Reports

Pioneer Venus Results: An Overview

Abstract. *A summary is presented of the scientific results obtained during the first 120 days of the Pioneer Venus orbiter mission and produced by analysis of multiprobe data as of about 1 April 1979. The summary is essentially a guide to the material presented in the reports devoted to Pioneer Venus results in this issue of* Science.

Recent results obtained during the Pioneer Venus mission are presented in a series of reports that follow this overview. A summary of these results is presented here. In some instances information is available for the first 120 days of the orbiter mission. Analysis of data from the multiprobe mission has advanced impressively. This is not a general review of Venus science and will not compare Pioneer Venus with Venera 11 and 12 results.

Composition of the lower atmosphere. There is still considerable uncertainty regarding the values of rare gas concentrations in the mixed atmosphere that will finally emerge from the analysis of data obtained by the several relevant instruments (Table 1). The estimates of ^{36}Ar and ^{40}Ar mixing ratios now provided by the large probe neutral mass spectrometer (LNMS) are, respectively: 40 ± 30 ppm and 50 ± 35 ppm. The quoted uncertainties are large enough to allow the total Ar mixing ratio to overlap the large probe gas chromatograph (LGC) value of 18.6 ± 2.4 ppm at 24 km. The ratio of ^{36}Ar and ^{38}Ar obtained by the LNMS near 50 km, where absolute ^{36}Ar and ^{38}Ar mixing ratios were measured, is 5; this agrees with the ratio measured below 25 km, and lends credibility to the low altitude measurement of 0.85 ± 0.1 for the ratio of ^{36}Ar to ^{40}Ar. Hence, a case can be made for assuming that about half of the Ar detected by the LGC is ^{36}Ar. The value for the ratio of ^{20}Ne to ^{36}Ar of 0.5 ± 0.3 obtained by the LNMS is likewise in accordance with the LGC observations.

Unfortunately, the data obtained by the bus neutral mass spectrometer (BNMS) and the orbiter neutral mass spectrometer (ONMS) that would provide further information on the question of the rare gas abundances have not been completely analyzed. This leaves open the possibility that further confusion will develop regarding this fundamental question. However, with the information available at present, it seems as though the mixing ratio of ^{36}Ar in the atmosphere of Venus may lie somewhere between 10 and 100 ppm and that ^{20}Ne is less abundant than ^{36}Ar by about a factor of 2. Per gram of planetary material, this would put Cytherean ^{36}Ar between about 8×10^{-10} and 8×10^{-9} g/g, compared with 4.6×10^{-11} g/g for Earth and 2.2×10^{-13} g/g for Mars. The ratio of ^{36}Ar to ^{38}Ar is about 5 in all three atmospheres. Similarly, the abundance of ^{20}Ne would lie between about 2×10^{-10} and 2×10^{-9} g/g for Venus, while it is 1.1×10^{-11} g/g for Earth and 4.2×10^{-14} g/g on Mars. Two fundamental facts stand out in these results: the amount of nonreactive volatiles per unit mass of planetary material decreases in order of magnitude steps from Venus to Earth to Mars, and the mass of neon is significantly lower than that of nonradiogenic argon on all three planets. The abundance of neon is 17 times greater than that of argon in the solar atmosphere.

The LNMS also reports a nitrogen mixing ratio of 3.5^{+3}_{-2} percent. This agrees well with values reported or inferred from LGC, BNMS, and ONMS measurements. The nitrogen abundance in the Cytherean atmosphere is in the neighborhood of 2×10^{-6} g/g and is almost identical with the terrestrial value. The total CO_2 inventories of Earth and Venus are also similar. On the other hand, the amount of N_2 and CO_2 per gram of planet that has at one time entered the atmosphere of Mars is uncertain but apparently is rather less than that evolved on the other two planets (*1*). These results put strong restraints on models for the formation of the terrestrial planets and the evolution of their atmospheres. In particular, they seem to exclude models in which the atmospheres have a significant contribution from the sun or have evolved from material common to all three planets whether similar to meteoric matter or not. The ratios of isotopes of ^{13}C to ^{12}C and ^{18}O to ^{16}O are found to be within 5 percent of terrestrial values.

