CUME 342
Administered by Jim Murphy
March 07, 2009

This exam is based upon material presented in the accompanying journal paper, "**Variable winds on Venus mapped in three dimensions**", by Sanchez-Lavega et al., Geophysical Research Letters, Vol 35, L13204, doi:10.1029/2008GL033817, 2008.

It is anticipated that a score of 70% (= 59.5 points) on the exam will constitute a 'PASS' grade. The exam is worth a total of 85 points.

Possibly Useful Constant Values:

Venus' Orbital semi-major axis = 0.72 AU
Venus' surface gravitational acceleration = 8.89 m s^{-2}
Venus' Geometric albedo (integrated over wavelength) = 0.85
Venus' Phase function (integrated over wavelength) = 0.9
Venus' density = 5.2 g cm^{-3}
Venus' surface pressure = 90 bar (9 x 10^6 Pa)
Venus' Sidereal rotation period = 243 days (retrograde)
Venus' atmospheric composition: ~96.5% CO_2, ~3.5 N_2, … other minor species
Specific heat at constant pressure (C_p) of CO_2 = 850 J kg^{-1} K^{-1}
Dynamic Viscosity of CO_2 = (1.59 x 10^{-6} x ($T^{1.5}$))/(T+244.4) where T = atmospheric temperature in Kelvin; units are kg m^{-1} sec^{-1}
Gas Constant for CO_2 = 189 J kg^{-1} K^{-1}
Specific heat at constant volume (C_v) for CO_2 = 661 J kg^{-1} K^{-1}

I) WRITE ON ONLY ONE SIDE OF YOUR ANSWER PAGES.

II) CLEARLY NUMBER YOUR ANSWERS TO THE QUESTIONS, AND WHEN YOU HAVE COMPLETED THE EXAM STAPLE YOUR ANSWERS TOGETHER IN THE PROPER NUMERIC ORDER.

III) IF YOU DO NOT PROVIDE AN ANSWER FOR A QUESTION, BRIEFLY INDICATE THAT SITUATION ON YOUR ANSWER PAGES.

SECTION I: OBSERVATIONS / SPACECRAFT (27.5 points)

1) Describe the physical conditions of and within the venusian cloud layers that permit the discrimination of the three distinct vertical layers that the VIRTIS instrument is able to investigate with its 380 nm, 980 nm, and near IR (1.7μm and 2.3μm) wavelength channels. You should address each of the three wavelengths employed by VIRTIS and how they are able to provide for the determinations arrived at in this paper. [**10 points**]

2) Discuss how effective the three VIRTIS wavelengths would be in investigating clouds and winds in Mars' atmosphere. Indicate why situations would be similar or different to those in Venus' atmosphere. [**5 points**]

3) Describe how spectral measurements in the 15 μm wavelength region can potentially provide information about the atmospheric temperatures in the three venusian altitude layers investigated in this paper. Discuss what physical limitations might prevent the cloud altitude levels from actually being probed in this way. [**7.5 points**]

4) Calculate the length of time required for the Venus Express spacecraft to have reached Venus if it was launched on a minimum energy orbit path. [**5 points**]

SECTION II: ATMOSPHERIC DYNAMICS (27.5 points)

5) The authors, in paragraph #2 of the text, invoke the concept of "cyclostrophic wind", for which there is a balance between the pressure gradient force and centripetal force. The authors do not invoke the more commonly employed "geostrophic wind" concept.

a) Provide an explanation that clearly indicates why the cyclostrophic wind approximation is more appropriate than the geostrophic wind approximation in the context of this paper. [**5 points**]

b) Quantitatively demonstrate that the geostrophic wind approximation is not appropriate for the majority of the conditions indicated within this paper. [**5 points**]

6) Define/describe the basic thermodynamics of a "HADLEY CIRCULATION", and include an appropriate drawing to illustrate the nature of such a circulation. [**5 points**]

7) For the latitudinal variation of zonal wind speeds (in the region from the equator to 50 South latitude) presented in Figures 1A and 2A, indicate both **quantitatively** and in a **written** description form if those wind structures satisfy angular momentum conservation constraints for air moving from equator to pole (or pole to equator). [**12.5 points**]

SECTION III: ATMOSPHERIC THERMODYNAMICS (30 points)

