
Space — the ultimate frontier. As our heroic astronauts from the daring crew of the Swine-trek, push back the outer limits of knowledge through extraterres trial exploration, they find wonders beyond belief...
nothing has prepared you for....
PIGS IN SPACE

Magnetic remote sensing of planetary oceans and the importance of tidal heat in preventing freezing

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ASTR695
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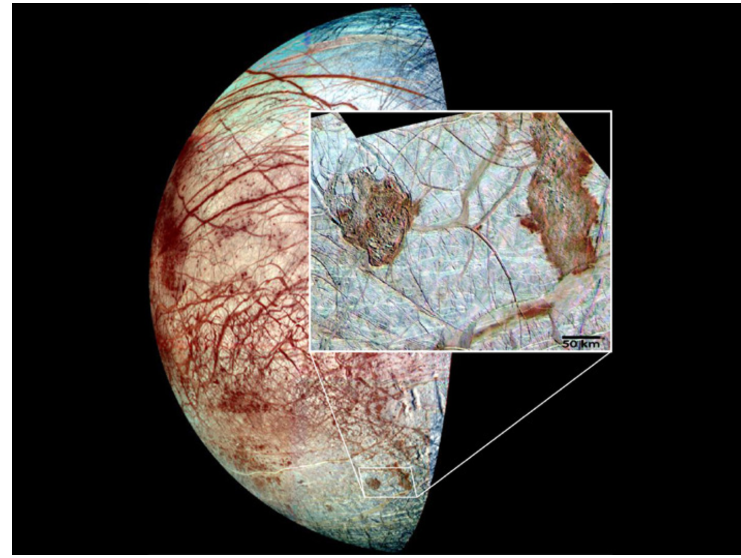
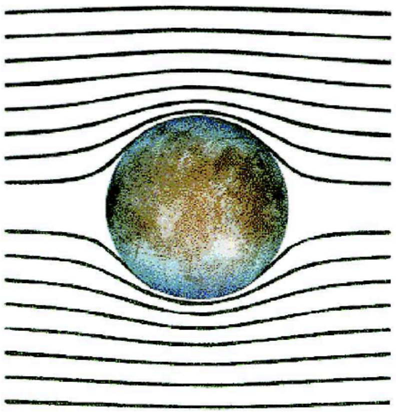
Case for oceans:

