Unraveling the atmosphere of Venus, Earth's unlucky twin

(Modeling the Venus atmosphere with Terrestrial Knowledge and Experience)

(Report of the meeting held at ISSI, Bern, 7-9 April 2008)

Foreword

A meeting to discuss scientific issues of the Venus Climate and Atmosphere took place at ISSI, Bern 7-9 April 2008 with the following participants:

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The report and recommendations by the group is given below.

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1. Background and Rationale

Venus has been explored with space missions since 1962, beginning with the Mariner 2 fly-by. Since then, it has been investigated with numerous missions from orbit, fly-bys, through entry probes descending to the surface and even from balloons. Currently ESA's Venus Express mission is returning daily observations useful for understanding the dynamic atmosphere of Venus. Despite these efforts, understanding the atmosphere of Venus and its many intriguing features has been a challenge due to observational problems. In the hostile environment of Venus, it is very difficult to obtain the observations and we consequently need in depth theoretical studies and dedicated modeling efforts to support the space missions. Much can be learned from the studies of the Earth's atmosphere undertaken during the last decades. A strategic approach in that respect is the main objective of this report.

A very dense atmosphere dominated by carbon dioxide characterizes Venus. However, it is unique among the terrestrial planets due to its backward spin, its super-rotating atmosphere the persistent cloud cover and its properties. Undoubtedly its climate has evolved over time and is intimately connected with its geological evolution, but the history of its evolution is unknown. We still do not know to what extent Venus is still geologically active. Nevertheless, there is a general notion of a global "catastrophic" resurfacing that occurred on the planet in its geologically recent past, around 700 million years (Myr) ago. Some key questions of the evolution include the following:

- A rapid global change would affect atmospheric composition and dynamics. In particular, the clouds are a product of SO_2 and some out-gassing is needed in order to maintain those clouds.
- On Venus there have likely been multiple feedbacks between volcanism, surface reactions, and photochemistry. For example there could have been a positive feedback between partial melting in the interior and surface temperature increase due to volcanic activity.
- The deep link between geology and climate on Venus has some counterparts on Earth, where the global climate has been affected by large-scale geological processes, such as Large Igneous Provinces (LIP) emplacement in different areas on Earth but less extreme than on Venus.

- The first, and possibly most important major change in Venus history could have been the loss of an early ocean due to a runaway greenhouse effect. Such a dramatic change would have affected all further evolution of Venus, including the inefficient mantle heat dissipation due to the lack of plate tectonics: this would have doomed Venus, thus determining its present hellish state. Indeed, the present atmosphere of Venus contains 10^5 less H_2O than that on Earth, although the initial amount of water, derived from the current amount HDO, would have been compatible with the presence of an Earth-like ocean.
- The timing of such a presumed loss is also problematic. It might have disappeared rather earlier, or it might have lasted for a significant period, providing possibly habitable conditions for a reasonable period of time.

Understanding the current atmosphere of Venus and its possible evolution through time to its current state of an extreme "greenhouse" to exhibit a globally uniform surface temperature of ~ 470K is also relevant for the possible very long-term evolution of Earth's climate and atmosphere as solar irradiation will increase. A better understanding of Venus atmosphere and its climate is also useful in another context. A comparative study of the atmospheres of Venus and the Earth could be of paramount importance in the search, detection and study of possibly hospitable exoplanets, since future space missions will allow not only the detection of Jupiter-sized exoplanets, but also terrestrial-sized ones.

2. Current observational understanding

Venus mass and diameter are very close to those of the Earth, but its almost circular orbit is much closer to the Sun: while the orbital period is of about 225 days, its rotation is retrograde with a very small rate (243 days). The origin of this slow rotation is still not well understood, although several hypotheses have been put forward, with a role of the early accretive processes on Venus, e.g. due to large impacts of planetesimals modifying the forming planet angular momentum.

The very low rotation rate, together with the almost circular orbit and the low spin axis inclination lead to very weak seasonal variations on Venus and its atmosphere and can be ignored in view of variations on other time scales. The small Coriolis force on Venus compared to the Earth is likely to require independent wind and temperature observations and corresponding demands on the modeling and data assimilation.

