The Tallest Dunes in the Solar System ? Dune Heights on Earth, Mars, Titan and Venus

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Introduction

We initiated this study, to consider what are the tallest dunes on each planetary body, largely out of curiosity given that a somewhat unified perspective on dune morphology and its relationship to planetary circumstances has emerged [1,2]. However, the exercise raises interesting questions about sand supply and dune growth and ultimate limits on dune size. The search for a superlative is always a work in progress: we have attempted only a preliminary survey here and we welcome suggestions of yet larger dunes.

Mars

While Mars is often thought to be dune-covered (an impression reinforced by ripples and drifts commonly seen by rovers and landers), in fact the area coverage fraction of Mars by dunes is rather small, with most dunes, apart from the circumpolar Olympia Undae, confined in sand traps such as crater basins [3]. Dunes in some locations have been measured via stereo imaging, or in a few cases by laser altimetry, to be ~200m high, with most dunes only a few tens of meters tall (e.g. [3,4]). A prominent exception (Fig.1) is the large crescent-shaped dune in Russell Crater, which stereo data (Fig.2) shows to be 450m – 600m tall, depending on the assumed base level (a challenge common to estimating dune heights elsewhere).

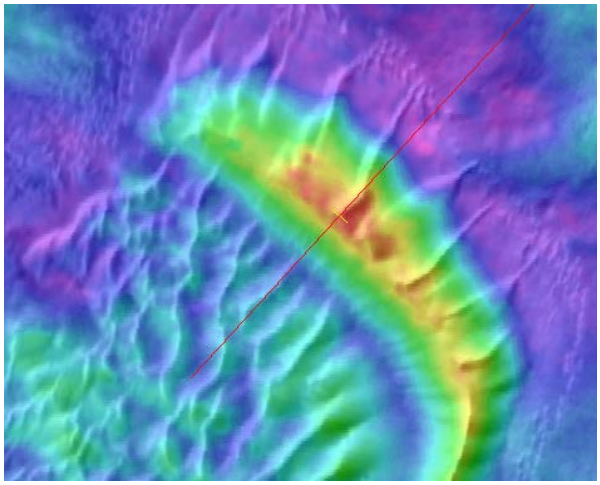

Figure 1. The tallest dune on Mars? A DEM (H2247_0000_DT4) of the large dune in Russell Crater acquired by HRSC superpimposed on a THEMIS daytime IR map. The red line denotes the profile in figure 2. Note that the base level is different on the two sides of the dune.

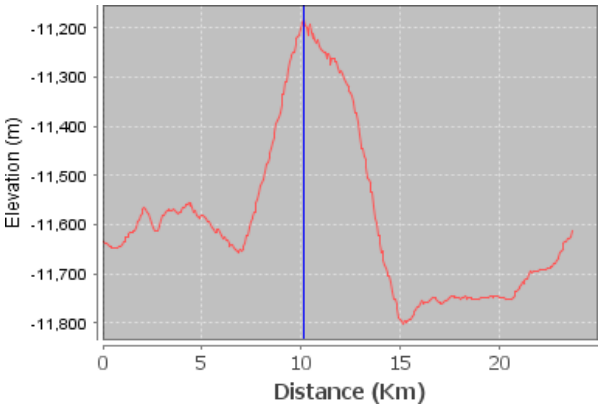

Figure 2. Topographic profile from figure 1, indicating a height of at least ~450m.

Titan

Titan is in fact the most dune-covered planetary body known [1,2] (roughly 15% of its land area is dune-covered, compared with ~2% for Earth), and the discovery of its giant equatorial fields of linear dunes was enabled by their large size, making them recognizable even in the rather coarse (~350m+) resolution radar data from Cassini [4]. Radarclinometry [5], altimetry, and near-infrared photoclinometry have been applied to Titan's dunes, but the tallest appear to be the first ones recognized, in the Belet sand sea. These have heights determined to be 100-175m tall.

Venus

Venus has very few dunes resolvable in Magellan data. Only recently [6] has one height determination been made, using radarclinometric methods. That sudy suggested the Fortuna-Meshkenet dunes (Al-Uzza Undae) may have heights of 40-80m.

Earth

The dunes on our own planet are likely to be the most contentious in terms of superlative claims: we report here only claims in the literature. As for Mars and elsewhere, it is important to distinguish between large free-standing dunes, dunes that mantle bedrock topography, and dunes that form large accumulations of sand (e.g. Great Sand Dunes, Colorado), which have a thickness of 100-180 m [7].

Dunes (mostly of complex linear form) with a height of 150 – 200 m are widespread in sand seas in Namibia and Arabia. Much larger dunes (height > 200 m) are commonly of complex star or reversing form and ap-

pear to be associated with areas of multi-directional and/or opposed wind directions, as well as topographic obstacles. Such dunes are common in the Lut Sand Sea of Iran [8], Grand Erg Oriental, Issaouane-N-Irarraren, and other northern Saharan sand seas.

Dunes with a height of 300 – 400 m are known from the Sossus Vlei area of the Namib Sand Sea [9]; the Badain Jaran sand sea of China [10] and the small Erg Guidi and Erg Tihodaine in the central Sahara [11].

