AN EXOGENIC SOURCE FOR TITAN'S DUNE PARTICLES?

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Motivation. A key goal of NASA's Dragonfly mission is to explore the nature and origin of Titan's organic-rich dunes [1]. A common assumption is that the dune particles are endogenic; they formed in Titan's atmosphere as dark micron-sized bodies, grew on the surface to sizes of a few hundred microns, broke free of the ground ice, and then experienced saltation like terrestrial sand [2]. This scenario has been used to explain Titan's equatorial dunes, which have a net volume of ~1.5 to 4.5 × 10^5 km^3 (i.e., equivalent of a $D >$ 70 km diameter body) [3]. Possible problems are that several steps in making such concretions have yet to be verified, and it is unclear whether ice-organics-Tholin mixtures are strong enough to saltate like sand [4].

Here we postulate that Titan's dune particles may be comet materials derived from (i) irregular satellite debris and (ii) KBOs striking Titan at early times. Comet particles are the right size for saltation in Titan's atmosphere (~200 μm) [5], they are stronger than ice [e.g., 4], and they may be a better match with dune field spectra than organic-rich regions (see below) [6]. Large quantities of dark particles are also found on several Titan-sized worlds without atmospheres (e.g., Callisto; oldest regions of Ganymede) [e.g., 7].

Using a new collisional and dynamical model of the primordial Kuiper belt [8], we have quantified the volume of comet material delivered to Titan over time. If much of this material stays near the surface, it can provide a plausible source for Titan's dune particles.

Nature of Comet Particles. Much of our knowledge about comet particles comes from meteoroids. Models that can reproduce IRAS observations of the Zodiacal cloud show most meteoroids are particles from disrupted Jupiter-family comets [9]. These bodies evolve toward the Sun via Poynting-Robertson (P-R) drag, and many strike spacecraft and the Earth. Small craters on the Long Duration Exposure Facility (LDEF) [5] and particles found in Antarctic water wells [10] both indicate much of the mass of meteoroids is in ~200 μm particles. The particles themselves are organic-rich and have CI-like carbonaceous chondrite (CC) compositions [11]. Some are also strong enough to survive passage through Earth's atmosphere. These traits mean comet particles could plausibly survive their passage to Titan's surface.

Sources for Comet Particles at Titan. Our next step is to quantify how much comet material can be delivered to Titan. This means simulating outer solar system evolution at early times. Here we apply a version of the so-called "Nice model", where the giant planets started on orbits between 5 and 20 au [12]. Beyond the initial orbit of Neptune, we assume a primordial Kuiper belt (PKB) existed between 24-30 au that had ~30 Earth masses, most in the form of $D \sim$ 100 km diameter bodies. Using a collisional and dynamical evolution model, we tracked the evolution of the PKB [8]. Our results suggest it lasted for a few tens of Myr after the dissipation of the solar nebula. At that time, Neptune entered the PKB and migrated across it, pushing ~99.9% of the PKB's population onto giant planet-crossing orbits. This "destabilized population" triggered a giant planet instability that led to our system of planets and small bodies [e.g., 12]. From here, our Titan story branches into two parts.

Particles from Irregular Satellites. In the first part, post-instability encounters between the giant planets occurred while numerous escaped KBOs were nearby. This allowed many of them to become trapped onto stable orbits where the irregular satellites of the giant planets are found today [13]. From there, these populations, which were similar in size to Jupiter's Trojans, experienced extensive collisional evolution, with nearly all of the mass pulverized into small particles [14]. This result explains why the irregular satellites of all giant planets have extremely shallow size distributions.

Using a P-R drag model [7], we tracked what happened to this material in the Saturn system. We found most debris ends up on Iapetus (15%) and Titan (10%), while relatively little goes to the inner satellites of Saturn (1%). The net volume delivered to Titan in non-ice materials was ~10^6 km^3, ~2-4 times more than Titan's dunes. In the Jupiter system, a comparable volume was delivered to Callisto and Ganymede, possibly explaining why their oldest terrains are covered by dark particles with CC-like spectra [7].

Particles from Impacts. In the second part, we calculated what happened to the rest of the PKB's destabilized population [8]. These bodies are the main source of bombardment for the giant planet satellites over time, with long-lived members residing in the scattered disk that resupplies the Jupiter-family comet and Centaur populations. We found all giant planet satellites were hit early on by objects much larger than suggested by their basin/crater records. These large impacts resurfaced, shattered or disrupted the satellites (though most ejected material was readily reaccreted).

Titan was struck by many tens of $D >$ 100 km bodies over its first few hundreds of Myr (as was Ganymede and Callisto). Collectively, these KBOs delivered many times the volume of Titan's dunes (**Fig. 1**).

