Venus Dunes

14

14.1 Introduction

Since Venus has a thick atmosphere (Fig. 14.1), it seems a natural place to contemplate aeolian transport. Although speculations about Venus' surface ranged from a global ocean world (of water), to a tarry swamp, other speculations were of a desert world. In many respects, this last perspective has been borne out, although Venus seems largely to be a rocky rather than a sandy world, dominated by volcanic and tectonic processes, rather than erosion and deposition.

Authoritative research reviews of Venus science as a whole are given in two books in the University of Arizona planetary science series, namely *Venus* (edited by Hunten et al. 1983, written in the wake of Russian probes and Pioneer Venus) and *Venus II* (Bougher et al. 1997, a mere 1362 pages compiled in the wake of Magellan) and an AGU volume (Esposito et al. 2007). An excellent and readable text is that by Marov and Grinspoon (1998). The best comprehensive review of Venusian aeolian processes specifically is the chapter in *Venus II* by Greeley et al. (1997a).

14.2 History of Venus Exploration

Even before space probes revealed the details of surface conditions on Venus, it was expected to be a windswept place. Indeed, one early theory (Öpik 1961) even advanced friction by wind-blown dust as being the reason that Venus' surface might be hot, although this mechanism doesn't stand up to thermodynamic scrutiny. As early spacecraft data came in, it became obvious that the greenhouse effect was responsible for elevating Venus' surface temperatures, but until probes reached the surface in the 1970s, it was not known how dense and hot the atmosphere really was, nor which greenhouse gases might be responsible. One theory—which formed the Ph.D. thesis of the later-prominent climate scientist James Hansen—was that airborne dust would provide greenhouse warming. In fact, we now know that the lower atmosphere of Venus is relatively clear, and the greenhouse effect is due primarily to carbon dioxide and water vapor.

The Venus probes revealed the atmospheric pressure at the surface to be some 90 bar: this translates, given the molecular weight of the predominantly CO_2 atmosphere and the high temperatures, to an air density of about 64 kg/m^3, or about 50 times that of sea-level air on Earth. This high density might lead one to expect aeolian transport to be rather easy. However, in contrast to the abundant sand drifts seen in images from the surface of Mars by the Viking landers in 1976, images returned from the torrid Venusian surface by several Soviet Venera probes[1] showed (Fig. 14.2) relatively little fine-grained material (compared with the Moon or Mars), although there were some indications that the landings kicked up a cloud of dust. Since the Venusian surface is hidden from view at optical wavelengths, there was no camera survey of Venus from orbit comparable with the Mariner 9 and Viking orbiter surveys of Mars which had revealed ample evidence of aeolian activity on that world.

Wider reconnaissance of the Venusian surface was accomplished with radar measurements using large radio telescopes on Earth, and later by radar mapping of the northern polar regions of Venus by the Venera 15 and 16 spacecraft in the early 1980s. However, these techniques had spatial resolutions (1 $\sim$ 2 km) too poor to resolve dunes.

The next (and for the moment, latest) step was the near-global radar mapping at $\sim$120 m resolution by the NASA Magellan spacecraft in the early 1990s (Fig. 14.3). Despite the thick atmosphere which might a priori suggest aeolian features might be widespread, only a couple of areas of resolvable dunes were discovered on Venus in Magellan radar imaging (e.g., Greeley et al. 1992; Weitz et al. 1994;

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[1] Florensky et al. (1977) suggest on the basis of Venera 9 and 10 imaging that fines have been moved in the atmosphere, but there are no obvious bedforms.

R. D. Lorenz and J. R. Zimbelman, *Dune Worlds*, Springer Praxis Books,
DOI: 10.1007/978-3-540-89725-5_14, © Springer-Verlag Berlin Heidelberg 2014

