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, allowing an exchange between the interior and the latter. These mechanisms raise major questions such as the supply of methane to the atmosphere, or the interaction between the liquid water and the organic matter present on the surface.
One of the mechanisms considered for these interior-surface exchanges 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 which will allow us to study their spatial extension, their solidification and their degassing.

Physics of terrestrial lavas

Terrestrial lavas are mainly silicate lavas. They are studied mainly to observe their potential impact on human infrastructures.
Several models exist to describe the flow of these lavas:

- A newtonian fluid (example: water);
- A non-newtonian fluid, where several models exist:
  - A Bigham fluid (example : paint);
  - A Herschel-Bulkley fluid (more general).

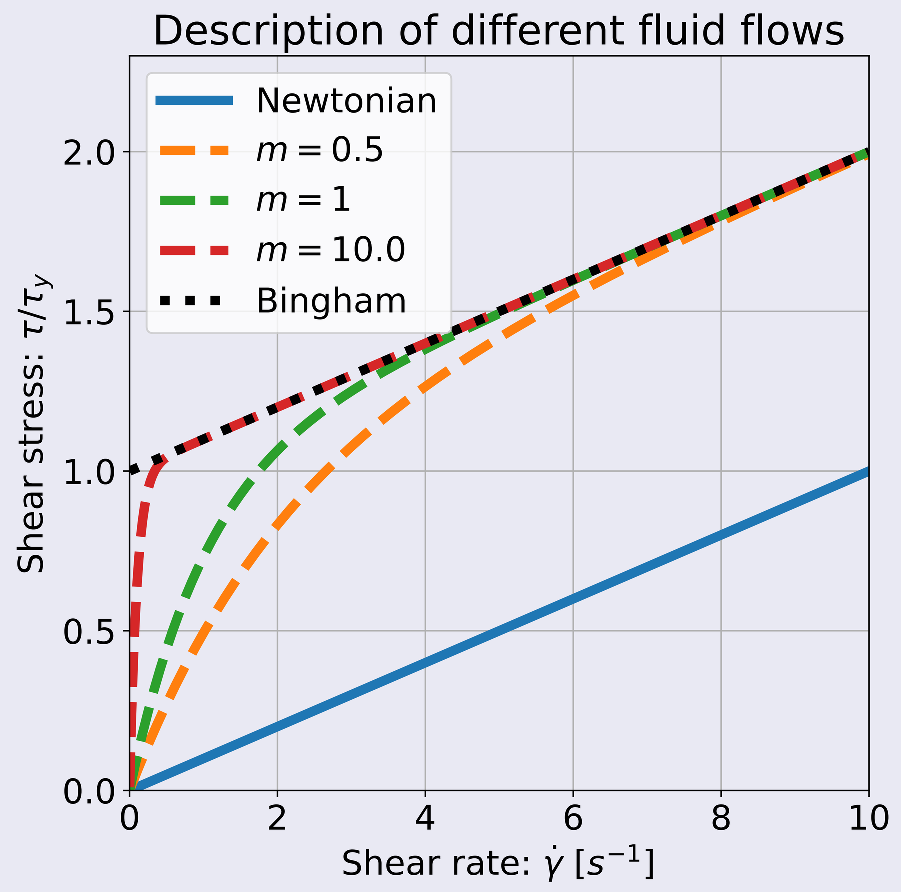


Figure 1: Description of different fluid flows, for Newtonian, Bingham, and several Herschel-Bulkley rheologies

Description of cryolava – Impact on rheology

No direct observation of a cryovolcano has been established. However, several candidates have been established, such as Ganesa Macula thanks to the SAR images from Cassini.
The composition of cryovolcanoes is still a mystery, however, it is assumed that Titan's cryovolcanoes are composed mostly of water, with a concentration C of ammonia that can vary from 16% to 32% of the content, which affects its rheology:

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

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

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:

$$S_y = \frac{\rho g h^2}{w} \quad (1)$$

with S_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)* 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.

