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Thermal convection in the porous methane-soaked regolith of Titan: Investigation of stability

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ABSTRACT

Titan is the only body, other than the Earth where liquid is present on the surface. In the present work we consider behavior of methane in the pores of Titan's regolith. Using numerical model we investigate quantitative conditions necessary for the onset of convection. We have found that the methane convection in Titan's regolith is possible. It can be expected in regions where the regolith has sufficiently high porosity, independently of the geothermal heat flux.

1. Introduction

Titan is rather unusual celestial body. It is the only one in the Solar System (with the exception of Earth), where the p–T conditions allow an active hydrological cycle (based on hydrocarbons), as well as permanent presence of liquid on its surface. Existence of the methane ocean or lakes on Titan was suggested a decade ago, based on photochemical considerations (e.g. Stevenson and Potter, 1986; Raulin, 1987). The present atmospheric stock of methane should have been depleted by photolysis in 10^7 years if it was not replenished (e.g. Lunine, 1993; Tobie et al., 2006a). Thus, the present existence of methane suggests a possible surface (or near-surface) reservoir of methane. Further, the dominant photochemical product, ethane, is liquid at the surface p–T conditions. Young et al. (1984) suggested that the methane photolysis over the age of the Solar System should lead to a layer of ethane 600 m thick on average (see also Tokano, 2005). This would imply the presence of an ethane-rich ocean. The presence of methane just beneath the surface, in the porous regolith, was also considered – Stevenson (1992), Kossacki and Lorenz (1996). Recently, observations confirm that some liquid methane is present on the surface of Titan. The Huygens Probe detected features that indicate the presence of some liquid on the Titan's surface: methane clouds and high surface relative humidity in the vicinity of its landing site. Of course, the term 'humidity' is used here to describe the methane and/or ethane vapor in Titan's atmosphere. The presence of liquid methane is indicated also by the results of GCMS (gas chromatograph mass spectrometer) and by good cooling properties of the regolith (e.g. Tomasko et al., 2005; Lorenz et al., 2006a). Those observations are sufficient to expect the presence of surface, or sub-surface sources of methane that replenish this gas against photo- and charged-particle chemical loss (Atreya et al., 2006). In addition, reservoirs of liquid at the surface are indicated by radar observations. Imaging failed to find evidence of a global ocean, although radar observations provided definitive evidence for the presence of lakes (Stofan et al., 2007; Hayes et al., 2008; Brown et al., 2008). Therefore, in some regions, Titan's regolith is probably filled with liquid methane and/or ethane. The Cassini Orbiter remote sensing shows also dry and even desert-like landscapes with dunes (Lorenz et al., 2006b). More recently the properties of the Titan surface were described by Lunine et al. (2008) and Paganelli et al. (2008). Taking into account the diversity of the Titan landscapes we expect, that the regolith can be, in some regions, free of any liquid, or dry to a large depth. However, the presence of lakes suggests small depth to the liquid table (at least in some regions) at high latitudes in the northern hemisphere. Mitri et al. (2007) argue that high relative humidity of methane in Titan's lower atmosphere could be maintained by evaporation from lakes. They state that lakes covering 2% of the whole surface are sufficient to maintain the observed amount of atmospheric methane. This may indicate that gas exchange between the subsurface methane reservoirs and the atmosphere is slow, possibly due to the presence of some dry material with low gas permeability above the liquid table. It should be noted, that the area of lakes calculated by Mitri et al. (2007) is just a lower estimate. Probably the lakes occupy more than 2% of the Titan's surface. The processes of evaporation and subsequent precipitation lead to global transport of hydrocarbons. Note also that the lakes

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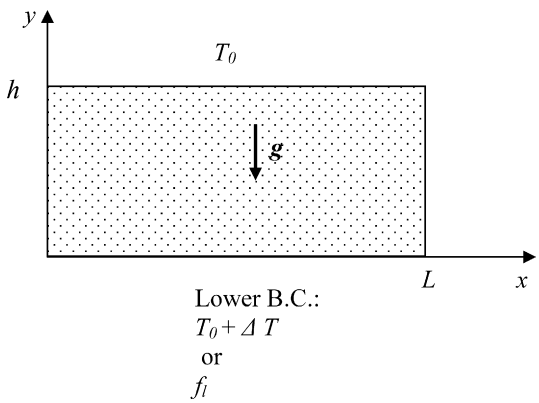

Fig. 1. The considered region and the boundary conditions.

are probably filled with some mixtures of ethane, methane, and nitrogen rather than pure methane. The total area of lakes would have to be larger than for pure methane lakes to account for the present concentration of methane in the atmosphere.

In the present paper we investigate the possibility of thermal convection in the Titan's regolith. We assume that the regolith is saturated with liquid methane and heated from below by the geothermal heat sources. In such physical situation convection of the liquid can be expected. We attempt to determine the conditions necessary for the onset of convection. Usually convection is a more efficient mechanism of heat transfer than conduction; therefore the presence of convection should lead to a substantial change of heat flow and/or temperature distribution in the regolith. Moreover, the convection could dramatically redistribute the heat flow leading to origin of some specific surface structures like geysers. Different types of convection in the Titan's interior were already discussed (e.g. Tobie et al., 2006b). Different models of the Titan's volcanism were also presented (e.g. Fortes and Grindrod, 2005; Fortes et al., 2006; Alekseev, 2008). However, to our best knowledge our current work is the first dealing with convection in the shallow near-surface layer of the Titan's regolith.

The paper is organized as follows: In Section 2 we describe the numerical model. Section 3 contains the results of the stability investigations. In Section 4 we discuss application of our calculations to Titan. The conclusions are in Section 5.

