THE UPPER ATMOSPHERE OF VENUS OBSERVED BY VENUS EXPRESS

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Abstract: The upper atmosphere of Venus is still nowadays a highly unknown region in the scientific context of the terrestrial planetary atmospheres. The Earth's stratosphere and mesosphere continue being studied with increasingly sophisticated sounders and in-situ instrumentation [1, 2]. Also on Mars, its intensive on-going exploration is gathering a whole new set of data on its upper atmosphere [3, 4, 5]. On Venus, however, the only recent progress came from theoretical model developments, from ground observations and from revisits of past missions' data, like Pioneer Venus. More and new data are needed [6, 7, 8]. The arrival of the European Venus Express (VEX) mission at Venus on April 2006 marked the start of an exciting period with new data from a systematic sounding of the Venus atmosphere from orbit [9, 10]. A suite of diverse instrumentation is obtaining new observations of the atmosphere of Venus. After one and a half years in orbit, and although the data are still under validation and extensive analysis, first results are starting to be published. In addition to those global descriptions of VEX and its first achievements, we present here a review on what VEX data are adding to the exploration of this upper region of the atmosphere of Venus. We present measurements at those altitudes from one of the infrared sounders aboard VEX, the instrument VIRTIS, as an example of unique insights on the upper mesosphere and lower thermosphere of Venus, and discuss briefly the synergy with other instruments on VEX. We will conclude with our opinion on the importance and limitations of the Venus Express mission in order to broaden our global understanding of the upper layers of the terrestrial atmospheres.

Keywords: Venus Express – Planetary atmospheres – Remote sounding – Atmospheric dynamics – Airglow – Ionospheres – Non-LTE emissions

1 Introduction

A new air full of new data is flowing over the research on the atmospheres of the terrestrial planets, Mars and Venus. The second, in particular, has been severely affected by the lack of detailed observations from space for more than two decades. This is specially severe in the case of the upper atmosphere, the layers above the tropopause or equivalent layer (see Figure 1). The recent Venus Express mission is trying to change the trend, and its recent results promise to partially fill this gap.

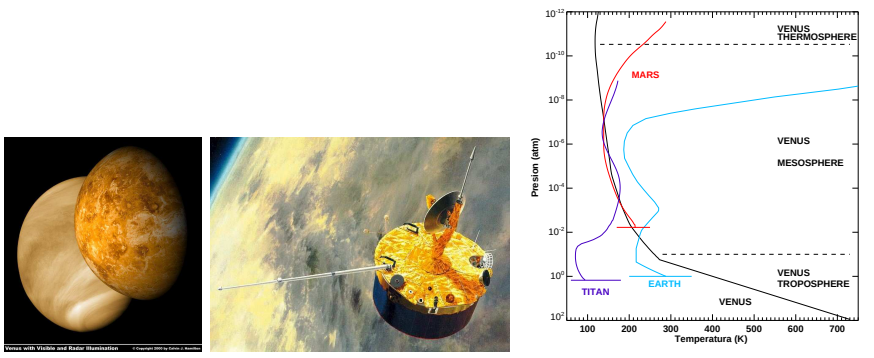

Figure 1: Left: Visible and radar views of Venus, from Mariner 10 and Magellan, mapping the cloud layer and the surface. Center: artistic vision of Pioneer Venus in orbit; credit: NASA. Right: Typical profiles of atmospheric temperature in Earth, Mars, Venus and Titan

About eight years ago, in a review on Comparative Aeronomy in the Solar System [11], a number of developments in atmospheric modeling of the upper atmospheres of the terrestrial planets were reported, but mostly based on the data from mission to Mars and Venus in the 70s and 80s. As an example, in the case of these planets' ionospheres, Nagy and Cravens mentioned in that review that the few we know about them comes from the Venus case, and from one single mission, Pioneer Venus (PVO, hereonafter), and much of what was found at that time was extrapolated to Mars given the expected similarity [12]. Only a few years later, however, a peculiar third ionospheric layer was found by the radio science experiment on Mars Express ([13]), and also that in contrast to Venus, a sudden ionopause seems to be absent, a result recently confirmed by Venus Express [14]. Also Bougher and colleagues concluded then [23] that in spite of the fruitful modeling of the basic parameters of the upper atmospheres of the terrestrial planets, like the governing patterns of their general circulation or their exospheric temperatures, the current models suffer from a "geocentric perspective" which should be revised once global measurements of com-

position, temperature and wind measurements are taken. These suffice to stress the need of data, ideally on a systematic basis, as a basic requirement for a sounded advance in our understanding of these layers.

However, sounding of the upper atmosphere is a difficult goal for several reasons. In-situ measurements, either from balloons or during the periapsis of satellite orbits, can normally study either the lower or the upper boundaries of the upper atmosphere. Most part of what we call the upper atmosphere, requires remote sounding techniques for its observation. Moreover the low densities at these altitudes demand a limb sounding. The lack of orbiters with technological capabilities for limb sounding has been for a long time a serious limitation. This technique was first applied to the investigation of the Earth's upper atmosphere in the late 70s with the NASA Nimbus series of satellites. Instruments on Nimbus 7 scrutinized our stratosphere for temperature and composition with a pointing and a precise inversion which were novelties at that time. These first limb radiometers were followed by a subsequent series of improved instrumentation on the Upper Atmosphere Research Satellite, in the 80s, with technological improvements but still mostly radiometers [16]. Another step in limb sounding of the Earth's atmosphere was performed in the 80s, with the use of high spectral resolution interferometers, like ATMOS, on the SpaceLab [17]. And in the 90s, with lighter versions which sounded even higher, like the MIPAS interferometer on board the European ENVISAT satellite [1, 18]. The wealth of data acquired by these missions include detailed photochemistry of the ozone hole [19], studies of the global dynamics of the stratosphere and the polar vortex [20], the detection of the atmospheric response to solar storms and energetic particles [21], the development of local climatologies, or the tracking of trends and climatic changes affecting the higher atmosphere [22, 18].

