THE ATMOSPHERE OF VENUS: WINDS AND CLOUDS OBSERVED BY VIRTIS/VENUS EXPRESS

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Abstract: After decades without a dedicated space mission, Venus, sometimes referred as Earth's twin planet, is again the subject of intense exploration. Venus Express (VEX), a mission of the European Space Agency, was launched in November 2005 and arrived to the planet in April 2006 where it is now in orbit. Among its scientific payload, the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) is an instrument well suited for the study of a plethora of atmospheric processes through its visual and spectral modes. In this work we will review some of the first results obtained with this instrument. The set of observations characterizes the properties of the multiple cloud layers in Venus, the global atmospheric dynamics and its variability as well as the structure of particular meteorological structures like the polar vortex and the nearly ubiquitous systems of gravity waves.

Keywords: Venus – Atmosphere dynamics – Meteorology.

1 Introduction

Venus is the planet closest to Earth in distance to the Sun, mass, radius, density and chemical composition. Yet, the similarities end here. Venus has a massive atmosphere made up of carbon dioxide with surface pressures of 90 bar, clouds of sulphuric acid and a hot, dry and young surface according to geological standards. Understanding the similarities and differences between Earth and Venus motivated an intense exploration of this planet paused on the last decades in part by the lure of the exploration of Mars, more attractive to the search of life.

Venus Express is an orbiter based on the Mars Express spacecraft and is the first mission dedicated to Venus atmospheric investigations since NASA's Pioneer Venus and the Soviet Vega and Venera programs, both more than a quarter of a century ago. It was launched from Baikonur in Kazakhstan on November 9, 2005 and arrived to

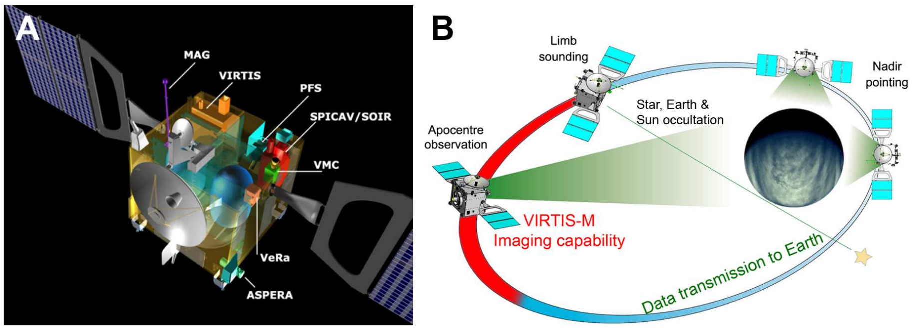

Figure 1: VEX instruments (left) and orbit (right). The scientific payload is composed of ASPERA-4 (Analyser of Space Plasmas and Energetic Atoms), MAG (Magnetometer), PFS (Planetary Fourier Spectrometer; this instrument did not deploy and it is not operational), SPICAV (Spectroscopy for Investigation of Characteristics of the Atmosphere of Venus), VeRa (Venus Radio Science), VIRTIS (Visible and Infrared Thermal Imaging Spectrometer), and VMC (Venus Monitoring Camera). The orbit characteristics allow to obtain nadir observations of Venus South Hemisphere and high-resolution VMC images of Northern latitudes as well as limb-observations including occultation experiments. Data is sent everyday to the Earth in the descending branch of the orbit. The operational maneuvers and data acquisition are complicated by the requirement of keeping the spacecraft and instruments cool under the intense solar radiation while maximizing the data flow to Earth during different observing seasons.

Venus on April 11, 2006. Since then it follows a highly elliptical polar orbit (apocenter at 60,000 km over the South Pole and pericenter at 250 km over the North Pole) with a 24 hr period. The highly elliptical polar orbit combines global nadir observations of the southern hemisphere with close-up snapshots of the equatorial and northern latitudes. The scientific payload consists of seven instruments detailed on Figure 1. While the initial nominal mission was proposed to last for 486 days, roughly 2 Venus days, it has been extended at least to September 2009. The mission description and science operations plans are presented in [1,2].

