# Solar Tides in the winds of the southern polar region of Venus using VIRTIS-M/VEX images.

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## ABSTRACT:

The effect of the solar tides on the winds at the top of the clouds in Venus has been studied for the first time with same altitude winds from the day and nightside simultaneously. In the latitude range between 70ºS and 85ºS a clear diurnal tide (wavenumber 1) affects the meridional component of the wind, with amplitudes and phases suggestve of a solar-anti-solar circulation. A meridional wavenumber 6 and a vertical wavelength of ~240 m are estimated through the meridional variation of the tidal amplitude. The associated thermal structure is also studied and compared with numerical models and previous missions.

## DATA DESCRIPTION AND METHOD:

Using automatic cloud tracking [4] more than 14,000 wind measurements have been extracted from pairs of VIRTIS-M images at wavelengths 3.9 and 5.0 μm, thermal radiation from the tops of the Venusian clouds (~65 km). This has allowed to explore for solar tides and other waves in the windfield at the day and night side simultaneously. Latitudes between 70ºS-80ºS and a total of 289 days were covered by the data.

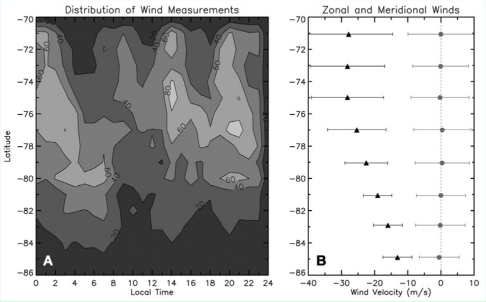


**Figure 1:**
The graph (A) on the left displays the coverage of our wind measurements in terms of local time and latitude, while what graph (B) exhibits is the meridional profile for the zonally averaged zonal (black triangles) and meridional (grey circles) components of the wind.

The complete procedure was the following:

1º) Low-quality wind measurements are filtered using a weighted mean that was applied to latitude intervals of 1º.

2º) Once we have the zonal average for the zonal and meridional components, we subtract them to obtain the wind disturbances.

3º) Wind disturbances are sortered in latitude intervals, in local time coordinates and, finally, averaged to infer the solar-fixed wind disturbances.

4º) A Lomb-Scargle Periodogram is used to find the main solar harmonics. A sine fit is applied for a physical characterization and confirmation.

5º) The Amplitude and Phase of the waves are studied to characterize the horizontal structure and constrain several atmospheric parameters.

## SOLAR TIDE EFFECTS ON THE WIND:

The zonal and meridional wind disturbances (sorted in local time) were studied within latitude intervals of 1º. While the meridional disturbances exhibit a strong and clear effect of the diurnal tide, for the zonal case the tidal effect is weak or absent.

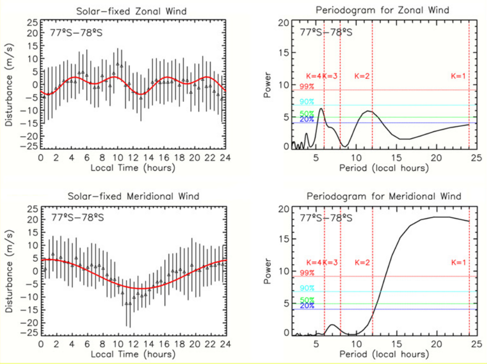
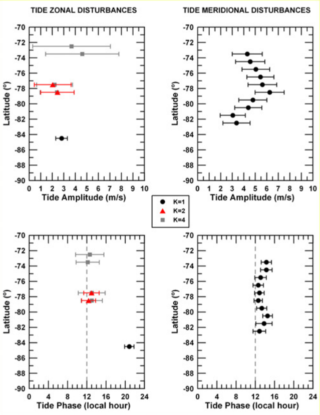


**Figure 2:**
The tidal harmonics detected for the latitude interval 77ºS-78ºS are exhibited here. The graphs on the left display the averaged wind disturbances in solar-fixed coordinates, and the best tidal fit is shown in red. The graphs on the right are the corresponding Lomb-Scargle periodograms, showing the main tidal harmonics (dashed vertical lines) and confidence levels (dashed horizontal lines). Graphs above belong to the zonal disturbances, while the ones below are for the meridional ones.

Figure 3, on the left, exhibits the latitude dependence for the main tidal parameters from our fits. Amplitude and phase for the zonal (left) and meridional component (right) are displayed. Tidal harmonics with zonal wavenumber 1, 2 and 4 are each marked with black circles, red triangles and grey squares. The phase indicates the local time where we have westward and poleward accelerations (for zonal and meridional case, respectively). Clearly, the tidal amplitudes in the meridional direction are crucial in determining the sense of the meridional flow, and they seem to imply a solar-antisolar circulation with a poleward acceleration in the day side and equatorwards in the night side.



## SPATIAL STRUCTURE FOR THE DIURNAL TIDE:

In the case of the Earth, the horizontal structure of the solar tides is well described as an expansion of Hough functions, which are solutions of the Laplace Tidal Equation. This solution is determined by the ratio of the sidereal and solar days [2]. In Venus, this ratio for the diurnal tide is close to the one for the terrestrial semidiurnal tide [3]. However, it has not been possible to fit the Venus diurnal tide using Hough functions; an alternative approach based on a Legendre polynomial expansion was followed here.

