Numerical simulations of cryolava flows at the surface of Titan

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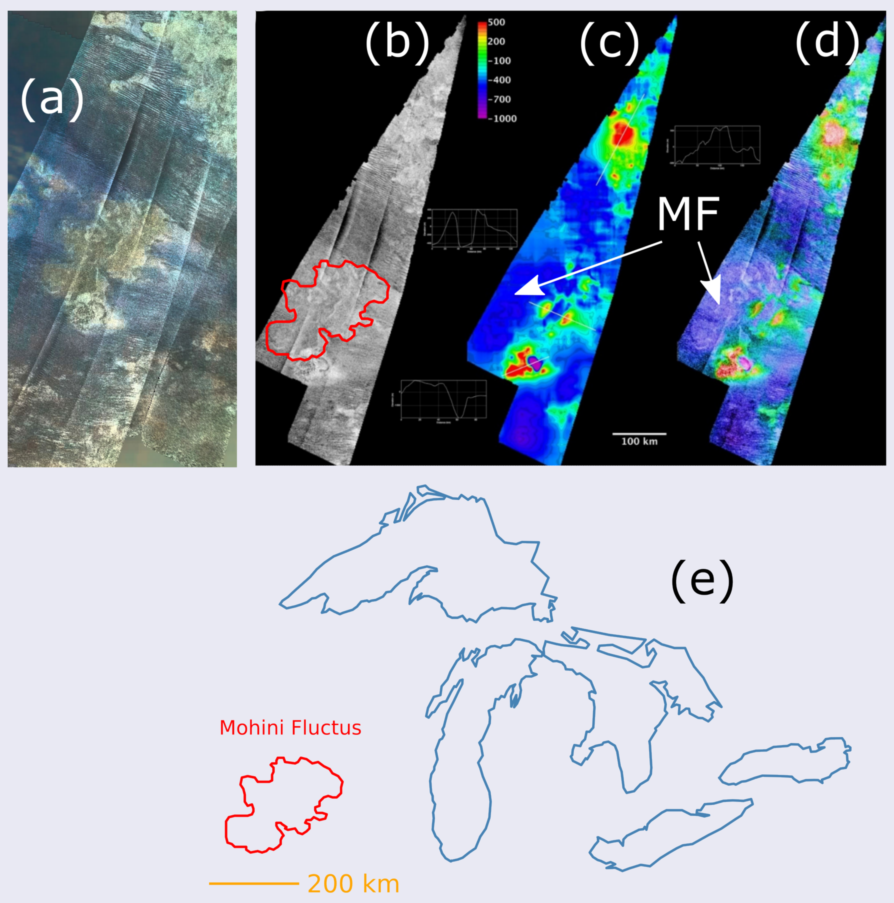
Introduction

Titan, Saturn's main satellite, is a unique object in the solar system. This satellite has a dense atmosphere and a liquid water ocean under its surface. These mechanisms raise major questions such as the possible interaction between the liquid water and the organic matter present on the surface.
One of the mechanisms considered for these interior-surface interactions is cryovolcanism. Many candidate cryovolcanoes have been selected, and the observation of cryolavas would allow us to constrain their physico-chemical properties.
In order to study these phenomena, we have developed a model based on the "Smoothed-Particle Hydrodynamics" (SPH) method. This model will be validated for a fluid at rest and compared with the litterature.

Volcanism in the Solar System



Multiple objects that are subject to volcanism in the Solar System: Earth, Enceladе or even Titan. Two types of physical processes are known to produce "cryolava" on Titan:

- Impact craters (Selk, [1])
- Cryovolcanoes (not observed, but several candidates, fig. 1)

Figure 1: (a) SAR and VIMS data for the Sotra Patera region. (b, c, d) Results of SAR stereo over the Sotra region. (b) SAR. (c) Color-coded DTM. (d) Merged SAR and DTM. (e) Scale comparison between Mohini Fluctus and the Great Lakes. Adapted from *Lopes et al. (2013)* [4]

A word on SPH

The SPH method [2] is a numerical method for solving the equations of fluid dynamics by replacing the fluid by a set of "particles", points where we can compute its properties (fig. 2). This Lagrangian method, although initially applied to astrophysics, and in particular to stars, is today applied in many fields such as the simulation of terrestrial lava flows. This method has many advantages:

- It is a meshless method: the method is particularly adapted to free surface flows;
- The method, although slightly more computationally intensive, is highly parallelizable;
- Deformations are easier to model than with a finite element method.

