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Is the Four-Day "Rotation" of Venus Illusory?

by

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Running head: Four-Day Illusion on Venus

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Abstract

An overlooked systematic error exists in the apparent radial velocities of solar lines reflected from regions of Venus near the terminator, owing to a combination of the finite angular size of the Sun and its large (2 km/sec) equatorial velocity of rotation. This error produces an apparent, but fictitious, retrograde component of planetary rotation, typically on the order of 40 meters/sec. Spectroscopic, photometric, and radiometric evidence against a 4-day atmospheric rotation is also reviewed. The bulk of the somewhat contradictory evidence seems to favor slow motions, on the order of 5 m/sec, in the atmosphere of Venus; the 4-day "rotation" may be due to a traveling wave-like disturbance, not bulk motions, driven by the UV albedo differences.

Introduction

An apparent four-day rotation of the atmosphere of Venus was first inferred from ultraviolet cloud features by Boyer and Camichel in 1961, and has since been studied by a large number of workers, who have generally assumed that the UV features are embedded in, and moving with, the cloud material. This requires a general zonal circulation of the entire atmosphere, at least within 50 or 60 degrees of the equator, at speeds on the order of 100 meters/second. However, radar studies, (e.g., Carpenter, 1970) show that the surface of the planet rotates only once in 243 days, at about 1.8 m/sec at the equator; both the solid-body rotation and the inferred atmospheric rotation are retrograde. The dynamical problem of maintaining high winds on a slowly-rotating planet has not been solved quantitatively (Leovy, 1973), although there are several arm-waving "explanations" in the literature; on the contrary, detailed numerical models (Kálnay de Rivas, 1973; Young and Pollack, 1974) yields maximum wind speeds on the order of 8-10 meters/second. Nevertheless, the apparent velocity of rotation has been inferred from the Doppler shifts of solar lines, and recent measurements (Guinot and Feissel, 1968; Carleton and Traub, 1972) agree with the 100 m/sec retrograde rotation; although Richardson (1958) obtained only 32 ± 33 (s.e.) m/sec, which would exclude a value as large as 100 m/sec at the 95% confidence level.

Recently, Young et al. (1974) have published spectroscopic data which are inconsistent with a 4-day atmospheric rotation. Because of these data, and the earlier results of Richardson (1958) and

Slipher (1903), which are consistent with a very slow atmospheric rotation; and also, because there is no satisfactory dynamical explanation for the presumed atmospheric rotation, I have considered measuring some recent high-dispersion spectra to obtain Doppler velocities. While thinking about possible systematic errors that would cause problems, I found a serious one that has clearly caused problems in the past.

The Solar-Rotation Effect

Fig. 1 shows the geometry responsible for this effect. Because the Sun has a finite angular diameter, points near the terminator of Venus are unequally illuminated by the approaching and receding limbs (V and R, respectively) of the Sun. If we neglect the slow rotation and orbital motions of Venus for the moment, this means that the average illumination reaching a point P near the sunset terminator T_R , say, will have a velocity somewhat redshifted with respect to the Sun itself. Similarly, points near the sunrise terminator, T_V , preferentially receive violet-shifted light. As a result, an outside observer unaware of this effect will infer that the region near T_V is approaching the Sun and that T_R is receding from it, and therefore that the planet is in retrograde rotation, even if the planet is stationary. We can also see that the subsolar point M is equally illuminated by the two limbs, so it should show no radial velocity with respect to the Sun. Obviously, the effect is on the order of the solar equatorial velocity (2 km/sec), multiplied by the ratio of its angular semidiameter, s_\odot , to the angular distance, θ ,

of the point P from the terminator. The Sun's semidiameter as seen from Venus is .00644 radian, so this ratio reaches 1/20 at 0.129 radian (about 7.4 degrees) from the terminator of Venus; in this neighborhood, the effect is of the same order as the 100 m/sec "rotation" popularly ascribed to the atmosphere of Venus. Thus it is possible that most of the reported retrograde "rotation" of Venus's atmosphere is spurious.

