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ATMOSPHERE OF VENUS

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ABSTRACT

Venus Atmosphere Notes.

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1. INTRODUCTION

Venus has an extremely unusual atmosphere. Temperatures at the surface reach nearly 500°C. The atmosphere is composed of nearly all CO_2, but it still has more N_2 in its atmosphere than the Earth, even though it makes up a much smaller fraction. It has three layers of thick clouds near 50 km. The upper two layers are made of hydrated sulfuric acid and give the planet its yellow color. Their thickness gives Venus a very high albedo and also prevents most sunlight from penetrating the planet, with just 2 to 3% absorbed by the surface.

The high mass of Venus's atmosphere makes it very opaque across all wavelengths, making it the primary reason for the planet's high surface temperature. In addition, Venus's clouds as well as its CO_2 concentration further increase its opacity, though the latter only contributes at specific infrared wavelengths.

2. PRESSURE-TEMPERATURE PROFILE

Figures 1 and 2 show the pressure-temperature and altitude-temperature profiles in Venus's atmosphere.

2.1. *Properties*

Venus is characterized as having an atmosphere 92 times more massive than that of the Earth. Consequently, the surface pressure reaches 92 bars, which is also larger than the Earth by that same amount. Like the Earth, Venus exhibits a temperature inversion above the cloud layers. However, clouds on Venus ($\sim$ 50 km) are at a much higher altitude than those on Earth ($\sim$ 10 km). Solar heating is primarily responsible for the temperature increase above 100 km.

At the middle altitudes in the upper stratosphere where the temperature is already constant as a function of height, the temperature is also mostly constant throughout each day-night cycle, despite Venus's incredibly slow rotation period. For example, at 115 km, the temperature is fixed at 180 K to within 15 K. However in both the upper and lower atmosphere, there is a much more significant difference due to the length of Venus's day. For example, at 150 km, the temperature reaches 300 K during the day, but drops to below 150 K during the night (Taylor 2014).

Venus has very little temperature variation as a function of latitude. Despite its high temperatures, the poles are only 30 K colder than the equator (Taylor 2014).

2.2. *Measurements*

The middle parts of these profiles (40 to 100 km – the stratosphere) were measured with the radio occultation experiment aboard the Pioneer Venus Orbiter in the late 1970s (Kliore & Patel 1980). In this method, the orbiter emits a radio signal from behind Venus (as viewed from Earth) and through its atmosphere. The signal is then deflected based on the atmosphere's precise temperature and pressure at the tangent point. After exiting the atmosphere, the signal travels to either JPL Deep Space Network (DSS-14) or Tidbinbilla, Australia (DSS-43) depending on the time of day. The orbiter uses two different wavelengths: the X-band (3.5 cm) and the S-band (13 cm). It also maintains a local oscillator at each of these frequencies in order to measure the deflection later. Even with this local reference signal, determining the deflection is not straightforward due to the signal's high wavelength. As a result, the deflection can only be measured in directly through the signal's Doppler shift, which is then decomposed into an index of refraction mathematically using an Abel transform – a "Fourier transform" for spherically symmetric functions. The temperature and pressure can then be extracted from the index of refraction. Radio occultations are preferred for measuring these profiles because they have the highest resolution of any method at better than 1 km (Lellouch et al. 1997).

At higher altitudes ($>$ 100 km – the thermosphere) corresponding to lower pressures, the temperature profiles were measured with thermal sensors on descent probes from Pioneer and Venera 8-12. The density profiles, which are needed for determining the pressure, are measured with accelerometers also on board the descent probes (Lellouch et al. 1997).

The lowest altitudes ($<$ 40 km – the troposphere) are probed using near-infrared sounding at 0.9 to 2.5 μm on the night-side of the planet. This emission can be measured from the ground in addition to from space. At these wavelengths, very little of the emission is scattered due to the size and properties of the sulfuric acid cloud droplets that scatter light. Similarly, very little of the emission is absorbed since the relevant CO_2 spectral lines are not as broad as expected. As a result, the atmosphere is very optically thin, making the light that escapes into space perfect for examining the lower atmosphere (Taylor et al. 1997).

The temperature profile can also be measured through spectroscopy using assorted molecular bands (e.g. CO_2 4.3 μm or 15 μm) or lines (e.g. CO $J = 2 \rightarrow 1$). This method takes advantage of the fact that specific frequency intervals correspond to particular altitudes depending on the transmission from a given pressure level to space. Spectroscopic methods only have a resolution of 5 to 10 km (Lellouch et al. 1997).