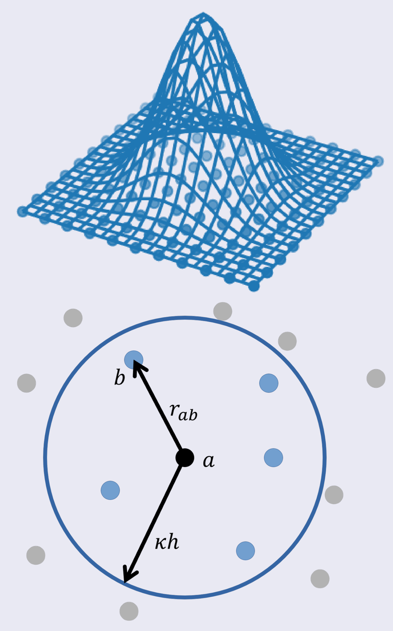


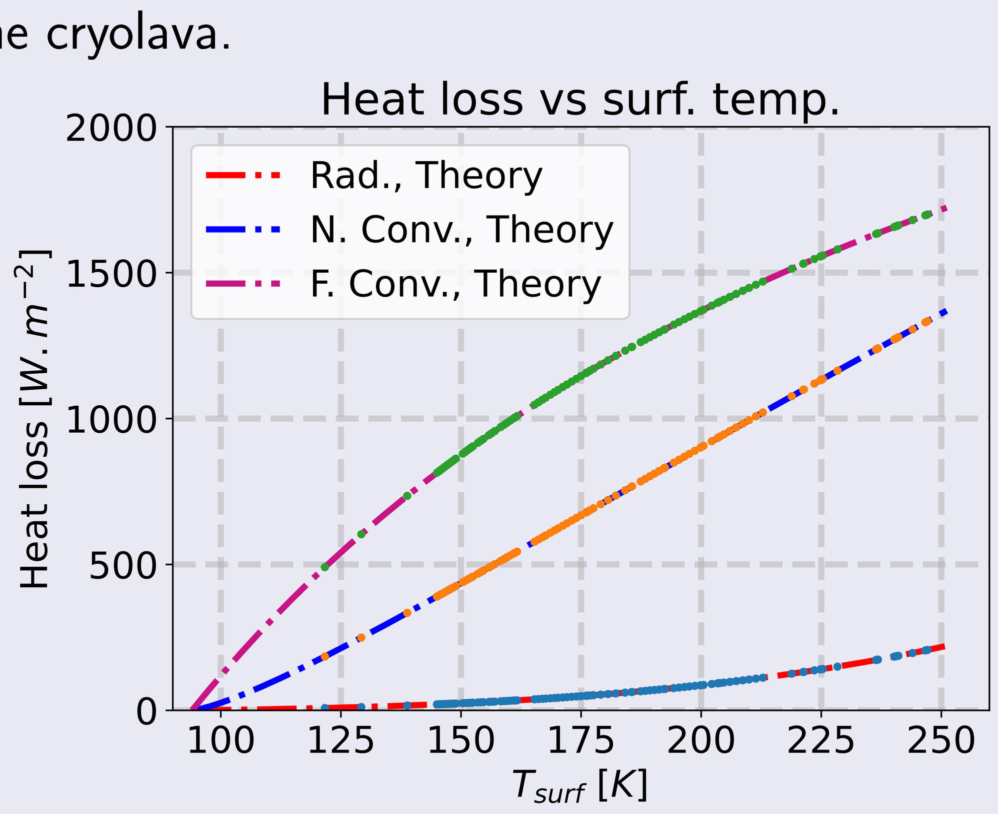
Figure 2: Representation of a smoothing function used for the representation of a physical quantity in SPH.

