Small-scale turbulence in the Venus middle cloud layer

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Measurements of the Doppler-velocity fluctuations indicated by the radio signals from the *Vega* balloons testify to strong turbulence in the nightside as well as the dayside Venus cloud layer. Wind speeds vary by up to 2 m/sec on time scales of 30–100 sec.

1. INTRODUCTION

Several previous lines of evidence have suggested that the Venus atmosphere is experiencing small-scale turbulent motions. The variations in the descent rate of the Venera-series landers have been attributed to turbulence,[1,2] radio-signal amplitudes fluctuate because of temperature variations,[3-5] and ultraviolet photographs of Venus disclose small convection cells.[6]

The Venera results demonstrated that appreciable turbulence is often, although not always, present above the 40-45 km level; the velocity fluctuations may reach 1-3 m/sec, the turbulence is distributed uniformly, and the motions occur on scales ranging from 300 m to 1000-1200 m. Most recently, the radio amplitude fluctuations have been interpreted as indicating a two-layer distribution of turbulence at heights of about 60 and 49 km, with an outside scale of ≈ 5000 m in the upper layer.

From the Doppler tracking of the Vega balloon probes we now have some new information on the turbulence in the middle cloud layer — one of the regions most important from the standpoint of atmospheric dynamics. When the experiment was in the planning stage it was anticipated the since the balloons would undergo a Lagrangian-type motion (comoving with the air masses), only minor variations in velocity would be observed.

2. MEASURMENTS

To explore the turbulence we have utilized non-interrrogative Doppler measurements at 0.5-sec intervals, as derived at the Institute of Radio Engineering and Electronics in Moscow through digital processing of the signals recorded at the Evpatoriya tracking station. For both balloons the data set comprises 62 intervals, each 332 sec long. Each measurement is subject to less than 5 cm/sec error. Accuracy is limited by the signal/noise ratio and by the short-term stability of the on-board oscillator. In due course data will be obtained from all the telemetry frames for each balloon.

The Doppler-shift variations are directly related to the balloon's actual motions as projected on the line of sight. Thus when the balloon was located near the Venus limb, the variations on Doppler velocity were produced mainly by fluctuations in the horizontal velocity; when near the central meridian, by fluctuations in the vertical velocity; and when in intermediate zones, by a combination of both.

Since the temperature lapse rate at the float height is nearly adiabatic, the small-scale turbulence is presumably isotropic, and the vertical- and horizontal-velocity fluctuations ought to be roughly the same. The balloon's vertical motions on intermediate time scales (fairly long compared with its minimum time constant of 10 sec but short compared with the 300-sec maximum time constant) represent a good tracer of the atmospheric motions. For 30-100 sec time scales a correction factor of ≈1.5 should be applied for vertical motions and ≈ 1.2 for horizontal motions. Later we intend to allow for the balloon dynamics by considering numerical models.

One important remark should now be made. The balloon surface is a quite smooth sphere, and if the relative gas velocities are low (0.5-2 m/sec) the Reynolds numbers will have near-critical values. Experiments in the terrestrial atmosphere indicate[7] that in this event the self-motion of a spherical balloon may be oscillatory, with a period of ⩾ 5 sec. Hence one cannot rule out that the observed Doppler-velocity variations might to some extent result from such a self-oscillating instability. We believe, however, that the character, period, and amplitude of the variations observed all suggest the principal factor is not self-motion but atmospheric turbulence. A firm conclusion on this point will of course require a more careful analysis. Subject to this caveat, we shall henceforth regard the velocity fluctuations with periods ⩾ 30 sec as evidence for turbulence in the Venus atmosphere.

3. RESULTS

The dynamical activity in the atmosphere of Venus has proved considerably stronger and more variable than hitherto suspected — a finding borne out by all the balloon experiments. Figures 1, 2 illustrate typical velocity fluctuations for the two balloons. In each case we show examples of motion

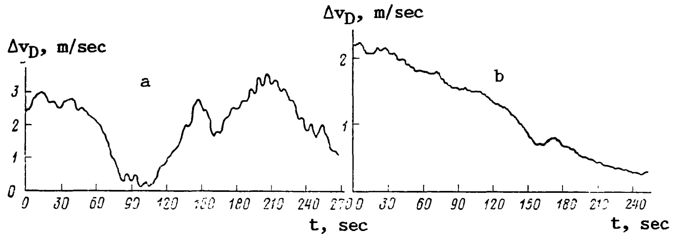

FIG. 1. Sample velocity fluctuations of the Vega 1 balloon, a) Frame 15, commencing at $09^h24^m15^s$ elapsed time (from June 11^d00^h UT); b) frame 17, commencing at $10^h24^m36^s$.

