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The deep atmosphere of Venus

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Venus as a planet resembles the Earth, but has a much hotter and denser atmosphere due to an extreme case of the greenhouse effect, caused by compositional differences and the thick cloud cover. Studies of the lower atmosphere are inhibited by the cloud opacity, which makes remote measurements at most frequencies short of the radio range quite difficult. Progress in understanding of the composition and thermal structure below the clouds has been made by the Pioneer and Venera entry probes of the 1970s, and more recently with results from the Galileo fly-by in 1990. The latter exploited the newly discovered near-infrared 'windows' to achieve measurements of carbon monoxide and water vapour abundances in the deep atmosphere, and provided the first detailed view of the global cloud structure. The morphology and spatial variations seen in the main mass of clouds are remarkable, and suggest a powerful and diverse meteorology dominated by convection. Carbon monoxide is significantly more abundant at high northern latitudes than at low latitudes in either hemisphere.

1. Introduction

The upper atmosphere of Venus, above the thick and ubiquitous cloud deck, has been extensively studied from the Earth and from spacecraft. It exhibits a rather Earth-like regime of temperature and pressure, but is somewhat cooler in spite of being closer to the Sun. The lower temperatures are due primarily to the preponderance of carbon dioxide in its composition, and the absence of an appreciable ozone layer. Very high winds are present, which are not simple to explain on such a slowly rotating planet, and there is evidence for extremely complex and mysterious dynamical activity in the polar vortices (Taylor *et al.* 1981).

Knowledge of the deep atmosphere of the Earth's nearest planetary neighbour and near-twin remains even more limited in many important respects. The reason for this is the near-opaque cloud cover which extends over the whole planet and makes remote sensing of the atmosphere extremely difficult. It was not until 1958, for example, that the high temperatures near the surface were discovered when radio observations allowed probing beneath the clouds (Mayer *et al.* 1960).

Most information about the atmosphere beneath the clouds since then has come from space missions, especially the Venera and Pioneer probes and the Vega balloons. The coverage obtained by these probes is extensive, but the interpretation of results obtained at isolated times and locations is inevitably somewhat limited and ambiguous. As a result, even such fundamental questions as the nature

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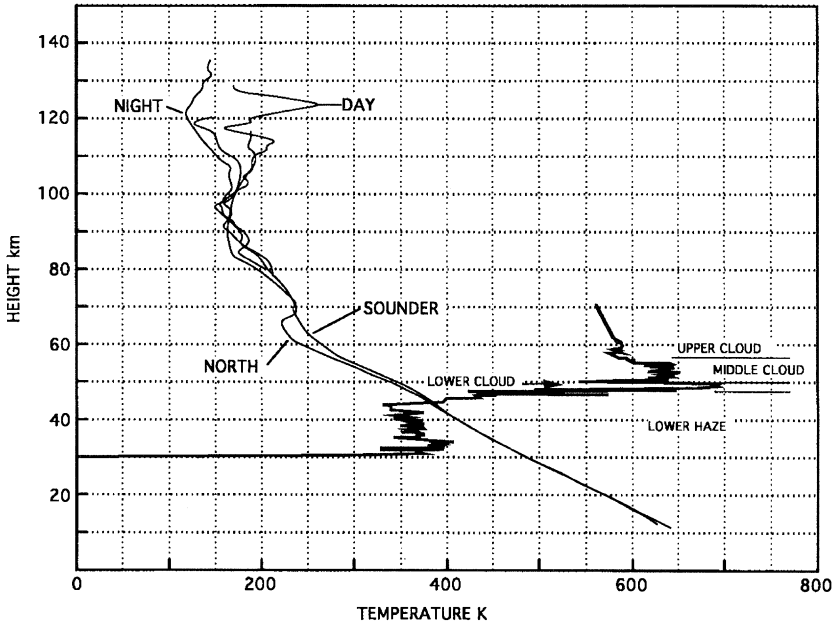

Figure 1. Pioneer Venus temperature profiles and relative cloud mass loading measurements after Seiff (1983) and Esposito *et al.* (1983).

of the general circulation on Venus, and the basic dynamical and chemical processes which maintain the sulphur-based cloud system, which is the key factor controlling the extreme climate, remain unanswered. Almost nothing is known about the time dependence of the environment on Venus, although theoretical arguments suggest that it could be quite variable on relatively short time-scales (decades to centuries). The smaller-scale structure, including weather systems and other aspects of the meteorology, are again virtually a closed book; a most disturbing state of affairs when it is considered how much Venus and Earth resemble each other, and how important it is to understand weather, climate and greenhouse-driven climate change on Earth.

2. General atmospheric structure

Spacecraft missions have so far given us a clear picture only of the general vertical structure of the atmosphere on Venus (figure 1). Below the clouds the temperature profiles measured are remarkably similar, particularly if we disregard early probe results which probably suffered from instrumental problems in making accurate measurements in such a harsh environment. The temperature profiles show a generally stable profile beneath the clouds except near the surface and just below the clouds. The cloud layers themselves have been categorized as four layers (Esposito *et al.* 1983): upper, middle, lower and lower haze each with multiple particle size regimes with larger particles becoming more numerous in the lower clouds.

