Project report AT-323 "Thermomechanics of sea ice cover and loads on structures"

Thermal stresses on the ice crust of Jupiter's moon Europa

Christian Katlein

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Department of Arctic Technology, University Centre on Svalbard
Institute for Theoretical Astrophysics, University Tübingen

Abstract

The features on Jupiter's Moon Europa and their formation have been discussed a lot. Mostly the observed cracks on Europas surface are said to be related to different tidal forces. As thermal expansion has never been considered but plays a major role in sea ice movement on earth's Arctic Oceans, this report for the Course AT-323 "Thermodynamics of sea ice and loads on structures" at the University Centre of Svalbard (UNIS) tries to estimate the impact of thermal stresses on Europa's ice crust and its relevance for visible surface structures. For that purpose the ice cover and its behaviour is modeled in a mathematical MATLAB-model.

Contents

1 Introduction

Europa is one of the four Galilean Satellites of Jupiter discovered by *Galileo Galilei* in the year 1610. In modern times Europa has been visited and examined by the spacecrafts *Voyager*(1979) and *Galileo*(1995). Pictures from Europa's surface show features that resemble the ice surface of the Arctic Oceans on earth and spectral data reveals that the crust mainly consists of H_2O.

This existence of water increased the interest of scientists as some of the water could be in a liquid state and therefore is a potential place for the discovery of extraterrestrial life. There are several evidences for a liquid ocean under the solid ice crust, whereas ice thickness is still a point of great discussion with values ranging from less than one up to hundred kilometres, depending on which features on Europa are used for ice-thickness variations

Europa has no internal heat source. Therefore estimations on ice thickness are based on the process of tidal heating, as Europa resides in a very close orbit to Jupiter and is locked into an 4:2:1 orbital resonance with two others of the Galilean Sattelites, *Ganymede* and *Io*. This resonance forces Europa on an eccentric orbit resulting in –though locked in synchronous rotation– high tidal forces. These forces are seen as the reason for several surface features. Calculations of the tidal forces can describe some of the crack patterns on Europa but have the problem that stresses induced by diurnal tides are probably not big enough (100 kPA) for breaking ice. Material parameters of ice under the temperature conditions on Europa around 100 K are completely unknown but extrapolation from terrestrial data reveals tensile strengths of around 200 kPa [1]. Some papers [2, 21] suggest a slightly non-synchronous rotation of Europa. This would be a possibility to reach values high enough for crack formation even in ice behaving like on earth. Another possibility is a strongly decreased tensile strength of Europa's ice crust, potentially due to salt content and high porosity.

This paper aims to discuss the thermal stresses on the ice cover to compare it with the tidal stresses, as thermal expansion can be very important in sea ice movement on the earth. Effects of thermal expansion under the conditions on Europa are pretty unknown – and most papers (except Chumachenko [3]) neglect it – as no experiments are known to the author for temperatures around 100 K and the knowledge of major factors like porosity and salinity is far too small. Nevertheless it is possible to do some estimations with extrapolated material parameters to determine if thermal stresses are relevant compared to the found tidal stresses.

1.1 The ice crust on Europa

Data from the two spacecraft missions revealed that Europa has a solid core and an outer layer of H_2O which is completely or partly frozen. Estimates for the ice thickness were derived from several surface features resulting in values ranging from about 1 to 100 km. The thickness of this ice layer is still not determined and it might vary a lot in space and time [4]. The existence of a liquid water ocean under the ice crust is still unsure, though there exists some evidence through feature structures and crack propagation patterns.

1.2 Features on the ice crust

The ice crust of Europa is pretty even compared to the earth's moon. Already on the first pictures from the *Voyager* missions were obvious long linear structures visible, but high resolution data from *Galileo* also