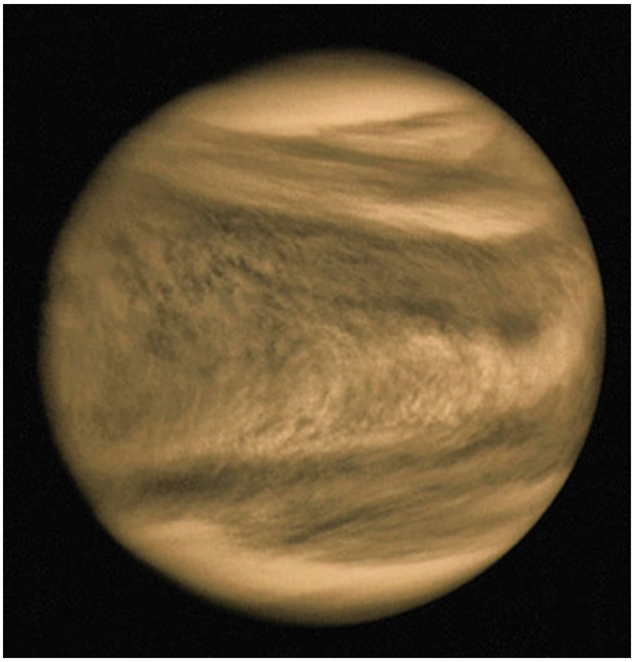

Fig. 14.1 Venus in ultraviolet light, observed in 1972 by Mariner 10. At visible wavelengths (like Titan) Venus appears nearly featureless because of its thick, cloudy atmosphere. *Credit* NASA

Greeley et al. 1995), although wind streaks and downwind dispersal of impact ejecta were observed in many locations, and some possible yardangs were also identified.

14.3 Venus Dunes

The two prominent dune fields identified on Venus are Algaonice (Fig. 14.4) and Fortuna-Meshkenet (Greeley et al. 1992) (Fig. 14.5). The Algaonice dunes at 25°S, 340°E cover some 1300 km^2 (about the same size as the Lencois Maranhenses dunefield in Brazil) at the end of the ejecta outflow channel from the impact crater of that name (the dunes themselves were subsequently formally named Menat Undae, although the Algaonice name seems to have been more widely used). The dunes are 0.5–5 km in length and are quite bright, likely because there are slip faces oriented towards the radar illumination, which was at an incidence of 35°.

The more northern dune field, Fortuna-Meshkenet lies at 67°N, 91°E in a valley between Ishtar Terra and Meshkenet Tessera (the dunes are formally named Al-Uzza Undae). The dunes are 0.5–10 km long, 0.2–0.5 km wide and spaced by an average of 0.5 km. They appear to be transverse dunes, in that there are several bright wind streaks visible in the region, which seem generally orthogonal to the dunes. Glints are not observed strongly on these dunes, although here the incidence angle of the radar observation was 22–25°.

Small dunes, however, might be much more widespread than the fields of resolved dunes above. In many areas where no resolvable dunes were detected, it was noted that the radar echo had a substantially different strength when the area was observed from one side versus another. One explanation of this radar asymmetry is that unresolved 'microdunes' may be present (Weitz et al. 1994; Kreslavsky and Vdovichenko 1998), wherein the asymmetry is due to shallow stoss slopes being prominent from one direction against the steeper slip faces seen from the other (Fig. 14.6). A possible additional factor in shaping the radar reflectivity of microdunes is that wind tunnel experiments (see later) show that in a sand of mixed composition, dense (and therefore radar-reflective) minerals such as pyrite or chromite become concentrated on the windward (stoss) side of the microdune (Greeley et al. 1991a).

A significant reason for the lack of observed dunes may be a planetwide paucity of sediment. The Venusian surface may have been completely resurfaced by lava flows about 500 Myr ago, and the kinetics of breakdown of basalt by the Venusian atmosphere is uncertain (and of course, other sand-generating processes such as freeze–thaw, glacial action or fluvial erosion do not occur on present-day Venus). Indeed, the dominant source of sand-sized sediment may be the ejecta from impact craters. Garvin (1990) calculated that impacts could produce enough fine-grained materials (<1 mm) to form at most a globally-averaged layer 1 m thick. Note that the Fortuna and Algaonice dunefields likely account for only about 1000 km^3 of sediment in total.

14.4 Aeolian Transport Under Venus Conditions: Experiments

The conditions on the surface of Venus are far from common terrestrial experience (although somewhat similar conditions are generated in certain industrial processes). The three major factors (surface gravitational acceleration at 8.79 ms^{-2} being not too different from the terrestrial 9.81 ms^{-2}) are the 90 bar pressure, the 750 K temperature, and the principal gas being CO$_2$. One reason these features were interpreted to be microdunes rather than ripples is that they have slip faces and form bedding planes (see Chap. 5) (Figs. 14.7 and 14.8).

