Timescales of Dune Obliteration and Repair on Titan

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Abstract:
A process perspective is given on Titan's dunes, by integrating model rates of Aeolian sand transport with modeled and observed rates of pluvial activity on Titan. Heavy low-latitude rainfall likely occurs at ~100-1000yr intervals, but pluvial sediment transport is generally exceeded by Aeolian by a factor of 5-500 if Global Circulation Model winds are adopted and the threshold wind speed is 0.9-1.1m/s.

Introduction:

We find massive seas of sand [1] on Titan. We lack observational data of sufficient resolution to characterize the activity associated with these predominantly linear dunes, although the maintenance of apparently sand-free interdunes implies present-day or at least recent Aeolian transport.

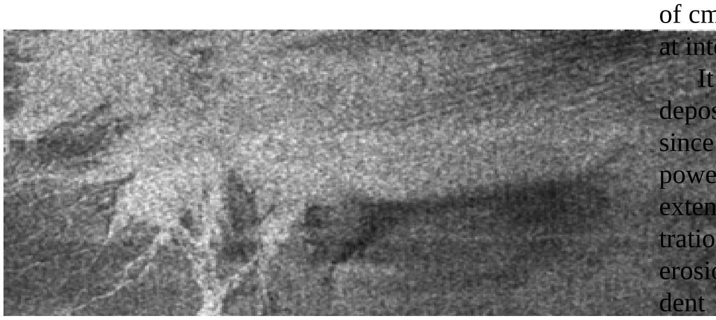

Figure 1. 250kmx150km section of T3 radar image : dunes at right are superposed on bright outwash plain from Elivagar Flumina branching river system. Dunes form in the eastern part away from the rivers - does this imply that rivers outcompete dunes at the left (yes - see discussion on next page).

Although on Mars there is now observational data of sufficient fidelity and resolution [2] to identify ripples have been superposed by small (few m diameter) impact craters, as well as of course many craters that have been superposed by ripples and dunes, on Titan we only have examples of the latter. Atmospheric shielding on Titan essentially eliminates small craters, so the few (~50) craters known are large and thus old. However, while Aeolian and impact craters compete on Mars, fluvial activity is essentially zero in the present-day, whereas Titan is hydrologically-active. Thus dunes compete against rain and rivers on that world. While Aeolian change has not (and likely cannot) be detected with Cassini, the widespread presence of apparently active/unmodified dunes, and the observation of clouds and rain, allow quantification of process rates.

Fluvial Processes:

Cassini has observed two events of surface darkening associated with cloud activity; these are best interpreted as rainfall events. In 2004 Arrakis Planitia (34,000km^2, 80°S) and in 2010 Concordia Regio (510,000km^2, 20°S). Together, these represent ~0.7% of Titan's surface, in 6 years. Crudely, 100% of the surface would then be rained on in 6*100/0.7~860 years [3]. These rates are reassuringly consistent with the notion that ~1cm per Earth year of rain falls on average [4], but that this average reflects infrequent events that correspond to ~1m of rainfall, and that rain occurs preferentially (x10) at the poles, thus in the low latitudes at which dunes are found, there may be ~10s of cm to meters of rainfall in an event a few hours long at intervals of some centuries.

It is of course not a given that even 1m of rainfall deposited in a short time can destroy a duneform : since individual drops fall rather slowly, their erosive power by splash transport is quite modest [4]. The extent to which rain may be simply absorbed by infiltration, versus runoff and thus sheet flow and gully erosion, is essentially unknown (and is likely dependent on a variety of factors such as cementation by solute transport, as is the case on Earth).

By terrestrial analogy, we might consider that on average, pluvial liquid may transport some fraction (say 1-10%) of its volume of loose sediment. If this is the case, then we can simply equate the implied average destructive pluvial effect (~0.01-0.1cm/yr) to the average sand transport rate in order to allow dunes to be preserved.

Sand Transport:

A key difficulty in estimating bulk sand transport rates is that sand transport usually doesn't happen : the saltation threshold is higher than the average winds. Thus the sand transport is a convolution of a skewed windspeed distribution (e.g.[5]) and a windspeed-transport relationship that is typically assumed to be proportional to the cube of windspeed when that speed is above some threshold.