A second spectroscopic method involves extracting temperatures from relative strengths of spectral lines in nightglow emission. This emission can come from

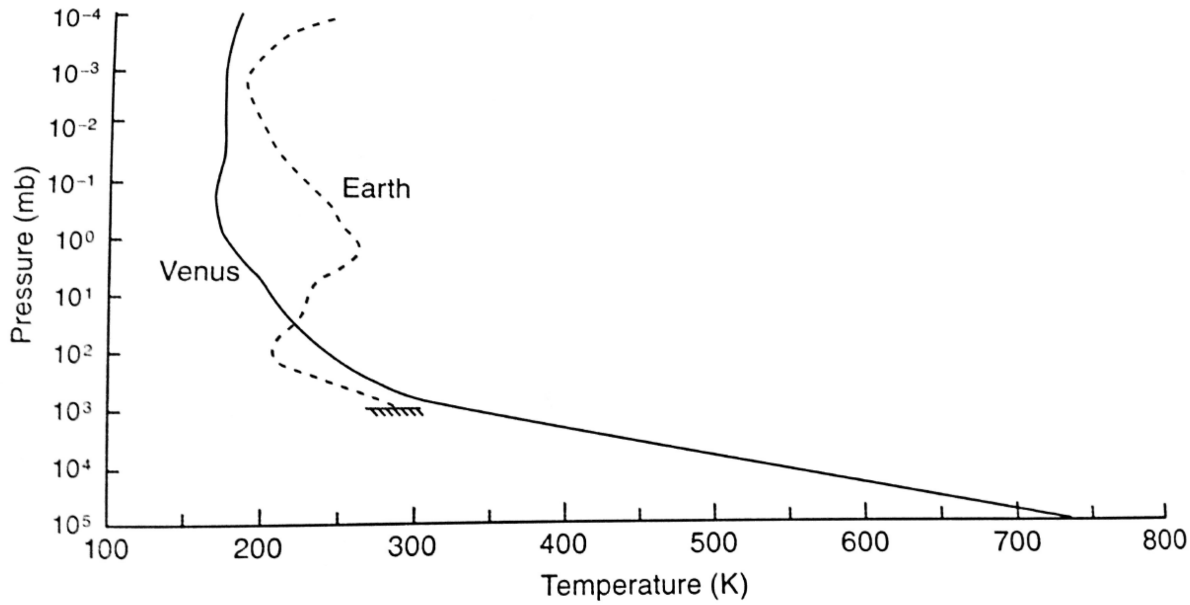

Figure 1. Pressure-temperature profile from Pioneer (Figure 10.1 from Taylor 2014).

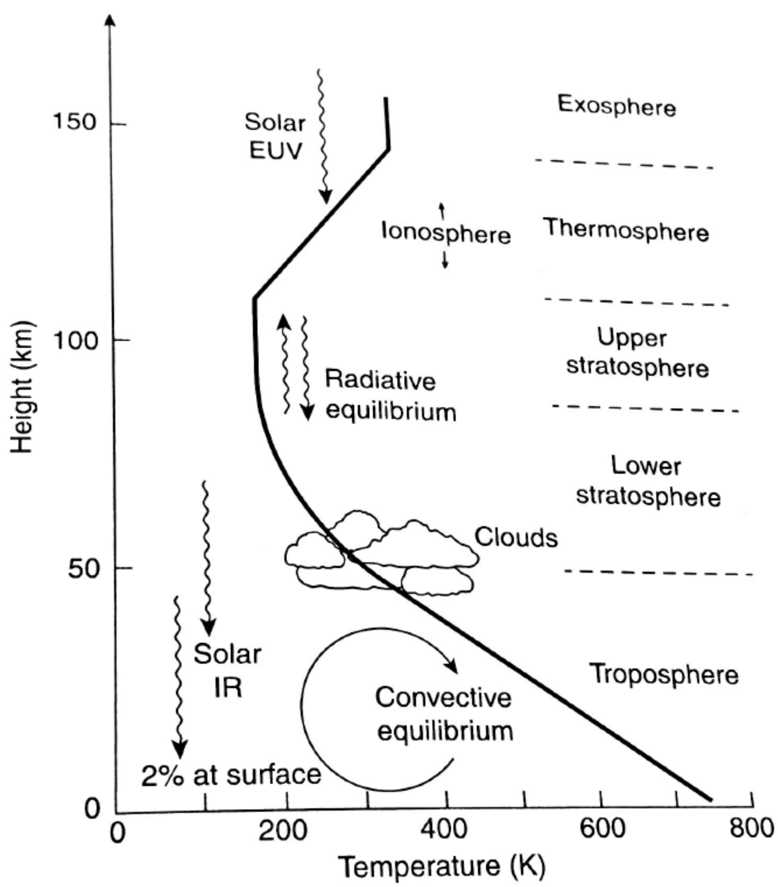

Figure 2. Altitude-temperature profile from Pioneer (Figure 10.2 from Taylor 2014).