The LNMS has also reported the presence of large concentrations of sulfur compounds in the lower atmosphere in the form of SO_2, OCS, and H_2S, as well as free sulphur perhaps derived from some other constituent in the atmosphere. The concentrations of S, OCS, and, to a lesser degree, H_2S decrease dramatically between 20 and 25 km. These results, combined with those of the LGC and the cloud particle size spectrometer (LCPS), appear to present problems for sulfur chemistry and the sulfur inventory in the atmosphere since the total amount of S below 20 km according to the LNMS appears to be above 1000 ppm, whereas at 24 km it lies between 30 and 500 ppm in the form of SO_2 according to the LGC, and in the main cloud layer is not greater than 100 ppm in the form of condensed material according to results obtained by the LCPS. Reconciling these measurements, if they are reconcilable, would seem to require conversion of the sulfur in the lower atmosphere into some form of noncondensing gas at higher altitudes.

Structure of the lower atmosphere. Further analysis of the measurements of pressure, temperature, and density (LAS and SAS) confirm the remarkably small thermal and pressure contrast at all subcloud altitudes in the four regions through which the probes descended. The atmosphere is statically stable against overturning except in two regions: the middle cloud layer from 56 to 52 km and below the clouds from 29 to 20 km (11 to 22 bars). Temperature offsets as great as 20 K occur in the clouds, probably because of absorption of thermal radiation. An abrupt change in temperature was observed at 270 K in the region of transition from the middle to the upper cloud layers (56 to 59 km). The temperature is that at which an 80 percent solution of H_2SO_4 freezes. Above 70 km there is reasonable accord between temperature measurements in situ and those obtained by the infrared radiometer (OIR) on the orbiter.

The OIR also has shown that a diurnal variation in temperature develops above 80 km at latitudes below 60°. At 100 km the subsolar region is 15 to 20 K warmer than the antisolar region near the equator. An increase in temperature of 20 K from equator to pole observed at 80 km disappears by 100 km. Planetary scale waves with a 5- to 6-day period apparently have been detected above 65 km. Atmospheric drag analysis indicates that

 0036-8075/79/0706-0041$00.75/0

these propagate upward producing large periodic oscillations in density at 155 km.

Winds. Above 40 km where meridional gradients in pressure exist, zonal wind speeds decreasing from 130 m/sec easterly at 60 km to 60 m/sec at 40 km are inferred from cyclostrophic balance. The zonal winds deduced at 40 km from cyclostrophic balance agree with wind profiles now available for the day and north probes from the differential long-baseline interferometry (DLBI) experiment. Analysis by DLBI for the north probe indicates an easterly wind increasing from less than 2 to 3 m/sec at the surface to 50 m/sec at 40 km without significant shear. Meridional components as large as 4 m/sec occur above 25 km. At 30°S where the day probe descended, the easterly wind increased from less than 1 to 2 m/sec to about 60 m/sec at 50 km. There was shear between 10 and 20 km and also above 35 km. Strong variability in zonal and meridional wind components above 35 km suggest large-scale turbulence along the path of the day probe. In the clouds, between 49 and 55 km, the southerly component of velocity for the day probe increased sharply from 2 to 25 m/sec, while the easterly component rose to more than 200 m/sec. Thus, direct measurement indicates that the apparent motions of 100 m/sec observed by remote measuring in the upper clouds are winds and not wave motions.

Ultraviolet images obtained by the cloud photopolarimeter (OCPP) show that planetary scale features undergo secular variations. Cloud forms commonly known as Y features recur periodically at intervals of about 4 days but can disappear for several weeks.

From the temperature data obtained by the OIR in the stratosphere, mean circulation patterns have been deduced that show the mean zonal wind speed decreasing rapidly with altitude while the meridional circulation grows. The circulation is from equator to pole below 90 km with a return flow above that altitude.

No scintillations due to atmospheric turbulence have been detected from the probe radio signals. The results disagree with the indications of strong turbulence at 60 and 45 km previously reported.

