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On the tidal heating of Enceladus

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Abstract

Enceladus, one of Saturn's moons, shows significant volcanic activity identified by the Cassini spacecraft. The aim of the present study is to investigate - with the adaptation of mathematical tools used in geodynamics - the extent of tidal heating due to the mean motion resonance with Dione. For the purpose of calculations a two-layer model of Enceladus was used. The inner part of the model is a "rocky core" with a relative radius 0.55, while the outer part is composed of water ice. The results of model calculations show that the effective tidal heating is not uniformly distributed within Enceladus. It was found for the selected model of Enceladus, that the tidal heating is maximum within the depth interval (25-75) km. Due to the inhomogeneity within Enceladus, 85% of the tidal energy is generated in a volume that contains just 39% of its mass. In time intervals of 3.0×10^8 and 5.3×10^8 years the temperature increase in the relative depth range $0.70 \leq r/a_E \leq 0.90$ is approximately 270° and 370° Kelvin, respectively.

Keywords: Saturn, Enceladus, tide, solid body

1. Introduction

The medium size, spherical satellites of Saturn (listed in Table 1) were probably locked into synchronized rotation states with Saturn early in their history. Consequently, their tidal bulge has no motion in a coordinate system fixed to the body of the moon. Under this condition there is no tidal friction influencing the axial spin. However, this situation changes if the orbital motion of a moon is also in resonance with the orbital motions of other members of the satellite system. This resonance generates a forced eccentricity that leads to temporal variation of the tidal bulge due to gravitation from the central body of the system (Peale & Cassen, 1979; Wisdom, 2004). Enceladus (mean radius $a_E = 252.1$ km) orbits around Saturn between Mimas and Tethys. Its orbit has evolved into mean motion resonance with Dione which generates its orbital eccentricity 0.0045 (Table 1).

Enceladus is probably the brightest object in the solar system, its water ice surface reflecting almost 100% of the sunlight (Spencer et al., 2006). Contrary to its neighbours Mimas and Tethys the surface of Enceladus shows the presence of both internal and external tectonic processes. Cryovolcanism almost certainly has resurfaced Enceladus at various epochs of its history (Peale, 2003). According to Ross and Schubert (1989) the geologic activity of resurfaced regions could be as old as 1.0-1.7 Gyr, which suggests a similar age for the presence of orbital resonance. An essential part of Enceladus is covered by almost crater-free plains with north-south trending fractures with Y-shaped discontinuities (Porco et al. 2006). Similar linear structures were observed on the surface of the Earth in the the cosmogeological map of the former Soviet Union (Brjukkanov et al. 1984). This fault system on the surface of the Earth is not caused by recent tectonic activity, has a regular distribution with respect to the axis of rotation and has been explained by stress fields of a despinning planet (Melosh 1977).

No object in the solar system smaller than Enceladus is known to be tectonically active. Traces of recent eruptions on Enceladus were detected already by Squyres et al. (1983) in

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form of the resurfacing of fresh materials on the surface. Plumes erupting from the south polar region of Enceladus have been detected in pictures taken by the Cassini spacecraft from 16 January 2005 (Porco *et al.* 2006). A fountain higher than 435 km was detected in Cassini images observed on 25 November 2005. The elevated South Pole temperature anomaly detected by Cassini, connected with plumes emanating from this region, corresponds closely to a recently active region of four linear depressions called “tiger stripes”. This circumstance renders probable that these structures are deep enough to conduct the water vapour from the interior of Enceladus to the surface. Very recently Hurford *et al.* (2007) “...report a mechanism in which temporal variations in tidal stress open and close the tiger stripe rifts, governing the timing of eruptions. During each orbit, every portion of each tiger stripe rift spends about half the time in tension, which allows the rift to open, exposing volatiles and allowing eruptions”. This phenomenon requires large subsurface tidal stresses that imply the presence of a liquid ocean.