2 Observations

The VIRTIS instrument is an imaging spectrometer inherited from the VIRTIS instrument onboard the Rosetta mission [3]. It is a dual instrument with separate telescopes operating on two channels: (1) VIRTIS-M, a mapping spectrometer with

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two CCD detectors working in the visible (VIRTIS-M-vis from 0.3 to 1 μm) and in the infrared (VIRTIS-M-IR from 1 to 5 μm) and (2) VIRTIS-H, a high-resolution spectrometer with a spectral range in the infrared $2-5$ μm ([4,5]). VIRTIS-M obtains image "qubes" using a mirror-scanning technique that simultaneously provides more than 430 images of the same field in the wavelength range of each detector. VIRTIS-M-vis obtains data of the day-side of the planet in reflected light while VIRTIS-M-IR obtains most of its data from thermal radiation escaping from the planet and observed during the night-side (see Figure 2).

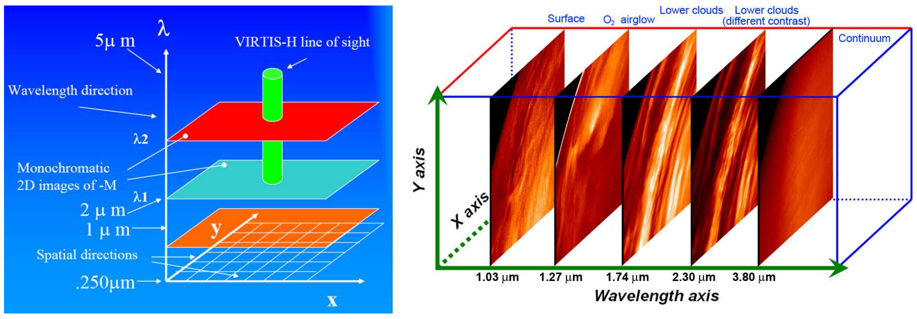

Figure 2: Organization of a VIRTIS data qube. The three-dimensional data qubes contain a full spectra for each x-y pixel and an image for each wavelength. The high-resolution spectral mode allows to obtain 432 images on the spectral range of the instrument (different for VIRTIS-M-vis and VIRTIS-M-IR). The detector is a 256x432 CCD where the spectra produced by a diffraction slit is captured. Each of the 256 pixel lines register a single spectrum. A scanning mirror is used to change the direction of the light obtaining a full data qube in minutes. This information can be used to simultaneously study several vertical layers of the planet, from the surface to the clouds, as well as basic chemical composition and thermal structure of the upper troposphere. The right panel shows representative images of one VIRTIS data qube.

3 Venus vertical cloud structure

Venus is known to have a thick and highly reflective cloud cover which fully encircles the planet [6]. This cloud deck is composed of sulphuric acid droplets in a concentration of 75%. When observing Venus reflected spectrum in the vicinity of 1 μm a few notable characteristics arise (see Figure 3). The spectrum is mostly flat from around 500 nm. Below this wavelength an unknown absorber produces a sharp decrease of reflectivity [7]. At even shorter wavelengths (around 300nm) the gaseous

SO_2 absorption (highly dependent on different temporal and spatial scales) is also present. Other gaseous absorption is produced by CO_2 above 1 μm in various bands of increasing intensity. The H_2SO_4 forming cloud particulates also produce some absorption features closer to 2 μm wavelengths. Focusing on the VIRTIS instrument capabilities the information we can retrieve from the analysis of Venus reflected spectrum includes: (a) SO_2 concentration and its variation over time and space; (b) the nature and origin of the UV absorber, together with its temporal variability; (c) the density and particle size of cloud decks; (d) the vertical extent of the cloud layers and its variation with latitude and time. On the other hand, night-side observations in the infrared allow to sound deeper clouds and even the surface through different observation windows as also shown on Figure 3.

