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12. A large number of people have contributed to the construction, testing, and calibration of the BNMS instrument. We thank all of them, especially H.-J. Hoffmann, K. Pelka, W. Schulte, and H. Baumann of the University of Bonn as well as D. Linkert, P. Gammelin, G. Matt, and W. Schneider of the Max-Planck-Institut für Kernphysik. We appreciate the efforts of K. H. Fricke and G. Meitzner of the University of Bonn for data analysis and model calculations and the members of the Pioneer Project Office for many years of excellent cooperation. Work at the University of Bonn and the Max-Planck-Institut für Kernphysik was supported by the Bundesministerium für Forschung und Technologie, Bonn, under grants WRK 275 as part of the German program on extraterrestrial research. Work at the University of Minnesota was supported by NASA contracts NAS2-7900 and NAS2-8812 with Ames Research Center.

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Venus Upper Atmosphere Neutral Composition: Preliminary Results from the Pioneer Venus Orbiter

Abstract. *Measurements in situ of the neutral composition and temperature of the thermosphere of Venus are being made with a quadrupole mass spectrometer on the Pioneer Venus orbiter. The presence of many gases, including the major constituents CO_2, CO, N_2, O, and He has been confirmed. Carbon dioxide is the most abundant constituent at altitudes below about 155 kilometers in the terminator region. Above this altitude atomic oxygen is the major constituent, with O/CO_2 ratios in the upper atmosphere being greater than was commonly expected. Isotope ratios of O and C are close to terrestrial values. The temperature inferred from scale heights above 180 kilometers is about 400 K on the dayside near the evening terminator at a solar zenith angle of about 69°. It decreases to about 230 K when the solar zenith angle is about 90°.*

The neutral gas composition of the Venus thermosphere is being measured in situ by means of a mass spectrometer (ONMS) on the Pioneer Venus orbiter. The initial periapsis pass occurred on 5 December 1978, at an altitude of 385 km, during which He was detected. Gradual lowering of periapsis permitted the measurement of other constituents of the upper atmosphere including CO_2, N_2, O, and CO. The orbit has an inclination of 105° and the initial periapsis was on the dayside of the planet at 18.5°N celestial latitude close to the evening terminator. Because the orbit is inertially stable, it "rotates" about the planet at the orbital rate of Venus permitting a full cycle of observations in about 243 Earth days. Since the initial observation was made, measurements are being obtained nearly every orbit, one per Earth day, as periapsis moves through the terminator region to the nightside of the planet. We report here some of the data obtained.

A quadrupole mass spectrometer with a dual energy (70 and 27 eV) electron impact ion source and a secondary electron multiplier ion detector is used. The mass peaks produced have flat tops permitting magnitude determination by a single measurement without peak scanning.

The ambient gases are introduced through a 2-cm^2 orifice in the stainless steel antechamber that encloses the ion source. The gas particles entering the antechamber collide many times with the inner surfaces and reach thermal equilibrium with the surfaces. Because the velocity of the spacecraft is much greater than the thermal velocity of the gas, the density of the gas in the enclosure greatly exceeds the ambient density. This results in a significant increase in the effective sensitivity; for example, the ratio of source to ambient density for CO_2 is approximately 100 when the orifice is pointing in the direction of the spacecraft velocity. The ionization volume is located behind the orifice so that gas entering through the orifice can also be ionized directly without prior surface collisions. The number of directly ionized particles is small compared to all ions produced, but because of the large momentum of the directly ionized particle they can be separated from the ions generated from the thermalized gas by means of a retarding potential. Reactive gases that may be adsorbed on the walls of the enclosure can hence be measured directly. The orifice of the ion source enclosure is pointed at an angle of 27° to the inertially stabilized orbiter spin axis, which is maintained normal to the ecliptic. The orientation of the sensor and the spacecraft orbit plane position result in an optimum minimum angle of attack for the instrument in the periapsis region.

The instrument can be commanded each orbit to accomplish either a periodic sampling of a maximum of eight selected masses or a scan of all masses up to 46 amu, stepping from peak to peak. The sensitivity of the sensor is approximately one ion per second per 5×10^4 nitrogen molecules per cubic centimeter. The instrument was baked, sealed, and maintained evacuated during transit, and opened to the atmosphere after orbit insertion [for details, see (*1*)].

An example of typical "raw" data for a number of the atmospheric constituents in the ion source obtained during the descending part of orbit 17 is shown in Fig. 1. Each mass was sampled alternately in the retarding and nonretarding mode of operation, and the sampling time per mass was 167 msec. Only the nonretarded measurements are shown in Fig. 1. The electron beam energy for this pass was 70 eV. Variations due to angle of attack change are apparent, particularly for mass 44, because of the higher sampling rate. The occasional deep modulation seen at most masses is believed to be due to the antenna intercepting the gas stream when the instrument points opposite to the direction of motion.