To explain this phenomenon of recent tectonic activity a heat source within Enceladus is needed. Possibilities are:

- tidal heating associated with eccentricity of the orbit
- tidal heating due to the librations of Enceladus
- presence of radioactive heating.

The main goal in this paper is to show to what extent the tidal heating can melt the outer icy part of Enceladus. The frictional energy due to the tides can be dissipated as heat.

The released heat from the south polar tiger stripes region has been estimated to be (5.8 ± 1.9) GW (Spencer *et al.*, 2006). Contributions published until now were not able to establish a complete theoretical model able to produce such a heating rate. Most of them were based on a radially homogeneous model of Enceladus and used the Kelvin type Love numbers corresponding to this structure. Squyres *et al.* (1983) already remark that the rate of tidal heating (in case of homogeneous inner structure) is not sufficient to keep up the current rate of Enceladus tectonic activity. The rate of tidal heating estimated by Porco *et al.* (2006) is about 0.12 GW. Recently Meyer & Wisdom (2007) find that equilibrium tidal heating can not account for the observed heat released by Enceladus. Generally speaking it can be concluded that recent observations require more heat generation than current estimates based on homogeneous models provide.

Data listed in Table 1 show characteristics of some moons of Saturn (together with the similar data of Io, Europa, Ganymedes, Callisto and the Earth’s moon). It is immediately evident that Enceladus has no physical properties significantly different from other moons of Saturn (except Titan), with only one exception: the observed high average density of the moon. Since its surface is formed by water ice, the high mean density proves its significant internal inhomogeneity. This circumstance results in a significantly different tidal energy distribution from that in a homogeneous model. Since homogeneous models were unable to provide sufficient heat generation by tidal friction we introduce a spherically symmetric radially heterogeneous model of Enceladus in order to see if tidal heating in such a model can explain the observed heat generation.

To do so in the present contribution the tools of global geodynamics are used which are shortly described in the second section of the paper. The third section describes a somewhat arbitrarily selected model of Enceladus, while the fourth describes the physics of the heating in case of the chosen model.

2. Description of elastic deformation of a spherical body

In 1863 Thomson (Kelvin) (Thomson, 1863) on the basis of earlier studies of W. Hopkins derived an equation for estimation of the effective shear modulus μ of the Earth with the use of tide gauge records. On the basis of Kelvin’s work Love (1944) obtained the following expressions for the tidal deformation of a homogeneous and elastic planet

$$h = \frac{5f}{2f+1}; k = \frac{3f}{2f+1}; l = \frac{3f}{2(2f+1)}; f = \frac{g \cdot \rho \cdot a}{19\mu}$$

(here h , k , l are the Love and Shida numbers g , ρ and a are the surface gravity, the mean density and the mean radius of the investigated object respectively). The Love-Shida numbers related to each other this case are: $k=0.6h=2l$. In case of Enceladus $k=0.0018$, $h=0.0030$ and $l=0.0009$ if the data listed in the first line of Table 3 are used.

The shear modulus and the density of planets and moons are functions of depth even in case of homogeneous bodies due to hydrostatic pressure. This circumstance makes the use of above mentioned equations of Love problematic. To obtain the effective shear modulus and mean density for the equations of Love is even more controversial when a radially inhomogeneous body (like our Enceladus model) is the object of investigations. When Kelvin type Love numbers are used the real inner structure is replaced by a homogeneous body with significantly different inner composition.

To overcome this problem in our investigation methods used in modern earth sciences are employed to determine stresses within Enceladus.

Stresses produced by tidal forces in Enceladus were calculated with the use of the sixth order system of inhomogeneous differential equations of elasticity for a gravitating sphere given independently by Takeuchi (1950), Molodensky (1953) and Alterman *et al.* (1959). These stresses are dependent on the radial distribution of the density $\rho=\rho(r)$ and Lamé parameters $\mu=\mu(r)$, $\lambda=\lambda(r)$ and can be described within the elastic sphere with the use of three dimensionless auxiliary functions which depend on the distance r from the centre of Enceladus influenced by the tidal effect. $H_n(r)$ describes the radial displacement, $T_n(r)$ gives the horizontal displacement, $R_n(r)$ is associated with the gravitational potential. $H_n(r)$, $T_n(r)$ and $R_n(r)-1$ at the surface $r=a$ take the values of the Love numbers $k_n=R_n(a)-1$, $h_n=H_n(a)$ and Shida number $l_n=T_n(a)$ (n is the degree of spherical harmonics, which takes the value $n=2$ in case of tidal studies).