We now analyze the effect in some detail. Although the Lambert diffuser is in the same class with the frictionless pulley and the perfect absorber, it is a useful approximation for a semiinfinite, conservatively scattering atmosphere. Furthermore, measurements along the equator of Venus (Minnaert, 1946; Ross, 1928; Richardson, 1955) show that, near elongation, it presents nearly the triangular intensity profile expected from a Lambert sphere, at least at visible wavelengths. We therefore adopt the Lambert approximation, in which the amount of light reflected is proportional to the cosine of the angle of incidence, i .

Consider a point P on the Venusian equator where the angle of incidence from the center of the Sun is i . If P is an angular distance θ from the "red" terminator T_R , we have $i = 90^\circ - \theta$; then the angle of incidence for the red-shifted solar limb is $i_R = i - s_\odot$, and the angle of incidence for the violet-shifted limb is $i_V = i + s_\odot$. The intensity reflected from the red limb of the Sun is proportional to

$$\begin{aligned} \cos i_R &= \cos(i - s_\odot) = \cos i \cos s_\odot + \sin i \sin s_\odot \\ &\approx \cos i + s_\odot \sin i, \end{aligned} \quad (1)$$

since $\cos s_{\odot} = 0.99998$ and $\sin s_{\odot} \approx s_{\odot}$. Similarly, the intensity reflected from the violet solar limb is proportional to $\cos (i+s_{\odot}) \approx \cos i + s_{\odot} \sin i$.

To find the mean velocity of the reflected light, we must add up contributions from all points on the solar disk (see Fig. 2). The velocity at a point Q, a fraction $f = r/s_{\odot}$ of the solar radius from the center of the disk, is

$$v = Vf \cos \phi = Vx, \quad (2)$$

where $V = 2$ km/sec is the rotational speed at the equator, and x goes from -1 at the violet limb V to $+1$ at the red limb R. If we neglect differential rotation, v is constant along a strip (shaded in Fig. 2) perpendicular to the equator; the length of this strip is $s_{\odot} (1-x^2)^{1/2}$.

The observed contribution from the strip of speed v is proportional to the product of its area and the reflected brightness, which is proportional to $(\cos i + s_{\odot} \sin i)$. Hence,

$$\bar{v}(i) = \frac{\int_{-1}^{+1} v(x) (\cos i + x s_{\odot} \sin i) s_{\odot} (1-x^2)^{1/2} dx}{\int_{-1}^{+1} (\cos i + x s_{\odot} \sin i) s_{\odot} (1-x^2)^{1/2} dx} \quad (3)$$

Since the integrals of terms containing odd powers of x are zero, this reduces to

$$\bar{v}(i) = \frac{V \int_{-1}^{+1} x^2 s_{\odot}^2 \sin i (1-x^2)^{1/2} dx}{\int_{-1}^{+1} \cos i s_{\odot} (1-x^2)^{1/2} dx}$$

$$\begin{aligned}
 &= V_{\odot} \tan i \frac{\int_{-1}^{+1} x^2 (1-x^2)^{1/2} dx}{\int_{-1}^{+1} (1-x^2)^{1/2} dx} \\
 &= \frac{V_{\odot} \tan i}{4} = 3.2 \tan i \text{ (m/sec)}. \quad (4)
 \end{aligned}$$

This does not include limb effects, which should be important because of the x^2 weighting in the upper integral. However, for the weak lines that are best for velocity measurements, the center-to-limb increase in equivalent width (Allen, 1963; p.166) very nearly balances the decrease in continuum intensity (Allen, 1963; p. 170) near 7000 Å. The center/limb variation of line strength also depends on the excitation potential of the lower state for each line; unfortunately the particular lines used have not usually been identified. To include limb effects, the integrals should be done in polar (r, ϕ) coordinates instead of over x .