a variety of sources including cosmic ray luminescence, energy from chemical reactions, and atoms that were ionized during the day recombining.

3. LAPSE RATES

3.1. *Dry Lapse Rate*

The dry-lapse rate is given by

$$\Gamma_d = -\frac{dT}{dz} = \frac{g}{c_p}. \tag{1}$$

With a mass of $M_V = 0.82\ M_\oplus = 4.87 \times 10^{24}$ kg and a radius of $R_V = 0.95\ R_\oplus = 6.05 \times 10^3$ km, Venus has a surface gravity of

$$g_V = GM_V/R_V^2 = [0.82/0.95^2]g_\oplus = 0.91 g_\oplus = 8.87\,\mathrm{m/s^2}. \tag{2}$$

The specific heat capacity at constant pressure, c_p, can be determined easily by approximating the atmosphere – which is 96.5% CO_2 – as purely carbon dioxide. At the surface, Venus has an air pressure of 92 bars and a temperature of 740 K. Under these conditions, $c_p = 1.16$ kJ / kg / K for pure CO_2. Just above the surface at 50 km, Venus has a pressure of 1.08 bars and a temperature of 350 K, corresponding to $c_p = 0.90$ kJ / kg / K. Thus, at the surface, Venus has a dry lapse rate of $\Gamma_d = 7.6$ K / km. At an altitude of 50 km, $\Gamma_d = 9.9$ K / km, a sharp increase from the surface already.

3.2. *Wet Lapse Rate*

The wet lapse rate is given by

$$\Gamma_w = -\frac{dT}{dz} = g\frac{1 + \frac{H_v r}{R_{sw} T}}{c_p + \frac{H_v^2 r}{R_{sw} T^2}}, \tag{3}$$

where $g = 8.87$ m / s^2 is Venus's surface gravity, $H_v = 2.5 \times 10^6$ J / kg is the Heat of vaporization of water, $R_{sd} = 188.9$ J / kg / K is the specific gas constant of dry air, $R_{sw} = 461.5$ J / kg / K is the specific gas constant of water vapor, $c_p = 1.16$ kJ / kg / K is the specific heat capacity, and $r = (R_{sd}/R_{sw}) \times p_w/(p - p_w) = 4 \times 10^{-5}$ is the mixing ratio of water to air. Since the partial pressure of water $p_w/p = 10^{-4} \ll 1$, the difference between the dry lapse rate and the wet lapse rate is negligible. At the surface, $\Gamma_w = 7.6$ K / km. At 50 km, $\Gamma_w = 9.8$ K / km.

3.3. *Comparison*

Below an altitude of 55 km (≈ 0.5 bars), the temperature gradient is in good agreement with the dry lapse rate. Figure 3 shows the atmosphere's static stability, the difference between the actual temperature gradient and the dry lapse rate ($dT/dz - \Gamma$). Except near 45 km, the static stability never exceeds 2 K / km. This suggests that the lower atmosphere (the troposphere) is largely in convective equilibrium. Interestingly, at very close to the surface (2 to 4 km), in the middle of the troposphere (near 18 km), and near the top of the troposphere (49 to 55 km), the static stability is negative. This suggests the atmosphere is slightly unstable at these altitudes. The top region of instability may be due to the presence of clouds.

Despite this agreement with the dry lapse rate, Venus is still much hotter than the blackbody temperature one would expect from just solar heating. Assuming no internal heating, the atmospheric temperature of Venus at the surface would be

$$T = \left(\frac{1}{16\pi\sigma}(1 - A_♀)\frac{L_\odot}{d_♀^2} \right)^{1/4}, \tag{4}$$

where the bond albedo of Venus is $A_♀ = 0.77$, the semi-major axis of Venus is $d_♀ = 0.72$ AU, and the luminosity of the Sun is $L_\odot = 3.8 \times 10^{26}$ W. This yields a temperature of T = 227 K. Had an albedo of zero been assumed, the surface temperature would still be only T = 327 K, less than half of the actual surface temperature of T = 740 K. Thus, Venus has a very strong greenhouse effect.