Net radiative flux. Eventually, when the DLBI wind data are available for all four probes, they will be combined with the atmospheric structure data and the net radiative and solar flux data to construct a comprehensive picture of the hemispherical circulation on Venus from at least 12.5 km to the cloud tops. Preliminary results from the small probe net flux radiometer (SNFR) experiments are now available. These data give the net upward radiative flux between about 0.2 and 50 μm. They indicate the existence of three vertical regions or layers in which the thermal behavior of the atmosphere and consequently the general circulation pattern is quite different. Below about 35 km, the net flux varies smoothly with altitude. However, at 60°N during the night (north probe) the atmosphere cools radiatively but at an unexpectedly low rate that decreases, rather than increases, with altitude up to 36 km. The net flux at the lowest altitude is several times greater than expected even for an atmosphere containing a water vapor mixing ratio of 10^{-4} by volume. The lower atmosphere at this latitude appears to be much less opaque in the infrared than expected. At 30°S (night probe) low radiative cooling comparable to that at 60°N is observed above 27 km. Heating occurs below 27 km. At a similar latitude, the day probe also indicates radiative heating below 27 km. The low latitude heating and high latitude cooling in this layer, at least below 27 km, should lead to a slowly overturning cell, provided no other factors such as friction are dominant. The difference between the day and night net flux for the three small probes indicates a solar net flux about four times greater than that measured near the equator by the large probe solar net flux radiometer (LSFR). If this effect is real, it implies a significant difference in cloud opacity above 65 km at the site of sounder probe entry and that of some of the other probes. In the region between 35 km and the base of the main cloud layer, alternating layers of heating and cooling occur at all three probe locations. Stratified layers of gases or very small particles are suggested in this subadiabatic region. (However, the evidence for large-scale turbulence from the DLBI day probe wind profile above 35 km must be reconciled with this picture.) In the clouds, major changes in nephelometer (SN) backscatter coincide with major changes in net flux, indicating large differences in infrared opacities among the various cloud layers. A region of very great infrared opacity was found by the north probe at 60 km. Only weak corresponding backscatter at 0.9 μm was observed there by the SN. This dichotomy suggests the existence of unusual cloud or gas properties at high latitude.

Table 1. A list of the instruments on board the Pioneer Venus orbiter, large probe, and small probes.

Abbreviation	Name of instrument
LNMS	Large probe neutral mass spectrometer
LGC	Large probe gas chromatograph
BNMS	Bus neutral mass spectrometer
ONMS	Orbiter neutral mass spectrometer
LCPS	Cloud particle size spectrometer
LAS	Large probe atmospheric structure
SAS	Small probe atmospheric structure
OIR	Orbiter infrared radiometer
DLBI	Differential long-baseline interferometer
OCPP	Orbiter cloud photopolarimeter
SNFR	Small probe net flux radiometer
LSFR	Large probe solar net flux radiometer
SN	Small probe nephelometer
LN	Large probe nephelometer
OUVS	Orbiter ultraviolet spectrometer
OIMS	Orbiter ion mass spectrometer
OPA	Orbiter plasma analyzer
OETP	Orbiter electron temperature probe
ORPA	Orbiter retarding potential analyzer
OEFD	Orbiter electric field detecter
OMAG	Orbiter magnetometer
ORAD	Orbiter radar
OGBD	Orbiter gamma burst detecter

Clouds. Very complex infrared structure has been found by the OIR at the cloud tops in the polar region. "Collar" clouds, optically thick in the infrared extending up to 75 km, are found near 60°. Within the collar are two bright crescent features near 80° latitude on either side of the pole. This dipole rotates retrograde with a 2.7-day period. The temperature in these features is as high as 260 K, so they may correspond to drastic lowering or clearing of the main cloud deck.

Four distinct cloud layers are still distinguished by the sounder probe instruments: an upper layer (68 to 58 km) separated by a sharp boundary from a middle layer (58 to 52 km), a lower cloud layer extending only from 52 to 48 km but dominating the others in mass per unit volume, and finally a region of haze extending downward to 31 km. The LCPS indicates that a trimodal size distribution characterized the cloud particles: mode 1 particles (diameter 1 μm or less), mode 2 (2 to 3 μm), and mode 3 (7 to 8 μm). All layers contain mode 1 particles, the upper, middle, and lower clouds, mode 2 particles, and the middle and lower clouds, mode 3 particles. In the lower or main cloud deck, mode 2 particles are concentrated near the top and bottom of the layer. The size dispersion of mode 2 particles is very small at any given level, although the mean diameter changes with altitude.

