SATSTRESS: A WEB-ACCESSIBLE MODEL OF VISCOELASTIC TIDAL STRESSES IN ICY SATELLITES.

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Introduction: We have developed a viscoelastic model of the membrane stresses on the surface of an icy satellite with a decoupled ice shell, including the effects of viscous stress relaxation [1,2]. We call the model SatStress. Initial studies indicate that there exist plausible combinations of input parameters (ice viscosity, and ice shell rotation period), for which viscous relaxation is expected to be significant, reducing the surface stresses available for generating fractures.

Additionally we have created a web interface allowing researchers to access and use SatStress, which was developed at the University of Colorado. The application will be generally accessible concurrent with publication of our paper describing the underlying physics it implements, and our initial results. This will allow readers to explore model results in more depth, and more easily understand how the model behaves as reported in published work. We plan to subsequently release the model source code via the same website, allowing it to be inspected by other interested researchers. The application is available at: <http://www.icymoons.com/satstress>.

The Model: We use gravitational potential theory to derive surface membrane stresses due to non-synchronous rotation (NSR) of an ice shell, and diurnal variations in a satellite's figure as it experiences a time-variable potential due to an eccentric orbit about its parent planet. The approach is well established for modeling tidal deformation in the Earth-Moon system. The method has several advantages over previous methods applied to icy satellites:

1) it explicitly incorporates Love numbers representing the satellite's deformation in response to a gravitational potential based on the satellite's interior structure;
2) its formulation allows us to consider multiple terms in the gravitational potential simultaneously;
3) it allows derivation of explicit analytical expressions for principal membrane stresses on the satellite surface; and
4) it easily allows the incorporation of frequency dependent viscoelastic rheologies (e.g. Maxwell solids).

Our method does not yet account for stresses that result from change of a satellite's spin axis, or non-zero orbital inclination.

Benefits of Web Accessibility: As the mathematical and physical models used to attempt to describe scientific problems grow in complexity, the burden placed on a researcher who wishes to reproduce published work increases. Commonly there is a large amount of programming "infrastructure" required that is ultimately unrelated to the scientific problem at hand, creating an unnecessary barrier to the reproduction of work. This has sometimes meant years pass before independent confirmation (or denial) of model results. The web-based Satstress alleviates these problems.

Making our implementation of the model accessible to others via the web has several specific benefits:

Other researchers may access results. In addition to providing plots in our publications, we can include references to the numerical output associated with each model run mentioned in a paper, allowing later researchers to do quantitative analysis of and comparison to our results more easily.

Users always have up to date code. When sharing code with collaborators, it is easy for software versions to get out of synchronozation. Providing a web interface to the model means that the software version is always up to date.

Archiving of parameters used in model runs. Instead of each user having to individually track all the parameters which go into each model run, the parameters are stored on the web server, and can be referenced with a unique run ID, which is embedded in all model output . This allows users to easily re-create or experiment with variations on a particular run of theirs or another researcher.

Users do not have to re-implement the model. Instead of starting from scratch, and re-implementing the model based on the math and physics in the published paper, interested users can immediately start making use of the model. Additionally, we provide a basic plotting interface allowing users to obtain graphical output of model runs, in addition to the numerical output (which, of course, may be plotted differently if desired).

Benefits of Open Source Development: Allowing other researchers direct use of our model without requiring them to re-implement it based on our derivations of course introduces the problem that, if *we* have made any mathematical or coding error, it would propagate into their results. For this reason, we also intend to publicly release the source code implementing the published model, and future versions of the software as it develops, via a web-based interface to the version control software (Subversion) which we use to maintain the code. Providing the source code with an appropriate license agreement will also allow others to build upon the work that we have done more easily, while still acknowledging our original work.

Applications/Results: We are initially applying the model to determining the importance of viscous relaxation of non-synchronous rotation (NSR) stresses in Europa's ice shell to the overall stress field available on the surface for fracturing the ice. The model allows the user to specify straightforward physical parameters: depth of the subsurface ocean, thickness of the ice shell, viscosity of the ice shell, period of NSR, etc., and uses these parameters to calculate the Love numbers h_2 and l_2, which are then fed into expressions of the stresses, which are based on gravitational potential theory [1,2].