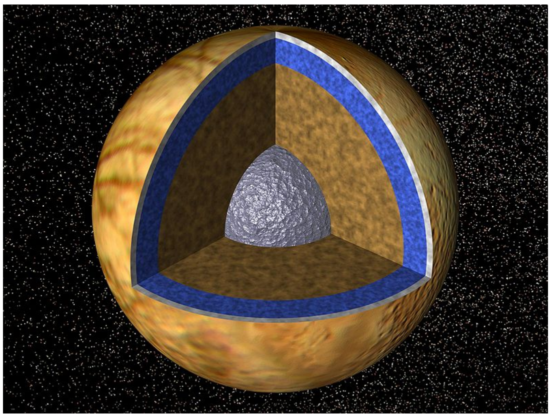

Figure 1: Probable constitution of Europa with ice crust, liquid ocean and solid core [5]

Figure 2: Linea features and Lenticulae on Europa [8]

revealed a lot of other features already described by Greeley [6]. In general the ice surface appears in different colors, as in some parts the pure ice seems to be contaminated by salts and other minerals or an upper layer of redish regolith.

Linea

There are several types of linear structures on Europa's surface. These features are typically several hundred kilometers in elongation but only about maximum hundred metres in elevation. There are bands with absolutely flat ground, which can also be disturbed by other surface features. Millions of cracks spread over the surface of Europa. Some of them look like simple cracks, whereas others more look like double ridge structures. Especially in the midlatitudes several ridge features on the surface have a cycloidal shape who's origin was for example discussed by Hoppa et al. [7]. It seems like these features – even though looking alike – are very different from ice ridges in the earth's Arctic Oceans which are built up by compression forces. Analysis of tidal force patterns [2] leads to the conclusion that tensile failure and a different mode of ridge build up is much more likely on Europa.

Lenticulae

Lenticulae are rounded surface features with uneven terrain but no big elevation above the surface. They look like a disturbance of the ice layer and might be related to extrusion of material from the liquid below. Thermal stresses have been discussed [9] as factor for crack formation and material breakup but as ice thickness is unknown the ongoing processes are hardly understood. The average size of such features is about 10 km in diameter.

Chaos terrain

Huge areas of Europas surface are covered with so called chaos terrain. The surface is structured by cracks, iceblocks and ice rafts drifting around in that chaos terrain. This appearance leads to the conclusion that the ice shell must be – or has been – relatively shallow during the formation of chaos terrain and big relative displacements of ice rafts indicate a highly mobile or even liquid underlaying layer. Chaos terrain appears darker with lower albedo and is often at a slightly lower altitude than the surrounding plains.

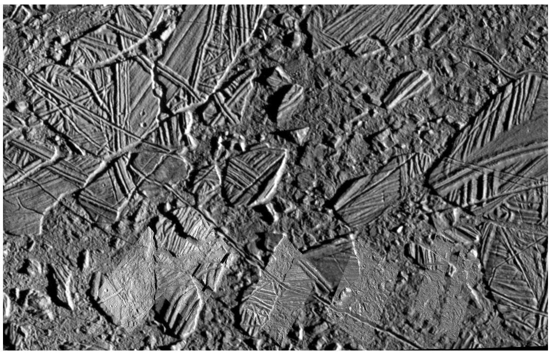

Figure 3: Ice rafts in chaotic terrain on Europa [10]

Figure 4: colour enhanced image of the impact structure Pwyll [12]

Impact structures

One of the most striking facts about Europas surface structure is the lack of impact structures compared to e.g. our moon or the other galilean satellites. This is evidence for a continuous surface renewal and a geological young surface. Extrapolations from the impact rate in that part of the solar system led to a surface age of not more than one billion years [11], so the surface must have reshaped during the evolution of the satellite.

1.3 Formation of ice crust features

The processes of surface feature formation are not completey understood, but there are quite some evidences for the following processes of surface formation by interaction of the ice shell with the liquid ocean below:

Linear features: Creation of linear features is connected to crack opening induced by tidal forces. Crack opening due to thermal stresses will be discussed later in this paper. The opening crack fills up with "liquid" material from below which freezes and forms in this repeated process double ridges. This process works analogous to the landforming rift valleys at earth's ocean floors. Compressive forces on the ridge line lead to elastic deformation of the ice sheet and can explain the observed forebulges with flanking cracks [13].

