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Divergent Evolution Among Earth-like Planets: The Case for Venus Exploration

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Abstract. The planet Venus is our most Earth-like neighbor in size, mass, and distance from the sun. In spite of these similarities, and the intense scrutiny that it received early in the space age, the Venus surface and atmosphere are characterized by some of the most enigmatic features seen anywhere in the solar system. A reinvigorated Venus exploration program is essential to the development of a comprehensive understanding of the origin and evolution of Earth-like terrestrial planets. The present NASA inner planets strategy, which focuses exclusively on Mars, will provide an incomplete, and possibly misleading description of processes that produce these objects. If Venus-like terrestrial planets are common, this approach will also impede efforts to interpret observations of extrasolar terrestrial planets, which are expected to become available by the end of the decade. Here, we propose a Venus exploration program that has been designed to explain the origin and divergent evolution of the interiors, surfaces, and atmospheres of the terrestrial planets in our solar system, and provide greater insight into the conditions that may affect the habitability of terrestrial planets in other solar systems.

EXECUTIVE SUMMARY

Venus was once thought to be Earth's twin because of its similar size, mass, and solar distance. These factors, combined with its relative proximity made it the target of intense scrutiny during the first three decades of the space age. The first planetary spacecraft, Mariner 2, flew past Venus 40 years ago on 14 December 1962. That mission and subsequent observational and theoretical work indicate that although Venus and Earth were apparently formed nearby in the solar nebula, sharing common inventories of refractory and volatile constituents, they followed dramatically different evolutionary paths. While the Earth evolved into the only known oasis for life, Venus developed an almost unimaginably hostile environment, characterized by a massive (90-bar) CO_2 atmosphere, a hellish (730 K, 854 °F) surface temperature, and a global cloud deck composed of sulfuric acid (H_2SO_4) particles. Some of the processes that contributed to the divergent evolution of these two planets can be attributed to the fact that Venus is closer to the sun (0.7 AU), and receives about twice as much solar radiation as Earth. The intense solar insolation may have helped to induce a runaway greenhouse in the early Venus atmosphere producing surface temperatures high enough to ensure that the water vapor CO_2, and sulfur gases emitted by volcanic processes remained in the atmosphere.

Other aspects of the environment of Earth's sister planet are among the most enigmatic in the solar system. For example, although the volatile inventory of Venus is not as well characterized as that of Earth and Mars, existing measurements indicate that the relative abundances of the noble gases in its atmosphere are much more solar-like than those on the other two terrestrial planets, whose atmospheres appear to be strongly altered. Similarly, contemporary Venus is almost 100,000 times drier than Earth while the deuterium to hydrogen ratio is $\sim$150 times larger, suggesting that Venus may have lost the equivalent of an ocean of water. The specific processes and timing of this large loss of water are currently not known. The atmospheric dynamics are equally perplexing. Although the surface of Venus rotates very slowly, with a $\sim$242 day period, the cloud-level atmosphere ($\sim$70 km) appears to rotate almost as a solid body, with a period of 4 days, or about 60 times faster than the surface. The mechanism(s) driving this atmospheric superrotation have evaded explanation since its discovery more than three decades ago.

A planet-wide cloud deck completely hides Venus' surface at visible wavelengths, but radar observations by the Pioneer Venus, Venera 15, and Magellan orbiters show that it is also mysterious. In particular, the cratering record indicates that the average age of the surface is about 750 million years, but the crater mophology suggests that there has been very little geologic activity since that time. In particular, while the surface records a rich geologic history, it lacks plate boundary features and other evidence of plate tectonics. In addition, while there are numerous features that appear to be of volcanic origin, there is currently no direct evidence for active volcanism or other processes that would indicate whether the planet is geologically dead or alive.

The processes that produced the surface morphology and their implications for the evolution of terrestrial planet interiors remain controversial. Some have interpreted these features as evidence for an internal cooling mechanism characterized by episodic, catastrophic, global resurfacing events, the last one of which occurred $\sim$750 million years ago. Others believe that these surface features simply indicate that the Venus lithosphere thickened significantly over the past $\sim$1 billion years, such that the interior now loses heat primarily through sluggish or stagnant lid tectonics. The available data are not adequate to clearly differentiate between these two mechanisms, or to resolve the effects of other processes that may have affected the evolution of the Venus interior, such as the slow rotation rate, the low present-day water abundance, or the high surface temperatures.

As NASA embarks on its search for extrasolar terrestrial planets, with a focus on origins, it is interesting to note that Venus has been ignored for over a decade. A reinvigorated Venus exploration program could yield great dividends by dramatically improving our understanding of the origin, evolution, and habitability of terrestrial planets. Specifically, a comprehensive inventory of the noble gases and isotopes of carbon, hydrogen, oxygen, and nitrogen in the Venus atmosphere would help us to understand our past by clarifying the conditions in the primordial solar nebula that produced the unique character of our home planet. A detailed investigation of the processes controlling the current surface and atmospheric environment on Venus will help us to obtain a deeper understanding of the processes operating on Earth, including greenhouse effects, atmospheric photochemistry, heterogeneous chemistry, thermal chemistry, atmospheric dynamics, surface chemical weathering, and intraplate geology. Finally a more comprehensive understanding of Venus could yield important clues about our future by providing constraints on atmospheric compositional stability and loss processes, and, perhaps the geophysical evolution of the Earth, if plate tectonics evolves toward the tectonic processes seen on Venus.

For the reasons described above, coordinated Venus and Mars programs are essential to the development of a comprehensive understanding of the origin and evolution of Earth-like terrestrial planets. The present NASA inner planets strategy, which focuses exclusively on Mars, will provide an incomplete, and possibly misleading description of processes that produced the current environments of Venus, Earth, and Mars. This could also impede efforts to interpret observations of extrasolar terrestrial planets, which may be available within a decade.

Although it is not possible to address all of these questions with a single dedicated Venus mission, we can dramatically improve our understanding of our sister planet within the constraints of a coordinated program of small (Discovery Class), medium (New Frontiers Class), and large (∼$1 B FY01) missions conducted by NASA and our international partners over the next 10 to 20 years. We strongly urge NASA to expand the inner planets program to include a Venus mission line. This mission line need not be as large or ambitious as the Mars Exploration Program, but its objectives and schedule should be designed to maintain an appropriate balance with that program.

The NASA mission with the highest priority and greatest technological maturity is the Noble Gas/Trace Gas Explorer. The other missions listed below have similar priorities, but different levels of technological maturity, and should fly as their critical technologies become available.

- 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 and trace 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 geologic 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 Explorer 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.
- A sample return mission will eventually be needed to conduct investigations of the Venus surface and atmosphere that cannot be conducted by instruments on remote sensing platforms or on entry probes. This will probably require a large mission and significant technology development.

Two international Venus missions complement the missions described above. The first is the ESA Venus Express mission. This mission would use the spare Mars Express bus to conduct a remote sensing investigation of the trace gas abundances in the lower atmosphere and the cloud properties. It may also carry a surface-penetrating radar (with NASA contributions) for studies of the subsurface. This mission has been selected by the ESA Space Science Advisory Committee, but funding has not yet been allocated. The second is the Japanese (ISAS) Venus Climate Orbiter. This mission will carry ultraviolet, visible, and near infrared imaging systems for studies of the cloud level dynamics. It may also carry space physics instruments for studies of the exosphere. This mission has been approved by the ISAS Space Science Committee as the third Japanese deep space mission (Planet C), and is seeking approval as a new start.

REPORT

1. Unifying Scientific Themes

1.1. Past: Origin of terrestrial planets in our solar system

A detailed analysis of the noble gas inventories on Venus, Earth, and Mars may provide the best possible understanding of the conditions of the primordial solar nebula from which these planets were formed (Pepin 1991, 1997). However, a much more comprehensive, accurate inventory of noble gases and their isotopic ratios is needed for Venus to construct a coherent picture of these conditions. The volatile inventory of Venus is poorly constrained, but existing evidence suggests that the Venus noble gas inventory may be more representative of the primordial solar nebula than that on either Earth or Mars. In situ atmospheric measurements of noble gases, their isotopes, and other key volatiles such as H_2O, CO, OCS, and SO_2 would contribute directly to our understanding of the origin and evolution of terrestrial planets in this solar system. This information will be essential for interpreting observations of terrestrial planets around other stars.

1.2. Present: What processes shape the terrestrial planets

Because the atmospheric, surface, and interior processes have evolved so differently on Venus, Earth and Mars, coordinated investigations of these planets provide opportunities to identify those factors most important to the environment of a terrestrial planet, and how processes currently acting on Earth might produce different outcomes under slightly different conditions. In particular, such a comparison could delineate the roles of the exogenic processes (e.g., solar insolation, impacts, tidal effects) that define its local environment in the solar system, from the endogenic physical, chemical, and thermodynamic processes that represent the planet's response to that environment.

1.3. Future: What does Venus tell us about the fate of the Earth's environment?

Is Venus a future Earth? Probably not. Nevertheless, processes occurring on Venus today are relevant to predicting how the Earth might evolve. For example, the massive CO_2 greenhouse in the Venus atmosphere is driven by radiative processes similar to those operating in the Earth's atmosphere as the atmospheric CO_2 concentration continues to increase. Venus' past may also be relevant to the Earth's future. Stellar evolution models predict that the solar luminosity will continue to increase, such that in about a billion years, the Earth could suffer a runaway greenhouse. Venus is thought to be a prime example of such an event. There is a similar analogy concerning interior processes. Will the Earth eventually evolve to an internal state where plate tectonics disappear, and heat loss from the interior evolves to the sluggish or stagnant lid conditions like those that are thought to now characterize Venus?