We notice that even for observations made near the subsolar point at small phase angles, where the true radial velocity would be $V_{\text{rot}} \sin i$, there would appear to be a spurious "rotational" velocity of 3.2 meters/sec, nearly twice the rotation speed of the solid planet. For observations near the terminator, the spurious velocity increases in the ratio of $\tan i / \sin i$, or inversely proportional to $\cos i$ (or the Lambertian surface brightness.) As $\cos i = \sin \theta$, this means that the effect is proportional to $V_{\odot} / \sin \theta \approx V_{\odot} / \theta$, for small values of θ (near the terminator), as expected.

For a non-Lambertian planet, one should use the true brightness gradient at P (projected onto the planet) in place of $\sin i$, and the apparent brightness in place of $\cos i$, in Eqs. 1-4. One could also extend the theory to observations at high latitudes on Venus; however, deviations from Lambertian behavior are generally stronger there than along the equator, and the inclination of the solar equator to that of Venus should also produce appreciable effects near the cusps.

Application to Published Results

The measurements by Richardson (1958) were mainly made on 0.84 Å/mm spectra, taken with the slit along the planetary equator. All the spectra used to obtain his final value were taken in the 6300 Å region, using telluric lines for comparison. Richardson says that the spectra were measured at 0.076 planetary radii inside both limb and terminator. The phase angles ranged from 60 to 101 degrees, with a mean near 85 degrees; thus typical values of i are about 23° near the limb, and 85.6 degrees ($\theta=4.4^\circ$) near the terminator. These values correspond to spurious Doppler shifts of 1.3 and 42 meters/sec, respectively. The latter figure shows that the solar-rotation effect accounts for the entirety of Richardson's value of 32 ± 33 m/sec (retrograde), leaving an excess of some 10 m/sec unaccounted for, although small compared to the mean error. Thus Richardson's data, correctly interpreted, indicate a negligible rotation of the atmosphere - probably not exceeding 20 m/sec in the retrograde direction.

Guinot and Feissel (1968) used a 4 Å/mm spectrograph dispersion crossed with a Fabry-Perot interferometer. Their observation and reduction technique is more complicated and less direct than that of Richardson, and probably is more likely to introduce systematic errors.* Lacking an image rotator, they used a short slit corresponding to some 3.6 seconds of arc on the sky for most of their spectra. At 90° phase, the apparent radius of Venus is about 12"; thus 3.6" is about 17 degrees on the planet. However, the angle between slit and terminator generally made the region observed somewhat narrower than this in longitude; I shall adopt 12° as a rough estimate (corresponding to a 45° angle).

Near the terminator, the brightness of the planet is proportional to $\cos i = \sin \theta \approx \theta$. But the spurious Doppler velocity is inversely proportional to $\sin \theta$, as mentioned above. Hence the intensity-weighted velocity contribution from each degree of longitude is symmetrically distributed about the center of the slit, and the mean velocity of the light observed corresponds to the center of the slit. Thus, if the slit center was, on the average, 6° from the terminator, a spurious velocity on the order of 31 m/sec should be observed at the terminator side, and about 2 m/sec at the limb side of the disc.

* Richardson (1958) tested his technique for systematic errors by measuring the rotations of the Sun and Mars; his errors are -6 m/sec and +4 m/sec in these cases. Guinot and Feissel (1968) performed no such tests.

The difference of 29 m/sec must be divided by an average value of Guinot and Feissel's factor k , which they used to convert observed velocity differences into rotation velocities. The mean absolute value of k is 0.816. Since we use the reciprocal of k to scale the correction, the mean reciprocal is also of interest; its value is 1.447, corresponding to $k = 0.691$. The corresponding corrections to the rotational velocity are 35.6 and 42.0 m/sec, for the straight mean and harmonic mean values of k , respectively.

The true rotational speeds, corrected for solar-rotation effect, are about 67 and 61 m/sec, corresponding to rotational periods of 6.6 and 7.2 days. Although these speeds are not negligible, they are clearly incompatible with the 4 or 5-day rotation needed to explain the UV cloud "motions". Even at 67 m/sec, the stated probable error of 10 m/sec allows us to reject a value as high as 100 m/sec with about 97% confidence, or 90 m/sec with better than 85% confidence.

