MODELING THE THERMAL STATE OF TITAN VOLATILES AND SHALLOW MELTING INVOLVING HYDROCARBONS, ORGANICS, AND ICE.

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Introduction: The extraordinary low thermal conductivities of most volatile rich solid in the outer solar system (e.g. most non-H_2O ices, clathrate hydrates, salt hydrates and hydrocarbons) have a profound effect on the phase states of and the geological processes involving such materials comprising surface and crust of solid volatile-rich objects. Indeed, compared to the thermal conductivities of ordinary water-ice 1h and most silicates, these materials have thermal conductivities that are factors of 2 to 20 lower. As a consequence, this widely variable parameter most-likely plays a major role in controlling the heat flow distribution through and beneath volatile deposits and resulting control in geological activity.

Titan is one of the candidate icy satellites to be controlled by thermal properties the volatile-rich crust. It has been recognized since the early results of *Cassini* and the landing of *Huygens* that Titan has a complex, geologically active history [1], including possible evaporitic or marine plains deposition [2]. It is also a likely place for a subsurface ammonia-water ocean [3]. There must be an internal source for Titan's atmospheric methane [4], [5], and this source may be methane clathrate. The existence of latitude-correlated polar and subpolar methane and ethane clouds [6, 7], and of lake-like polar landforms are compelling arguments that either methane rain-driven dissolution of soluble hydrocarbons or polar condensation of highly volatile hydrocarbons is important.

Our long-term goal is to understand how the physical properties and stability of carbonaceous volatiles operate to control the geological processess occurring on Titan and on other solid bodies in the outer solar system. Here, we focus on a specific problem, i.e. understanding the thermal environment within, beneath and adjacent to hydrocarbon sand dunes overlying a water-ice crust on Titan. Moreover we are interested in understanding what hydrocarbons could melt due to insulation caused by the dune fields. Finite Element Modeling will provide a key basis for the analysis.

Titan Sand Dunes Thermal Modeling: Figure 1 shows two Cassini radar scenes illustrating juxtaposed sand dunes (hydrocarbon sands?) and channels developed in an unknown, possibly icy material on Titan. We have modeled the thermal anomaly related both to the low-conductivity hydrocarbon composition of the hypothesized idealized dunes and their porous nature; when both are relevant, the thermal anomaly can be quite large and may control key geological processes. Figure 2 shows the key geometrical parameters used in the simulation. We considered a 2-D section of an idealized topography where dunes are emplaced. We assumed that the fundamental mode of heat transport is conduction; intergranular gas convection and radiation are ignored. Application of energy conservation coupled with Fourier's heat law yield the well-known heat equation which must be locally satisfied by the temperature distribution. For 2-D steady state models, the temperature distribution must, in any given region, satisfy the Laplace equation:

$$k_i(T)\nabla^2 T_i(x,y) = Q_i(x,y)$$
$$(x,y)\in\Omega_i,\ i=1,2,....$$

$T_i(x,y)$ is the desired temperature distribution in the region Ω_i (i varies depending on the model geometry. Most of the proposed models have a 2-region configuration.) $Q_i(x,y)$ (in W/m^3) is the source density in the i-th region, $k_i(T)$ (in W/mK) is the thermal conductivity of the i-th region. Since the model regions will be assumed to be ice and/or frozen simulated hydrocarbon mixtures, the thermal conductivity depends on temperature [8]. The problem is inherently nonlinear. The equations are equipped with the appropriate boundary conditions.

On the surface we impose fixed temperature (Dirichelet boundary condition), and for Titan we assume constant surface temperature of 94 K (the constancy achieved by a balance of upwelling and downwelling radiation owing to equilibrium between the surface and a thermally homogenized lower atmosphere, low magnitudes of the direct unscattered solar beam, and small magnitudes of geothermal flux compared to upwelling and downwelling fluxes in the atmosphere). At the interface between regions, a continuity of temperature and flux is guaranteed.

Heat flux coming from the interior is imposed as the bottom boundary condition (Neumann boundary condition). The heat sources are radiogenic and/or tidal. Although volumetric heating will be included in some simulations, so far we have assumed that radiogenic heat is produced beneath the model domain and flows upward.

The multi-region nonlinear Laplace equation for complicated geometries generally cannot be solved in terms of elementary functions. Finite Element Method

(FEM), coupled with non-linear, iterative techniques has been used to provide accurate numerical solutions.

