TITAN'S BISTABLE, CYCLICAL CLIMATE: A SONG OF SLUSH AND PHOTODESTRUCTION.
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Introduction: Titan is the only extraterrestrial body known to host a hydrologic cycle and stable lakes on its surface [1-3], albeit composed primarily of methane, rather than water. These features are enabled by Titan's atmospheric methane, which forms raindrops and drives a greenhouse effect that keeps the surface and atmosphere near methane's triple point temperature of 90.17 K.

Nevertheless, the source of this methane is an enigma. Atmospheric methane is short-lived, as photodestruction should deplete Titan of all known surface methane in a few ~10 Myr [4]. Furthermore, $^{12}C/^{13}C$ isotope ratios suggest that Titan's methane has resided in its atmosphere for no more than a few ~100 Myr [5], suggesting that such methane was recently released.

Cryovolcanism could release methane to Titan's surface, however this would require a rapid release of methane to outpace photodestruction, and there is little evidence of such largescale cryovolcanic activity in Titan's recent past [4]. Meanwhile, the lack of atmospheric methane would eliminate Titan's methane greenhouse, causing its surface temperature to plunge to ~80K or below [6,7]. Such conditions would cause Titan's atmosphere to partially collapse, forming a global-scale nitrogen ocean [6,7].

Here we show that, in such a frigid "slushball" state, any methane released into Titan's atmosphere (e.g., through cryovolcanism) would dissolve in the nitrogen ocean, leaving an insufficient amount of methane in the atmosphere to drive a methane greenhouse effect. This results in a bistable climate: a colder "Slushball Titan" regime (in which all surface methane is sequestered in the depths of the global nitrogen-dominated ocean), and the present warm climatic regime in which nearly all surface methane is atmospheric. Furthermore, methane sequestration and photodissociation cause Titan to naturally cycle between these two regimes.

Methods: We use our TITANPOOL code [8] to model the composition of Titan's surface liquids and atmosphere under these climactic regimes. TITANPOOL [8] uses the GERG-2008 Equation of State for hydrocarbon mixtures [9,10], which is contained in the REFPROP program published by NIST [11]. TITANPOOL uses composition and thermodynamic variables (e.g., pressure, temperature) and GERG-2008 to compute the equilibrium partition of nitrogen and hydrocarbons (chiefly methane) into liquid and gas phases on Titan.

We use this capability to compute the composition of Titan's atmosphere and surface liquids as Titan cools toward the "slushball" state: surface pressure of ~0.7 bar and temperature of ~80 K or less [6,7]. At lower temperatures, methane is increasingly drawn out of the atmosphere and into the nitrogen ocean. Below some critical temperature, Titan's atmosphere will contain insufficient methane to drive a greenhouse effect (when methane partial pressure is less than ~0.01 bar [6]), causing the surface temperature to plunge and setting off a slushball state. We use TITANPOOL to identity this temperature, along with the composition of Titan's atmosphere and lakes/ocean as a function of temperature.

Climate Bistability: We find that, were Titan to cool to below ~83 K, sufficient atmospheric methane would dissolve into surface liquids to shut down the methane greenhouse effect (figure 1). Thus, Titan's surface temperature would plunge into a slushball climate were it to cool to below ~83K. Above ~84K, sufficient methane remains in the atmosphere to drive a methane greenhouse, driving the surface temperature toward the warm Titan climate observed today.

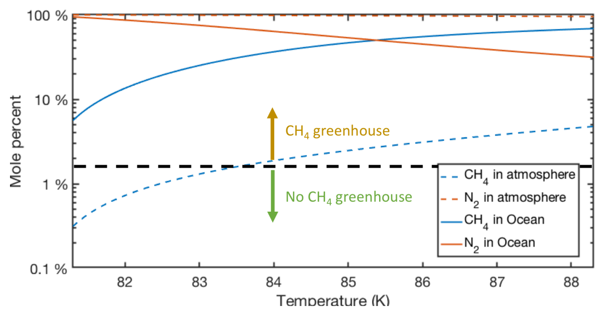

Figure 1: Equilibrium surface composition of Titan's atmosphere and surface liquids as a function temperature. This model assumes an atmosphere and surface liquids composed solely of nitrogen and methane.

