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Enceladus-Mimas paradox: a result of different early evolutions of satellites?

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Abstract

Thermal history of Mimas and Enceladus is investigated from the beginning of accretion to 400 Myr. The following heat sources are included: short lived and long lived radioactive isotopes, accretion, serpentinization, and phase changes. We find that temperature of Mimas' interior was significantly lower than of Enceladus. Comparison of thermal models of Mimas and Enceladus indicates that conditions favorable for starting tidal heating lasted for short time (~10^7 yr) in Mimas and for ~10^8 yr in Enceladus. This could explain Mimas-Enceladus paradox.

1. Numerical model

In our calculations we use numerical model developed by Czechowski (2012) (see e.g. description in [1]). The model is based on parameterized theory of convection combined with 1-dimensional equation of the heat transfer in spherical coordinates:

$$\rho c_p \frac{\partial T(r,t)}{\partial t} = \mathrm{div}(k(r,T)\,\mathrm{grad}T(r,t)) +$$

where r is the radial distance (spherical coordinate), ρ is the density [kg m^{-3}], c_p [J kg^{1} K^{-1}] is the specific heat, Q [W kg^{-1}] is the heating rate, and k [W m^{-1} K^{-1}] is the thermal conductivity. $Q(r, t)$ includes sources and sinks of the heat. The equation is solved in time dependent region [0, R(t)]. During accretion the radius $R(t)$ increases in time according to formula: $R(t) = a\, t$ for $t_{\mathrm{ini}} < t < t_{\mathrm{ac}}$, and $R(t) = R_{sat}$ for $t > t_{\mathrm{ac}}$, i.e. after the accretion (see e.g. [2]), where t_{ini} denotes beginning of accretion and t_{ac} denotes duration of this process.

If the Rayleigh number in the considered layer exceeds its critical value Ra_{cr} then convection starts. It leads to effective heat transfer. The full description of convection is given by a velocity field and temperature distribution. However, we are interested in convection as a process of heat transport only. For solid state convection (SSC) heat transport can be described by dimensionless Nusselt number Nu. We use the following definition of the Nu:

Nu= (True total surface heat flow)/(Total heat flow without convection).

The heat transport by SSC is modelled simply by multiplying the coefficient of the heat conduction in the considered layer, i.e.:

$$k_{\mathrm{conv}} = Nu\, k.$$

This approach is used successfully in parameterized theory of convection for SSC in the Earth and other planets (e.g. [3], [4]).

Parameterization of liquid state convection (LSC) is even simpler. Ra in molten region is very high (usually higher than 10^{16}). The LSC could be very intensive resulting in almost adiabatic temperature gradient given by:

$$\frac{dT}{dr} = \frac{g\alpha_m T}{c_{pm}},$$

where α_{m} and c_{pm} are thermal expansion coefficient and specific heat in molten region, g is the local gravity. In Enceladus and Mimas the adiabatic gradient is low and therefore LSC region is almost isothermal.

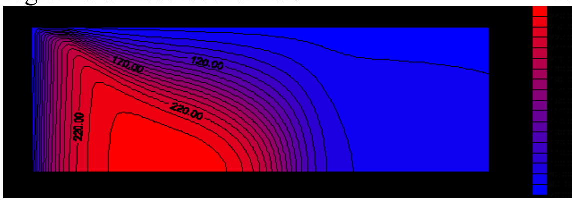

Fig.1 Thermal evolution of Mimas for the following values of parameters: ηm of 10^{14} Pa s, c_{hyd}= 240000 J kg^{-1}, E= 5×10^4 J $mole^{-1}$, $t$ac =0.1 Myr, k_{sil}=4.2 W m^{-1} K^{-1}, t_{ini} =1.8 Myr. Vertical axis gives distance from the center of the satellite (r/R_{Sat}). Horizontal axis gives log10(time in Myr) Note that initially the isotherms are going up following increasing radius of the accreting body. For the first Myr's the temperature increases fast because of high concentration of the radioactive elements. The maximum is reached in a few millions of years and subsequently isotherms corresponding to high temperature (say 220 K) move down.

2. Results

Comparison of thermal models of Mimas and Enceladus indicates that conditions favorable for starting tidal heating (interior hot enough) lasted for short time (~10^7 yr) in Mimas and for ~10^8 yr in Enceladus. This could explain Mimas-Enceladus paradox – see Fig. 1 and Fig. 2.

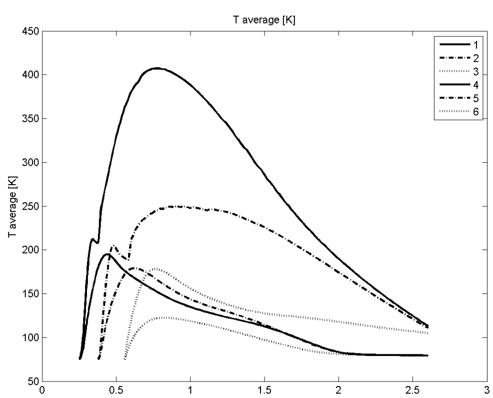

Fig.2 Comparison of average temperature T_{ave} for Enceladus and Mimas. Parameters: viscosity of 10^{14} Pa s, c_{hyd}= 240000 J kg^{-1}, E= 5×10^4 J ole^{-1}, t_{ac} =0.1 Myr, k_{sil}=4.2 W m^{-1} K^{-1}, t_{ini} =1.8, 4, 3.6 Myr for lines 1 (and 4), 2 (and 5), 3 (and , respectively. Initial temperatures of both tellites are the same; note common point at t = (leftmost). All lines for Mimas are below the corresponding lines for Enceladus indicating lower temperature in smaller Mimas. Note also that all lines for Mimas for large time converge for substantially

Conclusions

The Mimas-Enceladus paradox is probably the result of short time when Mimas was hot enough to allow for substantial tidal heating. The Mimas-Tethys resonance formed later when Mimas was already cool. (see also [1, 4]) The full text of the paper will be published in Acta Geophysica [5].

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