Review of Doctoral Thesis

Dynamics of Icy Satellites with a Liquid Phase

by

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In the thesis by Klára Kalousová a model for the transport of liquid water within an ice shell is developed in application to icy satellites. The relevant conditions are very different from terrestrial ices and therefore a new set of governing equations had to be derived. The model is applied to Jupiter's moon Europa to answer the question whether liquid water could exist and persist in the shallow subsurface of this moon.

Part I of the thesis summarizes the context and the open questions regarding Europa to which the present work contributes and –starting with terrestrial applications– the state of the art regarding water transport in ices. The sections show that the author has a profound background of the relevant questions. The style, including e.g. the correct references at the right places and the correct use of terminology is very accurate. With part 1 the reader is provided with the correct background and motivation for the present study.

The theoretical model and its numerical implementation are described in part 2. It is appreciated that a previous theory describing the multi-phase flow equations is re-derived in section 3.2. This helps the reader to understand the approach. However, this section might have been included in an appendix while focusing on the newly developed method in the main text. This is, however, only a minor weakness. Major strengths of this section are the accurate mathematical description of the model and the very concise summaries of the complex mathematical details guiding the reader through each part. Based on balance equations and conservation laws the approach is very general and comprehensible even for readers not familiar with the description of multi-phase flows. A further strength of this section is the use of different numerical implementations to verify whether the obtained results are reproducible by independent methods applied to several test cases. A summary of part 2 (similar to the summary of part 1 on page 31) is missing.

In part 3 the influence of several parameters, e.g. permeability or rheological parameters of the ice shell, on the time-scales of water propagation through a temperate ice shell is investigated using one-dimensional and two-dimensional descriptions. The two-dimensional model shows that water lenses at the top of the ice layer are gravitationally unstable and have therefore short propagation times reaching the ocean at the bottom within a few thousand years. As an important 'pre-result' the time-scales of propagation of liquid water through a 30-km thick ice shell are found to be small in general even when the relevant parameters are varied over a wide range and different assumptions on rheology or heat production are used.

In part 4 the theory and the numerical implementation of the liquid water transport are applied to two example cases which are geo-dynamically relevant for Europa: (a) Liquid water at low viscosity zones within a thermally convective plume in the ice shell, and (b) liquid water due to shear motions along tidally activated strike-slip faults close to the surface of Europa. This is the main result section where the theory is applied to 'real' situations on Europa. These results are original and highly

relevant for understanding the possible persistence of liquid water in the shallow sub-surface on Europa. Again a 1-dimensional and a 2-dimensional approach are used.
As a major result, which has not been quantitatively obtained before, it is found that water lenses produced by upwelling 'hot' plumes of ice are removed from the shell very quickly. This makes the current existence of such reservoirs unlikely in regions on Europa which are believed to have been modified by upwelling plumes. Also at locations with tidally activated strike-slip faults liquid water is removed within a few thousand years. However, being as close as 3 km to the surface such regions would be promising candidates for the search for liquid water on Europa. Both results are extremely relevant for planned space mission to Europa.
In the concluding chapter the perspectives and future work is described focusing on further development of the model and possible applications to other moons.

Investigation of Europa and in particular evaluating the persistence of liquid water in Europa's ice shell is a topic of extremely high relevance. Major space agencies, e.g. NASA and ESA, are planning missions to the Jupiter system (Jupiter Icy Moons Explorer (JUICE) by ESA, Europa Clipper by NASA) to investigate the Galilean Satellites. On Europa the conditions might be most favorable for life-forms to evolve which makes the relevance of the topic obvious. In a more direct sense the thesis is an invaluable contribution to select possible sites (e.g. for Europa flybys) that are best candidates searching for liquid water near the surface. Such water reservoirs would be accessible for investigation by sub-surface radar sounding aiming at detecting liquid water in Europa's ice shell. As correctly pointed out in the thesis the theory developed here would be applicable to other target bodies as well. It would be worthwhile to apply the new models investigating the cryo-volcanic activity of Saturn's moon Enceladus as well as possible liquid water reservoirs in Neptune's moon Triton.
In a broader context the models might also be applied to terrestrial ices. In particular Lake Vostok and similar lakes in Antarctica might be a promising application. Whether this would be possible is a question I would like to ask the author, if possible. In that case the results can be directly set in context to radar measurements and possibly also to drilling cores acquired from the ice sheet. This could also be done in preparation for future missions to Europa. In a broader sense the studies might therefore also be relevant for processes related to climate change on Earth.

The thesis is very well-structured. Starting with the motivation and broad context written in a comprehensive but very sound way, the model is described in detail. The mathematical subject makes the details, of course, difficult to read at some places. However, each part of the mathematical model is summarized in a concise way in corresponding sections making it (despite the complex subject) easy for the reader to follow the arguments. As a minor weakness I see the numbering of the chapters (1 through 8) which is independent from the parts. This is sometimes confusing. I would have preferred subsections in the individual parts.
Results are presented mainly in figures in a very comprehensible way. In most cases I would have preferred larger figures but that is only a very minor aspect, since all the information in the figures is well-readable.
The style is absolutely adequate including also the list of references and other formal aspects.
At some places throughout the document the English language could be improved, but again this can be considered as a minor weakness.

Having obtained original results (see above) which are highly relevant for the scientific community the thesis definitely proves the author's ability for creative scientific work. As already shown by publications in the relevant area the author is able to communicate the obtained results in an adequate way to the scientific community.

The present thesis does not show any major weaknesses. As a minor weakness I see that at some places the text is 'packed with details'. I sometimes had the impression that the author wanted to show each detail obtained in the studies instead of focusing on the main results. Therefore, the reader interested in Europa has to wait until page 141 (part 4) to see major results in application to Europa. However, even in very detailed descriptions the line of evidence and the logic within the model descriptions is not lost and therefore I note this only as a minor aspect.
Regarding Europa the questions posed in part 1 are only briefly re-considered in the concluding chapter. It would have been interesting to see, e.g. consequences of the models for the lense collapse model described in Fig. 1.10 discussed in more detail. Are time-scales with liquid water long enough to make that model work? Even if –according to the present results– prospects are not so good with respect to the persistence of liquid water, what would be the best candidates to search for liquid water on Europa with a radar instrument? How many of these locations are distributed at Europa's surface? Addressing these questions would have closed the loop with the context described in part 1. However, I regard this also as a minor aspect.

In summary the author has proven to be able to develop and apply a physical-mathematical model of high relevance on international scientific level. The thesis shows many major-strengths and only minor weaknesses in the description of the model as well as in the results discussed. The results obtained are original and communicated in a sound and concise way.
Therefore I highly recommend admitting the thesis for defense. Overall I would rank the thesis between 'very good' and 'excellent'.

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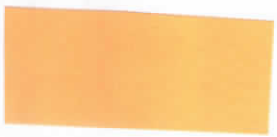

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