Why Explore Venus Now?

During the 9th VEXAG (August 30 – 31, 2011, Chantilly, Virginia) Dr. Waleed Abdalati, NASA Chief Scientist, asked for some feedback on why Venus is important to explore now. He also requested a summary of past meetings that made recommendations, their outcomes, and outstanding scientific questions from those efforts. Below is a brief overview of findings that emphasize the importance of exploring Venus now, with thanks to Kevin Baines (JPL/UW- Madison), Mark Bullock (SwRI), David Grinspoon (DNMS), Ajay Limaye (CalTech), Paul Menzel (UW-Madison) and other colleagues for valuable input and comments. VEXAG hopes that this is the beginning of a continuing dialog.

4 November 2011 *Sanjay S. Limaye, VEXAG Chair*

Introduction

2011 marks the 250th anniversary of the discovery of the atmosphere of Venus by Lomonosov (Marov, 2004) and half a century since the high surface temperature was proposed by Sagan (1960) to arise from a runaway greenhouse effect. Since then, Venus continues to be a suitable natural laboratory to enhance our understanding of Earth's atmospheric processes and future climates. Similar to the Earth in size and many physical properties, Venus presents a simpler atmosphere to model – no seasons by virtue of its rotational axis being nearly perpendicular to its orbital plane, nearly spherical with much smaller elevation differences, no hydrologic cycle and a global cloud cover. Yet there are key differences which can illuminate the role of a variety of climatic processes. The upper clouds contain a variable amount of an unknown ultraviolet absorber which is responsible for a major fraction of the solar energy being absorbed in the upper atmosphere some 55 km above the surface. With a surface pressure of over 90 bars from a 95% carbon dioxide and 3% nitrogen atmosphere with traces of water vapor, sulfuric acid, carbon monoxide and other molecules, Venus presents an extreme case of the role of the greenhouse effect on global warming. Another key difference between Venus and Earth is the rotation rate – Venus rotates backward, at a rate 243 times slower than the spin of the Earth, which in turn both lengthens the solar day and reduces the Coriolis force by two orders of magnitude. Why it spins backwards is an anomaly whose origins are not understood at all, but the impact on atmospheric circulation and climate is significant. Studying how our neighboring planet operates under a significantly different set of environmental conditions enables a better understanding of the planetary atmospheres in general and

Earth in particular. Venus presents an atmosphere with a wide range of dynamical and radiative heating time constants (Stone, 1975), and our inability to apply the models with the same basic physics strongly suggests that the parameterization schemes are not applicable to the wider range of conditions encountered. Venus presents opportunities for "stress" tests of the climate models with significant increases in greenhouse gases which will boost the confidence in predictions Earth's future climate.

Time and again, studying Venus has resulted in revolutionary changes to our thinking about Earth. The first glimpse of the depths of Venus by the very first interplanetary spacecraft, Mariner 2 in 1962, revealed an unexpectedly hot atmosphere 200 K warmer than predicted, thus revealing the importance of the greenhouse effect in determining planetary climates. As well, the role of CFC (chlorofluorocarbons) in ozone chemistry - so important in explaining the ozone hole in the Earth's southern polar atmosphere - was discovered by Venus scientists to explain the chemistry of chlorine and other trace molecules in Venus' upper atmosphere. The recent discovery of an ozone layer (and other species) in Venus' atmosphere by ESA's Venus Express orbiter provides an opportunity for comparative atmospheric studies. As a another example, a widely accepted mechanism for the demise of the dinosaurs on Earth was the development of a decade-long, globe-girdling Venusian-style sulfuric acid cloud layer resulting from the impact of a bolide in the Yucatan peninsula some 65 million years ago, which resulted in a dramatic cooling at the Earth's surface. The enhanced CO_2 content due to extensive fires generated by the impact then warmed the planet to historically high temperatures. Both of these severe climatic results of the dinosaur-killing impact stemmed directly from Venus studies.

