar wind is additionally ionized by charge exchange and impact ionization. The electric field of the solar wind accelerates these ions so that they spiral around the interplanetary magnetic field and drift away from the planet along cycloidal trajectories.

ionization occurs throughout the dayside ionosphere but recombination is most rapid at low altitudes, there is a net downward circulation in the subsolar ionosphere.) Ultimately this magnetic flux diffuses through the bottom of the ionosphere into the atmosphere maintaining a weak magnetic field in the ionospheric cavity. The day-to-night circulation of ionospheric plasma also carries this magnetic field into the tail region. The layered magnetic field structure on the day side becomes a more vertically structured magnetic field on the night side. Thus, the magnetic field appears to be draped over the planet on the day side but pulled down the wake in the antisolar direction at night. Because there must be pressure balance across these structures and because the pressure in the magnetic field and plasma are comparable, regions of strong magnetic field have low plasma densities and regions of high plasma density have low magnetic field strengths. Because the former regions are less common than the latter, the former regions are termed "ionospheric holes."

When the ionosphere is strong and the solar wind pressure is relatively weak, classical magnetic diffusion is not sufficient to bring magnetic flux into the ionosphere. Nonetheless, magnetic flux does appear in the ionosphere but in a form quite unlike that described above. Thin tubes of magnetic field, or flux ropes appear. This phenomenon is now realized to be quite prevalent in the magnetized plasmas of the solar system but is found in a novel form at Venus. High in the ionosphere the flux tube consists of fairly straight magnetic field lines and the pressure in the magnetic field is balanced by the pressure in the surrounding plasma. At low altitudes, as shown in Fig. 17, the magnetic field lines become tightly twisted around the axis of the flux tube so that the magnetic pressure forces in the tube balance themselves without the assistance of plasma pressure. Such structures are called force-free magnetic flux tubes. Force-free magnetic flux ropes are also found on the Sun but in a much different plasma regime in which the magnetic pressure forces dominate over the plasma pressure forces everywhere, not just in the rope. For more details on the magnetization of the ionosphere the interested reader is referred to the review by Luhmann and Cravens (1991) and the chapter by Cravens et al.

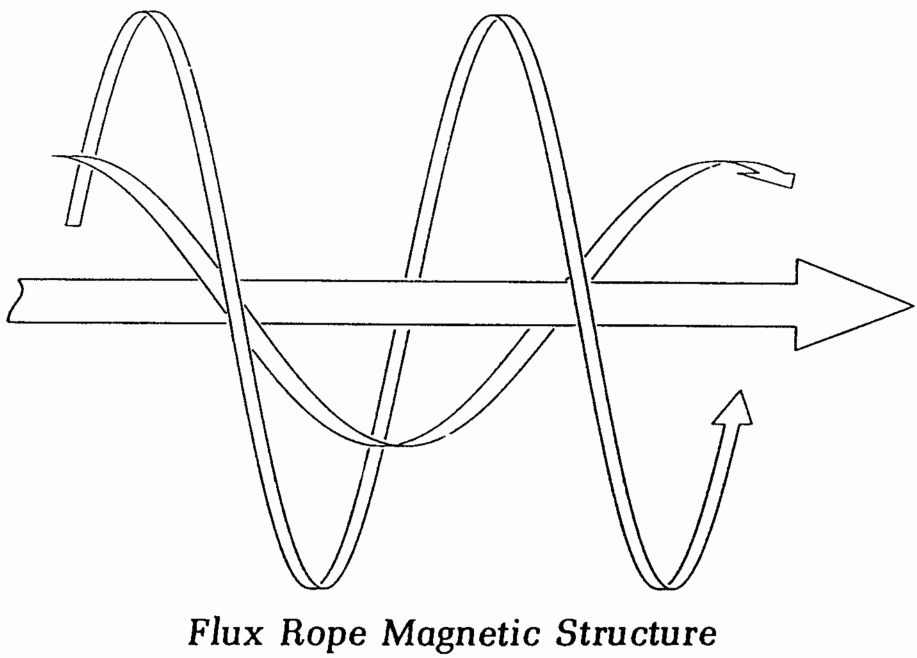


Figure 17. The structure of a magnetic flux rope. The interior field points along the axis and is strong. The field weakens with distance from the center of the rope and twists around the axis with greater pitch. The outward pressure gradient associated with the decreasing magnetic field strength exactly balances the inward force due to the curvature of the magnetic field lines in a force-free magnetic rope (figure from Elphic and Russell 1983).