Just above the saltation threshold, at 0.63 m/s, ~18 cm long dunes with slip faces developed. The wavelength became shorter as windspeed was increased, reaching 8 cm for a windspeed of 1.07 m/s. The dunes became more degraded at this point, with the slip faces tending to

Fig. 14.2 Surface image from Venera 14 (note the distortion—the image was scanned cylindrically, looking down at an oblique angle). Most of the surface here is platy lava, probably somewhat representative of the surface as a whole. Some other landing site images show more blocky terrain, and a few more patches of regolith, some of which may be fine enough to saltate. *Image* NASA NSSDC

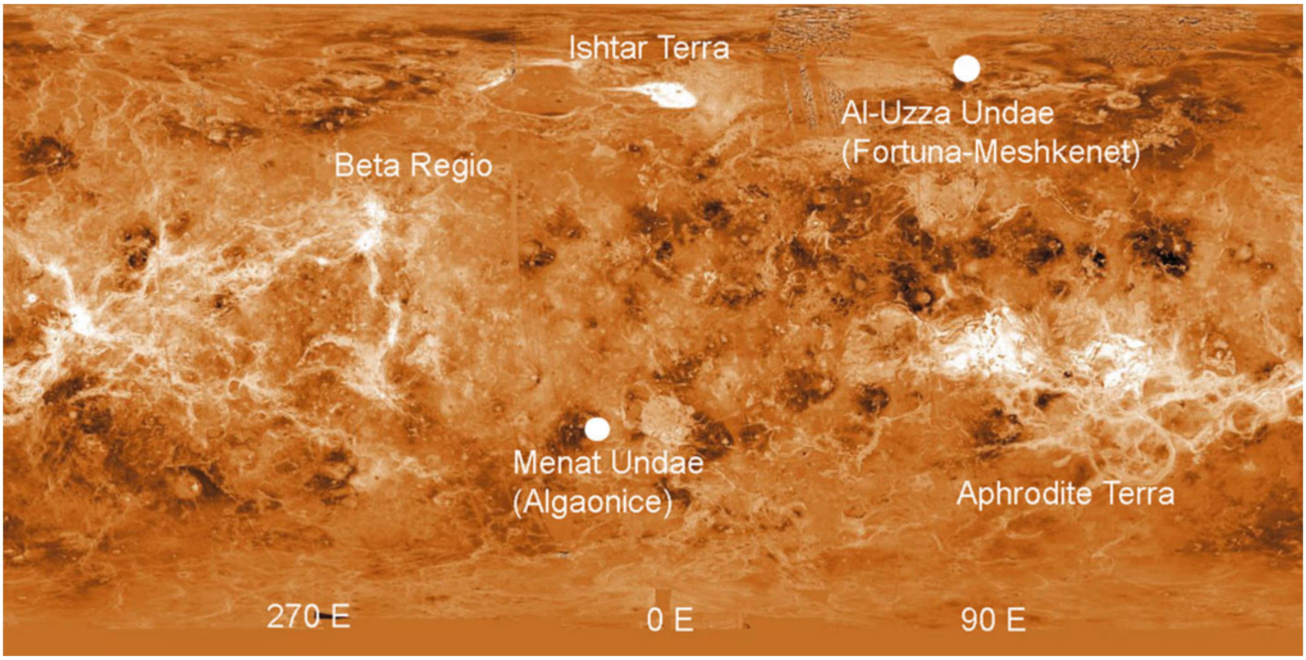

Fig. 14.3 A global mosaic of radar reflectivity measured by the Magellan spacecraft (cylindrical projection). The two major dunefields are marked with *circles*. *Image* NASA/JPL

disappear. Further increases in windspeed caused the 'waves' (they may not meet the definition of dunes any more) to grow longer, to 27 cm for a windspeed of 1.35 m/s. At 1.5 m/s and higher no dunes or waves were formed.

Greeley et al. suggest that at the high wind speeds, particles are able to jump across the lee of a wave onto another, such that there is no longer a clear separation between zones of deposition and removal of sand, and thus the slip faces are lost. The transfer of material from one structure to another resembles that in ripples, but the length of the saltation path may be rather higher (compared to the wavelength of the structures) than is the case for terrestrial ripples.

