ending in February 1979. During the extended mission in the fall of 1979 over 100 profiles of the daytime ionosphere at various values of χ will be obtained.

ARVYDAS J. KLIORE, RICHARD WOO
JOHN W. ARMSTRONG, INDU R. PATEL
Jet Propulsion Laboratory,
California Institute of Technology,
Pasadena 91103
THOMAS A. CROFT
SRI International,
Menlo Park, California 94025

References and Notes

1. L. Colin, *Science* **203**, 743 (1979).
2. ——— and C. F. Hall, *Space Sci. Rev.* **20**, 283 (1977).
3. V. R. Eshleman, P. B. Gallagher, R. C. Barthle, *J. Geophys. Res.* **65**, 3079 (1960).
4. G. Fjeldbo and V. R. Eshleman, *Radio Sci.* **4**, 879 (1969).
5. ———, *Planet. Space Sci.* **76**, 123 (1968); A. J. Kliore, in *Mathematics of Profile Inversion*, L. Colin, Ed. (Publication TMX-62, 150, National Aeronautics and Space Administration, Washington, D.C., 1972), p. 3-2.
6. R. H. Chen and A. F. Nagy, *J. Geophys. Res.* **83**, 1133 (1978).
7. G. Fjeldbo, B. Seidel, D. Sweetman, T. Howard, *J. Atmos. Sci.* **32**, 1232 (1975).
8. G. S. Ivanov-Cholodny *et al.*, preprint of paper No. D.2.4, Twenty-first COSPAR meeting, Innsbruck, Austria (Academy of Sciences of the U.S.S.R., Institute of Radio Engineering and Electronics, Moscow, 1978).
9. S. J. Bauer and R. E. Hartle, *Geophys. Res. Lett.* **1**, 7 (1974); S. Kumar and D. M. Hunten, *J. Geophys. Res.* **79**, 2529 (1974).
10. The normal uncertainty (three standard deviations) in the time of closest approach of orbit solutions is about 0.03 to 0.06 second, corresponding to an uncertainty in the altitudes of the electron density profiles of about 0.2 to 0.4 km. Because of the effects on the solar flare activity of 13 December 1978, the corresponding uncertainty for orbit 9 is about 0.9 second, leading to an altitude uncertainty of about 6 km.
11. We thank the many people whose contributions were essential to the success of the radio occultation experiment. The following Pioneer Project, Jet Propulsion Laboratory, and Deep Space Network personnel deserve our special gratitude: C. F. Hall, J. Dyer, J. Cowley, and R. Ramos of NASA Ames Research Center for their design and execution of the mission; R. B. Miller, R. Elwood, W. Hietzke, J. Wackley. D. W. Johnston, and T. Howe of the DSN for their valuable support; W. E. Kirhofer, R. Jacobsen, B. Williams, and T. Lubeley of the JPL Pioneer navigation team for providing us with trajectories as well as predictions for the occultation data recording; P. Laing for the occultation prediction software; and G. H. Pettengill, the leader of the radio science team. We also thank A. F. Nagy for his valuable comments. This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under NASA contract NAS 7-100.

16 January 1979

Venus Thermosphere: In situ Composition Measurements, the Temperature Profile, and the Homopause Altitude

Abstract. *The neutral mass spectrometer on board the Pioneer Venus multiprobe bus measured composition and structural parameters of the dayside Venus upper atmosphere on 9 December 1978. Carbon dioxide and helium number densities were 6×10^9 and 5×10^6 per cubic centimeter, respectively, at an altitude of 150 kilometers. The mixing ratios of both argon-36 and argon-40 were approximately 80 parts per million at an altitude of 135 kilometers. The exospheric temperature from 160 to 170 kilometers was 285 ± 10 K. The helium homopause was found at an altitude of about 137 kilometers.*

The primary objectives of the neutral mass spectrometer (BNMS) experiment on board the Pioneer Venus multiprobe bus were to study the composition and temperature of the Venus upper atmosphere. Of particular interest were measurements near the homopause and the ionospheric peak. The bus passed the 200-km level of the Venus thermosphere on 9 December 1978 at 40°S celestial latitude, at a local solar time of 0835 hours and a local solar zenith angle of 60°. Although it descended through the atmosphere at a rather shallow angle the verticle velocity component of the bus was still 1.4 km per second at the 150-km level where the atmospheric pressure scale height was about 6 km.