From among three boundary conditions necessary to solve the above differential equation system two are related to the normal (radial) $N_n(r)$ and tangential (horizontal) $M_n(r)$ stresses, while the third equation is the Poisson formula.

By the definition of elastic theory of tidal deformations $N(a)=M(a)=0$ (Molodensky, 1953). At the core-mantle boundary $r=b$, $N(b)$ is equal to the hydrodynamic pressure and the value of $M(b)$ depends on the structure of the core.

The normal (radial) $N_n(r)$ and tangential (horizontal) $M_n(r)$ stresses can be obtained on the basis of auxiliary functions $H_n(r)$, $T_n(r)$ and their derivatives $\frac{\partial H_n(r)}{\partial r}$, $\frac{\partial T_n(r)}{\partial r}$ together with the radial functions of the Lamé parameters $\mu=\mu(r)$, $\lambda=\lambda(r)$ with the use of relations (Molodensky, 1953)

$$N_n(r) = \left[\lambda(r) + 2\mu(r) \right] \cdot \frac{\partial H_n(r)}{\partial r} + \lambda(r) \left[\frac{2}{r} \cdot H_n(r) - \frac{n(n+1)}{r^2} \cdot T_n(r) \right] \quad (1)$$

$$M_n(r) = \mu(r) \left[\frac{\partial T_n(r)}{\partial r} - \frac{2}{r} T_n(r) + H_n(r) \right] \quad (2)$$

In the following sections, due to uncertainty of inner structure of Enceladus it will be assumed that $\mu(r) = \lambda(r)$.

Earlier experience (Varga & Denis, 1988) shows that the auxiliary functions $H_n(r)$, $T_n(r)$ and their radial derivatives depend significantly on the inner composition of the investigated elastic gravitating object. Consequently the radial distributions of normal (radial) $N_n(r)$ and tangential (horizontal) $M_n(r)$ stresses determined by Eqs. 1 and 2 are also model dependent. On the contrary the surface values ($r=a$) of the auxiliary functions – the Love-Shida numbers – are significantly less modified by variation of the inner structure (Varga 1985, 1992; Varga & Denis, 1988). To illustrate this last statement it should be mentioned that for the significantly inhomogeneous model of Enceladus (described in next section) we calculated Love-Shida numbers $k=0.0017$, $h=0.0028$, $l=0.0011$ which practically coincide

with the results obtained with equations based on the work of Kelvin. In the next section we show that significant differences arise for the stresses as functions of radius when a homogeneous body is replaced by a two-layer model.

3. Distribution of tidal stresses within the radially inhomogeneous model of Enceladus

For the model of the inner structure of Enceladus, somewhat arbitrary, two homogeneous layers are considered:

- „icy” mantle $1 \geq r/a > 0.55$
- „rocky” core $0.55 \geq r/a_E \geq 0$

The model described in Table 3 of course has the same mean density as Enceladus, but it is somewhat artificial. Arbitrarily the boundary between the core and the mantle of Enceladus is placed at $r/a_E=0.55$ (like in the case of the Earth). The density of the “icy” mantle is taken somewhat higher than density of pure water ($\rho=1100 \text{ kg/m}^3$). Auxiliary functions $H_n(r)$, $T_n(r)$, their derivatives $\frac{\partial H_n(r)}{\partial r}$, $\frac{\partial T_n(r)}{\partial r}$ and the normal $N_n(r)$ and tangential $M_n(r)$ stresses