The study of the ionosphere of Venus has taught us much about the behavior of magnetized plasmas. However, we have gleaned little about how the magnetic flux ropes are formed, in part because of the lack of high temporal resolution plasma measurements in the structures. It is hoped that future missions may be designed to provide a complete set of plasma diagnostics at high temporal resolution to be able to understand more fully this intriguing and important plasma phenomenon.

XVI. SOLAR WIND INTERACTION

In some senses the solar wind interaction with Venus is the inverse of that with the Earth. The terrestrial magnetosphere is a region, in which the magnetic field forces exceed those of the plasma, confined by a flowing plasma, in which the plasma forces generally well exceed the magnetic. However, as shown in Fig. 18, at Venus the obstacle is essentially an unmagnetized plasma and the solar wind forces are transmitted to this plasma by a magnetic layer or barrier that forms between the solar wind and the ionosphere. The formation of the barrier depends on dynamical forces in the plasma that allows the plasma to be deflected along the magnetic field and around the planet. It can also be visualized in kinetic terms. As the plasma flows toward the ionosphere, its speed perpendicular to the magnetic field line decreases, but its thermal velocity remains nearly constant. Because of the three-dimensional geometry, hotter, faster particles can escape along the magnetic field line leaving the colder, slower particles behind. Thus as the field line gradually is pushed against the ionosphere, its plasma density decreases with time leaving particles with low velocities parallel to the magnetic field lines. The resulting magnetic layer only slowly diffuses into the ionosphere as discussed above, keeping the solar wind and ionospheric plasmas apart.

Because the solar wind plasma is almost completely deflected by the planet (at least at solar cycle maximum when the ionosphere is strong), and because the solar wind bulk velocity far exceeds its thermal velocity, the plasma must pass through a shock in order to be slowed, heated and deflected about the planet. This shock stands in the flow some distance in front of Venus like the bow wavc of a ship. This distance is such that the plasma that passes through the shock can pass between the shock front and the planetary obstacle. The location of this bow shock varies with the solar cycle, being furthest from the planet at solar maximum and closest at solar minimum. Because the planet's size is constant during the solar cycle and the ionosphere is but a thin layer surrounding the planet, the explanation for this variation must lie in the absorption of the solar wind plasma at solar minimum when the ionosphere is weaker and less able to deflect the solar wind flow.

Behind Venus, as illustrated in Fig. 19, the solar wind wake stretches for at least 12 planetary radii and is largely magnetized as part of the solar wind interaction. The magnetic field is nearly parallel to the solar wind flow in two oppositely directed lobes, called the induced magnetotail. The magnetic structure evolves down the tail in a manner expected for a flow that is being accelerated back up to solar wind flow speeds by the magnetic forces in the tail. The two lobes are separated by a sheet of plasma apparently similar to the plasma sheet in the geomagnetic tail. More details on the solar wind interaction with Venus can be found in the reviews by Russell and Vaisberg (1983) and Luhmann (1986) and in the chapters by Luhmann et al. and by Huba and Strangeway.

The exact origin of the magnetotail and its plasmas still remain somewhat of a mystery because none of the plasma analyzers carried to Venus to date have had the sensitivities and the mass resolution to provide compositional constraints on the origin of the plasmas. It is hoped that future generations