At altitudes above 250 km, background counts at mass 44 and 28 are apparent. These are due to surface degassing of CO_2 and CO adsorbed during the previous periapsis pass which was not observed during the early orbits with higher periapsis altitudes where the CO_2 and CO concentrations were significantly lower.

Preliminary values of ambient particle

Table 1. Data on the most abundant gases detected in the atmosphere of Venus at 150 km altitude near the evening terminator at a solar zenith angle of 88°.

Component	Density (particle/cm^3)
Carbon dioxide	1.1×10^9
Carbon monoxide	2.4×10^8
Molecular nitrogen	2.1×10^8
Atomic oxygen	6.6×10^8
Helium	2×10^6

density plotted against altitude are shown in Fig. 2 for orbit 17. The He values were computed directly by using laboratory calibration constants, orbital velocity, and spacecraft orientation. The nitrogen concentrations were computed from the mass 14 peak resulting from dissociatively ionized N_2. Carbon monoxide concentrations were computed from the mass 28 peaks by subtracting the N_2 contribution and the cracking fractions due to CO_2. The CO_2 values were computed directly from the mass 44 peak and are considered reliable below 180 km. Above that altitude, CO, combined on the surfaces with atomic oxygen, adds significantly to the 44 peak. This becomes apparent when the mass 44 scale height approaches the mass 28 scale height. Atomic oxygen was computed from the mass 16 peak and the mass 32 (O_2) peak (surface recombined atomic oxygen). The mass 16 peak is the sum of the atomic oxygen and the cracking fractions from CO_2, O_2, and CO which must be subtracted to obtain atomic oxygen. The oxygen values shown are considered lower limits since all possible losses of oxygen in the ion source due to surface effects have not been evaluated. Loss of oxygen is also suggested by the somewhat lower than expected scale height of the oxygen profile compared to that of the other constituents assuming identical kinetic temperatures. At periapsis the data obtained for oxygen in the retarding mode agreed with those obtained in the nonretarding mode within 20 percent. Concentrations of the major atmospheric constituents at 150 km are listed in Table 1.

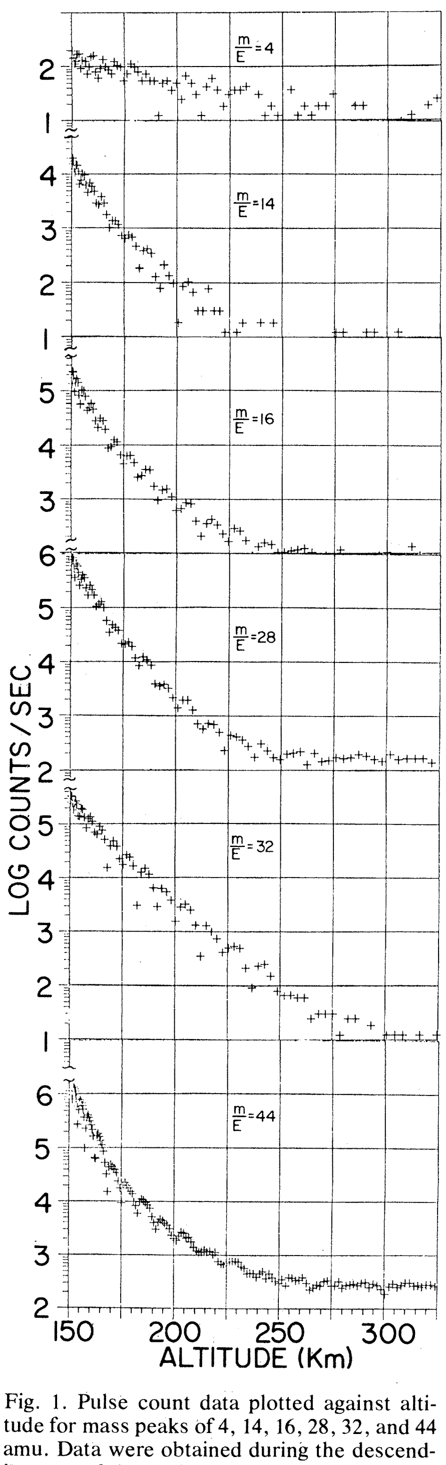

Fig. 1. Pulse count data plotted against altitude for mass peaks of 4, 14, 16, 28, 32, and 44 amu. Data were obtained during the descending part of the orbit 17 periapsis pass.

The observed O/CO_2 ratio is considerably larger than predicted by photochemical models (*2*) invoking large eddy diffusion coefficients, $K_e > 10^7$ cm²/sec, to account for the apparent absence of large nonthermal hydrogen escape fluxes. However, these models should be interpreted with caution because they represent average dayside conditions, whereas our data reflect terminator values that may not be representative of the whole dayside.