Large probe nephelometer (LN) backscattering measurements indicate that the index of refraction of the mode 2 particles in the upper layer is 1.44, a value characteristic of liquid sulfuric acid droplets at a concentration of 80 to 85 percent. This characterization agrees with previous Earth-based evidence. In the middle cloud the refractive index is 1.40 for mode 3 particles but drops to 1.32 for mode 3 in the lower cloud. The index of refraction of the smaller particles in these two layers appears to be 1.44 also. However, this value is very uncertain in the middle and lower cloud layers wherever backscattering of light is dominated by the mode 3 particles. Mode 1 particles may be aerosol debris at all levels with an uncertain refractive index that could be as high as 1.9 in the upper cloud.

Optical properties of the clouds and the surrounding atmosphere were determined from observations made by the LN (and SN), the LSFR, the ultraviolet spectrometer on the orbiter (OUVS), and the OCPP, and from observations previously made from Earth and from Mariner 10. Upward looking ultraviolet (0.3 to 0.4 μm) and visual (0.45 to 0.6 μm) photometers on the nephelometers and the LSFR demonstrate that significant absorption in the ultraviolet occurs throughout the three highest cloud strata. The spectrum of the spherical albedo of the clouds decreases rapidly between 0.5 and 0.3 μm. The contrast between bright and dark cloud features in the ultraviolet changes rapidly with phase angle, and strong limb darkening near 0.23 μm has been observed by the OUVS. Hence, the ultraviolet absorber cannot lie above the clouds and probably increases in concentration with depth. A model that successfully reproduces these observations is one in which the absorber is SO_2 and no cloud particles are absorbing. The SO_2 mixing ratio was assumed to be 200 ppm at low altitudes, in agreement with the LGC measurements, to decrease with a 1-km scale height in the upper cloud layer, in accordance with the OUVS observations, and to attain a value of 10^{-7} above the clouds. Many other models were tested, but they failed to match the vertical ultraviolet and visible absorption profiles. Among these were models in which all mode 3 particles, all mode 1 particles, or both mode 1 and mode 3 particles were sulfur. Also tried was a model in which the ultraviolet absorbers were sulfur particles located at a level of several optical depths in the clouds. While some of these models succeed in reproducing the albedo spectrum, none except the SO_2 absorption model fits the vertical absorption profiles.

The SN's demonstrate that the characteristics of most cloud layers vary considerably over the planet. The middle cloud appears to be very similar at all four entry sites, but the lower cloud layer, which is dominant in the sounder and night probe observations, almost disappears in the north probe and day probe data. The properties of the upper layer are also quite variable.

Some absorption of near ultraviolet (0.365 μm) radiation occurs down to 26 km and the LN-SN and LSFR data indicate the presence of a substance below 20 km that absorbs below 0.6 μm.

Composition and structure of the upper atmosphere. In the upper atmosphere, ONMS and drag data revealed a dramatic and abrupt drop in the exospheric temperature and atmospheric composition as the satellite periapsis crossed the evening terminator. The ONMS, which measured a temperature of about 400 K at a solar zenith angle of 70°, inferred a value of 230 K at the terminator that then dropped rapidly to 130 K at 120° and 112 K at the subsolar point. An even sharper decrease at the terminator to a minimum of about 90 K after midnight was indicated from the drag measurements. Molecular densities decreased rapidly near the terminator and atomic oxygen became the dominant constituent above 140 km. An increase in the density of helium with increasing solar zenith angle was observed by the ONMS, and a similar increase in hydrogen was inferred from ONMS and ion mass spectrometer measurements. The observations reproduce qualitatively but disagree in significant quantitative ways with the prediction of the Dickinson-Ridley dynamic model (*2*). According to that model, upward flow and dissociation of CO_2 into CO and O near the subsolar point induce a strong flow across the terminator; a nocturnal bulge in O, He, and H; and downward flow on the nightside of the terminator. No oxygen bulge occurred and the temperature variation was much larger and more rapidly varying near the terminator than predicted. In fact, nocturnal exospheric temperatures were much lower than those at the mesopause despite the energy transported across the terminator. Some nonradiative cooling mechanism such as strong eddy conduction of heat may have to be invoked to account for the required energy sink.

