PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Pioneer Venus Atmospheric Observations [and Discussion]

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Pioneer Venus atmospheric observations

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[Plate 1]

Some selected results from the scientific experiments on the recent Pioneer missions to Venus are reviewed, with particular emphasis on data from the infrared remote sensing experiment on the orbiter. Various aspects of the structure, dynamics and energy budget of the atmosphere, as revealed by the measurements, are presented for discussion.

1. Introduction

The Pioneer mission to Venus consisted of four atmospheric entry probes and a low periapsis altitude orbiter, all of which arrived at the planet in December 1978. The primary objective of the mission was to study the composition, structure and dynamics of the planet's mysterious atmosphere. This was accomplished most successfully. The purpose of the present paper is to review some of the significant findings from the mission, and to discuss their interpretation and implications. We are particularly interested in similarities and differences between the properties of Venus's atmosphere and those of that of its near twin, Earth. The measurements from all of the Pioneer experiments, with details of their acquisition, calibration and so on, may be found in a recent issue of *Journal of geophysical research* (Special Pioneer Venus edition, 26 December 1980). However, we shall present here some major new results from the Oxford University – Jet Propulsion Laboratory orbiter infrared radiometer (o.i.r.), in addition to reviewing selected results already announced elsewhere from this and other experiments.

2. Outstanding problems before Pioneer

The face of Venus, as seen from Earth and earlier spacecraft, is completely covered by cloud. At visible wavelengths the cloud is virtually featureless. In the ultraviolet, however, contrasts are visible that rotate rapidly around the planet in the zonal direction (parallel to the equator) and migrate slowly poleward while doing so. The origin of the markings and, more fundamentally, the nature of the general circulation régime responsible for the motions was not known. The zonal motions are about 60 times faster than the surface rotation, the latter having a sidereal period of 243 Earth days.

We turn next to the vertical structure of the atmosphere. Figure 1 shows a fairly typical profile of temperature versus pressure, as measured by remote sounding by means of the o.i.r. (Taylor *et al.* 1980). Also shown is a profile for the corresponding location on the Earth, as measured by a similar instrument on the Nimbus 7 weather satellite, the stratospheric and mesospheric sounder (Drummond *et al.* 1980). The main difference is the temperature maximum in the Earth's stratosphere, caused by ozone heating, which clearly is not an important effect on Venus. A question of particular interest is the study of the variability in space and time of temperature and cloud structure on Venus in this region, where the temperatures and pressures are similar to those on Earth, to gain at least an elementary understanding of weather and climate on our planetary neighbour. Figure 1 shows only the 'Earth-like' part of the Venus atmosphere. Below the 1 bar† level there lies a layer of atmosphere more than 50 km deep, which is very hot and very dense, reaching a pressure of about 95 atm† and a temperature of about 750 K at the surface. Clearly we are interested in why Venus is so different from Earth in this respect, given that the main external variable, the distance of each planet from the Sun, differs only by a factor of $2^{\frac{1}{2}}$. In a simple equilibrium model this would only raise the temperature by a factor of $2^{\frac{1}{4}}$, to about 350 K.

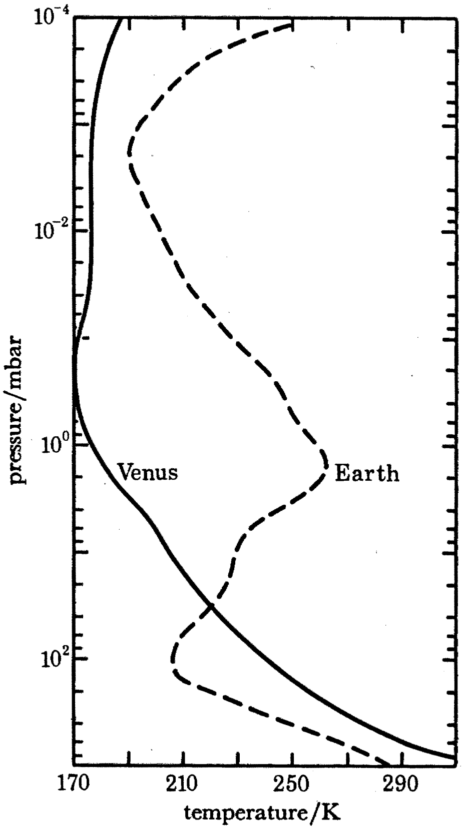

Figure 1. Vertical temperature profiles over the same pressure range, and at approximately the same latitude (30° N) on Venus and Earth. The profile for Venus was obtained by infrared remote sounding from the Pioneer orbiter, and that for Earth by a similar technique by the stratospheric and mesospheric sounder on the Nimbus 7 satellite.