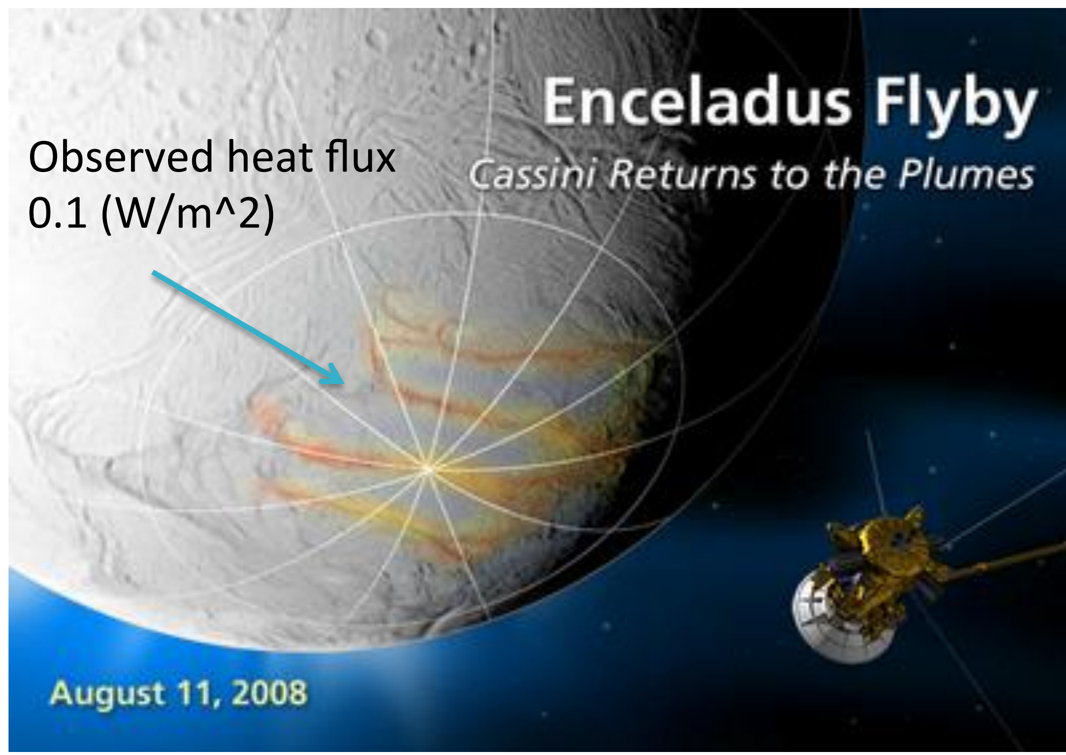
surface
features



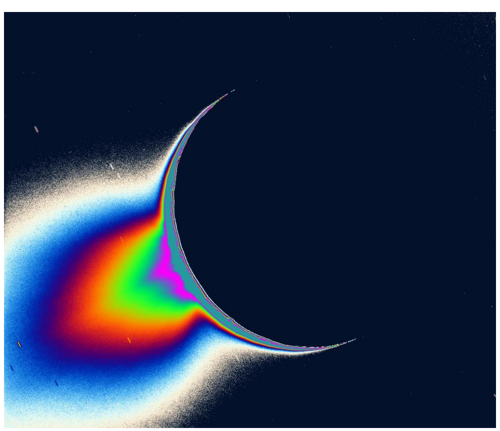
magnetic
data



heat flux



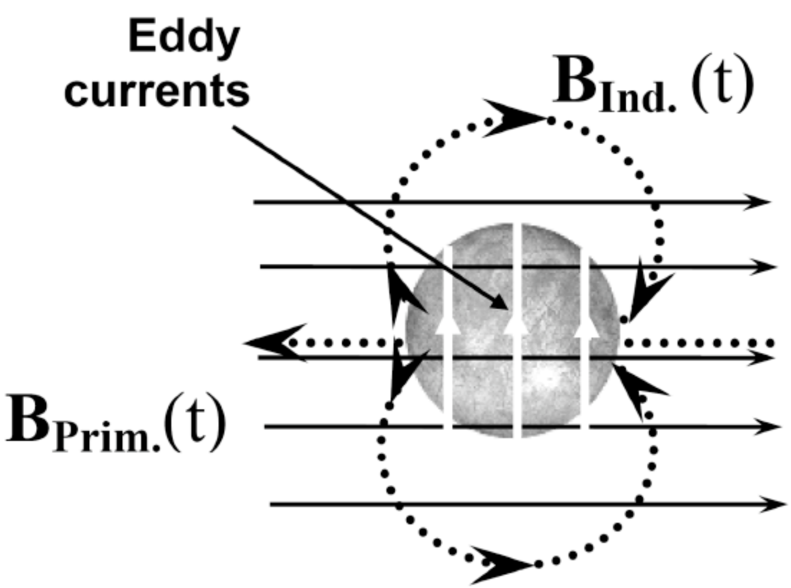
plumes



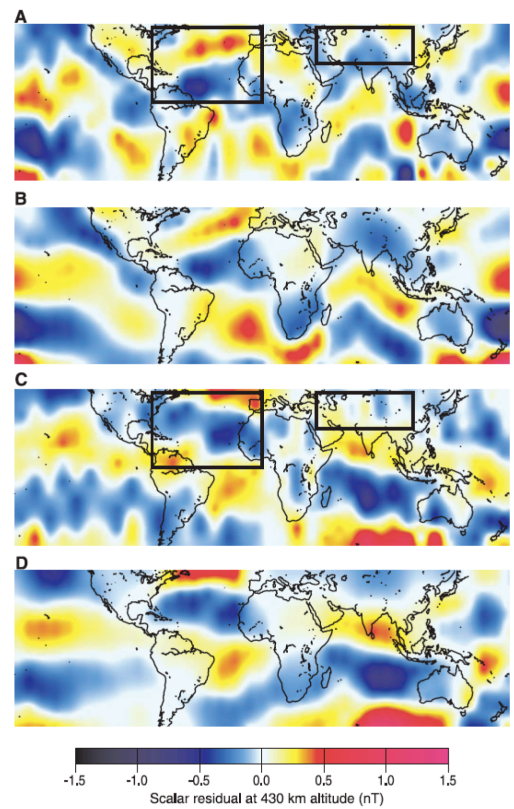
Magnetic remote sensing of planetary oceans

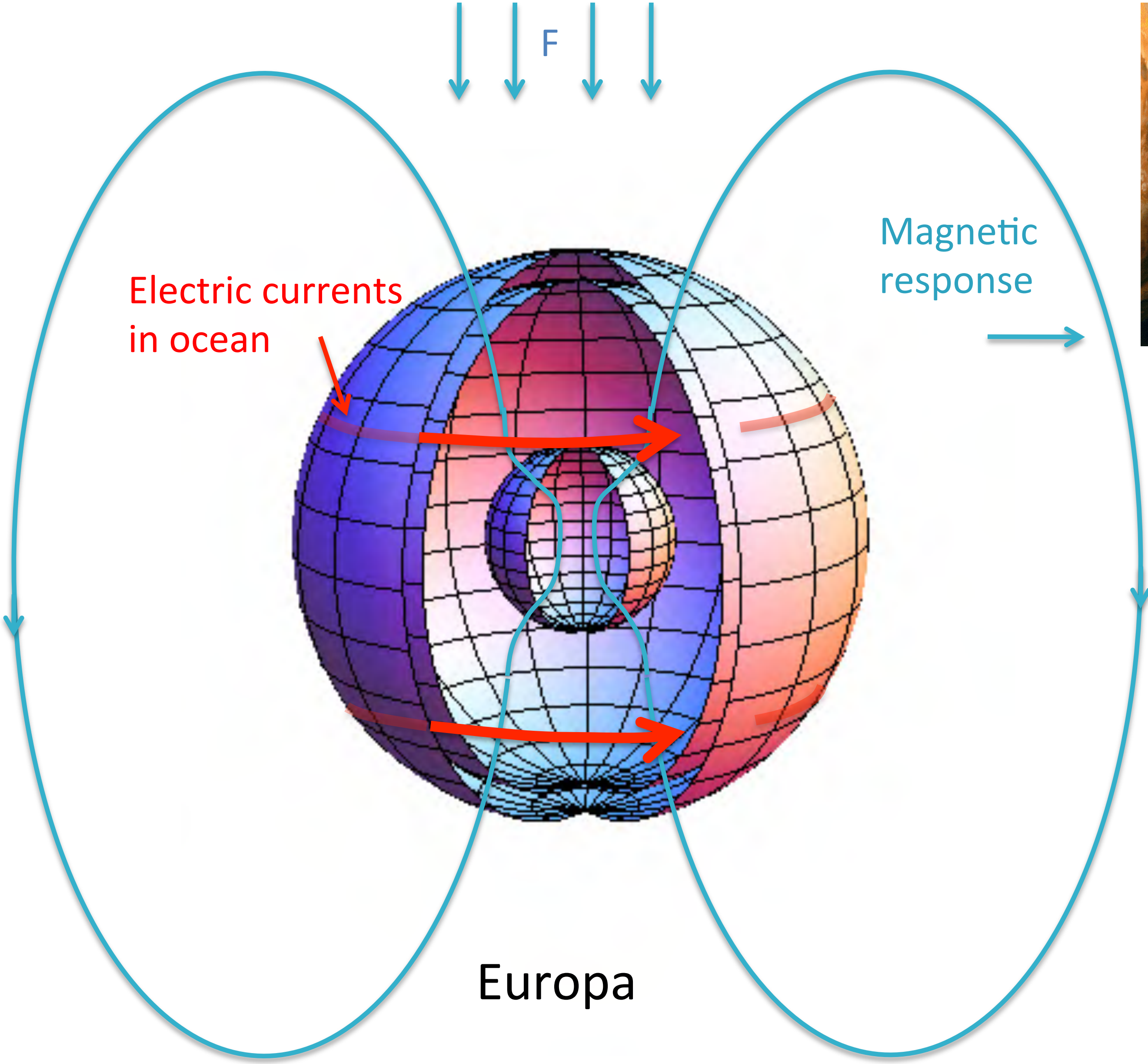
Two examples:

Induction response of Europa
(Khurana, et al., *Nature*, 1998)



Magnetic fields of Earth's ocean tides
(Tyler, et al., *Science*, 2003)



