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Future of Venus Research and Exploration

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Abstract

A great deal is known about Venus from the *Venera*, *Pioneer-Venus*, *Magellan*, and *Venus Express* missions. However, many significant questions remain regarding the origin, evolution and current geologic and atmospheric processes. Much can be learned from theoretical modeling of the planetary interior and atmospheric circulation, as well as from laboratory spectroscopic studies. However, to answer many of the outstanding questions, new space flight missions are needed. Multiple international space agencies are considering Venus as a possible destination for future exploration. Collaborative international participation provides a viable path to further understanding of Earth's sister planet and her role in the formation of our solar system.

1. Introduction

Despite similarities to Earth in mass, composition and location in the solar system, Venus has evolved along a very different path. Understanding when and why Venus diverged from Earth is fundamental to understanding the formation and evolution of terrestrial planets, the fate of Earth's climate, and to interpreting observations of newly discovered extra-solar planets. Some of the most fundamental science questions include: what was Venus's original volatile inventory (particularly noble gases) and how has that inventory been modified; how does Venus lose its internal heat; how did the present spin state of Venus come about; what is the origin of the highland tessera terrain, what is the history of volcanic resurfacing; is Venus still volcanically active; when and how did Venus lose its water; how does solar energy drive atmospheric circulation, cloud formation and chemical cycles; and when and how was the runaway greenhouse initiated [3], [8]?

2. Venus Research Focus Areas

Earth-based observations of Venus are increasingly capable. Doppler velocimetry using reflected sunlight has been shown as viable for cloud-top wind speed monitoring. Sub-mm and infrared non-LTE lines have been used for monitoring transitions between zonal retrograde and solar-antisolar flow regimes in the mesosphere.

Aspects of atmospheric chemistry, too, can be examined from Earth. The high spectral resolution of ground-based observatories allows mapping of trace species from the troposphere to the mesosphere. Of particular interest is the measurement of SO_2 and related species; both IRTF/TEXES and HST have recently been used successfully. Ground-based radar offers exciting possibilities for surface studies of Venus. Transmitting from Green Bank Radio Telescope and Receiving at Arecibo, achievable spatial resolution approaches 1-2 km [1], allowing for surface change detection and calculation of Venus' rotation rate.

Data provided by Earth-based observations and past Venus missions has provided a wealth of information and motivation for many laboratory and theoretical modeling studies to better interpret the data that are already in hand. For example, the dramatic change in surface dielectric properties observed in Magellan images to occur at elevations ~2 km above mean planetary radius [6]. Laboratory studies of candidate materials and their stability under Venus surface conditions can lead to better understanding of this unusual characteristic of the Venus surface. Likewise, laboratory spectroscopic studies of candidates or the unknown ultra-violet absorber [5] is needed to better understand the chemical cycles and radiative balance of the upper Venus atmosphere.

Theoretical modeling studies are also needed. Modelling the Venus atmosphere is challenging due to the long spin-up and equilibration timescales of the Venus atmosphere. Increased computing power will enable higher resolution and will enable more representative radiative and microphysical processes to be included. Multiple, independent efforts are desired given the diversity of terrestrial climate

models and their results with intercomparisons. In addition to global dynamics, modelling of cloud-scale buoyant convection and associated microphysics is needed. Numerical models of planetary interiors can be used to place constraints on the conditions under which plate tectonics can be established, as well as mechanisms for formation of large mantle plumes that are capable of feeding volcanic provinces [7].

3. International Space Exploration

The recent Roadmap for Venus Exploration [9] developed by the Venus Exploration Analysis Group provides several possible paths. These include a range of small to large missions. In many cases, these missions would be well addressed through international collaboration.

Many international space agencies are considering Venus for future exploration. The Japan Aerospace Exploration Agency (JAXA) is preparing for a second attempt at Venus orbit insertion for *Akatsuki* in 2016. *Akatsuki* will investigate Venusian meteorology including detection of lightning.

Following *Venus Express* (*VEx*), mission concepts recently pursued in Europe include the *European Venus Explorer* (*EVE*) cloud-level balloon [11] and *EnVision* radar orbiter [4]. The US Planetary Decadal Survey [3] identifies two key missions to Venus. The Venus In Situ Explorer, a New Frontiers-class mission, addresses key questions regarding the origin and evolution of the Venus atmosphere as well as the chemistry and mineralogy of the surface. The Venus Climate Mission, is Flagship-class, and aimed at understanding the Venus current climate and its place in the context of Earth and extra-solar planets.

Interest appears to be growing in considering Venus as an exploration target within the Indian Space Research Organisation (ISRO) and Russia is currently planning for the *Venera-D* mission, with anticipated launch in 2023 or later. *Venera-D*, a Flagship-class mission includes an orbiter, lander, sub-satellite, and long-life surface station. *Venera-D* includes both in-situ and remote investigations of Venus, its surface and atmosphere, as well as the plasma environment and solar wind interaction. The mission is focused on understanding the modern climate of Venus, meteorology, thermal balance, dynamics, origin and evolution of the atmosphere, composition and mineralogy of the surface, and the fate of water.

6. Summary and Conclusions

Venus is a fascinating destination for exploration, holding the keys to better understanding the birth of our solar system, the fate of Earth's climate, and providing context for interpreting observations of extra-solar planets. Much can be done to advance our understanding of Venus through Earth-based observations, laboratory studies, and theoretical modeling. However, new investigations at Venus are needed to answer the most compelling questions. International cooperation on future missions may provide a path forward for a timely return to Venus.

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