Fundamental differences between Venus and Earth which affect the dynamics include the facts that more of the solar heating occurs in the clouds rather than

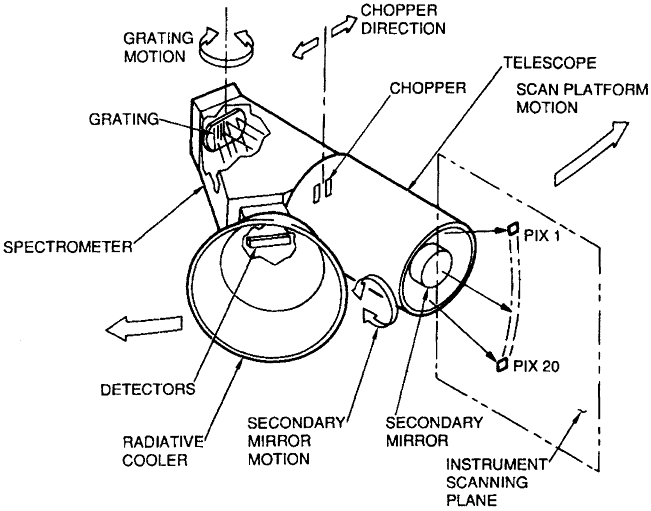

Figure 2. Schematic of the Galileo NIMS instrument (Carlson *et al.* 1991).

at the surface, that there is negligible axial tilt so no seasonal effects are expected, and that topographic effects are more limited since the surface of Venus is flatter. The circulation is dominated at cloud top heights (about 60 km above the surface) by a four-day retrograde (east to west) superrotation, generally with faster mid-latitude jets. The rotation rate of the planet leads us to expect the atmosphere to be in cyclostrophic rather than geostrophic balance and cyclostrophic winds calculated from temperature measurements agree well with the observed winds. This gives us a self-consistent picture of the superrotation but still does not determine its underlying cause.

On a slowly rotating, non-axially inclined planet we should expect an extensive overturning of the atmosphere from equator to high latitudes in each hemisphere, the so-called Hadley circulation, and this is confirmed by meridional wind measurements. Below the clouds, however, we can only speculate on the circulation pattern. Layers of differing stability deduced from probe temperature profiles hint at the possibility of three or more ‘stacked’ Hadley cells, but confirmation of this is still lacking.

Effects at high latitudes are even more difficult to interpret. The poleward transport of angular momentum leads us to expect the formation of a vortex at the poles. The observations, however, show a complex circulation with a curiously shaped wave number two feature surrounded by a cold polar collar. The explanation of these observations clearly needs to address both the detailed dynamics and the cloud formation in these regions. The data available, however, remain too limited for a complete explanation to emerge.

3. Galileo observations of Venus

The fly-by of Venus by the Galileo spacecraft in February 1990 provided an opportunity to extend significantly the range of studies of Venus. This fly-by was initially unplanned and only introduced as a means of allowing Galileo to reach Jupiter using a solid fuel upper stage, after liquid fuel stages were withdrawn from use in the space shuttle as a safety precaution following the *Challenger* accident.

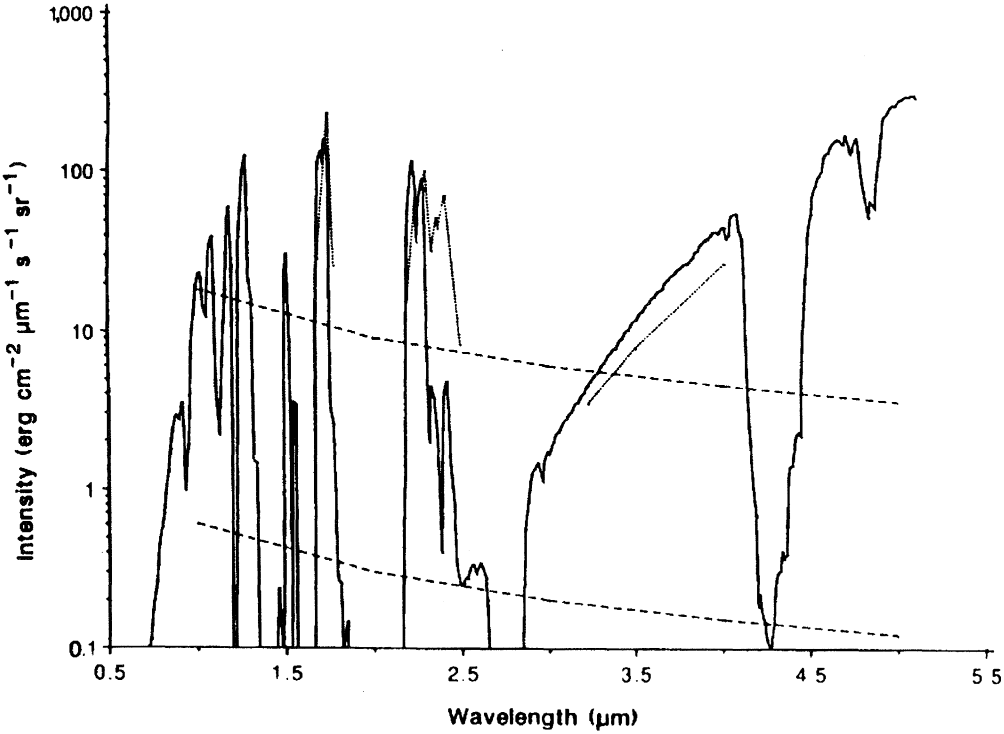

Figure 3. Venus near-infrared thermal emission spectrum (Kamp *et al.* 1988).