As earlier missions to Venus have taught us about the nature of Earth's environment and climate, so too will future explorations.

Background

In "**Discovery of Global Warming**" Spencer Weart (www.aip.org/history/climate/index.htm) writes:

> *"In the 1960s and 1970s, observations of Mars and Venus showed that planets that seemed much like the Earth could have frightfully different atmospheres. The greenhouse effect had made Venus a furnace, while lack of atmosphere had locked Mars in a deep freeze. This was visible evidence that climate can be delicately balanced, so that a planet's atmosphere could flip*

> *from a livable state to a deadly one.*
>
> *A planet is not a lump in the laboratory that scientists can subject to different pressures and radiations, comparing how it reacts to this or that. We have only one Earth, and that makes climate science difficult. To be sure, we can learn a lot by studying how past climates were different from the present one. And observing how the climate changes in reaction to humanity's "large scale geophysical experiment" of emitting greenhouse gases may teach us a great deal. But these are limited comparisons — different breeds of cat, but still cats. Fortunately our solar system contains wholly other species, planets with radically different atmospheres."*

Further, he writes:

> *"Could study of these strange atmospheres provide, by comparison, insights into the Earth's weather and climate? With this ambitious hope Harry Wexler, head of the U.S. Weather Bureau, instigated a "Project on Planetary Atmospheres" in 1948. Several leading scientists joined the interdisciplinary effort. But the other planets were so unlike the Earth, and information about their atmospheres was so minimal, that the scientists could reach no general conclusions about climate. The project was mostly canceled in 1952" (Doel, 1966).*

Fortunately, during the last fifty years the situation has improved dramatically. Spacecraft exploration of Venus over the last half century (beginning with Mariner 2's fly-by in 1962 up to the current monitoring by ESA's Venus Express) has revealed the similarities and differences between Earth and Venus. How these two planets evolved so differently remains the fundamental question where the answer will greatly enhance our understanding of Earth's future climate. The key questions that we still seek answers to include: How does Venus lose its heat? What happened to its inventory of water? Why doesn't Venus have plate tectonics? Why does it spin so slowly? What drives its superrotating atmosphere? Why is the thermospheric circulation so variable? Why doesn't Venus have a magnetic field? Answering these questions is critical to understanding the terrestrial planets rapidly being discovered around other stars by the Kepler and Corot missions from NASA and ESA and by ground based telescopes.

Since the 1980s, various NRC studies have highlighted the value of Venus exploration. In response, since the beginning of the Discovery Program in 1992, at least twenty four proposals for Venus missions have been submitted to seven Discovery proposal opportunities, with four of them being selected for the second round (Concept Study Report) .

These missions have attempted to answer some of the most crucial questions noted by the first Decadal Surveys and earlier National Academy reports. Yet, none of them were selected for launch.

The 1988 NRC report noted that the goals of planetary exploration are met through observations and missions in which the levels of investigation are generally progressive. For geoscience studies through network science, sample return and surface meteorology, Venus was deemed to have the highest priority (NRC 1988). However, the report noted that "the high surface temperatures will make this mission very difficult". The report, published before Magellan data were obtained, nevertheless noted subsequent exploration (p. 107):

> *"In the case of Venus, a good map is partially in hand; completion is expected with the planned radar mapper mission (Magellan). Current lack of this map inhibits detailed projections for future missions. An initial set of geochemical and mapping information has been obtained from Soviet investigations. The hostile environment of the planet requires much more technological development for future missions than is the case for the other terrestrial planets. Nevertheless, the kind of geophysical and geochemical information desired from Venus is similar to that desired from the other terrestrial planets, and the means needed to acquire this will include probes, the establishment of a global network, and sample returns. Accomplishing these objectives will provide interesting technological challenges".*

The Report from the Workshop on Dynamics of Planetary Atmospheres (Suomi and Leovy, 1978) concluded that the observational goals for the Venus atmosphere are:

(1) To determine, more completely, the vertical and horizontal distributions of radiative heating and cooling, and the relationship of radiation fluxes to clouds,