The atmosphere is composed mostly of CO_2, with few percentage of nitrogen and traces of H_2O. CO_2 is the principal greenhouse gas, which together with H_2O, SO_2 and cloud effects is able to keep the surface temperature around 470° C. A sulfuric acid cloud deck, responsible for the high reflectivity of Venus atmosphere, is present between ~ 48 km and 65 to 70 km altitude globally with observed latitudinal variation in the cloud top (unit optical depth) and small opacity variations between 1 and 3.5μ.

Observations of Venus in the infrared and ultraviolet spectrum show a variety of intriguing wave and vortex patterns. Cloud patterns could be related to variations in cloud top height (hence temperature) induced by vertical motions, rather than variations in cloud thickness. A striking feature of Venus atmosphere is constituted by its south polar vortex, characterized by a complex structure and imaged in detail by VEX (first observed from Mariner 10 in 1974, Suomi and Limaye, 1978).

Among the different space missions that imaged and analyzed Venus atmosphere, the European Space Agency (ESA) Venus Express (VEX) mission is providing data on the atmosphere with a temporal coverage that should be extended as long as practically feasible. This is required for observing and monitoring atmospheric circulation patterns and to be able to compare their dynamic evolution with the result of modeling efforts. The patterns visible in the data from VEX experiments are due to variations in the cloud distributions, and for the most part reflect motions taking place at altitudes of 45-60 km. There should be a subsiding motion near the pole, but the extent of vertical motions associated with these cloud patterns is not well known.

The atmosphere of Venus has two global dynamical regimes: *zonal super-rotation* in the troposphere and mesosphere (0-100 km) and *solar-antisolar circulation* across the terminator in the thermosphere (100-200 km). The observations show that the lower atmosphere has zonal wind velocities with maximum well above of ~100 m/s at the cloud tops decreasing to ~ 1 m/s near the surface and at the mesopause (~100 km). In addition to zonal super-rotation of the upper troposphere there appears to be a slower overturning of the atmosphere from equator to pole with meridional velocities of 10-20 m/s and giant vortices at each pole recycling the air downwards. Physical mechanisms maintaining the observed circulation pattern on Venus are virtually unknown. The distribution of radiative fluxes in the dense Venus atmosphere determines energy deposition pattern that eventually forces atmospheric motions. However only a few measurements of scattered solar radiation are available from the earlier descent probes thus leaving the radiative role of clouds one of the most important uncertainties in the energy balance and dynamics of the Venus atmosphere.

Venus Express has started global monitoring of the atmospheric motions, temperature field and cloud properties (Svedhem et al., 2007). Planet-C plans to continue meteorological investigations starting from 2010 (Nakamura et al., 2007). Observations by these two missions will provide a breakthrough in our understanding of Venus climate that would eventually lead to better understanding of the climate of the Earth.

3. Scientific issues

3.1 Super-rotation of the Venus Atmosphere

Most part of the atmosphere of Venus rotates faster than the underlying solid planet and in the same direction. This has been known for nearly four decades, but its origin and mechanisms that maintain it are still unknown. Leovy (1973) pointed out that the super rotation is likely to be in a state of cyclostrophic balance given the very small Coriolis force. While observations of the thermal structure have shown this to be the case, the unbalanced part of the circulation is a main component of the Venus atmosphere and likely a key aspect of the atmospheric processes that maintain the super-rotation.

At least at the ultraviolet cloud level (as obtained by the ultraviolet imager), the rapid zonal flow is weakly directed toward the respective rotation pole in each hemisphere. The presence oft the weak poleward component leads to a state of non rigid body rotation in the low and mid latitudes and the build up of mid latitude jets which have cores located at ~ 62 km altitude at ~ 45 degrees latitude as inferred from thermal structure data and the existence of cyclostrophic balance. The mean meridional flow transports absolute angular momentum that must be dissipated in polar latitudes due to viscous forces that leads to a tendency towards rigid body rotation in polar latitudes, consistent with the Rankine vortex structure that Venus exhibits. The re-supply of the angular momentum in equatorial regions to maintain the super-rotation has been suggested to occur through one or both of two key atmospheric processes – solar thermal tides and eddy circulations associated with atmospheric waves ranging from small scale gravity waves to a single Kelvin wave. Yet, dynamical observations available to date have been unable to verify this equatorward transport of angular momentum.