The instrumentation on board was, of course, designed for use at Jupiter but was sufficiently versatile that new and unique measurements were possible.

The near-infrared mapping spectrometer (NIMS) instrument in particular was extremely well suited to the study of Venus (figure 2). This is a grating spectrometer covering the wavelength range 0.7–5.2 µm with a spectral resolution of 0.025 µm (Carlson *et al.* 1992). The combination of a scanning telescope secondary and the motion of the scan platform upon which the instrument is mounted are used to build up an image of the planet in which each pixel is a near-infrared spectrum.

It has been known since the telescopic observations of Allen & Crawford (1984) that Venus has emission features in the near-infrared. Kamp *et al.* (1988) showed that the spectra of these emissions were consistent with radiative transfer models of thermal emission from the hot lower atmosphere, scattered through cloud layers similar to those deduced from probe measurements. Figure 3 shows the data of Allen & Crawford along with the modelling results of Kamp *et al.* These show that there are in fact several spectral windows throughout the near-infrared where the lower atmosphere is accessible to a remote sounding instrument.

The scope of the NIMS investigation at Venus was limited by the short duration of the encounter and the total data volume available. Only a low data rate for transmission to Earth was possible through a low gain antenna so that the whole observation sequence, for all instruments, was recorded on tape. For thermal reasons, no attempt was made to open the main antenna until well after the Venus fly-by. The NIMS data obtained, therefore, consisted principally of three

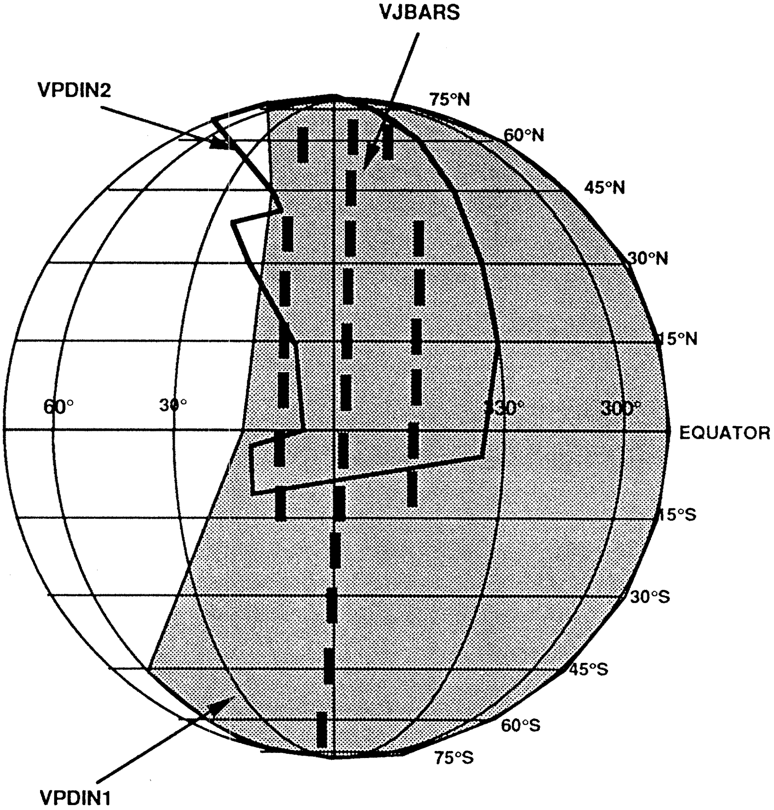

Figure 4. Coverage of NIMS Venus observations.

north–south strips of spectra with complete wavelength coverage, plus two images of the planet taken at 17 discrete wavelengths (figure 4).

The images of Venus obtained by NIMS in the near-infrared 'windows' (figure 5) appear very different from the relatively bland appearance recorded in the visible and ultraviolet. The 2.3 μm image (figure 5*a*) shows the thermal emission from the deep atmosphere, strongly modulated by variation in the main cloud layer. The 4.84 μm image (figure 5*b*), by contrast, is not in a 'window' but rather a spectral region of strong CO_2 absorption. It shows thermal emission from well above the cloud layer, and the warm polar areas previously measured by Pioneer Venus (Taylor *et al.* 1981). Figure 6 is a typical nightside spectrum, showing thermal emission characteristic of cloud-top temperatures at longer wavelengths, and the emission 'windows' in the near-infrared. In the 1.18 μm 'window', calculations indicate that it is possible to detect high-altitude features on the surface of Venus, due to the thermal emission contrasts expected as a result of the vertical temperature gradient of some 10 K km^{-1}. This is supported by correlations between features observed with NIMS and the location of Maxwell Montes (Lecacheux *et al.* 1993).