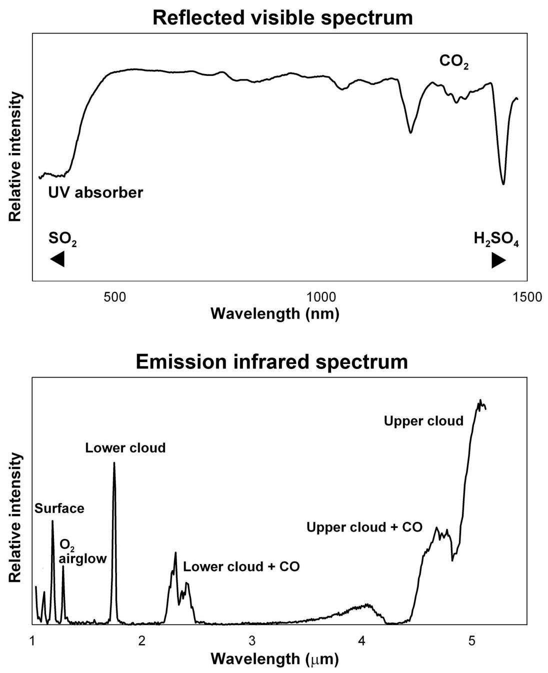

Figure 3: Venus reflected and emitted spectrum. The top panel shows the spectrum in reflected light on the day-side in the vicinity of 1 μm with a mean reflective of $\sim 70\%$. The bottom panel shows the infrared emission spectrum obtained by VIRTIS on the night-side of the planet with particular observation windows detailed on the figure.

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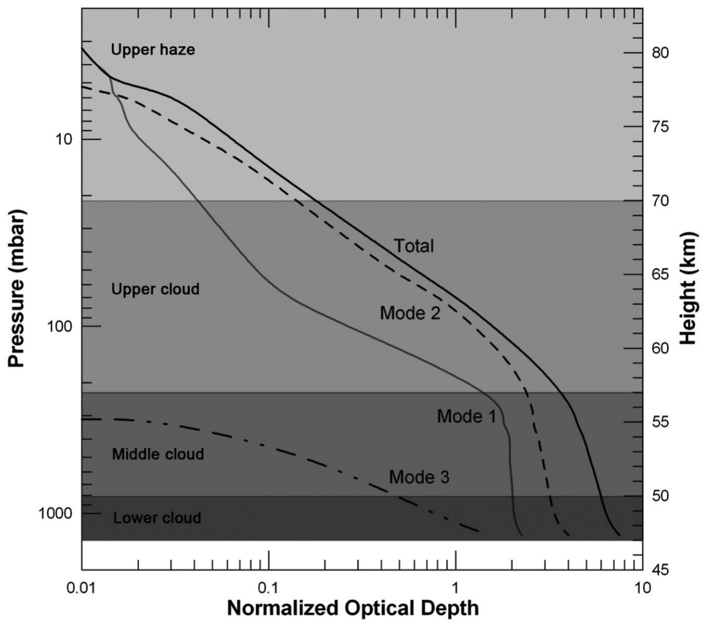

Figure 4: Vertical distribution of particles in Venus atmosphere. Shaded areas mark the extension of the three cloud decks and the haze above. Lines show the contribution to the total optical thickness normalized to the value at 630 nm for an isotropic scatterer. Modes represent different particle sizes. Adapted from [8].