Lenticulae: The formation of Lenticulae is said to be related to convective plumes of warmer material from the inside ocean. Rising water thaws the ice crust, upward loads and thermal thrusts are able to break it. As well as chaos terrain, Lenticulae appear darker than their environment which is a hint to a higher salt or mineral content of the liquid ocean. On Earth, multi year sea ice also looses its brine content due to brine drainage leading to fresher ice flows than the water below. This process should be similar on Europa indicating that surface areas with higher mineral content are formed of material which has emerged from the ocean not too long time ago. This optical impression was confirmed by *Galileo*'s near infrared investigations shown in Figure 5.

Chaos terrain: Chaos terrain seems to be a "bigger" variant of Lenticulae with ice floes still floating – or floating during the creation of that surface part – on the liquid water ocean. Its browner colour shows that the material is young on a geological timescale.

2 Modelling

To evaluate the influence of thermal stresses on the formation of cracks and to compare the effect to the effects of tidal stresses, the thermal and mechanical development of Europa's surface layer in the sun's radiation field were modelled for this investigation.

2.1 Radiation model

Europa encircles Jupiter with a period of 3.6 days. It has a diameter of 3122 km and a mean density of 3010 $\frac{kg}{m^3}$. The mean temperature is stated as about 100 K in the NASA fact sheet [15]. It's measured surface albedo of $a = 0.68$ [16] is one of the highest in the solar system caused by the high reflectivity of the ice crust. The solar constant is about $c_s = 50\ \frac{W}{m^2}$ at the distance of Jupiter from the sun.

For the simulation of temperatures, Europa was overlayn with a grid in rectangular projection with the spacing of one degree. The solarflux Φ heating the sun-facing hemisphere could be calculated for each position and time step by

$$(1)\Phi_{sun} = c_s \cdot (1 - a) \cdot \sin(\psi + \theta) \cdot \cos\phi$$

with ψ the orbit anomaly, longitude θ and latitude ϕ. The calculated solarflux is shown in Figure 6.

Opposed to this solar heating Europa cools down due to radiative energy loss–especially on the sun averted hemisphere. As no atmosphere exists the radiative processes are not too complex and can be approximated by standard blackbody radiation:

$$(2) \qquad \Phi_{blackbody} = \sigma_b \cdot T^4$$

with σ_b the Stefan-Boltzmann constant and T the surface temperature.

Internal heating due to tidal heating has been discussed [9] and estimated to $0.05 - 0.2\ \frac{W}{m^2}$. As this model does not consider tidal processes the heating rate has been estimated by a simple energy balance to make the model consistent: The temperature at the poles is known to be around 50 K [15]. As the rotational axis of Europa is more or less parallel to the orbital axis of Jupiter, there are no seasons on the satellite and solar influx at the poles should be negligable. Therefore internal heating and blackbody radiation should be in balance, which leads to an internal heating flux of:

$$(3)\ \ \Phi_{heating} = \sigma_b \cdot 50\ K^4 = 0.3544\ \frac{W}{m^2}$$

This result lies slightly above the numbers

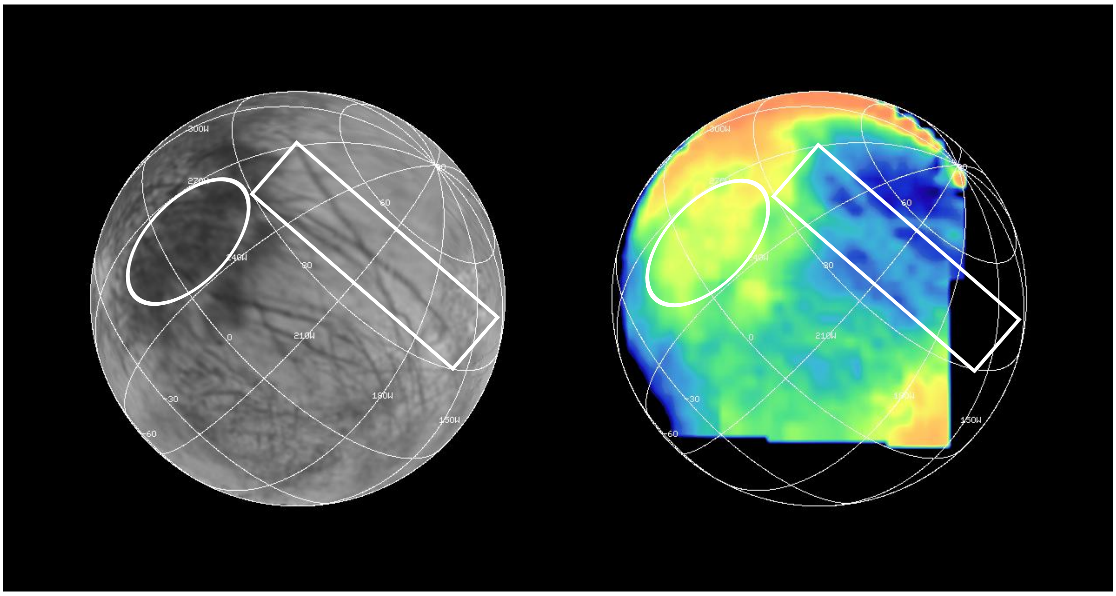

Figure 5: Comparison of a optical *Voyager* image (left) to a *Near Infrared Mapping Spectrometer* image (right) from the *Galileo* orbiter of the Jupiter averted Hemisphere. Higher Mineral content is shown in a brighter color and can be connected to visible surface features as linea (box) and chaos terrain (ellipse) [14]

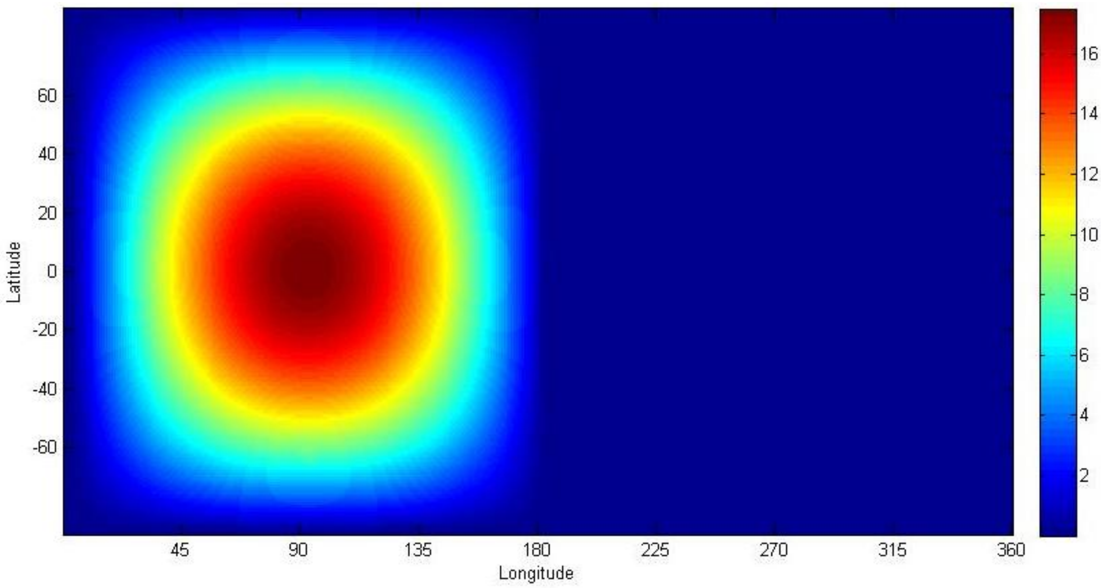

Figure 6: Europa – calculated solar flux $[W/m^2]$

estimated by Ruiz [9] but the difference is not big concerning the numeric model.

The model calculates these three energy fluxes for each point and sums them up to a total energy flux. This energy is disposed in the uppermost layer of the ice crust. Estimation of the radiation penetration depth of solar light into the ice crust reveals that only the very uppermost part is affected by the diurnal radiative variaton. For a good approximation it is enough not to solve the complete *Stefan-Problem* but only calculate the temperature change due to this energy disposal in a well defined volume of ice.

$$\frac{\partial T}{\partial t} = \frac{\Phi_{total} \cdot A \cdot t}{c_v \cdot m_{ice}} \tag{4}$$

with $c_v = 4187 \frac{J}{kg \cdot K}$ the specific heat capacity of sea ice, A the model cell area, m_{ice} the mass of affected ice and t the simulation time interval which was chosen to be 1/100 of an orbit.