2. Current Knowledge and Future Directions

2.1. What led to Earth's unique character?

Because of their proximity, it is reasonable to assume that Venus, Earth, and Mars originated in the same part of the primordial solar nebula, with similar inventories of volatile and refractory elements. A comprehensive theory of the origin and evolution of terrestrial planets must therefore explain the observed properties of all three bodies. Precise measurements of noble gases in the atmospheres and surface materials of these three planets will provide the best clues to each planet's original supply of volatile elements. This information must be combined with measurements of its internal structure, surface age and record of geological processes, and the atmospheric composition and thermal structure to characterize the evolution of each planet's environment over time. A more detailed understanding of these processes is essential to interpret observations of extrasolar terrestrial planets, once they become available (Owen 2000). Each of these requirements is described in more detail below.

Noble gases: The isotopic constraints on models of atmospheric history are much weaker for Venus than for Earth and Mars because the Pioneer Venus and Venera missions obtained no measurements of the heaviest noble gases, krypton (Kr) and xenon (Xe). Interestingly, in spite of their large uncertainties, the available measurements of noble gases on Venus indicate high abundances and solar-like elemental ratios (Pepin 1991, Owen et al. 1992). This suggests that at least the heavier noble gases on Venus have not evolved substantially from their primordial states. Neon and argon isotope ratios also appear to be displaced toward solar values compared to their terrestrial counterparts (Figure 1). Venus consequently occupies a unique position among this triad of terrestrial planets in that its atmosphere may have experienced much less alteration from its initial composition by planet-specific fractionating loss mechanisms, while Earth and Mars appear to have been much more highly processed.

A more complete assessment and understanding of the composition of the atmosphere of Venus is therefore enormously important in the context of models for the origin and evolution of terrestrial planet volatiles. Measurement of the isotopic composition of Venusian Xe would immediately provide a critical test of two very different proposed mechanisms for generating the strong fractionation pattern, relative to solar, displayed by atmospheric Xe on Earth and Mars. Did this separation occur in the planetesimal stage prior to planetary formation, implying a similar composition on Venus, or afterward, when energy deposited in a giant impact on Earth and Mars blew off parts of their atmospheres while the Venusian Xe remained near its initial solar composition? An equally important question is whether the nonradiogenic heavy noble gases on Venus are relatively unaltered samples of the ancient gaseous nebula. Improved constraints on the nebular gas composition during planetary formation are needed to discriminate between models that propose direct (gravitational condensation) or indirect (cometary accretion) nebular sources of primordial volatiles on terrestrial planets (Owen and Bar-Nun 1995).

Trace gases and their isotopes: The concentrations and isotopic ratios of other volatile species are also poorly known for Venus. Pioneer Venus and Venera measurements indicate that the Venus atmosphere is 96.5% CO_2 and 3.5% N_2. Other trace gases include H_2O, SO_2, OCS, CO, HCl, and HF, but there are large uncertainties in their abundances, especially below the cloud tops (Esposito et al. 1997). Excited atomic and molecular oxygen have been detected via airglow emission from the upper atmosphere, but ground-state oxygen has not yet been detected in the bulk atmosphere. An improved understanding of the distribution of these trace gases is needed both for models of solar nebula formation and planetary accretion, and to understand their role in the greenhouse mechanism that maintains the planet's high surface temperature.

The Pioneer Venus and Venera probes returned measurements of the H_2O abundance that varied from less than 20 to more than 5000 parts per million by volume (Hoffman et al. 1980, Moroz 1983). Recent measurements from Earth-based near-infrared observations of the night side (Bézard et al. 1990, de Bergh et al. 1995, Meadows and Crisp 1996) indicate H_2O mixing ratios closer to 30 ± 10 ppm. This result is supported by a reanalysis of results from the Pioneer Venus Large Probe Neutral Mass Spectrometer (Donahue and Hodges 1993) and the Venera 13-14 Spectrophotometers. These values are 4 to 5 orders

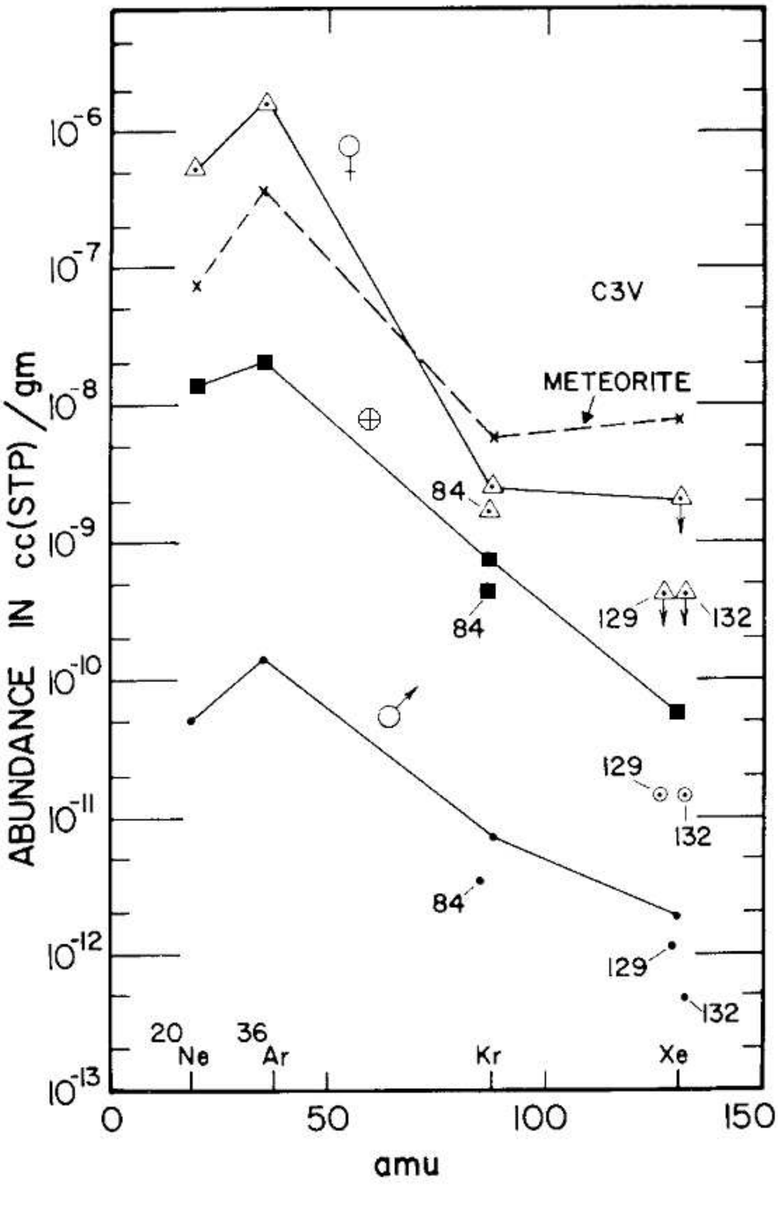

Figure 1. Comparison of noble gas abundances on Venus, Earth, and Mars with that of C3V Carbonaceous condrites (from Donahue and Pollock 1983).

of magnitude smaller than terrestrial values. This indicates that either the primordial abundance of volatiles on Venus was significantly different than that of Earth, which is difficult to explain with current models of solar system formation (Wetherill 1981), or that Venus lost much of its primordial water inventory over time.

The latter explanation is supported by the anomalously high deuterium to hydrogen (D/H) ratio of Venusian water, which is 150 ± 30 times greater than that of standard mean ocean water on Earth (de Bergh et al. 1991, Donahue and Hodges 1993). Although models indicate that this high D/H ratio could have been produced by the photo-dissociation of water vapor at levels above the cloud tops, and the subsequent preferential loss of hydrogen over deuterium, the loss rates and dominant loss mechanisms are still too uncertain to determine when Venus lost the bulk of its water. This information is essential for understanding the early runaway greenhouse mechanism, and for studies of the role of water in the evolution of the Venus crust and volcanotectonic processes.

The abundance and distribution of the sulfur bearing gases, SO_2, OCS, H_2S, and H_2SO_4 are also poorly known at levels below the cloud tops (Bézard et al. 1993, Pollack et al. 1993). Improved measurements of these gases are needed both for studies of the processes that maintain the global H_2SO_4 clouds and to constrain the current rates of volcanism and surface chemical weathering (Fegley et al. 1997).

CRITICAL MEASUREMENTS NEEDED: A complete, accurate inventory of the noble gases and their isotopes is essential to our understanding of the origin and evolution of Venus. Measurements of the isotopes of Xe are of highest priority because their concentrations have not been measured on Venus, and this gas is expected to provide the best possible estimate of the initial noble gas inventory because it should be least modified by atmospheric escape. A more complete and accurate altitude-dependent description of the trace gas inventory is needed below the cloud tops. The noble gas measurements could be made by a single entry probe carrying a state-of-the-art mass spectrometer with a noble gas enrichment system. This probe should also carry instruments to record trace gas profiles between the cloud tops and the surface.

Surface properties: A comprehensive description of the processes that have shaped the Venus surface and controlled the exchange of volatiles between the interior and the atmosphere is also essential to our understanding of the origin and divergent evolution of the environments of Venus, Earth, and Mars. Images of the surface from the Venera landers (Florenskiy et al. 1983) show rocks intermixed with soil. X-ray fluorescence spectrometers aboard these Venera spacecraft indicate that the composition of these rocks is consistent with that of terrestrial basalts (e.g., Barsukov et al. 1986). Efforts to locate the Venera landing sites using Magellan data indicate that these properties characterize the lowland plains, which may have formed by extensive lava flows. The composition of the surface materials that cover highland regions, giving them anomalously low microwave emissivities, is not yet known (Fegley et al. 1997). However, laboratory studies indicate that the foundations of these regions are also likely to be basaltic.

Age of the Venus surface: Improved constraints on the age of the Venus surface would be of particular value in studies of the evolution of its interior and atmosphere. The cratering record offers the only available chronometer for timing absolute age of Venus' surface. Existing observations from the Venera 15 and Magellan radar mapping missions and Earth-based radars indicate that the number of craters is small (~950), and that their distribution is remarkably uniform across the planet. The cratering statistics derived from Magellan observations indicate that the average age of the surface is ~750 million year (Ma), which is comparable to the mean age of the Earth's surface. This young age was surprising because unlike Earth, Venus shows no evidence of plate tectonics.