3. Pioneer observations

Observations of the polar regions were prime objectives for addressing the question of the global circulation régime on Venus. Suomi & Limaye (1978) had suggested, from their analysis of ultraviolet images obtained by Mariner 10 in 1974, that the poles of Venus were the seats of giant vortices, where the atmosphere recirculated itself downwards after rising at the equator (under the influence of solar heating) and then migrating polewards (as traced by the ultraviolet markings). In other words, the general circulation on Venus, at the cloud-top level at least, was thought to resemble that proposed by Hadley two centuries ago for the Earth, one

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† 1 bar = 10^5 Pa; 1 atm ≈ 10^5 Pa.

giant cell in each hemisphere, but with the added complexity of the rapid zonal flow superimposed. Since rapidly descending air produces regions of low cloudiness on all other planets of our knowledge, V. E. Suomi (personal communication, 1974) predicted that infrared maps of the Venusian pole would show an 'eye' analogous to that at the centre of terrestrial hurricanes. This was duly observed (Taylor *et al.* 1979) when Pioneer made its first high-resolution pass over the north pole on 14 December 1979. Surprisingly, however, later more complete maps show not one but two 'eyes', about 10° of latitude either side of the pole and rotating fairly rapidly around it (Taylor *et al.* 1980). Apparently, a simple vortex is unstable and a version with a strong wavenumber 2 component is preferred. The reason for this may be connected with the transportation to the pole of large amounts of angular momentum by the Hadley cell. Angular momentum, as well as mass, has to be transported vertically (evidently downwards) at high latitudes to satisfy the conservation laws. It is intuitively likely that a rotating dipole can accomplish this more efficiently than can a monopolar mode, but a properly detailed model is lacking at present. Understanding the detailed dynamics of the polar region takes its place alongside understanding the origin of the rapid zonal flow near the equator, among key questions in the study of Venusian atmospheric dynamics.

Measurements made by tracking the entry probes have revealed the vertical profile of the winds below the clouds, but not their forcing mechanism. Conversely, infrared temperature sounding has revealed the forces affecting the circulation of the atmosphere *above* the clouds, but there are no measurements of the winds themselves. This topic is taken up further in the next section.

4. The global temperature field

Several thousand vertical temperature profiles, similar to that in figure 1, were measured at various locations on the planet during each of the first 72 orbits of Venus made by the Pioneer spacecraft (4 December 1978 until 14 February 1979). The results can be synthesized into a representation of the three-dimensional temperature field over a certain vertical range (roughly 65 to 110 km above the surface). Here, we present results obtained from data over the whole 72 day period, averaged in solar-fixed coordinates. The method of retrieval is described by Schofield & Taylor (1981). As well as thermal structure, it also yields the mean cloud-top pressure on a coarse latitude–longitude grid, and an estimate of the cloud opacity scale height. Figures 2 and 3 show some examples of the results.

Among the most interesting features of the data are the variations in temperature at a given altitude with local time of day (the 'thermal tides'). These can be seen in figure 2, which shows the variation of temperature with solar longitude (i.e. with local time of day) in a narrow range of latitudes near the equator. At altitudes near the cloud top, a single maximum and a single minimum of temperature occur around a latitude circle, with the highest temperature occurring during the first part of the night. This type of wavenumber 1 thermal tide is also typical of the Earth's atmosphere at these pressures. At higher levels on Venus, however, the tide develops a definite wavenumber 2 character, with temperature maxima occurring near solar longitudes of 90° (sunrise) and 270° (sunset). The effect is strongest at an altitude of approximately 80 km above the surface, where the pressure is about 10 mbar (figure 2). At higher levels still, the tide tends to revert to the condition where wavenumber 1 dominates.