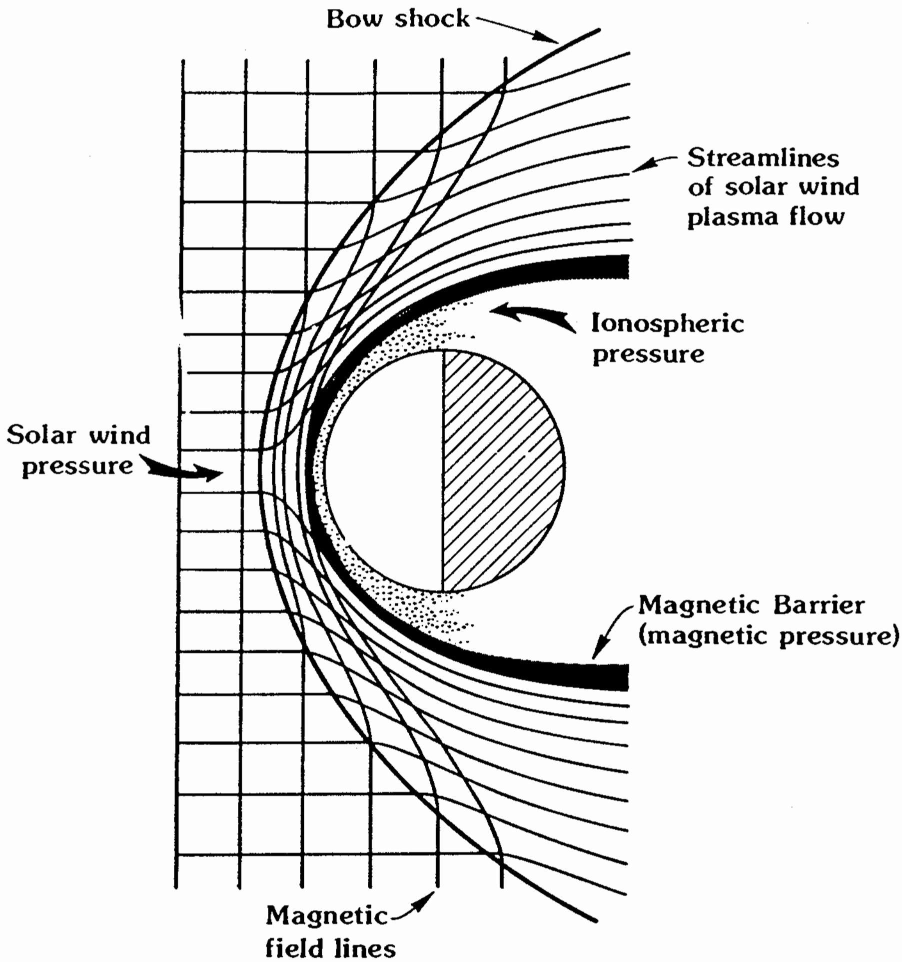


Figure 18. The solar wind interaction with Venus showing the streamlines of the flow, the magnetic field carried with the flow and the bow shock where the flow becomes subsonic and is deflected around the planet. The obstacle to the solar wind is the planetary ionosphere which the magnetized solar wind cannot penetrate. A magnetic layer builds up just above the ionosphere which itself forms part of the barrier to the solar wind flow (figure from Luhmann 1986).

of spacecraft will carry such instrumentation so that we will both unfold the processes that form the magnetotail of Venus and determine how much plasma is removed from Venus by tail acceleration processes.

XVII. CONCLUSIONS

Despite the great advances in our understanding of the atmosphere and plasma environment of Venus, achieved with the wealth of information gathered by the space science missions of the 1970s, serious gaps remain. These have been identified in a few sentences at the end of each section of this chapter. To summarize: Where atmospheric composition is concerned, the most important properties of the atmosphere that need to be more firmly established by future