The analysis of these images and spectra is made complex for three main reasons. Firstly, the radiative transfer models involved are intrinsically complex due to the possible wide variations in the multiple scattering properties of the clouds. Secondly, thermal emission by the gases occurs at very high temperatures and

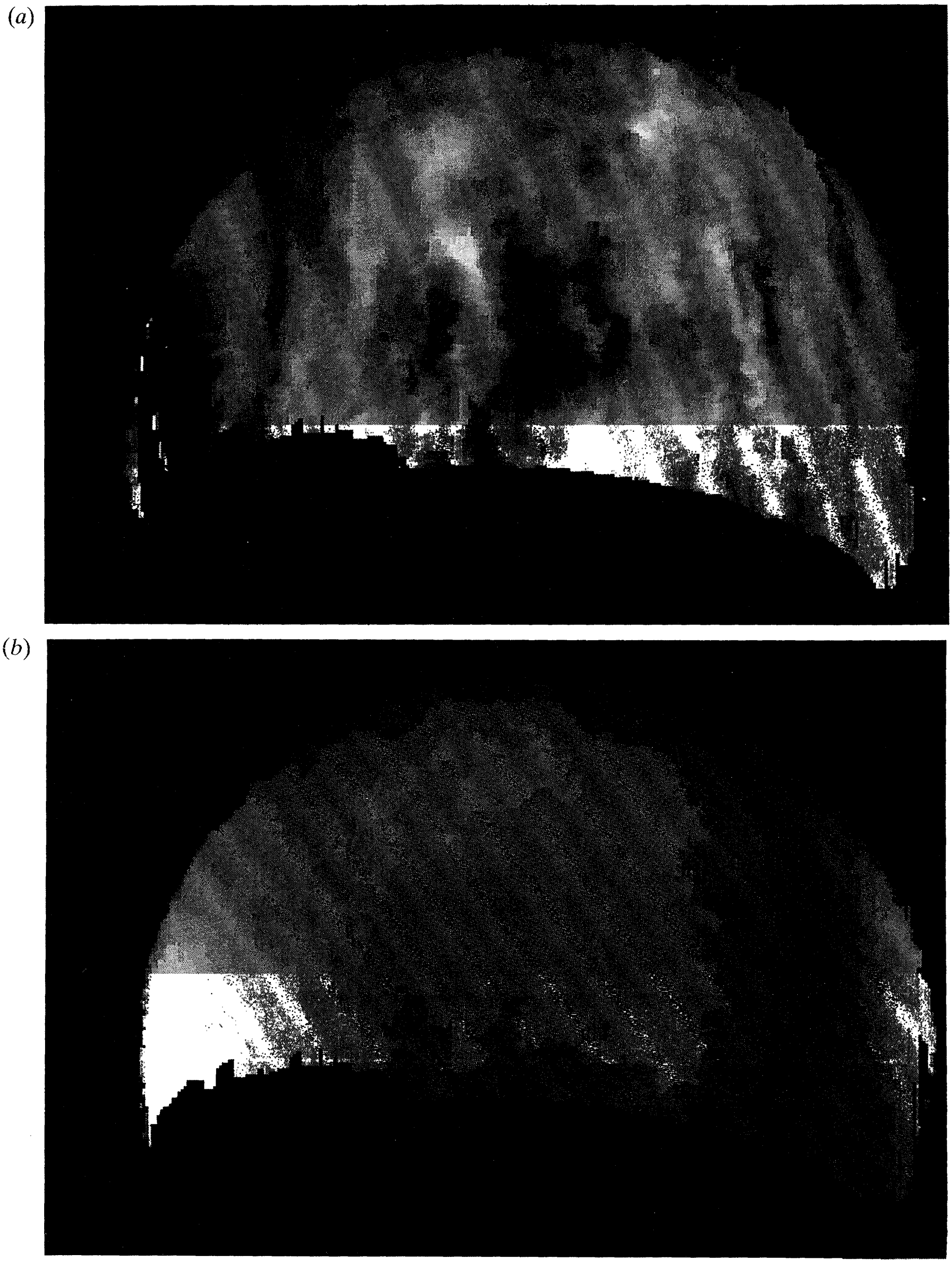

Figure 5. (*a*) 2.3 μm image of Venus; (*b*) 4.84 μm image of Venus (Carlson *et al.* 1993).

pressures which have not been simulated in laboratory experiments. Much of the analysis, therefore, depends upon theoretical modelling of the emission properties of the gases (Wattson & Rothman 1993) giving rise to larger than usual uncertainties. Finally, the full characterization of the NIMS instrument, including significant

