Chapter 3
The Surface and Atmosphere of Venus: Evolution and Present State

David Grinspoon

3.1 Early Evolution of the Atmosphere

Most models of atmospheric evolution start with the reasonable but unverified assumption that the original atmospheric inventories of Venus and Earth were similar. Although the two planets have similar overall abundances of nitrogen and carbon, the present day water inventory of Venus is lower than that of Earth by a factor of 10^5. The original water abundance of Venus is highly unconstrained. The high D/H ratio observed, 2.5×10^{-2} or ≈ 150 times terrestrial (Donahue et al. 1997) has been cited as evidence of a large primordial water endowment (Donahue et al. 1982). Yet, given the likelihood of geologically recent water sources and the large uncertainty in the modern and past hydrogen and deuterium escape fluxes, the large D/H may not reflect the primordial water abundance but rather may result from the history of escape and resupply in the most recent $\approx 10^9$ years of planetary evolution (Grinspoon 1997, 1993; Donahue et al. 1997). Thus, at present the best arguments for a sizable early Venusian water endowment remain dependent on models of planet formation and early volatile delivery. Most models of water delivery to early Earth involve impact processes that would have also supplied Venus with abundant water (Morbidelli et al. 2000; Grinspoon 1987; Ip et al. 1998). Stochastic processes could have created large inequities in original volatile inventory among neighboring planets (Morbidelli et al. 2000). However, given the great similarity in bulk densities and their close proximity in the Solar System the best assumption at present is that Venus and Earth started with similar water abundances.

The loss of water has been modeled as occurring during a phase of hydrodynamic escape driven by the large early solar EUV flux in a runaway climate driven by water

---

D. Grinspoon
Denver Museum of Nature & Science, Denver, USA
e-mail: dgrinspoon@dmns.org

L. Bengtsson et al. (eds.), *Towards Understanding the Climate of Venus*, ISSI Scientific Report Series 11, DOI 10.1007/978-1-4614-5064-1_3,

vapor feedback (Kasting et al. 1984; Kasting 1988) followed by loss of hydrogen through various thermal and non thermal escape processes, including Jeans escape, charge exchange, collisional ejection (Kumar et al. 1983), and an electric field driven flow of ions in the night-side hydrogen bulge (Donahue et al. 1997).

Kasting (1988) derived a timescale of several hundred million years for the loss of water, but this timescale remains highly uncertain. One of the largest uncertainties in understanding the nature and timescale for water loss is understanding the effects of clouds on the early environment. Cloud feedback is not included in any of the currently published models of the moist greenhouse. Grinspoon and Bullock (2007) presented simple grey-model simulations that suggested the role of clouds in the thermal balance during water loss would be to stabilize surface temperatures and thus greatly prolong the period of stable surface water, perhaps extending to 2 or 3 billion years.

3.2 Geological and Climate Evolution

The Magellan mission mapped nearly the entire surface of Venus, revealing a surface dominated by volcanic features exhibiting wide variety of morphologies, ranging from vast basaltic plains which cover 80 % of the planet and blanket the lowland areas, to a wide range of individual edifices including annular volcanic/tectonic features called coronae, steep sided domes apparently formed from more viscous magmas, and shield volcanoes ranging in size from 5 to hundreds of kilometers across (Basilevsky and McGill 2007). The largest of these are clustered in areas that are believed to be “hot spots” or mantle plumes, on the basis of Magellan gravity data (Smrekar et al. 2007). This distribution, and the lack of large-scale linear tectonic features or chains of volcanic features have been used to infer that Venus lacks plate tectonics.

Approximately 8 % of the surface consists of highly faulted and folded tessera terrain, which lies topographically above the surrounding volcanic plains (Basilevsky and McGill 2007). The tesserae are the oldest areas of Venus and may represent remnants from an epoch of fundamentally different geological processes. Given the apparent strong coupling between surface and atmospheric evolution on Venus, this also suggests that the tesserae may have been witness to a great transition in the atmosphere and climate as well. The current lack of plate tectonics may reflect the interior dynamics of a desiccated Earth-like planet. Thus the loss of water over time may ultimately explain the very different geology of Venus and Earth as well as their climatic divergence (Grinspoon and Bullock 2007).

