HIGH-LATITUDE ZONAL WINDS IN THE VENUSIAN ATMOSPHERE FROM VENERA-15 AND -16 RADIO OCCULTATION DATA

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Abstract

Vertical temperature and pressure profiles in the atmosphere of Venus obtained by the radio occultation (RO) method using the Venera-15 and -16 spacecraft measurements made from October 1983 to September 1984 are used for a wind speed analysis. The altitude and latitude profiles of a zonal wind speed in the middle atmosphere for Northern and Southern hemispheres of planet at altitudes from 50 to 80 km and in the latitude interval from 60° to 85° have been found. Zonal wind speeds were determined assuming cyclostrophic balance. The jet with a maximum wind speed ~100 m/s located at an altitude of ~60 km and latitudes 73–75°N is shown to exist in the Northern near-polar atmosphere. Above an altitude level of 65 km in the Northern hemisphere, the polar atmosphere is warmer than the near-polar one and a wind speed usually decreases with increasing altitude at these levels. The wind speed determination results at Southern latitudes show clearly the presence of the jet with a maximum speed ~115 m/s located at an altitude of ~62 km and latitudes 70–72°S. These high-latitude jets are due to by the negative latitude-temperature gradients at altitudes below jet axes in the near-polar atmosphere.

Introduction

The available data indicate a zonal wind rotation of the Venus's atmosphere from East to West. The wind speed changes almost monotonically with altitude, reaching about 100 m/s at the level of upper cloud layer. The strong zonal winds near the cloud tops and below are essentially in cyclostrophic balance in which the equatorward horizontal component of centrifugal force on a zonally rotating atmospheric parcel is balanced by the poleward meridional pressure gradient force (Leovy, 1973; Schubert et al., 1980; Schubert, 1983; Newman et al., 1984). The cyclostrophic balance approximation and results of the temperature and pressure determination from the RO data of Pioneer Venus Orbiter were used to derive the zonal wind profiles in the atmosphere of planet (Newman et al., 1984; Limaye, 1985). The zonal wind speeds were determined at altitudes from 40 to 80 km in the latitude range from 15 to 85° under the assumption of the thermal symmetry in the Northern and Southern hemispheres (Newman et al., 1984). The authors of the work (Newman et al., 1984) have indicated that the radio occultation events used in their study had been carried out, in general, at low latitudes (below 65°S) in the Southern hemisphere, and at high latitudes (>60°N) in the Northern one. However, they did not exclude the violation of hemispheric symmetry at high latitudes. The vertical pressure and temperature profiles from the Venus Express RO sounding (Tellmann et al., 2009) were used to derive cyclostrophic zonal winds in the mesosphere of Venus assuming hemispheric symmetry, also (Piccialli et al., 2012). In the investigation made by (Piccialli et al., 2012), the selected 116 vertical profiles had a complete latitudinal coverage in the Southern hemisphere only, but measurements in the Northern hemisphere were mainly constrained to high latitudes. In this context, it is important to derive the zonal wind speeds for the Northern and Southern hemispheres, separately. The aim of our research is to determine a zonal wind speed in the polar and near-polar regions of Venus at altitudes from 50 to 80 km from an analysis of the Venera-15 and -16 spacecraft RO data.

Processing and analysis of the original Venera-15 and -16 radio occultation data

For determining the zonal wind speed we used the cyclostrophic balance approximation and results of the RO measurements at latitudes from 60 to 87° in 17 regions of the Southern hemisphere, and in 27 regions of the Northern hemisphere of Venus. These measurements were made during the period from October 1983 to September 1984. Orbits of the Venera-15 and -16 spacecraft were such that the entries into occultation took place in the Northern hemisphere and exits in the Southern one. Some information about the Venera-15 and -16 spacecraft investigations, the dates and locations of the RO measurements in latitude, longitude, solar zenith angle can be found in the works (Yakovlev et al., 1991; Gubenko et al., 2001, 2008; Gubenko, Andreev, 2003). To find a zonal wind speed, we used the altitude profiles of temperature and pressure obtained from the processing of radio occultation data at a decimeter radio wavelength (λ = 32 cm). The characteristic properties of the RO technique and experimental data processing are described by (Yakovlev et al., 1991; Gubenko et al., 2008). The results of the radio occultation data processing are the vertical temperature and pressure profiles, which provide the values of these parameters at various altitudes in the interval from 40 to 90 km (Yakovlev et al., 1991). In the range of pressure variations from 1098 to 5 mbar corresponding to the 50–80 km altitude interval, we marked 28 fixed "standard" pressure levels (nodes). The temperatures at these nodes were found by linear interpolation based on the RO temperature retrievals in the points nearest to the chosen levels. The number of chosen nodes allowed the retention of individual characteristics in the temperature profiles.