calculated with the use of our model of inner structure of Enceladus are shown on Fig. 1. Experience from studying of very different models of the Earth shows: the shape of the functions (but not the magnitude) of $M_2(r)$ and $N_2(r)$ remain similar for quite different models of the mantle in cases, when the depth of the core-mantle boundary remains the same and when a jump in density is present (Varga, 1985, 1988, 1992). The alteration of the physical model of the core (e.g. density and radius) has a strong effect on the geometry (depth, sharpness and magnitude of maxima) of auxiliary relations $M_2(r)$ and $N_2(r)$. In case of expanded core the peaks of the auxiliary relations for the normal and tangential stresses are situated closer to the surface and they are sharper. Oppositely in case of reduced core the maxima of $M_2(r)$ and $N_2(r)$ are smoothed and are deeper (in case of homogeneous body in the vicinity of the middle the mantle). This means: to some extent the numerical results described in the next paragraph can be modified by variation of the position of the core-mantle boundary and this way the tide generated heat can be increased or decreased.

4. Tidal heating of Enceladus

Due to synchronous rotation of Enceladus the tidal bulge varies due to forced eccentricity caused by 2:1 orbital tidal resonance with Dione. The corresponding variation of second-degree tidal potential can be given by (Melchior, 1973)

$$\Delta W_2 = \frac{G \cdot M_S \cdot a_E^2}{R_E} \left(\frac{3}{2} \cos^2 \zeta - \frac{1}{2} \right) \left(\frac{r}{a_E} \right)^2 \frac{2e_E}{(1-e_E)R_E} \quad (3)$$

(ζ is the angle between the radius-vector of an arbitrary point of Enceladus and the radius vector between the centre of gravity Saturn and Enceladus; another symbols of Eq. 3 are explained in Table 2).

The normal and tangential second degree tidal stresses can be expressed with the use of auxiliary functions $N_2(r)$ and $M_2(r)$ and tidal potential ΔW_2 (Eqs. 1 - 3) as

$$\sigma_N(r) = N_2(r) \frac{\Delta W_2(r)}{g_E \cdot r^2} \cdot \left(\frac{r}{a_E} \right)^2 \quad (4)$$

$$\sigma_M(r) = M_2(r) \frac{\partial(\Delta W_2(r))}{\partial \Psi} \cdot \frac{1}{g_E \cdot r^2} \cdot \left(\frac{r}{a_E} \right)^2 \quad (5)$$

(Ψ is an arbitrary azimuth angle on Enceladus)

Stress generated internal energy at a distance r from the centre in a unit volume $E_{UNIT}=E/V$ is

$$E_{UNIT}(r) = \frac{1}{2} \sigma(r) \tau(r) = \frac{1}{2} \frac{\sigma^2(r)}{\mu(r)}$$

because $\tau(r) = \frac{\sigma(r)}{\mu(r)}$ (where $\sigma(r)$, $\tau(r)$ and $\mu(r)$ are the stress, the strain and the shear respectively). Consequently E_N or E_M in a spherical layer of thickness Δr can be obtained with

$$E_{LAYER}(r) = 2\pi \frac{\sigma^2(r)}{\mu(r)} r^2 \Delta r$$

The total energy is consequently

$$E = \int_0^{a_E} E_{LAYER}(r) dr = 2\pi \int_0^{a_E} \frac{\sigma^2(r)}{\mu(r)} r^2 dr \quad (6)$$

Results of calculations obtained with the use of Eqs. (4)-(6) are plotted on Fig.2. They show that in the “icy” mantle there is an energy anomaly due to tangential (E_M) and normal (E_N) stress of the order of 10^{16} - 10^{17} Joule. Most of the tidal energy (above 85%) is generated in a spherical layer $0.70 \leq r/a_E \leq 0.90$ i.e. in the 39% of the mass. This means: the tidal heat is not smoothly distributed within Enceladus, it is focused to the upper part of the mantle.