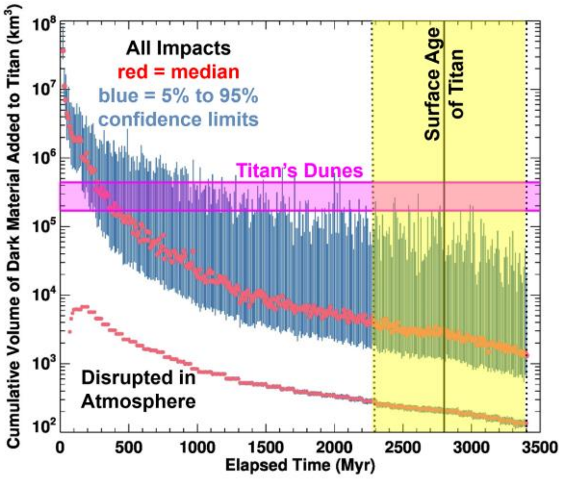

Fig. 1. *Cumulative volume of dark material added to Titan by impacts. Purple curves show volume of dunes.*

Using craters from [15], we also calculated the surface age of Titan, which is 1760 [-600, +500] Myr old (**Fig. 2**). Prior to this time, large impacts likely resurfaced Titan multiple times (**Fig. 1**). Our work shows Titan's surface is ~1 and ~2 Gyr younger than ancient terrains on Ganymede and Callisto, respectively. This disparity could suggest (i) impact resurfacing is easier on Titan, which has an atmosphere, or (ii) geologic processes on Titan were capable of erasing craters for a longer time than on Ganymede/Callisto.

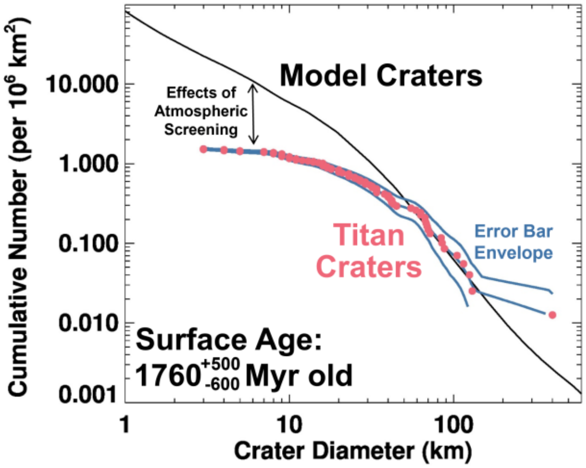

Fig. 2. *Model vs Titan craters, and Titan's surface age.*

Evolution of Comet Particles on Titan. The fate of cometary materials from irregular satellites debris and KBO projectiles is difficult to quantify at present. Impacts and early geology should mix dark material into the near surface, but to unknown depths.

On the other hand, large impactors hitting early Titan (and early Ganymede/Callisto) should produce widespread melting of the near surface via flows of hot materials spreading from the impact site [16]. This mechanism may help concentrate and liberate dark debris mixed into the near surface (e.g., a "dirty snowbank" at the end of winter). This effect would presumably work on Titan, Ganymede, and Callisto, though it might be most effective on Titan, given that its thick atmosphere could slow cooling within hot ejecta flows.

Wind and fluid flow on Titan can also liberate dark particles mixed into the ice. Many channels are located within Titan's equatorial dunes fields, which means some dark particles could be delivered directly to where they are needed [e.g., 17].

A possible test of our idea comes from Cassini atmospheric-corrected VIMS spectra [6]. They show Titan's dune fields are an excellent spectral match for the ice-rich ejecta fields of Sinlap crater (i.e., analogous to our dirty snowbank scenario). A poor match is found, however, for the organic-rich region of Tui Regio, which appears to be covered by precipitated atmospheric hydrocarbons. For reference, Tui Regio is a drainage basin and a compositional endmember in the Xanadu region, which is a bright "plains" unit.

Implications. NASA's Dragonfly mission will visit Titan's dunes near Selk crater. This makes our hypothesis testable, provided *in situ* measurements can distinguish indigenous organics from comet particles.

Conclusions. A summary of our results are:

- The sizes, strengths, spectra, and net volume of Titan's dune particles provide challenging constraints for endogenic formation models.
- The delivery of cometary materials to Titan can potentially match these constraints.
- Irregular satellite debris and early KBO impacts can potentially deliver enough CC-like solids to Titan to explain its dune fields, provided these materials stay near the surface.
- Dark CC-like materials on Callisto and Ganymede may be derived from similar sources.

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