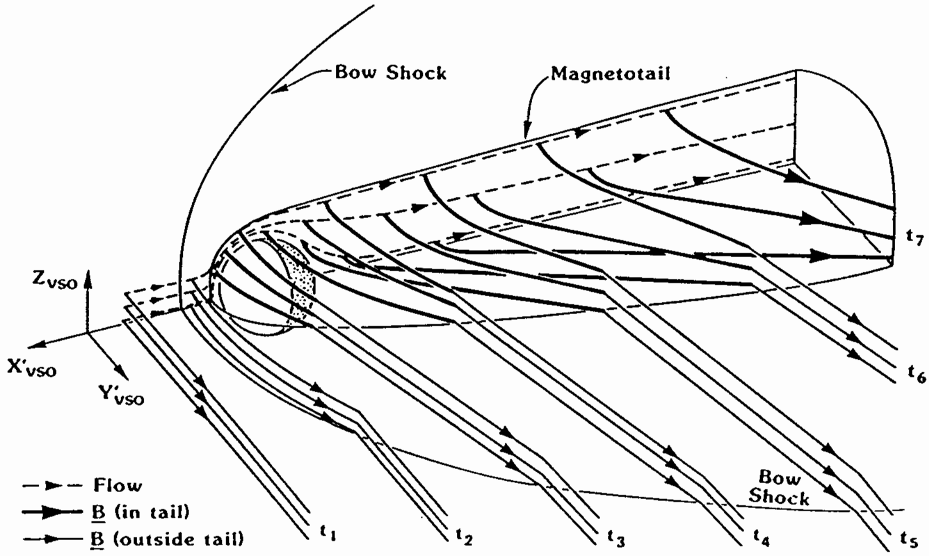


Figure 19. The formation of the magnetotail of Venus. Three magnetic field lines are followed as they flow over and around the planetary obstacle. The field lines closest to the planet move most slowly, become the most highly mass-loaded and are stretched most into a tail-like configuration. Magnetic pressure and curvature forces accelerate the plasma down the tail and the field lines gradually regain their original interplanetary directions (figure from Saunders and Russell 1986).

missions to Venus appear to be the isotopic ratios of krypton and xenon, the helium abundance, the sulfur chemistry and the redox state of the lower atmosphere. These are crucial for understanding the origin and evolution of the atmosphere and its interaction with the surface and interior. The rates at which hydrogen and deuterium are being introduced by outgassing and by cometary impact must be determined for comparison with the well-established escape rates and the deuterium to hydrogen ratio in atmospheric water vapor if the issue of the existence of a large early ocean is to be resolved. Determination of the abundance of CO, O_2 and potential catalysts, such as Cl, in the middle atmosphere is necessary before the chemical processes that so efficiently recombine CO_2 in the atmosphere can be identified.

Understanding the large-scale global atmospheric circulation system, which was a principal objective of the Pioneer Venus Multiprobe mission, has not been attained, partly because of a failure of atmospheric structure instruments on the probes below 10 km. Thus that goal, which is as important today as it was in the 1970s, remains to be attained.

At higher elevations the ubiquitous clouds are no longer impenetrable barriers to our sensors. Probes have cut through the cloud layers, balloon missions have floated in the clouds, radar measurements have covered the planetary surface, infrared sensors have detected spectroscopic emissions from all altitudes and even terrestrial telescopic data now can be obtained below the clouds. Yet the clouds still provide many mysteries, not the least of which is the mechanism for the generation of lightning and its rate of generation. While many sensors have provided evidence for lightning, controversy still abounds over the discharge rate. In particular we need a method to deduce the rate of lightning occurrence over the day side of the planet. This requires either new measurements, or possibly a study of the Magellan radiometer mode data for evidence of lightning discharges.

The ionosphere of Venus also was full of surprises. Prior to the Pioneer Venus mission the electrodynamics of the ionosphere was treated as a resistor, but soon it became evident that the ionosphere was more like a magnetohydrodynamic fluid with mass, momentum, magnetic forces, diffusion and dissipation. Nevertheless this more sophisticated treatment did not predict the formation of small magnetic flux bundles, or flux ropes, that at times permeate the entire dayside ionosphere. To study these structures requires a new generation of plasma sensors with much higher temporal resolution and perhaps even multiple probes.

The study of the solar wind interaction with Venus suffered from two deficiencies of the Pioneer Venus Orbiter mission. First, its ion spectrometer lacked mass resolution and, second, the orbit was not optimum for the study of the interaction. Thus, there are literally holes in our knowledge of the environment of Venus, and we do not know the present loss rates of the various species of ions. It is hoped that future missions to Venus can carry a more complete set of plasma diagnostics with high temporal resolution.

Early Earth was almost certainly much more similar to early Venus than to early Mars. To understand in what important ways these pristine planets differed and why Venus has evolved into a planet so dramatically different from Earth we must return to Venus.

Acknowledgment. While many missions from both the former Soviet Union and the United States have contributed to the study of Venus, the authors are particularly indebted to the many individuals who worked so hard on the Pioneer Venus mission. They made it a success and allowed scientists to reap the rewards of their efforts.

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