3.4. *Greenhouse Effect*

Like the Earth, Venus's actual surface temperature is much higher than the planet's effective temperature based on its albedo and its distance from the Sun. Unlike the Earth, that difference is more than a factor of three, while on Earth it is only about 15%. This greenhouse effect results from the atmosphere's variation in opacity as a function

The origin of the greenhouse effect resides in the fact that planets do not emit light in the same wavelength range as the Sun. With the Sun's temperature of 5770 K, it emits a Planck spectrum that peaks in the visible range. However, since Venus is much colder than the Sun, it emits a Planck spectrum that peaks in the infrared (μm) range that for the most part, does not overlap with the received light from the Sun. As a result, the light from the Sun may be able to pass through the atmosphere (in its wavelength range), but the energy re-emited by the planet may not be able to escape the atmosphere into space (since it emits in a different wavelength range).

On Venus, only a very small fraction of sunlight reaches the planet, with 77% reflected and just 3% absorbed by the surface. Meanwhile, the remaining 20% is absorbed by the atmosphere, which then tries to reradiated it uniformly in all directions. However, the ex-

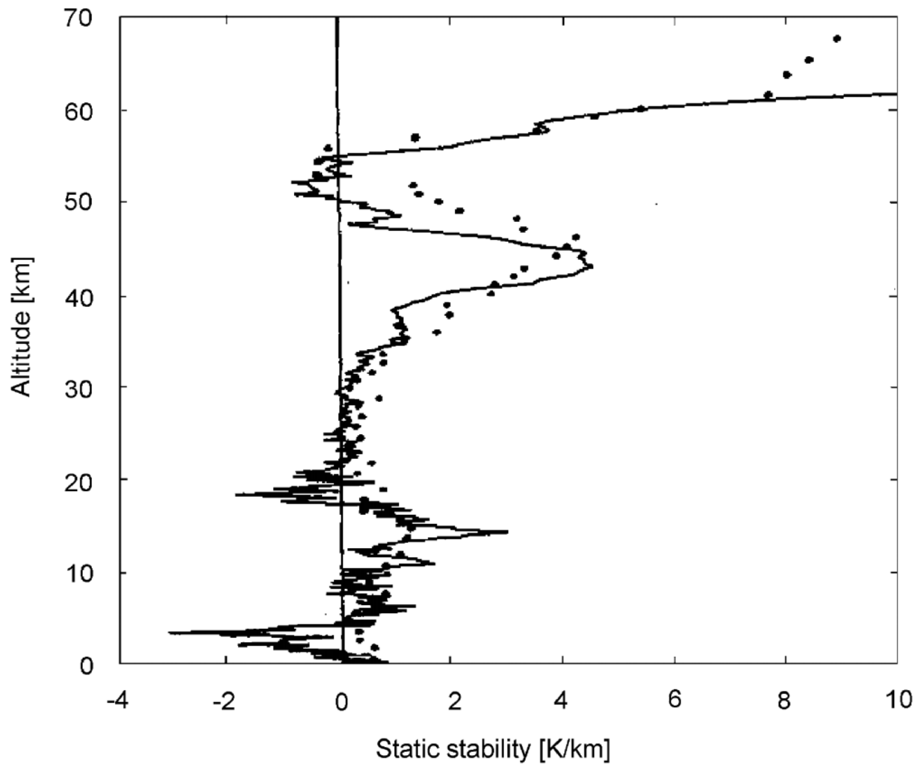

Figure 3. Static stability of atmosphere for VEGA 2 data (solid line) and the VIRA model (dots). The VEGA 2 data suggests the atmosphere is unstable at altitudes of 2-4 km, near 18 km, and at 49-55 km (Figure 2 from Zasova et al. 2007).

tremely high mass of the atmosphere makes it easy for the planet to trap any radiation that the atmosphere is re-emitting. The clouds further contribute to making the planet opaque to outgoing radiation. Yet even without these clouds, the planet's surface. would still be extremely hot. Additionally, the atmosphere's high CO_2 concentration further increases the opacity, but only at the wavelengths where CO_2 absorbs. Since the planet needs to be opaque across the entire wavelength range where it is re-emitting light in order to have a strong greenhouse effect, CO_2 is not the primary driver of Venus's high surface temperature.