Titan's crust is assumed to have a thermal conductivity similar to ice (which varies non-linearly with the temperature, [8]). The sand dune thermal conductivity is estimated from the data for solid benzene [8] (Ross et al. 1979). Our analysis includes a pressure correction factor (also from [8]) to adjust the pressure down to 0.0002 GPa (a near-surface pressure), and an additional factor to consider the porosity and granular structure of the sand and filling of pore space by 5 bars of N_2 gas. Benzene's thermal conductivity properties are similar to those of solidified heavy and light alkanes, anthracene, asphalt, polyethylene, and other pure and mixed hydrocarbons, which explains its choice considering the available data.

Model Interpretation: There are many variables for most planetary numerical modeling problems, and observations may help constraining the input parameters . If achievement of melting temperatures within or at shallow depths beneath the dunes is the goal of the model (designed to satisfy some geologic interpretations, e.g., identification of channels shown in Figure 1 near the dunes, which may or may not have a causal relationship), then only a limited range of plausible parameter space can achieve that. For instance, in Figure 2, the warm anomaly is sufficient to reach into the 2-phase solid-liquid region of the ethylene-methane system if ethylene-rich solid hydrocarbons are produced by evaporation of ethylene-bearing liquids, and then the ethylene-rich solids are buried, for example, inside an ethylene-bearing dune deposit.

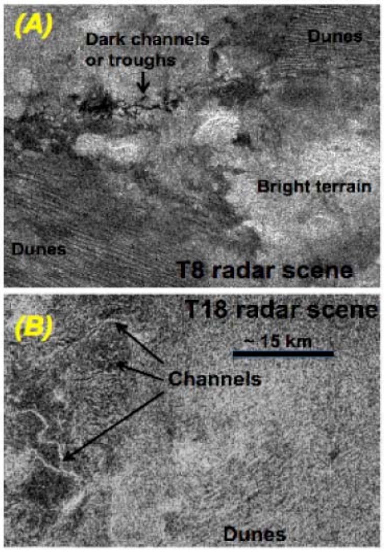

Figure 1: Cassini radar images of (hydrocarbon?) sand dunes and possibly icy channels.

Many scenarios may result in near-surface melting of hydrocarbon solids on Titan, but most conceivable situations are hard-pressed to produce melting temperatures. Thus, the channels in Figure 1B might be caused by melting dunes, or by melting sub- s, but only if the ithin certain constraints. Things like the porosity of the sands matter as much as their composition, and so possible grain annealing and reductions in porosity and increases in thermal conductivity have to be considered before reaching any conclusions. On the other hand, if the channels in Figure 1B are not related to the dune sands, and no melting has taken place, then other compositions besides ethylene might be more probable; for instance acetylene or heavy alkane sands would not likely melt on Titan even if their porosity is high and sand grain contact angles are low

We are exploring the thermal environments and likely processes involving other types of landforms and compositions on Titan. The sand dune model suffices to show that self insulating effects of hydrocarbon deposits can yield thermal anomalies sufficient to drive melting within or beneath the deposits.

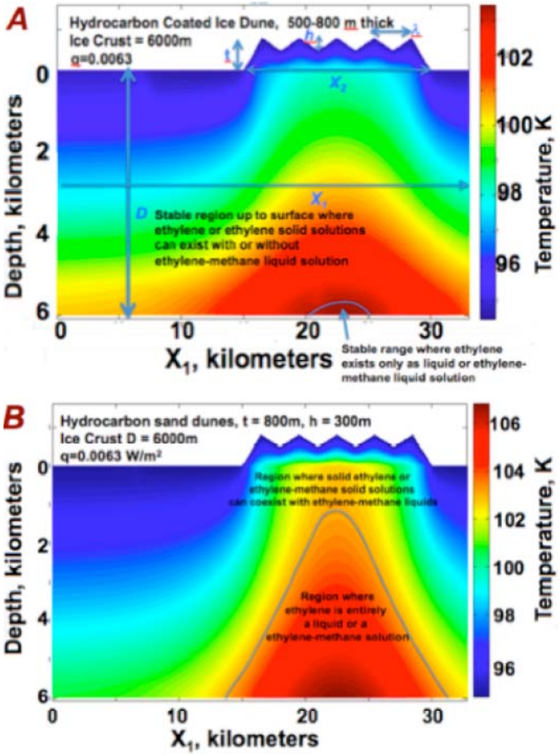

Figure 2: Schematic thermal models showing warm thermal anomalies within and beneath hydrocarbon sands resting on an ce crust

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