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A Recipe for Geophysical Exploration of Enceladus
A white paper submitted to
the Committee on the Planetary Science Decadal Survey (2023-2032) of
The National Academies of Sciences

Anton I. Ermakov¹, Julie C. Castillo-Rogez², Ryan S. Park², Christophe Sotin², Joseph Lazio², Samuel M. Howell², James T. Keane², Douglas J. Hemingway³, Francis Nimmo⁴, Edwin Kite⁵, Vishnu Viswanathan^{6,7}, Gregor Steinbrügge⁸, Gabriel Tobie⁹, Valery Lainey¹⁰

¹ *Department of Earth and Planetary Science, University of California, Berkeley, CA 94720, USA*

² *JPL, California Institute of Technology, 4800 Oak Grove Dr. Pasadena, CA 91109, USA*

³ *Carnegie Institution for Science, 5241 Broad Branch Road NW, Washington, DC 20015, USA*

⁴ *Department of Earth and Planetary Sciences, University of California, Santa-Cruz, CA 95064, USA*

⁵ *University of Chicago, Chicago, IL 60637*

⁶ *NASA Goddard Space Flight Center, 8800 Greenbelt Rd, Greenbelt, MD 20771, USA*

⁷ *University of Maryland, Baltimore County, 1000 Hilltop Cir, Baltimore, MD 21250, USA*

⁸ *Department of Geophysics, Stanford University, Stanford, CA 94305, USA*

⁹ *Laboratoire de Planétologie et Géodynamique, CNRS/Université de Nantes, France*

¹⁰ *IMCCE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Université, Univ. Lille, 77 Avenue Denfert-Rochereau, 75014 Paris, France*

Lead Author Contact Information:

Dr. Anton I. Ermakov

University of California, Berkeley

Berkeley, California, 94720

Email: eai@berkeley.edu

Phone number: +15104805269

This white paper can be endorsed here: <https://tinyurl.com/y9qhuuw>

Acknowledgements: *A portion of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.*

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Anton I. Ermakov et al.

Science Questions

Key Measurements

- ✓ Measured
- ① Partial / Incomplete
- ✗ Not Measured

Orbital Migration Rate (da/dt) ✓
sets the equilibrium dissipation rate within Enceladus.

Shell Libration ✓
constrains Enceladus' moment of inertia and interior structure.

Q3: Is Enceladus in Steady State?

Is Enceladus in thermal steady-state, where heat in = heat out?

Is Enceladus in orbital steady-state, where its orbital eccentricity isn't changing ($de/dt=0$)?

Recommendations:

We strongly advocate for a New Frontiers or Flagship class Enceladus Orbiter.

#1: Geophysical measurements should be an essential component of future Enceladus exploration.

#2: A GRAIL-like investigation can be added to New Frontiers or Flagship-class mission concepts to Enceladus for little additional resource requirements by leveraging current and upcoming developments in CubeSat technologies and small radios.

Oblivuity ✗, Precession ✗, and Nutation ✗ constrain Enceladus' spin moment of inertia and interior structure.

Are there lateral heterogeneities in the crust? If so, what can they tell us of Enceladus' geologic history?

How is non-hydrostaticity partitioned between the core and the shell?

What is the composition, density, and porosity of the core?

Q2: Where is heat generated and how is it transported?

Where and how is tidal heat dissipated within Enceladus? What is the balance between heating in: the core, ocean, or ice shell?

What is the thermal structure of Enceladus' ice shell?

Convection in the lower shell could enhance viscous flow and relaxation of crustal topography.