The BNMS (*1*, *2*) included a semiopen electron impact ion source, double-focusing analyzing fields, four ion detectors (two multipliers and two electrometers), two pumps, and an in-flight calibration system. The combination of electrometers and ion-counting multipliers together with differential pumping between ion source and analyzing fields made it possible to measure particle densities over eight orders of magnitude. Only the maxima of selected mass peaks were sampled for each 0.1 second. The mass numbers chosen included those expected on the basis of our pre-Pioneer Venus knowledge of the composition of the Venus atmosphere as well as masses associated with anticipated impurities.

Table 1. Temperatures as derived from the measured CO_2 profile.

Altitude (km)	Temperature (K)
200	284
180	281
160	269
150	253
140	221

Table 2. Altitude levels (in kilometers) on dayside of terrestrial planets (*7*).

Level	Venus	Earth	Mars
Exobase	~180	~500	~185
Ionospheric peak	142	270	132
Homopause	137	105	125

As the bus approached Venus, the first gas to be detected was helium at an altitude of about 700 km. Upon sensing a predetermined level of the mass 28 signal the instrument switched automatically to a special low-altitude mass program at 206 km. Data were obtained down to an altitude of approximately 130 km where the ion source operated in the 10^{-3} mbar pressure range. Figure 1 shows particle density profiles for CO_2 and He. The altitude values are preliminary, but are believed to be accurate to 3 km below an altitude of 250 km.

The mass 44 signals started to rise rapidly below 300 km with a gradient that increased down to 200 km; at this altitude the gradient stabilized, at a value corresponding to a scale height of approximately 6 km. The smaller slope above 200 km is tentatively attributed to the contribution of impurities at the mass 44 position, possibly CO_2 produced by the reaction of ambient atomic oxygen with contaminants on the instrument surfaces. Below 200 km, however, the ambient CO_2 becomes the dominant contributor to the mass 44 peak, the impurity effect becoming negligible.

The smoothed CO_2 density profile was used to derive a temperature for the upper thermosphere and exosphere (see Table 1). Our "low" dayside exospheric temperature of 285 K agrees fairly well with that obtained from the orbiter (*3*) and by the ultraviolet spectrometer on Mariner 10 (*4*). The value is close to that predicted by the low-heating-efficiency model of Dickinson and Ridley (*5*). However, it emphasizes that the exosphere temperature, T_{ex}, cannot be obtained from the topside scale height of the ionosphere unless the ratio of oxygen atoms to CO_2 molecules is known.

The instrument He sensitivity was successfully calibrated in flight 2 days before the bus entered the Venus thermosphere. This enables us to place considerable confidence in the absolute He number densities reported here. At 145 km our absolute density is a factor of 3 greater than that found by Kumar and Broadfoot (*4*). At 135 km our ratio for $n(He)/n(CO_2)$, where n is the total number density, is about 130 ppm and is still decreasing toward lower altitudes. The 10 ppm mixing ratio derived by Kumar and Broadfoot (4) was based on an assumed CO_2 density much higher than our measured value.

The distribution of He, with its small atomic mass, should be strongly affected by vertical and horizontal transport processes. It was thus surprising to find that the measured He profile can be matched well by a simple one-dimensional diffusive equilibrium profile with a constant exospheric temperature $T_{ex} = 285 \pm 10$ K between 160 and 700 km altitude (see Fig. 1). Moreover, this T_{ex} agrees well with the exospheric temperature derived from the measured CO_2 distribution. The slight excess of He observed at the highest altitudes when compared with the diffusion model may be an indication of the postulated nightside He bulge (6), since the solar zenith angle was 15° larger at 700 km than at 135 km.