3.2 Vortex Circulation on Venus

That global cloud morphology and cloud level winds are consistent with atmospheric circulation being organized into a vortex in each hemisphere. This was shown from the images from Mariner 10 in 1974. In 2006, Venus Express observations showed that the vortex organization was present (Limaye, 2007), and in fact was identified on both the day and night side simultaneously from the VIRTIS reflected solar ultraviolet and emitted radiation in the near infrared. Although the northern hemisphere is not observed sufficiently well by Venus Express due to the nature of its orbit, it is believed that the northern hemisphere also has a similar vortex centered over the pole.

The vortex is characterized at the ultraviolet cloud level (~ 67 km at the equator, ~ 70 km at about 45 to 50 degrees latitude and ~ 65 km over the pole) by a gradual increase in the rotational velocity from equator to about 45 degrees latitude and weakening towards the pole at a rate comparable but not exactly, to a rigid body rotation. The accompanying meridional flow at the cloud level on the dayside starts from near zero magnitude near the equator and peaks near the latitude where the angular velocity peaks. It then weakens toward the pole. This is characteristic of the Rankine vortex, which has been extensively studied. The flow and the morphology of the ultraviolet clouds are visually very similar to a mature tropical cyclone, except for the size. Another examples having similar dimensions are the winter polar stratospheric vortices on Earth.

The vortex structure on Venus is intriguing in that it has been observed for over three decades and may be a dominant or permanent feature of the Venus atmosphere, just like the super-rotation. While the basic characteristics of the Venus vortex have been observed, many others questions remain unknown. Examples are given below. It is believed that suitably designed numerical simulations might at least partially answer them.

- ***How deep is the vortex circulation?***

  The VIRTIS night side observations are inconclusive of the direction of the average night side meridional flow at ~ 47 to 55 km level, but the magnitude is weaker compared to what is observed on the dayside from ultraviolet cloud winds.

- ***How long has the vortex circulation existed in the Venus atmosphere? Does it ever breakdown?***

  Baroclinic effects are likely present in the polar regions given the observed thermal contrasts, but the low rotation rate resulting in a negligible Coriolis force likely suppresses the terrestrial equivalent of planetary waves, but inertial waves may be excited.

- ***Is the vortex circulation a consequence or cause for the super-rotation? Is there any interplay between the vortex and the super-rotation?***

  It has been inferred from polarization maps of Venus acquired from Pioneer Venus OCPP that a haze of submicron sized particles present in the upper reaches of the main cloud layer has a greater optical thickness which leads to brighter polar regions at visible wavelengths. What controls the apparent changes in the haze optical depth which must be responsible for the brightening? Is it related to changes in the vortex circulation in the core region?

There are likely many similarities between the stratospheric polar vortices observed on Earth in the northern and southern hemispheres and those on Venus, although the asymmetry between the two hemispheres observed on Earth is not expected on Venus. Earth's stratospheric polar vortex is well simulated in high-resolution numerical models of the Earth's atmosphere and it can be anticipated that such models can be of substantial value in understanding the vortex circulations on Venus.

3.3 Quantifying the role of topography

Modeling studies of the Venus atmosphere indicate a clear sensitivity to topography. The topography on Venus is well known and sufficient for numerical modeling. However, the way the topography influences the circulation through the depth of the atmosphere is not clear, and the relative contribution from a direct coupling to the large-scale circulation and by means of gravity wave action needs to be clarified. The experience we have from Earth modeling is that topography requires high resolution as sharp features are poorly represented in low resolution models. There are ways around this such as mapping the topography consistently with the resolution along lines, which was previously done at ECMWF. The way topography acts on Venus is presumably more complex compared to the Earth as the surface wind are rather weak but must nevertheless be accurately determined.

