

Simulation of cryovolcanism on Saturn's moon Enceladus with the Green-Naghdi theory of thermoelasticity

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Abstract

In 2005, the Cassini spacecraft proved the existence of cryovolcanism, *i.e.*, the icy counterpart of volcanism on Earth, on Saturn's moon Enceladus during its close fly-bys. In particular, water-rich plume venting was discovered in the south polar region. Thus, Enceladus was found to be one out of three outer solar bodies to be geologically active. This contribution is concerned with the modelling and computation of this phenomenon. For the underlying thermoelastic description of ice at cryogenic temperatures, we resort to the Green-Naghdi approach. The Green-Naghdi theory includes the classical Fourier approach, but, in addition to that, it is a lot more general as it also allows for other types of heat propagation. The numerical implementation is carried out with the help of the finite element method. Results show that lateral spreading of internal and surface warming away from an active volcanic vent increases strongly with increasing contribution of the non-classical heat flux. Agreement with available high-resolution surface temperature data based on infrared spectrometry seems to be best if the non-classical heat flux contributes significantly to the total heat transport. Complementary laboratory studies would be required in order to strengthen this speculative, yet promising idea.

1. Introduction

Enceladus is one of Saturn's inner satellites. It was discovered in 1789 and orbits Saturn in an almost circular orbit with a semi-major axis of 237,948 km and a period of 1.37 days. Enceladus has the shape of a flattened ellipsoid with a mean diameter of 504 km, which makes it the sixth-largest Saturnian moon. It consists of a rocky core and an icy mantle and surface, the mean surface temperature being at a cryogenic value of 77 K. In many ways, the general properties of Enceladus are very different from those of other satellites, and thus, it is a very active research topic. With an albedo of 0.99, it has the most reflective surface of any body in the solar system. Moreover, it shows recent geological activity, which is very unusual for such a small body.

Of particular interest is Enceladus' south polar region. Active cryovolcanism was found there in 2005 during a fly-by of the Cassini spacecraft (Porco *et al.* 2006), which makes Enceladus the fourth body in the

solar system (along with the Earth, Jupiter's moon Io and Neptune's moon Triton) where volcanic eruptions have been observed. This finding goes along with the spectrometric detection of a distinctive warm spot centered on the south pole with a temperature of approximately 85 K, which is 15 K more than expected from a simple radiation balance (Fig. 1; Spencer *et al.* 2006).

Cryovolcanoes are icy equivalents of the well-known terrestrial volcanoes. Their main features are illustrated in Fig. 2. Instead of magma, Enceladus' cryovolcanoes erupt water, which has its source in pressurized sub-surface water chambers (Porco *et al.* 2006). No ammonia, which would lower the melting point, was found (Buratti *et al.* 1990), suggesting that the cryomagma is pure H₂O. Cryovolcanoes on other icy moons may also erupt a mixture of water and, for example, ammonia or methane.

The exact source which produces the cryovolcanic water plumes is still subject to research. In the literature, different mechanisms have been proposed to explain the plume origin. Collins and Goodman

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