The spatial uniformity of the crater distribution, combined with the relatively pristine condition of the existing crater population has been interpreted as evidence that the surface was subject to a global resurfacing event 350 to 1000 Ma ago, followed by a period of much slower geologic activity (Strom et al. 1994). If catastrophic resurfacing events occur episodically with a mean period of 300–500 Ma, this process could provide an interior heat release mechanism as efficient as plate tectonics (Parmentier and Hess 1992, Head et al. 1994). This interpretation is intriguing but it remains controversial for several reasons. First, the accuracy of the cratering chronometer has been questioned because it has never been adequately calibrated for a planet with a massive atmosphere. Second, the cratering densities are too low to constrain the ages of specific regions or geologic features on the Venus surface (Herrick and Phillips 1994, Hauck et al. 1998, Campbell 1999). Third, some geophysical models show that the cratering record and other surface properties can be explained adequately by a more gradual evolutionary transition from a thin, mobile lithosphere, to a thicker, stagnant lithosphere (Phillips and Hansen 1998), precluding the need for episodic catastrophic resurfacing events. In short, although the Venus surface apparently records a rich volcanic and tectonic history, uncertainties in the time scales of the resurfacing processes have continued to produce significant controversy. In fact, the existing data are not adequate to determine whether the planet is currently volcanically active.

Other aspects of the Venus geologic record are slowly being unraveled. If Venus had an internal heat budget similar to Earth, it apparently cools by mechanisms other than plate tectonics (Soloman et al. 1992). Earth's surface is transected by large scale linear structures marking divergent and convergent plate boundaries–regions where new crust is formed and recycled, respectively. Earth also displays two types of crust that have different compositions: thick low-density continental crust and thinner, higher density oceanic crust. Earth's crustal differentiation and plate tectonics together result in a surface comprised of large tracts of old crust (continents) and young crust (ocean basins).

In contrast, Venus displays a surface characterized by globally distributed circular, rather than linear, structures. The circular structures include the ~950 impact craters that pepper Venus' surface (Schaber et al. 1992, Phillips et al. 1992), recording an average surface age of ~750 Ma (McKinnon et al. 1997). The near random spatial distribution of the craters indicates that, unlike Earth, Venus lacks large tracts of very old and very young surfaces (Phillips 1993).

Venus hosts two distinct sizes of endogenic circular features. These include about 20 large (1600–2600-km diameter) quasi-circular volcanic rises and crustal

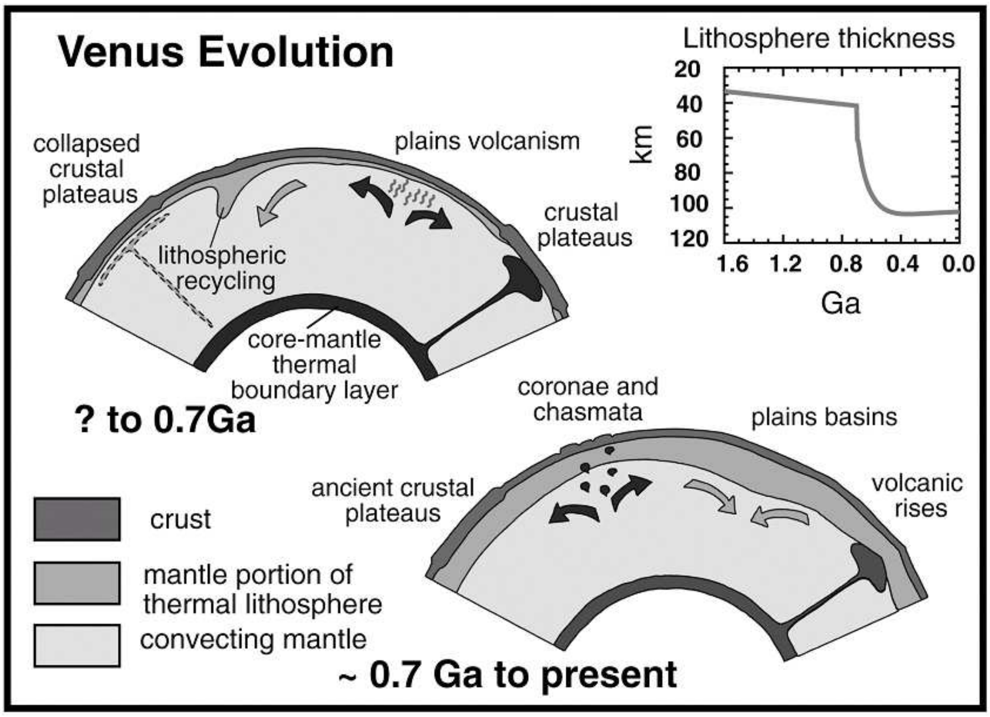

Figure 2. Evolution of the Venus interior showing early and present processes (from Phillips and Hansen 1998)

plateaus, and 360–400 relatively small (100–1010 km diameter, 200-km median diameter) quasi-circular coronae. The volcanic rises and crustal plateaus are thought to be the surface signatures of deep mantle plumes on a contemporary thick lithosphere (McGill et al. 1981, Phillips and Malin 1984, Smrekar et al. 1997) and an ancient thin lithosphere (Hansen et al. 1997, Hansen and Willis 1998, Hansen et al. 1999, 2000, Phillips and Hansen 1994, 1998), respectively. Coronae are also widely accepted as the surface signature of mantle diapirs (Squyres et al. 1992, Janes et al. 1992, Stofan et al. 1991, 1992, 1997).

The physical mechanisms that form these structures and their implications for the evolution of the Venus interior are still controversial. For example, the bimodality of Venus' large (plateaus/rises) and small (coronae) diapiric structures, and their distribution on the surface, may reflect the different locations and mechanisms of diapir formation (Hansen 2001). In these models, thermally driven deep mantle plumes form along a warm core-mantle boundary layer and rise through the mantle to the lithosphere, forming plateaus and rises and transferring heat from the core (Figure 2). Compositional diapirs that form at relatively shallow levels in the upper mantle may rise to form coronae chains and transfer heat from the mantle (Phillips and Hansen 1994). Coronae clusters may result from compositional diapers spawned locally by plumes of deep mantle origin (Hansen 2002). Alternatively, they might be associated with heat transfer processes originating elsewhere in the mantle, but triggered by thermal anomalies from the core-mantle boundary. Improved constraints on the internal structure, heat flow, seismisity, mineralogy, and reology are needed to discriminate and validate these models.

CRITICAL MEASUREMENTS NEEDED: Venus clearly records detailed geologic histories across its surface. A series of carefully coordinated steps will be needed to unravel these histories and to infer their implications for the evolution of the planet. The best existing constraints on these surface properties have been derived from the moderate-resolution, global, Magellan data sets. The next logical step in this process would be to collect imagery and altimetry observations with horizontal and vertical resolutions similar to those currently being obtained for Mars. This could be accomplished by a polar orbiter carrying a state-of-the-art X or C-band radar designed to acquire either global stereo or interferometric measurements (e.g., the recent Shuttle Radar Topography Mission, SRTM).

Given this global context, the next step would be to obtain improved constraints on the chemical composition and mechanical properties of the selected surface regions to better constrain models of the cratering record and endogenic processes that have altered the surface. This could be accomplished by deploying in situ instruments on a small network of surface landers (three to five). Each lander would carry instruments to measure long and short period seismic activity, surface thermal properties, and sensors to characterize the surface chemistry and mineralogy.

Finally, given a comprehensive understanding of the geological context, samples should be collected for age dating. This last step will require advanced technologies for precision landing, sample acquisition, and processing. The analysis of samples collected at the high temperatures and pressures of the Venus surface, and may require the return of the sample to Earth. Advanced age dating techniques must also be developed and calibrated for this application, because the methods commonly used to date terrestrial geologic samples would not be reliable for application to samples that formed and evolved in the Venus surface environment.

The role of volatiles in interior evolution: Volatiles in the interior and atmosphere play a key role in determining the geologic style of a planet. The planetary volatile inventory is directly coupled to the interior evolution through its role in controlling the rheology of the lithosphere. Water may be the key element enabling plate tectonics on Earth. The role of water in weakening the terrestrial lower lithosphere may allow the initiation of subduction (Regnauer-Lieb et al. 2001). Weakening of the upper mantle by water may also be responsible for the low viscosity zone at the top of Earth's asthenosphere. This zone may lubricate the motion of tectonic plates and promote a convective pattern favorable to plate tectonics. In fact, water may be necessary to produce the chemically distinct, buoyant crust that forms the continents.

The extremely low abundance of water on Venus may have contributed to its entirely distinct style of lithospheric deformation. Despite the high surface temperatures on Venus, the strength of the crust is believed to be comparable to that of the mantle due to the low abundance of water in the interior (Mackwell et al. 1998). The very high ratios of gravity and topography indicate a strong coupling between mantle convection and deformation of the lithosphere. Thus no significant low viscosity zone exists on Venus. The strong Venusian lithosphere and the lack of an underlying low viscosity zone inhibit lateral motion of the lithosphere. The current low lithospheric recycling rate reduces the amount of heat loss to the exterior, possibly leading to a 'stagnant lid' mode of convection where the interior heats up due to the strong, insulating outer layer (Weinstein and Olson 1992, Moresi and Solomatov 1998). Recycling of the crust occurs through delamination of the lower crust, if at all (Parmentier and Hess 1992).