As the observations of Carleton and Traub (1972) have not been published in detail, it is not possible to treat them here. However, one can anticipate from the above results that the solar-rotation effect was partly responsible for their measured "rotation", and that corrected values would be inconsistent with the supposition that the UV cloud "motions" are mass motions in the atmosphere of Venus. In any case, they obtained a large velocity at only one elongation and not at the other, so their data do not strongly support a 4-day rotation, even if taken at face value.

Finally, I should mention the winds inferred from Venera 8 and earlier entry probes (Marov et al., 1973). These are not subject to the

effect noted above, but are liable to other systematic errors. The position taken by Marov et al. (1973) is that the winds inferred from earlier probes, which do not agree very well with the supposed 100 m/sec atmospheric circulation, are unreliable. Venera 8 data do agree with the presumed atmospheric rotation. However, their data were reduced in such a way as to force the speed to be zero at the surface of Venus; hence, any unrecognized drift in the spacecraft oscillator will appear as a wind speed increasing with height. Furthermore, the Venera 8 data do not agree with the revised optical Doppler measurements discussed above. Only new data can resolve this conflict.

Other Evidence Against High Winds

There are three types of evidence that are inconsistent with a four-day atmospheric rotation: spectroscopic, photometric, and radio-metric.

The spectroscopic evidence is the most direct. Young et al. (1974) found a persistent limb-terminator asymmetry in CO_2 absorption during September, 1972, although a four-day quasi-periodic variation, discovered by Young et al. (1973), is prominent in these data. The limb and terminator data appear to vary almost synchronously with the rest of the disk, although a 4-day atmospheric rotation would require a large phase lag in the cycle when observed at the limb, compared to the terminator.

Perhaps the most prominent example is shown by limb and terminator spectra taken on September 26, 1972. Several spectra were taken in various positions on the planet on September 25, 26, and 27; a marked decrease in CO₂ absorption occurred during this time, with about 5% decrease from each day to the next. If this were due to a rapid atmospheric circulation, we would infer that the cloud tops were about 5% of a scale height (i.e., some 250 meters) higher in the gas brought into view each day by the 4-day rotation. As the new gas would appear at the morning terminator, and the "limb" spectra were taken near the subsolar point and about 60° away from the "terminator" spectra, this would require that the "terminator" spectrum on the 26th should show about 3% less CO₂ absorption than the "limb" spectrum on that day. On the contrary, the terminator showed almost 5% more CO₂ than the limb. This discrepancy of 8% from the prediction based on a 4-day rotation is about two standard deviations, as the standard deviation for a single plate is between 2.5 and 3.0 per cent, and the standard deviation for the difference of two plates would be $2^{\frac{1}{2}}$ times this, or about 4%. Thus, this one day's data appear to reject the 4-day rotation at the 90% confidence level. Additional support is provided by data on other days that show the same limb-terminator gradient, regardless of phase in the 4-day cycle.

During this time, UV photographs were taken, and showed prominent cloud markings. My own impression from these pictures is that the same general pattern appears day after day, but is intensified every four days. Thus, it cannot be claimed that the spectroscopic variations are unrelated to the UV ones, or that a period markedly different from

four days was present during September, 1972.

There are also some unpublished observations made by Barker (1974), which do not show the limb-terminator gradient observed by Young et al. (1974), but also do not show the expected phase shift between limb and terminator in the day-to-day variations. Apparently the limb-terminator gradient observed by Young et al. (1974) was fairly long-lived, but may not be a permanent feature of the Venus atmosphere.

On the other hand, Minnaert (1946) pointed out an apparently permanent limb-terminator gradient in published photometric data: taking into account the reciprocity relation, he showed that the limb was systematically too faint, compared to the terminator. I would be inclined to attribute this effect solely to a systematic error resulting from the effects of "seeing"; however, one would expect such an error to be largest at long wave lengths, where the limb-terminator gradient is strongest, but instead Minnaert found "it is striking that the mean differences gradually increase from the red to the violet." He also found a slight dissymmetry between the two halves of the disc, with larger deviations from reciprocity at what we now know to be the sunset terminator. (However, this is observed at evening elongations on Earth, when the scattered sky light and the "seeing" tend to be worse.)