Out of equations 1-4 the thermal development of Europa's surface can be calculated.

2.2 Temperature distribution

As the spatial temperature distribution is unknown, the model starts with a constant estimated mean temperature value and obtains the equilibrium state after 105 orbits. This temperature distribution is shown in Figure 7. It matches the described polar temperatures of about 50 K and temperatures slightly above 100 K for the equatorial region. Spacecraft measurements from *Galileo* reveal even bigger temperatures around 125 K (cf. Figure 8) in some regions. This might be due to uncertainties in the model's material parameters and the fact that the surface in some regions does not consist of pure ice but for example some regolith dust which is warmed up much faster. This small difference does not affect the relevance of the model.

In general the model reproduced the same spatial temperature distribution as shown by the infrared picture of *Galileo* [17] and the modeled mean temperature (calculated by a weighted average out of the calculated latitude's mean temperatures) is about 95K, which is fitting to the known mean temperature.

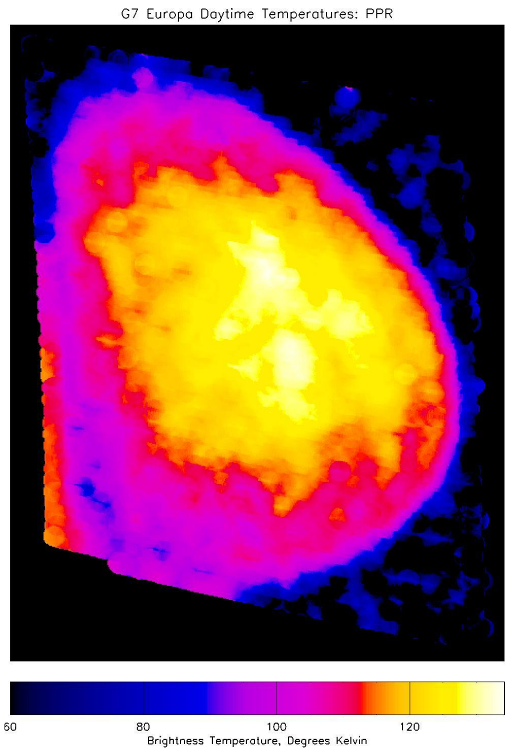

Figure 8: *Galileo* infrared image[17] of Europa's surface showing temperatures very similar to the modeled ones shown in Figure 7.

2.3 Thermal stresses

Out of this spatial and orbital temperature distribution it is possible to determine thermal stresses in the uppermost ice crust. Due to relaxation the surface ice is without