8) Venus' observed globally averaged ground temperature is 730 Kelvin. Quantitatively determine the magnitude of Venus' GREENHOUSE warming of its surface. That is, how much hotter is Venus' ground temperature than it would be in the absence of its greenhouse producing atmosphere? Indicate any assumptions you make in arriving at your answer. **[7.5 points]**

9) Provide a quantitative estimate of the venusian atmosphere's infrared opacity assuming Venus' atmosphere is in radiative equilibrium. Your answer to Question 8 is valuable here; if you did not obtain an answer for Question #8 make a good guess for that temperature and indicate that guessed value. Describe your ideas and methods for arriving at your quantitative estimate. **[10 points]**

10) With Venus' ground temperature being 730 Kelvin, what is the minimum temperature that can be thermodynamically anticipated at the base (bottom) of Venus' lower cloud deck? Describe your reasoning. Is this a realistic temperature?**[7.5 points]**

11) The venusian clouds are composed of sulfuric acid. That acid is photochemically produced by the dissociation of sulfur dioxide (by wavelengths <= 230 nm) and subsequent combination of the dissociation products with free oxygen atoms and with water molecules. The resultant vapor ultimately condenses to form cloud-sized particles.

With the above information in mind, does the <u>cloud formation process</u> likely play a role in affecting the vertical temperature structure within the vertical region containing the three cloud layers? Explain your reasoning. **[5 points]**

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Variable winds on Venus mapped in three dimensions

A. Sánchez-Lavega,[1] R. Hueso,[1] G. Piccioni,[2] P. Drossart,[3] J. Peralta,[1] S. Pérez-Hoyos,[1] C. F. Wilson,[4] F. W. Taylor,[4] K. H. Baines,[5] D. Luz,[3,6] S. Erard,[3] and S. Lebonnois[7]

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[1] We present zonal and meridional wind measurements at three altitude levels within the cloud layers of Venus from cloud tracking using images taken with the VIRTIS instrument on board Venus Express. At low latitudes, zonal winds in the Southern hemisphere are nearly constant with latitude with westward velocities of 105 ms^{-1} at cloud-tops (altitude $\sim$ 66 km) and 60–70 ms^{-1} at the cloud-base (altitude $\sim$ 47 km). At high latitudes, zonal wind speeds decrease linearly with latitude with no detectable vertical wind shear (values lower than 15 ms^{-1}), indicating the possibility of a vertically coherent vortex structure. Meridional winds at the cloud-tops are poleward with peak speed of 10 ms^{-1} at 55° S but below the cloud tops and averaged over the South hemisphere are found to be smaller than 5 ms^{-1}. We also report the detection at subpolar latitudes of wind variability due to the solar tide.
Citation: Sánchez-Lavega, A., et al. (2008), Variable winds on Venus mapped in three dimensions, *Geophys. Res. Lett.*, *35*, L13204, doi:10.1029/2008GL033817.

1. Introduction

[2] The three-dimensional structure of the winds on Venus within the cloud and haze layers (altitudes 30–70 km) is dominated by a strong westward zonal flow (the super-rotation), which has been measured by numerous spacecraft and ground-based telescopic observations (see *Schubert* [1983] and *Gierasch et al.* [1997] for detailed reviews up to 1997 and *Limaye* [2007] and *Peralta et al.* [2007] for extended recent analysis). Fluctuations in the mean wind speed due to the thermal solar tide and other wave motions have also been detected. A meridional poleward motion has been identified in the upper cloud [*Belton et al.*, 1991; *Limaye*, 2007], but there are few measurements of the magnitude of the flow below the level of the upper cloud [*Belton et al.*, 1991; *Carlson et al.*, 1991]. The heterogeneous nature of the measurements, and limitations in their spatial and temporal coverage, have so far prevented a deep understanding of the general circulation in the three main cloud layers. For example, in situ measurements during the descent of the Venera series and Pioneer Venus atmospheric entry probes occurred at single locations and at a particular local time [*Schubert*, 1983; *Gierasch et al.*, 1997, and references therein], while the Vega balloons did not drift much in latitude and altitude within the middle cloud [*Preston et al.*, 1986]. Cloud tracking studies performed by flyby spacecraft (Mariner 10 and Galileo) and ground-based observation are necessarily limited in temporal coverage [*Limaye and Suomi*, 1981; *Carlson et al.*, 1991; *Crisp et al.*, 1991; *Peralta et al.*, 2007]. The most extensive dataset used for cloud-tracking was obtained over nine years by the Pioneer Venus Orbiter OCPP; however, the cloud tracking was mainly at a single wavelength (365 nm) [*Rossow et al.*, 1990; *Limaye*, 2007]. Finally, indirect estimations of the zonal wind speeds made from temperature measurements under the assumption of cyclostrophic dynamical balance are limited on the one hand by the accurate determination of the reference base wind profile and its altitude, on the other, by waves and other perturbations to the temperature field [e.g., *Newman et al.*, 1984]. However, a direct application of the cyclostrophic balance to derive the wind structure has been presented [*Limaye*, 1985].