The evolution of volatiles and tectonics may be closely coupled on Venus by the feedback between geologic processes and climate change. Early in its history, when Venus apparently had a thin, presumably mobile lithosphere, widespread pressure release melting of the mantle may have resulted in globally widespread volcanism. This volcanism would have released water and other greenhouse gases into the Venus atmosphere, raising surface temperatures at least 100 K above present day values (Bullock and Grinspoon 1996, 2001) and perhaps as high as 1000 K (Phillips et al. 2001). As interior heat escaped and the planet cooled, the lithosphere thickened, changing from a thin, presumably mobile state to a thick stagnant lid. This change resulted in a significant decrease in pressure release melting and a decrease in global volcanic activity, which in turn led to cooling of the global surface temperature to today's value as volcanic greenhouse gases were no longer produced at such rapid rates. The change from a thin to a thick lithosphere is recorded by ancient crustal plateaus and contemporary volcanic rises which record the surface signature of deep mantle plumes on thin and thick lithosphere, respectively. The global cooling may have resulted in widespread low strain deformation of the surface (Anderson and Smrekar 1999, Solomon et al. 1999).

CRITICAL MEASUREMENTS NEEDED: Interpretations of Magellan data have produced significantly different, but plausible, competing global geological histories. The available imagery and altimetry are inadequate to resolve the regional and local details necessary to differentiate among these hypotheses. Imagery and altimetry data comparable in resolution to that provided by the Mars Global Surveyor mission would provide a similar advancement in our understanding of Venus. An orbiter with an X or C-band radar could be used to obtain global stereo imaging, or used as an interferometer with the addition of a long (tens of meters) boom, to yield altimetry data with a spatial resolution of 25 to 50 m. Higher resolution data could be acquired over more limited regions with optical and infrared imagers and radar altimeters on balloons or aircraft.

Measurements that constrain the present day composition of the atmosphere and the nature of chemical weathering at the surface are also needed to define the role of volatiles in the history of Venus. These measurements could be obtained by a lander that collects images, spectra, and uses in situ instruments to collect other critical geochemical data at the surface. These data would be used to identify the surface mineral composition, soil types, and weathering products. A long term seismic network is needed to constrain present day rates of geologic activity. A seismic network is also needed to provide constraints on the crustal thickness and to determine whether the core is solid or liquid. Heat flow measurements would help constrain the present day geothermal gradient and the rate of heat loss from the interior, providing important constraints on the recent history of the lithosphere.

2.2. Present: What common processes shape Earth-like planets?

The Venus greenhouse mechanism: Climate models show that greenhouse gases in the massive, 90-bar atmosphere, combined with the thermally-opaque planet wide sulfuric acid cloud deck, can maintain the anomalously high surface temperatures on Venus (Crisp and Titov 1997). The high infrared opacity of the major atmospheric constituent, CO_2, plays a key role in producing a strong greenhouse effect, while trace gases (SO_2 and H_2O) and the planet wide H_2SO_4 cloud deck fill spectral windows at all infrared wavelengths longer than 2.5 μm where CO_2 is transparent. Existing measurements show that SO_2, H_2O and other trace gases are spatially and temporally variable on Venus, but these measurements are not adequate to constrain their horizontal and vertical distributions at levels below the cloud tops. Furthermore, at the high temperatures and pressures of the lower atmosphere of Venus, the opacities of many gases are not well known, and the spectral distributions of solar and thermal radiation are poorly constrained. Nevertheless, radiative transfer models based on the best available estimates of the composition have successfully reproduced the atmospheric thermal structure. While these results support the greenhouse explanation for high surface temperature, they are not adequate to resolve the relative roles of specific radiative processes.

Several greenhouse processes that contribute to the Earth's climate are much more effective, and easier to study in the atmosphere of Venus. For example, gas absorption by weak absorption lines, the far wings of strong lines, and pressure-induced absorption are essential components of the Venus greenhouse. These factors also produce measurable changes in the Earth's atmosphere, but are much more difficult to study there. Aerosol scattering and absorption also produce a much larger radiative forcing of the climate within the main Venus cloud deck, where they play a critical role in the Venus greenhouse. Preliminary studies of these clouds provided the theoretical basis for studies of the effects of volcanic aerosols emitted by the Mount St. Helens, Chichon, and Pinatubo eruptions on the Earth's climate. Studies of the impacts of these radiative processes on Venus have also provided many of the tools currently being used to gain greater insight into the early climates of Earth and Mars.

CRITICAL MEASUREMENTS NEEDED: Improved, spectrally resolved measurements of the solar and thermal radiation fields are needed at altitudes between the cloud tops and the surface. These measurements must be combined with simultaneous constraints on the abundances and distributions of radiatively active trace gases and aerosols to clearly identify their effects on the atmospheric thermal balance. A single entry probe with a suite of state-of-the-art instruments for trace gas measurements (mass spectrometer, gas chromatograph, tunable diode lasers, grating spectrometers) could provide dramatic improvements in our understanding of the vertical profiles of all known radiatively active gases in the Venus atmosphere. These measurements should be combined with UV, near IR and microwave remote sensing observations from orbit to characterize the horizontal distributions of these species.

Improved, spatially resolved measurements of the Venus clouds are also needed to understand their effects on the solar and thermal radiation fields. Pioneer Venus and Venera measurements show that the clouds reflect ~80% of the incident solar radiation and absorb over half of the solar energy that is deposited on Venus. An unknown UV absorber in the upper cloud is responsible for about half of this absorption. In situ observations in the upper cloud (58–60 km) may needed to identify the composition of this absorber. The effects of the clouds on the thermal radiation field are not well understood, in part because the middle and lower clouds are spatially inhomogeneous. Entry probe and near IR remote sensing observations document spatial variations in cloud opacity, but provide limited information about their vertical distribution, their radiative impacts or the mechanisms responsible for their production and maintenance. Long term in situ observations of the the cloud particle properties (shape, size, number density, and composition) must be combined with simultaneous measurements of the solar and thermal radiation fields above, within, and below the clouds to resolve these uncertainties and quantify the effects of clouds on the greenhouse.

Atmospheric superrotation: Since its confirmation over 30 years ago, the superrotation of the Venus atmosphere has remained one of the most intriguing enigmas in planetary science (Gierasch et al. 1997). At cloud-top levels, the Venus atmosphere rotates almost 60 times faster than the solid surface of the planet. The wind direction is westward everywhere between the surface and ∼0 km (Figure 3). At low latitudes, the wind speeds increase with altitude from values near zero at the surface, to values near 100 m/sec in the upper cloud (60 - 70 km). Several candidate mechanisms have been proposed for generating and maintaining these winds, but this anomalous circulation has not yet been simulated by even the most comprehensive global general circulation models. This raises concerns about our understanding of the dynamics of slowly rotating planetary atmospheres and the range of validity of the best available climate and weather prediction models.

Above the clouds, the amplitude of the superrotation decreases rapidly with altitude and the equator to pole temperature gradient reverses, such that the poles are warmer than the equator throughout much of the mesosphere (70 to 90 km; Taylor et al. 1980). This deceleration is thought to be a consequence of the interaction of atmospheric thermal tides with the westward superrotating zonal winds (Crisp 1986, Baker and Leovy 1987). It is interesting to note, however, that westward superrotating winds also dominate the circulation again at altitudes above 100 km in the thermosphere. Modeling studies (Zhang et al. 1996) suggest that these superrotating winds may be forced by the interaction of gravity waves and the subsolar to antisolar flow at these levels, but the observations are not adequate to verify this theory.

CRITICAL MEASUREMENTS NEEDED: A global description of both the steady and transient components of the wind field is needed at altitudes between the surface and the cloud tops. At levels within the clouds, these measurements can be obtained by tracking cloud feature motions from an orbiting spacecraft. The winds at levels near the cloud tops can be inferred by tracking motions of the UV features (Limaye 1988). These measurements can be combined with near-infrared observations of the night side, which reveal motions in the middle and lower cloud decks (Crisp et al. 1991) to yield a comprehensive, 3-dimensional description of the cloud dynamics. To be of use in diagnosing the atmospheric circulation, the altitude of the features being tracked must be known to within a few kilometers. This information can be acquired by deploying UV and IR imaging spectrometers rather than simple imagers.

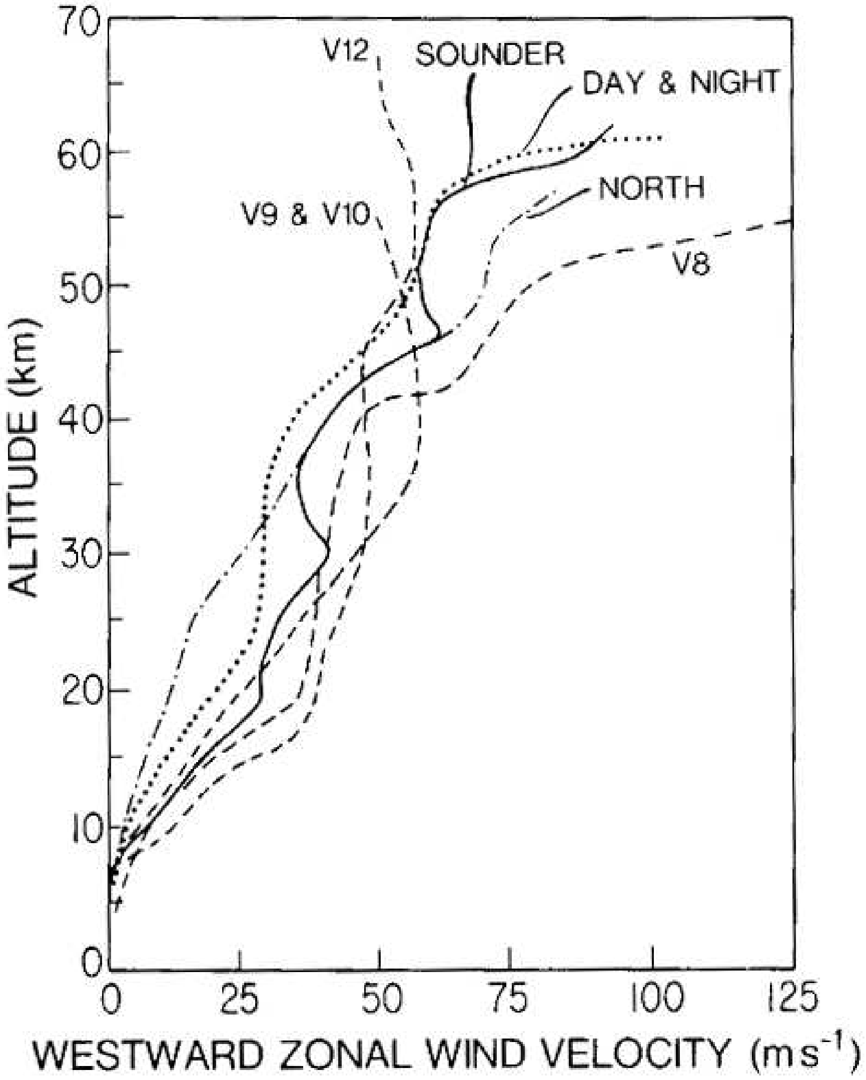

Figure 3. Wind velocity profiles measured by the Pioneer Venus Day, Night, North, and Sounder probes are compared to those measured by the Venera 8, 9, 10, and 12 (V8, V9, V10, and V12). The winds blow from east to west all altitudes and latitudes where measurements exist (from Schubert et al. 1980).