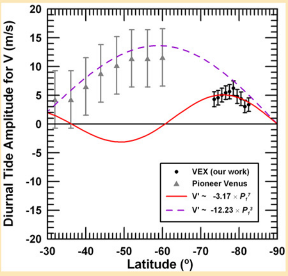
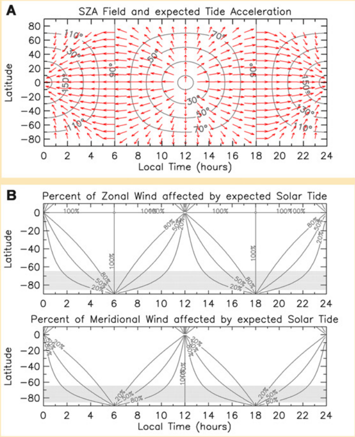


**Figure 4:**
Latitude profiles for the diurnal tide amplitudes affecting the meridional component of the wind in 1982 from the Pioneer Venus data [1] and from our work with Venus Express data covering years 2007-2008. Due to the limited latitude coverage, expansions were carried out using a single normalized Legendre polynomial $P_s^n$ with a fixed zonal wavenumber $s=1$ and varying the mode $n$. The meridional wavenumber is, then, $(|n|-s)$ [2]. A meridional wavenumber 2 is found for the Pioneer Venus data, while 6 is inferred from our work, what also implies a vertical wavenumber of about 240 m if we assume for the diurnal tide the dispersion equation for long gravity waves in a fluid with constant Brunt-Vaisala frequency [5].

Figure 5 (right) displays tidal accelerations and expected flow when we have the case of wave fronts tangent to the Solar Zenith Angle isolines (panel 5A). The corresponding degree of tidal influence on both zonal and meridional components of the wind attending to the latitude and local time is shown in panel 5B, with the latitude region of our study shaded. This horizontal structure for the diurnal tide, with zonal retrograde acceleration at the evening terminator and poleward acceleration in the day side, is not only consistent with our results, but also helps to explain the non-detection of a diurnal tidal effect in the zonal direction.



## ASSOCIATED THERMAL STRUCTURE FOR DIURNAL TIDE:

Introducing the Rayleigh friction forcing in the momentum equations and removing the Coriolis terms, one can arrive at the following expressions [7]:

$$\left[i\cdot\left(\Omega+\frac{\overline{u}}{a\cdot\cos\phi}\right)+K_R\right]\cdot u'+\left(\frac{1}{a}\frac{\partial\overline{u}}{\partial\phi}-\frac{\overline{u}}{a}\tan\phi\right)\cdot v'+\left(\frac{\partial\overline{u}}{\partial z}+\frac{\overline{u}}{a}\right)\cdot w'=-\frac{i}{\rho_0\cdot a\cdot\cos\phi}\cdot P'$$

$$\left(\frac{2\cdot\overline{u}}{a}\tan\phi\right)\cdot u'+\left[i\cdot\left(\Omega+\frac{\overline{u}}{a\cdot\cos\phi}\right)+K_R\right]\cdot v'=-\frac{1}{\rho_0\cdot a}\cdot\frac{\partial P'}{\partial\phi}$$

Adding both equations and separating real and imaginary parts, further operations leads to the next expression, valid when $u'\approx 0$ and $w'\approx 0$:

$$T'\approx-\frac{1}{R}\cdot(\overline{u}+\Omega\cdot a\cdot\cos\phi)\cdot(v')$$

This allows to estimate the thermal disturbances associated to the tidal effects. Figure 6 shows a comparison with previous missions and numerical models.

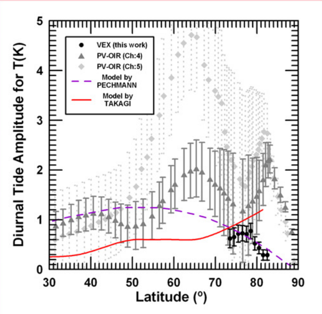


**Figure 6:**
Latitudinal profiles for the diurnal tide amplitudes affecting the atmospheric temperature. There seems to be a good accordance with the represented models for solar tides in Venus [5,6], and discrepancies lower than 2ºK with temperature amplitudes by PV-OIR [5].

## CONCLUSIONS:

- Solar Tides are detected in the windfield of the southern polar region of Venus.
- Stronger amplitudes are found for disturbances in the meridional component of the wind.
- The diurnal tide seems to only affect the meridional component, what suggests tidal wave fronts aligned with SZA isolines. Weaker semi-diurnal and quarter-diurnal harmonics are found for the zonal wind. The apparent decoupling in both components agrees with isothermal atmospheric conditions [7].
- The diurnal tide fits a meridional wavenumber 6 and vertical wavelength of ~240 m. It can determine the meridional sense, apparently forcing solar-antisolar circulation across the pole.
- Tidally induced thermal disturbances seem proportional to the ones in the meridional wind, and are in the range of magnitudes of numerical models [5,6] and results from previous missions [5].

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