in a calm and in a turbulent atmosphere. For Vega 1 both intervals selected belong to the early part of the flight and therefore exhibit variations in the horizontal velocity; for Vega 2 the curves both represent phases near the end of the active life and correspond to variations in the vertical velocity. The transition time between the quiet and the turbulent periods was comparatively short: 1^h–3^h.

Velocity fluctuations during the Doppler-tracking intervals (each 330 sec long) occurred on two different time scales: 7-10 sec and 60-130 sec. The shorter ones presumably represent pendulum swings of the gondola (a 7-8 sec period). These pendulum oscillations have a very small amplitude, less than 1°, which corresponds to a 1-Hz amplitude in the Doppler-shift variations, or 20 cm/sec in velocity. They are distinctly apparent early in the Vega 1 flight, where considerable turbulence was encountered and where perturbations originating from the balloon deployment and inflation process might still have been present. During this stage the Doppler shift was sensitive to horizontal velocities.

Natural balloon oscillations of a different kind – the vertical excursions occurring as the buoyant craft sought to maintain its equilibrium float height have a much longer period, 300-400 sec. Nevertheless their amplitude (in velocity units) is only ≈20 cm/sec, and they do not significantly affect the interpretation of the Doppler measurements.

Most important of all are the fluctuations with a 60-130 sec time scale, as these are more indicative of true turbulent motions in the atmosphere. Figure 3 plots the maximum amplitudes of Doppler-velocity variation over the life of each balloon. The actual fluctuations in wind velocity exceed these amplitudes by a factor of ≈ 1.5.

It is clear from Fig. 3, as well as from Figs. 1, 2, that the turbulence undergoes strong and irregular changes. We would emphasize that the fluctuations shown here do reflect a genuine variability of the turbulence rather than simply errors of measurement. The Doppler data correlate closely with the balloon's average vertical excursions, as indicated by the temperature and pressure telemetry.

The velocity fluctuations range in amplitude from 0.05 to 1 m/sec for Vega 2, and to as much as 2 m/sec for Vega 1. The changeover from a calm to a turbulent interval can occur rapidly and irregularly (Figs. 1a and 1b, for example, are separated by only 1^h), on both Vega 1 and Vega 2. Even so, certain general features may be noted. During the first 11^h of flight, Vega 1 experienced substantially greater horizontal velocities than Vega 2, whose behavior was very quiet in this phase. By contrast, between elapsed time 24^h and 37^h, when the balloons were near the central meridian (so that the Doppler data were sensitive mainly to vertical-velocity fluctuations), Vega 2 showed two or three times the velocity amplitude of Vega 1.

4. DISCUSSION

If we adopt a 0.2-m/sec fluctuation amplitude as a threshold for the detection of turbulence, we see from Fig. 3 that the probability of turbulence being present over the 4^d cumulative flight time was more than 50%, well above the probability in the terrestrial atmosphere. While a comparably high probability for the incidence of turbulence at these heights in the atmosphere had been deduced from Doppler tracking on the earlier Venera missions, it was entirely unexpected that such substantial turbulence would also be recorded on the night side during an experiment with balloons, which may be regarded as Lagrangian particles moving along with the gas.

The disparity between the Vega 1 and Vega 2 data indicates that the Venus atmosphere contains neighboring regions whose properties differ. Perhaps the strong turbulence encountered by Vega 1 during the first quarter of its flight reflects the fact that Vega 1 was traveling in a warmer air mass.[8,9] It also is possible that the large vertical excursions of the Vega 2 balloon on its second day may have had something to do with its passage above the mountain range in Aphrodite Terra. The most likely cause of turbulence at the float altitudes would be thermal convection (the temperature gradient is nearly adiabatic here[8,9]).