The diminution of energy which is dissipated per cycle (T) is the ratio of tide generated energy E and effective tidal dissipation parameter Q : $\Delta E = 2\pi E \cdot Q^{-1}$. Most of the authors dealing with dissipation of Enceladus and other celestial bodies are estimating the dissipation in this way (e.g. Hubbard, 1984; Peale 2003; Meyer et al., 2008; Squyres et al., 1983), however the value of Q is not known for Enceladus from observations.

To estimate the amount of energy dissipated during the tidal process we use for the present study $Q = 20$ (close to value valid for ice) and $Q = 300$ (obtained for Earth by Ray et al., 1996).

This results in $\frac{dE}{dt} = \Delta E \cdot T^{-1} = 2 \times 10^{14} - 5 \times 10^{14}$ Joule.

The phenomenon that tidal energies are concentrated within the mantle is a general property of moons and planets. It is so - independently of the selected model – due to features of $N_2(r)$ and $M_2(r)$ and due to $\left(\frac{r}{a}\right)^2$ in Eqs. (4) and (5).

For example this phenomenon explains the radial distribution of quakes within the Earth’s moon. Foci of deep moonquakes are concentrated in the middle mantle (Nakamura 1983) in accordance with results of stress model calculations. Shallow focus seismic events of the Moon are in relationship to variations of surface temperature and meteorite impacts.

For the energy dissipation one gets (Melchior 1973)

$$-\left[\frac{dE}{dt}\right]_E = J \cdot \eta \cdot K \cdot M_{0.70 \leq r/a_E \leq 0.9} \quad (7)$$

where J is the mechanical equivalent of heat (4.182 Joule), η expresses the specific heat of the ice (≈ 2000 Joule/kg). $M_{0.70 \leq r/a_E \leq 0.9}$ is the mass of the part of icy mantle ($= 2.8 \cdot 10^{19}$ kg), where the tidal stresses are acting. To calculate the warm up K (in degree/s), we get for dissipation from $\Delta E \approx 5 \cdot 10^{14}$ Joule and $\Delta T = 1/2 T_E = 0.685$ day

$$-\left[\frac{dE}{dt}\right]_E = 6 \cdot 1GW \quad (8)$$

With the use of the mentioned data one gets $K = 2.7 \times 10^{-14}$ degree/s. This means that during 1 million year the temperature enlargement in the whole “middle mantle” can be ≈ 0.9 Kelvin, i.e. the central part of the icy mantle is growing warm from 0^0 K to 270^0 K and 370^0 K within 300 and 530 million year. (For a comparison for the Earth $K = 5 \cdot 10^{-15}$ degree/s, i.e. 1 Kelvin during 10^9 year was obtained).

For realistic estimation of the warming up process the possible heat energy losses should be considered. They are the thermal convection and the conductive heat loss.

During the warming process the energy loss can be theoretically due the thermal convection and conducted heat. In case of such a small body as Enceladus the Rayleigh number

$$Ra = \frac{g_E \cdot \alpha \cdot \Delta T \cdot a_E^3}{\nu \cdot \kappa} \ll Ra_c \approx 700$$

(α is the thermal expansion coefficient ($10^{-6} \cdot K^{-1}$); $\Delta T = 270^\circ K$; the kinematic viscosity is $\nu = 1.5 \cdot 10^{10} m^2 \cdot s^{-1}$; the thermal diffusivity $\kappa = 1.2 \cdot 10^{-6} m^2 \cdot s^{-1}$) is much smaller than the critical Rayleigh number Ra_c . Consequently the thermal convection is not possible.

The conductive heat ΔH loss is small. With thermal conductivity $k = 2 W \cdot m^{-1} \cdot K^{-1}$ and estimated temperature gradient $dT/dr \sim 5 \cdot 10^{-3} K/m$ (if $\Delta T = 270 K$ and $\Delta r = 5 \cdot 10^4 m$) one gets

$$\Delta H = 4\pi a_E^2 \cdot k \cdot dT/dr = 8.6 \cdot 10^7 W$$

what is ~ 1 per cent of $\left[\frac{dE}{dt} \right]$ in Eq.(8). The absence of thermal convection and the low value

of heat loss through conductivity support the warm-up due to tide in the layer $0.9 > r/a > 0.7$.