Figure 1 shows a series of model calculations demonstrating the effects of increasing the ratio γ of the period of NSR to the Maxwell relaxation time of the upper layer of the ice shell. The result is that, over the three orders of magnitude variation shown, NSR stresses go from being overwhelmingly dominant (first panel) to relaxing away nearly completely. Additionally, the overall pattern of the stresses shifts to the west as a result of the phase lag in the viscoelastic body's response to the rotation of the ice shell. This will make it difficult to use the apparent longitude of fracture formation as a proxy for time. The last two panels are shown at a different scale, allowing the diurnal stresses to be displayed. When $\gamma > \sim 10^{2.5}$, diurnal stresses dominate over the relaxed NSR stresses.

This series demonstrates the viscous relaxation of NSR stresses is potentially important, because the value of γ is uncertain to more than three orders of magnitude and the surface stresses change both in magnitude and orientation significantly over the range of uncertainty.

References: [1] Z.A. Crawford et al. (2006) AGU Fall Meeting P23E-0097. [2] Wahr, J., et al., Modeling satellite diurnal and non-synchronous rotation stresses: Application of potential theory, *Icarus*, submitted.

Acknowledgements: Funding support has been provided PGG and OPR Programs, and by the NAI.

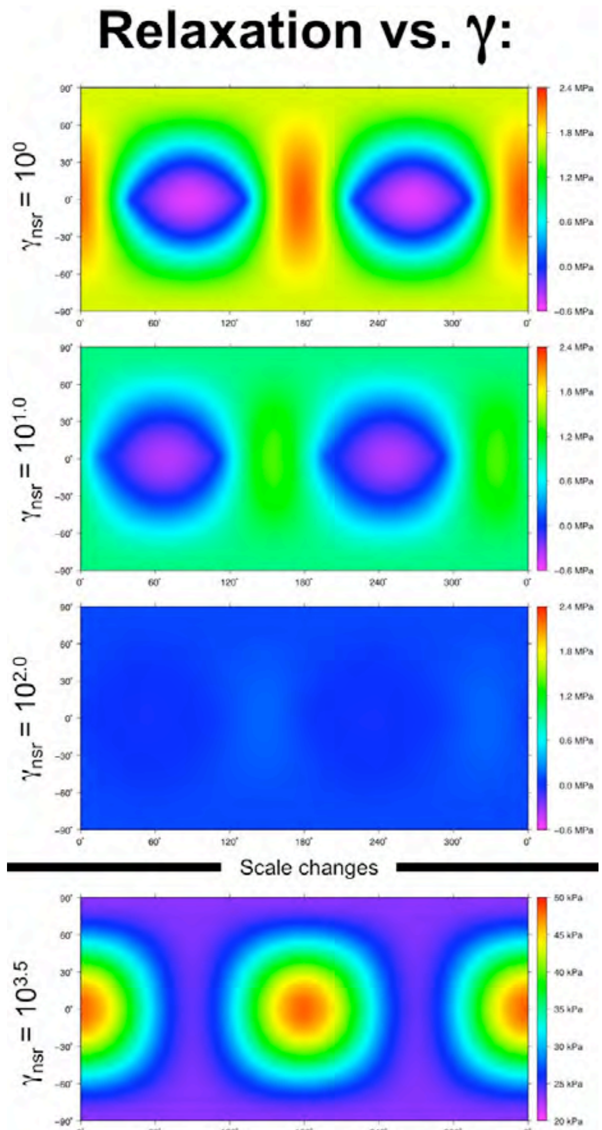

Figure 1: Color indicates the magnitude of the most tensile (least compressive) principal component of the surface stress on Europa. Values of γ at left indicate the ratio of the NSR forcing period to the Maxwell relaxation time of the ice shell's upper layer. Values of γ range over several orders of magnitude, but all are within plausible limits. All panels include stresses both from NSR and diurnal tides. Note the westward translation of regions experiencing the greatest tensile stress in the first three panels, due to the viscous response of the ice.