Wind measurements at levels below the cloud base must be acquired by in situ sensors, because there are no known tracers at those levels that can be tracked by remote sensing observations. High temporal resolution delta-delta-VLBI tracking of long-lived balloons would be best for this application because this would reveal both the mean and transient components of the flow (Crisp et al. 1990). One approach would deploy strings of three to five very simple, long-lived balloons at equatorial, mid-latitude, and high-latitude sites. At each site, the balloons could be deployed successively from a single entry probe as it falls through the atmosphere, and float at altitudes near 5, 20, 30, 40, and 50 km. A lifetime of about one week should be adequate to resolve most of the important components of the circulation. Besides transmitters, the balloons should carry pressure and temperature sensors to define the balloon altitude and atmospheric thermal structure. Relative wind sensors (and/or accelerometers) are needed to detect gusts and other transient phenomena. The atmospheric structure experiment should also be carried to the surface by the entry system to yield detailed profiles of pressures and temperature throughout the lower atmosphere at the balloon entry sites.

Lightning: Lightning plays an important role in the electrical and chemical compositions of the atmospheres of Earth and Jupiter. There is tentative evidence for its presence on Venus (Hunten 1995), but its role in the Venus environment is still controversial.

CRITICAL MEASUREMENTS NEEDED: Long-term simultaneous optical and electromagnetic observations, above, within, and below the clouds are needed to determine whether lightning plays a major role on Venus.

Middle atmosphere composition: The composition of the Venus middle atmosphere is the product of multiple local chemical processes and global circulation (Lellouch et al. 1997). The dominant constituent in the atmosphere, CO_2, is photodissociated to form carbon monoxide (CO) and atomic oxygen (O). Over time, CO and O_2 (from atomic O recombination) would become primary atmospheric constituents in the absence of catalytic processes that increase the rate at which CO_2 is reformed. However, CO and O_2 are transported to lower altitudes where their abundances decrease as a result of conversion to CO_2 through a series of homogeneous and/or heterogeneous reactions involving sulfur oxides (SO_x), hydrogen oxides (HO_x), or chlorine (Cl_x) radicals. Observations of intense $O_2(a^1\Delta_g)$ emission imply that atomic O recombination is highly efficient.

In addition to CO oxidation, the oxidation of SO_2 to form H_2SO_4 is a second loss process for O_2. H_2SO_4 condenses to produce aerosols that provide the sites for heterogeneous chemical reactions, leading to chemical processing not possible in pure gas phase reactions. This is balanced by transport to the troposphere and subsequent conversion back to SO_2. Mass exchange between the troposphere and the middle atmosphere must also result in transport of the hydrogen-, sulfur-, nitrogen-, and chlorine constituents that serve as sources for transient molecules involved in catalytic chemistry. Spatial and temporal changes in composition are forced by diurnal and latitudinal variations in insolation and transport, but very few measurements are available for even a rough characterization of these behaviors. Changes in the tropospheric composition resulting from volcanic eruptions may also lead to variability in middle atmosphere constituent abundances, but the evidence for this is still controversial.

CRITICAL MEASUREMENTS NEEDED: Spatially resolved global measurements of the vertical distributions of mesospheric densities and temperatures at vertical resolutions finer than 1 scale height (< 5 km) are needed to define the atmospheric thermal structure. Global measurements of the abundances of CO, O_2, O_3, ClO, H_2O, H_2O_2, NO, SO, SO_2, HCl and other important trace species are need at similar spatial resolution. These measurements should be performed over one to two Venus years to establish the amplitude of long-term secular variations.

Middle atmosphere dynamics: Thermally driven atmospheric tides are forced by the motion of the subsolar point across the upper cloud, where most of the sunlight is absorbed. The solar thermal tides assume the form of a solar-fixed wave disturbance that propagates eastward (upwind) and upward through the superrotating mean flow. The tides are readily apparent in the Pioneer Venus infrared temperature retrievals, but the height resolution is not sufficient to define the vertical structure through the middle atmosphere.

A key question about atmosphere dynamics is why the superrotation reaches a maximum near 70 km and then decays at higher altitudes (Lellouch et al. 1997). Two candidate mechanisms have been proposed. Atmospheric thermal tides induced by solar heating within and above the upper cloud are expected to produce downward momentum transports and poleward heat transport throughout the mesosphere. Vertically propagating, small scale gravity waves, discovered by Magellan radio occultation measurements, may also create sufficient wave drag to affect the mean zonal flow at some mesospheric levels. The relative roles of these two mechanisms are not yet understood.

The Venus middle atmosphere also serves as a dynamical transition from zonal circulation of the lower atmosphere to the extremely rapid and efficient subsolar-to-antisolar circulation within the thermosphere. This circulation transports the products of CO_2 photolysis (CO, O, and O_2) in the day side middle atmosphere to the nightside thermosphere, creating large night side enhancements in CO and (presumably) O_2 at high altitudes. Very little is known about the dynamical transition between zonal and the subsolar-to-antisolar flow within the middle atmosphere. However, existing measurements of the thermal structure and Doppler velocities indicate large amplitude, global scale changes in the upper mesospheric circulation on time scales of less than 1 year. The mechanisms responsible for these changes have not yet been identified.

CRITICAL MEASUREMENTS NEEDED: Direct Doppler measurements of global and vertical distributions of zonal and meridional winds are needed between the cloud tops and $>$100 km. These measurements need a vertical resolution of one scale height ($\sim$5 km) or less. Like the compositional measurements, these data should be collected over long enough time scale to establish the scale of long-term secular variations.

Thermospheric composition and dynamics: Venus has no appreciable intrinsic magnetic field. Hence, the solar wind interacts directly with its ionosphere forming a magnetic barrier and ionopause. Most of the survey-level upper atmospheric investigations were carried out by the Pioneer Venus Probes and Orbiter

(Kasprzak et al. 1997). In particular, UV imaging and limb scanning measurements were made by the Pioneer Venus Orbiter (PVO) Ultraviolet Spectrometer (OUVS) throughout the solar cycle, illustrating the variable nature of the chemical, energetic and dynamical processes of the thermosphere, ionosphere, and exosphere over time. In addition, PVO orbital decay measurements of atmospheric densities and temperatures and neutral mass spectrometer (NMS) measurements of several species (CO_2, CO, N_2, O, N, He) were made near the equator spanning altitudes between 130 and 250 km over a fraction of the 11-year solar cycle. Atmospheric drag measurements by Magellan provided a more global description of the density structure, and extended the observations over the entire solar cycle (Keating and Hsu 1993). These measurements also revealed a 4-day oscillation in the thermospheric density structure that is thought to be related to the thermospheric superrotation.

CRITICAL MEASUREMENTS NEEDED: There is a compelling need to follow up on the survey-level orbital decay, NMS, and OUVS measurements with a monitoring program focused on the regular observation of atmospheric densities, neutral winds, and atmospheric species subject to volatile escape. Direct wind measurements at thermospheric levels could be obtained by a Fabry-Perot interferometer or a baffled neutral mass spectrometer on a Venus orbiter. Densities and temperatures can be inferred from accelerometer measurements of orbit decay. In addition, tracers of upper atmospheric winds, including strong IR (O_2 1.27-μm) and UV (NO 198.0-nm) emissions, can be monitored to reveal spatial and temporal variations of the circulation.

Ionospheric structure, composition, and dynamics: The processes contributing to the volatile escape of hydrogen and oxygen from Venus are not well constrained for the present epoch (Fox and Kliore 1997, Nagy and Cravens 1997). Hence, they are difficult to extrapolate into the past for studies of Venus water loss. Pioneer Venus measurements provided an initial sampling of the UV emissions and tailward ion flow needed to identify potential loss mechanisms, but these measurements were not adequate to quantify the loss processes.

CRITICAL MEASUREMENTS NEEDED: Both H and O coronas were identified and periodically measured by the OUVS. However, an ongoing monitoring program of key UV emissions (130.4-nm, 135.6-nm, 121.6-nm, etc.) and tailward ion density flows (H^+, O^+, etc.) is needed to properly constrain loss mechanisms and their rates over the solar cycle. In addition, O_2^+ densities (lower ionosphere) are needed simultaneously to constrain the dissociative recombination rates which control the exospheric hot-O seed population for ion-pickup (O^+) loss. Such data sets will enable model extrapolations of volatile escape rates to be made (into the past) with enhanced reliability.

3. Interconnections: The Volatile History of Venus

As noted above, the volatile inventory of Venus appears to be more representative of the primordial solar nebula than Earth and Mars. A coordinated investigation of the volatile inventories of Venus and Mars may be essential to understand the origin and evolution of terrestrial planets, a critical focus of the Astrophysical

Origins Program. An investigation of Venus volatiles would also provide an obvious link to NASA's current Mars strategy, where water plays a central role.