Also on Mars, the wave of missions to the red planet during the last decade has improved the study of the upper atmosphere significantly. This started in 1997 with the descent of Pathfinder through the Martian atmosphere, and continued with Mars Global Surveyor and Mars Odyssey orbiters, with exciting results at high altitudes. Details can be found in a companion paper in this issue [23]. There are also interesting results about the upper atmosphere of Mars obtained by Mars Express [5], a mission which will continue in operation until 2009, at least. This mission included some of the observational improvements which were so successful on the Earth's upper atmosphere, like limb sounding and a relatively high spectral resolution. This is the case of the Planetary Fourier Spectrometer, PFS [24], with limb capabilities in the infrared at a resolution of 1.5 cm-1, or the case of SPICAM [25], an stellar occultation experiment, which is sounding densities well above 140 km, or the case of the OMEGA instrument [26], with a fantastic vertical resolution at the limb (about 400 m [27]). The teams of these instruments are reporting the detection of auroral emissions on Mars[28], high altitude CO_2 ice clouds [29], or daytime fluorescence by CO_2 and CO [30]; the last ones occur at mesospheric and thermospheric layers and confirm at last

old predictions by non-local thermodynamic equilibrium (non-LTE) models [31, 32].

Research on the Venus atmosphere was certainly behind the developments in their neighbor planets. Demands of new data by the scientific community in the 90s [7, 33], together with interesting and new ground based observations [34, 36], and with the availability of optimal instrumentation from other missions (Rosetta and Mars Express), paved the way for ESA to take the initiative of promoting a mission to study Venus in the 2001 [37]. VEX was finally launched in November 2005, and represents, in the case of the study of the Venus atmosphere, the first mission designed for such purpose in more than 25 years.

This paper focuses on a review of the VEX mission and its ability to study the upper atmosphere of Venus. The term upper atmosphere is used freely by different scientific communities. In our work, this region is defined as that fraction of the Venus atmosphere laying above the cloud tops, above about 70 km. VEX is in normal scientific operations around our neighbor planet since June 2006. First findings have been recently published in a special issue in Nature [9]. This is an exciting time where new results are starting to emerge and to be published. We aim here at describing in a global sense how VEX instruments and observational strategy are prepared to contribute to our understanding of this special region in Venus, its upper atmosphere, adding to what is known so far about it. We start in section 2 with a small review of the current description of the Venus atmosphere, with basic results from previous observations and space missions. In section 3 we focus on its upper regions, scientific interest and particular problems which remain open. Then we describe briefly the VEX instrumentation, in section 4. We present results from one of these experiments, VIRTIS, in section 5, and in Section 6 discuss the synergy with other instruments on VEX. We will summarize our perspectives for the coming years of VEX in section 7.

2 Peculiarities of the atmosphere of Venus

The basic characteristics of the atmosphere of Venus can be reviewed from an historical perspective, following a selection of highlights of its observations.

Venus is sometimes considered as the twin planet of Earth, sharing similar size, density, formation age and distance from the Sun [10, 8]. However, strong differences exist between the two planets in atmospheric basic properties, these including very high temperatures and pressures at the surface, about 730 K and 90 bar, an almost pure CO_2 composition, and a sky fully and continuously covered by thick clouds with a complex layered structure containing sulfuric acid droplets. Also the planet's rotation is retrograde (177 degree inclination, hence no seasonal changes) and very slow (243 Earth's days), which nowadays is recognized as one key ingredient of the very different and peculiar atmospheric dynamics on Venus [39, 40]. These harsh conditions at the surface explain the fact that Venus research was neglected for a

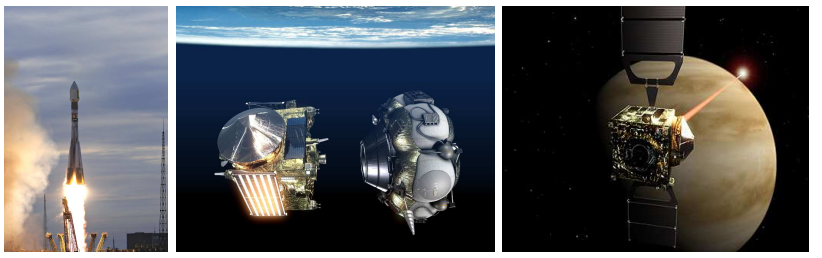

Figure 2: Launch of VEX from Baikonur, November 25, 2005 (left panel), composition of pictures to depict its separation from the Fregat vehicle (central panel), and diagram of the limb sounding of the atmosphere by stellar occultation (right panel).

long time, given the impossibility to harbor eventual human exploration [33].