There is no information about the volume of the really melted deep-seated ice and on the extent of cooling after an eruption. After the warming up of the layer $0.90 > r/a_E > 0.70$, to keep the volcanic activity running the heat generated by tidal friction is only needed to compensate the quantity of lost heat.

5. Conclusions

Tidal stresses and energies in the case of a radially inhomogeneous model of Enceladus are focused chiefly in the upper part of its icy mantle (25-75 km). The position of the layer where the most of the heating effect is concentrated depends on the composition of course. After a considerably long time interval (300 Ma) the tide generated heat can melt the mantle layer of Enceladus and produce the observed volcanism. It should be mentioned here, that this period of heating could be too long in comparison with the usually estimated duration of resonances of the order 10Ma -100Ma (Roberts, J.H., Nimmo F., 2008). In this case the described heating process in the past could be related to different resonances. The recently observed eruptive activity is connected with the natural regulator of tiger stripes, which keeps the tidal heating of Enceladus in present epoch close to equilibrium. The capacity of such a tidal engine – as it was shown above by model calculations – is 6.1 GW (see Eq. 8), in a good agreement with results of observations: $(5.8 \pm 1.9) GW$ (Spencer et al., 2006). The efficiency of the warming up depends on the inner structure of Enceladus, of course.

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References

- Alterman, Z., Jarosch, H., Pekeris, C.I., 1959. Oscillations of the Earth, Proc. R. Soc. London, Ser. A 252, 80-95.
 Brjukanov et al., 1984. Cosmogeological map of the USSR of the scale 1 : 2 500 000. Paper presented at the 27th International Geological Congress, Section C 18, Nauka, Moscow.
 Hubbard, W.B., 1984: Planetary interiors, Van Nostrand Reinhold Company
 Hurford, T.A., Helfenstein, P., Hoppa, G.V., Greenberg, R., Bills, B.G., 2007. Eruptions arising from tidally controlled periodic openings of rifts on Enceladus, Nature, 447, 292-294.
 Love, A.E.H., 1944. A treatise on the mathematical theory of elasticity, 4th edition, Dover, New York.
 Melchior, P., 1973. Physique et dynamique planétaires, volume 4 Geodynamique
 Melosh, M.J., 1977. Global tectonics of a despun planet, Icarus, 31, 221-243.
 Meyer J., Wisdom J., 2007. Tidal heating in Enceladus. Icarus, 188, 535-539.

Molodensky, M.S., 1953. Elastic tides, free nutations and some problems of the Earth's structure. Trudi Geophys. Inst., 19 (146), 3-52.

Nakamura, Y., 1983. Seismic velocity structure of the lunar mantle, J. Geophys. Res., 88, 677-686.

