Ge 131  
Chapter 24  
Outer Solar system Solid Bodies; Galilean Satellites

Read Showman and Malhotra, Science Oct. 1 1999, p.77

Location matters! Size matters (but less so!) Volatility Matters!

Earth’s moon is “geologically dead”. Similar size (and even smaller) bodies in the outer solar system are not. Why?

In terrestrial bodies we are used to the dominant role of radioactive heating. In giant planets, secular cooling and differentiation dominate. But in satellites, many of the most interesting things are due to tides (current or past). And this depends crucially on location. It is part of the reason why small bodies can have interesting endogenic processes. It is more important than size! Example: Enceladus has a tectonically deformed surface. Callisto, which is much larger, does not. Composition, especially volatility, plays a major role too, since it allows small bodies to do interesting things, even with modest energy budgets. It doesn’t take much energy to set methane ice flowing. So Triton can have a fascinating surface despite being a small body.

General Comments about Satellite Classes and Composition.

Io is in a class of its own: The only large outer solar system body that is ice-free. This is presumably a legacy of its location close to Jupiter. The severe tidal heating is certainly due to location. It is Earth-Moonlike to a first approximation but loaded with volatiles that the Moon does not have (never had?).

[Europa is also in a class of its own and we’ll give it special attention. It is actually more similar to Io than to Ganymede.]
Ganymede, Callisto and Titan are remarkably similar in size and in bulk composition (roughly 50/50 water ice and rock by mass). Titan has a dense atmosphere and may be more volatile rich in general.

Triton and Pluto are more rock rich but have ice-dominated surfaces. They are probably genetically similar (meaning they formed in a similar environment by similar processes) and Triton was then captured by Neptune.
Causes and Consequences of Tidal Heating

When a body is in an eccentric orbit, it is flexed every orbit because of the changing position and magnitude of the tidal potential (as seen from the uniformly rotating frame of the satellite). In the absence of any other factors, this will remove energy from the orbit (at fixed angular momentum) and the eccentricity of the orbit will be damped. But satellites in resonance are continuously pumped and their orbits expand because of the tide raised on Jupiter. In the case of Io (the most striking example) it is continuous action of Jupiter that keeps the tidal energy release high. Indeed, in an average or quasistatic sense, it is the dissipation (the Q) of Jupiter that keeps Io volcanic.

Traditionally, the problem of tidal heating has been approached by thinking of the heated material as being quasi-elastic; meaning that the strain field is that appropriate for an elastic body, but inserting hysteresis through a dimensionless parameter called Q. Large Q means low heating; small Q means high heating. The problem with this is that not all parts of the body behave equally. We can appreciate the complexity by considering the case of Io:

The “Classic” Argument for Tidal Heating of Io

Prior to Voyager’s arrival at Jupiter in 1979, Peale, Cassen and Reynolds predicted volcanism. Here is the essence of their argument:

1. The standard homogenous body (constant Q, elastic strain) theory predicts that tidal heating will be largest at the center of the body. As a consequence, melting will begin at the center.

2. As the melting zone propagates out, the strain increases because the remaining elastic shell is thinner, and the response of a thin shell is larger than that for a thick shell. (This is called the Love number. It is roughly the ratio of the tide actually raised to that which would be raised if the body were a fluid. So a solid Io has a Love number of ~0.01 and this increases to ~1 as the shell thins.)
3. Eventually the body equilibrates when the Love number is about as large as it can get, and thinning the shell further can only reduce the heat flow (by reducing the volume of material that is strained).

This predicts that Io has a thin elastic shell overlying a magma ocean.

**Problems with the Classic Model**

1. The melting point increases with pressure and hence depth, with the result that the melting does not begin at the center of the planet.

2. One must take into account the density differences between solid and liquid. Basalt is buoyant, but ultramafic liquids will (upon freezing) produce a surface layer that founders (because it is of the same composition as but colder than the interior). So a simple magma ocean picture may be gravitationally unstable.

3. Io has large mountains, suggesting highly variable heat flow. This argues against a simple (spherically symmetric) picture for the tidal heating.

*This problem is not solved.*
What is Europa?

Europa is a rocky body (Moon-like) with a thin (~150km) layer of H₂O (water or ice) on top. This model is strongly implied by the mean density and moment of inertia. The amount of water is roughly consistent with what you would get from dehydration of hydrated silicates. The water/rock ratio is accordingly very small compared to Ganymede. It should thus be thought of as a rocky body with some H₂O added, rather than as an icy satellite. It is of special interest because it is probably the only body in the solar system that is undergoing continuous substantial tidal heating in ice. Here is a likely model for Europa:
Why is it thought that Europa has a Water Ocean Underlying the Ice Shell?