2.1 Microwave observations

It the 50s, during the early days of radioastronomy, strong microwave emissions indicated very high surface temperatures [38]. The rotation period was also detected by radio observations from Earth in the early 60s. This gave Venus the honorable first place in the objectives of space exploration of that time: the Mariner 2 mission was sent to Venus in 1962 [41]. Still nowadays radio ground-based observations of Venus are performed frequently, which are useful to sound the Venus mesosphere. These observations are supplying winds and distribution of minor compounds like CO at those altitudes [42]. During the Venus Express mission microwave observations are particularly useful for their addition of complementary observations, and were part of a recent VEX validation campaign by ground-based observations [45].

After the first microwave measurements confirmed the rotation of the solid body, the superrotation of the Venus atmosphere was established. Still the origin and mechanisms of this effect is an open issue, with debatable and alternatives theories. The general view is that it is induced or related to the slow rotation of the planet, combined with some effective transfer of momentum from the lower atmosphere to the clouds' altitude.

2.2 Spacecrafts and landers

More than 30 missions have made the trip to Venus [9], including the Mariner series of fly-by from 1962 to 1975, the Venera series (descent probes with landers) from 1967 to 1985, the Pioneer Venus mission (one orbiter and four probes) from 1978 to 1982, the two Vega missions (including 2 balloon stations and 2 landers) on 1985, the

American orbiter Magellan from 1990 to 1994, and the fly-by by Galileo and Cassini in 1991 and 2001, respectively. Reviews of all of them can be found elsewhere [8].

The atmospheric composition, density and thermal structure are essential properties of an atmosphere, and were among the first objectives of the first missions. The first probes plunged into the Venus atmosphere found almost identical thermal profiles, with few horizontal variations [44]. This was not surprising, given the large density of the atmosphere; the mass of the Venus atmosphere should store and distribute heat efficiently. In those early years of Venus exploration there were serious problems to understand the greenhouse effect observed, the high temperatures at the surface. After the first determinations of the precise composition of the atmosphere, it was clear that such a CO_2-dominated atmosphere should have numerous gaps in the infrared where radiation could escape to space, and consequently, cool the atmosphere. The small amounts of water vapor present below the clouds did not close those infrared windows [7]. A quantitative understanding only started much later, after the composition of the top clouds was determined by the series of probes (H_2SO_4 droplets are efficient absorbers in the near-IR and highly transparent in the visible), after advances in spectroscopic high temperature databases, and after an improved treatment of line shape effects into radiative transfer models [47].

A lot of what we know about the Venus atmosphere comes from the Pioneer Venus mission, orbiter and probes, which reached Venus in 1978. One of the many innovative investigations from the orbiter was to use cameras at different wavelengths for the study of the clouds and the surface emissivity. These confirmed the superrotation of the lower atmosphere and found that the maximum occurred at the altitude of the clouds. Their measurement of radiative fluxes at the cloud deck demonstrated that half the solar radiation absorbed in the Venus atmosphere is actually deposited there, by some efficient and unknown absorber in the UV [7]. Many questions still remain regarding the clouds, like their actual role in driving the circulation at those altitudes. They may merely respond to microphysical processes and photochemical reactions, which might be highly independent on the atmosphere's movements.

A number of key measurements of the atmosphere of Venus above the clouds were obtained by PVO, including the thermal structure, the dynamics of the mesosphere, and the ionosphere. We discuss them in the next section.

3 The upper atmosphere of Venus.

The upper layers of an atmosphere are exciting from various viewpoints or disciplines in planetary science. Diverse escape processes occur there and constitute one key factor in the long term evolution of the atmosphere and of the planet. The interaction with the solar wind is strongest at these altitudes; the solar radiation is filtered and partially transmitted to lower regions, and therefore, the conditions below and at the

planet's surface depend on the densities and compositions higher up. In addition, these peculiar conditions offer an excellent benchmark to study specific chemical and physical processes which test our understanding in fields like spectroscopy, radiative transfer, convection and hydrodynamics, to mention a few. These layers can supply also useful information to infer geophysical properties of the planet, like its internal structure, and to supply correct boundary conditions for the general dynamics and chemistry of the whole atmosphere. An advantage of the outermost layers is their accessibility, sometimes better than lower layers; they can be reached by low orbiting satellites, and by the remote sounding of the different airglow emissions produced at these altitudes. Describing in detail those emissions and using these layer's densities to modify the satellites orbits are also among the objectives of the research on the upper atmosphere. All these conditions concur in the case of the Venus thermosphere, and have been investigated with the data available so far. In this section we review briefly a selection of the results and problems which require further measurements.

3.1 Thermal structure

The thermal structure obtained by radio occultation and by the PVO infrared radiometer and probes, responded to convective and radiative processes up to about 90 km, as expected [44, 46, 47], but showed peculiar latitudinal variations, with a positive gradient towards the poles at altitude between 70 and 90 km [48]. At high latitudes the atmosphere at that layer is well stratified, with a colder region below, termed the cold collar, and which seems to surround the pole [52]. It is not known if this cold collar is frequent or not (Magellan radio occultation did not reveal it [60]).

A transition to the upper atmosphere, with an isothermal or inversion layer equivalent to the Earth's tropopause, above which the energy balance is controlled by radiation, is not as well marked in Venus as it is on Earth. Normally the Venus mesosphere is simply taken as that region from the cloud top, to the base of the thermosphere, typically at 0.1 μb, around or above 120 km. One-dimensional global models predicted a mesopeak, produced by solar absorption in CO_2 near-IR bands and located around 1 μb, or about 100 km altitude. This layer seems to be confirmed by ground-based microwave observations, and has been used as a different definition of the mesopause, [43], since large variability is observed above it. But it has not been described in a systematic manner from instrumentation in orbit. An interesting result reported at those altitudes from SPICAM on VEX, and not observed previously, is a strong inversion layer reported there [51], which opens an additional debate about its source and its relation with the mesopeak.