Relevance of the method

We first focus on a cryolava at rest in contact with Methane Clathrate Hydrates, and study its behavior, compared to the results of *Davies et al (2010)* [3]. Duration of the simulation:
$\sim$60 hours on 8 cpus

Figure 3: Heat loss per unit area from a flow or impact melt upper surface as a function of surface temperature and process of heat removal. Adapted from *Davies et al 2010*

The next step is to study the rheological behavior of the cryolava.



Physics of terrestrial lavas

Terrestrial lavas are mainly silicate lavas. They are studied mainly to observe their potential impact on human infrastructures.
We can relate the shear stress of a fluid τ as function of its shear rate $\dot{\gamma}$:

$$\tau \sim \eta_{app}\dot{\gamma} \quad (1)$$

Several rheological models exist to describe the flow of these lavas (fig. 4):

- A newtonian fluid (example: water);
- A non-newtonian fluid:
  - A Bingham fluid (example: paint);
  - A power-law fluid (example: suspensions)
  - A Herschel-Bulkley (HB) fluid (more general; see eq. (2)).

The HB model is as followed:

$$\eta_{app} = \eta\dot{\gamma}^{n-1} + \frac{\tau_y}{\dot{\gamma}}\left(1 - e^{-m\dot{\gamma}}\right) \quad (2)$$

with n and m: parameters; example: $n = 1$
$m \rightarrow \infty \Rightarrow$Bingham; $m = 0 \Rightarrow$Newton