[3] In this paper we present a study of the three-dimensional structure and temporal variability of Venus winds based on a homogeneous and well sampled set of images obtained by the Visible and InfraRed Thermal Imaging Spectrometer (VIRTIS) instrument [*Drossart et al.*, 2007] on board Venus Express (VEX) [*Svedhem et al.*, 2007]. This is the first time it has been possible to use images from the same instrument with the same measurement methodology to retrieve winds at three wavelengths, i. e. three separated altitude levels within the cloud cover.

2. Observations and Analysis

[4] Since April 11, 2006 VEX has been in a highly elliptical polar orbit around Venus (apocenter at 60,000 km over the South Pole and pericenter at 250 km over the North Pole) with a 24 hr period. The VIRTIS spectral images used for this report were obtained between April 2006 and June 2007 — a detailed list of observations used is found in the auxiliary material[1] for this article. VIRTIS images at three different wavelengths were used to sound the cloud layers at three different altitudes. In dayside images at the ultraviolet wavelength of 380 nm we detect cloud features in the upper cloud, which corresponds to an altitude range of 62 – 70 km (hereafter referred to as 66 km).

[1]Escuela Superior de Ingeniería, Universidad del País Vasco, Bilbao, Spain.
[2]Istituto Nazionale di Astrofisica and Istituto di Astrofisica Spaziale e Fisica Cosmica, Rome, Italy.
[3]Laboratoire d' Etudes Spatiales et d' Instrumentation en Astrophysique, Observatoire de Paris, CNRS, UPMC, Université Paris-Diderot, Meudon, France.
[4]Atmospheric, Oceanic and Planetary Physics, Department of Physics, University of Oxford, Oxford, UK.
[5]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.
[6]Also at Centro de Astronomia e Astrofísica da Universidade de Lisboa/Observatório Astronómico de Lisboa, Lisbon, Portugal.
[7]Laboratoire de Météorologie Dynamique/IPSL, CNRS/UPMC, Paris, France.

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL033817.