This suggests that Titan's climate is presently bistable. If Titan were cooled to below ~83 K, its present atmospheric methane would almost entirely dissolve into a growing, global nitrogen ocean. This would shut down the methane greenhouse, stabilizing Titan into this slushball climate regime. Thus, Titan could stably exist in either the Slushball Titan or Warm Titan climate regimes.

Titan's Climate Cycle: Titan's bistable climate is controlled entirely by the presence/absence of a methane greenhouse effect. Thus, processes that destroy or release atmospheric methane cause Titan's climate to naturally cycle between these two climate regimes. Presently, Titan's warm climate keeps most of its surface methane in its atmosphere, where it is susceptible to photodestrution. Over the next few ~10 Myr, Titan will lose its atmospheric methane to photodestruction [4], shutting down the methane greenhouse. This will cause Titan's climate to transition into the Slushball regime, with any remaining atmospheric methane preferentially dissolving into the nitrogen-dominated ocean.

Once in the Slushball regime, any methane released into the atmosphere from Titan's interior (e.g., through cryovolcanism) will preferentially dissolve into the nitrogen ocean, keeping Titan's atmosphere relatively methane-free. However, once the ocean saturates, additional methane will begin to build up in the atmosphere. Seasonal forcing and/or lake dynamics may cause additional periodic methane releases from the nitrogen ocean. Eventually, sufficient methane will be released into the atmosphere to reestablish a methane greenhouse effect. This will cause the surface to rapidly warm, largely evaporating the nitrogen ocean and expelling its dissolved methane into Titan's atmosphere. This rapidly transitions Titan into the Warm climate regime, where photodestruction can continue Titan's climate cycle anew.

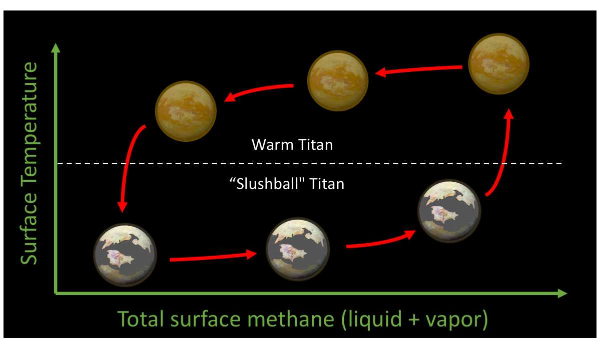

Figure 2: A cartoon of Titan's climate cycle. Photodestruction of methane drives the transition from Warm Titan to Slushball Titan; slow buildup of methane in the global ocean and the eventual reestablishment of the methane greenhouse drives Slushball Titan back into the Warm Titan regime.

Evidence of recent "Slushball" state. Observations of Titan suggest that it was in a Slushball climate a few ~100 Myr ago. $^{12}C/^{13}C$ isotope ratios constrain methane fractionation in the atmosphere, and suggest that Titan's methane has been in its atmosphere for less than ~470 Myr [5]. This is consistent with the ~200-1000 Myr cratering age of Titan [12], which implies recent resurfacing on Titan. Titan's craters are preferentially found in Titan's higher elevations [13], suggesting erasure at lower elevations consistent with a global-scale nitrogen ocean, which is consistent with fluvial features in Titan's low latitudes [14]. Titan also contains too many small craters given the expected effects of atmospheric shielding [12], consistent with the atmosphere being recently thinner [12] and partially collapsed onto the surface. Titan's observed global "flattening" via ethane replacing methane in clathrate structures in the crust would require ~300-1200 Myr [15]. Finally, the observed dune materials on Titan would require ~50 – 630 Myr to form from atmospheric methane [4].

Conclusions: Titan's climate is presently bistable, and controlled by the present/absence of an atmospheric methane greenhouse effect. Titan could be in a Warm Titan regime (in which methane is largely atmospheric), or a cold Slushball Titan regime (in which methane is dissolved in a nearly global Nitrogen ocean). Processes on Titan that affect atmospheric methane concentrations (e.g., photodestruction) cause Titan's climate to naturally cycle between these two regimes. Observational evidence suggests that Titan last transitioned out of the Slushball Titan regime a few ~100 Myr ago.

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