What makes a planet habitable?
Ice covered oceans, continued
Logistics

• Presentation

• Homework 6 will be issued tonight and due in class next Tuesday (last lecture).

• A review session will be offered in Reading Period (default: same-time-same-place as the usual Thursday lecture).
Key points from today’s lecture

• evidence for global sub-ice oceans in the outer Solar System;
• the “ideal” sub-ice ocean for biology (and ways in which Europa, Ganymede and Enceladus deviate from that ideal).
Ice-covered oceans

Persistent global ice cover:

DATA

PHYSICAL BASIS FOR LONG-TERM OCEAN STABILITY

ENERGETIC CONSTRAINTS ON BIOSPHERES

FUTURE TESTS AND TECHNIQUES
Persistent global ice cover:

DATA

PHYSICAL BASIS FOR LONG-TERM OCEAN STABILITY

ENERGETIC CONSTRAINTS ON BIOSPERES

FUTURE TESTS AND TECHNIQUES
Candidate cryovolcanic (water vapor) plumes detected by HST
Europa is differentiated into a $\text{H}_2\text{O}$ layer, rock mantle, and metal core. The ice above the ocean is at least 1 km thick (best estimate 30 km thick).
Gravity data constrain Europa’s ocean thickness

Fig. 2. Details of the intersection of the model surface of Fig. 1 with the horizontal outer shell density = 1050 kg m\(^{-3}\) plane. Europa three-layer models having an ice density (outer shell density) of 1050 kg m\(^{-3}\) are shown for an Fe core (A) and an Fe-FeS core (B). The solid curve labeled 131.5 \((\times 10^{-6})\) defines models constrained by Europa’s mean density and the indicated values of \(C_{22}\) used in constructing the model surfaces in Fig. 1. The curves designated 129 and 134 \((\times 10^{-6})\) delineate models with the \(\pm 1\sigma\) values of \(C_{22}\). The numbers within the curves denote the outer shell thickness (in kilometers).

\(C_{22}\) = gravitational anomaly associated with tidal elongation towards and away from Jupiter

Anderson et al. Science 1998
Magnetic data require a conducting fluid inside Europa; most likely a salty ocean.

This technique works because Jupiter has an inclined magnetic field (10 degrees). Magnetic field strength varies from 400 nT to 500 nT every 5 hours. It does not work at Saturn (axially aligned magnetic field).

Solid lines: data
Dashed lines: induced-dipole model

Khuruna et al., Astrobiology 2002
Ice-covered oceans

Persistent global ice cover:

DATA

PHYSICAL BASIS FOR LONG-TERM OCEAN STABILITY

ENERGETIC CONSTRAINTS ON BIOSPHERES

FUTURE TESTS AND TECHNIQUES
Fig. 4.13. (a) The path of a satellite in an elliptical orbit in the frame centred on the planet. The satellite keeps one face (marked by an arrow) pointed toward the empty focus of its orbit. (b) The path of the planet in a frame centred on and rotating with the satellite. For small values of $e$ the planet moves about its guiding centre, $G$, on an ellipse with semi-major and semi-minor axes in the ratio 2:1.
Fig. 4.15. The orientation of the equipotential curves in the equatorial plane ($\theta = \pi/2$) for the extremes of the (a) radial tide and (b) librational tide induced in a satellite due to its orbital eccentricity. In each case the arrows mark the direction of the planet.
Tidal dissipation occurs in the silicate mantle, the ocean, and the ice shell. It is currently thought that dissipation in the ice shell is the most important (sustaining the ocean – warm insulation).
Fig. 3. Angular momentum and rotational energy of Jupiter are transferred to Io via tidal interaction between the satellite and the giant planet. Due to the resonances orbital energy and angular momentum are distributed from Io to Europa and Ganymede. Part of the orbital energy gained by the satellites is dissipated in the moons’ interiors because of tidal flexing caused by Jupiter. Dissipation rates depend strongly on the distance to Jupiter and are therefore most important for Io, much smaller but still significant on Europa, and at present negligible at Ganymede (sizes and distances are not to scale).

Io: 100x more volcanically active than Earth

Europa: Ice-covered, internal water ocean

Ganymede: Ice-covered, internal water oceans
Link between tidal dissipation and internal temperature allows oscillations in internal temperature.