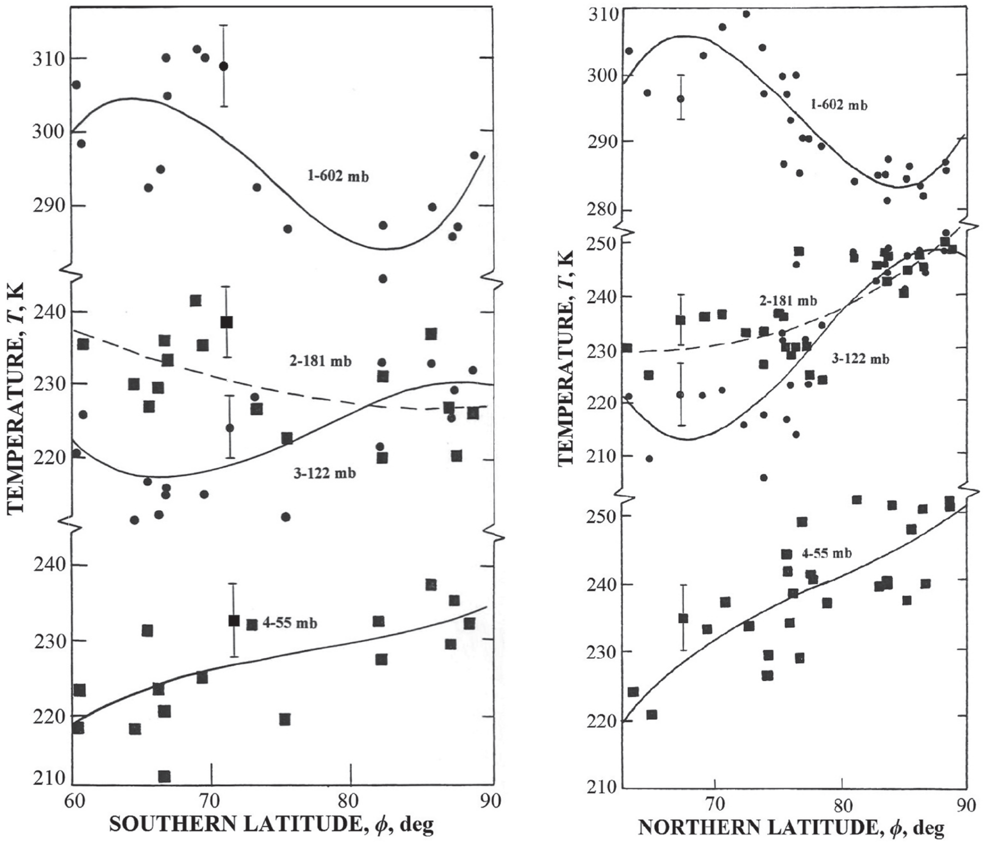

Figure 1: Profiles of temperature on latitude in the Southern (left panel) and Northern (right panel) hemispheres of Venus at four pressure levels: 1–602 mbar; 2–181 mbar; 3–122 mbar; 4–55 mbar