The OUVS has identified emissions from NO in the nightglow. Apparently the emission is produced by radiative recombination of N and O atoms transported from the dayside of the planet. The N to O density ratio required to produce the observed glow is a few percent. The distribution of the glow over the night hemisphere suggests that the largest convergence of the flow occurred near the equator about 30° beyond the antisolar meridian at latitudes below 60°.

The ionosphere. The behavior of the ionosphere, as observed by the orbiter ion mass spectrometer (OIMS) and radio occultation data, has provided major surprises. Below 160 km, very large electron densities persisted through the antisolar region to 10° from the terminator on the dawnside. The ion distribution in this region resembled a daytime distribution except that large NO^+ densities were measured. The dominant ions were O_2^+ and O^+. Above 160 km, the ionosphere was extremely variable. The distribution often changed from a fully developed ionosphere with an ionopause at several thousand kilometers in one orbit to an ionosphere that scarcely contained any ions above 200 km 24 hours later. Horizontal ion drifts with velocities as high as 1 km/sec have been observed. The altitude of the electron density maximum was usually within a few kilometers of 142 km. The peak density varied by about 7×10^3 cm^{-3} about a mean value of 1.7×10^4 cm^{-3}. Candidate processes for maintainence of the lower ionosphere at night are transport of O^+ from the dayside and low energy electron precipitation. Both mechanisms appear to be adequate to account for the nocturnal ionosphere and both may be playing important roles. Low energy electron fluxes observed by the orbiter plasma analyzer (OPA), in fact, appear to be able to produce ionization profiles that match very well those obtained from the occultation, OIMS, and orbiter electron temperature probe (OETP) data.

The OETP and the retarding potential analyzer (ORPA) both report surprisingly large electron and ion temperatures throughout the night: between 4000 and 8000 K near the ionopause, decreasing to about 1000 K near 150 km. A very large transport of heat of the order of several times 10^{10} eV cm^{-2} sec^{-1} across the nighttime ionopause is required to explain these observations.

Examination of the ion chemistry required to account for the distribution of ions observed in the daytime reveals little problem in accounting for major ions such as O_2^+, O^+, CO_2^+, He^+, and H^+. Some outstanding questions remain in understanding the prominence of other ions, particularly C^+.

Solar wind-ionosheath-atmosphere interactions. The electric field detector (OEFD) has been used to investigate dynamical dissipation processes at the ionosphere boundary that are important in transferring energy from the solar wind to the ionosphere and atmosphere. It appears that Landau damping of whistler mode waves from the ionosheath by ionospheric electrons is a significant heat source for electrons in the daytime. This is not the case at night where the ionosphere and the shocked solar wind do not seem to be in intimate contact. However, whistler mode waves, associated perhaps with lightning, have often been detected deep in the ionosphere at night.

Measurements by the OPA of the dynamic and direct interaction between the solar wind and the ionosphere and atmosphere of Venus reveal the presence of photoelectrons and shock heated solar wind electrons in the daytime ionosheath. The low energy photoelectron population was absent in the night ionosphere. However, as was already stated, the total ionization rate of the electrons between 50 and 500 eV appears to be adequate to produce observed electron density profiles. There is evidence that ionosheath flow is occasionally deflected into a conical cavity that appears to exist between the boundary of the ionosphere and the ionosheath downstream from the terminator.

Magnetic field. The orbiter magnetometer (OMAG) data on the nightside of Venus indicated sometimes strong but variable fields that were draped around the planet. There was little evidence for a systematic vertical component of the field. The upper limit on an intrinsic planetary moment is shrinking toward a value much less than 10^{22} gauss-cm^3.

Surface and interior. Topographic results obtained by the orbiter radar (ORAD) operating in the altimetry mode indicate that the radar bright feature called Maxwell is a broad plateau with a rough surface 1000 km by 700 km in extent rising 6 km above the surrounding plain. A ridge 6 km higher still runs parallel to the northwest-southeast plateau margins. A smooth pear-shaped region west of Maxwell is a plateau 1000 km across elevated to 5 km above plains to its south and west. This feature appears to be tectonic, whereas Maxwell might be either of tectonic or of complex volcanic origin. The radar bright features Gauss and Hertz may be volcanic. The first data obtained in the imaging mode at a longitude of about 340° in the northern hemisphere appeared to show impact craters about 250 km in diameter with only about 600 m of relief.