Venus clouds have been analyzed by remote sounding and in situ investigations which were able to characterize the vertical distribution of particles. As summarized on Figure 4 the clouds are accepted to be highly stratified in several extended layers with different types of particles. Most of the visible radiation is reflected from the upper or middle part of the cloud, being the shortest wavelengths strongly affected by the variable presence of the upper haze. Inside each cloud layer, different particle size distributions ("modes") coexist. Mode 1 corresponds to the smallest particles with radii around 0.1 μm. These are dominant in the upper part of the atmosphere and probably have their origin in the photochemical processes taking place in even higher locations of the atmosphere [6]. At deeper atmospheric levels particles tend to be somewhat larger and Modes 2 (radii $\sim 1.0\mu m$) and 3 (radii around $3.0 - 5.0\mu m$)

are found. The former is the strongest contributing particle size to the total optical thickness of the cloud layers and being representative of the mean particle size. This multilayered cloud structure implies a total optical depth at the surface of ~ 30.

VIRTIS observations depend strongly on the wavelength and three cloud layers are clearly observed with uncorrelated structures at 380 nm and 980 nm in reflected light and at 1.74 μm in infrared transmitted light. In order to determine the altitude location of these clouds we used the following approach. For 380 and 980 nm we considered two vertical cloud structure models [7,8] including their expected spatial and temporal variability. The total optical depth is calculated as a function of height for the wavelengths of interest [9,10]. For each wavelength the altitude sounded is assumed to be that in which the total optical depth is $\tau = 1 - 3$. For observations of transmitted radiation at 1.74 μm the expected sounding level is that at which the maximum concentration of particles is located. With these approaches the sounding levels retrieved are ~ 65 km at 380 nm, ~ 60 km at 980 nm and ~ 50 km, in good agreement with previous estimations [11,12].

4 Atmospheric dynamics at cloud levels

4.1 Global circulation

The global atmospheric circulation is characterized at cloud level by a zonal super rotation which is one of the most intriguing aspects of the atmosphere [13-18]. Whereas the planet turns around its axis in retrograde sense (from East to West) in 243 days, its atmosphere at the upper cloud level and low latitudes takes only 4 days to encircle the planet. Despite much modeling efforts and observations from different spacecrafts (orbiters, probes and balloons), the underlying mechanism is far from being understood [16].

Venus Express observes the planet in a polar orbit that allows to perform a global study of the South hemisphere of Venus. While the Venus Monitoring Camera (VMC) has provided high-resolution observations of the upper clouds and mean wind profiles at their altitude (~ 65 km) [19] VIRTIS has been able to study the different cloud layers showing that two fundamentally different circulation regimes separated at latitudes 55° simultaneously operate at the three cloud levels. At low latitudes, zonal winds in the Southern hemisphere at altitudes ranging from 47 to 66 km are nearly constant with latitude with westward velocities of 105 m/s at cloud-tops and 60-70 m/s at the cloud-base. At high latitudes, zonal wind speeds decrease linearly with virtually no vertical wind shear, indicating a vertically coherent vortex structure. Meridional winds at the cloud-tops are poleward with peak speed of 10 m/s at 55°S but are found to be light below the cloud tops [20]. 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.