The cold collar mentioned above and tidal waves observed on Venus upper atmosphere, are deviations from the radiative equilibrium situation [44], and which might be partly related to the superrotation; they present challenges to future global modelling of the Venus atmosphere. Also, it is not known why large latitudinal variations

are present while the longitudinal changes, following similar solar illumination, are very modest [53]. Among the opened questions, from the observational point of view, are the confirmation of these structures, and the study of their repeatability and variability in both hemispheres.

In the thermosphere, PVO observations show relatively mild dayside temperatures, and very cold nighttime temperatures, what is refereed to as the Venus cryosphere. This was a puzzle for a long time, in view of the proximity to the Sun. A solution, at least partial, was found in the early 90s. Reanalysis of non-LTE CO_2 measurements in the Earths upper atmosphere [55, 56] revealed a much more powerful role of CO_2 as a cooling agent of the atmosphere, due to a more efficient energy transfer between CO_2 and atomic oxygen than previously assumed. This explained the strong buffering of solar variations by the Venus thermosphere, explaining the low response to the solar cycle. Still there are uncertainties in this rate coefficient, specially at low temperatures, where measurements in laboratory are difficult [58].

3.2 Dynamics, waves and large scale transport

Some reviews examined the fundamental problems in the atmospheric dynamics of Venus below the clouds and in the lower mesosphere [39]. A companion paper in this issue also tackles this topic [35]. A number of works summarize also our current understanding of the dynamics of the upper atmosphere [58]. We present here our own view of the most interesting problems at these altitudes.

Above the cloud top the circulation has been linked to the thermal structure observed, using the assumption of cyclostrophic balance [54, 57]. Nevertheless, a systematic sounding of temperatures would be needed to establish the extent of this approximation. The situation was originally described by one Hadley cell type of circulation, raising at mid latitudes and cooling the mesosphere, then moving towards the poles in the upper mesosphere, and descending at the poles; the returning would take place at altitudes below the clouds [52]. Actually, a revision with better radiative equilibrium models one decade later revealed key details of the nature of this mesospheric circulation [39, 46]. As this circulation would be against the radiative balance, it must be thermodynamically induced in an indirect manner, perhaps from an interaction of the tides with the mean flow of the zonal superrotation, this being retarded by them [47]. Indeed, small longitudinal variations were detected by PVO in the upper mesosphere, from 5 to 10 K, which indicate tidal propagation [39]. How this is combined with the cyclostrophic balance, and how it merges with the thermospheric circulation is not well known. The altitude decrease of the superrotation might be simply due to the increasing solar warming at higher altitudes [10]. Few data from microwave ground-based observations suggest that, at the 100 km level, 1-week long changes occur between both regimes [43]. In order to clarify this topic, systematic sounding of temperatures and winds, in the mesosphere, together with

precise radiative models, would be very beneficial.

At thermospheric altitudes, open questions also exist. The strong temperature gradients between dayside and nightside seem to drive an interhemispheric large scale circulation. The winds, however, seem to be lower than the expected 400 m/s value, which indicates that some retarding mechanism must be operating [58]. It is expected that the interhemispheric flow and the rising and downwelling branches of such circulation will affect the transport of minor species and might produce some diabatic heating. Such heating has very recently conjectured as responsible for inversion layers in the nightside observed by SPICAM on VEX [51]. Evidences were also found in NO airglow emissions, showing an increase in the nightside thermosphere, approximately where the subsidence may occur [58]. It has also been suggested that this downwelling may enrich the nighttime mesosphere in atomic oxygen, in order to explain the strong emission by molecular oxygen observed by ground-based telescopes. These observations, at 1.27 μm, showed large spatial and temporal variations, in addition to very high levels of emission [34]. The usual explanation, under debate in its details, include downwelling of atomic oxygen followed by recombination. Convection, or some transient dynamical phenomena, like wave breaking might play a role in its variability [49]. New data from VEX is starting to clarify the situation [59].

The existence of wave activity at high altitudes of the Venus atmosphere has been speculated for a long time, but not much observational evidence was available. One set of data showing clear signs of gravity waves come from the few radio occultation by Magellan [60]. Another evidence reported [61] is the perturbation in densities of CO_2, O and He detected by the neutral mass spectrometer on PVO, which show larger amplitudes during nighttime than during daytime, and this is supported by a model of gravity wave propagation [62]. Another interesting example comes also from the Magellan mission, but from a very recent analysis of the radar tracking of the orbit [63], showing for the first time a 9-day period oscillation in the thermosphere, and which seems to be restricted between dusk and midnight. The lack of previous detection suggests, in these authors' opinion, either peculiar modes of propagation and interaction with the mean flow, or perhaps the existence of excitation sources above the cloud tops. The wavy nature of the upper atmosphere is a very open topic, and is hoped that missions like Venus Express may shed some light on it [63].

Transport of minor gases is a useful mean to track the dynamics of the atmosphere. In the lower atmosphere, latitudinal gradients of CO have been observed [64]. An explanation makes use of the circulation in the lower atmosphere, but the strong mixing expected there might preclude the gradient. The alternative is that descent from the CO-richer upper atmosphere may occur in the polar regions, as it happens on the Earth middle and upper atmosphere [65, 7]. Transport processes like these are, however, speculative and remain to be confirmed by new measurements.