The He density ($2 \pm 1 \times 10^6$ cm^{-3}) inferred from Mariner 10 airglow measurements (*3*) at 145 km is well supported by our observations (see Fig. 2). Furthermore, we find a modest increase of about 30 percent in the He density as the solar zenith angle increases from approximately 60° to 90°. This increase is consistent with the prediction of a nightside He bulge (*4*).

The ^{40}Ar measurement is temporarily obscured by an anomalously high mass 40 peak probably caused by NaOH and ^{40}K ions which are contaminants on the surface of the ion source grids. These ions are very efficiently sputtered by the high velocity (10 km per second) impact of CO_2 on the grids. In time the magnitude of the contaminants will be evaluated and corrections applied to yield a valid ^{40}Ar measurement. Identification of the contaminants was made from complete mass spectra. The spectra obtained also yield information on the ratios of the major isotopes. The oxygen isotope ratios $^{18}O/^{16}O$ and $^{17}O/^{16}O$, and the carbon isotope ratio $^{13}C/^{12}C$ evaluated from the 46, 45, 44, 34, 33, 32 and 13,12 amu peaks are close to the terrestrial values. Mass 36 is also being detected. Further measurements and analyses of the mass peaks adjacent to mass 36 should permit unambiguous identification of ^{36}Ar (*5*).

The atmospheric temperatures are inferred from the scale heights of the individual constituents. It is assumed that the constituents are in diffusive equilibrium and are not severely affected by chemical reactions with the surfaces in the ion source. Thus nonreactive gases

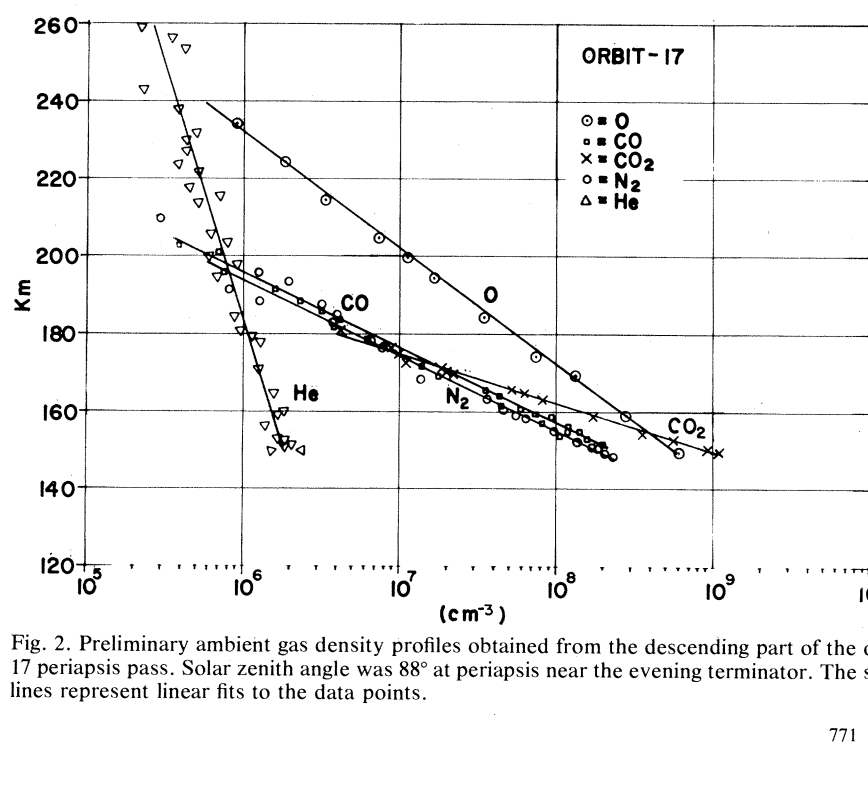

Fig. 2. Preliminary ambient gas density profiles obtained from the descending part of the orbit 17 periapsis pass. Solar zenith angle was 88° at periapsis near the evening terminator. The solid lines represent linear fits to the data points.

such as He and N_2 are expected to yield the most reliable values of temperature.

The He and N_2 data of Fig. 2, orbit 17 (solar zenith angle, $\simeq 88°$) lead to scale heights of about 57 km and 8.4 km, respectively, which correspond to a temperature of 230 K. The CO_2, CO, and O data indicate similar temperatures but are not considered as reliable. The He and N_2 data for orbits 3, 4, and 5 (solar zenith angle, $\simeq 69°$) when the periapsis was near 180 km (above exobase altitude of ~170 km) (*6*) give a temperature of about 400 K.