(2) To define the mean atmospheric state, including the large-scale wind distribution,

(3) To define smaller scale and transient wind systems, and identify their mechanisms,

(4) To discover whether clues to past atmospheric processes are imprinted in the surface

The observations recommended were: Composition of the atmosphere
Albedo and composition of the surface
Composition, microstructure, horizontal and vertical distribution of clouds and aerosols
Radiative flux divergence
Pressure and temperature as function of location and time
Winds as a function of location and time (*by direct measurement or by cloud motion analysis)*
High resolution radar imaging of the surface

The report further concluded:

> *"In addition to the opportunity to test the generality of physical parameterizations derived from terrestrial experience, under vastly different conditions, planetary*

> *science has already provided a number of examples in which the experience and skills developed in the study of other planets have accelerated progress in understanding of terrestrial problems. Speed in narrowing the uncertainties surrounding estimates of various earth climatic theories has become a clear need in view of such possible human influences on climate as the potential for alteration of the ozone layer or of changing the heat balance by increasing the* CO_2 *concentration. Research in both problem areas has already benefited from the existence of a planetary research program. For example, the study of the radiative properties of* CO_2 *for the conditions on Venus led to a parameterization of the* CO_2 *influence on radiation. Although originally intended for Venus application, this parameterization has subsequently been widely used for calculations in the earth's stratosphere. Undoubtedly, such a development would eventually have occurred for earth, but the existence of a scientific effort in planetary atmospheres speeded up the process considerably. In fact, much of radiative transfer theory now in common usage in earth applications was originally developed for extraterrestrial applications."*
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> *As another example, one component of some earth climatic theories is the parameterization of horizontal and vertical heat fluxes as functions of the large-scale thermal forcing. Some of these theories which are at the core of highly parameterized earth climate models, were originally developed in the context of comparative planetary studies. The point is not that such parameterizations are necessarily "correct," or even "optimal," but they have generated controversy and have stimulated others to explore this problem…"*

The report summarized its findings by identifying two items:

(1) Simulation models and mechanistic models can be applied to other planets as well as to the Earth. If the actual circulations of the planetary atmospheres are known, this application provides a means of testing model performance under very different conditions. In so doing, this helps to validate use of the models to examine climate, when the external conditions governing climate are very different from those of the present.

(2) Many physical processes which occur in the Earth's atmosphere also occur in the atmospheres of other planets, but in a more extreme form. The study of planetary atmospheres helps us to gain a better fundamental understanding of such processes, and perhaps even to identify terrestrial processes which would otherwise be missed.

Hunten (1992) reviewed the Pioneer Venus results on the presence of water vapor on Venus, and proposed in "Lessons for Earth" that the model examining the greenhouse effect in a steam atmosphere on Earth as might result from increased carbon dioxide should also work on Venus. He noted that, "There is no likelihood that the Earth will actually come to resemble Venus, but Venus serves both as a warning that major environmental effects can flow from seemingly small causes, and as a test bed, for our predictive models of the Earth".

In a review article, Gierasch et al. (1997) noted:

> *The overall spin of "superrotation" of the Venus atmosphere is a striking phenomenon… But the fundamental cause of the global superrotation remains a mystery in spite of data from Earth-based observatories, from Pioneer Venus, from several Russian probes, from a Russian/French balloon experiment, and from the NASA Galileo flyby. The key missing knowledge is of momentum transfer processes in the deep atmosphere, between the surface and the cloud deck. Neither the forcing nor the drag and dissipation mechanisms are known. ... It is concluded that further measurements, in conjunction with numerical modeling, will be required to resolve this puzzling and challenging question. New data must improve by an order of magnitude on the accuracies achieved by the Pioneer Venus probes.*

Sample Mission Concepts for a Better Understanding of Venus

Crisp et al. (2002) provided arguments for exploring Venus to elucidate the divergent evolution of Earth-like planets. This paper represents the community input for the first Planetary Science Decadal Survey (2003 – 2013) conducted by the US National Academies at NASA’s request. Crisp et al. presented a case for several missions:

- The Noble gas and Trace Gas Explorer is the highest priority mission because its data are vital to our understanding of the origin of Venus. This small mission requires a single entry probe that will carry the state-of-the-art instruments needed to complete the noble gas inventories between the cloud tops and the surface.
- The Global Geological Process Mapping Orbiter is a small to medium class mission. It will carry a C-and/or X-band radar designed for stereo or interferometric imaging, to provide global maps of the surface at horizontal resolutions of 25 to 50 meters. These data are needed to identify and characterize the geological processes that have shaped the Venus surface.
- The Atmospheric Composition Orbiter is a small mission that will carry remote sensing instruments for characterizing spatial and temporal variations in the clouds and trace gases throughout the atmosphere. This mission will collect the data needed to characterize the radiative, chemical, and dynamical processes that are maintaining the thermal structure and composition of the present atmosphere.
- The Atmospheric Dynamics Explorer is a small to medium mission that will deploy 12 to 24 long-lived balloons over a range of latitudes and levels of the Venus atmosphere to identify the mechanisms responsible for maintaining the atmospheric superrotation.
- The Surface and Interior Explore is a large mission that will deploy three or more long- lived landers on the Venus surface. Each lander will carry a seismometer for studies of the interior structure, as well as in-situ instruments for characterizing the surface mineralogy and elemental composition. This mission requires significant technology development.

From this community input, the 2003 Decadal Survey recommendations included a “Venus In Situ Explorer” as a candidate mission in the New Frontiers-2 Announcement of

Opportunity. A proposal “Surface and Geochemistry Explorer (SAGE)” (Esposito 2011) was submitted in response to this AO but was not selected. The mid-term review of the progress on the NRC recommendations resulted in slightly modified language in the NOSSE Report (NRC 2008) for VISE in the New Frontiers-3 AO for which two candidate missions were proposed. The report noted that:

> *“In some cases those mission-specific recommendations introduce significant changes into the possible mission, notably in defining the parameters for the Venus In Situ Explorer and the Network Science missions. The committee noted that these science goals may not all be achievable in a single mission but believes that the choice and prioritization of goals are best left to those proposing and evaluating the missions. “*

Of these, SAGE was selected for Concept Study Report due by January 2011. The mission was not ultimately selected for flight by NASA (June 2011). The New Frontiers-4 AO will presumably receive additional proposals for Venus.

In the meantime, NASA also undertook a study of a flagship mission to Venus (Bullock et al., 2009), just prior to the 2011 Decadal Survey of Planetary Science. A scaled down version of this mission was recommended by this survey (Venus Climate Orbiter). The Mars Express spare was sent to Venus by ESA in November 2005 to become the Venus Express orbiter, and JAXA launched Akatsuki/Venus Climate Orbiter in May 2010 which is now awaiting a second attempt at orbit insertion around Venus in 2015, having missed it the first time in December 2010. These and other missions proposed to Discovery Program remain hopes and dreams to obtain important new observations, but the time for NASA to explore Venus is now.

Why Explore Venus Now?

Modeling the Climate of Venus

The recent Decadal Survey (Visions and Voyages for Planetary Science in the Decade 2013-2022) summarized the outstanding questions about Venus. Some pertinent issues not addressed therein have to do with atmospheric modeling. Numerical models have been attempting to simulate Venus or Venus-like atmospheres through adaptations of Earth circulation models for the last several decades. Only in the last one or two decades have the models been able to produce superrotation using a very simplified approach. A Working Group on Climate

Modeling of Venus (International Space Science Institute, Bern, Switzerland) compared results of current models using the same initial conditions, similar to what has been done with terrestrial models, and the results are not very re-assuring. While most of these are able to achieve "superrotation", they disagree on the details of the circulation in the deep atmosphere and in the mechanisms that support the superrotation (Lebonnois et al., 2011, Lewis et al., 2011). The sub-solar to anti-solar circulation that was anticipated prior to the discovery of the superrotation of the Venus atmosphere has since been discovered in the thermosphere, but highly variable in the strength and even the direction of the flow in the 90-110 km layer above the surface. This variability also cannot be simulated and its causes are not yet understood (Limaye and Rengel, 2011). Similarly, the organization of the observed cloud level circulation in hemispheric vortices (Limaye et al., 2009) also cannot be simulated to probe its deeper structure, which is currently inaccessible through remote measurements.