3.3 Non-LTE emissions

Airglow and non-LTE emissions are among the characteristic features of the upper atmosphere. They usually supply direct diagnostic tools of the peculiar chemistry and physics at those altitudes, permit remote sounding of atmospheric temperatures and abundances, and via numerical models, drive the investigation of the energy balance of the atmosphere.

While a number of emissions are worth examining, we focus here on two specially interesting ones, for its potential for sounding the Venus upper atmosphere and because new light will be shed upon them after VEX.

Full understanding of these emissions requires careful 1-D modelling, including radiative transfer, microscopic physics, and spectroscopic databases. Sometimes, optically thin conditions facilitate their analysis. This is not the case of the intense non-LTE emissions by the major species of the Venus atmosphere, CO_2, as first pointed out by the pioneering radiative transfer modelling for Venus by Dickinson, in 1972 [66]. He realized the important role played by minor bands of CO_2 in the radiative balance of the mesosphere, and was the base of later model developments [67, 68, 69]. These came after the detection of strong infrared emissions from Venus and Mars, in the CO_2 laser bands at 10 μm [70, 71], and which were explained by solar fluorescence of the fundamental band of CO_2 at 4.3 μm, followed by radiative relaxation at 10 μm. During the last decade, and motivated by the prospect of IR sounding of the Martian atmosphere [72], more comprehensive non-LTE models were developed, including a larger number of CO_2 emissions covering from 1 to 20 μm [31, 32], which were later extended to the Venus atmosphere [73]. These efforts supply tools to analyze remote measurements, and quantify the radiative balance of the Venus atmosphere, dominated by the CO_2 infrared emissions in the upper mesosphere and lower thermosphere. However, few data so far were available for the validation of these models. A few limb spectra at 4.3 μm were taken during the Galileo fly-by with the NIMS instrument, and explained recently, in preparation for the VEX data analysis [74]. Fortunately, the instrument VIRTIS is detecting non-LTE CO_2 radiances systematically [59], which are helping to test the model and will hopeful be used to study the upper atmosphere [75].

Another important emission is the molecular oxygen's infrared system, at 1.27 μm, mentioned above. Its photochemistry is well known, but the above mentioned measurements puzzled the theory for a long time, unable to explain the peak emission and its strong variability. New data from the instrument VIRTIS/VEX have much better spatial coverage than ground-based measurements, and they are starting to clarify some of the issues, like the strong signal which seems to fit the theory [59]. The systematic sounding with VIRTIS is currently characterizing the morphology and variability of the O_2 emitting regions [76, 35].

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3.4 Ionospheric layers and atmospheric escape

The Venus atmosphere and surface are very dry and, assuming initial inventories similar to present Earth, an important loss of water, in the form of hydrogen escape and more important than on Earth, must have taken place on Venus during its evolution. This is supported by the about 100 times higher D/H ratio measured in Venus [77], showing a preferential loss of the heavier isotope via thermal escape. The loss rate estimated for Venus suggests that an Earth ocean could have been lost in about 100 million years [79]. The current escape rate is thought to be much smaller in Venus now, and must surely be by non-thermal mechanisms.

The Venus ionosphere was well described after radio occultation and in-situ data by PVO, and its basic characteristics, like an ionopause between 300 and 400 km varying with the solar activity, the nature of the primary ions (O_2, O and CO_2) and the altitude (around 140 km) and density of the electron peak [50]. Most of these results were well reproduced by models [50, 12] although many unknowns remained, like the role played by the solar wind in accelerating ions which could contribute to an important atmospheric escape. PVO measurements correspond to solar maximum conditions, and what the ionosphere looks like at solar minimum was unknown until Venus Express. VEX's magnetometer (MAG) is carrying out regular in-situ measurements of the near-Venus plasma during the orbital periapsis (about 250-350 km). It also has much better plasma analyzers than PVO. The first results show that the bow shock reflects a fully magnetized ionosphere, with no penetration of the solar wind into the ionosphere [80]. This may mean that no strong solar wind interaction is present [10], although according to the magnetometer team, the magnetic field observed might accelerate the ionospheric particles in the night tail, inducing atmospheric losses there. They suggest to confirm this by measurements of plasma velocities. Loss of ions has been observed by VEX by the plasma analyzer, at the boundary of the induced magnetosphere. These include O+ and H+, primarily, and their relative loss rates are close to the 2/1 value which would indicate water photolysis as the main source. This seems to indicate that there is an escaping mechanism operating at present in Venus, acting on the ions rather than on the neutrals [81].

4 The Venus Express mission.

In the previous section we have illustrated some key problems in our understanding of the known properties observed in the Venus atmosphere. VEX is equipped by a series of instruments with innovative characteristics which make them ideal for sounding the upper atmosphere of Venus, and which offer excellent chances to study some of the open problems listed above. Summaries of all the different instruments, goals and characteristics are given in detail elsewhere [45].