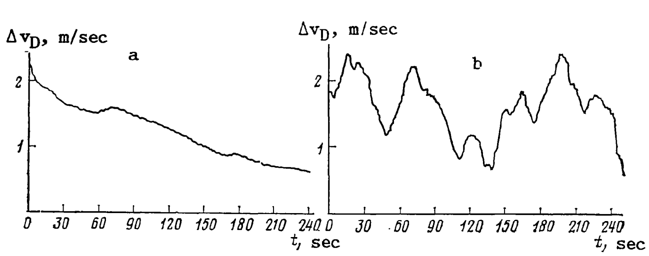

FIG. 2. Sample velocity fluctuations of the Vega 2 balloon. a) Frame 50, commencing at $33^h02^m30^s$ elapsed time (from June 15^d00^h UT); b) frame 56, commencing at $36^h03^m35^s$.

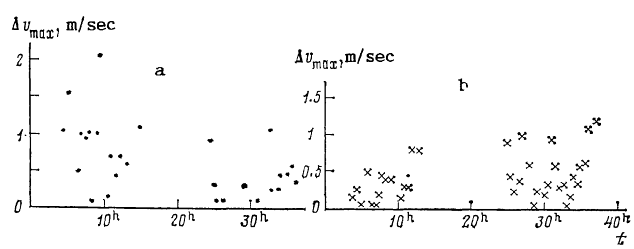

FIG. 3. Maximum amplitude of velocity variations attributable to turbulence for: a) the Vega 1 balloon; b) Vega 2.

Conceivably the 30-130 sec velocity fluctuations may represent the evolution of small convection cells, while the 30-90 min alternation of calm and turbulent zones may be associated with large cells. The travel speed of the windblown balloons was ≈70 m/sec, so in 60 sec (the average time scale of the turbulence) they covered ≈ 4 km, and in 330 sec (the length of a telemetry period) about 20 km. Between successive telemetry frames the balloons moved 130-250 km. Presumably the convection cells would have been treaveling somewhat more slowly than the mean zonal flow, at velocities a few meters per second below the average wind speed. In this event the 60-sec velocity fluctuations would correspond to cells several hundred meters across, and the 30-60 min variations to big cells measuring tens of kilometers in diameter. Interestingly, cells of this size were in fact observed at the top of cloud deck in the ultraviolet photographs [10] taken by Mariner 10, and they lasted several tens of minutes, similar to the lifetime indicated by the Vega Doppler tracking.

Both balloons were floating near the 54-km level, right between the presumed turbulent layers at 49 and 60 km which, according to Woo and Armstrong,[4] cause the fluctuations in radio-signal amplitude observed in radio sounding experiments. The balloon data confirm the findings from the Venera missions that the middle cloud layer is strongly turbulent as well, but with a more uniform turbulence distribution. The reason for this seeming discrepancy, as suggested previously,[2] might be that the radio amplitude fluctuations exhibit the effects of temperature pulsations, which in turn could stem from wind-speed pulsations that would disturb balloons floating in the atmosphere.

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Implications of preliminary *Vega* balloon results for the Venus atmosphere dynamics

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The typical 1–2 m/sec vertical winds encountered by the *Vega* balloons probably result from thermal convection. The consistent 6.5-kelvin differential between the *Vega 1* and *Vega 2* temperatures is attributable to disturbances of synoptic or planetary scale. According to the Doppler tracking the winds were stronger than on earlier missions, perhaps because of solar thermal tides. The motions of *Vega 2* may have been affected by waves from mountainous terrain.

The Vega balloon experiment was designed to investigate certain characteristics of the Venus atmosphere at the float height, including the horizontal and vertical winds as well as the structure and properties of the cloud layer, with a goal of learning more about the dynamical processes at work there. In this letter we offer a provisional interpretation of the balloon measurements. Since the data are still being reduced, our comments are subject to future modification and supplement. In fact some of the experimental results, such as the VLBI trajectory determinations, are not yet available.

The vertical transport of momentum and heat is one of the principal factors controlling the general atmospheric circulation, so the Vega balloon vertical-wind measurements are of much interest. Among the most notable features of the data processed thus far is the high value of the vertical wind speed w, encountered not only on the day side but on the night side of the planet. The w values typically exceed 0.5 m/sec, and the peak vertical velocities reach 4-5 m/sec. Since the vertical-wind data contain a telemetry ambiguity, [1] the peak amplitudes might be smaller than we have reported,[2] but the mean amplitudes would not be affected.

Presumably the occurrence of substantial vertical

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