3.4 Nature and formation of clouds

The main Venus clouds extend from 48 to 65 km above the surface, and consist of three distinct decks with relatively clear air in between: the upper, middle and lower clouds. Detached hazes are often observed above and below the main cloud decks. The particle size distribution is trimodal. The mass of the clouds is dominated by mode 3, the largest particles, which may be non-spherical. Mode 2 is 1 micron spheres. Mode 1 is smaller and their composition and source are unknown. Chemical models can produce cloud droplets from photolysis (at the top) and condensation (at the bottom).

In situ spacecraft aerosol analysis shows sulfur, chlorine and phosphorous and hints of other species such as iron and magnesium. The sulfur chemical cycles that forms the H_2SO_4 cloud particles also recycle CO_2 and creates reactants with the surface and upper atmosphere. Some degree of ongoing volcanism is believed to be necessary to balance the photochemical formation of cloud particles with the loss of sulfur due to heterogeneous reactions with surface minerals. The above-cloud SO_2 abundance is observed to be highly variable. This may result from volcanic plumes or, alternatively, from dynamical interchange with the sulfur-rich below-cloud atmosphere. Since SO_2 and H_2O, the main cloud-forming constituents, are also important volcanogenic trace greenhouse gases, both volcanism and the clouds are believed to participate in important climate feedbacks.

The clouds also influence stability by absorbing incoming and outgoing radiation. This has a major role in the greenhouse effect. A large portion of incoming solar energy is absorbed in the clouds, especially by the “unknown ultraviolet absorber”. The unknown absorber is correlated with SO_2 and has a similar lifetime. It absorbs mainly in the layer between 58-62 km. Possible candidates include S_3, S_4, S_8, Cl_2, $FeCl_3$, SCl_2, S_2O, croconic acid, ammonium pyrosulfate, and nitrosulfuric acid. This massive solar absorption results in strong dynamic forcing by the clouds.

The clouds are valuable tracers of global dynamics, as their motions reveal the winds. Near-infrared images, both ground based and from spacecraft, show variation in the middle and lower cloud opacity. Radiative-dynamic feedbacks are believed to control the nature and timescale of these features. The extent to which radiation leaking through these holes affects the global radiative balance is unknown.

Future modeling should address the relationship between global cloud structure and global circulation, and in particular try to reproduce the convective motions believed to be responsible for forming and dissolving the lower clouds, in updrafts and downdrafts that result in thick and thin areas (holes) respectively.

4. Modeling the Atmospheric Circulation

Venus General Circulation Models (GCM) are currently in varying state of development. Super-rotation and polar vortex circulation are present in model simulations, but as yet there is not unanimity in their relative significance or prominence. The maturity of the circulation models including the realism regarding the representation of physical processes in the Venus atmosphere appear to be the main issues and it is likely that future developments will narrow the gap between the simulation results.

The modeling has naturally benefited from modeling the Earth atmosphere and it is obvious that several aspects of the building of a comprehensive model are common. However, modeling includes a number of empirical aspects typical of individual planets, which need to be determined and developed from observations and different process studies. Aspects like the small Coriolis force, the huge mass of Venus atmosphere and wide temperature range compared to the Earth as well as the complex role of clouds on Venus make modeling to a great challenge. We propose here a stepwise process where the first part will include a series of model sensitivity experiments using available models.

This work will consist of a comparative study of several General Circulation Models (GCM) of Venus that have been developed recently. Among these models, the GCMs developed at CCSR/NIES/FRCGC (Japan) and at Laboratoire de Meteorologie Dynamique (LMD, Paris, France) are the only two that include a full radiative transfer module that computes temperature structure self-consistently. These models are still under development, but some robust aspects may already be discussed. The LMD model includes a radiative transfer module based on Net Exchange Rates formulation (Eymet et al. 2008), while the

CCSR model uses a two-stream radiative scheme (based on Nakajima et al, 2000, using parameters from Matsuda & Matsuno, 1978, and Crisp, 1986, 1989).

Comparison of runs using full radiative transfer and simple Newtonian cooling (temperature structure forcing) clearly indicates that the meridional circulation, as well as zonal wind speeds obtained show significant differences. Several other models are still under development in order to include full radiative transfer, and may join the comparative studies as they develop during the project: UCLA group (model based on the CAM Earth GCM), Oxford (UK) group (derived from UKMO Earth GCM), CalTech group (model developed from the Planet WRF GCM).