It can also be seen from figure 2 that the mean cloud-top height (heavy line) varies with time of day, with a single maximum near sunset and a minimum, some 1–2 km lower, near dawn.

The most probable interpretation of this behaviour is to picture the cloud being uplifted by convection driven by solar heating on the day side, with cooling and sinking of the atmosphere and cloud on the night side. The observed phase lag suggests that the maximum heating takes place at a level substantially below the cloud tops.

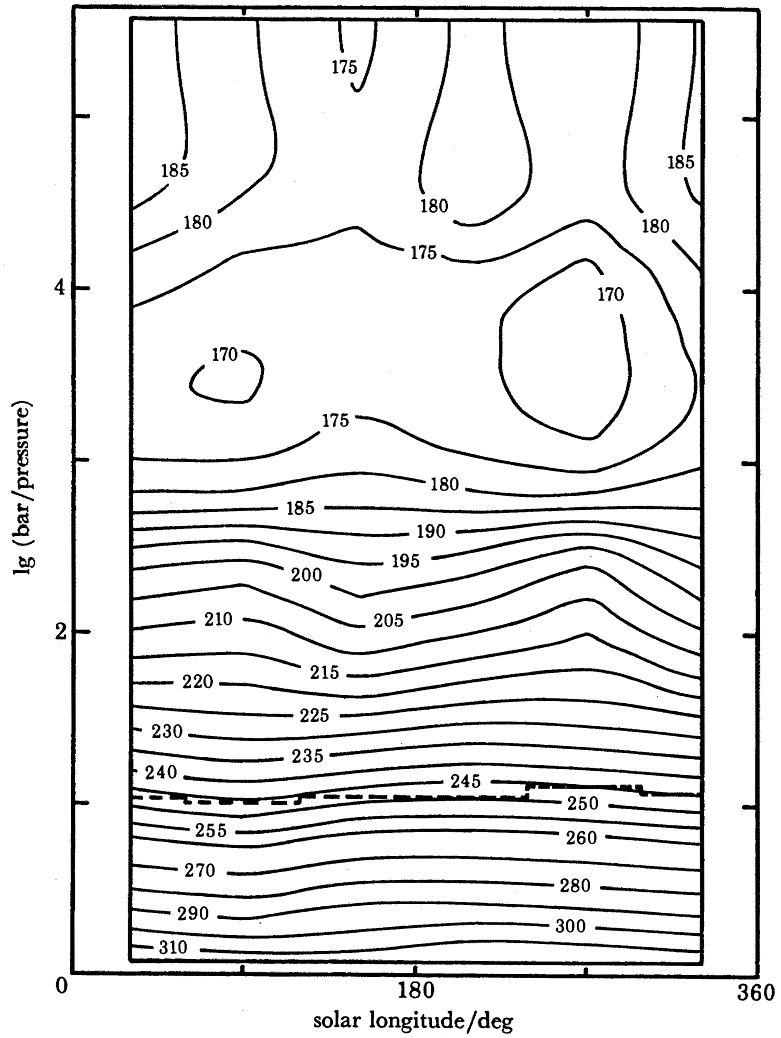


FIGURE 2. Contour plot of the mean retrieved Venusian temperature field round an equatorial latitude swath (0–10° N). Temperature in kelvins is displayed as a function of atmospheric pressure and solar longitude, effectively local time of day (0° ≡ noon, 90° ≡ sunrise, 180° ≡ midnight and 270° ≡ sunset). The pressure level corresponding to unit cloud optical depth is also indicated (dashed line). Temperature and cloud structure was retrieved from averaged data from five of the Pioneer orbiter infrared radiometer channels.

Figure 3 shows a meridional (equator to pole) cross section through the temperature field, with temperatures averaged around latitude circles. A very remarkable feature of this is the trend, over a certain range of heights, for the temperature to increase from equator to pole. This is probably a dynamical effect, since solar heating is greatest at the equator, but it is also possible that aerosol particles in the upper atmosphere (well above the main cloud deck) may be more numerous at high latitudes (Kawabata *et al.* 1980) and so produce differential heating by absorbing sunlight more strongly. In either case, the reversed equator to pole temperature gradient between about 70 and 90 km altitude corresponds, through the cyclostrophic relationship, to a tendency to produce strong vertical shear in the zonal winds. A detailed analysis by L. S. Elson (see: Taylor *et al.* 1980; Schubert *et al.* 1980) finds that the 100 m s^{-1} wind speed observed at the cloud tops should decrease to a low value, probably zero, at a level between 80 and 90 km altitude, depending on certain assumptions. Above 90 km, it can be seen (figure 3) that the atmosphere reverts to a simpler temperature distribution with the maximum over the equator and the minimum at the pole.