4. COMPOSITION

The major components of Venus's atmosphere are carbon dioxide (CO_2) at 96.5%, nitrogen (N_2) at 3.5%, sulfur dioxide (SO_2) at 150 ppm, argon (Ar) at 70 ppm, carbon monoxide (CO) at 40 ppm, and water vapor (H_2O) at 30 ppm (Taylor 2014).

The gas chromatograph on the Pioneer Venus orbiter measured the abundances of all of the main constituents of the atmosphere (Oyama et al. 1980).

Sulfur dioxide can also be measured with its $3\nu_3$ band at 2.45 μm on the night-side (de Bergh et al. 2006).

Carbon monoxide can also be detected with its $J = 2 \rightarrow 0$ absorption line at 2.3 μm on the night-side. It has also been constrained with radio observations at 1.3 and 2.6 mm (de Bergh et al. 2006).

Water vapor was first measured with ground-based near-infrared sounding. The descent probes Vega 1 and 2 also provide less precise constraints on its abundance (de Bergh et al. 2006).

5. CLOUDS

Venus has three layers of clouds that reside at altitudes from 47 to 70 km (Taylor 2014). These layers are believed to be separated by thin, clear regions. Above the top layer and below the bottom one, there are diffuse layers of haze that may span the entire region of clouds in-between. Figure 4 shows the structure of the clouds along with some of their other properties.

The lower layer (47 to 49 km) is the thinnest, but it also is the most dense, and has the largest particles in the atmosphere with sizes reaching more than 30 microns. Whereas the other layers of clouds are mostly uniform, this layer most closely resembles clouds on Earth. If you were on the surface, you would be able to see individual clouds that change shape and move throughout the day. The middle layer (49 to 57 km) is split from the upper layer by the tropopause, which marks the boundary at which convection stops taking place. The upper layer (57 to 70 km) contains similar clouds to those in

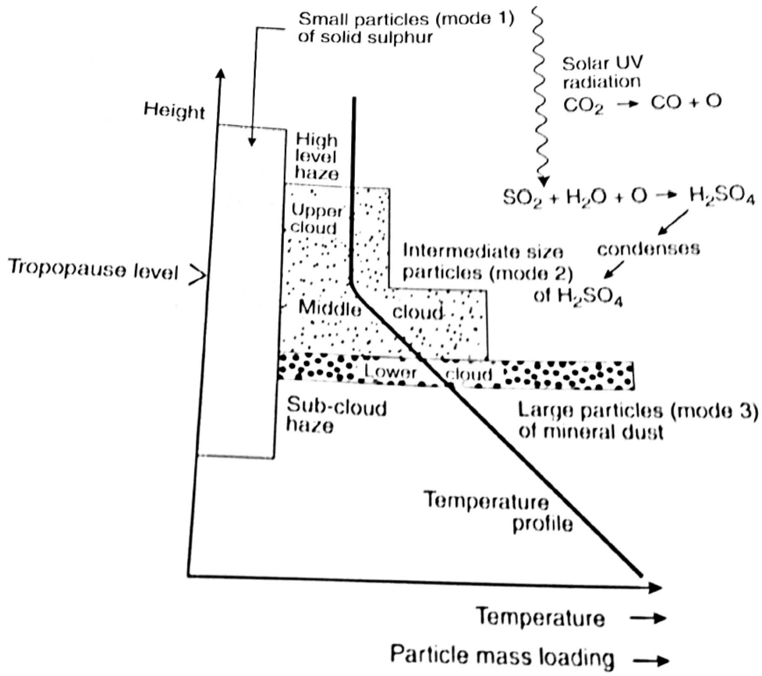

Figure 4. Different types of particles as a function of height and temperature. There are three cloud layers. There are also three modes of particles, one for the lower clouds, one for the middle and upper clouds, and one for the sulfur haze particles that are spread throughout the clouds layers as well as above and below (Figure 12.4 from Taylor 2014).

the middle layer, except that they do not reach as high of a temperature. These two layers are much less dense, and composed of much smaller particles. In particular, we can study properties of the upper layer (such as the distribution of particle sizes) by looking at polarization from here on Earth. Other properties of clouds have been derived from the Pioneer orbiter and the more recent Venus Express orbiter.

