Enceladus Saturn's Sparkling Gem

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Enceladus is a small icy moon of Saturn







Dione





Enceladus $R \sim 250 \text{ km}$, Density ~ 1.6 g/cc 150 km rock core, outer 100 km H₂O Orbits ~ 9 R_s away from Saturn outside bright rings, within tenuous *E*-ring $M_E/M_{\text{Saturn}} \sim 10^{-7}$ Thought to have a liquid water ocean Being observed by *Cassini* orbiter

Earth's Moon

R ~ 1700 km Density ~ 3 g/cc (Rock/Metal) Orbits 30 R_E away from us M_{moon}/M_{earth} ~ 10⁻² Enceladus ranks with Earth, Jupiter's moon lo, and possibly Venus and Neptunian satellite Triton as one of the few solar system objects shown to be geodynamically active at present.

Cassini spacecraft observations show that Enceladus has has jets of water vapor, dust, and other materials erupting from cracks in a warm and tectonically active region at its south pole.

Cassini CIRS estimates of brightness temperature (Spencer et al., 2008)





Take-Away Point from This Talk

Cassini observations of Enceladus provide us with a unique chance to test theories about icy satellite resurfacing developed from *Galileo* observations.

Understanding how Enceladus works will help us understand how all other icy moons work.

Outline

- I. Explain the scientific importance of Enceladus
- 2. Cassini data is allowing us to test theories about what drives resurfacing on icy satellites

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Icy Moons of the Outer Solar System





Known Kuiper Belt Objects, 2008



Direct (indirect) evidence for liquid water oceans Europa Ganymede Callisto (Enceladus) Titan (Dione) Miranda (Triton) (Pluto/Charon) & Kuiper Belt Objects

Distance from the Sun

Only Certain Moons Show Signs of Geological Activity



riton







What do these moons have in common?

All these moons have experienced tidal flexing stretching and squeezing due to eccentricity tides

Icy moons that experience tidal flexing experience endogenic resurfacing, regardless of size, location in the solar system, or composition!



Raising and lowering of tidal bulge makes the satellite do work against its own rigidity. Dissipates energy in its interior. Orbital energy is converted to heat.



Wahr, Selvans, Mullen, Barr, Collins, Selvans, Pappalardo (2008)



A moon that has an ocean will deform *a lot*. A moon that has an ocean will be strongly heated from within.

Big Scientific Question How does the tidal deformation convert orbital energy to heat, and how does that drive resurfacing?

Because Enceladus is active *today*, and is being observed by a functioning, well-instrumented spacecraft, observations of Enceladus and interpretation of *Cassini* results will help us answer this question.

Understanding Enceladus helps us interpret data from past, present, and future spacecraft missions.

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- 2. Describe a "case study" of hypothesis testing in planetary science (a rare treat!)



Ojakangas & Stevenson 1989)

(Nimmo and Gaidos 2002; Nimmo et al., 2007)



(Peale & Cassen 1978; Peale 1979; Ojakangas & Stevenson 1989) Nimmo et al., 2007)

Europa's Lines Provide a Clue about Tidal Heating





Europa's Lines Provide a Clue about Tidal Heating



Double ridges are a specific type of linear feature thought to represent to be shallow cracks formed by tidal stresses in a floating ice shell

Central crack is flanked by double ridge.

Ridge heights ~ hundreds of meters

May represent locations of cyclical strike/ slip motion driven by tidal flexing of Europa's ice shell

Shear heating along fault in center of ridge dissipates orbital energy (Nimmo & Gaidos 2002)

Thermal buoyancy results in upwarped flanks (Nimmo & Gaidos 2002)

Cassini spacecraft observations:

Hottest parts of south polar terrain are the "tiger stripes", which bear striking resemblance to Europan double ridges.

Provides compelling evidence that shear heating is one process that converts orbital energy to heat.

Presence of double ridge-like features on Triton suggests this occurs on all tidally flexed icy moons.