These temperatures support the concept of a relatively "cool" upper atmosphere as deduced most recently from the temperatures inferred from Mariner 5 (*7*) and Mariner 10 (*3*) airglow measurements as well as those suggested by theoretical models of the ionosphere (*8*, *9*). A rather strong decrease in temperature with increasing solar zenith angle also is observed, leading to a temperature gradient three times larger than predicted by a global thermosphere model (*10*).

The CO_2 density and gas temperature decrease with increasing solar zenith angle. If we assume that the global circulation model of Dickinson and Ridley (*10*) is valid, then we can compare our measurements made near the evening terminator with those of the BNMS (*11*) made near the morning terminator, since the model invokes cylindrical symmetry about the sun-planet axis. Thus, comparing our temperature of 230 K and CO_2 density of 1.1×10^9 cm^{-3} at 150 km and a solar zenith angle of 88° with the BNMS temperature of 253 K and CO_2 density of 6×10^9 cm^{-3} at the same altitude and a solar zenith angle of about 60°, we see that both the density and temperature decrease with increasing solar zenith angle. If this comparison is feasible then a kinetic pressure imbalance is present which must be balanced by a dynamical pressure resulting from horizontal flow from day to night as suggested originally by Dickinson and Ridley (*10*).

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5. The ^{36}Ar measurement can be obscured by HCl, a possible contaminant in the instrument, which yields mass peaks at 35, 36, 37, and 38 amu with relative peak heights of 12, 100, 4, and 33 percent, respectively. The limited time for which these mass peaks have been sampled did not allow a proper magnitude determination of the peak heights.
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Venus Thermosphere and Exosphere: First Satellite Drag Measurements of an Extraterrestrial Atmosphere

Abstract. *Atmospheric drag measurements obtained from the study of the orbital decay of Pioneer Venus 1 indicate that atomic oxygen predominates in the Venus atmosphere above 160 kilometers. Drag measurements give evidence that conditions characteristic of a planetary thermosphere disappear near sundown, with inferred exospheric temperatures sharply dropping from approximately 300 K to less than 150 K. Observed densities are generally lower than given by theoretical models.*

Atmospheric drag measurements obtained from the orbital decay of Earth satellites have been used since the beginning of the space age to determine upper atmosphere density from which composition and temperature are inferred. The atmospheric characteristics derived from those satellite drag measurements have formed the basis of a number of standard upper atmospheric models of the earth (*1*). From the present study of the orbital decay of Pioneer Venus 1 (orbiter) comes the first detection of atmospheric drag from a spacecraft orbiting another planet (*2*). In this report we discuss the determination of atmospheric densities from satellite orbital decay, and then describe an atmospheric composition model that is consistent with the observed variation of density with altitude. Finally, we use a model with variable exospheric temperature to study the nature of the diurnal variation of the upper atmosphere of Venus. The measurements were all obtained near 18.4°N latitude between 7 December 1978 and 1 January 1979 at altitudes of 150 to 190 km.

The density ρ_A (in grams per cubic centimeter) at a distance 1/2 H^* above periapsis (position of closest approach to planet surface), where H^* is the estimate of density scale height at periapsis (in centimeters), can be determined from the following equation if one assumes nominal Pioneer Venus 1 values of orbital eccentricity (0.84) and semimajor axis (39,600 km) (*3*).

$$\rho_A = \frac{4.35 \times 10^{-14}\, \Delta T}{\sqrt{H^*}}\, \frac{m}{C_D S} \qquad (1)$$

where ΔT is the change of orbital period per revolution caused by atmospheric drag, in seconds per revolution; m is the mass of the spacecraft, in grams; C_D is the coefficient of drag; and S is the effective cross-sectional area, in square centimeters. In practice, densities are determined by numerical integration through an atmosphere (*4*). The densities are evaluated above periapsis at the "effective" altitude of the drag effect to minimize errors associated with assumed value of H^*. With this technique, an error of 25 percent in H^* results in only a 1.2 percent error in the density a half scale height above periapsis.

The value of m, C_D, and S were approximately 361.7 kg, 3, and 6.15×10^4 cm^2, respectively. The mass of Pioneer Venus 1 decreased from 361.9 to 361.5 kg because of the expenditure of fuel in orbital maneuvers. The C_D value of 3 was determined after we considered experimental results consistent with values close to 3 as well as theoretical extremes of 2 and 4. The effective satellite cross section was constant at periapsis. Within 50 km altitude of periapsis where drag effects can be relevant, this cross section ranged from 6.06×10^4 to 6.20×10^4 cm^2.

The orbital elements, used to determine the change of orbital period (ΔT), were computed by a differential correction orbit determination program applied to S-band Doppler data received by the Deep Space Network (*5*). In order to isolate the atmospheric drag effect, which is concentrated near periapsis, changes in the orbital period due to other phenome-