We find that the measured He densities below 160 km can be represented by a diffusion model calculated with an eddy diffusion coefficient $K_e \propto n^{-1/2}$, where n is the total number density, a limiting value of K_e (max) $= 4 \times 10^8$ cm^2/sec, and the temperature profile derived from the CO_2 densities (see Fig. 1). For this model the eddy diffusion coefficient and the molecular diffusion coefficient of He in CO_2 are equal at 137 km, which is a measure for the altitude of the He homopause (7). This is the highest level of a homopause found on any of the terrestrial planets (see Table 2).

An examination of the mass peaks in the neighborhood of Ar showed unexpected signals at 41 and 42 as well as at 40 and 36 (mass 38 was not monitored). In the exosphere all of these appeared to have approximately the same scale height, with a value too high to be associated with Ar. At the lowest altitude of measurements, however, the mass 40 and 36 profile slopes approach the values expected for Ar. We believe that the high altitude data represent primarily impurities of unknown origin. Extrapolations of the data to lower altitudes enables us to derive a correction for the mass 40 and 36 peaks with the remainders attributed to Ar. With these assumptions we find that ^{40}Ar and ^{36}Ar have about the same abundance at 135 km. The mixing ratio of each relative to CO_2 is tentatively taken as 80 ppm. This value is in reasonable agreement with the findings of the Pioneer Venus large probe mass spectrometer (8).

Definitive statements concerning Ne, N_2, CO, O_2, and O as well as some other possible species will require additional analysis.

The discovery of major amounts of ^{36}Ar, ^{40}Ar, and ^{4}He in the Venus atmosphere requires a reconsideration of current theories concerning not only the history of outgassing of Venus, but also the complex interactions of the planet with the solar wind. It has been suggested (9) that the rare gas inventory of the atmosphere of terrestrial planets is controlled by a varying degree of outgassing of a prototype material resembling chrondritic matter. The fact that the amount of ^{40}Ar per gram of planet material found for Venus is very similar to the value on Earth suggests that both planets have accumulated near equal amounts of ^{40}K and also have been outgassed to a similar extent. At the same time, however, about 300 times more ^{36}Ar relative to ^{40}Ar is present in the atmosphere of Venus compared to that of Earth. This could mean either that, compared to Earth, Venus has received a greater supply of noble gases during the process of planet formation, or that after planet formation Venus has accreted more noble gases. A later addition of noble gases could have been the result of surface admixtures of volatile-rich material or the result of accretion from a solar wind that originated on the sun and was unimpeded by an intrinsic magnetic field. Which process is most likely cannot be determined until more information is obtained on the amounts of other noble gases present, such as Ne. If noble gas accretion has occurred by admixtures of grains, surface saturated by solar wind, or from the solar wind proper, rare gas abundance patterns of a solar rather than planetary type are to be expected.