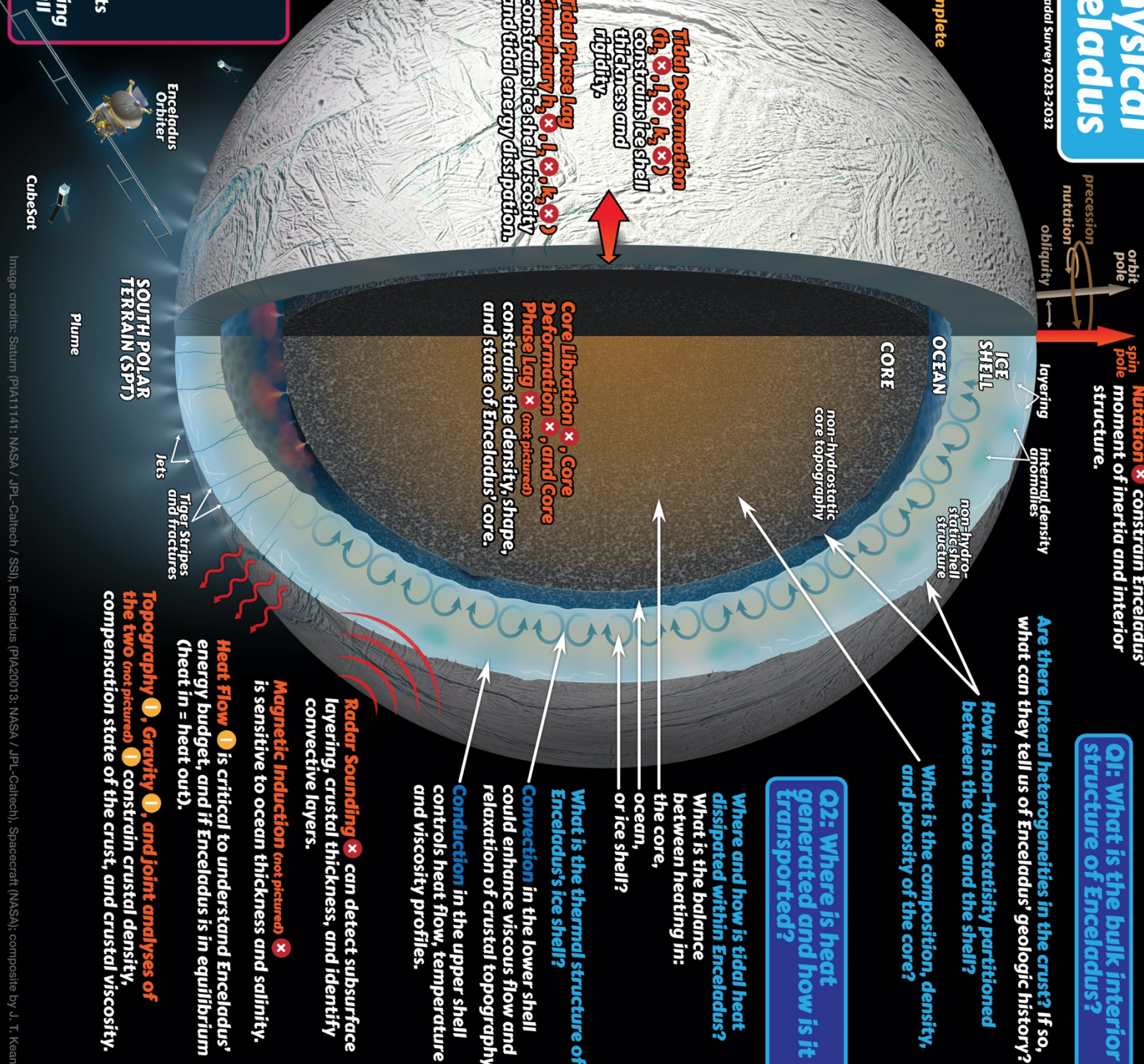
Conduction in the upper shell controls heat flow, temperature and viscosity profiles.

Radar Sounding ✗ can detect subsurface layering, crustal thickness, and identify convective layers.

Magnetic Induction (not pictured) ✗ is sensitive to ocean thickness and salinity.

Heat Flow ① is critical to understand Enceladus' energy budget, and if Enceladus is in equilibrium (heat in = heat out).

Topography ①, Gravity ①, and joint analyses of the two (not pictured) ① constrain crustal density, compensation state of the crust, and crustal viscosity.



Executive summary:

Orbital geophysical investigations of Enceladus are critical to understand its energy balance. Mapping Enceladus' gravity field, improving the accuracy of the physical libration amplitude, and measuring Enceladus' tidal response would provide critical constraints on the internal structure, thus establishing a framework for assessing Enceladus' long-term habitability.