Close-up pictures of tiger stripes show that they look somewhat like double ridges on Europa







Cassini CIRS estimates of brightness temperature (Spencer et al., 2008) Observations of Europa gave rise to two theories about conversion of orbital energy to heat

Viscous Dissipation







In warmest ice At depth Possible feedback with convection Micro- or grain-scale (Peale & Cassen 1978; Peale 1979; Ojakangas & Stevenson 1989) Shear heating is probably a significant source of dissipation.

Double ridge-like features on almost all tidally flexed icy moons (including Enceladus and Triton) I don't think shear heating is the whole story.

I. Shear heating may not make enough energy to explain flux from tiger stripes.

2. The entire south pole is a region of lithospheric spreading.

Back-and-forth fault motion that drives shear heating does not drive spreading.

Viscous Dissipation

Tidally deformed satellite does work against its own internal friction.

Cyclical deformation of warm ice results in dissipation of tidal energy inside a satellite. (viscous dissipation; grain- or micro-scale)



Maxwell rheology relates stress, strain, viscosity, and rigidity

Energy dissipation
per unit volume $\oint_T \sigma \varepsilon dt \sim \frac{\varepsilon_0^2 \omega^2 \eta}{2(1 + \omega^2 \tau_M^2)}$ Ojakangas &
Stevenson (1989)Maximized when
forcing $T = T_M$ $\tau_M = \eta/\mu$

For Europa, $T=85^{h}$, and $T=T_{M}$ for $\eta = 10^{13} \text{ Pa s}$ a plausible viscosity for ice at its melting point Warm ice in Europa (& Enceladus) should be highly dissipative If this process is occurring, is there any manifestation of it on Europa's surface?

Ice Shell Convection

Over millions of years, solid water ice behaves like a fluid. Cold ice sinks, warm ice rises, just like Earth's mantle. An ice shell heated from within by viscous dissipation would convect, just like Earth's mantle.



Thermal convection in 100x100x30 km portion of basally heated ice shell Strongly temperature-dependent viscosity (diffusion creep) Rayleigh number = slightly lower than Earth's mantle



Convection in an Ice Shell with Weak South Pole of Enceladus



Spencer et al., (2006)

Simulation of convection in an ice shell on Enceladus heated from beneath

(warm ice at base of shell gets heated by viscous dissipation)



Barr in prep, (2009)

This style of convection explains the heat flux & tectonic setting at Enceladus' south polar terrain

Ice shell physical properties giving a convective heat flux $F \sim F_{CIRS}$ predicts crustal extension in SPT that would resurface the region in 0.1 to 10 Myr.

Comparable to the estimated surface age of 0.5 Myr (Porco et al., 2006)

Crustal extension at flanks and alongside to tiger stripes supports this hypothesis

Last step (this year) will be to add shear heating into model and see how it interacts with convection.









What happens when both of these processes are included?



Tiger stripes "attract" convective upwellings and become sites of tremendous heat loss (loosely analogous to terrestrial mid-ocean ridges)

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See article by Carolyn Porco, PI of the *Cassini* camera in the December 2008 *Scientific American*

Confirmation of theories will allow us to go back and re-examine Europa data, aid in planning for next mission

Slated to enter Jupiter orbit in 2035, so if you are an undergrad, now is the time to join the field!

NASA Planetary Geology & Geophysics Program Internships

http://www.acsu.buffalo.edu/~tgregg/pggurp.html



Understanding Europa's geology also sheds light on habitability (Surface/Ocean Material Exchange)



I. Can Europa's resurfacing processes allow near-surface oxidized ice to be buried in the ocean where it could power a biosphere? (Phillips and Chyba 2002)

2. Can resurfacing processes on Europa allow material from its ocean to be delivered to the surface where we can detect it?

Resurfacing processes either permit direct surface/ocean communication, or permit communication between surface ice and warm, convecting ice underneath (Barr Ph.D. thesis 2004)

Possible Geophysical Processes Enhancing the Habitability of Enceladus



I. Is material in Enceladus' plume from the near-surface or from the deep interior?

2. Can the plume resurface Enceladus and prevent ocean chemistry from stagnating?

Parkinson, Barr, Liang & Yung, submitted (2007)