- Peale, S.J., 2003. Tidally induced volcanism. *Celestial Mechanics and Dynamical Astronomy*, 87, 129-155.
- Porco, C.C. et al., 2006. Cassini observes the active south pole of Enceladus. *Science*, 311, 10 March, 1393-1401.
- Roberts, J.H., Nimmo F., 2008. Tidal heating and the long-term stability of a subsurface *ocean* on Enceladus. *Icarus* 194, 675-689
- Spencer J. R., Pearl J. C., Segura M., Flasar F. M., Mamoutkine A., Romani P., Buratti B. J., Hendrix A. R., Spilker L. J., Lopes R. M. C., 2006. Cassini Encounters Enceladus: Background and the Discovery of a South Polar Hot Spot, *Science*, 311, 5766, 1401 - 1405
- Squyres, S.W., Reynolds, R.T., Cassen, P.M., 1983. The evolution of Enceladus. *Icarus*, 53, 319-331.
- Takeuchi, H., 1950. On the earth tide of the compressible earth of variable density and elasticity. *Transactions American Geophysical Union*, 31, 5, 651-689.
- Thomson W., 1863. On the rigidity of the Earth, *Philosophical Transactions of the Royal Society of London*, 153, 573-582.
- Tobie, G., Mocquet, A., Sotin, C., 2005. Tidal dissipation within large satellites : Application to Europa and Titan. *Icarus*, 177, 534-549
- Varga, P., 1985. Influence of external forces on the triggering of earthquakes, *Earthq. Predict Res.*, 3, 191-201.
- Varga, P. and Denis C., 1988. A study of the variation of tidal Love numbers with Earth structure., *Geophys. Transact.*, 34, 4, 263-282.
- Varga, P., 1992. Stresses of lunisolar origin acting at the core mantle boundary. *Manuscripta Geodetica*, 17, 351-355.
- Varga, P., 1998. Earth tidal phase lag and the tidal development of the Earth-Moon system. *Proceedings of the Thirteenth International Symposium on Earth Tides*. Obs. Roy. Belgique, Série Geophysique, 297-305, Bruxelles.
- Wisdom, J., 2004. Spin-orbit secondary resonance dynamics of Enceladus. *The Astronomical Journal*, 128, 484-491.

Table captions

Table 1. Comparison of properties of main Saturn satellites, the Galilean moons of Jupiter and Earth's moon. Data are taken from Porco et al. (2006), and Tobie et al. (2006)

Table 2. Some physical properties of Enceladus

Table 3. Two-layered Model of Enceladus.

Table 1
SATURN

Moon (1)	Mean distance from central planet (km) (2)	Orbital eccentricity (3)	Orbital periods (days) (4)	Equatorial radius (km) (5)	Mean density (kgm ⁻³) (6)
Mimas	185 520	0.0202	0.942	196	1170
Enceladus	238 020	0.0045	1.370	250	1610
Thetys	294 660	0.0000	1.888	530	1210
Dione	377 400	0.0022	2.737	560	1430
Rhea	527 040	0.0010	4.518	765	1330
Titan	1 221 850	0.0292	15.945	2575	1880
Hyperion	1 481 000	0.1042	21.277	205	1400
Iapetus	3 561 300	0.0283	79.330	730	1201
JUPITER					
Io	421 600	0.004	1.77	1815	3550
Europa	670 900	0.009	3.55	1569	3010
Ganymedes	1 070 000	0.002	7.15	2631	1940
Callisto	1 883 000	0.007	16.69	2400	1860
EARTH					
Moon	384 300	0.054	27.32	1738	3360

Table 2

Orbital characteristics	Physical characteristics
Semi major axis (R_E): $2.37948 \cdot 10^8$ m	Mean radius (a_E): $2.521 \cdot 10^5$ m
Eccentricity (e_E): $4.5 \cdot 10^{-3}$	Mass (M_E): $1.08 \cdot 10^{20}$ kg
Orbital period (T_E): 1.3702 day	Volume: $6.712 \cdot 10^{16}$ m ³
Mean surface temperature: 75 K	Mean density (ρ_E): 1610 kg·m ⁻³
(Mass of Saturn (M_S): $5.68 \cdot 10^{26}$ kg)	Surface gravity: 0.078 m·s ⁻²

Table 3

	Mass (kg)	Volume (m ³)	Density (kg·m ⁻³)	μ GPa	λ GPa
„icy” mantle	$6.15 \cdot 10^{19}$	$5.59 \cdot 10^{16}$	1100	5	5
„rocky” core	$4.64 \cdot 10^{19}$	$1.12 \cdot 10^{16}$	4150	20	20

Figure captions

Fig. 1. Distribution of auxiliary functions $H_n(r)$, $T_n(r)$, their derivatives $\frac{\partial H_n(r)}{\partial r}$, $\frac{\partial T_n(r)}{\partial r}$, the normal $N_n(r)$ and tangential $M_n(r)$ stresses along the radius according to the model of the inner structure of Encelads given in Table 3.