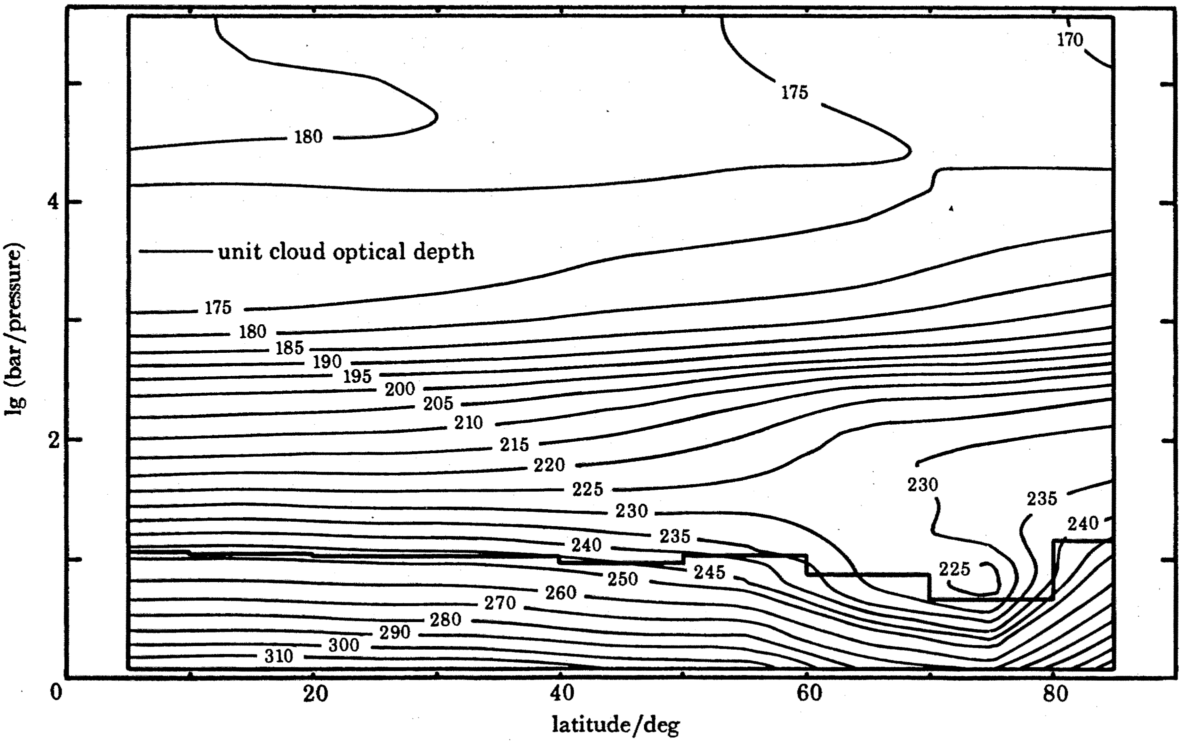


FIGURE 3. Contour plot of the zonal-mean retrieved Venusian temperature field, derived by averaging retrieved profiles such as those represented in figure 2, along latitude circles. Temperature in kelvins is displayed as a function of atmospheric pressure and latitude, and the pressure level corresponding to mean cloud unit optical depth is indicated. In the coordinates used, the latitude pole is identical to the orbit pole of Venus and the subsolar point lies at zero longitude on the equator.

Another remarkable feature of the temperature cross section is the strong feature near latitude 75° N and 100 mbar pressure. This was present throughout the period of the Pioneer observations and has also been detected, in spite of the unfavourable viewing geometry, in Earth-based observations (Diner & Westphal 1978). It appears to be a long-lived planetary-scale wave, probably originating (like the polar dipole) in an instability in the zonal flow as individual air parcels tend to accelerate, in an attempt to conserve angular momentum as they travel poleward. Again, a detailed model of this process is awaited.