If Minnaert's phenomenon is really on Venus, it would be difficult to understand on the basis of a rapidly-rotating atmosphere. Polarization data have shown that the mean particle radius in the Venus clouds near optical depth unity is about 1.05 microns (Hansen and Arking, 1971; Hansen and Hovenier, 1974).

If the particles are made of sulfuric acid, as seems likely, they fall at a speed of only some 25 meters per day (Young, 1973); whatever their composition, this is the right order of magnitude. As such particles cannot evaporate at the low temperature of the cloud tops, any variations in cloud structure must be essentially frozen-in, and carried around the planet by a 4-day rotation. Thus, if there were a terminator-limb asymmetry of the sort Minnaert found, it should be of one sign half the time and of the other sign the other half. That is, Minnaert's phenomenon is just as incompatible with a 4-day rotation of the atmosphere as the long-lived asymmetry observed spectroscopically by Young et al. (1974). Furthermore, such frozen-in spatial variations should rapidly be effaced by turbulent mixing; we then would need mechanisms for maintaining not only the 100 m/sec winds, but also the patchy distribution of whatever properties (such as number density, mean radius, or concentration of absorber) are responsible for the periodic UV and CO₂ variations.

On the other hand, if the atmospheric rotation is slow, we still have a problem with the 4-day meteorological pattern. For, if the aerosol droplets can only fall 25 m/day, this represents the maximum change to be expected in cloud-top height from one day to the next; this argument was first advanced by Kuiper (1952), who thus concluded, from his pioneering observations of day-to-day changes, that the particle size must be on the order of 10 microns.

We shall return to this problem. For the present, we note that the limb-terminator asymmetries noted by Minnaert (1946) and Young et al. (1974) are easily explained by the circulation pattern first proposed by Clayden (1909) and studied numerically by Kálmán de Rivas (1973) and by Young and Pollack (1974). In this model, solar heating causes rising convection currents near the subsolar point and descending convection on the dark side; the modern numerical models have shown a slow additional zonal flow, due to the slow rotation of Venus. We can thus expect the clouds to be highest near the subsolar region (the "limb" region as seen at large elongations), and lower at the terminator. The data of Young et al. (1974) show a mean gradient of about 8% in CO_2 abundance per radian of longitude on Venus, making the effective cloud-top some 400 meters lower near the terminator than in the subsolar region. If this is due to a settling-out of 25 m/day, about 16 days are required; during this time, the gas moves 6100 kilometers (one radian on Venus), corresponding to a mean flow of 4.4 m/sec, which is quite consistent with the numerical models.

Can such a slow wind supply enough heat to the dark hemisphere to account for its thermal emission? I believe that it can. The effective temperature observed in the thermal infrared (Sinton, 1961) is 226°K . Thus each square centimeter of the cloud tops radiates about 1.5×10^5 erg/sec; this power must be supplied to the dark side by a flow of gas from the sunlit hemisphere.

How deep is this flow? According to the Mariner 5 radio occultation data (Fjeldbo et al. 1971), the temperature gradient is almost exactly

adiabatic between the $T=280^{\circ}\text{K}$ and $T=360^{\circ}\text{K}$ levels, with a considerably lower lapse rate between 360°K ($P=1.26\text{ atm}$) and at least 390°K ($P=2.3\text{ atm}$). It seems likely that the great opacity of the cloud in the thermal infrared (Young, 1974) causes strong convection in the upper region, which would account for its adiabatic lapse rate. For several kilometers near the cloud base (which is ($P=5\text{ atm}$, $T=450^{\circ}\text{K}$, according to Marov et al., 1973), radiative transport is significant and the lapse rate is sub-adiabatic. However, in the lowest part of the atmosphere the opacity of the gas alone is great enough to force convective mixing. Thus the lowest 40 km is roughly analogous to the terrestrial troposphere; the subadiabatic region around 45 km is a stratosphere, governed by radiative heat transport; and the cloudy, strongly convective region contains a second, upper troposphere. Above about optical depth unity, radiation can escape from the cloud, and the upper layers are in radiative equilibrium again; this is the region we can observe. Because of convective momentum exchange we should not expect large gradients of horizontal velocity within either the upper or the lower troposphere; hence the stably-stratified region between them seems likely to separate the upper layer of gas that carries heat to the dark side of Venus from the returning, surface, current.