Greeley et al. also found that a run of 90 s of wind at 1.25 m/s removed as much material as a 5 h run at 0.6 m/s, near the threshold. Thus occasional 'high' winds (and 1 m/s winds had been measured at the Venusian surface by the Venera landers) could quickly obliterate small dune forms.

Although the Venus conditions replicated in the tunnel are of most interest in understanding bedforms on Venus itself, the range of pressures (and thus atmospheric density) that can be explored in the tunnel is useful in understanding aeolian processes more generally. Marshall and Greeley (1992) mapped out the parameter space of windspeed, atmospheric density and particle size, and found distinct regions of behavior.

Fig. 14.4 Magellan radar mosaic of the Algaonice dunefield. The dunes form a roughly V-arrangement in the center of the image, just above the circular pts. More obvious than the small, bright dunes themselves are some background volcanic features and wind streaks that permeate the region. *Credit* NASA/JPL

14.5 Aeolian Transport Under Venus Conditions: Theory

The formulae for predicting the windspeed threshold of motion of particles can of course be applied to Venus conditions and, unsurprisingly, given the much denser atmosphere than any other world, the required threshold windspeed is low (see Chap. 4). Experiments in the Venus wind tunnel largely bear out the predictions (see Fig. 14.9).

The thick atmosphere essentially forces the momentum of a grain to rapidly couple to that of the freestream airflow. White (1981) predicted the shape of Venusian saltation trajectories using relatively simple equations of motion, and found that for the likely 1–2 m/s surface winds, saltation trajectories would be likely to be only 2–8 mm long, with similar height. Under the assumption (common at the time) that ripple length scales might relate to the saltation length, White (1981) predicted that ripple wavelengths would be small—likely too small to affect radar remote sensing by Bragg scattering.

Perhaps counterintuitively, the saltation flux on Venus under dynamically similar conditions (same ratio of friction speed to threshold) would be 10 times less than on Earth (White 1981). This is largely because the threshold speeds are so low on Venus, and flux scales roughly as the third power of friction speed. Measurements in the Venus wind tunnel appear to support these predictions (Greeley et al. 1984a).

As discussed in Sect. 4.6, Claudin and Andreotti (2006) have advanced a scaling theory for the scale of an 'elementary' duneform, the wavelength at which a flat bed of sediment will destabilize most quickly. This scale λ is found to be $\lambda \sim 53(\rho_s/\rho_a)d$ wherein a particle of size d, density ρ_s is accelerated to a velocity approaching that of the wind in air of density ρ_a. In the Venus atmosphere, where ρ_a is quite large, this scale is rather small. Specifically, for particles of $\rho_s \sim 3000\ \text{kgm}^{-3}$ and $d \sim 0.1$ mm λ is predicted to be $\sim$22 cm. This is in rather good accord[2] with the experiments by Greeley in the Venus wind tunnel which ranged from 8 to 27 cm, depending on windspeed.

At present, little is known about the Venusian boundary layer and so the success of the theory that the size of dunes is limited by the boundary layer thickness cannot be assessed. However, if it is to hold, the $\sim$1 km wavelength of the Fortuna-Meshkenet dunes is the benchmark to be met.

14.6 Venus Winds

Venus has a thick, torrid atmosphere. Although winds at altitude sweep the cloudtops rather swiftly in the sense of the planet's rotation (much as there is a superrotating flow