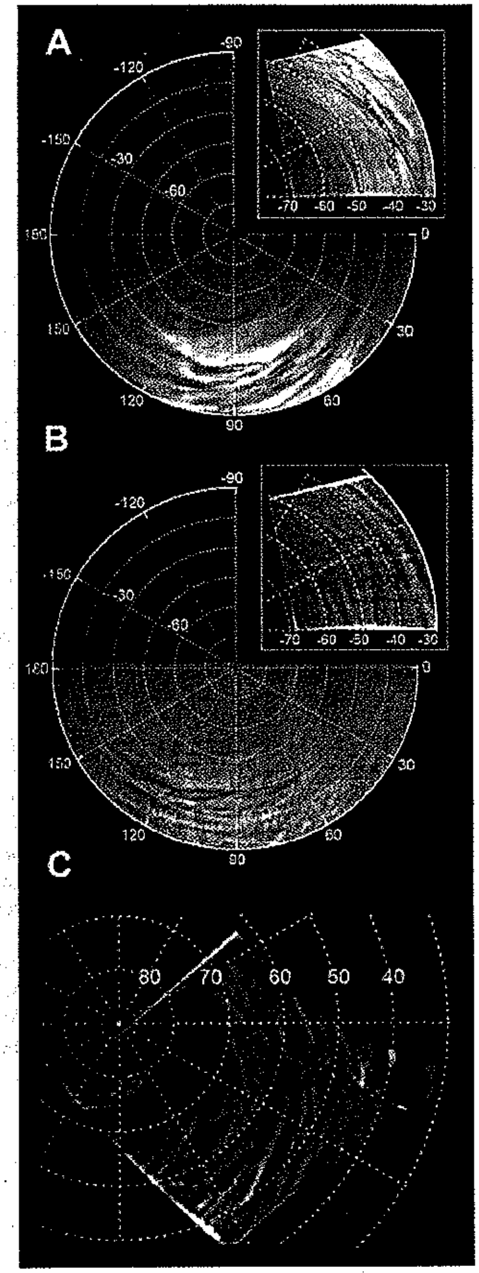

Figure 1. Projected maps of Venus cloud features at different wavelengths as observed by VIRTIS-VEX between April 19, 2006 and June 2007. (a) Day-time 380 nm polar map, April 19 2006. (b) Day-time 980 nm polar map, April 19 2006. (c) Night-time 1.74 μm polar map, 2 July 2006. Figure 1a and 1b show magnified insets of the cloud morphology in the area obtained on 29 June 2006.

In the near infrared at 980 nm, photons are more penetrating and reach the base of the upper cloud within an altitude range 58 – 64 km (hereafter, 61 km) [*Belton et al.*, 1991; *Peralta et al.*, 2007]. Compatibility of these altitudes requires always the 380 nm cloud features to be above the 980 nm features. Night side images of Venus were acquired at wavelengths of 1.74 and 2.3 μm where the radiance comes from altitude levels beneath the main clouds and is attenuated as it passes through the lower cloud layer at ~44 – 48 km [*Carlson et al.*, 1991; *Crisp et al.*, 1991]. There is uncertainty in the altitude of the cloud features observed at each wavelength because of our lack of knowledge of the cloud vertical structure variability. The altitudes quoted above are based on our own calculations, and are broadly consistent with previously published results by other authors, as detailed in the auxiliary material.

[5] VIRTIS images suitable for global wind measurements were selected to cover the whole southern hemisphere, corrected for defects (mainly striations), processed for contrast enhancement, navigated and geometrically projected into cylindrical or polar maps. Due to the orbital characteristics and instrument observational constraints, the images show different spatial resolutions, ranging from 15 to 105 km pix^{-1}.

[6] Figure 1 shows representative examples of the cloud texture and morphology at these wavelengths. The clouds are organized in partially tilted zonal bands with elongated features at mid-latitudes up to the dipole area poleward of 75°S [*Piccioni et al.*, 2007]. Abundant mottled, irregular and warped turbulent structures are present at lower latitudes, and packets of gravity waves are detected at different latitudes in the upper and lower clouds. Cloud tracking was performed on image pairs separated by 20 – 74 min in the three wavelengths. The methodology is fully explained by *Peralta et al.* [2007]. In total, we tracked 625 cloud elements at 380 nm, 662 at 980 nm and 932 at 1.74 μm. Table S1 with the full data set is presented in the auxiliary material. Combining the resolution limit and the navigation precision, the systematic uncertainty in the wind speeds for each individual tracked cloud feature is 4 – 12 ms^{-1} at polar and mid-latitudes (30°S to 90°S), and 13 – 20 ms^{-1} at equatorial latitudes (30° S – 0°S).

3. Zonal and Meridional Winds

[7] The spatial and temporal averaged zonal and meridional components of the wind, binned in latitude bands of 2°, are shown in Figure 2. The error bars displayed in Figure 2 are ~10 ms^{-1} and were obtained from the standard deviation ($1 - \sigma$) of measurements within each bin, which include both the formal measurement error of each individual point and the deviations from the mean flow due to dynamical processes. Figure 2a shows that the temporally and zonally averaged zonal and meridional wind velocity profiles present the same general behavior at all the wavelengths measured (i. e. different altitude levels). In the upper cloud level (day time, altitudes ~61 and 66 km) the zonal wind speed is constant from equator to ~55°S and then decreases steadily toward zero at the pole. The mean zonal wind in the latitude range from 0° and 55°S at $z \sim 66$ km is $\langle u \rangle = -102 \pm 10$ ms^{-1}, decreasing to zero at the pole with a meridional shear $\partial\langle u \rangle/\partial y = 0.026$ ms^{-1} per km. A similar trend has been recently reported from reanalysis of the Pioneer-Venus [*Limaye*, 2007] and Galileo images [*Peralta et al.*, 2007], although those studies had less coverage at high latitudes than the VIRTIS images. A comparison of our results with these previous studies shows that the zonal wind profiles measured for the upper cloud in these years