More than 960 impact craters have been identified in Magellan radar imagery (Schaber et al. 1992). Their size distribution is consistent with the filtering effects of the atmosphere, suggesting that the current thick atmosphere has existed for at least the age of the extensive global plains. This age has been estimated as 750 Myr, with an uncertainty of several hundred million years, on the basis of crater modeling and statistics. The observation that the spatial crater distribution is nearly indistinguishable from a random distribution suggests that, to first order, the global plains were largely formed over a geologically short time. This, combined with the observation that the fraction of craters that have been volcanically and tectonically disturbed is quite small, suggests that the global resurfacing that created the plains was extensive enough to fully bury the pre-existing crater population, and ceased relatively suddenly, followed by more localized volcanic and tectonic activity which may continue to the present day. This interpretation has been disputed, and more data from future Venus missions, with high resolution surface imaging or direct surface sampling, will be required to resolve the resurfacing history of Venus. Recent near-infrared maps made with the VIRTIS instrument on Venus Express have revealed areas of anomalous surface emissivity around hot spot regions, which may indicate recent or ongoing volcanic activity (Smrekar et al. 2010). Such present-day activity may be consistent with either catastrophic or episodic models for the volcanic plains.

The more recent climate evolution of Venus, over the approximately age of the surface visible in Magellan global radar imagery, has likely been characterized by the balance between volcanic outgassing of radiatively active gases, especially SO_2 and H_2O, heterogeneous reactions with surface minerals, and exospheric outgassing of hydrogen. Without continued outgassing the clouds would largely dissipate on a timescale of ≈30 million years (Bullock and Grinspoon 2001), Thus, Venus may have experienced cloud-free epochs. The onset and cessation of episodes of global outgassing, of the style that some researchers have interpreted to be responsible for the globally extensive plains seen in Magellan mapping, may result in surface temperature changes of the order of several hundred degrees Kelvin (Bullock and Grinspoon 2001). Climate changes of this magnitude could result in surface thermal stresses that may help explain several puzzling geological features seen in Magellan imagery (Solomon et al. 1999).

3.3 The Lower and Middle Atmosphere

By 1971, after the Venera 7 and 8 landings, it was clear that Venus possessed a surface temperature of ≈735 K and a surface pressure of ≈90 bars (Marov et al. 1973). Approximately 10 % of the solar radiation absorbed by Venus diffuses to the surface through the thick clouds and atmosphere, amounting to 17 W/m^2 of surface insolation (Tomasko et al. 1980). Even with this rather low surface insolation, the opacity of the overlying atmosphere is sufficient to create massive greenhouse warming, raising the surface temperature to 735 K.

Table 3.1 summarizes some bulk qualities of the atmosphere of Venus. The lower atmosphere forms a deep, convective troposphere extending from the surface to the cloud base at 45 km. The temperature and pressure values measured by Venera and Pioneer Venus spacecraft, in comparison with adiabatic profiles, allowed estimates of the stability of the atmosphere. Early analyses suggested an essentially stable atmosphere (Avduevsky et al. 1968, 1970) with an overall vertical temperature

Table 3.1 Atmospheric properties of Venus

Surface pressure	92 Bar
Surface density	≈65 kg/m^3
Scale height	15.9 km
Total mass of atmosphere	≈4.8 x 10^{20} kg
Average surface temperature	735 K
Diurnal temperature change	≈0
Wind speeds at surface	0.3–1.0 m/s
Mean molecular weight	43.45 g/mol
Atmospheric composition (near surface, by volume)	
Major gases	CO_2 96.5 %
	N_2 3.5 %
Minor gases (ppm)	SO_2 130
	Ar 70
	H_2O 30
	CO 17
	He 12
	Ne 7

gradient of 7.7 K/km, substantially less than the adiabatic lapse rate of 8.9 K/km (Marov and Grinspoon 1998). Later analyses revealed evidence of zones of instability at altitudes of 20–30 km and 25–33 km (Seiff 1983). These regions of instability are believed to be associated with convective motions and zones of turbulence. A region of minor instability in the near-surface atmosphere below 10 km was inferred by Marov (1978) and Seiff et al. (1985).