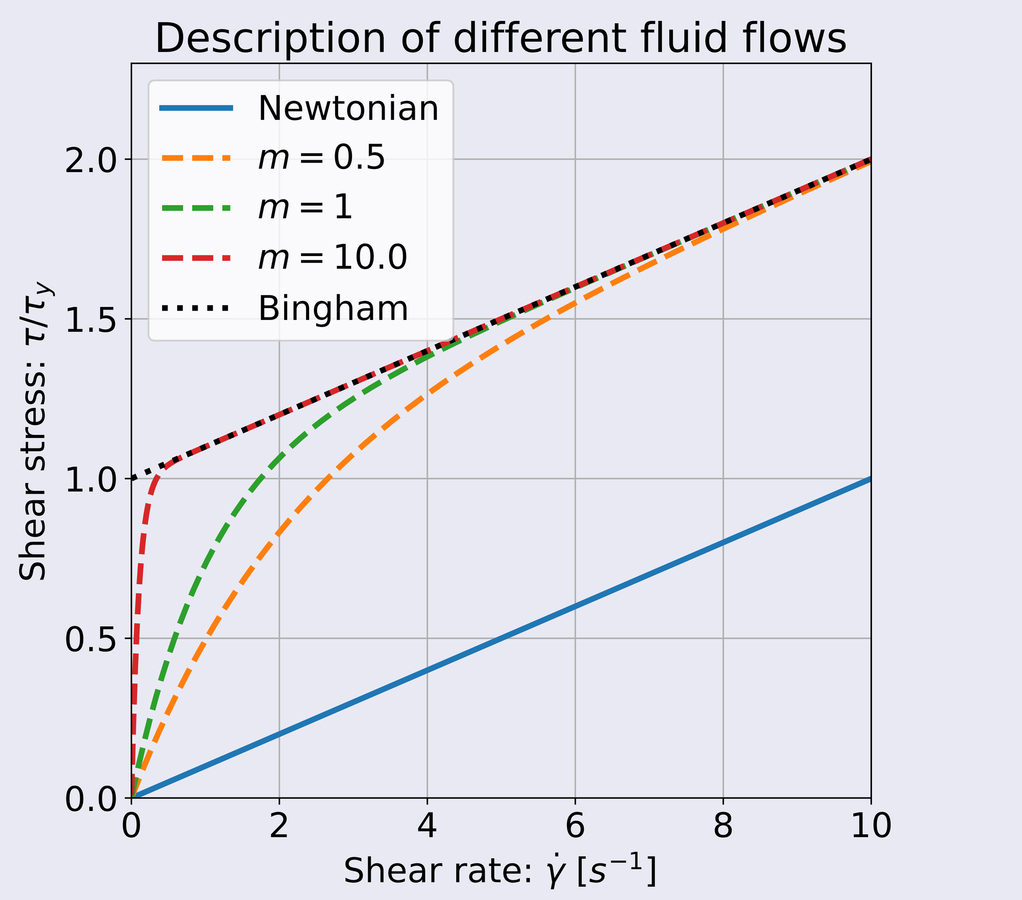


Figure 4: Description of different fluid flows, for Newtonian, Bingham, and several HB rheologies, $n = 1$.

Description of cryolava – Impact on rheology

The composition of cryolavas can affect their behavior, so it is important to understand their composition. It is assumed that Titan's cryolavas are composed mostly of water, with a concentration C of ammonia that can vary from 16% to 32% of the content, which affects their rheology [5]:

$$\begin{cases} \text{Newtonian} & \text{, if } C > 29\% \\ \text{non} - \text{Newtonian} & \text{, if } C \leq 29\% \end{cases}$$

In addition, the addition of even 1% methanol to the contents could totally change the rheology and therefore the behavior of the cryolava.

Deduce rheological properties of cryolava from observations

It is possible to deduce the rheological characteristics of a lava, and in particular the shear rate, from the observation of its flows. For a Bingham fluid, the relation is the following [6]:

$$\tau_y = \frac{\rho g h^2}{w} \quad (3)$$

with τ_y the yield strength, ρ the density, g the acceleration of gravity, h the height of the levee, w the width of the levee. *Lopes et al (2007)* [7] found with this technique an effective viscosity of $\sim 10^4$ $Pa\ s$.
The work of *Kargel (1991)* gives us an effective viscosity of $\sim 10^1$ $Pa\ s$ for $\{H_2O; NH_3\}$ mixtures, and $\sim 10^4$ $Pa\ s$ for $\{H_2O; NH_3; CH_3OH\}$ mixtures.

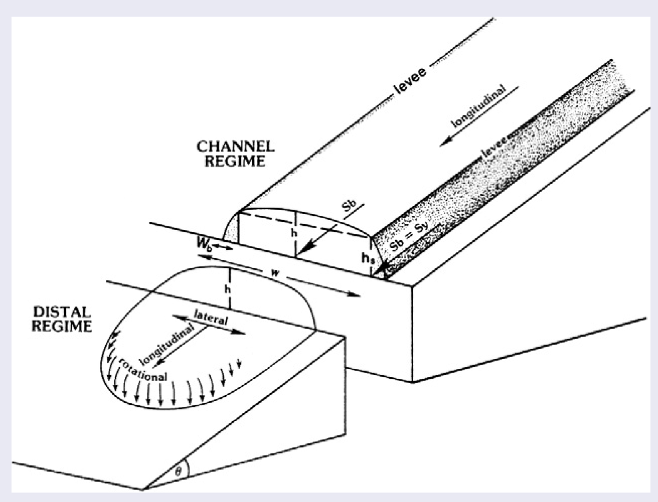


Figure 5: Schematic representation of a lava flow following the model of *Hulme (1974)* [6]. Adapted from *Wadge and Lopes (1991)* [8].

Conclusion and future work

The SPH method is a powerful method to simulate the physics of the cryolava on Titan. Our model, although simplistic, obtains satisfactory results, and can be adapted to more complex geometries. This model will be improved to include the Herschel-Bulkley model. It will allow us to carry out simulations from topographic data, and thus to study the exobiological implications of these flows (mixing of sediments, etc.) or to prepare cryolava detections by future missions.

References

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