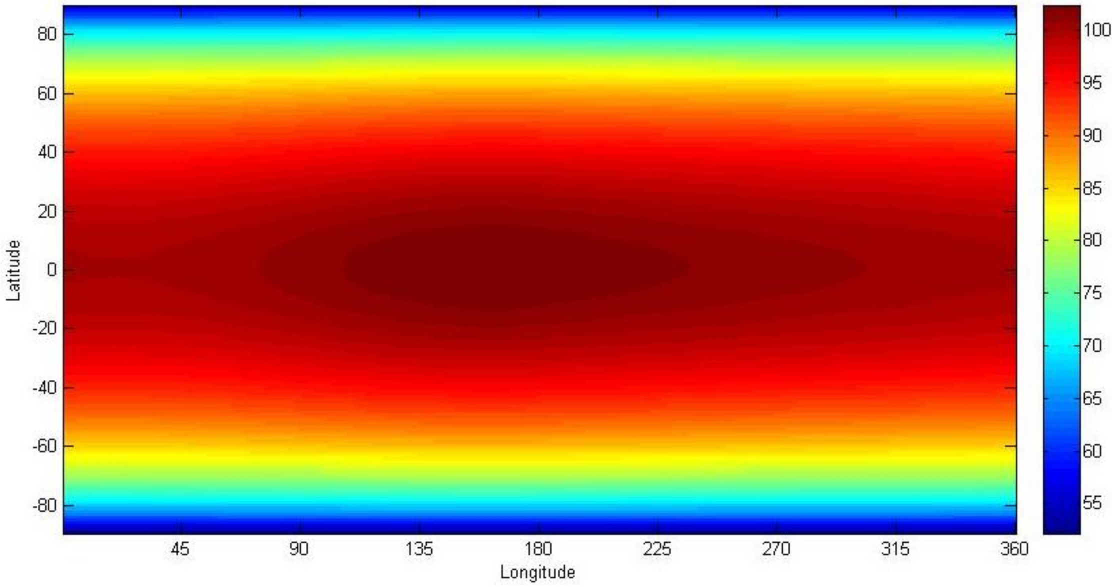

Figure 7: Modeled spatial temperature distribution in K

stresses on the mean temperature of each latitude. The differences to these mean temperatures are relevant for the thermal stresses at each point. Thermal stresses in each grid position are given by:

$$\sigma = E \cdot v_l \cdot (T - < T >) \quad (5)$$

With the Young modulus $E = 1\ GPa$ as a typical value for sea ice and the linear coefficient of thermal expansion for terrestrial sea ice $v_l = 1.6 \cdot 10^{-3}\ K^{-1}$. Both the Young modulus and the coefficient of thermal expansion might be different due to higher porosity, salinity and far lower temperatures. But as we don't know about that we can only assume the terrestrial values. Still the results concerning fracture opening should be valid even if parameters change about one order of magnitude.

The calculated stress distribution is shown in Figure 7. Stresses reach values above 1 MPa in compressive and tensile stresses, which is enough for tensile failure of sea ice. Compressive strength of sea ice is usually bigger, but the compressive forces could lead to the buildup of some features from ridge structures like flanking cracks and forebulges [13].

2.4 Stress and fracture patterns

The model shows that thermal stresses on the surface of Europa are big enough to initiate cracks. To identify the regions and directions of probable crack formation a map of the gradient of the stress field which is shown in Figure 10 was plotted. This pattern of stress directions looks pretty similar to the stress direction maps given by Greenberg et al. [2], hence the intensity of stress derived from tidal forces is with less than $10^5\ Pa$ at least one order of magnitude smaller than the modeled thermal stresses presented in this paper.

Cracks can be formed and propagate in those regions of Figure 9 where the calculated stress is bigger than around 1 MPa, the average tensile strength of sea ice.