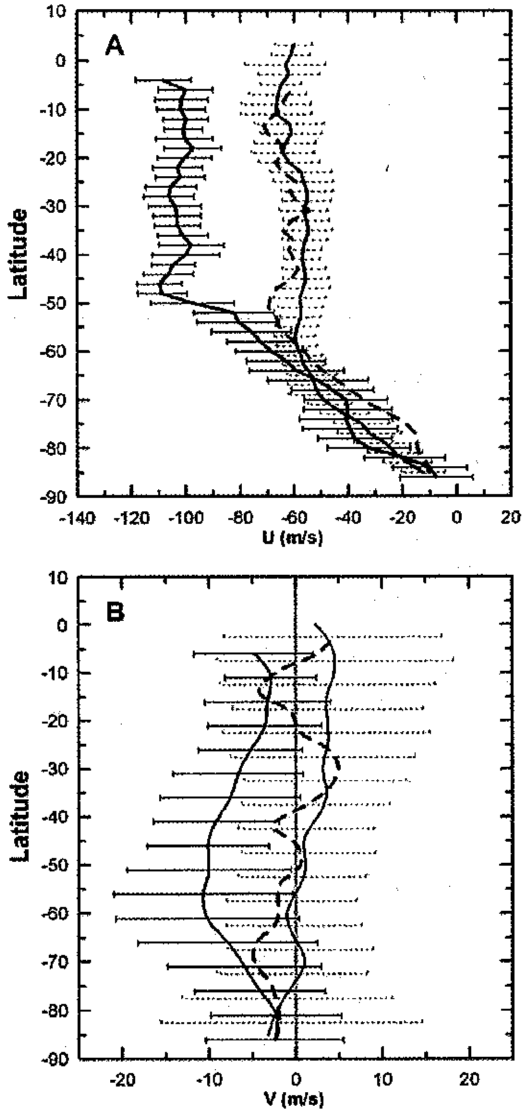

Figure 2. Averaged wind profiles in Venus southern hemisphere at cloud level (April 2006–July 2007). (a) The zonal velocity is drawn as a function of latitude as measured using cloud tracers at three wavelengths: ultraviolet (blue, 380 nm; upper cloud, altitude ~ 66 km; day time), near-infrared (violet, 980 nm; upper cloud, altitude ~ 61 km; day time), and infrared (red, 1.74 μm; lower cloud, altitude ~ 47 km; night time). (b) The meridional velocity is drawn as a function of latitude for the same three wavelengths. Errors bars for the 980 nm profile are not drawn for clarity but are similar to the other profiles.

(1979–85, 1990 and 2006–07) are broadly consistent, within the measurement uncertainties.

[8] However, we find a difference at $z \sim 61$ km, the base of the upper cloud, when comparing our averaged profile with that measured in the northern hemisphere using Galileo images [*Peralta et al.*, 2007]. The VIRTIS averaged wind speed between 0° and 55°S was $\langle u \rangle = -62 \pm 10$ ms^{-1} representing a drop in the mean equatorial speed relative to that from Galileo of ~10 ms^{-1}. This lower velocity is different to the VIRTIS orbital insertion data (April 2006, Figure 3a), when the average wind speed from 0° to 55°S was $\langle u \rangle = -75 \pm 10$ ms^{-1}, closer to the Galileo results [*Belton et al.*, 1991; *Peralta et al.*, 2007]. These tentatively detected wind changes at 61 km will need to be confirmed with further measurements over later orbits.

[9] The zonal winds at the lower cloud (night time, altitude 47 km, Figure 2a) show a similar latitude dependence with nearly constant speed from equator up to latitude 65° S and then a steady decrease toward zero velocity at the pole. The mean speed is $\langle u \rangle = -60 \pm 10$ ms^{-1} from 0° to 65°S and the meridional shear of the wind from 60°S to 90° S is $\partial \langle u \rangle / \partial y = 0.021$ ms^{-1} per km. Our wind measurements at different altitude levels within the cloud layers are consistent with the vertical shear of the zonal flow previously measured at localized points by the entry probes and Vega balloons [*Schubert*, 1983; *Gierasch et al.*, 1997] and with previous cloud tracking studies [*Carlson et al.*, 1991; *Crisp et al.*, 1991]. At equatorial and mid-latitudes (0° to 55°S) the vertical wind shear is $\partial \langle u \rangle / \partial z = 8 \pm 2$ ms^{-1} per km between altitudes $z \sim 61$ and 66 km, and is $\partial \langle u \rangle / \partial z < 1$ ms^{-1} per km between altitudes $z \sim 47$ and 61 km. In the sub-polar latitudes from 50°S–60°S to the pole, the vertical shear within the clouds (altitude 47 to 66 km) is weak, $\partial \langle u \rangle / \partial z \sim 2$ ms^{-1} per km (or lower).