Why is it so difficult to simulate the different aspects of the atmospheric and thermospheric circulation of Venus? It took many years for the Earth climate models to be "tuned" by tweaking the parameterization of key processes. That the high surface pressure and temperature should be such a great impediment to the successful numerical simulation of Venus' atmospheric circulation using some of the fastest computers available is one of the greatest frustrations of atmospheric science. The causes of this failure reside in imperfect parameterization of the radiative heating in the atmosphere and small scale processes. That the same processes are basic to the Earth climate models should give us a pause. The ultraviolet absorber on Venus plays a role very similar to the water vapor (and ozone to some degree) in Earth's atmosphere for deposition of energy above the surface but through different processes. Its global distribution is also similarly spatially and temporally highly variable. Unlike water vapor on Earth (mostly in the troposphere), however, the Venusian UV absorber also occurs far above the surface in the upper cloud layer (mesosphere). It certainly should boost confidence in long term projections of Earth's climate once we can successfully model Venus' atmospheric circulation. This is especially true as substantial increases in the carbon dioxide and water vapor are considered for Earth.

The warming that has been measured on Earth in recent decades has raised world-wide concern and has led to many independent climate modeling efforts (IPCC, 2007). The numerous models project a range of warming over the next decades, with some variation in the spatial details due to increased carbon dioxide. For the past several years, the US Department of Energy has organized an intercomparison of global climate models; an effort initiated and overseen by the World Climate Research Program, which started with the validation of atmospheric models. (Gates, 1992). Venus provides an opportunity for a "stress test" of such models as most attempts to realistically simulate the observed conditions use different Earth weather/climate models adapted for Venus physical conditions (Lebonnois et al., 2011) The inability of these models to agree upon the significant processes responsible for superrotation and the disagreement with available observations suggests that the "fine tuning" or parameterization of small scale processes and radiative heating may not be appropriate for Venus conditions. This raises the concern that the parameterization for large increases in the abundance of carbon dioxide in Earth's atmosphere should be examined. Venus provides an extreme case for such a test.

In the last few decades the discovery of life in extreme environments has led to a new concept of the habitable zone. As we look for life elsewhere, it is also important to remember that the Venus clouds present a potentially habitable environment for certain bacteria (Sagan, 1971; Schulze-Makuch and Irwin, 2002; Schulze-Makuch et al., 2004). Although they commonly originate from the surface, bacteria have been found at high altitudes, including in cosmic dust samples (Yang et al., 2009); hence it would be worth testing the habitability of the Venus clouds. An experiment to make such observations was described at the 9the VEXAG meeting (Juanes-Vallejo, 2011).

Sun-Climate Connection on Venus and Earth

While the connection between the sun and climate is obvious, the response of the climate to the solar variability is complicated and not fully understood (Lean and Rind, 1996). The NASA Living With a Star Sun-Climate Task Group (J. Eddy, Chair) noted in its report (Eddy, 2003) "at this time we simply do not know whether longer-term climatically-significant variations in solar irradiance exist or don't exist. Nor do we know the magnitude of these conceivable changes". Much of the difficulty is due to the different time scales characteristic of the climate markers to the solar irradiance. Other difficulties arise in terms of the spectral variability of the irradiance over time along with the total solar irradiance. It is in this instance that Venus serves as a near-perfect natural laboratory – uniform cloud cover containing heterogeneous ultraviolet absorber(s) responsible for controlling the climate. Therefore, one should expect variability in the Venus cloud cover in response to the solar output. Measurements to monitor such changes from orbit are feasible and may be simpler to some degree than for Earth.