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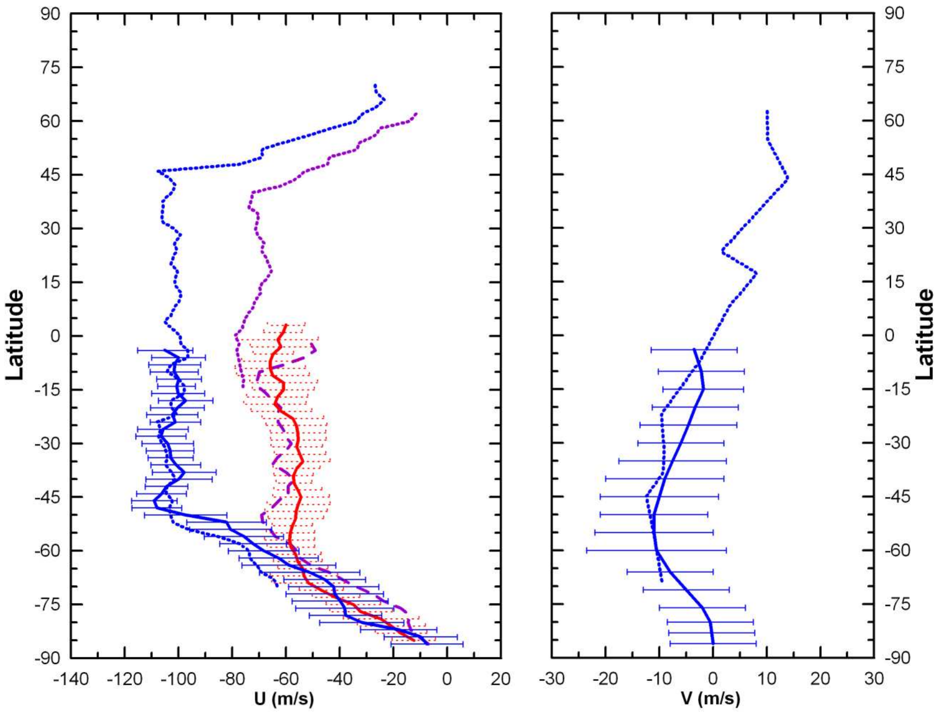

Figure 5: Comparison of zonal and meridional winds obtained by VIRTIS onboard Venus Express in 2007 in the South hemisphere (continuous and dashed lines, [20]) and data from the Galileo spacecraft flyby of Venus in 1991 (dotted lines, [19]). Zonal winds (left panel) are shown with different lines corresponding to winds measured in clouds observed at different wavelengths representative of different vertical altitudes: The left line with error bars represents the winds at 65 km altitude level (observations at 380 nm in the day-side of the planet); the intermediate dashed line without error bars represents the winds at 61 km (observations at 980 nm in the day-side) and the right line with dotted error bars represents the winds at 50 km (observations of the night-side at 1.74 microns). Meridional winds (right panel) indicate a global Hadley cell that transports heat from the Equator to the Poles [20].

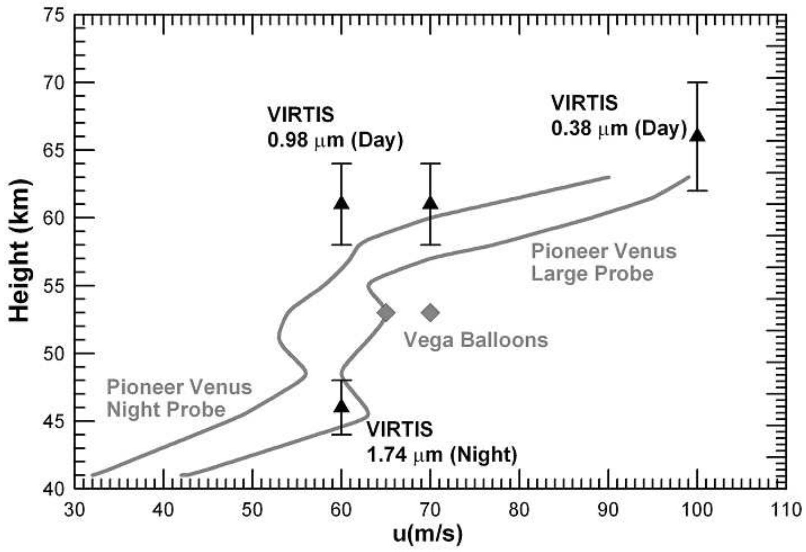

Figure 6: Venus zonal wind speeds as a function of height as measured by Pioneer Venus Probes (lines), Vega Balloons (rhombs) and VIRTIS measurements (triangles with dashed bars). Adapted from [20].

Figure 6 compares our results with the vertical profiles of the zonal winds as measured by Pioneer-Venus entry probes [13,16] in day time (for wavelength 380 nm) and night time (for 1.74 μm), and with the Vega balloons in night and day time [14]. There is good agreement between the VIRTIS observations and modeling of the cloud altitude and the *in situ* results obtained decades ago.