[10] The meridional component of the velocity is shown as a function of latitude in Figure 2b for the three altitudes. Although our data are at the limit of the measurement error (mean r.m.s. = 9 ms^{-1} for all filters from the scatter of the measured velocities), at $z \sim 66$ km the velocity increases from 0 ms^{-1} at equator to about 10 ms^{-1} at 55°S and then decreases to 0 ms^{-1} poleward. This motion likely represents the manifestation of the upper branch of a Hadley cell [Schubert et al., 1983; *Gierasch et al.*, 1997] and its zonal dependence agrees with the recent reanalysis of Pioneer-Venus data by *Limaye* [2007] and *Peralta et al.* [2007]. The peak speed at 55°S and the rapid wind decrease toward the pole are most probably related to the structure of the polar vortex. At 61 km and 47 km the mean value of the meridional velocity appears to be <5 m/s, and no conclusive latitudinal trend can be discerned, given the relatively large measurement uncertainty of ±9 m/s. Our results at 61 km agree with previous estimates obtained using Galileo images for the northern hemisphere and low latitudes in the southern hemisphere [*Belton et al.*, 1991].

[11] Analysis of the zonal wind velocity as a function of the local time and on a long-term basis using averages in latitudinal bands shows that part of the variability has a periodic spatial component. Figures 3b and 3c plot show the zonal wind as a function of latitude and solar time in the upper cloud level at $z \sim 66$ km. The presence of the thermal solar tide is apparent in the latitude range 50°S – 75°S, equivalent (for a constant cloud height) to increasing the zonal wind speed in the upper cloud at a rate of about -2.5 ± 0.5 ms^{-1} hr^{-1} from the morning (9 hr local time) to the afternoon (15 hr). At other latitudes we do not see evidence for this phenomenon, including the equator where the solar tide was previously reported [*Del Genio and Rossow*, 1990]. This result — that there is a solar tide signal in the zonal wind which is stronger at high latitudes than at the equator — is also found in the preliminary wind