Fig. 1 shows examples of latitude dependence of temperature at four constant pressure levels in the Southern (left panel) and Northern (right panel) hemispheres of Venus. The temperature values obtained from the RO data at corresponding latitudes and pressures are shown by circles and squares in Fig. 1. The circles apply to the curves 1 and 3, the squares — to the curves 2 and 4. The curves describing the latitude-temperature profiles are the cubic polynomials fitted by the least squares technique to the experimental data. These least squares fits were used in order to obtain the latitude-temperature gradients. The quality of fitting is defined by the root mean square variance σ on the every "standard" pressure level (representative values of σ are drawn as error bars for each curve in Fig. 1). From fitted curves in Fig. 1 (left panel) it is seen that the temperature decreases with increasing Southern latitude at a pressure level 602 mbar in the latitude interval from 66 to 82°S. This trend is characteristic also for latitude-temperature dependence at lower pressure levels down to 180 mbar. The transitional region lies within the pressure range of 180 to 120 mbar, corresponding to altitudes from 61 to 63 km, where a change of the sign of latitude-temperature gradient occurs in the latitude interval from 66 to 82°S as shown in Fig. 1 (curves 2 and 3, left panel). Small temperature contrasts between the Southern polar and near-polar atmosphere are characteristic of the transitional region (Yakovlev et al., 1991). In the Southern hemisphere, the temperature increases with increasing latitude at fixed pressure levels from 120 to 30 mbar, which correspond to altitudes from 63 to 70 km. For determining the zonal wind speed in the Northern hemisphere, we use the temperature and pressure data obtained from radio occultation in 27 regions at latitudes more than 60°N (Yakovlev et al., 1991). The temperature decreases with increasing latitude at a level of 602 mbar in the latitude interval from 69° to 84°N. This trend continues at lower levels down to 220 mbar. A change of sign of the latitude-temperature gradient at Northern latitudes from 69° to 84°N occurs in the pressure range from 220 to 180 mbar. A transitional atmospheric region, for which small values of the latitude-temperature gradient are characteristic, exists in this pressure range corresponding to the altitude interval from 60 to 61 km. Curve 2, corresponding to the upper boundary of this transitional region in the Northern hemisphere of Venus, illustrates this tendency. A temperature rise with increasing latitude (curves 3 and 4, right panel) is observed at pressure levels lower than 180 mbar. By comparing the latitude profiles of temperature in the Northern and Southern hemispheres, one notices that the latitude-temperature gradients are negative at pressures from 1100 to 220 mbar at high latitudes from 70 to 80°, and their values are almost the same at corresponding latitudes and pressure levels in the Northern and Southern hemispheres of Venus. This indicates hemispheric symmetry of the thermal structure in this pressure range. However, indicated symmetry no longer exists at pressures lower than 220 mbar, i.e. at altitudes higher than 60 km.

Technique of determining the zonal wind speed

It is known that the Venus's atmosphere from an altitude of ~10 km to the cloud tops in non-equator regions is in a state of approximate cyclostrophic balance, i.e. a dynamic state where the centrifugal force component directed towards the equator is balanced by the poleward meridional pressure gradient force (Schubert, 1983). Leovy (1973) first suggested that a cyclostrophic balance approximation is valid on Venus for both the upper and lower atmosphere layers. Following Schubert (1983) and Newman et al. (1984), the cyclostrophic balance equation can be written:

$$\frac{u^2}{a}\tan\varphi = -\frac{1}{\rho}\cdot\frac{\partial p}{\partial y}, \tag{1}$$

where u is the zonal wind speed; ρ is the atmosphere density; φ is latitude; y is a locally poleward pointing Cartesian coordinate; a is the radius of Venus; and p is the pressure. The validity of using Eq. (1) for the description of the middle atmospheric dynamics of Venus was proven by comparing the values of zonal wind speeds obtained on the basis of this approximation applied to the results of temperature and pressure measurements on Pioneer Venus probes (Seiff et al., 1980; Schubert et al., 1980; Seiff, 1982; Schubert, 1983) with the results of direct zonal wind measurements with the differential long-baseline interferometry experiment (Counselman et al., 1980). Taking into account the hydrostatic equation and the perfect gas law, one can find the thermal wind equation for cyclostrophic balance from Eq. (1):

$$2u\frac{\partial u}{\partial \xi} = -\frac{R}{\tan\varphi}\cdot\left.\frac{\partial T}{\partial \varphi}\right|_p, \tag{2}$$

where $R = 191.4$ J·kg^{-1}·K^{-1} is the gas constant of the Venus's atmosphere; $\xi = -\ln\,(p/p_0)$ is the log pressure coordinate; and $p_0 = 1098$ mbar is the pressure at a level assumed to be the lower boundary. For convenience of calculations, it is advantageous to integrate Eq. (2) normal to isobaric surfaces using a trapezoidal formula (Newman et al., 1984):

$$u_{n+1}^2 = u_n^2 - \frac{R\Delta\xi}{2\tan\varphi}\left[\frac{\partial T}{\partial \varphi_{n+1}} + \frac{\partial T}{\partial \varphi_n}\right], \tag{3}$$

where $\Delta\xi = \xi_{n+1} - \xi_n = \ln(p_n/p_{n+1})$, indices n and (n+1) correspond to adjacent pressure levels. The value of the index n increases with increasing altitude and changes from 0 to 27. The value $n = 0$ corresponds to the pressure $p_0 = 1098$ mbar, and $n = 27$ corresponds to the pressure 5 mbar. Pressure values on any adjacent levels chosen by us meet the condition $\Delta\xi = \ln(p_n/p_{n+1}) = 0.2$. The relationship determining the zonal wind speed u on an arbitrary pressure level (n+1) for given latitude φ follows from formula (3):

$$u_{n+1}^2 = u_0^2 - \frac{R\Delta\xi}{2\tan\varphi}\left[\frac{\partial T}{\partial \varphi_0} + \frac{\partial T}{\partial \varphi_{n+1}} + 2\sum_{i=1}^{n}\frac{\partial T}{\partial \varphi_i}\right]. \tag{4}$$