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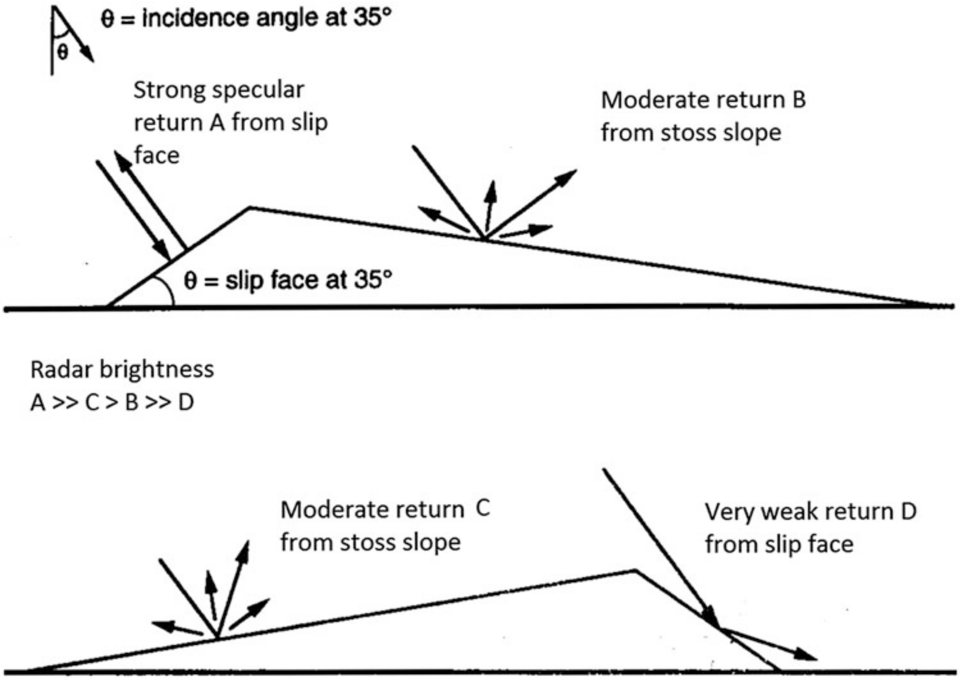
[2] One must be careful to avoid circular reasoning—the Venus wind tunnel data was one of the datapoints used to compute this relationship.

Fig. 14.5 Magellan radar mosaic of the Fortuna-Mesknet dunefield. These appear rather more extensive than the Algaonice dunes. Similar to those, the dunes appear to be transverse, orthogonal to the prominent windstreaks. *Credit* NASA/JPL

Fig. 14.6 The asymmetric slopes of microdunes lead to enhanced brightness when viewed from the slipface side than when viewed from the stoss side, an effect that is apparent even when the dunes themselves are too small to be resolved. See also Fig. 18.22



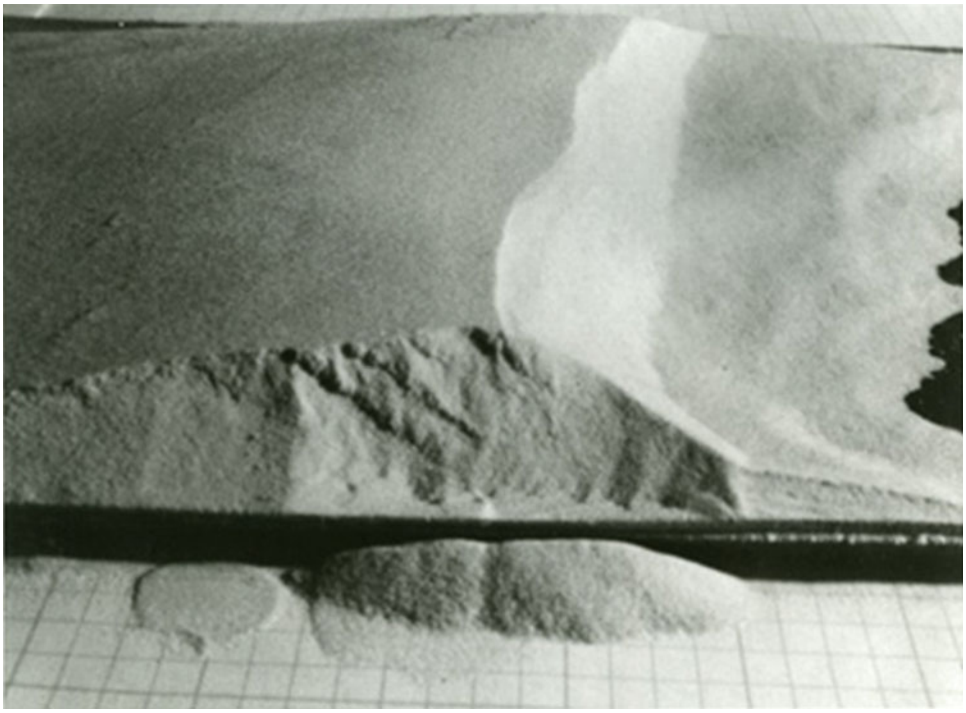


Fig. 14.7 Close-up view of a microdune formed in the Venus wind tunnel (see also Sect. 4.6). The bedding planes in the sand are visible, as is the steep slipface. *Image courtesy* of Ron Greeley