If we place this division at the $T=390^{\circ}\text{K}$, $P=2.3\text{ atm}$ level (which agrees with the large wind shear observed by Venera 8 near 45 km), the projected density of the overlying region is 2.4 kg/cm^2 . The average temperature of this region is about 350°K , at which the specific heat of CO_2 is 0.2 cal/deg/gm at constant pressure. If a typical column of gas spends about 16 days radiating at 226°K from the dark side of Venus, it loses about 2×10^{11} ergs or nearly 5 kcal; this

heat loss from 2.4 kg of CO_2 would cause a temperature drop of about 10°C . However, this temperature drop would cause a 3% decrease in scale height. The energy liberated by an average gravitational contraction of some 200 meters would be about 1 kcal for one 2.4 kg column of gas; thus only about 8° cooling should be observable, if the radiating surface remained at a fixed pressure level.

Actually, the radiating layer should be deeper in the atmosphere (at a higher pressure level) on the dark side, owing to continued aerosol fallout. Also, the above treatment sets an upper limit to cooling on the night side, because it neglects the heat capacity of the lower 98% of the atmosphere. If we were to assume that this heat source keeps the atmosphere temperature-pressure profile fixed, then the aerosol fallout of about 1 1/4 km (during the interval of about 50 days required for gas to move from the subsolar to the antisolar points) would produce an apparent increase in temperature of about 5°C at the radiating level.

Interestingly enough, Ingersoll and Orton (1974) have recently published an analysis of thermal-infrared maps of Venus, in which they find a brightness-temperature maximum, of the order of 5° , near the anti-solar point. This appears to be entirely consistent with the above picture, in which the typical wind speeds are near 5 m/sec. On the other hand, if winds were 20 times higher, the temperature distribution along the planet's equator should be uniform within half a degree or better, and no thermal pattern should be detectable.

Although Ingersoll and Orton failed to mention it, Pettit and Nicholson (1955) had previously found the dark side of Venus 5°C warmer than the bright side. Furthermore, they found the night side temperature

lower before inferior conjunctions than after, which is consistent with continued slow sinking of the aerosol at the radiating level if there is a slow zonal circulation in the direction of rotation. On the other hand, Ingersoll and Orton find the maximum dark-side temperature nearer the sunset than the sunrise terminator, which may agree better with Minnaert's larger asymmetry at sunset. Clearly, more thermal-infrared observations of weather on Venus are needed.

Arm-waving Discussion

I have reviewed several types of observational data that appear to contradict the simple interpretation of UV cloud-feature motions in terms of a 4-day rotation of the entire atmosphere. If we reject this interpretation of the cloud-feature motions, they must instead represent some kind of travelling wave phenomenon, whose phase velocity is near 100 m/sec.

What, then, is the nature of the UV markings? I must emphasize that speculation on this topic is extremely dangerous, for at present we do not know what material is responsible for the ultraviolet absorption, nor how it is produced, nor where it comes from. Furthermore, all the classical arguments that the yellow color "proved" the clouds could not be water are equally effective against the currently-popular sulfuric-acid clouds. Whether the patchy distribution in ultraviolet absorption represents variations in cloud structure, particle size, concentration of absorber, or what, is not yet clear.

Nevertheless, the appreciable variations in CO_2 absorption seem not to be accompanied by the corresponding variations in temperature that would be expected if the cloud-tops were really moving up and down.

