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Venus Upper Atmosphere Neutral Gas Composition: First Observations of the Diurnal Variations

Abstract. *Measurements of the composition, temperature, and diurnal variations of the major neutral constituents in the thermosphere of Venus are being made with a quadrupole mass spectrometer on the Pioneer Venus orbiter. Concentrations of carbon dioxide, carbon monoxide, molecular nitrogen, atomic oxygen, and helium are presented, in addition to an empirical model of the data. The concentrations of the heavy gases, carbon dioxide, carbon monoxide, and molecular nitrogen, rapidly decrease from the evening terminator toward the nightside; the concentration of atomic oxygen remains nearly constant and the helium concentration increases, an indication of a nightside bulge. The kinetic temperature inferred from scale heights drops rapidly from 230 K at the terminator to 130 K at a solar zenith angle of 120°, and to 112 K at the antisolar point.*

This is the second report of preliminary results obtained from the Pioneer Venus orbiter neutral mass spectrometer (ONMS). In the first report (*1*) we presented data on the initial composition of the major constituents of the atmosphere near the evening terminator. Later data from more than 100 orbits covering a range of solar zenith angles (SZA) from 80° near the evening terminator to 174° near the antisolar point and to approximately 130° toward the morning terminator have been obtained.

Details of the Pioneer Venus spacecraft and the orbit parameters have been described by Colin and Hall (*2*) and Colin (*3*). The measurement techniques used to obtain ambient gas densities and kinetic temperatures with the ONMS are described in (*1*). We present here the first observations of the diurnal variations of the composition and temperature in the thermosphere of Venus. We discuss only average conditions with the aid of an empirical model whose parameters are obtained by a numerical fit to the data. In contrast to the model values, the measured densities change from orbit to orbit for a given altitude; thus the atmosphere on the nightside of the planet is variable.

The preliminary global model of the Venus thermosphere we present has been developed with the same basic formalism used for the mass spectrometer and incoherent scatter model (*4*). Data from 60 selected orbits distributed over the range of SZA encountered, from 80° to 174°, were used. A lower bound of 130 km has been chosen, and the only independent variable is SZA. The temperature and lower-bound densities are expanded in a series of Legendre polynomials in SZA (rather than latitudes and local time). Polynomials up to order four were used for exospheric temperature, and only the first-order polynomial (P_1) was used for the lower-bound densities. Exospheric temperature was determined from a simultaneous fit of He and N_2 densities and adopted for fitting CO, CO_2, and O. The data used were limited to heights less than 250 km for He and less than 180 km for the other gases. The lower-bound temperature was fixed at 180 K to match the infrared temperature (*5*), and a Bates temperature profile was chosen.

An example of the measured N_2 densities in an altitude interval from 165 to 169 km is shown in Fig. 1. The large changes from orbit to orbit illustrate the dynamic character of the atmosphere. Multiple points at a particular orbit (vertical line) are due to differences in sampling altitude and latitudinal variations (data taken during descent and ascent are presented). The solid line in Fig. 1

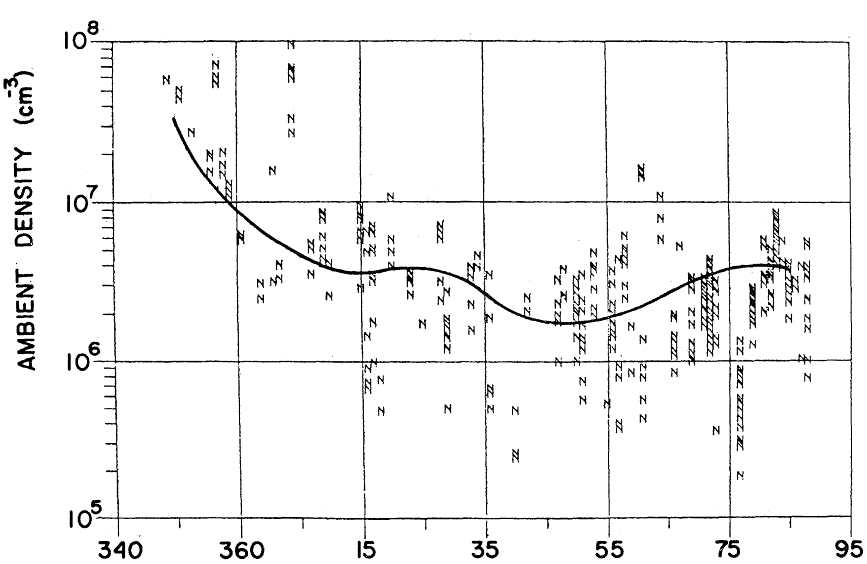


Fig. 1. Densities of N_2 versus time. Densities (*N*) were measured over an altitude interval from 165 to 169 km. The scatter reflects atmospheric variations and, to a small extent, altitude change. The solid line represents model values.