Most particles fall in a range between 0.6 to 1.5 microns, although the smallest particles reach about 0.3 microns and the largest reach 35 microns. There are three different populations of particles (known as 'modes') that are defined primarily by size and composition, although they do not perfectly match the three cloud layers (see Figure 4). The first mode consists of the smallest particles the atmosphere, which are located in the haze that surrounds and may be embedded throughout the cloud layers. Besides the haze, they also make up some of the upper cloud layer. They are composed of sulfuric acid (H_2SO_4) and possibly solid sulfur (S_8). The second mode consists of the intermediate-sized particles in the middle and upper cloud layers. They are composed of condensed hydrated sulfuric acid ($H_2SO_4 \bullet H_2O$) and give the planet its thick, "off-yellow" color. The third mode consists of the largest particles that make the up the lower cloud layer. They have an average size of 4 microns and are mostly not perfectly spherical. Their weird shapes suggests they may be volcanic ash spewed into the atmosphere.

5.1. *Chemical Processes*

Unlike many of the dynamical processes in Venus's atmosphere, the chemical processes that dictate cloud formation are well-understood. The underlying processes are shown in Figure 5. The material needed to form clouds originates in volcanoes that eject sulfur dioxide (SO_2) and water vapor (H_2O) into the atmosphere. In the lower atmosphere, these two combine to form sulfurous acid (H_2SO_3), which is then carried by the eddies to the upper atmosphere where it can combine with single oxygen atoms to form gaseous sulfuric acid (H_2SO_4) that is more stable. The oxygen atoms are the result of photodissociation of water and carbon dioxide. Due to the thick clouds, sunlight can only break up these molecules above the clouds.

Also near the cloud tops, the atmosphere is cold enough for the gaseous sulfuric acid to condense into liquid form. Some of the liquid sulfuric acid will deposit into the clouds, while the rest will sink to the lower atmosphere, where it will evaporate back into gas. From here, eddies will either (1) eddies carry it back into the clouds where it can condense again, or (2) carry it lower in the atmosphere where the heat will break it up into its

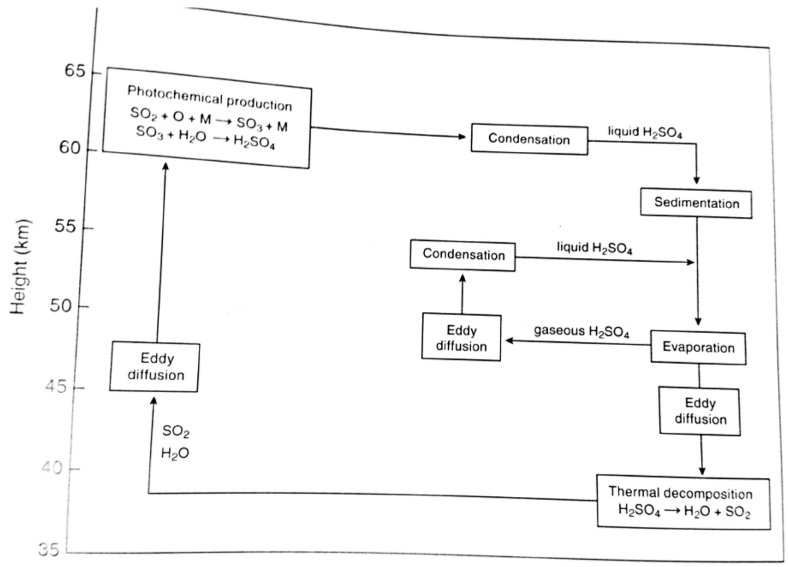

Figure 5. Chemical processes governing particle distributions in the atmosphere (Figure 12.5 from Taylor 2014).

original components, thereby starting the cycle of cloud formation over again.

5.2. *Variations*

Due to the superrotation of the atmosphere (see Section 6 below), there is very little variation in the cloud coverage during the day compared to during the night. Meanwhile, there is some variation in the clouds as a function of latitude. Since the lowest layer of clouds is set by the temperature at which sulfuric acid evaporates, the clouds are reach a slightly lower altitude at high latitudes where the temperature is colder. Meanwhile, clouds also have a higher concentration of sulfuric acid at higher latitudes, reaching a peak at 60°. Although sulfuric acid is easier to produce at the equator where there is more water (which is needed to produce sulfuric acid), the Hadley cells in the atmosphere carry this sulfuric acid from the equator to the high altitudes at high latitude, where it disproportionally settles. Since the Hadley cells end at 60°, there is very little sulfuric acid above this latitude. Closer to the poles, there are polar vortices instead of the usual clouds (see Section 6.3). These polar vortex clouds are much more difficult to probe, and we know little about their composition or other properties.