Tokano [6] shows the probability density distribution of windspeeds (noting that the curves for westerly and easterly winds cross - although winds are generally easterly, the fastest winds are more likely to be westerlies (especially around the equinox season): this solves [7] the apparent paradox that low-latitude zonal winds should be predominantly east-west, yet dunes are observed invariably suggesting west-east transport [8]. Approximately, winds of 1.0m/s are encountered ~0.2% of the time, while 1.2m/s are seen only 0.02%, and 1.4m/s only 0.002%, etc. (these values being referred to 300m altitude.) Essentially, this high-speed tail of the probability distribution is exponential, each 0.2 m/s increment causing an order of magnitude drop in relative frequency.

The sand volume transport rate (m^3/m/s) is typically written [5,6] in the form

$q_v \sim 2.6(\rho_a/\rho_d g)(u_* - u_{*t})(u_* + u_{*t})^2$

where u* is the friction speed (assumed to be ~1/25 of the windspeed at 300m.) Note that this expression is roughly linear for winds just above the threshold, but roughly cubic for winds well above the threshold.

Thus if we consider a threshold (300m) speed of 0.9m/s, and add up the contributions of the different fractions of time at different speeds, we find that the major contribution is from winds at 1m/s - the cubic dependence of sand transport due to faster winds is less significant than the exponential rarity of such winds. It therefore follows that the overall (annual-average) sand transport rate is acutely dependent on the choice of threshold. Some simple numerical trials indicate a transport rate, given the wind probabilities above, of ~5cm/yr for a threshold of 0.9 m/s, falling to ~1cm/yr for a threshold of 1.0 m/s, and about half that for a threshold of 1.1 m/s.

The optimum threshold friction speed u_{*t} estimated from the 'classical' empirical expressions [5] is ~4cm/s for 250um particles, or freestream speed of 1.0 m/s. Clearly if cohesion is higher on Titan than Earth, then the threshold would be higher; similarly, pushing the particle size by a factor of two in either direction would increase the threshold by about 20%. A threshold of 1.0m/s seems reasonable. It should also be noted that thresholds of >0.9m/s are required for the net sand transport to be eastwards in Tokano's model, and <1.4m/s to avoid forming transverse, rather than longitudinal, dunes.

Adopting a range of 0.9-1.1 m/s indicates overall transport rates are ~5 to ~500 times higher than the fluvial transports estimated previously, which would be consistent with Aeolian transport generally dominating. If, on the other hand, the threshold were e.g. 1.3 m/s, the transport is ~0.6mm/yr which is likely less than fluvial.

Dune Repair:

The foregoing discussion establishes the likely overall dominance of Aeolian processes. However, pluvial/fluvial effects are episodic on ~1000yr timescales, while sand movement likely occurs seasonally (i.e. every 15 years). If local flow on a dune carves a ~1m deep gully, we might crudely expect it to repair on timescales of ~100 years.

On the other hand, if a dune of height H is washed out (creating a gap H wide) by a river, it can grow back in a timescale $\sim H^2/q_v$: for H=10-100m, this implies timescales of 10kyr-1Myr. Thus a where a streambed width d that can wash 1% of its liquid volume flow away, that drains a watershed of area A, a 1m rainfall can remove .01A/d of material. If we consider Elivagar Flumina (fig.1) with $A \sim 10^5 km^2$ and d~100km, then the sediment that can be removed by a single typical rainfall event corresponds to a 100m high, 100m wide dune. Thus every time it rains here (1kyr) the dunes are destroyed, but take much longer to grow back, and thus the area (especially to the West) remains dune-free. The situation seems rather similar to, for example, the dune-free Sossusvlei gap in the Namib sand sea due to the ephemeral Tsauchab river.

Conclusions :

Relative rates of fluvial/pluvial and Aeolian transport have been considered. The widespread presence of largely unmodified dunes is consistent with continual Aeolian transport and low rain rates, but in areas where rainfall is concentrated by terrain, dunes may be obliterated faster than they can reform. These processes are consistent with GCM winds for saltation thresholds of 0.9-1.1m/s.

Acknowledgement :

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References

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