4.2 Winds variability

In spite of remarkable similarities in the wind regimes at low and high-latitudes between different spacecrafts separated decades in time, the winds are known to be variable at the levels of the upper cloud deck. The variability is due to the solar tide and to a 5 days global oscillation not fully understood. Both types of variability had been first discovered during the Galileo flyby of Venus in 1991 [21, 22] at equatorial latitudes but VIRTIS data shows that both oscillations extend to subtropical latitudes (50-70°) where they are even larger in magnitude [20] with wind amplitude variations of 10 m/s.

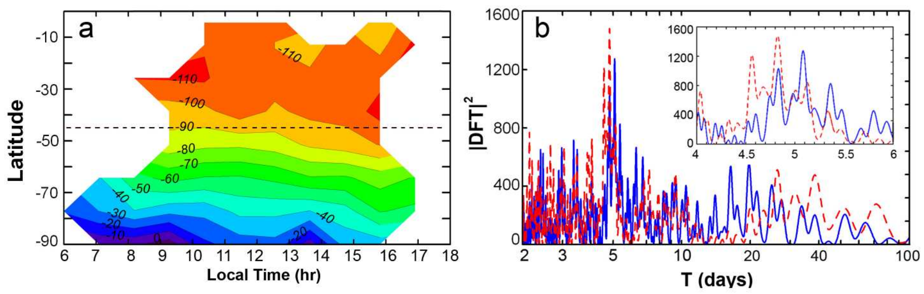

Figure 7: Wind variability in Venus. The left panel is a contour plot with velocities in ms^{-1} indicating the dependence of the zonal wind on the local time at each latitude. This effect is specially significant at high to subpolar latitudes. The right picture shows a periodogram of wind values obtained on different days of observations at sub-polar latitudes. The periodogram peaks at 5 days showing a cyclic variation of winds with this period. The two curves correspond to latitude intervals of 50-60° and 60-70°.

4.3 Vortices, waves and lightning

Among the first results from Venus Express lies the discovery of a double-eye vortex on the South Pole of Venus [23]. The polar dipole is similar to the dipole discovered years ago by different spacecrafts on the North Pole [24]. VIRTIS observations show that the vortex may extend down to the lower cloud layers at 50 km and perhaps deeper. The vortex is 10 K warmer than a surrounding cold collar and it might be an extension of a global Hadley cell descending at polar latitudes. The upper clouds of Venus are also prompt to the development of several wave systems. The most famous is the Y global planetary wave [16] but there is also an intense activity of small-scale wave observed by VEX on the upper and lower clouds [19, 25]. These waves are gravity waves arising on the vertically stable cloud layers [16] and probably excited by convection on the clouds. Their characteristic wavelength is ~ 100 km and their phase speed is $\sim 10 - 15$ m/s. They are probably gravity waves ducted in the cloud layers where the static stability is high. The waves observed in the upper and lower clouds do not seem to correlate and might be disconnected by the region of low static stability separating both clouds. The convection is assumed to be responsible of the intense lightning activity detected by VEX [26]. The South polar dipole and gravity waves in the upper and lower clouds are illustrated on Figure 8.