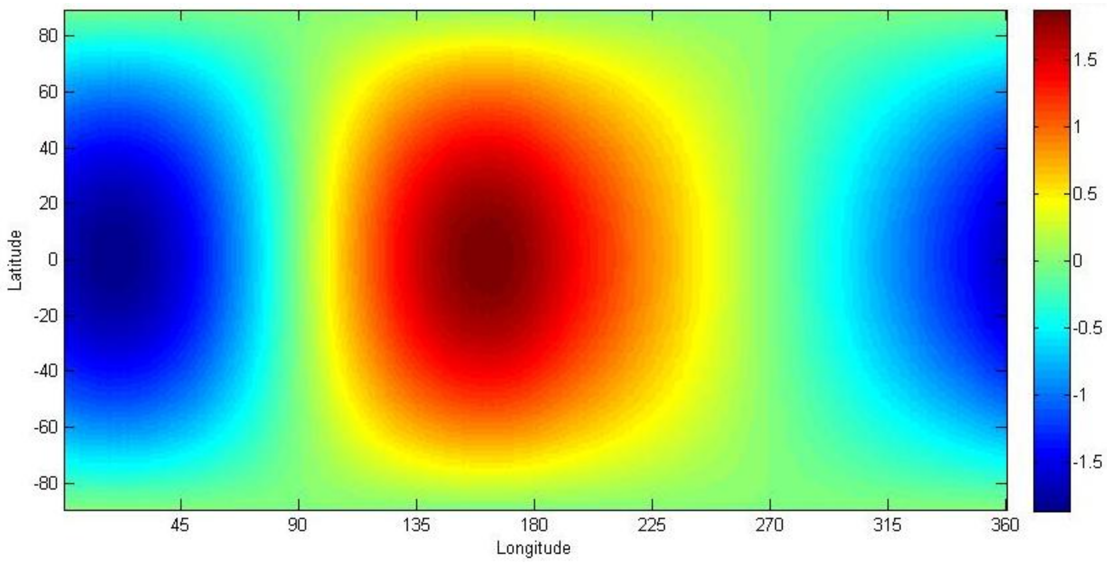

Figure 9: Modeled scalar stress distribution in MPa

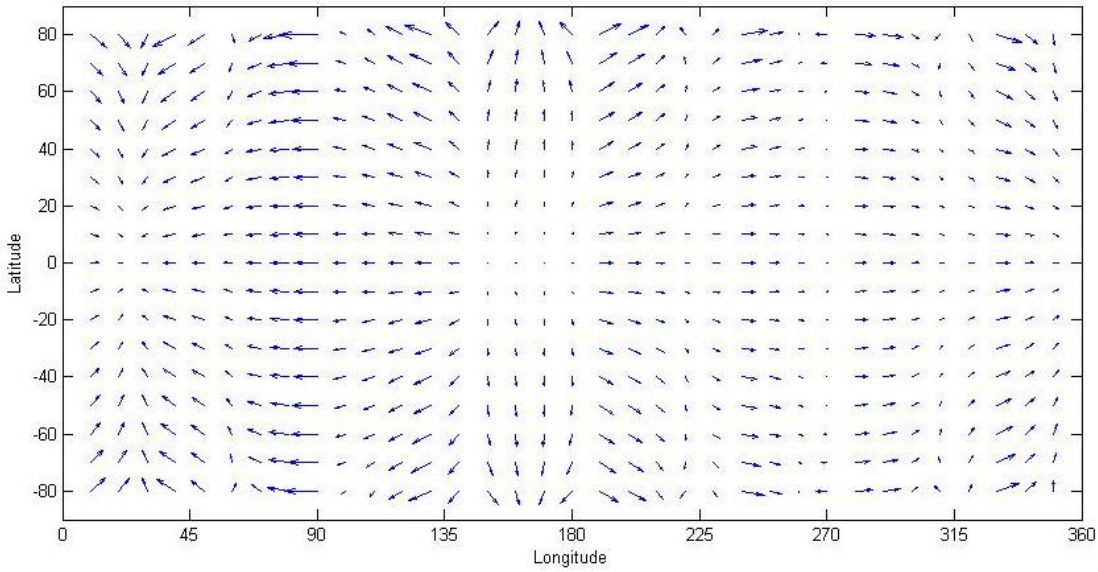

Figure 10: Gradient of the thermal induced stress field

Those cracks propagate in the directions orthogonal to the stress gradient. As the stress patterns are almost the same as for tidal forces given by Greenberg et al. [2], the crack patterns due to thermal thrusts should appear in an identical shape. Calculation of crack propagation patterns is already done in [2] and will not be repeated here.

As the stress patterns are identical also the formation process of cycloidal ridge features like those described by Hoppa et al. [7] can be driven by thermal forcing.

3 Results

The simulation of the thermomechanic development of Europa's ice surface under solar radiation reveals some interesting new facts about thermal expansion forces and surface formation processes:

- The obtained stress patterns are quite similar as previous investigations have revealed it to be for tidal forces. Because of that it is not possible to distinguish between tides or thermal thrust as the driving forces of crack formation from the crack patterns.

- Calculated values for thermal stresses around $10^6\ Pa$ are one order of magnitude bigger than tidal stresses. While the ability [18] of tidal forces (around $10^5 Pa$) to initiate cracks in the ice and to let them propagate down to the "liquid" layer is discussed a lot, this ability is without doubt for the calculated values.

- Taking into account that the material parameters of surface ice on Europa might be up to one order of magnitude smaller than the ones used in the simulation, the thermal stresses still have at least a comparable intensity to the tidal stresses and should not be neglected.

- Thermal and tidal forcings together should be able to initiate the observed surface cracks and there is nolonger a need for additional tidal forces, caused by nonsynchronous rotation, to explain crack formation. So the existence of cracks of these patterns does not proove nonsynchronous rotation.