There are three kinds of observational arguments, none of which is completely conclusive.

(1) Geological Evidence: Parts of the surface are broken up (“rafting”, “chaotic terrain”) and there are numerous examples of what appear to be rifts and rotations or translations of ice. There are a few instances of what have been interpreted as flows of highly mobile material (slush?) on the surface. At the very least, this argues for vigorous endogenic processes (cracking, convection, etc.) They might even require passage of water through the ice from underlying reservoirs (an ocean?) The problem with these arguments is that they mostly attest to the presence of mobility arising from brittle ice overlying soft ice, they do not attest directly to the presence of water. Even if liquid water is directly implicated, it might be possible to melt the ice in localized pockets, rather than invoke a global ocean.

(2) Spectroscopic Evidence: The near IR spectrum of Europa shows features that have been attributed by some to hydrated salts, plausibly MgSO$_4$.7H$_2$O. This could arise (as they do on Earth) from evaporites (i.e. dissolved in the ocean, carried to the surface then left behind as the warm ice sublimes or is sputtered away). Or it could be impurities in an ice-only shell. Or it could be delivered in water that came from localized melting within the ice shell. This kind of evidence is insufficient to decide whether there is an ocean (even aside from possible controversy with the spectral interpretation).

(3) Magnetic field. As discussed earlier, the magnetic field near Europa is reduced in just the way that you would expect if Europa were a conducting body. If this is interpreted as a conducting shell, then the criterion that must be satisfied to explain the data is:

$$\frac{\sigma}{1\text{S.m}^{-1}}(d/10\text{km}) > 1$$

where $\sigma$ is the conductivity of that shell and $d$ is its thickness. The conductivity of terrestrial ocean water is about 1 S/m (and much higher than that of fresh water). So an ocean certainly explains the data. Other possibilities seem implausible: Partially molten rock deep down would probably yield a smaller signal than observed (because it is deep down) and the ice is essentially an insulator even if loaded with ions (frozen brine).
There is still a problem: The observed magnetic field has other unexplained contributions comparable to the induced part. ("Unexplained" in this context almost certainly means plasma effects external to Europa; these confuse the interpretation of the induced component without completely destroying the merit of the interpretation.) However, the data in favor of an ocean has become increasingly convincing. See Stevenson, *Science* 289 1305 (2000).

**Theoretical Arguments for an Ocean**

The best way to appreciate the argument is to ask the following question: "What if I had an ocean? Would it freeze?" (Note, however, that this doesn't answer the question: "What if I never had an ocean? Would the ice shell then start to melt at it's base?" As you will see, this is a distinctly different question!)

The tidal potential at Europa's surface due to Jupiter is $\sim GM_j a^2/R^3$, where $M_j$ is the mass of Jupiter, $a$ is the radius of Europa and $R$ is the distance between Jupiter's center and Europa. The part of this that varies in time as Europa orbits is smaller by a factor of $e$, the orbital eccentricity. If the surface deforms as though it were a fluid, then the tidal amplitude $h_{eq}$ is just this tidal potential divided by $g$, the gravitational acceleration. Or:

$$h_{eq}/a \sim (eGM_j a^2/R^3)/ga \sim e (a/R)^3 (M_j/M_{Europa}) \sim 10^{-5}$$

which gives $h_{eq} \sim 30$ meters (if you put back in all the appropriate numerical factors). Now a thin ice shell underlain with water cannot provide enough elastic restoring force to prevent this near-equilibrium tidal distortion. To see this, suppose the actual tidal displacement is $h$. Then a hemispherical cap will feel a restoring force $\sim \mu (h/a) d 2\pi a$, where $\mu$ is the rigidity of the ice ($\sim 4 \times 10^{10}$ dynes/cm$^2$). However, there will be a net pressure on the underside of this cap of leading to a compensating force $-\rho g (h_{eq} - h) \pi a^2$.