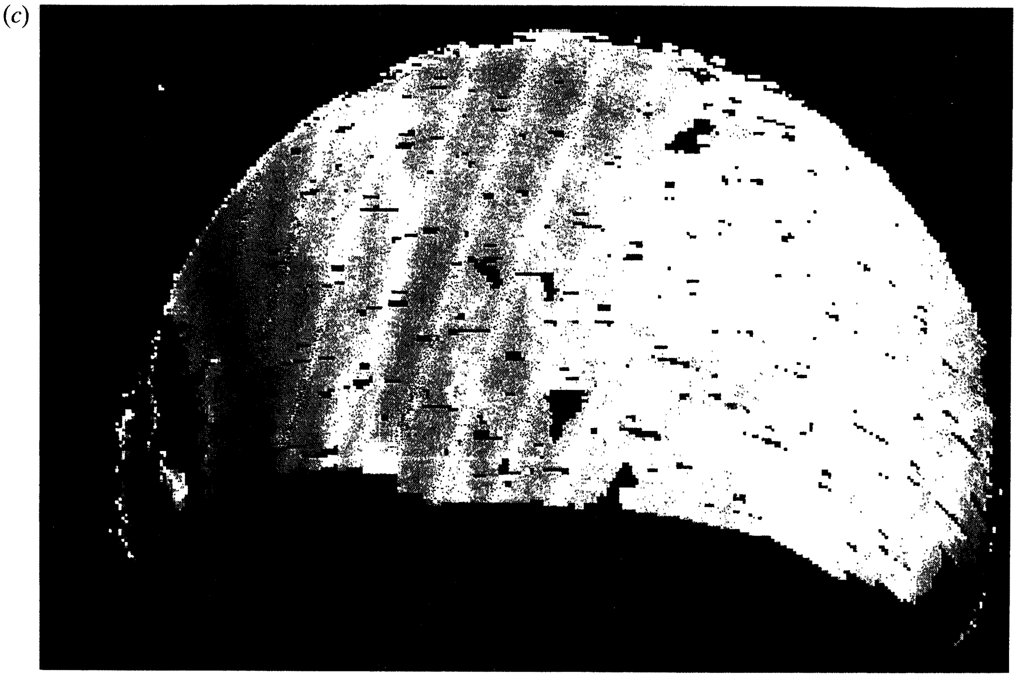

Figure 5. (*c*) Venus deep cloud variations deduced from NIMS data (Carlson *et al.* 1993).

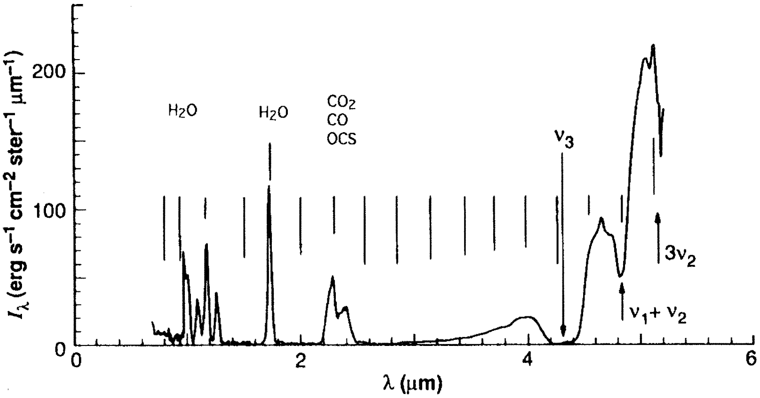

Figure 6. NIMS nightside spectrum of Venus (Carlson *et al.* 1991).

improvements to the calibration, will not take place until the Galileo spacecraft reaches Jupiter in December 1995. To minimize the uncertainties caused by these effects the determination of gaseous abundance and to some extent the cloud investigations were based on ratios of signals at different wavelengths rather than absolute values.

The main source of radiance variations in the near-infrared windows is due to the variability of the absorbing cloud layers. These variations are not seen at longer wavelengths and must therefore be due to opacity variations in the lowest clouds, which Pioneer probe data showed contain most of the mass of the clouds. Comparisons of the relative signals for two wavelengths (1.74 and

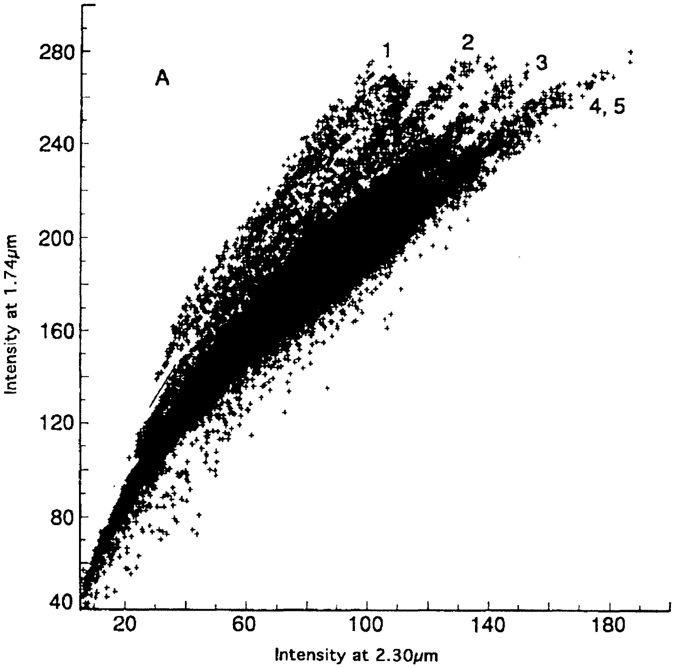

Figure 7. Spatially dependent branching of NIMS radiance ratios due to cloud variations (Carlson *et al.* 1993).

2.3 μm) reveal spatial variations in the cloud properties. The general appearance at the two wavelengths is similar although the contrasts are greater at 2.3 μm due to higher specific absorption by the cloud particles. A scatter plot of 1.74 μm radiance versus 2.3 μm radiance for different points on the planet should form approximately a straight line, but in practice is found to have multiple branches (figure 7). Carlson *et al.* (1993) have shown that these branches correspond to large-scale spatial variations in cloud type (figure 5*c*). Their model calculations indicate that the most likely explanation is that the cloud layer has more large, so-called mode 3 particles (approximately 7 μm in effective radius) in the northern hemisphere regions, although the reason for this is still unclear.

The availability of two deep cloud images, separated by 2 hours, allowed the determination of wind speed by feature tracking with a precision of about 3.2 m s^{-1} (Carlson *et al.* 1991). Figure 8 shows the results for both zonal and meridional velocities for a height of about 50 km, about 15 km lower than winds from previous feature tracking in the UV. The zonal winds are slower than those at the cloud tops, as expected, and there is again evidence of a jet at 45° N. The meridional winds are of the same magnitude as the uncertainty in the measurement, i.e. a few m s^{-1}, but are definitely poleward and so do not provide any evidence of the return path of the high-altitude Hadley cell. Presumably, this occurs deeper in the atmosphere where we are still lacking global wind measurements.