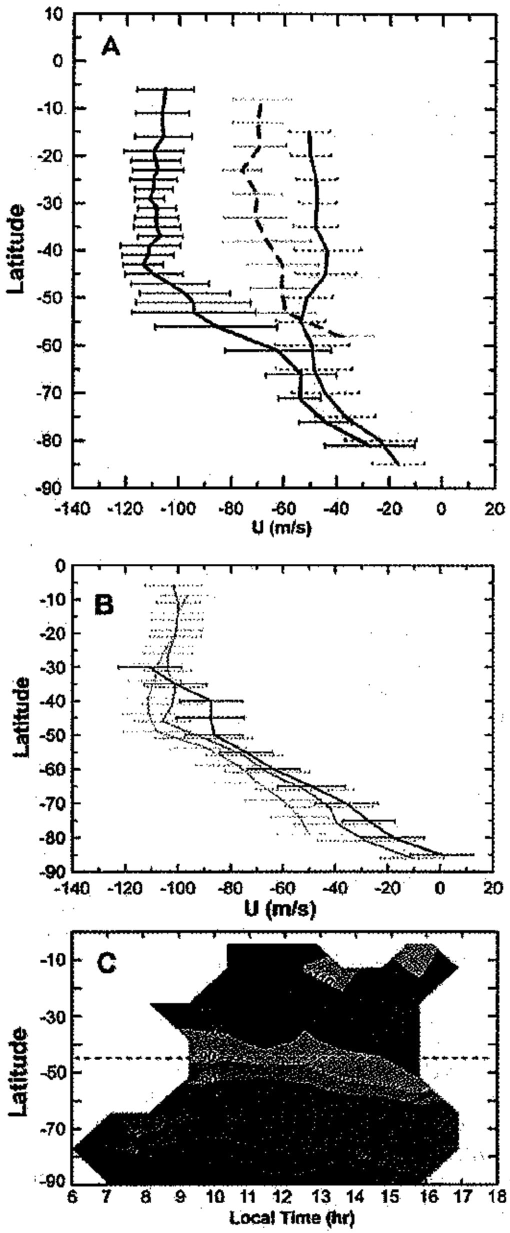

Figure 3. (a) Wind measurements performed almost simultaneously at the three wavelengths during the VEX Orbital insertion period in April 2006. The color code is as in Figure 2. Temporal changes in the wind profile at a wavelength of 980 nm ($z \sim 61$ km) are evident when comparing to the long-term average shown in Figure 2a. (b) Venus winds at 380 nm ($z \sim 66$ km) as a function of local time and latitude showing the effects of the solar tide. The green curve represents the zonal wind profile for local time 9 ± 0.8 hr, the yellow curve the zonal wind profile for local time 15 ± 0.5 hr and the grey curve the wind profile for intermediate local times. (c) The effect of the solar tide representing a contour plot of zonal wind profile at 380 nm as a function of local time and latitude.

data from Venus Express-VMC camera [*Markiewicz et al.*, 2007]. Within the data uncertainty, the solar tide was not detected at any latitude at the 61 km level, indicating that it is confined to near the cloud tops. Deeper, at $z \sim 47$ km on the night side, the solar tide is not expected, nor is it observed. The wave amplitude (~10 m/s) agrees with the analysis of Pioneer-Venus data [*Del Genio and Rossow*, 1990; *Limaye*, 2007] and Galileo [*Toigo et al.*, 1994].

4. Conclusions

[12] A firm conclusion from these results when combined with previous spacecraft data is that the zonal circulation changes sharply at ~55° latitude. At latitudes <55°, winds are nearly constant with latitude but exhibit strong vertical shear, with mean westward velocities of 60–70 ms^{-1} at the base of the cloud and 105 ms^{-1} at the top of the cloud. Poleward of 55° latitude, however, zonal wind speeds decrease linearly to the pole with virtually no vertical wind shear, indicating a vertically coherent vortex structure that ends at the poles forming the dipolar feature [*Piccioni et al.*, 2007]. The fact that the lower branch of the Hadley cell (returning from the pole) is not detected within the lower cloud (or is weaker than ~5 ms^{-1}) is perhaps not surprising since its velocity at this higher-pressure level could be significantly lower than in the upper branch, and hence smaller than the error in the measurements. Ongoing observations with VIRTIS over the next years will characterize the stability and temporal variability of the mean zonal winds at the upper and lower cloud levels.

[13] **Acknowledgments.** Venus Express is a mission of the European Space Agency. VIRTIS was supported by CNES (Centre National d'Etudes Spatiales) and ASI. This work has been funded by Spanish MEC AYA2006-07735 with FEDER support and Grupos UPV 15946/2004 and Grupos GV IT464-07. JP acknowledges a UPV fellowship and RH a "Ramón y Cajal" contract from MEC. DL acknowledges support from Fundação para a Ciência e a Tecnologia, through grant BPD/3630/2000 and project PPCDT/CTE-AST/57655/2004. The VIRTIS experiment has been built and operated by the science and technical team listed at the following address: http://servirtis.obspm.fr/Venus_Express/VIRTIS_Team.html.

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K. H. Baines, Jet Propulsion Laboratory, California Institute of Technology, Mail Stop 183-601, Pasadena, CA 91109, USA.
P. Drossart, S. Erard, and D. Luz, Laboratoire d' Etudes Spatiales et d' Instrumentation en Astrophysique, Observatoire de Paris, CNRS, UPMC, Université Paris-Diderot, F-92195 Meudon, France.
R. Hueso, J. Peralta, S. Pérez-Hoyos, and A. Sánchez-Lavega, Departamento de Física Aplicada I, Escuela Superior de Ingeniería, Universidad del País Vasco, Alameda Urquijo s/n, E-48013 Bilbao, Spain. (agustin.sanchez@ehu.es)
S. Lebonnois, Laboratoire de Météorologie Dynamique/IPSL, CNRS/ UPMC, F-75252 Paris, France.
G. Piccioni, Istituto Nazionale di Astrofisica and Istituto di Astrofisica Spaziale e Fisica Cosmica, via del fosso del cavaliere 100, I-00133, Rome, Italy.
F. W. Taylor and C. F. Wilson, Atmospheric, Oceanic and Planetary Physics, Department of Physics, University of Oxford, Oxford OX1 3PU, UK.