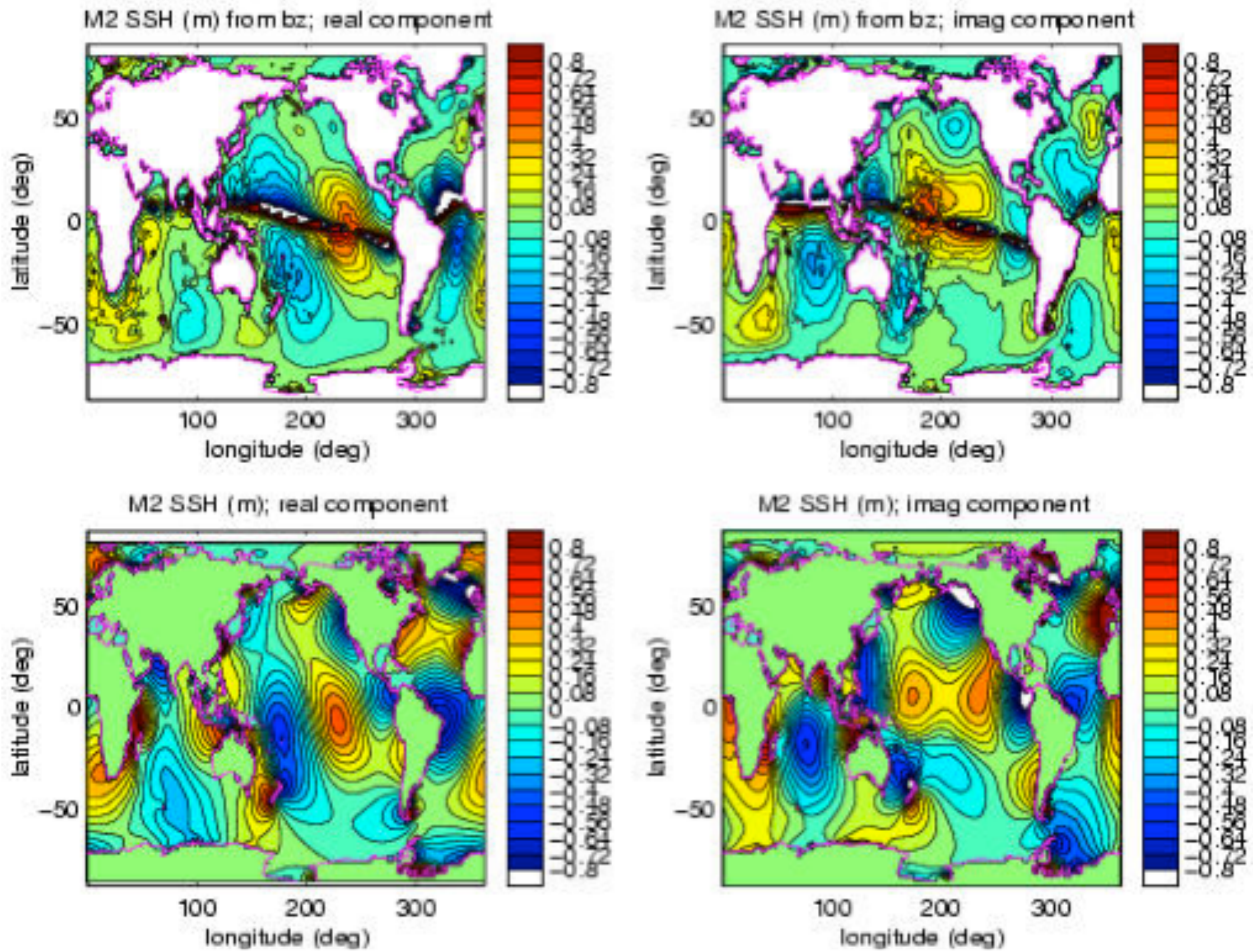

F
Electric currents
in ocean
Magnetic
response
Europa

Crude inversion of M2 tide (complex amplitude) from magnetic data at satellite altitude

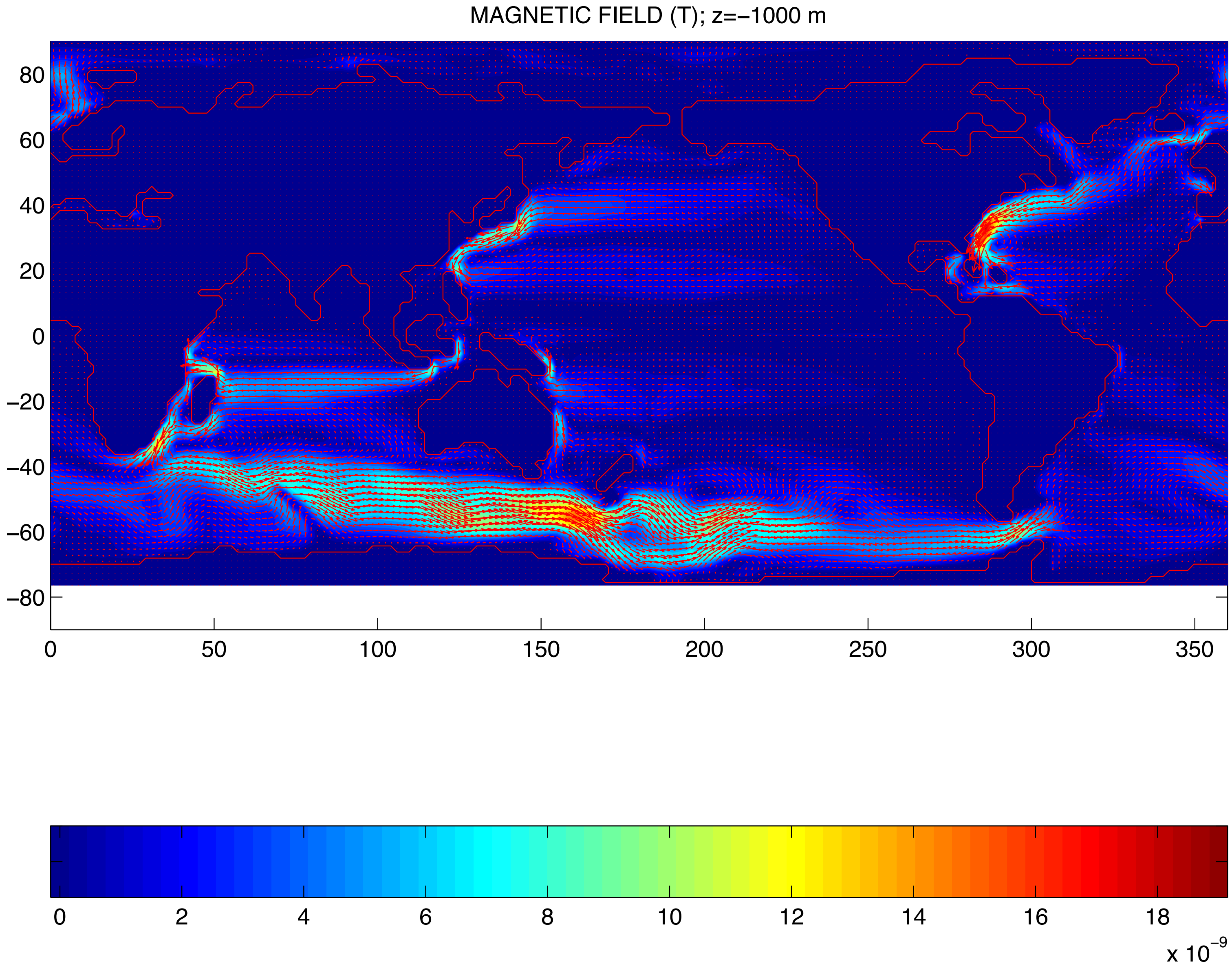
Real | Imaginary

Tide obtained from inversion of magnetic data →
(the crude approximation used in this simple inversion is not valid near mag. equator nor coastline).