The deep atmosphere CO abundance has been investigated using emission in its 2-0 band near 2.3 μm (Collard *et al.* 1993). The results in this case are consistent with enhanced CO abundance northwards of 47° N. Figure 9 shows spectra for the 'normal' and 'enhanced' CO abundance regions, normalized to a point at

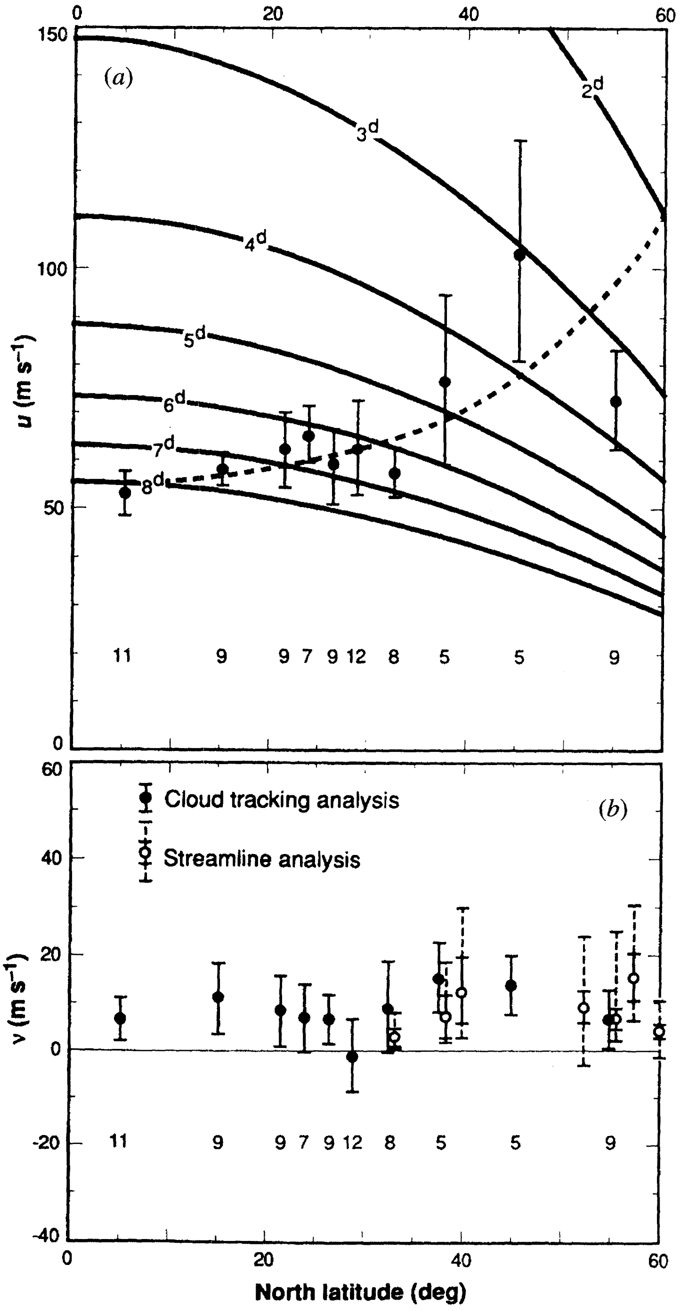

Figure 8. Cloud velocities deduced from NIMS (Carlson *et al.* 1991).

2.252 μm. The abundances correspond to 48.5 ± 4.0 and 66.0 ± 4.0 ppm respectively, both higher (by 17% and 59%) than the values obtained from the mass spectrometer experiment on Pioneer Venus (von Zahn *et al.* 1983).

The existence of variations in the deep cloud properties and in the carbon

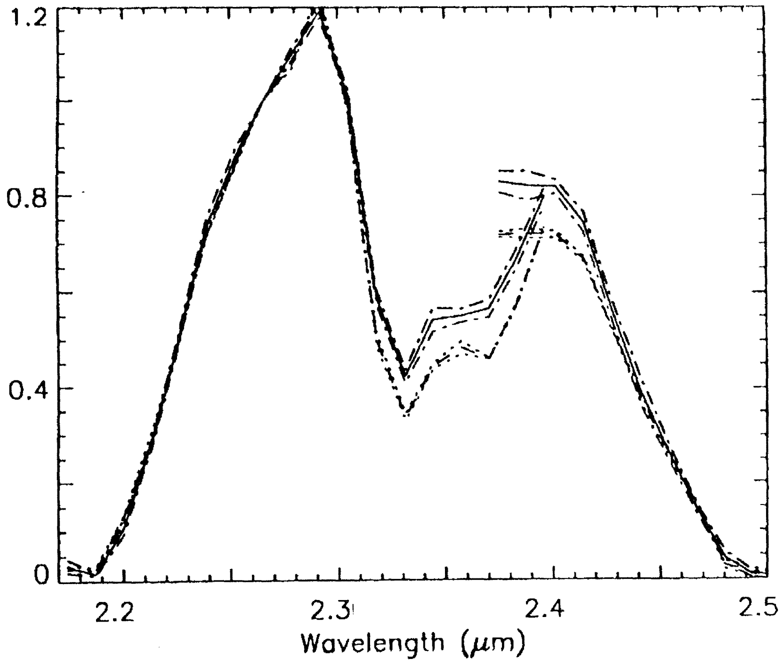

Figure 9. NIMS 2.3 μm emission spectra for varying CO abundance.