The data gap that hampered the effort in the late 1940's to simulate other atmospheres has now been significantly reduced, but not eliminated for Venus through the last few decades of spacecraft data from US, Soviet and European missions to Venus. Besides lending balance to the Planetary Science Division, exploration of Venus holds implications for extrasolar planets, the sun-Earth connection and habitability--all of topics of interest to the Earth Science, Heliophysics and Astrophysics Divisions of NASA/SMD. An effort comparative climatology of terrestrial planets by NASA/SMD is thus highly desirable.

Key questions about Venus have been discussed in VEXAG meetings and presented in its Goals and Objective document which is periodically updated (www.lpi.usra.edu/vexag). For the sake of brevity, these questions are not presented here in detail.

Summary

As we begin to discover terrestrial exoplanets orbiting other stars in our galaxy, some of them will be Venus-like, and learning how they reach this evolutionary state will be absolutely crucial for our understanding of the origin and longevity of habitable conditions on Earthlike planets. Pioneer Venus informed us about the past presence of water on Venus (Hunten, 1992). Its subsequent loss tells us that the history of water on Venus is even more significant for improving our capability to understand future Earth climates as the rising surface temperatures lead to increasing water vapor in the atmosphere which in turn raises the saturation vapor pressure, the same process that is believed to have raised the surface temperature on Venus and led to the loss of its (surface) water (Sagan, 1960).

A common thread for Venus and Mars is that the atmospheres on both planets appear to have undergone catastrophic change--Mars may have lost almost all its atmosphere, while Venus may have driven off much of the water in a runaway greenhouse and perhaps increased its atmosphere. While atmospheric studies of Mars and Venus are thus linked by this common thread of dramatic change, understanding Venus' current and past climate is more germane to understanding our own. It is therefore prudent that exploration of Venus receive at least a fraction of the resources that have been devoted to Mars.

"What happened to the water" is the question that has been a major driver of NASA's efforts to explore Mars in the last two decades with Mars Observer, Mars Pathfinder, Mars Polar Lander, Mars Climate Orbiter, Mars Global Surveyor, Mars Odyssey, Mars Reconnaissance Orbiter, Phoenix, and Spirit and Opportunity Rovers. NASA is now poised to launch the Mars Science Laboratory in November 2011. ESA is also participating in the exploration of Mars with its Mars Express and through a joint effort with NASA for future missions, and an international Mission to Mars led by Russia (Phobos Grunt) is also poised for launch in November 2005. In contrast to this very healthy and scientifically productive set of missions to Mars, the Magellan radar surface mapper, launched in 1989, is the last dedicated NASA mission to our other planetary neighbor, Venus, where "what happened to the atmosphere" is a paramount question also. ESA's Venus Express, the flight spare version of Mars Express, is a small step towards obtaining needed observations.

Efforts focusing on the evolution of Venus will help us understand not only the evolution of Earth but terrestrial planets around other stars as well. Since exoplanets are being discovered ever more rapidly, it is even more important to understand Venus and its evolution in order to interpret the more detailed data that will be obtained on exoplanets in the near future. This is in addition to the urgency in understanding planetary atmospheres well enough to save our own. Venus marks the inner boundary of the habitable zone in our solar system. As most of humanity would agree, it should be at least as important to learn about the Earth's future as its past.

In summary, Venus exploration now is crucial to better understand:

1. The role of the greenhouse effect on heating planetary atmospheres
2. How the global super rotating hurricane-force winds can arise and get organized into a tropical cyclone-like vortex and be sustained in Earth-like atmospheres
3. How the planets in the inner solar system, including Earth, formed and evolved
4. Plate tectonics on Earth, and
5. The future of the Earth's environment, especially its climate

To conclude, we need to study Venus to better understand Earth's future now.

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