Rotation of the Upper Atmosphere of Venus

CONWAY B. LEOVY

Dept. of Atmospheric Sciences and Geophysics Program, University of Washington, Seattle 98195

9 April 1973

The rapid retrograde motion of the clouds in the upper atmosphere of Venus has been described by a number of observers over the past several years (Dollphus, 1968; Smith, 1967; Scott and Reese, 1972; Caldwell, 1972). The rotating clouds occur near the 3-mb level [~80 km above the solid surface (Rea, 1972)]. Their rotation period is quite uniform over periods of weeks, but may vary slightly over periods of years. The most recent determination gives a period of 4.50±0.02 days (sidereal) corresponding to an equatorial tangential velocity of 98 m $\sec^{-1}$. In contrast, the equatorial tangential velocity of the surface is only 1.8 m $\sec^{-1}$. Persistence of the same large-scale features in the high clouds over several rotations with little change in shape strongly suggests solid rotation, at least in the latitude belt ±30°. There is an indication that a retrograde rotation of about the same magnitude persists down to the top of the main Venus cloud deck at about 240 mb, or 60 km (Traub and Carleton, 1971). Doppler tracking of the Venera 8 spacecraft indicates that retrograde zonal winds of smaller magnitude persist down to about 20 km, and that the zonal component of the wind is negligible below about 10 km (Marov, 1973, private communication). Vanishingly small low-level winds are also indicated by Veneras 4 and 7 (Kerzhanov *et al.*, 1972). Attempts to understand the mechanism have centered around the possibility that the traveling thermal wave due to solar heating can produce vertical transports of momentum (Schubert and Whitehead, 1969; Shubert and Young, 1970; Gierasch, 1970; Lindzen 1973), or on instability associated with vertical shear of the subsolar to antisolar thermally driven wind system (Thompson, 1970).

A fundamental aspect of the Venus wind system has apparently escaped notice. If Venus has a negligible meridional gradient of surface pressure, as the Venera data suggest, but has a small decrease in the average temperature from the equator to both poles, the pressure surfaces at high elevations will display an equatorial bulge. The pressure force associated with the bulge can only be balanced by an excess centrifugal force due to a rotation rate that increases with height. The balance is precisely that of the familiar thermal wind (Holton, 1972a) except that the Coriolis parameter is replaced by $\bar{u}\tan\phi/a$, where $\bar{u}(z,\phi)$ is the rotational speed, ϕ latitude, and a the planetary radius. Thus the force balance is

$$(\bar{u}^2 \tan\varphi)/a = -\frac{1}{\rho_0}\frac{\partial \bar{P}}{a\partial\phi}, \tag{1}$$

where $\bar{P}$ is the horizontally variable part of the pressure, and $\rho_0(z)$ is a standard density. The local angular velocity is $\bar{\omega}=\bar{u}/(a\cos\phi)$, and for simplicity, we assume $\bar{\omega}$ to be a function of height only. Again for simplicity, we assume that temperature varies only with latitude, and that the fractional variations are small. Then the hydrostatic equation reduces to

$$\frac{\partial \ln\bar{P}}{\partial z} = \frac{1}{H_0}\frac{\bar{T}}{T_0}, \tag{2}$$

where T_0 is a standard temperature, $\bar{T}$ the small variable part of the temperature, and $H_0=P_0/(\rho_0 g)$ the standard scale height [$P_0(z)$ is standard pressure and g the acceleration of gravity]. Then the thermal wind equation, obtained by combining (1) and (2), and using the assumption that the pressure gradient vanishes at the ground, is

$$\bar{\omega}^2(z) = -\frac{gz}{a^2 T_0 \cos\phi \sin\phi} \frac{\partial \bar{T}}{\partial \phi}. \qquad (3)$$

A solution to (3) is

$$\bar{T} = \hat{T} \cos^2\phi, \qquad (4)$$

where $\hat{T}$ is the amplitude of the temperature variation. For u (70 km, $\phi=0$) $=100$ m sec^{-1}, $\hat{T}$ has the modest value 3K. Note that the balance could occur for zonal winds in either direction. The indicated distribution of $\bar{T}$ is not unreasonable, although it does not correspond precisely to the distribution of insolation. On the other hand, it has special significance only if each atmospheric layer is precisely in solid rotation. The important point here is that the rotation of Venus' high cloud layer probably corresponds to the rotation required to balance a small equatorial temperature bulge. Conversely, the rapid rotation of the upper atmosphere of Venus indicates that there is an equatorial thermal bulge corresponding to a vertically averaged temperature variation of about 3K. Thus, the problem of the atmospheric rotation can usefully be thought of as a problem in adjustment to geostrophic equilibrium.