Orbital perturbation analysis for gravity field anomalies reveal no gravity signature near the great northern plateau (Maxwell). Hence, this feature appears to be isostatically compensated at depths of 100 km or less. Long wavelength anomalies were analyzed in three representative orbits for the power of the gravity spectrum. The power exceeded the terrestrial average spectrum by a factor of almost 4. It seems likely that these anomalies arise from the mantle as they do on Earth, rather from density anomalies in the lithosphere. Dynamic processes, such as convection in the mantle of Venus, would appear to be much more vigorous than in Earth's mantle.

Gamma bursts. The orbiter gamma burst detector (OGBD) has reported 14 gamma-ray burst events that have also been observed by detectors on other spacecraft. Preliminary locations for three events have been proposed, one of them in the direction of the Large Magellanic Cloud. None of the three lie in the plane of the galaxy. Hence, they appear to be either very near or very far from Earth on a galactic scale.

T. M. DONAHUE

University of Michigan, Ann Arbor 48109

References

1. M. B. McElroy, T. Y. Kong, Y. L. Yung, *J. Geophys. Res.* **82**, 4379 (1979).
2. R. E. Dickinson and E. C. Ridley, *Icarus* **30**, 162 (1977).

11 May 1979

Encounter with Venus: An Update

Abstract. *This report is an introduction to the accompanying collection of early results from the Pioneer Venus orbiter and multiprobe missions, which encountered Venus on 4 December and 9 December 1978, respectively. Initial results for the multiprobe mission and for the first 30 days of the orbiter mission were reported in the 23 February issue of* Science. *Additional mission features and updated mission parameters based on refined tracking data and trajectory computations are presented here. New scientific results for both missions are given in the subsequent reports which cover the first 130 days (or orbits) of the nominal 243-day orbiter mission.*

Several mission features and initial scientific results of the Pioneer Venus multiprobe and orbiter missions have been reported (*1*). The reader is referred to (*2*) and the references therein for a basic description of each mission. This report presents additional mission features and corrects other mission parameters, based on refined tracking data and trajectory computations.

Orbiter. Figure 1 is a scale drawing in solar ecliptic coordinates of orbit 5 on 9 December 1978 (multiprobe entry day). Precise orbit parameters are listed in table 1 of (*2*). Periapsis occurred at 180-km altitude, 17°N latitude on the dayside, about 22° longitude from the evening terminator. Figure 2 demonstrates the way certain orbit relationships vary during the course of the nominal 243-day orbiter mission. Venus revolves about the sun once in 224.7 days (sidereal period) in a counterclockwise direction as viewed from the north pole. Meanwhile, she rotates in a clockwise (retrograde) direction about her spin axis once in 243 days (*3*). The Pioneer Venus orbiter rotates about Venus in an inertially fixed frame, once in about 24 hours. Figure 1a is repeated at the bottom center of Fig. 2, although only the line of apsides is shown to represent the Pioneer Venus orbit. Proceeding counterclockwise in Fig. 2, the Pioneer Venus–Venus system is depicted in increments of 1/4 Venus year. (Earth locations at these times are not shown.) Note particularly the manner in which periapsis subsequently "samples" the dayside, crosses the evening terminator and samples the nightside, crosses the morning terminator, samples the dayside, and again crosses the evening terminator at the end of the nominal mission. It is interesting to observe that although all Venus local times can be sampled in 224.7 days, it requires the full 243 days to sample all planetographic longitudes.

As discussed in (*2*), periapsis altitude is strongly affected by solar gravity perturbations in a varying fashion during the mission, necessitating active control to maintain the altitude variations within acceptable limits. Figure 3 shows the his-

Table 1. Pioneer Venus multiprobe impact locations (semifinal determination).

Probe	Latitude* (deg)	Longitude* (deg)	Solar zenith angle (deg)	Venus local time
Sounder	4.4N	304.0	65.7	0738
North	59.3N	4.8	108.0	0335
Day	31.3S	317.0	79.9	0646
Night	28.7S	56.7	150.7	0007
Bus†	37.9S	290.9	60.7	0830
Subsolar point	0.5S	238.5	0	1200
Subearth point	1.6S	1.7	123.1	0347

*International Astronomical Union 1970 coordinates. †At 200-km altitude.