HUYGENS BOUNDARY LAYER DATA EXPLAIN THE ~3KM SPACING OF TITAN'S DUNES

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Abstract: Titan's linear dunes[1] resemble in morphology, size and spacing (1-3km) those seen on Earth. Although gravity, atmospheric density and sand composition are very different on these two worlds, this coincident size scale suggests that the controlling parameter limiting the growth of giant dunes, namely the boundary layer thickness, is similar. We show[2] that a ~3km boundary layer thickness is supported by Huygens descent data and is consistent with results from Global Circulation Models.

1. Introduction : About 20% of Saturn's moon Titan is covered by giant organic sand dunes, found almost exclusively in a band at the equator bounded by +/- 30^o latitude[3]. The dunes were discovered in Cassini Radar images, and appear morphologically identical[4], and indeed rather similar in size, to large linear dunes on Earth, such as those in the Namib or Arabian deserts. An initial survey[2] suggested typical lengths of 30-50km and a width of about 1km and spacing of 1-3km: radarclinometry indicates their height to be about 150m.

Recent work[5,6] has shown that there are two fundamental scaling parameters that control the sizeof dunes. The first is the so-called saturation length, i.e. the length over which the sediment flux relaxes towards its equilibrium value. This defines a scale of 'elementary dunes', of size ~53(ρ_s/ρ_f)d can grow and coalesce to form progressively larger dunes, but the growth rate asymptotically declines as the dune length scale approaches the second scale, the thickness of the atmospheric boundary layer. The static stability at the top of this layer provides a 'capping' function, much as does the free surface of the water for subaqueous dunes, and limits the dune growth. On Earth, elementary dunes have a scale of ~20m, whereas on Titan (ρ_f ~5.4kg/m^3) the corresponding size (assuming organic 'sand' with ρ_s ~800kg/m^3, d~200μm is ~1.5m, far below the resolution of Cassini instrumentation. The dunes observed by Cassini are therefore 'giant' dunes, formed by the growth or aggregation of elementary bedforms.

In the absence of direct measurement of the boundary layer , an effective proxy is ~$\delta\Theta/\gamma$, where $\delta\Theta$ is the characteristic (seasonal) variation in potential temperature near the ground, and γ is the potential temperature lapse rate $d\Theta/dz$. This correlation appears to hold for over an order of magnitude of terrestrial dune sizes from coastal dunes of ~300m to giant continental dunes of ~3.5km, and the arguments are based on completely general fluid dynamics considerations. Note that while the boundary layer thickness controls the limiting size of giant dunes, and also controls the size of helical roll vortices sometimes rendered visible by condensation forming long roll clouds, it should not be inferred that roll vortices necessarily form the dunes[7]. The two observable effects represent a common cause, not cause and effect.

2. Observations of Dune Spacing We measured[1] dune spacing in Cassini RADAR images such as figure 1 and found spacing spacing to be rather uniform 2.7-3.2km. Other studies have found spacings of 2.1km[8], and in one case[9] 1-2km.

There is no large-scale regional trend, nor an obvious variation with latitude. Since dune growth is limited by the thickness of the boundary layer[5], this suggests that the Titan layer must have been 3km or more when the dunes were formed.

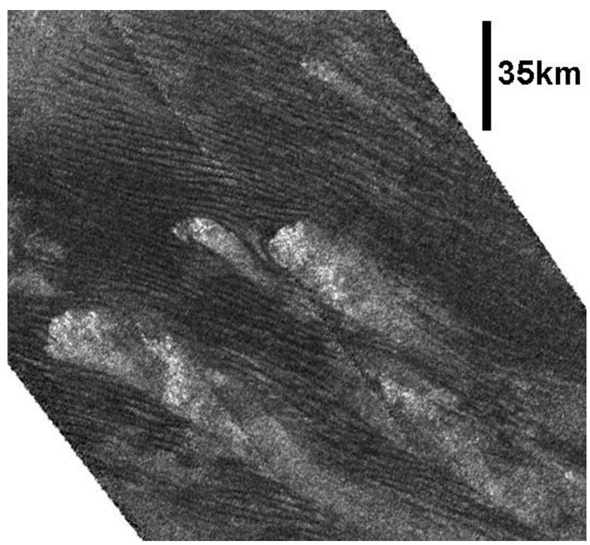

Figure 1. A section of the T41 SAR swath, south of the Huygens landing site, showing typical dune spacing. Although bright topographic obstacles can interrupt the dunefield, the characteristic ~3km spacing is evident.