The difficult aspects of the problem remain the following:

1) How did the vertical distribution of rotation rate arise in the first place?

2) How can the differential rotation, apparently required to balance temperature gradients, be maintained in the face of vertical shears which must tend to reduce vertical differential rotation by means of turbulent or molecular viscosity?

Although these questions are far from solved at this point, the concept of geostrophic adjustment may prove useful. A small initial differential rotation of the upper part of the atmosphere could arise as follows. If there is an initial thermal bulge, and the atmosphere is in slow co-rotation with the solid surface, the pressure gradient due to the bulge will be out of balance, and a meridional circulation will develop to bring about geostrophic adjustment. Adjustment takes place primarily by the transport of planetary angular momentum poleward at upper levels. This process is well understood (Eliassen, 1950), but fails very close to the equator. In the equatorial region, the meridional circulation would tend to produce an angular momentum distribution which is independent of latitude. At the same time, any lateral mixing, however weak, would tend to produce uniform vorticity in the region. Near the equator, constancy of both vorticity and angular momentum implies constant angular velocity. In other words, lateral mixing would smooth the angular velocity deficit which would otherwise tend to develop near the equator as a result of the meridional circulation. The momentum supply for the slowly accelerating upper level winds is provided by the equatorward return branch of the meridional circulation at low levels. Since it tends to conserve its angular momentum, this branch is rotating more slowly in low latitudes than the solid planet, and is acquiring angular momentum, in the sense of the slow planetary rotation, by surface friction. This acquired planetary angular momentum is transported upward in the equatorial branch of the cell. In this way, the ambiguity in the direction of rotation of the upper atmosphere is removed. The initial tendency causes it to accelerate in the direction of the planetary rotation.

This mechanism fails when the rotation rate of the upper atmosphere increases significantly over that of the planet. Let us pass over the difficult problems associated with intermediate stages of the transition to equilibrium and consider how the equilibrium itself can be maintained. At higher latitudes the meridional circulation can again balance the angular momentum losses from the upper part of the atmosphere which result from downward turbulent or viscous transport. Viscous or turbulent momentum transport will be downward near the equator as well, and angular momentum losses there cannot be restored by the meridional circulation. This is the crux of the problem, and most previous attempts to deal with it have concentrated on the possible upward momentum flux due to waves forced by the longitudinal variations in solar heating. Intuitively, however, it is implausible that an equatorial thermal bulge could be maintained out of geostrophic equilibrium, even if there were no longitudinal variations in solar heating. This suggests that upward momentum flux occurs in oscillations forced by small, non-zonally symmetric departures from the zonal geostrophic balance. Details of such oscillations are difficult to treat, since they depend on the details of the vertical distribution of $\bar{\omega}$, but they may be analogous in some respects to the equatorial Kelvin waves treated by Holton and Lindzen (1968) and by Lindzen (1970). Kelvin waves are essentially equatorial gravity waves which propagate phase in the direction of the atmospheric rotation. They also transport momentum, of the same direction, upward. If their phase velocity corresponds to the speed of the upper level winds, most of this momentum will be deposited in the height range of the upper level winds. Holton (1972b) has found that Kelvin waves are the preferred mode of response, in the earth's atmosphere, to forcing of large vertical and horizontal scale which is symmetric about the equator. Interestingly enough, a propagating wave of this kind with zonal wavenumber 1 might account for fluctuations in CO_2 line strengths which have been reported by Young (1972) and Young *et al.* (1973).