Fig.2. Energy due to tangential (E_M) and normal (E_N) tidal stress within the mantle of Enceladus

Fig.1

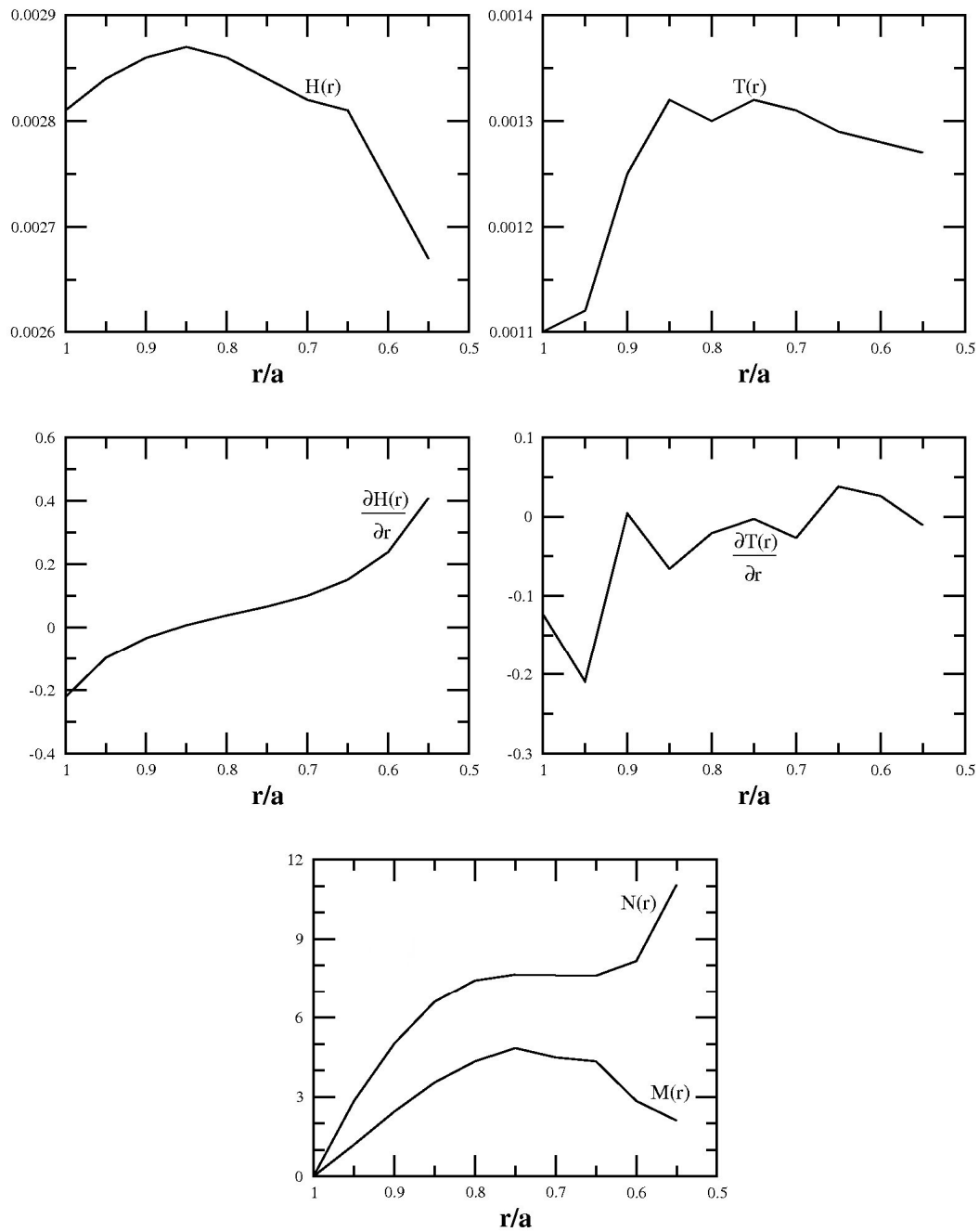


Fig.2