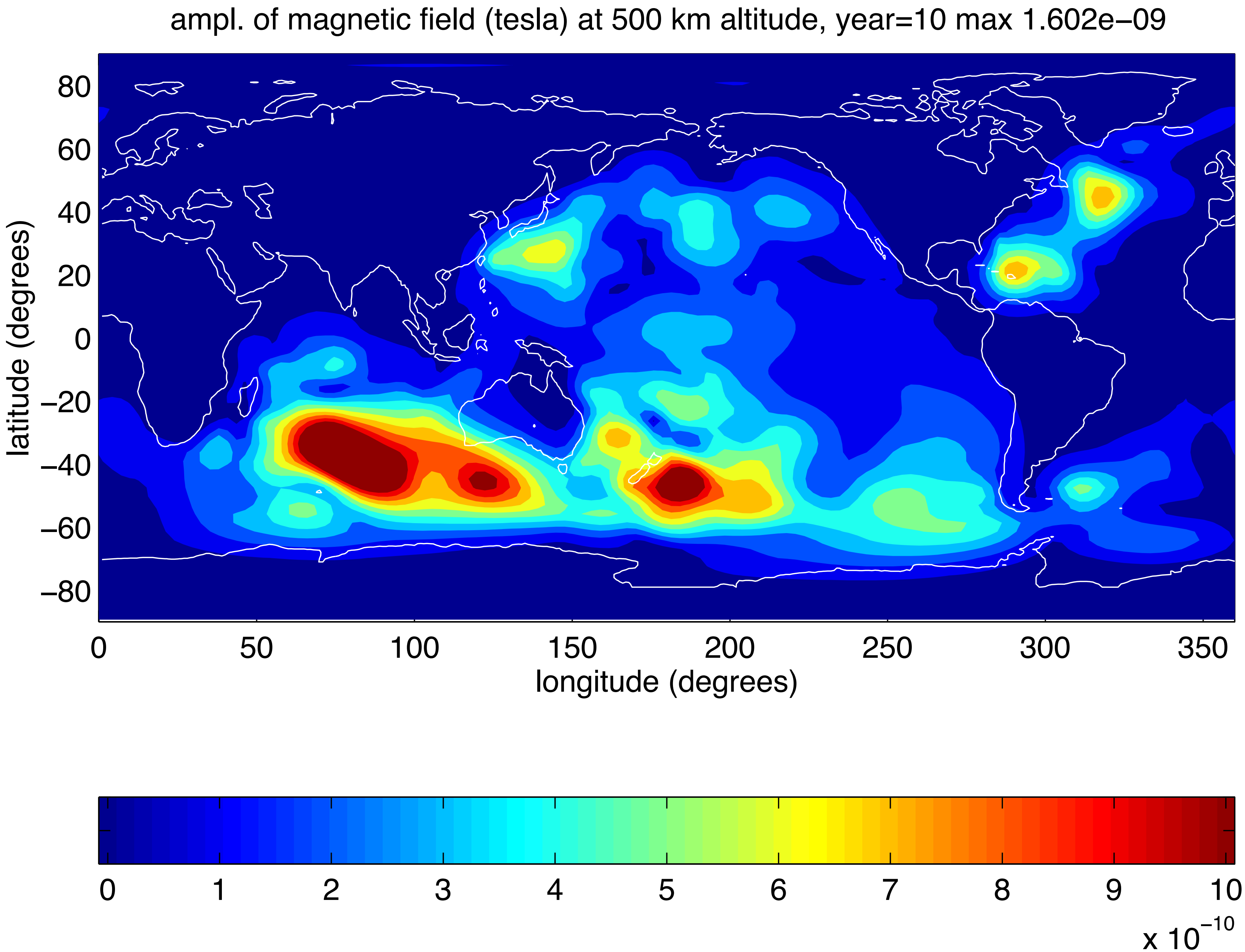
Tide which is correct →



Magnetic field of ocean circulation: toroidal component (within ocean)

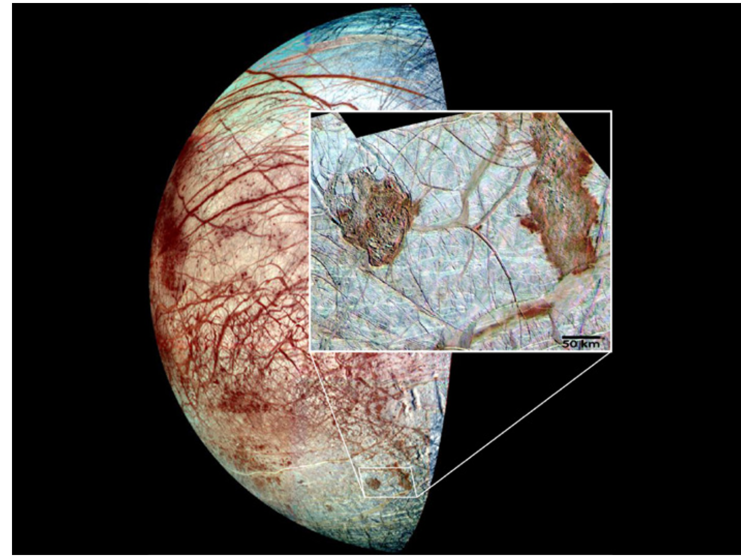


Magnetic field of ocean circulation: poloidal component (satellite altitude)

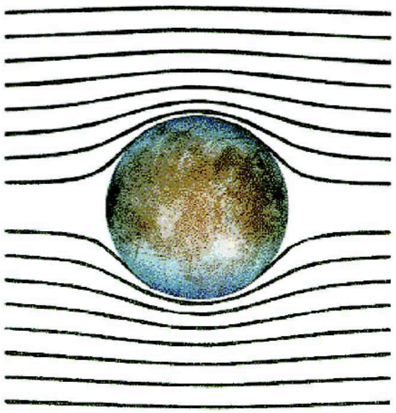


Back to the case for oceans in Outer Solar System:

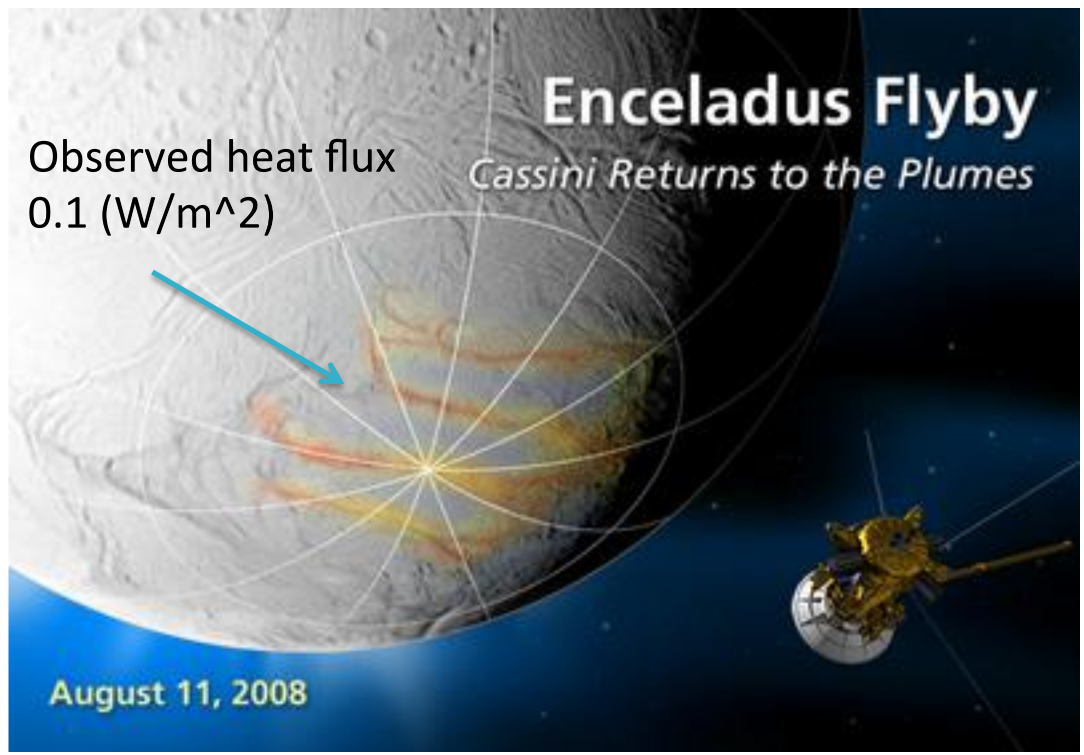
surface features



magnetic data

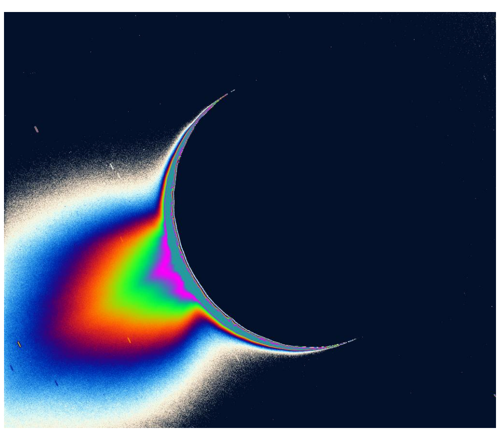


heat flux



Observed heat flux
0.1 (W/m^2)

plumes



Central Enigma

Many of these observations can be explained if there are subsurface oceans with a relatively large source of heat

But what is the heat source?

- Radiogenic
- Tidal flexing
- Shear heating in ice shell
- Antifreeze

← But what about Enceladus!

credits:

NASA, Outer Planets Research Program
NASA, Earth Surface and Interiors Program

Tyler R., Strong ocean tidal flow and heating on the outer moons, *Nature (Dec. 13, 2008*)

Bills B., Tidal Flows in Satellite Oceans, *Nature Geoscience (Jan. 2009)*

Tyler R., Ocean tides heat Enceladus, *Geophys. Res. Lett. (2009)*

Tyler R., Dynamical considerations suggest that oceans may be common in the universe, *J. Cosmology (2010)*

Tyler R., Tidal dynamical consideration constrain the state of an ocean on Enceladus, *Icarus (2011)*

Tyler R., Water Worlds and Oceans May be Common in the Universe. *Chapter in book:* The Biological Big Bang: Panspermia and the Origins of Life, edited by C. Wickramasinghe, Cosmology Science Publishers *(2010 In Press)*

Tyler R., Magnetic remote sensing of Europa's ocean, *Icarus (2011)*

First contribution:
Ocean tides can easily supply the required heat
(for "resonant" ocean configurations)

Second contribution:
These "resonant" ocean configurations are not just possible but appear inevitable
(for a satellite ocean attempting to freeze)

Third contribution:
-Not just satellites…
(also smaller and larger planetary bodies under synchronous or non-synchronous rotation)
-Not just barotropic modes…
(stratified response can be resonantly excited)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Resonance…

Moons and Men

- Europa, Ganymede, Callisto — Jupiter
- Enceladus, Titan — Saturn

Isaac Newton

Theory of gravitation
(equilibrium tidal response)

Pierre-Simon Laplace

Laplace tidal equations
(dynamical tidal response)

Carl-Gustaf Rossby

Rossby waves
(important in tidal response)

Previous calculations of the ocean tidal response on the outer moons:

Sagan and Dermott (Titan)
--neglected Coriolis forces

obeyed Newton

disregarded Laplace

Moore and Schubert (Europa, Ganymede, Callisto)
-- assumed equilibrium response (i.e. neglected Coriolis forces *and* ocean inertia)

did not consider Rossby at all!

Case for ocean tides as heat source:

1) Calculate the tidal forces on the ocean
   (What is the time-dependent gravitational pull of the planet on the moon's ocean?)

2) Calculate the ocean's response to these forces
   (How does the ocean slosh around as a result?)

3) Calculate the dissipation (heat) associated with this response
   (How much friction generated by flow?)

Gravitational force (gradient of gravitational potential)

$$\Phi = -(GM_J/q_o)(q_o/d)$$

$$\begin{aligned}
\frac{q_o}{d} &\approx \{1 + e\cos\Omega t\} \\
&+ \tfrac{a}{q_o} \{(\cos\phi + 2e\cos(\phi - \Omega t))\sin\theta + \theta_o((1 + 2e\cos\Omega t)\cos\theta\cos(\Omega t - \lambda_o))\} \\
&+ \tfrac{a^2}{q_o^2} \left\{\frac{1}{2}(-1 + 3\cos^2\phi\sin^2\theta) + e\left(\frac{3}{2}\cos\Omega t(-1 + 3\cos^2\phi\sin^2\theta) + 6\cos\phi\sin^2\theta\sin\phi\sin\Omega t\right)\right\} \\
&+ \tfrac{a^2}{q_o^2} \{\theta_o 3\cos\theta\sin\theta\cos\phi\cos(\Omega t - \lambda_o)\} \\
&+ \tfrac{a^2}{q_o^2} \{e\theta_o 3\cos\theta\sin\theta\cos(\Omega t - \lambda_o)(3\cos\phi\cos\Omega t + 2\sin\phi\sin\Omega t)\} \qquad (9)
\end{aligned}$$

Laplace Tidal Equations (with forcing and dissipation term added):

$$\partial_t \mathbf{s} - f\mathbf{s} \times \hat{\mathbf{r}} = -c^2\nabla(m - m_F) - \alpha\mathbf{s},$$

$$\partial_t m + \nabla \cdot \mathbf{s} = 0,$$

$$\mathbf{s} = \int_h \rho_o \mathbf{u} dr,$$

$$m = \rho_o \eta$$

Helmholtz decomposition:

$$\mathbf{s} = \nabla\Phi + \nabla \times (\Psi\hat{\mathbf{r}})$$

Governing equations:

$$\partial_t \left\{ (\partial_t + \alpha)\nabla^2\Phi + f\nabla^2\Psi + 2\frac{\Omega}{a^2}\partial_\phi\Phi + 2\frac{\Omega}{a^2}\sin^2\theta\frac{\partial\Psi}{\partial\cos\theta} \right\} - c^2\nabla^4\Phi = \partial_t\left\{c^2\nabla^2 m_F\right\} + \partial_t R_1$$

$$(\partial_t + \alpha)\nabla^2\Psi - f\nabla^2\Phi + 2\frac{\Omega}{a^2}\partial_\phi\Psi - 2\frac{\Omega}{a^2}\sin^2\theta\frac{\partial\Phi}{\partial\cos\theta} = R_2,$$