Setting these equal, we get

$$(1-h/h_{eq}) \sim \mu d/\rho g a^2 \sim 0.2 (d/100$km$)$$

This means that the ice shell responds to the equilibrium tide (i.e. has the same shape as an ocean) even for thicknesses of order 100km (and certainly for thinner shells).
This calculation does not apply if the ice is "welded" to the underlying rock, of course. So we conclude that there is a fundamental difference in the tidal amplitude for the case of an ocean (even a thin ocean) and the case of no ocean (where the rocky core—which has a factor of ten higher rigidity—would dominate). *This is crucial to ocean detection strategies.*

Now suppose that the ice is dissipating like a high viscosity fluid. The dissipation per unit volume $Q$ for a viscous fluid is $\eta (de/dt)^2$ where $e \sim h_{eq}/a$ is now the strain. So $e \sim 10m/1000km \sim 10^{-5}$. Of course, $e \sim e_{max} \sin \omega t$ where $\omega$ is the angular frequency of the tide ($\omega = 2\pi/3.5$ days $\sim 2 \times 10^{-5}$). So

$$Q \sim 4 \times 10^{-5} (\eta/10^{15} \text{Poise}) \text{ erg/cm}^2 \text{ sec}$$

Of course this only makes sense if the viscous stresses $\eta (de/dt)$ are smaller than the tidal stresses $\sim \rho g h_{eq} \sim 1 \text{ bar}$. This requires $\eta < 10^{15}$ Poise roughly. (By coincidence, this is roughly the actual viscosity of ice). Now recall (from homework) that the thermal conductive equilibrium state predicts $\Delta T = Qd^2/2k$, where $\Delta T$ is the temperature difference across the ice shell (necessarily $\sim 150K$ if there is ocean underneath), and $k$ is the thermal conductivity. This predicts

$$Q \sim 9 \times 10^{-5} \ (10 \text{km/d})^2$$

Comparison with the equation above shows that ice of the likely viscosity will indeed lead to an ice shell of order 10's of km thick.

Of course, the ice may not have a purely viscous response. We can instead set $Q = \mu e^2/PQ_{\text{tidal}}$ where $Q_{\text{tidal}}$ is the tidal quality factor and $P$ is the orbital period. *By definition*, it is the ratio of elastic energy stored to energy dissipated per cycle of the tide). This predicts $Q \sim 10^{-4}/Q_{\text{tidal}}$, similar to the viscous result if the quality factor is sufficiently small. In fact, ice in Europa is in the cross-over regime between viscous response and elastic response because the tidal period is roughly the Maxwell time (defined as the ratio of viscosity to rigidity).

**Does Convection Change this Conclusion?**
It is commonly supposed that convection can prevent an icy satellite from developing an ocean because it is so efficient in eliminating heat. But in this case, increasing the ice shell increases the heat flow. The expected heat flux at the surface of Europa (ignoring heat from the core) is $\sim Qd \sim 10(d/10\text{km})$ erg/cm$^2$.sec. Referring back to our stagnant lid convection scaling, we have

$$F_{\text{conv}} = 0.5k(g\alpha/\nu k)^{1/3} \gamma^{4/3} \sim 15 \left(10^{15}/\nu\right)^{1/3} \text{ erg/cm}^2.\text{sec}$$

and the kinematic viscosity of ice at the melting point is plausibly around $10^{14}$ cm$^2$/sec or more. Here, $\gamma \sim 5$ K (recall that $\gamma$ is the derivative of the log of viscosity with temperature). So a thickness exceeding a few tens of km is not possible. Convection may indeed happen, but it doesn’t change the arguments for persistence of an ocean.

Some people think the ice is very thin because of an additional large heat flow from the tidally heated rock core. This is controversial.

**A Comparison of Ganymede and Callisto - Why are they Different?**

These bodies have similar masses and mean densities yet different appearances and different interior properties: Ganymede has an Earthlike magnetic field and is fully differentiated; Callisto has neither attribute. The most important issue is the differing degrees of differentiation.

Possible explanations:
1. Ganymede is a little bigger.

2. Ganymede formed a little closer; this means it may have formed faster and in a warmer environment.

3. Ganymede passed through one or more resonances on its way to the Laplace commensurability and thus suffered significant tidal heating.

Look at the Showman and Malhotra paper for a much more thorough discussion of this.

**Why does Ganymede have a Dynamo?**

This was a surprise, but it suggests that small bodies do not have a *fundamental* difficulty in running a dynamo. ("Fundamental" would mean that bodies of that size simply cannot achieve a large enough magnetic Reynolds number). But why would Ganymede have a convecting core while Mars apparently does not? Perhaps it is because Ganymede has continued in the same convective regime throughout time, with no periods of mantle heat up. Or perhaps it is because Ganymede has a strongly varying radiogenic heat source (because of higher $^{40}$K content). Or perhaps it is because Ganymede had a "late stage" heating episode that caused core formation and dynamo turn-on in a geologically recent tidal resonance event. This problem is unsolved.