Apparently, we are seeing to about the same depth in the atmosphere, but through a varying optical path length or "air-mass" from day to day. This suggests a variation in the shape of the cloud-top surface - perhaps it is smooth some days, and crinkled or irregular on others. Since we see just about to the top of the convective part of the atmosphere, it may be that the cloud "surface" is rougher if there is stronger convective activity.

In the near infrared, the cloud albedo is indistinguishable from unity; and a lumpy white surface is just as white as a flat one. In the ultraviolet, where the clouds (or the atmosphere?) absorbs, an irregular surface looks darker than a smooth one, because light tends to be trapped in the low depressions, being reflected back and forth between their sides. Thus the UV dark markings may be regions of higher convective activity.

This model may well be wrong, but it provides a basis for argument, at least.

Now suppose that some travelling disturbance tends to promote or suppress convection. As it passes by, it will tend to enhance or suppress the visibility of convective regions as it passes over them. The result will be an apparent "motion" of the UV features, following the disturbance.

We might expect the "lifetime" of an individual small feature to be comparable to the time required for the 100 m/sec disturbance to pass across it. This seems to agree with the finding of Murray et al. (1974) that features 50-100 km across had lifetimes between 15 minutes (900 sec) and two hours (7200 sec); at 100 m/sec, 100 km is traversed in 1000 sec. On the other hand, if the light and dark regions were "frozen in", random motions on the order of 100 m/sec would be required

to make such features change; and this turbulence should quickly obliterate all UV contrast.

The "travelling-wave" picture also explains the repetition of UV features at intervals of a few days (the next time a "wave" encounters the same atmospheric structure); for example, Smith (1967) says, "some of our plates show strikingly similar cloud patterns at intervals of only 2 days, although individual cloud displacements during several hours on these same dates clearly exhibit motions corresponding to a period of 5 days." Also Scott and Reese (1972) reported the UV markings to be "quite ephemeral in nature, rarely enduring in a recognizable pattern for more than 20 days and usually much less." Notice that 20 days suffices to displace the actual gas itself through some 75° of longitude, at a rate of 4.4 m/sec, so that the underlying structure in which UV "clouds" are turning on and off is completely replaced in this time.

The travelling disturbance may well be internal gravity (density) waves at the cloud top (upper tropopause). It is interesting to note that Osaki (1974) has proposed that nonradial pulsations in the Beta Cephei stars may be excited by a coupling between overstable convection in the core and a wave travelling around the equator in the direction of rotation. This sounds like what may be happening on Venus, if one reads "lower atmosphere" for "core". The speed of such waves in the Venus atmosphere is on the order of 100 m/sec. Furthermore, this speed would vary somewhat, depending on the subadiabatic temperature gradient above the clouds (i.e., the degree of stability.) This gradient is known to be variable; comparison of Mariner 5 and Mariner 10 temperature profiles, or the gradients inferred from thermal-infrared spectra taken at different times, shows that the lapse rate in the stratosphere varies from $4^{\circ}/\text{km}$

down to 2 or 3°/km. Such variations would account for the 4-day "period" not being exactly fixed.

Thus the UV cloud features may be likened to the whitecaps on a stormy sea, occurring where intersecting waves build up enough amplitude to create a locally visible instability. The apparent speed of propagation of such features may be much greater than the actual speed of the mean fluid motion.

What Drives the Weather

While the general circulation seems to be driven by the day/night gradient, we can also ask what gradients are the source of the waves responsible for the UV features. Whatever their mechanism, these must be the ultraviolet cloud features themselves. For, the bulk of the sunlight absorbed by Venus is absorbed, somewhere near the visible cloud tops, by the unknown "ultraviolet absorber," whose spatial variations are seen as the UV cloud features (see Fig. 3).