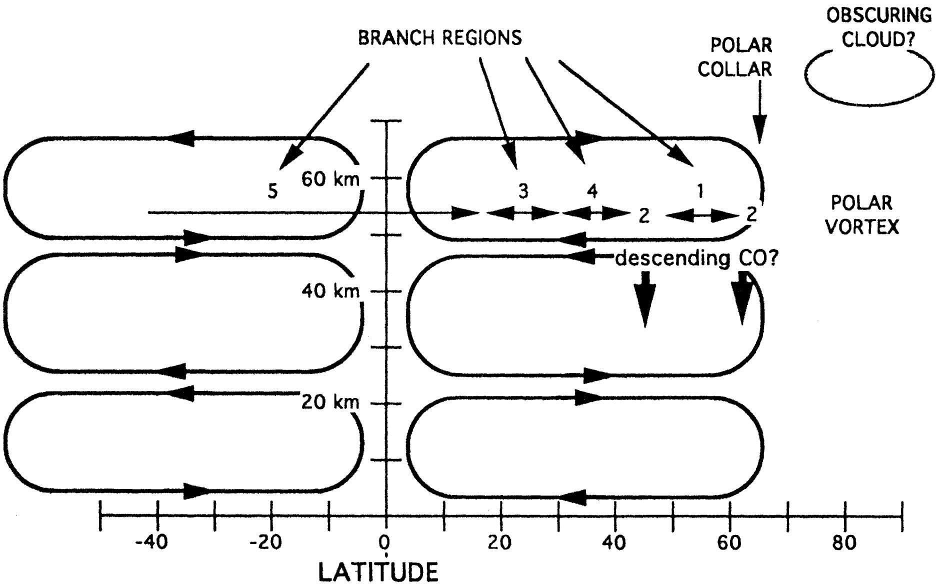

Figure 10. Schematic of Venus circulation compared to NIMS results.

monoxide abundance is well established, but we are still far from understanding their origins. Figure 10 is a sketch of a notional Venus meridional circulation, based on the very limited information currently available, with some of the structure seen by NIMS superimposed. The CO enhancement at high latitudes could be due to downward transport of photodissociation products of upper atmosphere CO_2. An alternative explanation is that active vulcanism in the mountainous region at high northern latitudes may produce enough carbon monoxide to explain the anomaly. There are problems with both of these explanations, however, when they are examined in detail.

The cloud variations are even more puzzling. The regions of thick and thin cloud show very large opacity contrasts, of more than an order of magnitude. This suggests a convective origin for the features, but their mesoscale dimensions and lack of any apparent organization appear chaotic. There is really no substitute for repeated imaging of the cloud properties from some future Venus orbiter to give the required insight into the space- and time-scales, and hence the basic modes, present. Until then, the meteorology of Venus and its link with the general circulation and climate remains a tantalizing mystery.

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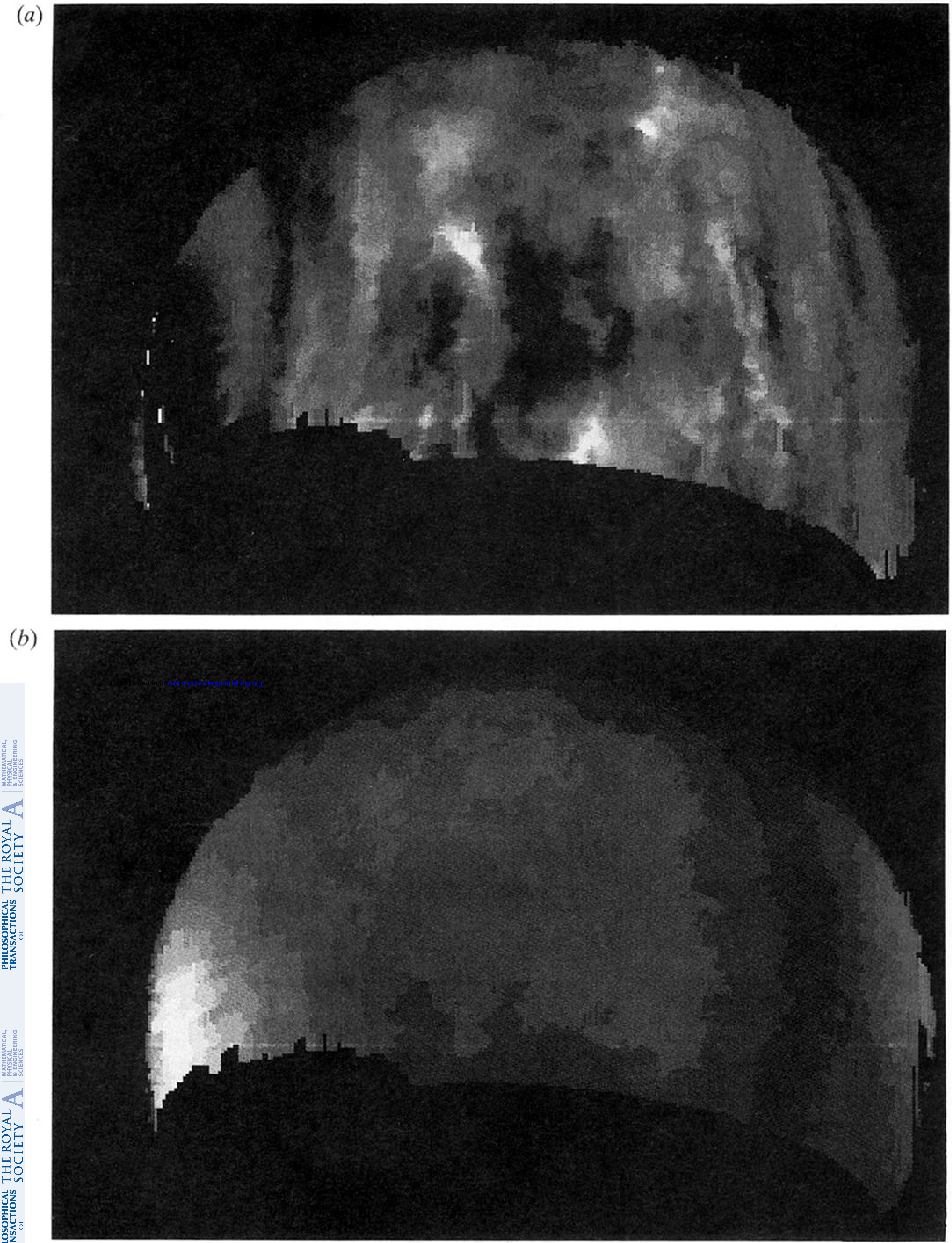