Table 1. Concentrations of the major atmospheric constituents at an altitude of 150 km and SZA = 180°.

Component	Density (particles per cubic centimeter)
CO_2	8.0×10^7
CO	1.7×10^7
N_2	5.0×10^7
O	4.4×10^8
He	1.3×10^7

Table 2. Heat sources for the nightside thermosphere (ergs per square centimeter per second averaged over the hemisphere). "Convective" refers to the heat carried across the terminator by the flowing gas; "compressional" refers to the heat generated by gas flowing downward.

Boundary (km)	Convective	Compressional	Conductive
120	2.6	0.52	0.017
140	0.03	0.006	0.0088

shows the model densities. Summaries of all model values for O, CO_2, N_2, CO, and He are shown versus SZA for altitudes of 150 and 167 km in Fig. 2, a and b, respectively, and the corresponding exospheric temperatures are shown in Fig. 3.

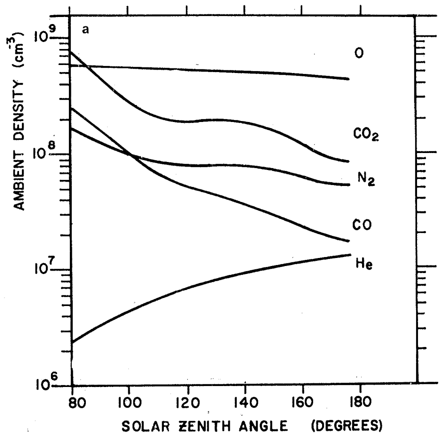
Concentrations at 150 km and SZA = 180° are listed in Table 1. A density decrease with increasing SZA is observed for all constituents except He, which clearly shows a nightside increase [in general agreement with the prediction by Mayr *et al.* (*6*)]. At the limit of the present observations, the He number density is still increasing; this finding suggests a retrograde rotation of the upper atmosphere.

Perhaps the most significant result is the very rapid temperature drop on the nightside (Fig. 3). The lowest temperature (112 K) is shown at the antisolar point because the model assumes symmetry with respect to SZA. The actual temperature minimum appears to be shifted toward the morning terminator, which is in agreement with the findings of Keating *et al.* (*7*). It remains to be seen from a second cycle of diurnal observation whether the shift is temporal or results from diurnal effects. A second minimum (130 K) appears at about SZA = 120°. The density increase at SZA = 140°, apparent in Fig. 2, is also reflected in the temperature, although the model estimate may be too high because of the small number of harmonics used in the model. For the same reason we expect the temperature drop near the terminator to be even more rapid than that shown in Fig. 3.

The sudden drop in pressure and temperature across the terminator is strongly reminiscent of the results obtained by Dickinson and Ridley (*8*) in their global thermospheric model; this result supports the concept that a wind is blowing from day to night as they predict. However, many detailed features in the prediction do not seem to be reproduced; in particular, the observed temperature drops much sooner and much further than in the Dickinson and Ridley model, whose mean nightside temperature at 150 km is about 250 K. Their model contains all the known sources of infrared emission, but in some way a temperature lower by more than a factor of 2 is maintained. To achieve this by radiation would require considerable opacity at a wavelength much longer than the 15-μm CO_2 band. This band is a very inefficient radiator at 110 K because of a very small Boltzmann factor.

An idea of the requirements on the energy sink is given in Table 2 (*9*). Here we show the energy brought in by the flow across the terminator, the compressional heating due to the corresponding subsidence, and the heat conducted upward from the mesopause, assumed to lie at 100 km with a temperature of 180 K (*5*). The heat has been arbitrarily averaged over the full hemisphere. Two assumptions (120 and 140 km) have been made for the lower boundary of the flow regime; 120 km seems the more likely. If so, the heat is fully comparable to that deposited on the dayside by solar ionizing radiation.

