Geophysical Study of Iapetus Constrained by Cassini Observations

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Icy objects contain information about the early Solar system and the development of potentially habitable environments.
IAPETUS - TWO PUZZLES

SHAPE:
OBLATE SPHEROID

(A-C) = 33 KM

PERIOD:
15 to 17 HRS

79 DAY EQUILIBRIUM
(A-C) = 10 M

SPIN STATE:
MOST DISTANT SYNCHRONOUS MOON IN THE SOLAR SYSTEM

D = 60 RS

PERIOD:
79.33 DAYS

(EQUATORIAL RIDGE)

(AND A CONUNDRUM:)

EQUATORIAL RIDGE)
A VERY ANCIENT FEATURES:
IAPETUS’ EQUATORIAL RIDGE

Length ~ 4680 km
Width ~ 100 km
Height up to 20 km
Very steep flanks, slope angle partly >30°
Age ~ same as surroundings (4.4 - 4.5 By)

Porco et al. (2005)
Model Requirements

- **Dissipative Interior** sufficient for Iapetus’ models to despin in less than the age of the Solar System

- **Stiff lithosphere** to retain the 17-h geoid and other topography
Approach

Simultaneous Solution of a System of Models

- Dynamical
- Thermal
- Rheological
- Lithospheric and Geological

AS A FUNCTION OF TIME
STATUS IN THE EARLY 80'S

Solar System's Age

Ellsworth and Schubert (1983)

$\frac{d\omega}{dt} = - \frac{3k_2GM_p^2a^5}{CD^6Q}$
Link between viscoelastic structure and dynamics

Initial impulse is of similar magnitude

The raw egg slows down faster than the cooked one!
Both eggs are disrupted from spinning in a similar way.

The cooked egg stops immediately while the raw one resumes spinning!
Rotation Period for Resonance

Viscosity (Pa s)

Rotation Period (h) at Resonance

Not Achievable over the Age of the Solar System

\[ T = 273 \text{ K with } 0-\epsilon \% \text{ melt fraction} \]
TEMPERATURE AT THE END OF ACCRETION

Maximum temperature is reached at about 20 km depth (after the model by Squyres et al. 1988)

Early Compaction

Early Melting

Maximum temperature is reached at about 20 km depth (after the model by Squyres et al. 1988).
MODELING MEDIUM-SIZED ICY SATELLITES

- Medium-sized satellites accrete cold and porous
- Water ice at 80 K is one of the most conductive planetary minerals
- The time scale to warm the interior from long-lived radionuclides decay is longer than the cooling time scale
- The conditions for tidal heating to become a significant heat source in cold objects are not understood

There is an obvious discrepancy between models and observations
Initial Conditions
- Presence of SLRS
- Formation time: 1.5 to 10 My after CAIs
- Presence of ammonia
- Planetesimals temperature
- Insulating regolith layer

Other sources
- Evolution of the surface temperature
- Silicate hydration heat
- Long-lived radionuclides
- Gravitational energy
- Tidal dissipation (if enabled)
MODELING APPROACH

DATA

Spin Data
Past: 6-10 hours – 17 hours
Present: 79.33 days

Shape Data
a-c = 33km
Lithosphere > 230 km

MODELS

Thermal Evolution
Despinning Despinning Despinning

Rheology
Lithospheric Thickness

HISTORIES
HEATING
- Short- and long-lived radiogenic isotopes
- Insulating, porous layer
- Saturn’s luminosity
- Impeded Convection (too cold)
- Tidal dissipation (coupled thermal-orbital evolution)

COOLING
- Runaway effect of temperature-dependent thermal conductivity
- Ammonia and other ice melting-point depressant (depends on their amount)
- Surface temperature
A REAL MYSTERY

Despinning Iapetus

Limit Heat Transfer
Impact Heating
Enrichment in LLRS

Rheology
% Ammonia
Extreme Orbital Evolution
Capture

$^{26}\text{Al}$ and SLRS

= Not Synchronous
= Wrong Shape
IAPETUS

Classical Model, after Ellsworth and Schubert (1983)
$^{26}$Al

- First identified in Calcium-Aluminum Inclusions
- Initial $^{26}$Al/$^{27}$Al $\sim 5-6.5 \times 10^{-5}$ (Pappanastassiou, Wasserburg, Lee)
- Half-life $\sim 0.717$ My
ROLE OF SLRS IN THERMAL EVOLUTION