3. Huygens Probe Boundary Layer Profile A single detailed profile of Titan's atmosphere was obtained by Huygens[10]. This profile occurred at around 9am local solar time, near 10^oS, 192^oW. A uniform region of potential temperature Θ between the surface and 300m altitude was initially interpreted[11] as the thickness of a weakly convecting planetary boundary layer. However, Θ is also near-constant[12] over the regions 0.5-0.7 km and 1-2 km, suggesting that an original 2km boundary layer may have been modified by subsequent surface evaporation or morning heating[2] to produce the lower steps in Θ. These, and the 3km inflection in the potential temperature profile show in figure 2 are likely remnants of the boundary layer formed in previous days, the so-called 'residual layer', while the convective boundary layer developing on landing day defines the most obvious 300m layer.

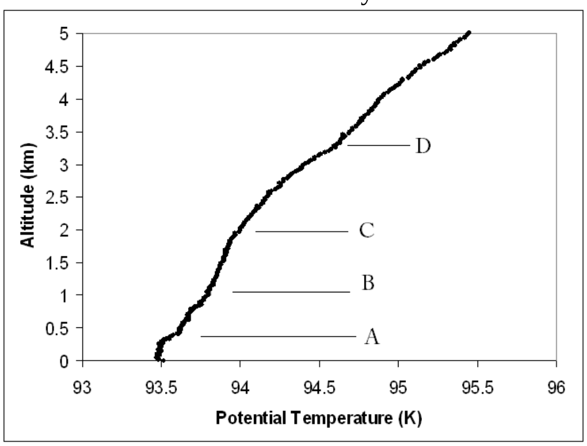

Figure 2. The near-surface potential temperature profile derived from Huygens data (Tokano et al., 2006) The constant Θ region 0-300m identified in that paper as the boundary layer is clearly seen (A); two additional steps in the profile at ~0.9km and ~2km (B,C) were suggested by Griffith et al. (2008) as suggesting a rather thicker, older boundary layer (C) had been modified subsequently (A,B). An additional inflection is seen at ~3.3km (D).

4. Global Circulation Model Predictions and Implications for Titan The boundary layer was estimated[13] pre-Cassini at ~700m. We can also use the heuristic $H \sim \Delta\Theta/\gamma$ as a proxy for the boundary layer thickness and dune spacing. Further, in the absence of additional data, we must assume that the potential temperature variation can be equated to the thermodynamic temperature variation (i.e. $\delta\Theta \sim \delta T$, which appears[5] correct to within ~20% for all the locations studied on Earth. For the relevant γ, we adopt the ~0.5 K/km seen in the lowermost few km of the Huygens profile (figure 2).

As discussed elsewhere[2] we may estimate the low-latitude surface temperature variation[14] at 2-4K with the boundary layer temperatures having δT at 1~2K. The hydrocarbon lake scenario, with an appropriately low albedo but higher thermal inertia than dune sands has similarly a surface low-latitude temperature swing of ~3K (note that latent heat effects of lake evaporation were not modeled, so in fact this scenario is a reasonable approximation of a sand sea, although it has a drag coefficient that may be small compared with that appropriate for a dune-covered terrain).

Taking these results together, it seems that δT of the order of 1-2K is not unreasonable, and thus $\delta T/\gamma$ of ~2-4km would be predicted, which is in encouraging agreement with the observed dune spacing, and the boundary layer thickness suggested by Huygens.

5. Conclusions Titan's dunes prove to be an important diagnostic of that world's atmosphere. It has already been shown[15,16] that the latitudinal extent of the dunes seems to be consistent with the transport of methane humidity away from low latitudes, and the prograde (West to East) sand transport implied by the dune morphology[1,3,4] poses some interesting challenges to circulation models, which expect low-latitude near-surface winds to be generally E-W.

We note in closing that there is much to be learned by studying Titan's landscape and atmosphere : the complexity of the Huygens profile suggests that meteorological characterization of the boundary layer and its variations will be important and interesting. Further, the small drag length in Titan's thick atmosphere and resultant elementary dune size of ~1.5m suggests that imaging of resolution ~0.1m will be needed on future missions to adequately characterize the aeolian geomorphology on Titan.

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