It is seen from expression (4) that, in addition to the latitude-temperature gradients, the latitude dependence of the zonal wind speed $u_0(\varphi)$ at the pressure level $p_0 = 1098$ mbar (lower boundary) must be known in order to calculate the wind speed field. The following expression was chosen to represent the lower boundary condition $u_0(\varphi)$ for both the Northern and Southern hemispheres of Venus:

$$u_0(\varphi) = 47.29 + 3.94(|\varphi| - 60) - 0.37(|\varphi| - 60)^2 + 6.1 \cdot 10^{-3}(|\varphi| - 60)^3, \quad (5)$$

where φ is expressed in degrees and u_0 is expressed in m/s. The choice $u_0(\varphi)$ for the Northern hemisphere corresponds to the results given in Fig. 9 by (Newman et al., 1984). Since data about circulation at high latitudes of the Southern hemisphere are absent at present, the application of the same function $u_0(\varphi)$ here is based on the assumption of a circulation symmetry in the two hemispheres at the level p_0 = 1098 mbar. An indirect evidence for this suggestion is the thermal structure symmetry for both hemispheres at pressure levels more than 220 mbar (Yakovlev et al., 1991), as discussed above.

Zonal winds in the Southern and Northern hemispheres of Venus

The previous circulation observations of the Venus's zonal speed exhibited a strong mid-latitude jet centered between 50 and 55° latitude with a maximum speed ranging from ~110 m/s (Zasova et al., 2000) to ~140 m/s (Newman et al., 1984). The Venera-15 and -16 radio occultation data have shown strong zonal jets with a maximum speed of 100–115 m/s centered at high latitudes (>70°) of both Southern and Northern hemispheres of Venus (Gubenko et al., 1992; Vaganov et al., 1992). The Northern high-latitude jet with a speed of 95 m/s centered at 70°N and 60 km altitude have been detected in the Pioneer Venus data, also (Newman et al., 1984). The vertical profiles of the zonal wind speed in the near-polar atmosphere of the Southern (left panel) and Northern (right panel) hemisphere of Venus at three latitude levels are given in Fig. 2. The altitude dependence of the zonal wind speed in the Southern near-polar atmosphere at latitudes of 66, 68 and 70°S are shown by curves 1, 2 and 3 in Fig. 2 (left panel). A common feature of vertical profiles of the wind speed at these latitudes is a speed increase with increasing altitude from 50 to 62 km. At an altitude of ~62 km corresponding to a pressure ~149 mbar, the wind speed reaches its maximum 114 m/s at the latitude 70°S, 106 m/s at 68°S, and 94 m/s at 66°S. The altitude dependence of the zonal wind speed in the Northern near-polar atmosphere at latitudes of 74, 76 and 78°N are shown by curves 1, 2 and 3 in Fig. 2 (right panel). It is seen that the wind speed increases with increasing altitude between 50 and 60 km at these latitudes. At an altitude of ~60 km corresponding to a pressure ~220 mbar, the wind speed reaches a maximum of 102 m/s at the latitude 74°N, 100 m/s at 76°N, and 90 m/s at 78°N. As it is followed from Fig. 2, the zonal wind speed decreases quickly with increasing altitude above 60 km and actually is zero at an altitude of 75 km, which is a characteristic of the Northern high-latitude atmosphere. In the Southern hemisphere, such circulation suppression is not observed. Fig. 3 shows examples of latitude dependence of the zonal wind speed at four constant pressure levels in the Southern (left panel) and Northern (right panel) hemispheres of Venus. It is seen from Fig. 3 (left panel) that there are maxima in the wind speed at Southern latitudes from 70 to 72°S. It points to the existence of the jet with the speed maximum ~115 m/s in this latitude interval of the Southern hemisphere, the center of which is located at an altitude of ~62 km. This jet is due to a negative latitude-temperature gradient at altitudes from 50 to 62 km in the Southern near-polar atmosphere of Venus. The results shown in Fig. 3 (right panel) reveals the jet in the latitude interval from 73° to 75°N of the Northern hemisphere with the wind speed maximum ~100 m/s, which is located at an altitude of ~60 km. The high-latitude jets found at Southern and Northern latitudes are due to by the negative latitude-temperature gradients at altitudes below jet axes in the near-polar atmosphere of Venus.