Dunes exceeding 400 m height have been identified in the Badain Jaran [10]; the Grand Erg Oriental [12] and Issaouane-N-Irarraren of Algeria [11]. These appear to be the tallest dunes reported on Earth: the global topography datasets from SRTM and ASTER would now permit a systematic survey.

Implications:

It has been suggested [14] that dunes may grow until they reach a height of ~H/12, where H is the thickness of the planetary boundary layer (PBL): coincidentally, the dune spacing then tends to ~H. At this point, the flow over the dune becomes constricted (much like at an obstacle in shallow water) and the shear at the crest suppresses further growth. This concept appears to describe the Namib sand sea, where the PBL grows from ~300m near the coast to ~3km inland: it is possible that the PBL thickness may be higher in continental interiors, especially at the somewhat high elevations of the Badain Jaran . This PBL thickness argument appears to be consistent with dune heights on Titan [15]. The Venus PBL has not been characterized – it may be that dune heights can at least establish a lower limit on its depth. On Mars, the PBL can be 10km thick, allowing (in principle) dunes some ~1km high, but none near this size are observed. Presumably either there is simply not enough sand, or the winds have not operated in a constant regime for long enough to allow sand accumulation at this scale. On Earth, and perhaps Titan too [16], large (100m+) dunes retain some memory of the last Croll-Milankovich climate cycle: 400m+ dunes on Mars require longer than a ~100kyr cyle to grow.

Conclusions: Mars appears to have the tallest dune known (~450-600m), consistent with it also having the thickest PBL, although most Martian dunes are much smaller, either due to local PBL suppression [17], or due to incomplete growth since climate cycles established the present wind regime, or to limited sand supply. The largest terrestrial dunes appear to be about 400m tall. Titan's dunes appear to have a mature pattern, with few dislocations, suggesting they may have reached a limiting height of ~175m, although the Titan heights have not been widely-surveyed. Venus' sparse dunes have only been measured to be 40-80m: in all probability, the same issue that limits the number of dunes on Venus (restricted sand supply) may also limit their height. The simple-sounding question posed in the title of this abstract illuminates interesting differences between dune worlds.

References :[1] Fenton, L. K., et al., Extraterrestrial Aeolian Landscapes, in Treatise on Geomorphology, pp.287-312 in vol. 11 Aeolian Geomorphology, pp, edited by J. Shroder et al., Elsevier, 2013 [2] Lorenz, R. and J. Zimbelman, Dune Worlds, Springer 2014 [3] Hayward, R. K., L. K. Fenton, and T. N. Titus (2014), Mars Global Digital Dune Database (MGD3): Global dune distribution and wind pattern observations, Icarus, 230, 38–46, [4] Bourke, M. C., et al. (2006), A comparison of methods used to estimate the height of sand dunes on Mars, Geomorphology, 81(3-4), 440–452 [5] Lorenz, R. D. et al., The Sand Seas of Titan : Cassini RADAR observations of Longitudinal Dunes, Science, 312, 724-727, 2006 [6] Neish, C. D. et al., Radarclinometry of the sand seas of Namibia and Saturn's Moon Titan, Icarus, 208, 385-394, 2011 [7] Lorenz, this meeting [8] Andrews, S., 1981. Sedimentology of Great Sand Dunes, Colorado. In: F.P. Ethridge, R.M. Flores (Eds.), Recent and Ancient Non Marine Depositional Environments: models for exploration. The Society of Economic Paleontologists and Mineralogists, Tulsa, OK, pp. 279-291. [9] Gabriel, A., 1938. The Southern Lut and Iranian Baluchistan. The Geographical Journal, 92(3), 193-208. [10] Lancaster, N., 1989. The Namib Sand Sea: Dune forms, processes, and sediments. A.A. Balkema, Rotterdam. [11] Yang, X. et al. , 2011. Formation of the highest sand dunes on Earth. Geomorphology, 135, 108-116. [12] Wilson, I.G., 1973. Ergs. Sedimentary Geology, 10, 77-106. [13] Mainguet, M., Chemin, M.-C., 1984. Les dunes pyramidales du Grand Erg Oriental. Travaux de l'Institut de Géographie de Reims, 59-60, 49-60. [14] Andreotti, B., et al (2009), Giant aeolian dune size determined by the average depth of the atmospheric boundary layer., *Nature*, *457*(7233), 1120–3 [15] Lorenz, R. D.,et al (2010), A 3km atmospheric boundary layer on Titan indicated by dune spacing and Huygens data, *Icarus*, *205*(2), 719–721 [15] Hinson, D. P. et al., (2008), The depth of the convective boundary layer on Mars, *Icarus*, *198*(1), 57–66, , [16] Ewing, R. C., Hayes, A. G., & Lucas, A. (2015). Sand dune patterns on Titan controlled by long-term climate cycles. Nature Geoscience, 8(1), 15-19. [17] Tyler, D., and J. R. Barnes (2013), Mesoscale Modeling of the Circulation in the Gale Crater Region : An Investigation into the Complex Forcing of Convective Boundary Layer Depths, Mars, 8, 58–77

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