6. ATMOSPHERIC DYNAMICS

Venus has a complex array of atmospheric dynamics that is not well understood (see review by Schubert et al. 2007). Whereas Venus itself is characterized by its slow retrograde motion, the atmosphere of Venus is best characterized by its retrograde superrotating zonal flow (RSZ) that can reach speeds up to 60 times faster than the rotation rate of the planet – hence, the name "superrotating"). As a slowly rotating planet with a thick atmosphere, Venus has some similarities with Titan, which also exhibits superrotation.

6.1. *Lower Atmosphere*

Venus's atmosphere is loosely divided by its cloud tops at an altitude of 90 km. The lower atmosphere can reach winds of up to 90 m/s as part of the RSZ described above. It is suspected that a strong Hadley cell – which flows up and towards the poles and equators, and flows down and towards the equator from the poles – plays a large role in generating these fast wind speeds (Gierasch 1975). However, no Hadley cell has been observed. Furthermore, current measurements constrain that the strongest possible Hadley cell that could go undetected should not be capable of producing such a strong superrotation.

Modeling Venus's atmospheric dynamics has had a bleak history. The first attempt by Young & Pollack (1977) overestimated the strength of the RSZ and still could not create any superrotation in the lower atmosphere below 30 km. Yet, it was still considered successful at the time for being the first model to create superrotation at all. The next "good" model was set up by del Genio et al. (1993) and was the first to generate superrotation at any height in the atmosphere. This superrotation requires that Venus have a layer of high static stability at the upper boundary of the lower atmosphere, which the planet does satisfy. The superrotation is generated by the barotropic instability, which itself requires that the vorticity reaches a peak or trough at some altitude (instead of monotonically increasing or decreasing). However to achieve superrotation, they needed to assume Venus's atmosphere had the same mass as that of the Earth, even though it is 100 times more massive.

It was not until this century that Yamamoto & Takahashi (2003) developed a model with the correct mass of Venus's atmosphere that could generate superrotation at all altitudes. However to achieve this, they needed to include an unrealistically high amount of heating in the lower atmosphere that would correspond to either (1) a Hadley cell large enough for us to be able to detect, or (2) a large graident in temperature across different latitudes that has not been observed to exist. More recently, Hollingsworth et al. (2007) developed a model that also generates superrotation as well as the proper wind speed of 90 m/s at 90 km. However, this also requires unrealistic heating near the surface. With an amount of heating consistent with observations, the zonal flows only reach 1 m/s near the surface and a maximum of 10 km/s at 90 km, about an order of magnitude too low.

As of now, there are three main possible explanations for Venus's superrotation. The first is that meridional circulation (north-south) helps induce non-axisymmetric eddies that speeds up zonal flows. The second is that variations in solar heating as Venus rotates can induce an instability that increases wind speeds. The third is that the atmosphere interacting with the surface through thermally-excited gravity waves is responsible. Gravity waves have been detected on Venus's surface, but not well enough to constrain models. These waves are generated when winds pass over uneven terrains, such as mountains.

6.2. *Upper Atmosphere*

The dynamics in the upper atmosphere above 90 km still overlap with those in the middle atmosphere. The top of the atmosphere is driven by solar UV heating as well as IR heating. At these altitudes near 200 km, winds can reach speeds of 200 m/s. The circulation at these altitudes are mostly stable and follow a subsolar-to-antisolar pattern across the terminator.

Like the winds in the lower atmosphere, it is not clear what sets the winds in the upper atmosphere. For example, while it is observed that the nightside maintains much colder temperatures than the dayside, models show that circulation between these two sides should heat the nightside. Yet, this does not happen – likely due to some mechanism decelerating these winds near the terminator. Like the mechanisms for superrotation, one possibility is that gravity wave breaking could play a role in transporting energy and momentum to the middle upper atmosphere altitudes, where the temperature starts to rise again. However, circulation models have failed to get gravity wave breaking to create this effect when the observed parameters for other variables (e.g. temperature) are used.