Although a radiative process may yet be found that can cope with this energy load at such a low temperature, we may have to revive the idea of eddy conduction, advocated years ago by Shimizu for Venus and Mars (*10*) and by Johnson



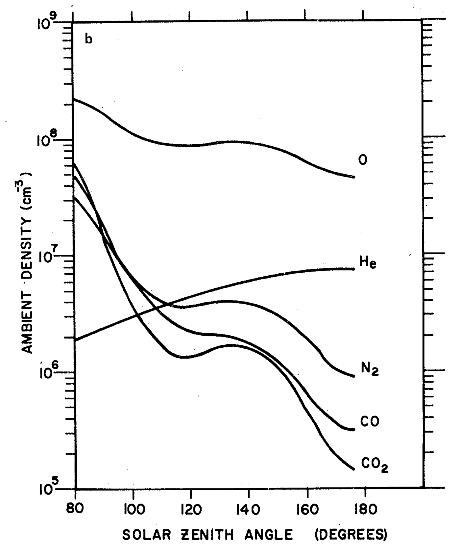


Fig. 2. Ambient densities of CO_2, CO, N_2, O, and He versus solar zenith angle. Average values at 150 km (a) and 167 km (b) are presented with the aid of a global empirical model fitted to the data obtained from 60 orbits.

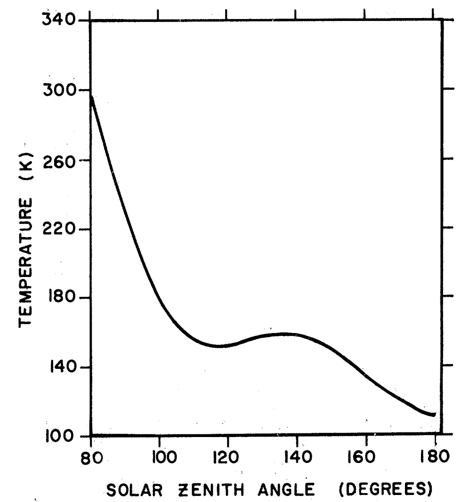


Fig. 3. Kinetic exospheric temperature derived from scale heights versus solar zenith angle.

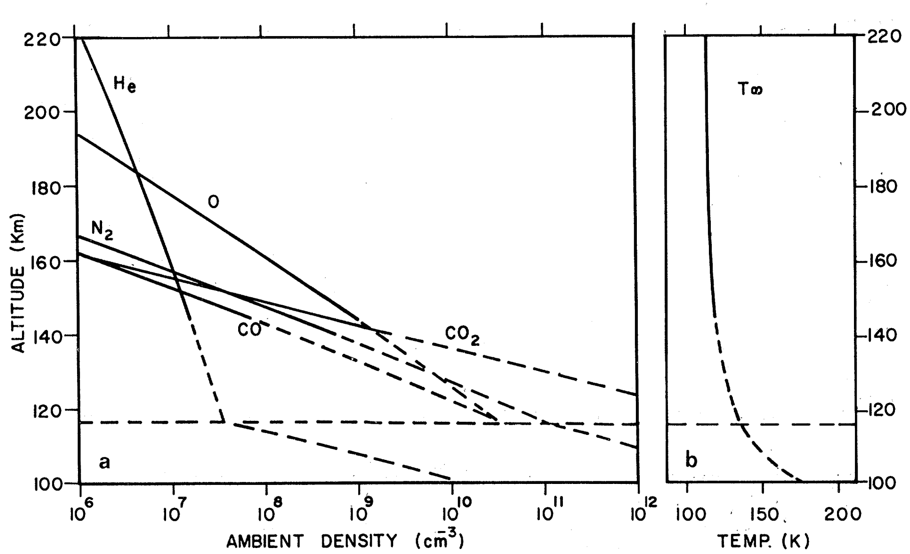


Fig. 4. (a) Preliminary ambient gas density profiles at a solar zenith angle of 180° obtained with the aid of an empirical model fitted to the data obtained from 60 selected orbits. The solid lines represents the fits to the actual data. The dashed lines are downward extrapolations to below the inferred homopause. (b) The temperature profile used in the extrapolation (*15*). The dashed horizontal line at 117 km shows the estimated homopause level.