Circulations obtained with the CCSR and LMD models feature super-rotation above the clouds, similar to observations, but it appears to be more difficult to induce super-rotation below the clouds, when simulations are started from a resting atmosphere. The convective region located in the lower and middle Venus clouds (47-55 km) is related to the heating of the cloud base from the hot lower atmosphere, and the cooling of the middle cloud to space, inducing thermal instability. Key questions that are currently being assessed with the CCSR and LMD GCMs include: role of the thermal tides in the build-up and maintanance of super-rotation above the clouds, role of topography, potential role of sub-grid scale gravity waves (their influence has been demonstrated with the CCSR GCM). The influence of the specific heat variations with temperature, which affects the adiabatic lapse rate and therefore the overall thermal structure, is also discussed with the LMD GCM.

5. What can be learned from the experience of modeling the Earth’s atmosphere and climate?

For obvious reasons, numerical modeling of the Earth atmosphere has attracted much more attention than the modeling of other planets. The simulation of the Venus atmosphere is still in a state of infancy compared to that of Earth. As Earth and Venus show a lot of similarities (e.g. the size; existence of clouds; dynamical structure of the atmosphere with the existence of polar vortices, Hadley cell type meridional circulation, and solar tides) it may be advisable to benefit from the experience with Earth modeling in numerical studies of the Venus atmosphere. It should however be noted that also large differences exist (e.g. a significantly slower rotation period of Venus; much denser Venus atmosphere consisting predominantly of carbon dioxide).

Two striking features of Venus dynamics are the super-rotation of its low to mid-latitude atmosphere and the stable polar vortices observed in both Polar Regions. The forcing mechanism leading to these two phenomena are still not sufficiently explained. In trying to explain them one may benefit from the experiences gained from numerical models of the entire Earth atmosphere like the Hamburg Model of the Neutral and Ionized Atmosphere (HAMMONIA), Schmidt et al. (2006). It is suggested that the super-rotation may be mainly forced by thermal tides or the meridional advection of angular momentum. Also small-scale gravity or larger scale planetary waves like Kelvin waves may have an influence. All these phenomena have also an influence on zonal winds observed in the equatorial Earth atmosphere dominated by the stratospheric quasi-biennial oscillation (QBO) and the semi-annual oscillations (SAO) in the stratopause and mesopause regions. These phenomena are reasonably well simulated in HAMMONIA. Besides that, recently, the model has been used to study sources and propagation of solar thermal tides. Venus modeling may benefit from experiences with parameterizations of the sub-grid scale gravity waves in Earth modeling as well as from the experience in analyses of the respective importance of the single forcing terms.

The observed polar vortices have not been simulated successfully for Venus. A comparison with the stratospheric polar vortices simulated in Earth models covering this region (like HAMMONIA or MAECHAM5) may help in identifying possible deficiencies in current Venus models.

One intriguing feature of the Venus atmosphere is the existence of dense clouds of sulfuric acid in the 50 to 70 km altitude region. Turbulence is observed at the lower boundary of this cloud layer. Both turbulence and clouds are small-scale phenomena that have to be parameterized in global models. It should be studied in how far Venus modeling can benefit from existing parameterizations of Earth turbulence, cloud and sulfate aerosol parameterizations.

6. Recommendations

To set up an ISSI working group from 1 July 2008 with a two year perspective having the following objectives:

1. To organize, to the extent possible, standardized comparative model simulation experiments of the Venus atmosphere with comprehensive models covering the depth of the atmosphere up to around 100 km. Specific aspects to explore are sensitivity to the basic model formulation (dynamical core), to initialization and to the boundary conditions. What is the time scale for reaching equilibrium and how does this depend on the initial state? What is the level of internal variability and what are the dominant scales?

2. Comparison with analogous terrestrial phenomena
3. To support this work with simpler conceptual models to help in the interpretation of the result.
4. To undertake validation using available data sets from Venus Express and other sources (temperature, wind field, and tracers and dynamical phenomena) such as the super-rotation and the polar vortices
5. To investigate whether data-assimilation of the data from Venus Express would be feasible
6. Based on results achieved provide advice for ongoing and future Venus missions

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