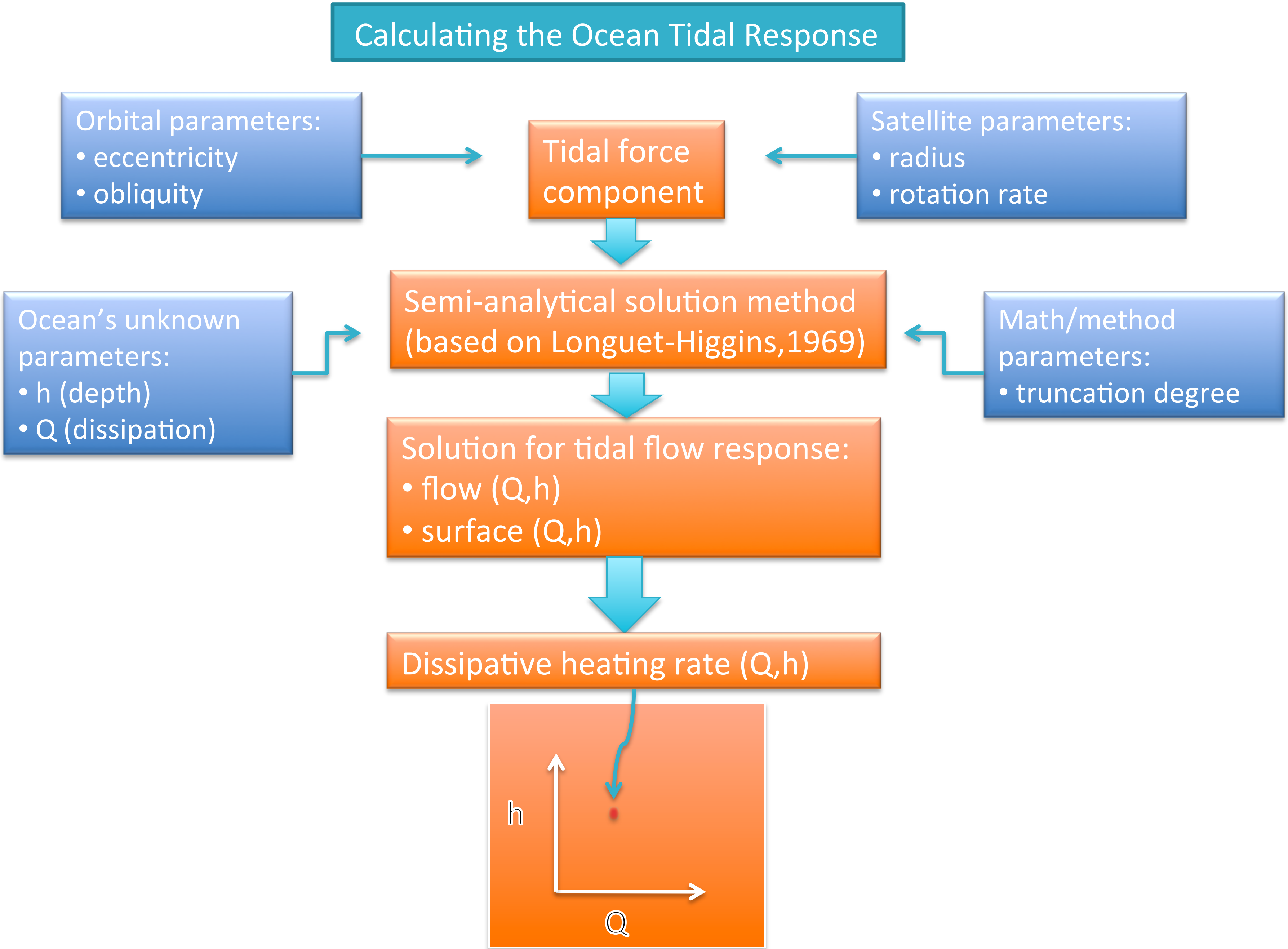
Solution method:
Solve using spherical-harmonic expansion of variables, and numerical inversion of resulting coefficient matrix

Dissipation (heating rate) calculated from an energy equation:

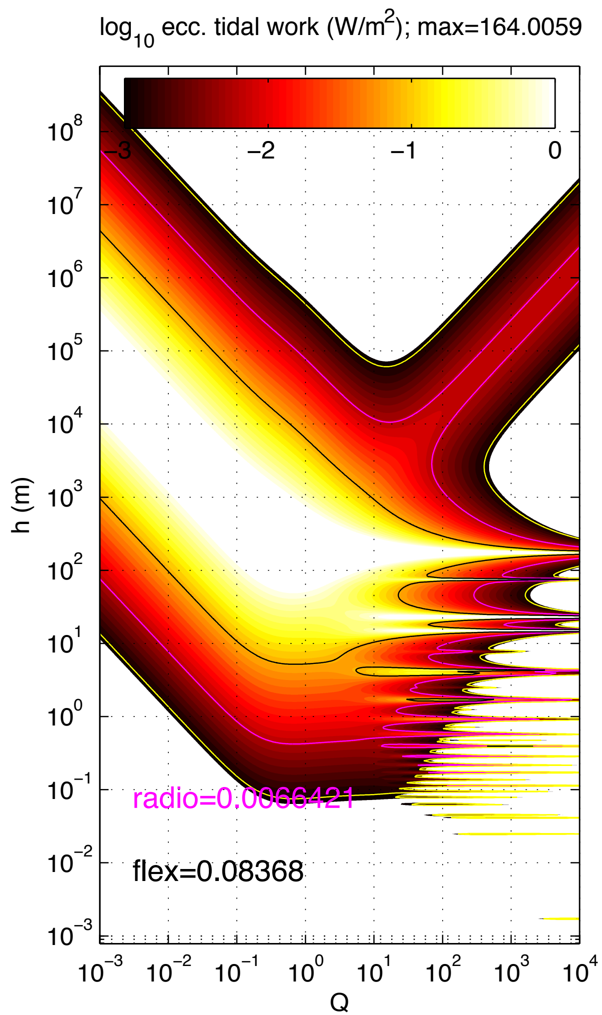
$$\partial_t(E_k + E_p) = -\nabla \cdot (\rho_o g h(\eta - \eta_F)\mathbf{u}) - \rho_o g(\eta - \eta_F)\partial_t \eta_F - \rho_o h \alpha \mathbf{u} \cdot \mathbf{u}$$

Work done on ocean by gravitational forces

Dissipation of tidal flow energy


Calculating the Ocean Tidal Response
Orbital parameters:
• eccentricity
• obliquity
Tidal force component
Satellite parameters:
• radius
• rotation rate
Ocean's unknown parameters:
• h (depth)
• Q (dissipation)
Semi-analytical solution method (based on Longuet-Higgins,1969)
Math/method parameters:
• truncation degree
Solution for tidal flow response:
• flow (Q,h)
• surface (Q,h)
Dissipative heating rate (Q,h)
h
Q

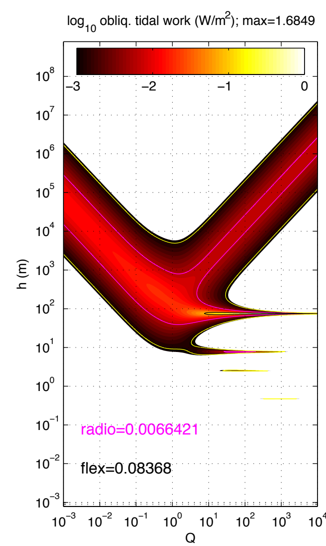
Dissipative heating rate (Q,h)