By focusing attention on the probable maintenance of the upper level Venus rotation by a geostrophic adjustment mechanism, we have been led to speculate that internal gravity waves propagating phase westward may provide the required upward transport of momentum;

the oscillations forced by solar heating may be incidental. Emphasis has been on adjustment of rotation to a thermal bulge, but since heat transport depends on both meridional circulation and waves, there must actually be a very complicated process of mutual adjustment of the temperature and rotation fields. It is tempting to speculate that any planetary atmosphere for which heating tends to produce an equatorial thermal bulge, but which cannot develop baroclinic or barotropic instabilities because of slow rotation or large damping, must develop excess rotation in the same sense as the planetary rotation at high levels. The super-rotation of the earth's thermosphere observed by King-Hele *et al.* (1970) may be another example of this phenomenon, as Caldwell has suggested.

Acknowledgments. I am indebted to J. M. Wallace for stimulating discussions of this problem. The research was supported in part by the National Aeronautics and Space Administration under Grant 48-002-073.

REFERENCES

Caldwell, J., 1972: Retrograde rotation of the upper atmosphere of Venus. *Icarus*, **17**, 608–616.

Dollphus, A., 1968: Synthesis on the ultraviolet survey of clouds in Venus' atmosphere. *The Atmospheres of Venus and Mars*, J. C. Brandt and M. E. McElroy, Eds., New York, Gordon and Breach, 133–146.

Eliassen, A., 1950: Slow thermally or frictionally controlled circulation in a thermal vortex. *Astrophys. Norv.*, **5**, 19–60.

Gierasch, P. J., 1970: The four-day rotation in the stratosphere of Venus: A study in radiative driving. *Icarus*, **13**, 25–33.

Holton, J. R., 1972a: *An Introduction to Dynamic Meteorology.* New York, Academic Press, p. 48.

——, 1972b: Waves in the equatorial stratosphere generated by tropospheric heat sources. *J. Atmos. Sci.*, **29**, 368–375.

——, and R. S. Lindzen, 1968: A note on "Kelvin" Waves in the atmosphere. *Mon. Wea. Rev.*, **96**, 385–386.

Kerzhanov, V. V., M. Ya. Marov and M. K. Rozhdestvensky, 1972: Data on dynamics of the sub-cloud Venus atmosphere from Venera space probe measurements. *Icarus*, **17**, 659–574.

King-Hele, D. G., D. W. Scott and D. M. C. Walker, 1970: Upper atmosphere rotational speed and its variation with height. *Planet. Space Sci.*, **18**, 1433–1446.

Lindzen, R. S., 1970: Internal equatorial planetary-scale waves in shear flow. *J. Atmos. Sci.*, **27**, 394–407.

——, 1973: Wave-mean flow interactions in the upper atmosphere. *Boundary Layer Meteor.*, 4, 327–343.

Rea, D. G., 1972: Composition of the upper clouds of Venus. *Rev. Geophys.*, **10**, 369–378.

Schubert, G., and J. B. Whitehead, 1969: Moving flame experiments with liquid mercury, possible implications for the Venus atmosphere. *Science*, **163**, 71–72.

——, and R. Young, 1970: The 4-day Venus circulation driven by periodic thermal forcing. *J. Atmos. Sci.*, **27**, 523–528.

Scott, A. H., and E. J. Reese, 1972: Venus: Atmospheric rotation. *Icarus*, **17**, 589–601.

Smith, B. A., 1967: Rotation of Venus, continuing contradictions. *Science*, **158**, 114–116.

Thompson, R., 1970: Venus's general circulation is a merry-go-round. *J. Atmos. Sci.*, **27**, 1107–1116.

Traub, W. A., and N. P. Carleton, 1971: Measurements of the differential Doppler effect on a CO_2 absorption line between various points on Venus. *Bull. Amer. Astron. Soc.*, **3**, 278 (abstract).

Young, L. D., 1972: High resolution spectra of Venus, a review. *Icarus*, **17**, 632–658.

——, A. T. Young, J. W. Young and J. T. Bergstrahl, 1973: The planet Venus: A new periodic spectrum variable. *Astrophys. J. Letters*, **181**, No. 1, L5–L8.