For a terrestrial planet, an investigation of volatiles provides critical constraints on the atmospheric origin and compositional history, emergence of a coupled atmosphere-surface system and climate evolution. A coordinated analysis of water and other volatiles on Venus, Earth, and Mars will provide improved constraints on the effects of atmospheric cratering, thermal escape, sputtering, and other exogenic processes that have contributed to the loss of oxygen and water from their atmospheres. An understanding of the early loss of water by these planets is also needed to understand the evolution of their surfaces. In particular, on Venus, the water loss rate affects the rheology and differentiation rate of the interior. These factors affect the surface morphology and its ability to record past geological processing.

Improved constraints on the history of water and other volatiles on Venus and Mars will provide benefits that extend well beyond an improved understanding of their relationship to the initial state of a particular planet and the mechanisms that drove it down its specific evolutionary track. Attempts to decipher planetary histories in the broader context of the evolution of the solar system as a whole are focusing more and more attention on the sources and processing of volatiles in the primordial solar accretion disk, in primitive meteorites, and on the terrestrial planets as a class. The proposed measurement of Venus noble gases, trace gases, and surface chemical composition and weathering products directly address this need.

4. Required Associated Activities

4.1. Technology development

Little or no technology development would be needed to enable the orbiter and in situ measurements of atmospheric noble gases and trace gas distributions. In fact, several technologically mature Discovery missions have been proposed to address these issues over the past decade. The radar technologies needed to enable improved high-resolution global mapping of the surface have been developed and validated in Earth orbit over the past decade. In contrast, a substantial amount of technology development is needed to enable long-lived in situ measurements in the high-temperature, high-pressure environment of the deep atmosphere and the surface.

The Atmosphere Dynamics Explorer described above employs long-lived balloons deployed over a range of altitudes. This mission requires technologies for lightweight, low-power, high-temperature electronics and power systems that can operate over the full range of temperatures encountered between the 730 K surface and the 240 K cloud tops. This mission also requires the development of advanced balloon materials and deployment systems.

The Surface and Interior Explorer will deploy three or more landers at the surface to acquire seismological and geochemical data up to a year. This mission requires the development of a broad range of technologies that can survive and operate in this environment. The acquisition of seismic data is a challenge because seismometers require excellent coupling to the surface, and a minimum of mechanical noise from winds and the spacecraft. In situ chemical analysis of surface samples requires technologies for acquiring samples (perhaps from a range of near-surface depths) and delivering them to the analytical instrumentation, which presumably works in conditions somewhat less harsh those that characterize the ambient environment. To support these instruments, the landers require long-lived power systems that can operate at the Venus surface, as well as thermal control systems, high temperature electronics, and other high-pressure, high-temperature mechanical systems (pressure vessels, feedthroughs, bearings, etc.). An even broader range of technologies will be needed to enable future Venus sample return missions.

4.2. Research and analysis

There are currently no focused Venus Data Analysis Programs because NASA has not sent a dedicated mission to Venus in more than a decade. Basic research on this planet has evolved into a fringe activity, supported intermittently by the Planetary Astronomy, Planetary Atmospheres, and Planetary Geology and Geophysics Programs. Much of the available NASA funding supports the development of advanced theoretical modeling tools, and the application of these tools to the further analysis of data collected by earlier dedicated missions (Magellan, Pioneer Venus, Venera) and recent flyby opportunities (e.g., Galileo and Cassini). This work continues to produce advances in our understanding of this enigmatic planet, but the rate of progress has slowed in recent years, following the precipitous decline in the level of support. Significant growth in these NASA R&A programs will be needed to support future flyby opportunities, such as the planned Discovery MESSENGER flybys in June 2004 and March 2006, and to optimize experiments for future dedicated missions.

In contrast to the relative dearth of spacecraft observations over the past decade, new instrumentation and observational techniques becoming available at ground-based astronomical observatories have yielded a treasure trove of new data to support some areas of Venus exploration. In particular, the development of advanced near-infrared and microwave instruments has provided new opportunities to study the thermal structure, composition, and dynamics of the Venus atmosphere. Although Venus is our nearest planetary neighbor and usually the third brightest object in the sky (after the sun and the moon) these new instruments produced surprises and breakthroughs at each Venus inferior conjunction throughout the 1990's. This work has played a major role in the development of Discovery proposals targeted at Venus.

Although some of these observations have yet to be analyzed or published because of the limited support available for basic research, a number of future advances in this area are anticipated as new observing capabilities become available and are exploited by individual researchers. In addition to these individual efforts, a great deal could be learned about Venus from coordinated ground based efforts that employ global networks of observatories to obtain long-term, round-the-clock measurements. Small scale efforts of this kind were organized to support the Galileo and Cassini fly-bys of Venus. More ambitious efforts that include more global coverage and a wider range of wavelengths (UV, near IR, thermal IR, and microwave) are being considered to support the Discovery MESSENGER encounters on 24 June 2004 and 16 March 2006, and to support the European Venus Express and Japanese Venus Climate Orbiter (Planet C) missions. These efforts will require enhanced support from the NASA Planetary Astronomy Program, or a dedicated Venus Research and Analysis Program.

5. Opportunities for Education and Public Outreach (E&PO)

Because Venus is Earth's sister planet, comparisons between Venus, Earth, and Mars provide valuable tools for teaching physical, chemical, and geological processes that affect the environment. In particular, comparisons of Venus, Earth, and Mars can also provide insight into processes such as:

- Clouds: Why does the Earth have water clouds, while Venus has sulfuric acid clouds, and Mars has both water and carbon dioxide (dry ice) clouds?
- Seasons: Why do Earth and Mars have seasons, while Venus does not?
- Climate: Are greenhouse effects real? How much can greenhouse effects alter a planet's climate (Venus is the 300,000 times CO_2 case)?
- Planetary rotation: How does the Earth's rotation rate affect its weather and climate? What happens on a very slowly rotating planet like Venus? Why does the sun rise in the east and set in the west on Earth. Does it rise in the west on Venus?
- Plate tectonics. Terrestrial geology is dominated by plate tectonics on large scales. What geologic processes dominate on planets that have no plate tectonics, like Venus?

In short, by providing a dramatic counterexample to the Earth, Venus provides an effective tool for illustrating how various processes affect our environment.

6. Specific Recommendations:

While it is not possible to address all of the questions with a single mission, it should be possible to dramatically improve our understanding of our sister planet within the constraints of a coordinated program of small (Discovery Class), medium (New Frontiers Class), and large (~$1 B class) missions that are conducted by NASA and its international partners over the next 10 to 20 years. The NASA mission with the highest priority and greatest technological maturity is the Noble Gas/Trace Gas Explorer. The other missions listed below have comparable priorities, but they focus on different topics and have different levels of technological maturity. These missions should fly as their critical technologies become available.

6.1. The Noble Gas and Trace Gas Explorer

This has been identified as the highest priority mission because its data are vital to our understanding of the origin of Venus and its implications for our understanding of the early evolution of terrestrial planets. This small mission requires a single entry probe that can carry the state-of-the-art instruments needed to complete the noble gas and trace gas inventories between the cloud tops and the surface. These instruments include:

- State-of-the-art mass spectrometer optimized for noble gases
- Near IR and UV spectrometers for high-precision trace gas profiling
- Pressure and temperature sensors for altitude reference
- Feed-forward technology, such as a validation experiment for surface imaging and surface chemistry

This mission could be combined with the Atmospheric Composition Orbiter described below to produce a Small to Medium class mission that provides a comprehensive description of the Venus trace gas distributions.

6.2. The Global Geological Process Mapping Orbiter

This is a Small to Medium class mission that will provide global maps of the surface at horizontal resolutions of 25 to 50 m. These data are needed to identify and characterize the geologic processes that have shaped the Venus surface. This mission will fly in a global orbit and carry an advanced C and/or X-band radar designed to provide global stereo or interferometric coverage. The latter approach would require the use of a long (tens of meters) boom, like that demonstrated recently by the Shuttle Radar Topography Mission (SRTM). It might also carry instruments for identifying the atmospheric signature of volcanic activity (plumes, surface fixed sources of volcanic gases or aerosols) and discriminating these from other atmospheric processes (e.g. cloud formation, aeolean processes). This mission would require a lifetime of at least one Venus year to yield global coverage, but two Venus years would be highly desirable to search for time dependent variations in the surface associated with ongoing geologic activity. This mission could fly alone, or be combined with the Surface and Interior Explorer described below to produce a large mission that provides a much greater science return per dollar.

6.3. The Atmospheric Composition Orbiter

This 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. It will carry the following instrumentation:

- A high resolution near-IR imaging spectrometer for characterizing clouds, lower atmosphere trace gases, and dynamics
- A UV imaging photopolarimeter for tracking cloud-top winds and characterizing the upper haze to constrain radiative processes and heterogeneous chemistry above the cloud tops
- A submillimeter heterodyne spectrometer for global measurements of middle atmosphere trace constituents and direct Doppler wind measurements

- An S-band and/or X-band radio science package allowing retrievals of: (a) Sulfuric acid vapor profiles below clouds, (b) The pressure, temperature, and density between 34 km and 100 km (c) Thermal wind profiles in this altitude range

- An instrument package for characterizing the thermospheric dynamics and exospheric mass loss, including (a) An accelerometer for thermospheric density scale heights (b) a neutral/ion mass spectrometer for in situ exospheric mass loss measurements and (c) a Fabry-Perot interferometer or baffled mass spectrometer for thermospheric dynamics

These data will be used to characterize the radiative, chemical, and dynamical processes that are maintaining the thermal structure and composition of the present atmosphere. As noted above, this mission could be combined with the Noble Gas and Trace Gas Explorer to produce a Small to Medium mission with a much larger science return.