• Play a role only in early evolution of the satellite early differentiation and geological activity)
  - e internal temperatures high enough for hydration (and consequent volume change)
  - e internal temperatures high enough for tidal tion to start
  - e internal temperatures high enough for ant porosity decrease
Porous Model, $t_0 > 6$ My after CAIs
Porous Model, $t_0 = 2.5$ My after CAIs
GEOLOGICAL CONSEQUENCES

(a)  
Radius (km)  
Time (My)  
Temperature (K) 

(b)  
Radius (km)  
Time (My) 

(c)  
Radius (km)  
Time (My) 

(d)  
Radius (km)  
Time (My)  
Porosity
$^{26}$Al IS NOT A FREE PARAMETER

Iapetus’ Age

Castillo-Rogez et al. (2007)
Planet Formation Timescales

Giant planets Models

• Gravitational instability – e.g. Boss
• Core nucleated accretion – currently favored
  • Time scale problem – analogy to terrestrial accretion yields $O(10^8 \text{ yrs})$ – too long compared with stellar evidence
  • “runaway growth” and Oligarchic growth models can result in $<10^7 \text{ yr}$ times scales (e.g. Lissauer, 1987)
Planet Formation Timescales

Evidence from stellar protoplanetary disks

• Gas loss <10^7 yr (Meyer et al., 2007)

• Spitzer studies for ~ solar mass stars show that stars with 3-5 x 10^6 yr ages lack indications of primordial planet-forming disks (e.g. Carpenter et al., 2006; Dahm and Hillenbrand 2007; Currie and Kenyon, 2008)
Evidence for Early Planet Formation

1 Million Year Old Planets?!

“A stellar prodigy has been spotted about 450 light-years away in a system called UX Tau A by NASA's Spitzer Space Telescope. Astronomers suspect this system's central Sun-like star, which is just one million years old, may already be surrounded by young planets.

Spitzer Science Center release 11/28/2007
THE FUTURE: LABORATORY-BASED MODELS

• Current models are not supported by laboratory measurements

• Viscoelastic response models rely on the Maxwell model, known to be applicable for a very limited range of conditions in satellites

Mechanical Measurements in Cryogenic Conditions at Low Frequencies and Stresses are Challenging
Maxwell Model

• $Q^{-1} \sim \omega^{-1}$, assumes one relaxation time $\tau = \eta / E$

• Easy to implement: depends only on two parameters

• Various measurements (lab-based, seismic data, glaciers) indicate that this model is not adequate
LABORATORY WORK

NEW EXPERIMENTAL FACILITIES AT JPL

First and only system able to simulate tidal dissipation under realistic satellite conditions
CAPABILITY OF NEW SYSTEM

Tidal Stress (MPa)

Tidal Forcing Frequency (Hz)

10^{-2} Hz
WHERE DO WE START?

- Monocrystalline ice in order to identify dislocation-driven anelasticity

- Dislocation creep is thought to drive anelasticity in many conditions: warm temperatures, large grain size, high stress (cf. terrestrial rocks)

• Results have demonstrated that existing models of dissipation need to be revised using our laboratory data.
SPECTRUM AT -30 deg. C

\[ Q^{-1} \sim f^{-0.9} \]

\[ Q^{-1} \sim f^{-0.3} \]

\( E / \eta \)

Maxwell frequency

Young's modulus

viscosity

\[ \sin \delta \]

Frequency (Hz)

Data (all)

Data (after 300 to 400 hrs)

Maxwell Model (commonly used)

Measurement-constrained Model (Andrade)
FUTURE CASSINI OBSERVATIONS WILL HELP CONSTRAIN THE FORMATION TIMESCALE FOR THE SATURNIAN SYSTEM
4.1.3.1

\[ J_2 (S \text{ pole}) = 5.2 - 7.8 \times 10^{-3} \]

\[ J_2n = 1.05 - 2.12 \times 10^{-3} \]

Density < 1200 kg/m³

MIMAS

TETHYS

IAPETUS

SLRS required for dynamical evolution

Density > 1200 kg/m³

ENCELADUS

DIONE

RHEA

Orbital Evolution Consistent with SLRS or LLRS only
POTENTIAL OBSERVATIONS

• **Geology**: Ongoing and Past Geologic Activity (*e.g.*, Enceladus)
• **Craters shape** (porosity, thermal gradient)
• **Surface Age**: Crater Counting and resurfacing
• **Equilibrium of the Shape**
• **Internal Structure**: (*e.g.*, for Rhea)
• **Dynamical Evolution** (*e.g.*, Iapetus)
• **Surface composition** (especially in craters, *e.g.*, Enceladus)