Let us recall that the driving idea of the whole VEX mission, and its design and

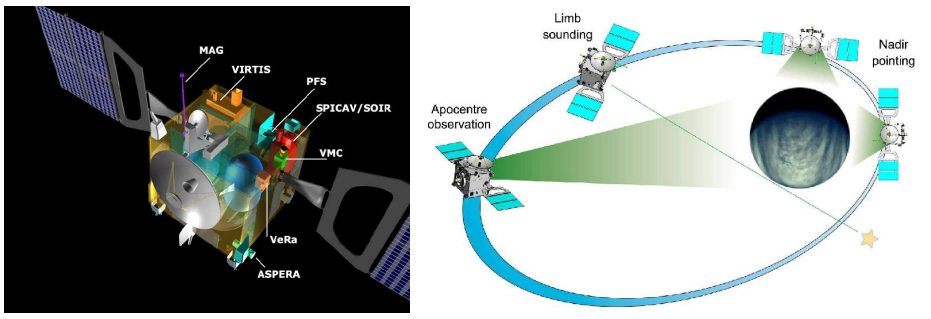

Figure 3: Diagrams showing the accommodation of the scientific payload of VEX on the spacecraft, and the observational phases. Credit: ESA

implementation at ESA have been very special, with a time record between concept (2001) and launch (2005). This was thanks to the use of a suite of instruments taken from previous missions, MEX and Rosetta, quickly assembled into a Mars Express platform, and launched with a Soyuz-Fregat to reach a very elliptical orbit on Venus, similar to that of Mars Express around Mars. A realistic road map of observations, with precise scheduling of the operational time for each instrument during the VEX orbit, is available elsewhere [45].

Figure 4 lists the VEX instruments, with their modes of operation and main scientific objectives. Figure 3 shows the accommodation of the instruments on the spacecraft. Some words about the VEX orbit are necessary. Each orbit lasts 24 hours, with about 10 hours devoted to data transmission to Earth. Some instruments are specially appropriate to operate near periapsis and others can observe from farther away. The actual Venus measurement period can be divided in two modes of observation, the imaging mode and the spectral mode, when the spacecraft is closer/farther than 12000 km from the planet, respectively. This is a relevant division for those instruments like VIRTIS, which can adapt their observation for example from nadir global images at low spectral resolution to limb sounding with higher spectral resolution.

VEX has a number of clear advantages to previous Venus missions. First of all, one is the technological improvement in all the instruments, compared to similar experiments about 20 years ago, including also the larger data transfer rates. Second, the better spacecraft 3-axis stability, permitting precise pointing, essential for limb sounding, and imaging spectroscopy; these were impossible with a spinning satellite like PVO. Third, new techniques are applied for the first time in orbit around Venus, like the "energetic neutral atom" imaging [37], or solar and stellar occultations. Four, the near polar orbit permits sounding of regions hardly accessible by previous mis-

sions, or from Earth observations. The large ellipticity of the orbit, which impose stringent limitations for close mapping and limb sounding, is an advantage however for a number of studies. These include image tracking and global viewing, which may permit observations of planetary waves, polar vortex studies, and time evolution of dynamical features, like winds and turbulence; as well as low periapsis passes, for in-situ exploration of the upper thermosphere.

Acronym	Original	Description	Scientific Objectives	Observation mode	Comment & advantages
ASPERA	MEX	Analyzer of Space Plasmas and Energetic Atoms	Neutrals (H,O), ions and electrons. Discriminate masses and angul.distrib	Entire orbit. Nadir at close approach	New technique in Venus
SPICAM /SOIR	MEX	UV/IR spectrometer for solar/stellar occultation	UV: densities upper atm IR: H2O,D/H,SO_2,hazes	Near Pericenter Limb	First time in Venus
PFS	MEX	High resolution IR Fourier Spectrometer	Full near-IR spectrum (1-5 μm), temp,compos.	Near pericenter Nadir & Limb	Not operating
VERA	Rosetta	Radio science instrument	Ionosphere Mesosphere: density&temp Surface properties	Entire orbit Nadir & Limb	New technique in Venus
VIRTIS	Rosetta	UV-visible-IR Imaging Spectrometer	Composition Mesosphere: temp struct. Airglow & non-LTE	Entire orbit Nadir & Limb	New technique in Venus. Improves upon NIMS&VIMS
VMC	MEX	UV-visible Camera	Images/movies of clouds and waves; UV absorber	Entire orbit Nadir	MEX's was monochromatic Space&time resolution >PVO

Figure 4: List of VEX instruments, description and objectives

5 Exploring the upper atmosphere with VIRTIS

Here we present new data on the upper atmosphere of Venus by the instrument VIRTIS. We focus on limb observations, which are specially adequate for such purpose, and also on fluorescent emissions by CO_2 at 4.3 μm, and their comparison with theoretical model predictions.

VIRTIS is operated to observe Venus in nadir/disc viewing when VEX is far from Venus, but also in a limb sounding geometry during periapsis. Although the large ellipticity of VEX takes VIRTIS as far as 60000 km away, the images from apoapsis can still be used to observe the atmospheric limb of the planet. Figure 5 shows a portion of the Venus disc, acquired during orbit #25, near the apoapsis of the VEX orbit. The