6.4. The Atmospheric Dynamics Explorer

This Medium mission includes both an orbiter and a network of entry probes. The four to eight entry probes will deploy twelve to twenty-four long-lived balloons at 3 to 4 altitudes between the surface and cloud tops at equatorial, mid, high latitudes. Each balloon will acquire time-resolved in situ measurements of pressure, temperature, and the solar and thermal radiation fields over its ~1 week lifetime. VLBI tracking and radio imaging by the orbiter will be used to determine the position and velocity of each balloon over this period. This information will be analyzed to yield both the mean and transient components of the wind field between the cloud levels and the surface. The orbiter is required for communications and balloon tracking. It will use UV and near IR imaging spectrometers for tracking winds in the upper, middle, and lower cloud decks and to record the near surface static stability. It will also carry an S- and/or X-band radio science package to retrieve pressure, temperature and density at altitudes between 34 km and 100 km (Jenkins et al. 1994, Hinson and Jenkins 1995). These data will be combined with the in situ measurements to identify the mechanisms responsible for maintaining the atmospheric superrotation.

6.5. The Surface and Interior Explorer

This Large mission 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. They may also carry meteorological instruments to identify mechanical disturbances associated with fluctuating winds, temperatures, and pressures that could compromise the interpretation of the seismic data. A lifetime of several months to a year is needed to address the science objectives of this mission. Because these landers must survive the harsh environment of the Venus surface, they require significant technology development for power systems, thermal control systems, electronics, and instruments.

6.6. Sample return mission

A sample return mission will eventually be needed to conduct investigations of the Venus surface and atmosphere that cannot be conducted by instruments on remote sensing platforms or on entry probes. The specific requirements for this mission are impossible to formulate at this time, but we anticipate that it will probably require a large mission and significant technology development.

7. Concluding Remarks:

Venus is our closest neighbor in this solar system, and the most Earth-like planet in size, mass, and solar distance. In spite of these similarities, and the intense scrutiny that it received early in space age, our understanding of its origin, evolution, and present environment are still shrouded in mystery. Information derived from a reinvigorated Venus Exploration Program could be combined with that provided by the ongoing Mars Exploration Program to dramatically improve our understanding of these properties of terrestrial planets. This information would be of great value in future efforts to interpret observations of extrasolar terrestrial planets, and to understand their range of habitability.

The only NASA spacecraft currently schedule to visit Venus is the Discovery MESSENGER mission, which will fly past this planet for a gravitational boost on 24 June 2004 at a distance of ~2500 km, and then again for a second time on 16 March 2006, at a distance of ~4300 km. While these brief encounters cannot provide answers to fundamental questions like those posed above, MESSENGER's instruments will provide new constraints on the enigmatic environment of our sister planet, and help to focus attention on our long-overlooked neighbor.

References

Anderson, F.S. and S.E. Smrekar 1999. Tectonic effects of climate change on Venus. *J. Geophys. Res.* **104**, 743-756.

Baker, N.L. and C.B. Leovy 1987. Zonal winds near Venus' cloud top level: A model study of the interactions between the zonal mean circulation and the semidiurnal tide. *Icarus* **69**, 202–220.

Barsukov V.L., S.P. Borunov, V.P. Volkov, V.A. Dorofeeva, M.I. Zolotov, S.V. Parotkin, I.V. Semenov, I.I. Sidorov, I.L. Khodakovskii, and A.I Shapkin 1986. Estimate of the mineral-composition of Venus soil at Venera-13, Venera-14 and Vega-2 landing sites (thermodynamic calculations). *Doklady Akademii Nauk SSSR* **287**, 415-418.

Bézard, B., C. de Bergh, D. Crisp, and J.-P. Maillard 1990. The deep atmosphere of Venus revealed by high-resolution nightside spectra. *Nature* **345**, 508–511.

Bézard B., C. de Bergh, B. Fegley, J.-P. Maillard, D. Crisp, T. Owen, J. B. Pollack, and D. Grinspoon 1993. The abundance of sulfur-dioxide below the clouds of Venus. *Geophys. Res. Lett.* **20**, 1587-1590.

Bullock, M.A. and D.H. Grinspoon 1996. The stability of climate on Venus. *J. Geophys. Res.* **101**, 752–2729.

Bullock, M.A. and D.H. Grinspoon 2001. The recent evolution of climate on Venus. *Icarus* **150**, 19-37.

Campbell, B.A. 1999. Surface Formation Rates and impact densities on Venus. *J. Geophys. Res.* **104**, 21951-21955.

Crisp, D. 1986. Radiative forcing of the Venus mesosphere I: Solar fluxes and heating rates. *Icarus* **67**, 484–514.

Crisp, D., A.P. Ingersoll, C.E. Hildebrand, and R.A. Preston 1990. VEGA Balloon meteorological measurements. *Adv. Space Res.* **10**, 109-124.

Crisp, D., S. McMuldroch, S.K. Stephens, W.M. Sinton, B. Ragent, K.W. Hodapp, R.G. Probst, L.R. Doyle, D.A. Allen, and J. Elias 1991. Ground-based near–infrared imaging observations of Venus during the Galileo Encounter. *Science* **253**, 1538-1541.

Crisp, D. and D. Titov 1997. The thermal balance of the Venus atmosphere. In *Venus II* (S.W. Bougher, D.M. Hunten, and R.J. Phillips, Eds.), pp. 353-384. Univ. of Arizona Press, Tucson.

de Bergh, C., B. Bézard, T. Owen, D. Crisp, J.-P. Maillard, and B.L. Lutz 1991. Deuterium on Venus: Observations from Earth. *Science* **251**, 547–549.

de Bergh, C., B. Bézard, D. Crisp, J.-P. Maillard , T. Owen, J. Pollack, and D. Grinspoon 1995. Water in the deep atmosphere of Venus from high-resolution spectra of the night side. *Adv. Space Res.* **15**, 79-88.

Donahue, T.M. and J.B. Pollack 1983. Origin and evolution of the Atmosphere of Venus. In *Venus* (D.M. Hunten, L. Colin, T.M. Donahue, and V.I. Moroz, Eds.), pp. 1003-1036. Univ. Arizona Press, Tucson.

Donahue, T.M. and R.R. Hodges 1993. Venus methane and water. *Geophys. Rev. Lett.* **20**, 591-594.

Esposito, L.W., J.-L. Bertraux, V. Krasnopolsky, and V.I. Moroz 1997. Chemistry of lower atmosphere and Clouds. In *Venus II* (S.W. Bougher, D.M. Hunten, and R.J. Phillips, Eds.), pp. 415-458. Univ. Arizona Press, Tucson.

Fegley, B., G. Klingelhofer, K. Lodders, and T. Widemann 1997. Geochemistry of surface-atmosphere interactions on Venus. In *Venus II* (S.W. Bougher, D.M. Hunten, and R.J. Phillips, Eds.), pp. 591-636. Univ. Arizona Press, Tucson.

Florenskiy, K.P., A.T. Bazilevskiy, G.A. Burba, O.V. Nikolayeva, A.A. Pronin, A.S. Selivanov, M.K. Narayeva, A.S. Panfilov, and V.P. Chemodanov 1983. Panorama of Venera 9 and 10 landing sites. In *Venus* (D.M. Hunten, L. Colin, T.M. Donahue, and V.I. Moroz, Eds.), pp. 137-153. Univ. Arizona Press, Tucson.

Fox, J.L., and A.J. Kliore,1997. Ionosphere: Solar cycle variations. In *Venus II* (S.W. Bougher, D.M. Hunten, and R.J. Phillips, Eds.), pp. 161-188. Univ. Arizona Press, Tucson.

Gierasch, P.J., R.M. Goody, R.E. Young, D. Crisp, C. Edwards, R. Kahn, D. Rider, A. Del Genio, R. Greeley, A. Hou, C.B. Leovy, D. McCleese, and M. Newman 1997. The general circulation of the Venus atmosphere: An assessment. In *Venus II* (S.W. Bougher, D.M. Hunten, and R.J. Phillips, Eds.), pp. 459-502. Univ. Arizona Press, Tucson.

Hansen, V.L., R.J. Phillips, J.J. Willis, and R.R. Ghent 2000. Structures in Tessera Terrain, Venus: Issues and Answers. *J. Geophys. Res.* **105**, 4135-4152.

Hansen, V.L. 2001. Venus diapirs, thermal or compositional? *LPSC* **XXXII**, 1036. (abstract)

Hansen, V.L. 2002. Artemis: signature of a deep venusian mantle plume. *Geol. Soc. Amer. Bull.*, in press.

Hansen, V.L., J.J. Willis, and W.B. Banerdt 1997. Tectonic overview and synthesis. In *Venus II* (S.W. Bougher, D.M. Hunten, and R.J. Phillips, Eds.), pp. 797-844. Univ. Arizona Press, Tucson.

Hansen, V.L. and J.J. Willis 1998. Ribbon terrain formation, southwestern Fortuna Tessera, Venus: Implications for lithosphere evolution. *Icarus* **132**, 321-343.

Hansen, V.L., B.K. Banks, and R.R. Ghent 1999. Tessera terrain and crustal plateaus, Venus. *Geology* **27**, 1071-1074.

Hauck, S.A., R.J. Phillips, and M.H. Prince 1998. Venus: Crater distribution and plans resurfacing models. *J. Geophys. Res.* **103**, 13635-13642.

Head, J.W., E.M. Parmentier, and P.C. Hess 1994. Venus–Vertical accretion of crust and depleted mantle and implications for geological history and processes. *Plan. Space Sci.*, **42** 803-811.

Herrick, R.R. and R.J. Phillips 1994. Implications of a global survey of Venusian impact craters. *Icarus* **111**, 387-416.

Hinson, D.P. and J.M. Jenkins 1995. Magellan radio occultation measurements of atmospheric waves on Venus. *Icarus* **114**, 310-327.