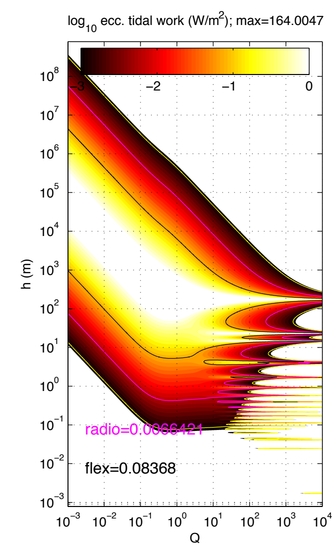
Obliquity + Eccentricity

Caveats in this discussion:

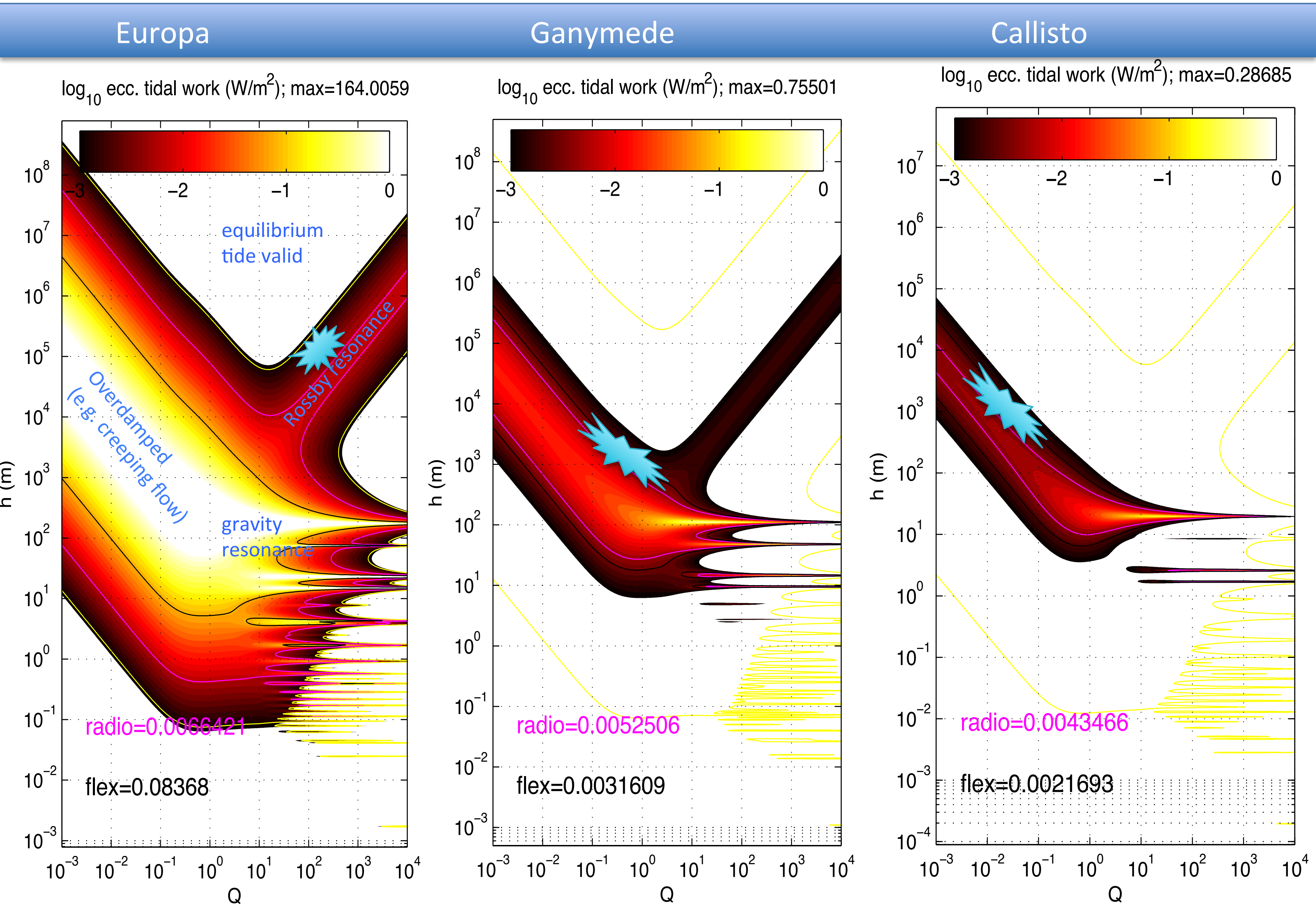
- **Not all (Q, h) combinations allowed**
- **Log10 scales**
- **Large axes range:**
  - **Q → damping by thick ice**
  - **h → "equivalent depth"**
- **Small contour plot range 0.001 — 1 (W/m^2)**
- **Obliquity usually unknown (use 0.1 deg ref.)**