Towards the middle of the atmosphere, the solar-driven part combines with the part driven by RSZ. This creates stronger winds near the terminator of the planet. There must be a mechanism responsible for cutting off the RSZ at these middle altitudes, so that the Sun can drive the top of the atmosphere. It is suspected that thermal tides (related to the planet's slow rotation) play a role in setting this cut-off. These tides help create the Hadley cells that should driving superrotation. However, if these tides are weaker in the upper layers of the lower atmosphere, they could help decouple the lower atmosphere from the upper atmosphere. This is consistent with observations which show that the lower layers of the lower atmosphere (near 20 km) have the largest amount of momentum per unit volume.

6.3. *Polar Vortices*

At latitudes above 60° towards the pole, Venus naturally has vortices due to zonal flows colliding more tightly with meridional flows (just as would happen on any rocky planet with an atmosphere). The vortices on Venus are stronger than those on Earth due to the superrotation throughout the planet's atmosphere (Taylor 2014).

REFERENCES

de Bergh, C., et al. 2006, *The composition of the atmosphere of Venus below 100 km altitude: An overview*, Planetary and Space Science, 54, 1389

Del Genio, A. D., et al. 1993, *Equatorial superrotation in a slowly rotating GCM: Implications for Titan and Venus*, Icarus, 101, 1.

Gierasch, P. J. 1975, *Meridional circulation and the maintenance of the Venus atmospheric rotation*, Journal of Atmospherc Science, 32, 1038.

Greeley, R., et al. 1995, *Wind-Related Features and Processes on Venus: Summary of Magellan Results*, Icarus, 115, 399

Hollingsworth, J. L., et al. 2007, *A simple-physics global circulation model for Venus: Sensitivity assessments of atmospheric superrotation*, Geophysical Research Letters, 34, L05202

Jenkins, J., et al. 1994, *Radio Occultation Studies of the Venus Atmosphere with the Magellan Spacecraft: 2. Results from the October 1991 Experiments*, Icarus, 110, 79

Kliore, A., & Patel, I. 1980, *Vertical Structure of the Atmosphere of Venus from Pioneer Venus Orbiter radio occultation studies*, Journal of Geophysical Research, 85, 7957

Lellouch, E., et al. 1997, *Monitoring of Mesospheric Structure and Dynamics*, in Bougher, S., Hunten, D., Phillips, R. eds, Venus II. University of Arizona Press, Tucson.

Markiewicz, M., et al. 2007, *Morphology and dynamics of the upper cloud layer of Venus*, Nature, 450, 633

Meadows, V., et al. 1996, *Ground-based near-infrared observations of the Venus nightside: The thermal structure and water abundance near the surface*, Journal of Geophysical Research, 101, 4595

Oyama, V., et al. 1980, *Pioneer Venus Gas Chromatography of the Lower Atmopshere of Venus*, Journal of Geophysical Research, 85, 7891

Patzold, M., et al. 2007, *The structure of Venus' middle atmosphere and ionosphere*, Nature, 450, 657P

Sanchez-Lavega, M., et al. 2008, *Variable winds on Venus mapped in three dimensions*, Geophysical Research Letters, 35, L13204

Schubert, G., et al. 2007, *Venus atmosphere dynamics: A continuing enigma*, in Exploring Venus as a Terrestrial Planet, Geophys. Monogr. Ser., vol. 176, edited by L. W. Esposito, E. R. Stofan, and T. E. Cravens, pp. 121-138, AGU, Washington, D.C.

Taylor, F., et al. 1997, *Near-infrared sounding of the lower atmosphere of Venus*, in Bougher, S., Hunten, D., Phillips, R. eds, Venus II. University of Arizona Press, Tucson.

Taylor, F. 2014, *The Scientific Exploration of Venus*, Cambridge University Press, New York.

Tellman, S., et al. 2009, *Structure of the Venus neutral atmosphere as observed by the RadioScience experiment VeRa on Venus Express*, Journal of Geophysical Research, 114, 36

Titov, D., et al. 2009, *Venus express: Highlights of the nominal mission*, Solar System Research, 43, 1855

Yamamoto, M., & M. Takahashi 2003, *Superrotation and equatorial waves in a T21 Venus-like AGCM*, Geophysical Research Letters, 30, 1449

Young, R. E., & J. B. Pollack 1977, *A three-dimensional model of dynamical processes in the Venus atmosphere*, Journal of Atmospheric Science, 34, 1315.

Zasova, L., et al. 2006, *Structure of the Venusian Atmosphere from Surface up to 100 km*, Cosmic Research, 44, 381

Zasova, L., et al. 2007, *Structure of the Venus atmosphere*, Planetary and Space Science, 55, 1712