Hoffman, J.H., R.R. Hodges, T.M. Donahue, and M.B. McElroy 1980. Composition of the Venus lower atmosphere from the Pioneer Venus mass spectrometer. *J. Geophys. Res.* **85**, 7882–7891.

Hunten, D.M. 1995. Venus Lightning - Pros and cons. *Adv. Space Res.* **15**, 109-112.

Janes, D.M., S.W. Squyres, D.L. Bindschadler, G. Baer, G. Schubert, V.L. Sharpton, and E.R. Stofan 1992. Geophysical models for the formation and evolution of coronae on Venus. *J. Geophys. Res.* **97**, 16055-16068.

Jenkins, J.M., P.G. Steffes, D.P. Hinson, J.D. Twicken, and G.L. Tyler 1994. Radio occultation studies of the Venus atmosphere with the Magellan spacecraft: 2. Results from the October 1991 experiments. *Icarus* **110**, 79-94.

Kasprzak W.T., G.M. Keating, N.C. Hsu, I.A.F. Stewart, W.B. Colwell, and S.W. Bougher,1997. Solar activity behavior of the thermosphere. In *Venus II* (S.W. Bougher, D.M. Hunten, and R.J. Phillips, Eds.), pp. 295-324. Univ. Arizona Press, Tucson.

Keating, G.M. and N.C. Hsu 1993. The Venus atmospheric response to solar cycle variations. *Geophys. Rev. Lett.* **20**, 2751-2754.

Lellouch, E., T. Clancy, D. Crisp, A.J. Kliore, D. Titov, and S.W.Bougher 1997. Monitoring of mesospheric structure and dynamics. In *Venus II* (S.W. Bougher, D.M. Hunten, and R.J. Phillips, Eds.), pp. 295-324. Univ. Arizona Press, Tucson.

Limaye, S.S. 1988. Venus - Cloud level circulation during 1982 as determined from Pioneer Cloud Photopolarimeter images. 2. Solar longitude dependent circulation. *Icarus* **73**, 212-226.

Mackwell, S.J., M. E. Zimmerman, and D.L. Kohlstedt 1998. High-temperature deformation of dry diabase with application to tectonics on Venus. *J. Geophys. Res.* **103**, 975-984.

McGill, G.E., S.J. Steenstrup, C. Barton, and P.G. Ford 1981. Continental rifting and the origin of Beta-Regio, Venus. *Geophys. Res. Lett.* **8**, 737-740.

McKinnon, W.B. , K.J. Zahnle, B.A. Ivanov and H.J. Melosh 1997. Cratering on Venus: Models and observations. In *Venus II*, (S.W. Bougher, D.M. Hunten and R.J. Phillips, Eds.), pp. 969-1014. Univ. Arizona Press, Tucson.

Meadows, V.S. and D. Crisp 1996. Ground-based near infrared observations of the Venus nightside: The thermal structure and water abundance near the surface. *J. Geophys. Res.* **101**, 4595-4622.

Moresi, L. and V. Solomatov 1998. Mantle convection with a brittle lithosphere: Thoughts on the global tectonic styles of the Earth and Venus. *Geophys. J. Int.* **133**, 669-682.

Moroz, V. I. 1983. Summary of preliminary results of the Venera 13 and Venera 14 missions. In *Venus* (D.M. Hunten, L. Colin, T.M. Donahue, and V.I. Moroz, Eds.), pp. 45-68. Univ. Arizona Press, Tucson.

Nagy, A.F. and T.E. Cravens 1997. Ionosphere: Energetics. In *Venus II* (S.W. Bougher, D.M. Hunten, and R.J. Phillips, Eds.), pp. 189-224. Univ. Arizona Press, Tucson.

Owen, T.C., A. Bar-Nun, and I. Kleinfeld 1992. Possible cometary origin of heavy noble gases in the atmospheres of Venus, Earth, and Mars. *Nature* **358**, 43-46.

Owen, T.C. and A. Bar-Nun 1995. Comets, impacts, and atmospheres. *Icarus* **116**, 215-226.

Owen, T.C. 2000. The prevalence of Earth-like planets. *Acta Astronautica* **46**, 617-620.

Parmentier, E.M. and P.C. Hess 1992. Chemical differentiation of a convecting planetary interior: consequences for a one plate planet such as Venus. *Geophys. Res. Lett.* **19**, 2015-2018.

Pepin, R.O. 1991. On the origin and early evolution of terrestrial planet atmospheres and meteoritic volatiles. *Icarus* **92**, 2-79.

Pepin, R.O. 1997. Evolution of the Earth's noble gases: Consequences of assuming hydrodynamic loss driven by giant impact. *Icarus* **126**, 148-156.

Phillips, R.J. and M.C. Malin 1984. Tectonics of Venus. *Annu. Rev. Earth Planet. Sci.* **12**, 411-443.

Phillips, R.J., R.F. Raubertas, R.E. Arvidson, I.C. Sarkar, R.R. Herrick, N. Izenberg, and R.E. Grimm 1992. Impact craters and Venus resurfacing history. *J. Geophys. Res.* **97**, 15923-15948.

Phillips, R.J. 1993. The age spectrum of the Venusian surface: *Eos* (Supplement) **74**(16), 187.

Phillips, R.J. and V.L. Hansen 1994. Tectonic and Magmatic Evolution of Venus. *Annu. Rev. Earth Planet. Sci.* **22**, 597-654.

Phillips, R.J. and V.L. Hansen 1998. Geological evolution of Venus: Rises, plains, plumes and plateaus. *Science* **279**, 1492-1497.

Phillips, R.J., M.A. Bullock, and S.A. Hauck 2001. Climate and interior coupled evolution of Venus. *Geophys. Res. Lett.* **28**, 1779-1782.

Pollack J.B., J. B. Dalton, D. Grinspoon, R.B. Wattson, R. Freedman, D. Crisp, D.A. Allen, B. Bézard, C. de Bergh, L.P. Giver, Q. Ma, and R. Tipping 1993. Near-infrared light from Venus nightside - A spectroscopic analysis. *Icarus* **103**, 1-42.

Regenauer-Lieb, K., D.A. Yuen, and J. Branlund 2001. The initiation of subduction: criticality by addition of water? *Science* **294**, 578-580.

Schaber, G.G., R.G. Strom, H.J. Moore, L.A. Soderblom, R.L. Kirk, D.J. Chadwick, D.D. Dawson, L.R. Gaddis, J.M. Boyce, and J. Russell 1992. Geology and distribution of impact craters on Venus - What are they telling us? *J. Geophys. Res.* **97**, 13257-13301.

Schubert, G., C. Covey, A. Del Genio, L.S. Elson, G. Keating, A. Seiff, R.E. Young, J. Apt, C.C. Counselman III, A.J. Kliore, S.S. Limaye, H.E. Revercombe, L.A. Sromovsky, V.E. Suomi, F. Taylor, R. Woo, and U. von Zahn 1980. Structure and circulation of the Venus atmosphere. *J. Geophys. Res.* **85**, 8007-8025.

Smrekar, S.E., W.S. Kiefer and E.R. Stofan 1997. Large volcanic rises on Venus. In *Venus II* (S.W. Bougher, D.M. Hunten, and R.J. Phillips, Eds.), pp. 845-879. Univ. Arizona Press, Tucson.

Solomon, S.C., S.E. Smrekar, D.L. Bindschadler, R.E. Grimm, W.M. Kaula, G.E. McGill, R.J. Phillips, R.S. Saunders, G. Schubert, S.W. Squyres, and E.R. Stofan 1992. Venus tectonics: an overview of Magellan observations. *J. Geophys. Res.* **97**, 13199-13255.

Solomon, S.C., M.A. Bullock, and D.H. Grinspoon 1999. Climate change as a regulator of tectonics on Venus. *Science* **286**, 87-90.

Squyres, S.W., D.M. Janes, G. Baer, D.L. Bindschadler, G. Schubert, V.L. Sharpton, and E.R. Stofan 1992. The morphology and evolution of coronae on Venus. *J. Geophys. Res.* **97**, 13611-13634.

Stofan, E.R., D.L. Bindschadler, J.W. Head, and E.M. Parmentier 1991. Corona structures on Venus: Models of origin. *J. Geophys. Res.* **96**, 20933-20946.

Stofan, E.R., V.L. Sharpton, G. Schubert, G. Baer, D.L. Bindschadler, D.M. Janes, and S.W. Squyres 1992. Global distribution and characteristics of coronae and related features on Venus: Implications for origin and relation to mantle processes. *J. Geophys. Res.* **97**, 13347-13378.

Stofan, E.R., V.E. Hamilton, D.M. Janes, and S.E. Smrekar 1997. Coronae on Venus: Morphology and origin. In *Venus II* (S.W. Bougher, D.M. Hunten, and R.J. Phillips, Eds.), pp. 931-968. Univ. Arizona Press, Tucson.

Strom, R.G., G.G. Schaber, and D.D. Dawson, 1994. The global resurfacing of Venus. *J. Geophys. Res.* **99**, 10899-10926.

Taylor, F.W., R. Beer, M. T. Chahine, D.J. Diner, L.S. Elson, R.D. Haskins, D.J. McCleese, J.V. Martonchik, P.E. Reichley, S.P. Bradley, J. Delderfield, J.T. Schofield, C.B. Farmer, L.Froidevaux, J. Leung, M.T. Coffey, and J.C. Gille 1980. Structure and meteorology of the middle atmosphere of Venus: Infrared remote sensing from the Pioneer Orbiter. *J. Geophys. Res.* **85**, 7963-8006.

Weinstein, S.A. and P.L. Olsen 1992. Thermal convection with non-Newtonian plates. *Geophys. J. Int.* **111**, 515-530.

Wetherill, G.W. 1981. Solar-wind origin of Ar-36 on Venus. *Icarus* **46**, 70-80.

Zhang, S., S.W. Bougher, and M.J. Alexander 1996. The impact of gravity waves on the Venus thermosphere and O_2 IR nightglow. *J. Geophys. Res.* **101**, 23195-23205.