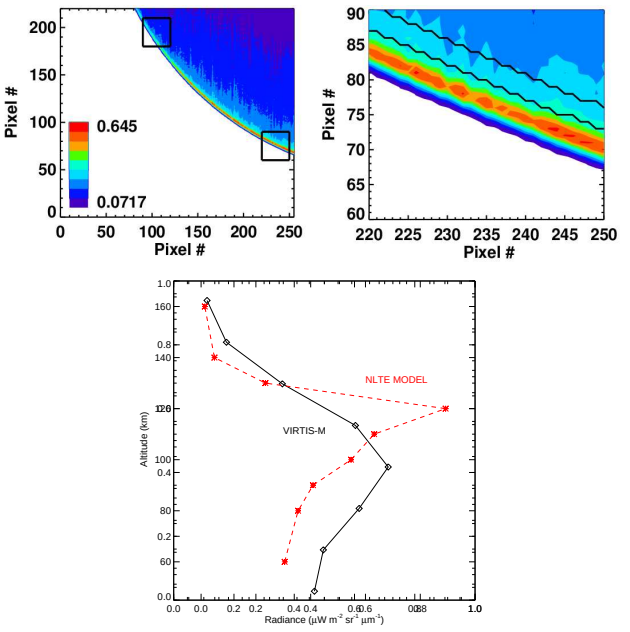

Figure 5: Left panel: Map of CO_2 radiances from VIRTIS-M, from Orbit#25, from apoapsis. Right panel: Zoom to detail the limb sounding capabilities. See text. Lower panel: Radiance profile and model simulation

radiance map corresponds to 4.32 μm, and clearly shows a limb brightening, colored here in red. A zoom of the frame illustrates more clearly the limb emission. The pixel size is depicted by the oscillation in the two reference lines added, to mark the surface and the 60 km tangent altitude. This shows a clear peak emission around 120 km, and at a relatively coarse vertical resolution, but still, similar to the only other detection of this emission in Venus, from NIMS/Galileo. The horizontal resolution is much better, and represents a unique view of this emission. The peak intensity and altitude location, the vertical profile, and the solar illumination variations are a number of features which pose challenges to theoretical simulations.

We built a vertical profile at the limb from this V-M image, at one particular location and at one of the central wavelengths of the CO_2 emission band, at 4.28 μm. It is shown in Figure 5. The model simulation, for a similar solar zenith angle and for a typical atmospheric temperature/density profile, is also shown in the figure. Any wavelength can be used, and [59] present a similar comparison at 4.33 μm. The data seem to follow the model prediction, both the shape of the profile and the peak's

intensity and altitude. The responsible for this emission, the first excited state of CO_2 in its asymmetric-stretching mode of vibration, $CO_2(001)$, reaches a very high solar pumping above about 120 km, according to the model. Below that altitude, the solar flux at 4.3 μm is severely absorbed, and the emission decreases when pointing at the lower mesosphere, or below. At higher altitudes, the $CO_2(001)$ relative population is about constant, but the total density decreases exponentially, and the CO_2 emission therefore decreases quickly as well. A quantitative fit, however, requires a quantitative determination of the density structure of the Venus atmosphere, which is not known at this point. Alternatively, once the non-LTE model is validated, it could be used to retrieve the density, by fitting these emission profiles.

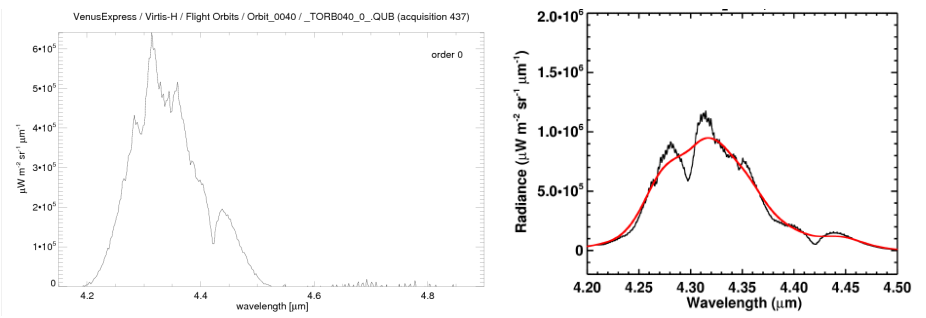

Figure 6: Left: Limb spectra from V-H at lower thermospheric altitudes. Right: Model simulation for V-H (black) and V-M (red). See text.

Figure 5 is an example from one of the signals of VIRTIS, at a resolving power R∼400, commonly used to produce global images or mosaics of Venus, and which is termed V-M. The other signal, at a higher resolution (R∼1800) is termed V-H, and Figure 6 shows one particular spectrum taken in this mode, acquired during periapsis pointing at about 120 km. Several interesting features can be observed above the noise level, which is much lower, at about 5000 μW m^{-2} sr^{-1} μm^{-1} confirming expectations after ground calibration [37]. Non-LTE model simulations of VIRTIS spectra [74] are also shown in the figure, and the agreement is good too. As studied by [74], a large number of bands conform the limb emission, with weak and isotopic CO_2 bands giving significant contributions in the wings of this spectral region. There seems to be, however, a portion of the spectrum which is not well represented by the model in absolute terms. The spectrum in the longward wavelength wing of the strong central emission, around 4.40 μm, seems to be smaller in the model. This problem seems to be systematic, in all the V-H spectra studied so far. We attribute this to a number of weak bands, surely hot and combinational transitions which are not included in the non-LTE model. They may not be relevant to the energy budget of the upper

atmosphere, but a good fit of the measurements require to revise the non-LTE model by adding those minor transitions. Alternatively, some extra excitation source, still unidentified, may be present. This work is in progress.

One of our aims is to perform a detailed analysis of the emission and their different contributing bands. Such study may result in model improvements, like modifications in the way the model describes how the solar energy is transfered between the different CO_2 vibrational states, which includes collisional processes not well determined yet. There are hopes also that these high resolution data from VIRTIS may teach us about some microscopic energy transfer mechanisms.