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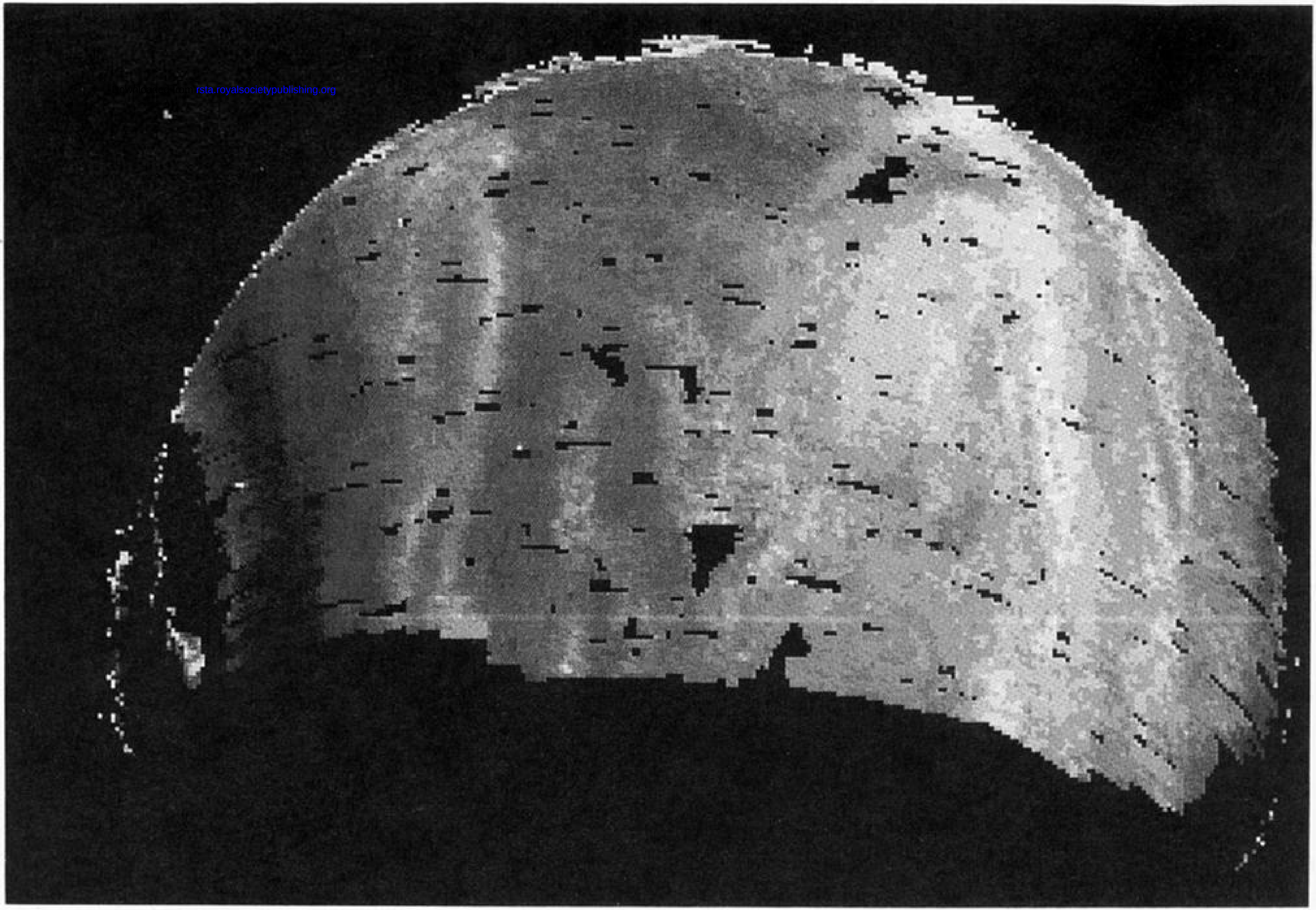

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