Temperature data can also be plotted as maps, which reveal the global climatology of Venus's atmosphere for the first time. A set of these, for the northern hemisphere only, appear in figures 4–7, plate 1. These show temperatures as a function of latitude and longitude, averaged over four different vertical layers, in the form of false-colour images. In these, the coldest temperatures are shown in blue and the warmest in red, merging into white in between. This type of representation is very effective in displaying large-scale features; small-scale structure is suppressed by spatial smoothing and, especially, by averaging over nearly 3 months. The four layers represented by figures 4–7 are centred approximately on heights of 70 km (about 50 mbar, just above the cloud tops), 80 km (about 5 mbar), 90 km (about 0.5 mbar) and 100 km (about 0.03 mbar). The spatial distribution of the polar warming and the latitudinal variation and phase of the solar tides can be seen quite clearly. Note also the longitudinal variation in the width and temperature of the polar collar; its predominantly wavenumber 1 character dominates a fairly narrow latitude band between the (solar-locked) wavenumber 2 tides in the equatorial region and the rapidly rotating wavenumber 2 polar dipole (not visible in these images because of low spatial resolution and time averaging; but see Taylor *et al.* 1980). It is particularly interesting to note the quite dramatic qualitative changes that take place in the temperature distribution between 90 and 100 km (figures 6 and 7, plate 1). The polar maximum vanishes, to be replaced by an extended warm region centred nearly over the subsolar point. The thermal tide also changes to predominantly wavenumber 1 (as revealed by Fourier analysis of the image), but with a secondary maximum near the antisolar point. We believe that the transition that takes place between 90 and 100 km altitude as revealed in these plates is the result of the decline of the rapid zonal winds to a value near zero at about this height. The subsolar maximum is characteristic of a slowly rotating atmosphere and the heating near local midnight may be evidence for a symmetric subsolar to antisolar component to the circulation at these levels (cf. Dickinson & Ridley 1977). In this scenario, the high temperatures are produced by compression at the descending end of a single, planet-wide cell, the net zonal and meridional velocities being zero. Some support is lent to this hypothesis by the existence of a maximum in the ultraviolet airglow near the middle of the night (Stewart *et al.* 1980). The molecules emitting this glow are excited on the sunlit hemisphere and it is difficult to picture how zonal transport alone to the dark hemisphere could produce an emission maximum at night.

DESCRIPTION OF PLATE 1

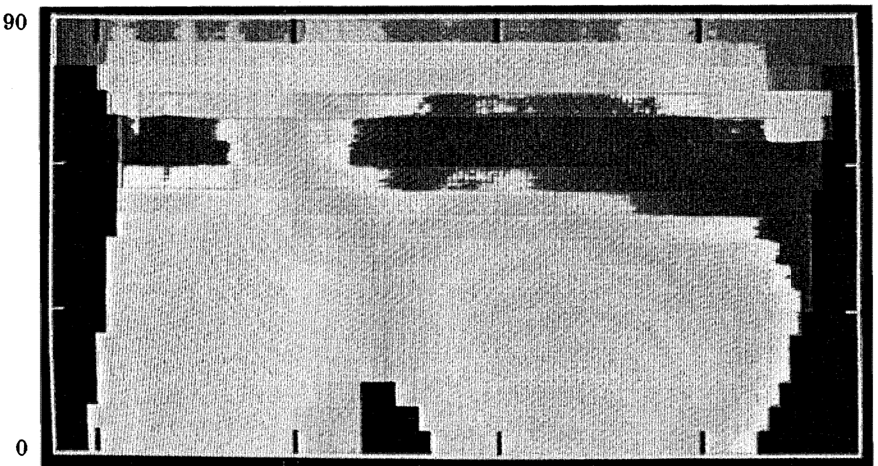
The solar-related temperature structure of Venus is illustrated in these false-colour images of mean brightness temperatures. Calibrated radiances from the 72 day period of observation have been averaged in a 5° grid of solar-fixed latitude and longitude. In this coordinate system the subsolar point is at zero latitude and longitude and the polar axis is parallel to Venus's orbital axis. Radiances are then converted to equivalent temperatures, spatially smoothed and represented by a colour scale from blue (cold) through white to red (hot). The effect of limb darkening or brightening upon figures 4–6 has been limited by restricting the angle between the line of sight and local vertical to less than 48°.