Other interesting limb atmospheric results from VIRTIS regard the nighttime emissions of O_2 at 1.27 μm, which indicate time and spatial variations at high resolution for the first time. This is the topic of a companion work in this issue [35].

6 Synergy between Venus Express instruments

VIRTIS is not the only instrument on board VEX to study the upper atmosphere (see Figure 4). Some of them will supply useful information for direct and indirect correlation with VIRTIS data, and vice-versa.

A key progress by VEX is expected in the description of the global temperature and density structure of the upper atmosphere, including tracking of minor neutral species and ions. These will be tackled directly by SPICAV using stellar and solar occultation, by VERA using radio occultation, by ASPERA with in-situ data, and indirectly by VIRTIS, via the strong non-LTE emissions there; these are affected by the actual density and the distribution of the emitting species.

The VERA team plans to assume cyclostrophic balance to use the meridional distribution of atmospheric temperature to obtain the zonal wind distribution. The first results from this instrument show neat temperature profiles, with very small measurement noise, from below the cloud deck, around 45 km, up to about 90 km.

The upper boundary of VERA is about the lower range of temperature sounding for SPICAV, this extending up to at least 140 km altitude, as reported recently [51]. Although the results seem to match, there is a intriguing result from SPICAV, a systematic warm layer just above its boundary layer, around 100 km. Previous data from PVO and microwave observations also have upper boundaries about 100 km, with not good quality determinations. This altitude range is therefore subject to specially difficult measurements. Those other previous determinations suggest some small heating, but nothing like the more than 40 K obtained by SPICAV in some profiles. If SPICAV data are confirmed, some strong heating mechanism may be needed there. Since the data presented correspond to nightside, the SPICAV team suggest the heating may be produced by adiabatic compression in the downwelling branch of the global thermospheric circulation, something simulated previously by

models, but with not such intensity [23]. An argument in favor of this interpretation is the increasing magnitude of the inversion as the solar zenithal angle (SZA) increases (closer to the anti-solar point). They also extend their results to estimate a downward velocity for the total atmosphere; their estimation does not include, however, non-LTE effects and is therefore overestimated. However, the data contains the information for a more detail calculation.

Regarding the correlation with VIRTIS, present validation activities and data analysis are focused on the characterization of the emissions. The foreseeable derivation of densities from the CO_2 non-LTE emissions will still take some time. Strong emissions from VIRTIS are observed from the cloud tops upward, even up to above 160 km in some individual spectra. However, eventual retrievals will have to cope with opacity properties and will surely be useful only around the peak emission and upward. As the VERA and SPICAV densities are already available, we plan to use these as input to our model simulations for VIRTIS, which is an indirect comparison strategy between them.

Ideally, a direct correlation between all three instruments should be performed on individual profiles. However, this is difficult given the different observational requirements by individual instruments. VIRTIS, for example, is detecting solar pumping emissions, while most of SPICAV data correspond to nighttime stellar occultations. SOIR data are more interesting, but also occur at high SZA, nominally at 90 degree, where the CO_2 excitation is low. Therefore, each instrument will build its own global maps of densities, and these should be compared.

7 Summary and perspectives

A new mission to Venus, the European VEX, is at last in orbit around Venus, obtaining exciting new data and results for about one year and half to date. First analysis of the data are starting to be published, although the validation activity and systematic analysis of the data is still on-going.

At this early stage, overviews like the one presented here, focused on the atmospheric layers above the cloud tops, may (and hopefully, will) be obsolete soon, as new results are emerging quickly. Regardless of whichever specific results are to be found in the near future, we are listing and discussing briefly a number of scientific problems of the upper atmosphere of Venus which require new data, and we are framing some of our hopes on the new techniques and observational abilities of the VEX mission.

Regarding the upper atmosphere, three instruments, SPICAV, VERA, and VIRTIS are specially prone to correlative measurements of the density and temperature structure of this region. The emissions of VIRTIS, under study, are giving for the first time, a detailed picture with spatial and time variations, which confirm model predictions and offer chances to learn about density variations, turbulence and transport,

and even microscopic physics in the upper atmosphere. The density and temperature profiles from SPICAV and VERA are supplying new results with unprecedented detail of the vertical variation, the dynamics at global scale, and the extension of the cloud deck and its impact on the thermal budget. No doubt these new data from VEX in the mesosphere and thermosphere will trigger modeling efforts to understand them in the near future. Some of these efforts are already on-going, with the development of a number of global circulation models, and the offer to create a climate database similar to the successful one we are building on Mars nowadays [78] .

Routine operations of VEX are granted by ESA until 2009. Extension of the VEX lifetime beyond 2009 is highly desirable. Not only Venus is under a different segment of the solar cycle, but a number of studies would be benefited from it. One is the correlation between different instruments, as mentioned above. A second one is the possibility to modify the VEX orbit, by using some fuel on board, which would supply new geographical perspectives of Venus. Most important, the scientific value of the new measurements merit such an extension. The present database promise already to keep us actively analyzing the data and testing our modelling tools for a long time. Also, the sister mission Mars Express is also operative on Mars at present, and with similar instrumentation, and this multiplies the scientific benefit from each of these missions. This is a unique opportunity for comparative planetology, and keeping both running would be a high priority for ESA and the European scientific community.

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