The middle atmosphere above the clouds (60–100 km) exhibits even higher stability, with dT/dZ less than 3–4 K/km, suggesting a stratified middle atmosphere close to radiative equilibrium (Seiff 1983). Overall, the lower and middle atmosphere are close to the adiabatic lapse rate, a finding confirmed by the Vega 1–2 balloons in a large area of the middle cloud layer, where minor deviations from adiabatic suggested regions of slight stable stratification (Linkin et al. 1986). Knowledge of the structure and basic properties of the atmosphere up to 100 km, prior to the Venus Express mission, are summarized in the COSPAR reference model VIRA-85 (Seiff et al. 1985).

References

V.S. Avduevsky, N.F. Borodin, A.I. Kuznetsov, A.I. Lifshits, M.Y. Marov, V.V. Mikhnevich, M.K. Rozhdestvenskii, V.A. Sokolov, Temperature pressure and density of atmosphere of Venus from information supplied by Venus-4 Space Probe. Doklady Akademii Nauk SSSR **179**, pp. 310 (1968)

V.S. Avduevsky, M.Y. Marov, A.I. Noykina, V.I. Polezhaev, F.S. Zavelevich, Heat transfer in Venus atmosphere. J. Atmos. Sci. **27**, 569–579 (1970)

A. Basilevsky, G.E. McGill, in *Surface Evoluton of Venus, in Exploring Venus as a Terrestrial Planet*, ed. by L.W. Esposito, E.R. Stofan, T.E. Cravens (American Geophysical Union, Washington, DC, 2007)

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

T. Donahue, D.H. Grinspoon, R.E. Hartle, R.R. Hodges Jr, in *Ion/neutral Escape of Hydrogen and Deuterium: Evolution of Water* ed. by S.W. Bougher, D.M. Hunten, R.J. Phillips. Venus II Geology, Geophysics, Atmosphere and Solar Wind Environment (University of Arizona Press, Tucson, 1997)

T.M. Donahue, J.H. Hoffman, R.R. Hodges, A.J. Watson, Venus was wet – a measurement of the ratio of deuterium to hydrogen. *Science* **216**, 630–633 (1982)

D.H. Grinspoon, Was Venus wet – deuterium reconsidered. *Science* **238**, 1702–1704 (1987)

D.H. Grinspoon, Implications of the high D/H ratio for the sources of water in Venus atmosphere. Nature **363**, 428–431 (1993)

D.H. Grinspoon, *Venus Revealed: A New Look Below the Clouds of Our Mysterious Twin Planet* (Helix Books, Perseus Piblishing, Cambridge, Massachusetts, 1997)

D.H. Grinspoon, M.A. Bullock, in *Astrobiology and Venus Exploration*, ed. by L.W. Esposito, E.R. Stofan, T.E. Cravens. Exploring Venus as a Terrestrial Planet (American Geophysical Union, Washington DC, 2007)

W.H. Ip, D.J. Williams, R.W. McEntire, B.H. Mauk, Ion sputtering and surface erosion at Europa. Geophys. Res. Lett. **25**, 829–832 (1998)

J.F. Kasting, Runaway and moist greenhouse atmospheres and the evolution of Earth and Venus. *Icarus* **74**, 472–494 (1988)

J.F. Kasting, J.B. Pollack, T.P. Ackerman, Response of Earth's atmosphere to increases in solar flux and implications for loss of water from Venus. *Icarus* **57**, 335–355 (1984)