FIGURE 4. Brightness temperature for a layer of the atmosphere of Venus about 10 km thick near 50 mbar (approximately 70 km above the surface). Temperatures range from 223 to 239 K.

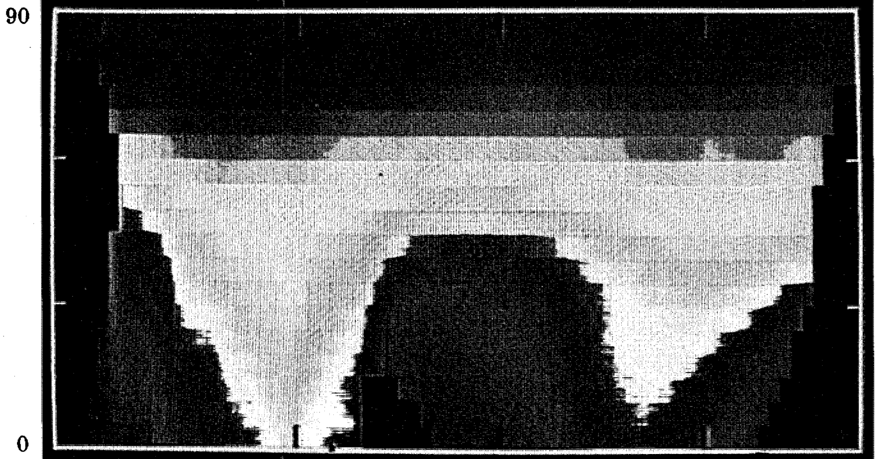
FIGURE 5. Brightness temperature for a layer about 10 km thick near 5 mbar (approximately 80 km above the surface). Temperatures range from 203 to 224 K.

FIGURE 6. Brightness temperature for a layer about 10 km thick near 0.5 mbar (approximately 90 km above the surface). Temperatures range from 172 to 191 K.

FIGURE 7. Brightness temperature for a layer about 15 km thick near 0.03 mbar (approximately 100 km above the surface). Temperatures range from 168 to 184 K.


90
0

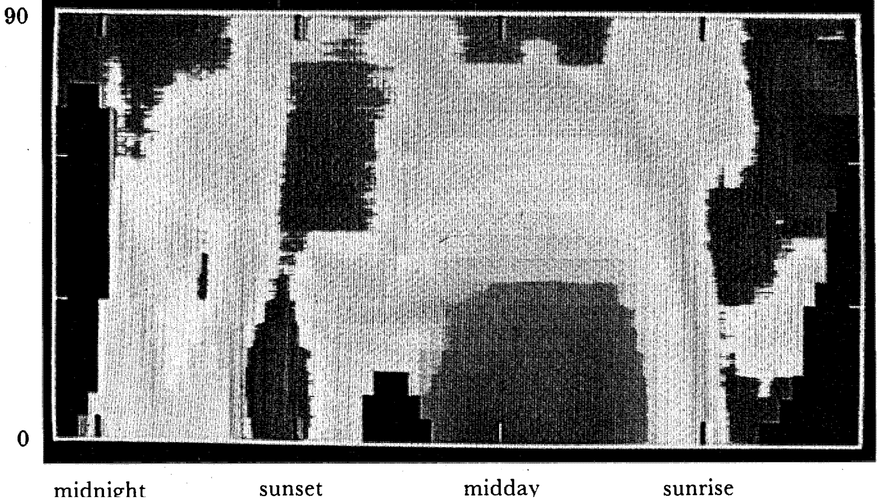
4


90
0
solar-fixed latitude north/deg

5


90
0

6


90
0
midnight
sunset
midday
sunrise

7

5. RADIATION BUDGET

Finally, we turn to the question of the global radiation budget of Venus. What is meant by this is the difference, normally expressed as a function of latitude, between the incoming solar energy and the outgoing thermal energy at the top of the atmosphere. From a study of this, it is possible to see how the atmosphere redistributes energy from the sun, acting as a thermodynamic engine with its 'boiler' in the tropics and its 'condenser' at the poles. This process also drives the general circulation.