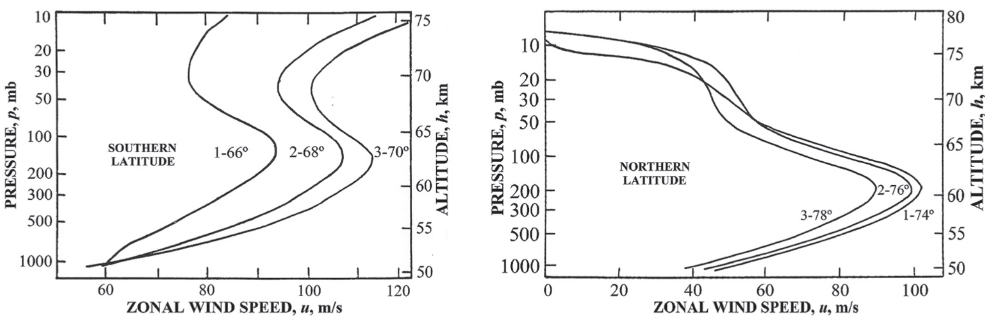

Figure 2: Vertical profiles of the zonal wind speed in the near-polar atmosphere of the Southern (left panel) and Northern (right panel) hemisphere of Venus at three latitude levels

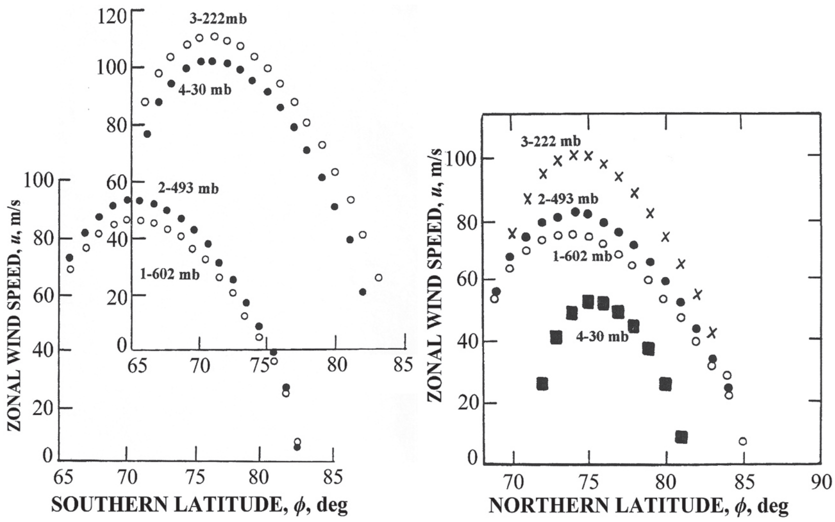

Figure 3: Latitude profiles of the zonal wind speed in the Southern (left panel) and Northern (right panel) hemispheres of Venus at four pressure levels: 1–602 mbar; 2–493 mbar; 3–222 mbar; 4–30 mbar

Conclusion

An analysis of the Pioneer Venus and Venera-15, -16 data on atmospheric circulation at high latitudes of the Northern hemisphere of Venus have provided evidence of the zonal wind speed stability at altitudes below 59 km in the time interval of 5 years between above-mentioned RO measurements. According to our results and data of (Newman et al., 1984), the high-latitude jet was observed in the Northern near-polar atmosphere, having a maximum speed of 95–100 m/s. The jet axis altitude remained practically the same (~60 km), and the jet axis latitude was confined in the interval 70°–74°N. If a small change in latitude (~4°) of the jet position is real, then this is important for understanding the dynamical processes in the Venus's atmosphere. A characteristic feature of the atmospheric state at high latitudes is the suppression of zonal circulation at altitudes >75 km in the Northern near-polar atmosphere of Venus. In the Southern hemisphere, such circulation suppression is not observed. The comparison of the wind speeds in both hemispheres indicates approximate hemispheric symmetry relative to the equatorial plane at altitudes below 59–60 km. According to our analysis of the Venera-15 and -16 data, there appears to be a violation of the hemispheric circulation symmetry at high latitudes above ~63 km.

Acknowledgements

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