To demonstrate this, note that the Venera 8 data (Marov et al. 1973) show that only 1% of the incident sunlight reaches the surface of Venus, so the remainder of the absorbed radiation is stopped in the atmosphere. The spectral albedo of Venus (Irvine, 1968) shows that some 23(±7) percent of the sunlight is absorbed by Venus, and that the bulk of this absorbed energy is in the neighborhood of 4000Å. Since only one of the 23 absorbed percent of the light reaches the surface; and since it is known from polarimetric (Hansen and Arking, 1971; Hansen and Hovenier, 1974) and spectroscopic data (Young, 1972) that the reflected sunlight penetrates only to a pressure of 50 millibars, on the average; the absorption must occur mainly within, and probably near the top of, the clouds, as stated above.

Given this situation, it seems plausible that there must be some coupling between differential heating, due to UV features, and the atmospheric motions that produce the UV features. Such differential heating has been observed; for Sinton (1961) points out that bright UV features are several degrees cooler than dark ones. A chronic example is the 10°C lower temperature near the poles, which are always bright in the UV.

Quite possibly there may be a resonance, with features of a certain spatial wavelength or temporal period selectively enhanced. But until the nature, depth distribution, and sources and sinks of the ultraviolet absorber are better understood, it seems unlikely that a detailed understanding of weather on Venus will be possible.

Conclusion

To sum up, it appears possible to interpret the atmospheric phenomena on Venus, while doing less violence to the bulk of both observational and theoretical results, if typical wind speeds closer to 5 m/sec than to 100 m/sec are assumed. The 4-day "rotation" must then be regarded as an illusion due to travelling waves of some sort, driven by differential heating between bright and dark UV features.

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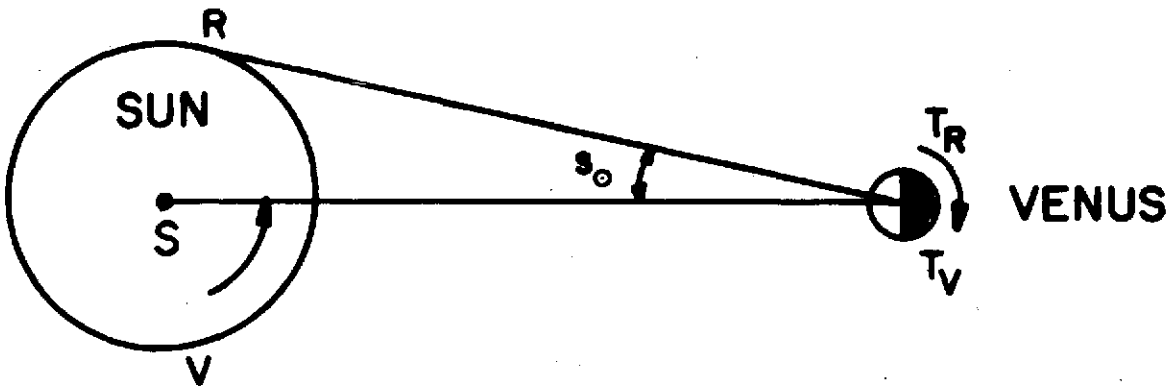
Figure Captions

Figure 1. (a) General view, from the north ecliptic pole, of the Sun and Venus. An observer on Venus sees violet-shifted light from the solar equatorial limb at V, and red-shifted light from R. Consequently, the Venus terminator at T_V is mainly illuminated by violet-shifted sunlight, and the terminator at T_R by red-shifted light. (b) Detailed illumination geometry. At the point P, an angular distance θ from the red-shifted terminator T_R , the angle of incidence from the red-shifted solar limb is i_R , and that from the violet-shifted limb is i_V . Note that $\theta + i = 90^\circ$, where i is the mean angle of incidence.

Figure 2. The solar disk as seen from Venus. The limbs V and R are as in Fig. 1. If we neglect differential rotation, all points along the shaded strip have the same Doppler shift.

Figure 3. The solar spectral energy distribution (upper curve); the fraction $(1-A_\lambda)$ absorbed by Venus (lower curve); and the spectral distribution of the energy absorbed by Venus (middle curve). The solar energy distribution is from Allen, 1963, p. 172, and the spectral albedoes of Venus, A_λ , are from Irvine (1968).

(a)



(b)