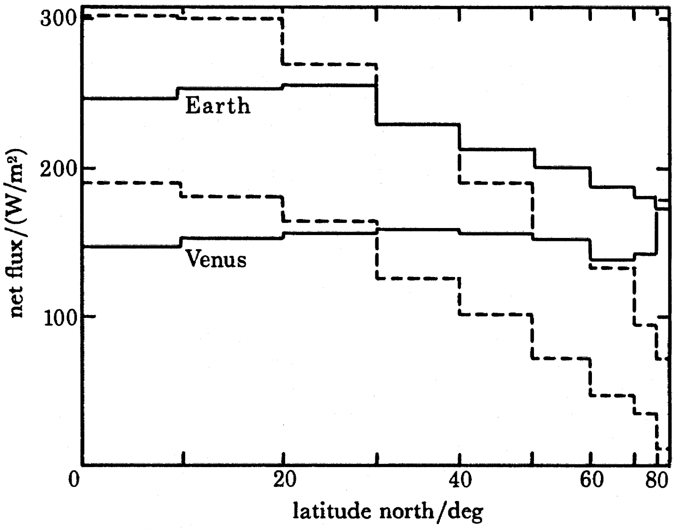


FIGURE 8. Comparison of the planetary radiation budget for the Earth (Vonder Haar & Suomi 1971) and that measured by the infrared radiometer on the Pioneer Venus orbiter for the northern hemisphere of Venus. The longitudinally averaged thermal emission (solid line) and absorbed solar energy (dashed line) at the top of the atmosphere are shown as functions of latitude.

The Pioneer radiometer measures the total reflected solar radiance as a function of location on the planet and solar and spacecraft zenith and azimuth angles as it traces its orbit. At the same time, it measures the upwelling thermal radiance in five narrow and one broad spectral band. From these data, the albedo and bolometric temperature of each location on a latitude–longitude grid can be calculated from the net flux obtained by integrating numerically over a hemisphere and, for the thermal flux, over wavelength too (Tomasko *et al.* 1980). These calculations are extremely tedious and are subject to numerous uncertainties. Some preliminary results are available, however, and these are summarized in figure 8. Similar plots for the Earth, by Vonder Haar & Suomi (1971) are shown for comparison. The smaller size of each component on Venus is due to the planet's high albedo (0.80 ± 0.02) which more than offsets its greater proximity to the Sun. The latitude variation of solar heating on Venus is due almost entirely to geometry, since the albedo is found to be nearly independent of latitude (Taylor *et al.* 1980). The relative flatness of the emission profile, which contrasts with that for Earth, is most probably due to the 'buffering' effect of the deep atmosphere on Venus, which acts like an infinite source of available heat energy for the layers above which radiate to space. The oceans perform something of the same function on Earth, but less efficiently.

It should be pointed out that the total integrated ingoing and outgoing energy fluxes for the northern hemisphere of Venus, obtained by integrating the areas below the curves in figure 8, do not balance exactly. The difference is a net outflux equal to about 15% of the total influx, or some 4×10^{15} W. It should not be concluded from this that Venus is necessarily in possession of an internal heat source of this magnitude, however, since the estimated error bars on the fluxes (which represent the synthesis of some 6×10^{6} individual radiance measurements) are of the same order as the excess. Much of the uncertainty results from incomplete angular coverage of some parts of the planet, especially at high latitudes, and lack of coverage of the entire thermal spectrum. Improved scattering and emission models are in preparation which are expected to improve the estimates somewhat in this respect, and in which we would expect the excess to become correspondingly smaller. Note also that the coverage of the southern hemisphere is not sufficient to allow us to obtain the budgets there. Symmetry between the hemispheres has therefore been implicitly assumed. This seems reasonable in view of the very small axial and orbital inclinations of Venus, and its low orbital eccentricity, but the absence of interhemispheric differences of the order of the observed excess remains to be definitely proven by some future Venus mission.

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Discussion

A. DOLLFUS (*Observatoire de Paris*, 92190 *Meudon, France*). We sensed some characteristics of the upper layers of aerosols in the Venus atmosphere on the basis of the Meudon and Pic-du-Midi observatories regional polarization survey covering from 1950 to 1972.