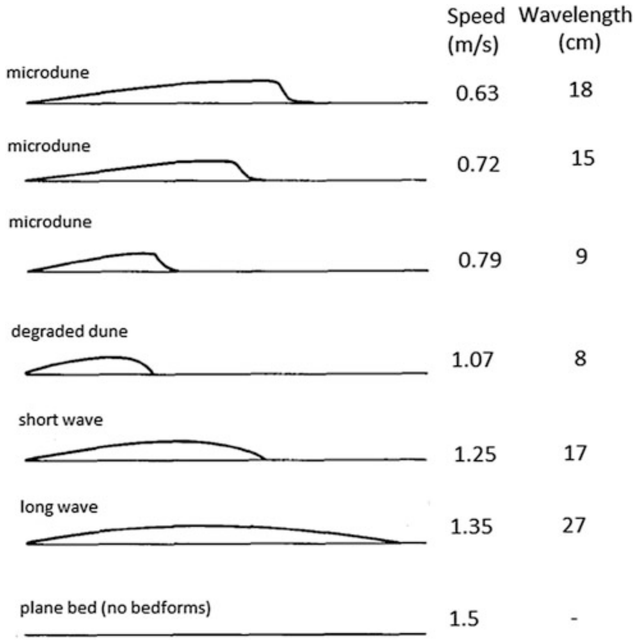


Fig. 14.8 Schematic (adapted from Greeley et al. 1984b) showing the progression of bedforms in the Venus wind tunnel at Venus densities as a function of speed (see also Fig. 4.18). At the lower windspeeds, sand is pushed up the stoss slopes and avalanches down to form a slipface. At higher speeds, the slipface disappears and a wave or ridge morphology appears, lengthening as windspeed increases. At higher winds yet, the waves become shallow and a plane surface results

in Titan's upper atmosphere), the near-surface winds are almost unknown except for a handful of radio tracking measurements of descent probes, some brief wind measurements on the surface, and indirect indication of winds such as the orientation of wind streaks.

Venus orbits the Sun in 224.7 terrestrial days, but because of the planet's slow retrograde rotation, a solar day (i.e., the time between successive solar noons, and thus the period with which atmospheric motions are forced) is 116.8 terrestrial days. The planet's orbital eccentricity is only 0.007, and the obliquity is 177.4° (i.e., a tilt of 2.6° with retrograde rotation), so seasons are effectively nonexistent. The cloud-tops can be tracked, especially at ultraviolet and infrared wavelengths, and the predominant motion is zonal, as noted above. The uneven deposition of sunlight drives a slow meridional (Hadley) circulation, and the angular momentum balance of this circulation is a key problem in Venus meteorology. Because the atmosphere is so massive, it has a large inertia or 'memory', which makes it rather challenging to simulate numerically.

Dobrovolskis (1993) suggests that slope winds on Venus may be significant, as on Mars, and that such winds may be strong enough to transport sand. This picture does seem to be borne out in part by the Magellan mapping of some 5700 wind streaks (Greeley et al. 1995) which show a preference in the downhill direction where slopes are observed (about 20 % of the total being biased downhill), even though the

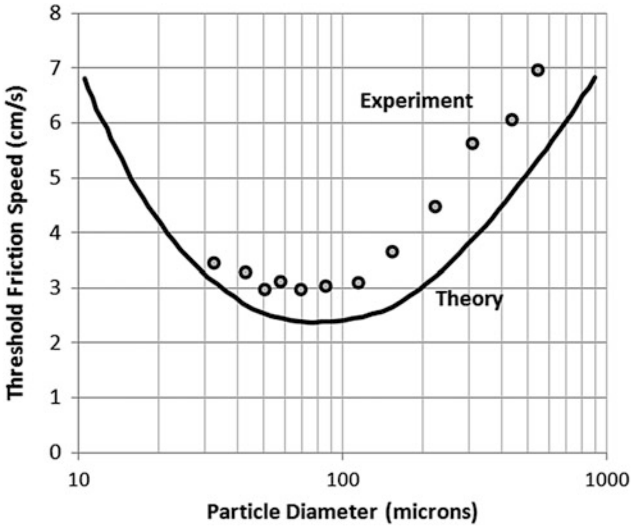


Fig. 14.9 Wind tunnel data for Venus conditions (gravity is 'faked' by using lower density rock, although the effect is in any case small) showing the optimum size for saltation. The experiments suggest a slightly higher threshold than theory would predict. This friction speed is an order of magnitude lower than that required on Earth. Data from Greeley and Iverson (1987)

slopes themselves are typically only ~0.3°. They also argue that a Hadley-type flow may control many of the wind directions inferred from streaks, although their maps of streak orientation do not make this obvious. Most likely local terrain may modify directions substantially.