**Cold state**
- high $Q/k$
- high $e_{eq}$
- low $e$
- low dissipation rate

- $e_{eq} > e$
- $e$ increases
- dissipation rate increases

**Hot state**
- low $Q/k$
- low $e_{eq}$
- high $e$
- high dissipation rate

- $e_{eq} < e$
- $e$ decreases
- dissipation rate decreases

Timescale set by cooling time of shell in which dissipation occurs (typically Myr)

Schubert et al. Space Science Reviews 2010
One possible solution for coupled Europa-Io orbital-thermal evolution: illustrative only

Hussmann & Spohn, Icarus, 2004
These feedbacks are common, and many mid-sized icy objects likely maintain H2O oceans.

Most of the habitable volume in the Solar System is likely water in sub-ice oceans.

Ammonia antifreeze is important at Saturn’s orbit and beyond.

This graphic is from 2010. There is now evidence (libration) that Mimas also has a global ocean.
Persistent global ice cover:

DATA

PHYSICAL BASIS FOR LONG-TERM OCEAN STABILITY

ENERGETIC CONSTRAINTS ON BIOSPHERES

FUTURE TESTS AND TECHNIQUES
Energy budget of Europa’s ocean

Hand et al. 2007
Thermodynamics: The Chemical Fuels and Oxidants of Life
Giant-planet magnetic fields entrain charged particles which bombard the trailing hemispheres of moons → radiolytic chemistry
Fig. 10. After Cooper and Sturner (2006). Dose rate vs. depth where 1 rad/s is equal to 100 erg/gm/s or about 0.06 eV/H$_2$O-molecule/yr. The curve labeled “trailing hemisphere” includes the dose rate of 1–20-MeV electrons only, whereas the curve below it labeled leading hemisphere displays the dose rate of 20–40-MeV electrons that drift opposite to corotation. The uppermost of all the curves is the dose rate corresponding to electrons from 10 keV to 100 MeV and the dose rate from protons between 10 keV and 100 MeV follows this curve below it. Spikes and fluctuations in the computed curves arise from statistics of limited number of Monte Carlo events used in the simulations and not from physical processes. Times in years are shown to give chemically significant (most bonds are broken at least once) dose of 100-eV/16-amu (60 Gigrads) at selected dose levels.
An oxygen-rich Europa ocean, supplied by recycling of radiolytically-processed material from the surface?
Ganymede

Ice I
Ice III snow
Ice V
Ice VI

Liquid ocean layers, more saline with depth

Moon

Mercury
Ice-covered oceans

Persistent global ice cover:

DATA

PHYSICAL BASIS FOR LONG-TERM OCEAN STABILITY

ENERGETIC CONSTRAINTS ON BIOSPHERES

FUTURE TESTS AND TECHNIQUES
How to confirm a global sub-ice ocean exists: decoupling of ice shell from deep interior by ocean increases the amplitude of gravity tides and/or physical libration

The Tides of Titan

Luciano Iess,1* Robert A. Jacobson,2 Marco Ducci,1 David J. Stevenson,3 Jonathan I. Lunine,4 John W. Armstrong,2 Sami W. Asmar,2 Paolo Racioppa,1 Nicole J. Rappaport,2 Paolo Tortora5

1Dipartimento di Ingegneria Meccanica e Aerospaziale, Università La Sapienza, via Eudossiana 18, 00184 Roma, Italy. 2Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109, USA. 3California Institute of Technology, 150-21 Pasadena, CA 91125, USA. 4Department of Astronomy, Cornell University, Ithaca, NY 14850, USA. 5DIME Facoltà di Ingegneria, Università di Bologna, I-47121 Forlì, Italy.

*To whom correspondence should be addressed. E-mail: luciano.iess@uniroma1.it

We have detected in Cassini data the signature of the periodic tidal stresses within Titan driven by the eccentricity (e = 0.028) of its 16-day orbit around Saturn. Precise measurements of the acceleration of the Cassini spacecraft during six close flybys between 2006 and 2011 have revealed that Titan responds to the variable tidal field exerted by Saturn with periodic changes of its quadrupole gravity, at about 4% of the static value. Two independent determinations of the corresponding degree-2 Love number yield $k_2 = 0.589 \pm 0.150$ and $k_2 = 0.637 \pm 0.224 (2\sigma)$. Such a large response to the tidal field requires that Titan’s interior is deformable over time scales of the orbital period, in a way that is consistent with a global ocean at depth.
Measuring the thickness of the ice shell