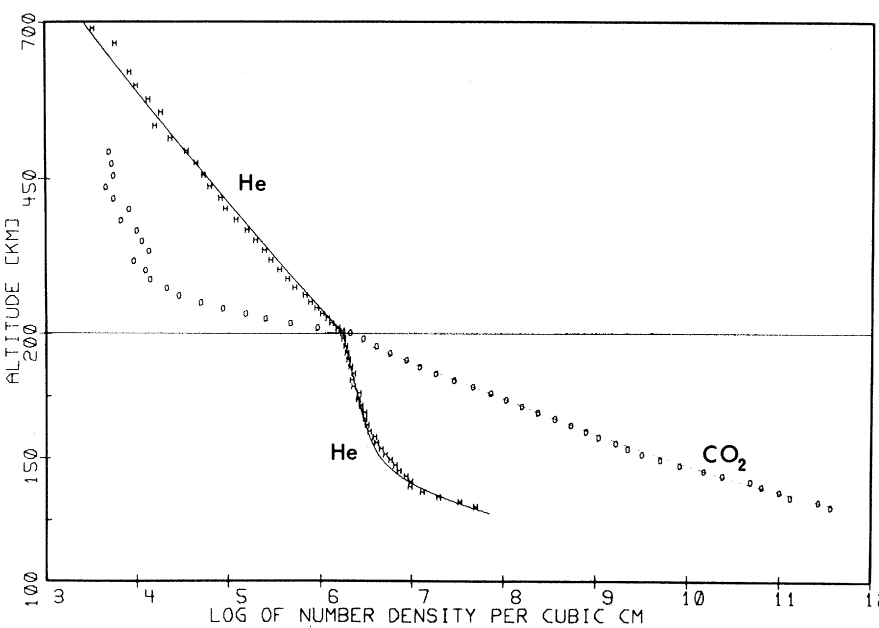

Fig. 1. Number densities for CO_2 and He measured by the BNMS plotted against altitude. Note that the altitude scale changes at 200 km. The average of the background signals as observed over the 1800- to 1000-km altitude range has been subtracted from both data sets. Solid curves represent smoothed profiles from model calculations with T_{ex} = 285 K as described in the text. Models based on 270 K and 300 K yield He densities at 700 km altitude that are 0.68 times lower and 1.41 times higher, respectively, than the 285 K solution.

Knudsen and Anderson (10) have shown that the Venus atmosphere should contain approximately 200 ppm of He; they assumed that the ^{4}He results entirely from radioactive decay, with subsequent outgassing from the planet, the production rates on Venus being equal to those for Earth, and there being negligible escape from the Venus exosphere. Their assumption of similar production rates on both planets has, in the meantime, been supported by measurements of the uranium and thorium abundances on the Venus surface by the Venera spacecraft (11). Our He measurements did not reach low enough in altitude to sample atmospheric regions where He is completely mixed. It is evident, however, that compared to Earth, Venus has kept in its atmosphere a much larger fraction of all the He outgassed over the lifetime of the planet.

U. VON ZAHN
Universität Bonn, 5300 Bonn 1, Federal Republic of Germany
D. KRANKOWSKY
Max-Planck-Institut für Kernphysik, 6900 Heidelberg 1, Federal Republic of Germany
K. MAUERSBERGER, A. O. NIER
University of Minnesota, Minneapolis 55455
D. M. HUNTEN
University of Arizona, Tuscon 85721

References and Notes

1. L. Colin and D. M. Hunten, *Space Sci. Rev.* **20**, 451 (1977); U. von Zahn and K. Mauersberger, *Rev. Sci. Instrum.* **49**, 1539 (1978).
2. L. Colin and C. F. Hall, *Space Sci. Rev.* **20**, 283 (1977).
3. H. B. Niemann, R. E. Hartle, W. T. Kasprzak, N. W. Spencer, D. M. Hunten, G. R. Carignan, *Science* **203**, 770 (1979); A. I. Stewart, D. E. Anderson, Jr., L. W. Esposito, C. A. Barth, *ibid.*, p. 777. The remaining differences may be real, due to different locations on Venus.
4. S. Kumar and A. L. Broadfoot, *Geophys. Res. Lett.* **2**, 357 (1975).
5. R. E. Dickinson and E. C. Ridley, *Icarus* **30**, 163 (1977).
6. H. G. Mayr, I. Harris, R. E. Hartle, W. R. Hoegy, *J. Geophys. Res.* **83**, 4411 (1978).
7. We derived the exobase and He homopause altitudes at Venus from our BNMS measurements and by using an appropriate atmospheric model. The altitude of the ionospheric peak at Venus was taken from D. M. Hunten *et al.* [*Space Sci. Rev.* **20**, 265 (1977)]. In the case of Earth the exobase and homopause altitudes were taken from the 1975 U.S. Standard Atmosphere (NASA TR R-459). The exobase and homopause altitudes on Mars were taken from A. O. Nier and M. B. McElroy [*J. Geophys. Res.* **82**, 4341 (1977)], and the ionospheric peak from W. B. Hanson *et al.* (*ibid.*, p. 4351).
8. J. H. Hoffman, R. R. Hodges, Jr., M. B. McElroy, T. M. Donahue, M. Kolpin, *Science* **203**, 800 (1979).
9. E. Anders and T. Owen, *ibid.* **198**, 453 (1977).
10. W. B. Knudsen and A. D. Anderson, *J. Geophys. Res.* **74**, 5629 (1969).
11. A. P. Vinogradov, Y. A. Surkov, F. F. Kirnozov, *Icarus* **20**, 253 (1973); C. P. Florensky, L. B. Ronca, A. T. Basilevsky, *Science* **196**, 869 (1977).

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.

16 January 1979

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