- Results also show that thermal stresses should not be neglected and might also play an important role in the formation of other nonlinear surface features like chaos terrain.

- Successful modelling of the radiation balance by a simple model, like described in 2.1, gives a hint that the thermal flux from Europa could be around 0.3 W/m^2. This would be on the upper boundary of values estimated until now and would indicate an ice thickness of only several hundred metres [9] as the lowest boundary value estimated until now, resulting in a good probability for a liquid water ocean under the ice crust with possibilities for the development of extraterrestrial life. Such ice cover would be comparable to big floating shelf ice masses on earth, like for example in Antarctica.

4 Discussion

None of the cited papers deals with thermal stresses as reason for formation of visible surface cracks, though none of the authors gives a reason or argument why they are neglecting this factor. Its effect seems to be totally underestimated as thermal expansion can be neglected in many problems. It seems like the effect is not negligable when talking about cracks on the ice shell of Europa, as its effect is at least as important and up to one order of magnitude higher than the tidal forces. This could also give a better explanation how cracks can propagate through the whole ice layer down to the liquid ocean, as the forces are bigger.

One point of discussion can be, that the thermal forces are only produced in the very top layer (maximum one to two meters depth) whereas the tidal forces are present throughout the whole ice layer. Probably thermal expansion forces crack formation on the surface. Those cracks can then propagate through the ice sheet forced by tidal forces. It is well probable, that thermal and tidal stresses together are the driving forces behind the formation of the observed cracks.

Material parameters for ice are unknown for the conditions on Europa. The simulation was run with rather maximal than minimal parameters, as the aim was to see if the effect of thermal loads is negligable or not. As the material parameters are very important for the stability of the simulation, a short discussion of the influence of the used parameters was made:

Surface constitution: The exact constitution of surface material is unknown. The ice cover consists mostly of water ice, but apart from pure water the existence of other substances like sulfuric acid is also prooved. It could be possible that some parts are covered by a very thin layer of regolith. As minerals have different material parameters it could of course affect the spatial distribution of crack formation. Some regions will warm up more, which is consistent with the infrared measurements, but the major temperature field stays the same. Coverage by regolith could, depending on its thickness, either isolate the ice preventing cracks, or lead to higher temperature differences causing cracks. So these effects should be opposed and negligable in average.

Specific heat capacity: In the model $c_v = 4187 \frac{J}{kg \cdot K}$ was used as the specific heat capacity of sea ice. This value was chosen maybe a little bit too big, but as values for fresh water ice are around $2090 \frac{J}{kg \cdot K}$ the big number takes into account the enormous high salinity and effects of the highly porous ice where vacuum is the pore-liquid which are totally uninvestigated. In general the model is not very sensitive on the choice of that value, as it counts only linear and it might vary a lot spatially.

Thermal expansion: The coefficient of thermal expansion of sea ice $v_l = 1.6 \cdot 10^{-3}\ K^{-1}$ is used in the simulation. This is a relatively high value due to high salinity. This parameter is the most crucial in the simulation and at the same time the worst defined parameter. Influence of salinity, minerality, porosity and especially extreme low temperatures is hardly known and values could be much smaller down to a range of $v_l = 1 \cdot 10^{-5}\ K^{-1}$. Still thermal expansion would not be totally negligable and important for surface feature formation.

Young modulus: The Young modulus is the only parameter which was assumed very conservatively. The simulation was done with a Young modulus of 1

GPa, whereas known values for terrestrial sea ice range between 1 and 10 GPa and other papers like Ruiz [9] calculate with 9 GPa.

All in all the chosen parameters give together a set of realistic variables which should meet the real value with an accuracy of one order of magnitude and are in any case not negligable.

5 Conclusion

The simulation shows that thermal stresses might be able to produce the observed crack patterns. The calculated heat flow leads to the conclusion of a rather shallow ice layer, not as big as considered in the past. This ice layer can be cracked up completely down to the liquid layer by thermal stresses causing new surface formation.

From our point of knowledge, the effect of thermal stresses can not be neglected compared to tidal stresses, but material parameters for both processes are very unknown and further research especially in form of petrophysical examinations of ice under extreme conditions, is necessary for better estimations.

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