There are sadly very few surface windspeed measurements, only those by Venera 9 and 10 in 1976. These carried cup anemometers able to operate at 500 °C. The Venera 9 wind record spans 49 min (Avduevsky et al., 1977) and that of Venera 10 only 90 s, sampled at a 0.4 Hz frequency with a resolution of the order of ~0.2 m/s. The Venera 9 and 10 records have been characterized as having a means of 0.4 and 0.9 m/s respectively, with standard deviations of 0.1 and 0.15 m/s (Golitsyn 1978). Surface winds were also estimated from the intensity of sounds recorded by the Groza microphone on Venera 13 and 14 to be in a similar range (Ksanfomality et al. 1983). These data do seem to show winds within a factor of 2 or so of the saltation threshold, even for a small number of observations, so aeolian transport may be common. However, more data are sorely needed.

14.7 Venus Sand

The expectation, given that Venus' relatively low population of craters suggests it has been resurfaced—principally by volcanism—is to give an effective surface age of ~500 Myr. Whether that resurfacing was a global cataclysm ~500 Myr ago, or was a more protracted process that yields this effective age is still under debate, but there seems little doubt that the Venusian surface is dominated by basalt. Without liquid water on the surface, more evolved igneous rocks are not produced (although perhaps outcrops of such, formed early in Venus' history, may be present).

In the absence of fluvial processes (or glacial abrasion, or freeze–thaw), it is hard to imagine how to make much sand. Similarly, the high atmospheric pressure on Venus prevents gas in magmas from expanding dramatically to produce Strombolian eruptions that erupt a lot of fine ash—most of the lava will have simply emerged from the ground and flowed. Some chemical weathering processes may produce some fines, and impact ejecta also produces fine particles (dark parabolic haloes around some impact craters may be radar-dark because they are made of smooth deposits of fine-grained material—these appear around the apparently youngest craters).

Regardless of how sand may be produced, there are questions about how materials behave under unfamiliar conditions (questions much like those which confront Titan). Specifically, is basalt at 500 °C hard enough to behave as sand?

Marshall et al. (1991) studied the adhesion of basalt particles at a range of temperatures, noting that rocks may be appreciably softer at Venus surface temperatures. A small jet of air, pulsed by a valve at roughly once a second, was used to propel ~3 mm angular particles of rock at a polished target slab at known speeds inside a chamber.

They found that at temperatures below 440 K, abrasion occurred as expected. Results were highly variable between 440 and 570 K: above 570 K particles almost always accreted (i.e., welded themselves onto the target). This adhesion threshold of about 500 K is roughly 40 % of the melting temperature and is higher than temperatures even on Venus' highest coolest spot (Maxwell Montes, ~650 K) and so grain adhesion may well be an important aspect of aeolian processes on Venus.

14.8 Future Exploration of Venus

Post-Magellan exploration of Venus has been dominated by atmospheric studies from two missions, Venus Express and Akatsuki. Venus Express is a mission launched by the European Space Agency in 2005, and has been operating at Venus since 2006. However, its instrumentation (with the exception of a handful of isolated radio science and infrared observations) does not address the surface. Akatsuki (formerly 'Venus Climate Orbiter' or 'Planet-C') was launched successfully in 2010, but suffered an engine failure during its attempted Venus orbit insertion (which may be re-attempted in 2015).

Future Venus exploration (Bullock et al. 2009) is likely to include platforms able to return image data on spatial scales 1–2 orders of magnitude better than Magellan, employing either higher-resolution (possibly interferometric) radar from orbit, or near-infrared imaging from a balloon near the surface. Such future missions will likely reveal many more duneforms than are presently known, and would likely reinvigorate aeolian studies on Venus.