and Gottlieb for Earth (*11*). Eddy conduction has also been considered by Dickinson (*12*). In principle, rapid vertical motion can enforce an adiabatic (negative) temperature gradient all the way to zero Kelvin, where the density also falls to zero. Some difficulties about the concept were pointed out by Hunten (*13*), and many of them have been resolved by Izakov (*14*); in particular, eddy conduction is inevitably accompanied by eddy heat dissipation, which almost certainly offsets and may even overcome the cooling. In principle, the relatively small difference can be of either sign; perhaps there is net cooling for Venus and Mars (CO_2), net heating for the sun and Jupiter (hydrogen), and near cancellation for Earth. [As Dickinson and Ridley pointed out (*8*), a coherent circulation transports heat and matter without dissipating energy at high altitudes; but it predicts much too high a temperature on the nightside.] An upper bound to the cooling rate, or a minimum requirement on the eddy diffusion coefficient K, can be derived by neglecting the eddy heating. With a little over 3 erg cm^{-2} sec^{-1} for 120 km (Table 2), we find that K should be at least 2×10^7 cm^2 sec^{-1}, which is in the range obtained for the dayside by von Zahn *et al.* (*15*). Such a large value is incompatible with the circulation regime as proposed by Dickinson and Ridley.

The cold thermosphere found for Mars on the Viking mission (*16*) is in accord with the idea that there is net eddy cooling in CO_2 atmospheres. The higher temperature of the dayside Venus thermosphere now becomes the anomaly; perhaps the heating efficiency should be increased again from the very low value (0.1) adopted by Dickinson and Ridley.

Altitude profiles of the densities of major gases at the antisolar point are shown in Fig. 4a. The solid lines represent fits to data. The dashed lines are downward extrapolations to below the homopause, based on the temperature profile (*17*) shown in Fig. 4b. Both CO and O are present in the thermosphere entirely as photolysis products of CO_2, since their mixing ratios are orders of magnitude greater than at the cloud tops. Moreover, any recombination is negligible to well below 100 km (*18*). The global mean downward fluxes of CO and O must therefore be equal at all heights considered here. The level at which their number densities become equal is therefore a special one, a "homopause" for whatever vertical transport processes are operating.

Our downward extrapolation of the nightside data places the homopause at 117 km, where the CO_2 density is about 10^{13} cm^{-3}, and the diffusion coefficient for CO in CO_2 is $D = 2.5 \times 10^5$ cm^2 sec^{-1} (*19*). If the homopause is formed by eddy mixing, K would also be 2.5×10^5 cm^2 sec^{-1}; for a vertical velocity v, D is divided by the scale height to give $v \sim 1$ cm sec^{-1}. These values, derived by extrapolation, are uncertain by at least a factor of 3. A height-dependent K, as found for the dayside by von Zahn *et al.* (*5*), is another possibility. The present crude state of analysis does not permit us to say whether this estimate of K is inconsistent with the larger requirement for heat conduction. We hope that further analysis, once we have a complete set of orbits for the nightside, will elucidate the true nature of the homopause and energy balance.

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Implications of the Gas Compositional Measurements of Pioneer Venus for the Origin of Planetary Atmospheres

Abstract. *Comparisons are made between the volatile inventories of the terrestrial planets, including Pioneer Venus data, and the predictions of three classes of theories for the origin of planetary atmospheres. Serious difficulties arise for the primary atmosphere and external source hypotheses. The grain accretion hypothesis can account for the trends in the volatile inventory from Venus to Earth to Mars, if volatiles were incorporated into planet-forming grains at nearly the same temperature for all of these planets, but at systematically lower pressures in the regions of planet formation farther from the center of the solar nebula.*

The Pioneer Venus spacecraft carried several mass spectrometers and a gas chromatograph, which measured the abundance of gaseous species in the upper and lower atmospheres. Species detected included several rare gases as well as N_2, H_2O vapor (below the clouds), and CO_2, the dominant atmospheric constituent. In this report, we compare the absolute abundances and the ratios of these species with their counterparts for Earth, Mars, chondritic meteorites, and the sun in order to assess the validity of alternative hypotheses for the origin of planetary atmospheres.

Tables 1 and 2 summarize currently available data on the absolute abundances and ratios of constituents of the volatile inventory of five classes of solar system objects (*1*, *2*). The absolute abundances refer to the ratio of the mass of a given volatile species to the object's total mass. In the case of the planets, of necessity, we took stock only of material outgassed into the atmosphere over the planet's lifetime, including material currently residing in near-surface reservoirs or known to be lost subsequently to space (*2*). However, in the case of the meteorites, we counted, again of necessity, nuclides capable of forming volatile compounds that are present throughout the mass of the object. The important trends displayed in Tables 1 and 2 are summarized below. (i) The absolute abundances of N_2 and CO_2 are essen-