2. Numerical model of convection in regolith

2.1. Physical situation

We consider a horizontal layer of porous regolith soaked with a liquid – Fig. 1 and Table 1.

Let h be the thickness of the layer, and L its length. Let also grad p be the pressure gradient. This gradient drives the flow of the liquid given by the Darcy's formula: $\mathbf{v} = -(k/\eta)$ grad p, where η is the dynamical viscosity of the liquid (Pa s), k (m^2) is the permeability and $\mathbf{v}$ ($\mathrm{m\,s^{-1}}$) is a volumetric flow rate, i.e. velocity averaged over some volume (the volume must be large comparing to size of pores) (e.g. Turcotte and Schubert, 2001, chap. 9). Note that $\mathbf{v}$ is not the true velocity of the fluid inside the pores. Due to very limited knowledge about Titan's regolith we describe the dependence of permeability k on depth using the simple formula:

$$k(y) = k_0 \exp\big((y - 0.5h)/H_\mathrm{p}\big), \tag{1}$$

where H_p (m) is a constant 'depth scale' and k_0 is the permeability in the middle of the considered layer (i.e. for $y = h/2$). Equation (1) approximately reproduces the results of numerical simulations dealing with the self-compaction of the regolith on Titan (Kossacki and Lorenz, 1996). The temperature at the upper boundary is T_0. At the lower boundary we consider two alternative boundary conditions (BC): temperature $T_\mathrm{l} = T_0 + \Delta T$ or the density of the heat flux f_l ($\mathrm{W\,m^{-2}}$). The first condition corresponds to the situation where below the regolith is a body with constant temperature (e.g. a cryomagma chamber). The second condition means the presence of a constant geothermal heat flux from below, the condition probably more appropriate for most regions of Titan. The lateral boundaries are assumed to be adiabatic (i.e., no heat flow):

$$\left.\frac{\partial T}{\partial x}\right|_{\text{for } x=0 \text{ and } x=d} = 0, \quad 0 < y < h. \tag{2}$$

Table 1
Notations.

c_m, c_f	$\mathrm{J\,kg^{-1}\,K^{-1}}$	specific heat for matrix and fluid, respectively
$C = (\rho_{0\mathrm{f}} c_\mathrm{f}/\rho_\mathrm{m} c_\mathrm{m})$	1	dimensionless number
f_l	$\mathrm{W\,m^{-2}}$	heat flow density at lower boundary
h	m	thickness of the regolith layer
H_p	m	depth scale
g	$\mathrm{m\,s^{-2}}$	gravity
k, k_0	m^2	permeability, reference permeability
p	Pa	pressure
Ra	1	Rayleigh number
T	K	temperature
T_0	K	surface temperature
T_l	K	temperature at the lower boundary
t	s	time
$\mathbf{v} = (\mathbf{v}_1, \mathbf{v}_2)$	$\mathrm{m\,s^{-1}}$	velocity vector
x	m	x-coordinate
y	m	y-coordinate
α	$\mathrm{K^{-1}}$	coefficient of thermal volume expansion of fluid
$\delta = \eta/k$	$\mathrm{Pa\,s\,m^{-2}}$	ratio of the viscosity η and the permeability k
ΔT	K	temperature difference
η	Pa s	viscosity
$\Theta = (T - T_0)/\Delta T$	K	natural temperature unit
$\kappa_\mathrm{m} = \lambda_\mathrm{m}/(\rho_\mathrm{m} c_\mathrm{m})$	$\mathrm{m^2\,s^{-1}}$	temperature diffusivity of matrix
λ_m	$\mathrm{J\,m^{-1}\,s^{-1}\,K^{-1}}$	thermal conductivity of matrix
ρ, ρ_0,	$\mathrm{kg\,m^{-3}}$	density, reference density
$\tau = h^2/\kappa_\mathrm{m}$	s	natural time unit
φ	$\mathrm{m^2\,s^{-1}}$	stream function
$\Phi = \kappa_\mathrm{m}$	$\mathrm{m^2\,s^{-1}}$	natural stream function unit
$\omega = \kappa_\mathrm{m}/h$	$\mathrm{m\,s^{-1}}$	natural velocity unit

2.2. Equations

We use the 2D numerical model based on the following system of equations: (i) the equations of motion for fluid in a porous medium, (ii) the equation of thermal conductivity, (iii) the equation of continuity and (iv) the equation of state. We assume that the liquid could be treated as incompressible so the equation of continuity and the equation of state are reduced to:

$$\nabla \cdot \mathbf{v} = 0 \tag{3}$$

and

$$\rho_\mathrm{f} = \rho_{0\mathrm{f}}\big(1 - \alpha(T - T_0)\big), \tag{4}$$

where $\mathbf{v}$, T, T_0, ρ_f, $\rho_{0\mathrm{f}}$, α, denote the average velocity of the fluid, temperature, reference temperature (i.e. the surface temperature), density of the fluid, reference density of the fluid, and coefficient of thermal expansion of the fluid, respectively. The equations of motion express the fact that the velocity is proportional to the pressure gradient (e.g. Turcotte and Schubert, 2001, chap. 9), i.e.

$$\mathbf{v}_1 = -\frac{1}{\delta}\frac{\partial p}{\partial x}, \tag{5}$$

$$\mathbf{v}_2 = -\frac{1}{\delta}\left(\frac{\partial p}{\partial y} + \rho_\mathrm{f}\alpha_\mathrm{f} g(T - T_0)\right), \tag{6}$$