Fig. 7. See Plate 38. The combination of (hypothetical) JEO measurements can constrain the thickness of the icy shell. Based on the bulk density and moment of inertia (from future flybys by JEO and other spacecraft), the thickness of the water + ice layer may be obtained (gray shading) (Anderson et al., 1998a,b); uncertainties arise mainly from lack of knowledge of the rocky interior density (bulk density is already known). Measuring time-variable gravity and topography gives the $k_2$ and $h_2$ Love numbers, respectively; hypothetical Love number constraints (red shading) assume observed $h_2$ and $k_2$ of 1.202 and 0.245, respectively, and constrain shell thickness as a function of rigidity $\mu$ (Moore and Schubert, 2000). The hypothetical values assumed here are characteristics of a moderately thick icy shell. In the example shown, the icy shell deformation is sufficiently large that a shell thickness in excess of 40 km is prohibited. Determining both $k_2$ and $h_2$ provides additional information. A lower bound on the icy shell thicknesses may be derived from radar data. Here, a tectonic model of icy shell properties is assumed (Moore, 2000), resulting in a radar penetration depth (and lower bound on shell thickness) of 15 km (green shading). Multiple frequency (hypothetical) set of observations results in a range of acceptable icy shell thickness (15–40 km) and a range of acceptable ocean thicknesses (45–70 km). A different set of observations would result in different constraints, but the combined constraints are more rigorous than could be achieved by any one technique alone. JEO would be able to provide those constraints to determine the thickness of Europa’s icy shell.
Landing and recovering ocean materials is required.

No nuclear reactor requirement.
A shortcut: sample material from the cryovolcanic plumes of Saturn’s moon Enceladus.
The ‘tiger stripes’ that launch Enceladus’ geysers are gateways to a global ocean

Fig. 1. The erupted flux from Enceladus (blue arrows) varies on diurnal timescales, which we attribute to daily flexing (dashed lines) of the source fissures by Saturn tidal stresses (horizontal arrows). Such flexing would also drive vertical flow in slots underneath the source fissures (vertical black arrow), which through viscous dissipation generates heat. This heat helps to maintain the slots against freezeout despite strong evaporitic cooling by vapor escaping from the water table (downward-pointing triangle). The vapor ultimately provides heat (via condensation) for the envelope of warm surface material bracketing the tiger stripes (orange arrows; “IR” corresponds to infrared cooling from this warm material).
Hydrothermal vents were active at the Enceladus seafloor geologically recently (inference: probably active today also)

not correct – now known to be global

Hsu et al. Nature 2015
Energy is available for life on Enceladus

\[
\text{CO}_2(aq) + 4\text{H}_2(aq) \rightarrow \text{CH}_4(aq) + 2\text{H}_2\text{O}(l)
\]

**Fig. 4. Apparent chemical affinity for hydrogenotrophic methanogenesis in the ocean of Enceladus (273 K, 1 bar).** The orange lines bracket the observed range in the mixing ratio of \( \text{H}_2 \) in the plume gas (Table 1). The dark blue lines are contours of constant ocean \( \text{pH} \), a key model parameter. The cyan region indicates affinities for a \( \text{pH} \) range that may provide the greatest consistency between the results of (13, 15, 25). The dashed burgundy line designates chemical equilibrium, where no energy would be available from methanogenesis. These nominal model results are based on \( \text{CH}_4/\text{CO}_2 = 0.4 \) (Table 1), a chlorinity of 0.1 molal, and 0.03 molal total dissolved carbonate (25). Reported ranges in these parameters propagate to give an uncertainty in the computed affinities of \( \sim 10 \) kJ (mol \( \text{CH}_4 \))

Ref: Waite et al. Nature 2017
Complex organic molecules are being launched into space from a scum layer on the top of Enceladus' ocean.

Extended Data Fig. 12 | Schematic on the formation of organic condensation cores from a refractory organic film. a, Ascending gas bubbles in the ocean \(^{25}\) efficiently transport organic material \(^{30}\) into water-filled cracks in the south polar ice crust. b, Organics ultimately concentrate in a thin organic layer (orange) on top of the water table, located inside the icy vents. When gas bubbles burst, they form aerosols made of insoluble organic material that later serve as efficient condensation cores for the production of an icy crust from water vapour, thereby forming HMOG-type particles. In parallel, larger, pure salt-water droplets form (blue), which freeze and are later detected by the CDA as salt-rich type-3 ice particles in the plume \(^{8,9}\).
Key points from today’s lecture

• evidence for global sub-ice oceans in the outer Solar System;

• the “ideal” sub-ice ocean for biology (and ways in which Europa, Ganymede and Enceladus deviate from that ideal).