The mapping of the polarized light over the surface of Venus is in overall agreement with the conclusion deduced from the integrated polarization by Hansen & Hovenier (1974): an upper haze layer at an altitude of around 70 km, made of transparent spherical particles of radius 1.05 μm with variance 0.07 and refraction index 1.44. However, this layer is shown not to extend in latitude up to the poles.

Above the two polar regions, the altitude of the main cloud layer is depressed by an amount variable with time but typically of the order of 3–5 km. The particle radius in these regions is variable with years, ranging from 0.75 to 1.65 μm; these size variations involve the two poles approximately similarly. In October 1959, exceptionally, the two poles were covered with a bright haze made of very small particles with radius less than 0.3 μm.

A thin haze layer of submicrometre-size aerosols is detected by polarimetry above the main cloud layer in which most of the polarization is formed (around an altitude of 70 km); optical thickness is of the order of several parts per hundred with particle radii of around 0.2 μm. This upper layer may be the extension to high altitude of the small micrometric particles probed by Pioneer between 50 and 60 km. Variations occur regionally and with time.

The clouds seen in the u.v. photographs of Venus do not correspond to the variations in polarization observed; the dark features had to be located deeper in the atmosphere than the altitude in which the polarization is formed, at an optical depth larger than 6, which is still reached by the light; they may be related to the large particles of at least 8 μm of the Pioneer B and C layers.

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R. Hide, F.R.S. (*Geophysical Fluid Dynamics Laboratory, Meteorological Office, London Road, Bracknell RG12 2SZ, U.K.*). I have one comment and one question on Dr Taylor's interesting paper on Venus's atmosphere.

Owing to the rotation of the planet a fluid element in the atmosphere would in the absence of strong frictional forces accelerate to very high zonal speeds on approaching the pole unless its angular momentum were greatly reduced by the action of east–west pressure gradients. Such gradients could be associated with the non-axisymmetric features described by Dr Taylor. Indeed, the *raison d'être* of these features is presumably the circumvention of the strong dynamical constraint on meridional flow imposed by the rotation of the planet.

My question concerns the evidence of internal heating amounting to about 15% of solar heating. There is comparatively little difficulty in accounting in general terms for substantial internal heat sources in Jupiter and Saturn, where shrinkage at the incredibly slow rate of about 1 mm/a suffices to account for internal sources comparable in magnitude with insolation. But Dr Taylor's 15% in the case of Venus would constitute a major discovery and require a considerable revision in our ideas about the internal structure and thermal history of the planet. I would like to ask Dr Taylor to elaborate on the errors and uncertainties in his calculation of the radiative imbalance before inviting members of the audience to join in a discussion of heat sources on Venus.

F. W. Taylor. The numbers quoted for total ingoing and total outgoing energy on Venus were determined by computing integrals of the measured flux over wavelength, emission angle, area and time. The error budget of such a calculation is made up of (*a*) uncertainties in instrument calibration, (*b*) gaps in the coverage in some dimensions that require interpolation, and (*c*) approximations in the integration scheme used in the computer. We expect to improve the first and the last of these by further work, and also to obtain a better estimate of the residual error. In the meantime, the 15% difference is better thought of as evidence for the preliminary nature of our analysis than as the discovery of a source on Venus. For the present I would direct your attention to the *relative* magnitudes in figure 8, which we believe are accurate to within a small percentage, even in the preliminary analysis. It is these that tell us most about the atmosphere as a thermodynamic machine. We shall be in a better position to address the overall energy balance of the planet at a later date.

The solar-related temperature structure of Venus is illustrated in these false-colour images of mean brightness emperatures. Calibrated radiances from the 72 day period of observation have been averaged in a 5° grid of olar-fixed latitude and longitude. In this coordinate system the subsolar point is at zero latitude and longitude nd the polar axis is parallel to Venus's orbital axis. Radiances are then converted to equivalent temperatures, patially smoothed and represented by a colour scale from blue (cold) through white to red (hot). The effect of imb darkening or brightening upon figures 4–6 has been limited by restricting the angle between the line of ight and local vertical to less than 48°.

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