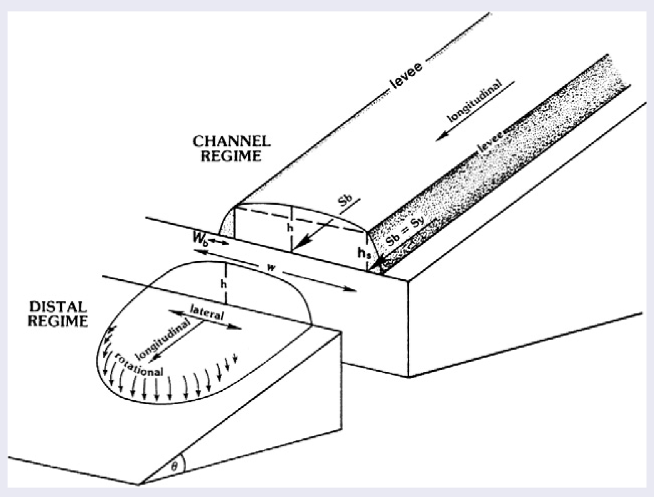
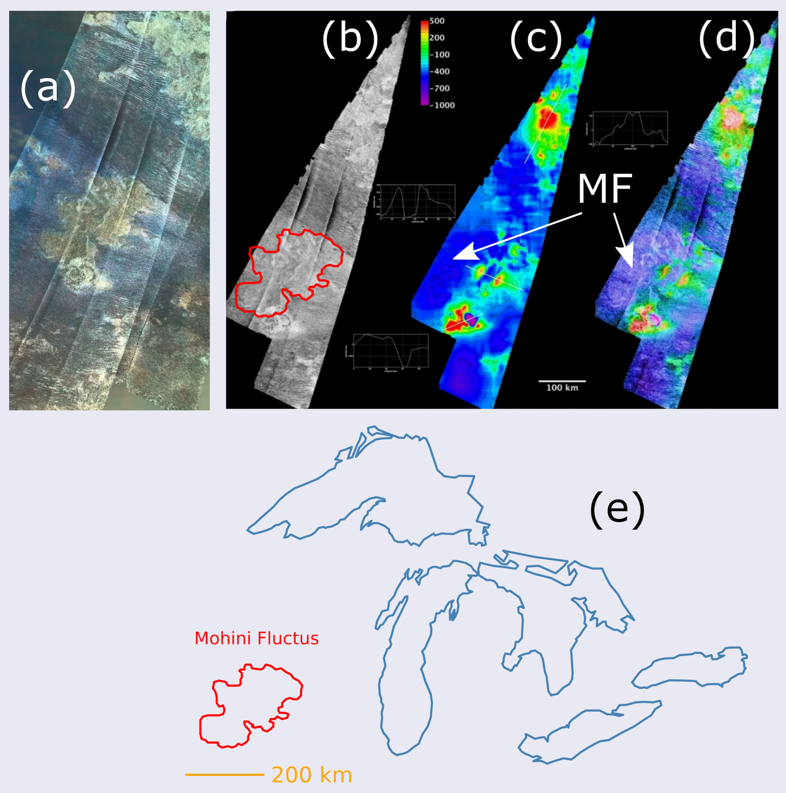


Figure 2: Schematic representation of a lava flow following the model of Hulme (1974). Adapted from Wadge and Lopes (1991)

Dimensions of candidate cryovolcanoes



In order to create realistic simulations, we must first consider the topography we might encounter on Titan. To do this, we will consider the topography of the Sotra Patera region, and particularly of a potential cryovolcano candidate : *Mohini Fluctus (MF)*.

Figure 3: (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.

A word on SPH

The SPH method 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. 4). 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.

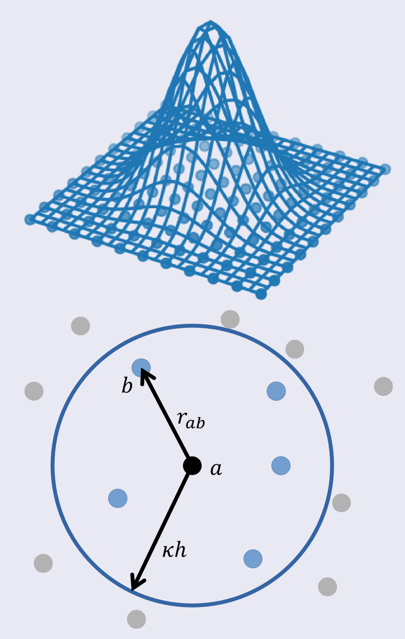


Figure 4: Representation of a smoothing function used for the representation of a physical quantity in SPH.

Preliminary results

The model has been created with the Python library PySPH, and will have run for x hours under y CPUs. The time step is adaptive and depends on the chosen spatial resolution: z meters here.
Simulations manquent de données (pas de drame), donc remplissage en attendant

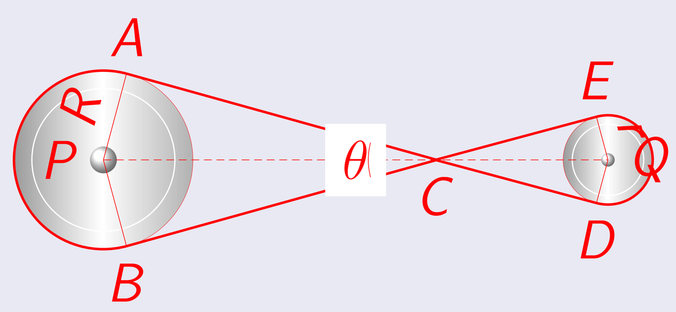


Figure 5: First tikz picture caption

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Conclusion and future work

The SPH method is a powerful method to simulate the physics of the cryolave on Titan. Our model, although simplistic, obtains satisfactory results, and can be adapted to more complex geometries. This model, once improved, will allow to simulate a 3D cryolave flow from topographic data, and thus to get closer to the field conditions to prepare a cryolave detection by future missions.

References

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