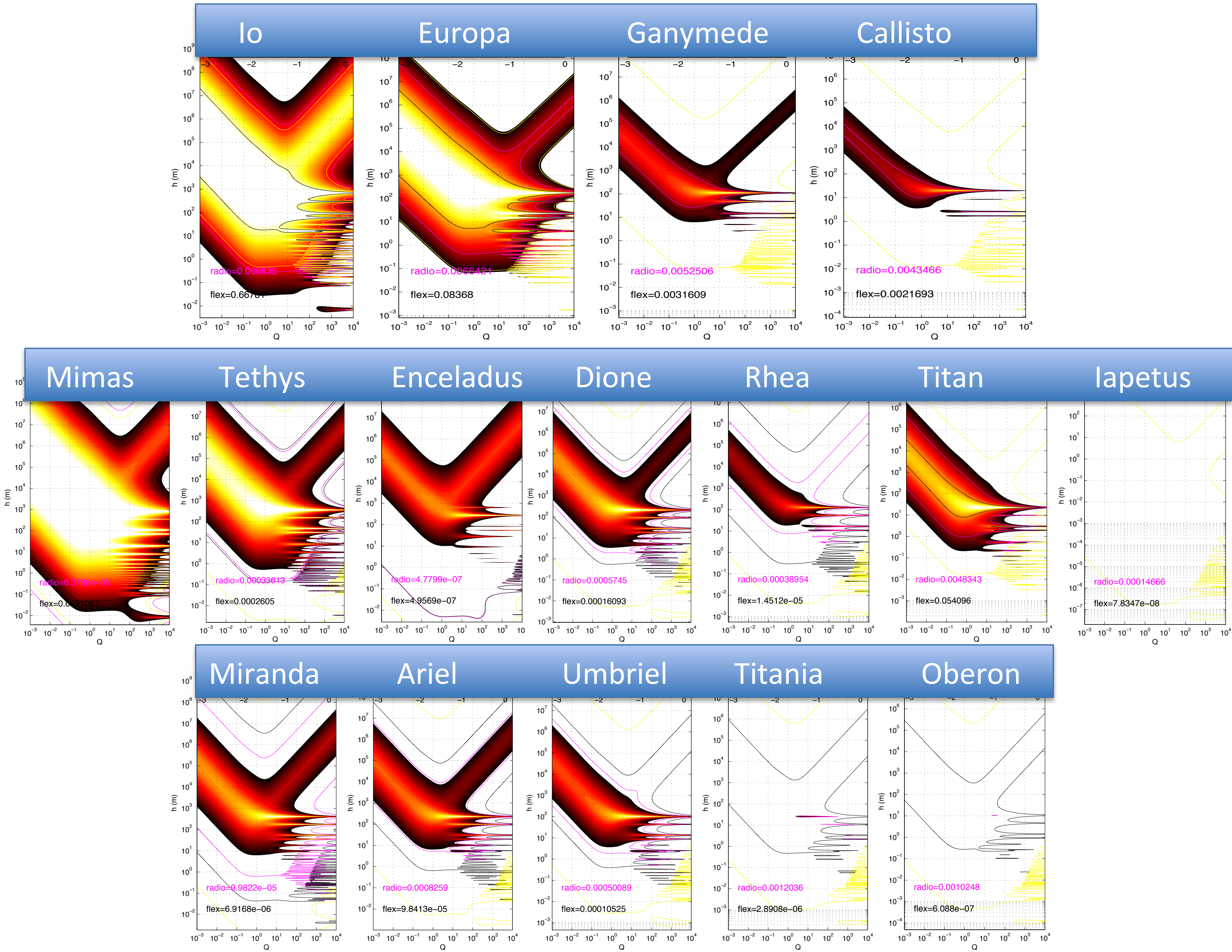
Obliquity



Eccentricity

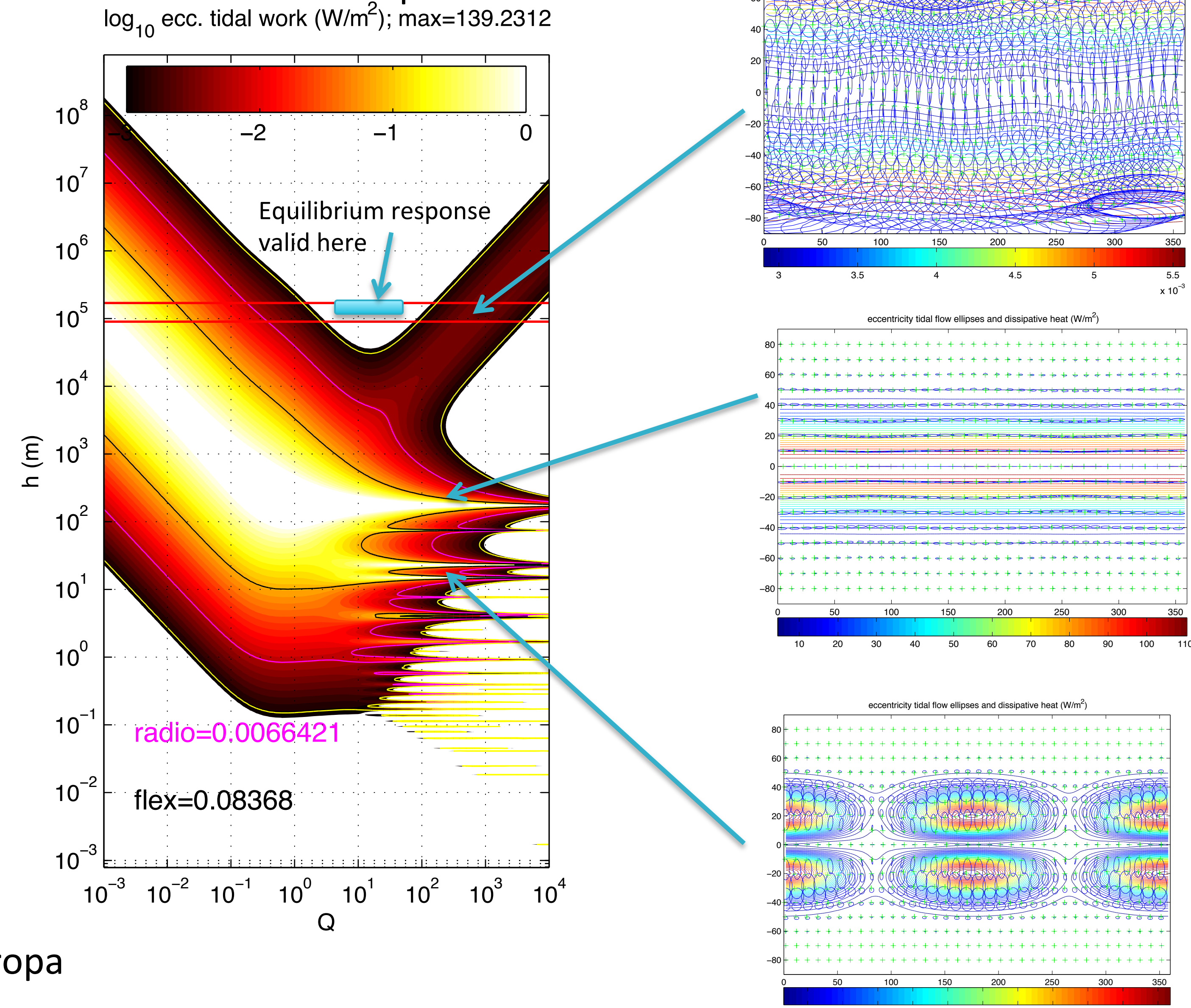


Europa
Ganymede
Callisto
log$_{10}$ ecc. tidal work (W/m^2); max=164.0059
log$_{10}$ ecc. tidal work (W/m^2); max=0.75501
log$_{10}$ ecc. tidal work (W/m^2); max=0.28685
equilibrium tide valid
Rossby resonance
Overdamped (e.g. creeping flow)
gravity resonance
radio=0.0066421
flex=0.08368
radio=0.0052506
flex=0.0031609
radio=0.0043466
flex=0.0021693
h (m)
Q



Io
Europa
Ganymede
Callisto
Mimas
Tethys
Enceladus
Dione
Rhea
Titan
Iapetus
Miranda
Ariel
Umbriel
Titania
Oberon
h (m)
Q
radio=0.009835
radio=0.0066421
flex=0.08368
radio=0.0052506
flex=0.0031609
radio=0.0043466
flex=0.0021693
radio=0.00033613
flex=0.0002605
radio=4.7799e−07
flex=4.9569e−07
radio=0.0005745
flex=0.00016093
radio=0.00038954
flex=1.4512e−05
radio=0.0048343
flex=0.054096
radio=0.00014666
flex=7.8347e−08
radio=9.9822e−05
flex=6.9168e−06
radio=0.0008259
flex=9.8413e−05
radio=0.00050089
flex=0.00010525
radio=0.0012036
flex=2.8908e−06
radio=0.0010248
flex=6.088e−07

Ocean tidal response depends sensitively on ocean thickness h (m), suggesting h can be inferred from observations of response.



Europa

Result of this research:

It is theoretically impossible to freeze an idealized global liquid ocean on a synchronously rotating moon subject to appreciable tidal forces

Combine with the following:

- synchronously rotating moons are probably ubiquitous
- Liquid water may be a common feature of planetary bodies, at least primordially or episodically
- The time scale for ocean tides to extract available energy from the orbit is very long

General Conclusion:

Liquid oceans may be very common in the universe

Importance to Astrobiology and NASA:

Follow the water!