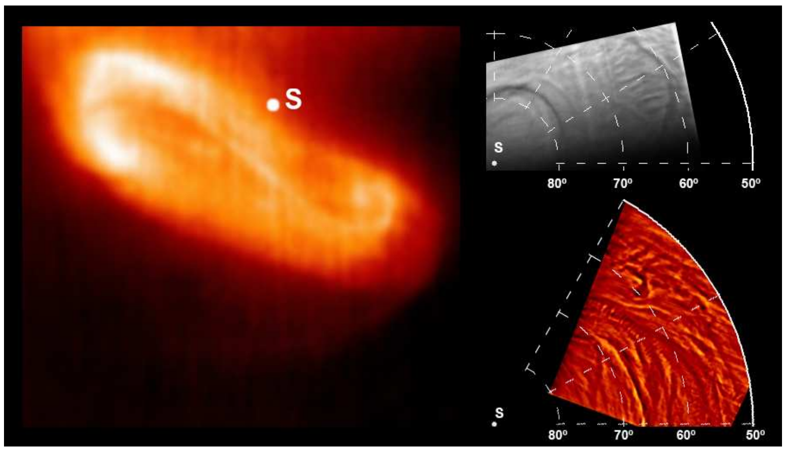

Figure 8: VIRTIS observations of the South polar dipole as seen at 3.8 μm in the night-side (left, with the South pole location indicated by the S) and systems of gravity waves observed in the visible (380 nm, right top) and the infrared (1.74 μm, right bottom). The 380 nm image (right top) also shows one side of the dipole on the upper cloud. Left and right figures not at scale

4.4 Mesospheric dynamics

Above the clouds the atmospheric dynamics can also be studied by Venus Express by following the evolution of airglow emissions caused by a complex photochemistry at low atmospheric densities [27]. Among them, the O_2 nightglow emission at 1.27 μm is the most intense [28,29]. VIRTIS observations spatially resolve the airglow activity which is spectacularly variable not only in its morphology and intensity but also in the apparent motions of the airglow structures [30,31]. Visual tracking of the bright features allowed to obtain mean zonal and meridional motions related to a subsolar to antisolar circulation expected at mesospheric levels at an altitude range of 95-107 km [31]. Figure 9 shows a map of airglow activity as well as the inferred motions in the oxygen airglow structures. The zonal velocity is dominated by an intense prograde jet (contrary to the retrograde planetary and lower atmosphere rotation). Typical zonal velocities range between +60 (prograde) to -50 (retrograde) m/s, whereas most meridional velocities range from -20 (polewards) to +100 m/s (equatorwards) with an average meridional circulation of +20 m/s towards low latitudes.

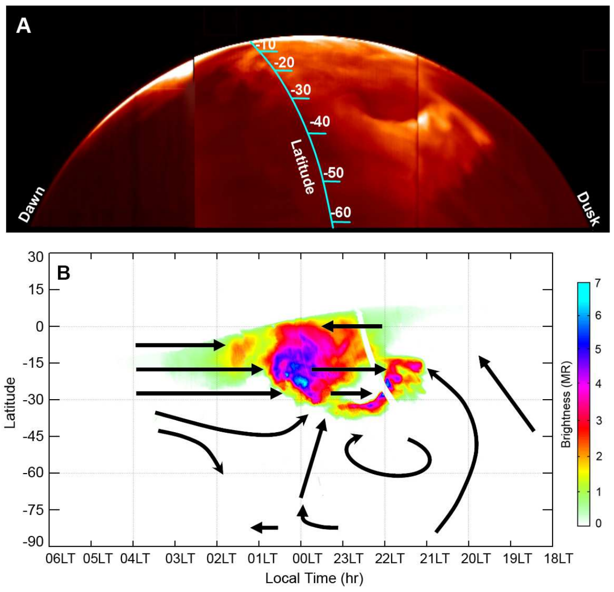

Figure 9: Airglow structures (bright patches) and average derived motions averaged over several Venus Express orbits. The airglow intensity largely increases at equatorial latitudes and specially at the antisolar point. Extracted from [27].

5 Conclusions

Venus Express is providing new insights of the atmosphere of this terrestrial planet. As the mission proceeds, it will produce a detailed view of atmospheric processes and dynamics over two full Venus years. Hopefully, the mission will be operative until the arrival of the Japanese Venus Climate Orbiter (also known as Planet-C) in 2009 that will enter an equatorial orbit of the planet. Longer term plans to continue the interrupted exploration of Venus are underway by ESA and NASA.

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