S. Kumar, D.M. Hunten, J.B. Pollack, Nonthermal escape of hydrogen and deuterium from Venus and implications for loss of water. *Icarus* **55**, 369–389 (1983)

V.M. Linkin, J. Blamont, A.N. Lipatov, A.A. Shurupov, C. Malique, S.P. Ignatova, G.A. Frank, L.I. Hlyustova, A.V. Terterashvili, A. Seiff, V.V. Kerzhanovich, B. Ragent, R. Young, E. Elson, R. Preston, A. Ingersoll, D. Crisp, Thermal structure of the Venus atmosphere in the middle cloud layer. Pis'ma v Astronomicheskie Zhurnal **12**, p. 36–40 (1986)

M.Y. Marov, Results of Venus missions. Ann. Rev. Astron. Astrophys. **16**, 141–169 (1978)

M.Y. Marov, D.H. Grinspoon, *The Planet Venus* (Yale University Press, New Haven, 1998)

M.Y. Marov, V.S. Avduevsk, N.F. Borodin, A.P. Ekonomov, V.V. Kerzhano, V.P. Lysov, B.Y. Moshkin, M.K. Rozhdest, O.L. Raybov, Preliminary results on Venus atmosphere from Venera-8 Descent Module. *Icarus* **20**, 407–421 (1973)

A. Morbidelli, J. Chambers, J.I. Lunine, J.M. Petit, F. Robert, G.B. Valsecchi, K.E. Cyr, Source regions and timescales for the delivery of water to the Earth. Meteorit. Planet. Sci. **35**, 1309–1320 (2000)

G.G. Schaber, R.G. Strom, H.J. Moore, L.A. Soderblom, R.L. Kirk, D.J. Chadwick, D.D., Dawson, L.R. Gaddis, J.M. Boyce, J. Russell, Geology and distribution of impact craters on Venus - what are they telling us. J. Geophys. Res.-Planets **97**, 13,257–13,301 (1992)

A. Seiff, Thermal structure of the atmosphere of Venus, in *Venus*, (A83-37401 17-31), ed. by D.M. Hunten, L. Colin, T.M. Donahue, V.I. Moroz, pp. 215–279 (Tucson, AZ, University of Arizona Press, 1983)

A. Seiff, J.T. Schofield, A.J. Kliore, F.W. Taylor, S.S Limaye, H.E. Revercomb, L.A. Sromovsky, V.V. Kerzahanovich, V.I. Moroz, M.Y. Marov, Models of the structure of the atmosphere of Venus from the surface to 100 kilometers altitude. Adv. Space Res. **5**(11), 3–58 (1985)

S. Smrekar, L. Elkins-Tanton, J. Leitner, A. Lenardic, L. Mackwell, L. Moresi, C. Sotin, E.R. Stofan, in *Tectonic and Thermal Evolution of Venus and the Role of Volatiles: Implications for Understanding the Terrestrial Planets*, ed. by L.W. Esposito, E.R. Stofan, T.E. Cravens. Exploring Venus as a Terrestrial Planet (American Geophysica Union, Washington DC, 2007)

S.E. Smrekar, E.R. Stofan, N. Mueller, A. Treiman, L. Elkins-Tanton, J. Helbert, G. Piccioni, P. Drossart, Recent hotspot volcanism on Venus from VIRTIS emissivity data. Science **328**, 605–608 (2010)

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

M.G. Tomasko, P.H. Smith, V.E. Suomi, L.A. Sromovsky, H.E. Revercomb, F.W. Taylor, D.J. Martonchik, A. Seiff, R. Boese, J.B. Pollack, A.P. Ingersoll, G. Schubert, C.C. Covey, The thermal balance of Venus in light of the Pioneer Venus mission. J. Geophys. Res.-Atmos., **85**, 8187–8199, doi:10.1029/JA085iA13p08187 (1980)