1) Introduction

Enceladus—a cryovolcanically active and potentially habitable satellite in the Saturn system—challenges our understanding of geodynamical processes governing the evolution of ocean worlds. Starting in 2005, the *Cassini* spacecraft revealed active eruptions in the southern hemisphere, confirmed the presence of a deep, global ocean with complex organic molecules¹ and provided direct evidence for recent hydrothermal activity². This makes Enceladus a high-priority astrobiology target (see White Paper by Cable et al.³). The mechanism powering the eruptions has been a matter of debate for over a decade. **Key to understanding how Enceladus works is the spatial and temporal distribution of the energy dissipated through tides.** This energy is necessary for the maintenance across geologic time of Enceladus' ocean—a potentially favorable habitat for life.

The goals of this white paper are:

- 1) to provide an overview of the science questions that geophysical data (see Table 1 and Page 1 illustration) at Enceladus could answer;**
- 2) to suggest implementation options to address these questions at low-cost as part of a larger Enceladus New Frontiers- or Flagship-class mission concept.**

The *Cassini* geophysical data^{4–6}, despite its limited resolution and lack of global coverage, have yielded valuable constraints on the interior state of Enceladus^{7–9}. The gravity data along with shape models were used to constrain the differentiation state^{5,8} and the long-wavelength variations in ice shell thickness^{9–12}. The physical libration data revealed that the icy shell is decoupled from the core by a liquid layer¹³. The measured heat flux in the South Polar Terrain (SPT) provided a lower bound on the amount of energy emitted from Enceladus^{14,15}. The coherent spatiotemporal pattern of cryovolcanic activity¹⁶ provided constraints on the rheology of and heat production within the cryovolcanically active region^{17–19} and provided hints of a longer-term variability²⁰.

The dependence of tidal dissipation on the interior structure introduces a feedback between orbital and internal state evolution^{14,21–23}. That feedback governs the long-term evolution of the satellite. The present-day internal structure determines the instantaneous spatially variable tidal dissipation rate. Depending on the efficiency of the transport of heat from the interior to the surface, Enceladus might or might not be in a steady state. In addition, the tidal migration also depends on the dissipation within Saturn. Fast tidal migration of the Saturnian moons observed astrometrically indicated strong dissipation within Saturn²⁴. This observed fast migration implies either that the major satellites are young or that the migration rates have not been steady, as predicted by the resonance locking mechanism with Saturn's normal modes^{24–26}. Therefore, the following interrelated **Priority Science Questions** should be addressed by future geophysical observations of Enceladus:

- Q1: What is the bulk internal structure of Enceladus?***
- Q2: Where is the heat generated and how is it transported?***
- Q3: Is Enceladus currently in a steady state?***

Table 1. Summary of the existing geophysical data and knowledge gaps. Also, see Page 1 illustration for more qualitative description of different measurements.

Quantity	Existing knowledge and/or knowledge gaps
Gravity field	Gravity field to degree 3 (500-km wavelength) was measured by <i>Cassini</i> [3]. This allows estimation of Enceladus' non-hydrostaticity but does not allow to discern the origin of the non-hydrostaticity.
Shape	Shape was estimated up to degree 16 (100-km wavelength) [6].
Obliquity	Not currently measured. <i>Cassini</i> -derived upper bound of 0.05° [27]. Upper theoretical bound of 0.0004° [28].
Physical libration	Measured amplitude at equator of $0.120 \pm 0.014^\circ$ [13]. Currently, only libration at the orbital frequency was measured.
Precession and nutation	Not currently measured. Theoretical value for precession of 2.6 rad/year [28].
Tidally-driven orbital evolution	Tidal migration was measured from astrometric data ²⁴ However, current accuracy precludes determination of dissipation within Enceladus from astrometry.
Tidal deformation	Potential Love number k_2 ; and radial and lateral displacement Love numbers h_2 and l_2 , respectively, are not currently measured.
Radar surface mapping	Not currently achieved.
Magnetic induction	Not currently measured.
Thermal IR mapping	A heat flux in the SPT is estimated at 4.2 GW [15]. Heat flux elsewhere has not been mapped.

2) **Priority Science Questions**

Q1: What is the bulk internal structure of Enceladus?

Gravity⁵ and shape data^{4,6} collected by *Cassini* coupled with libration data¹³ have been used to constrain⁷⁻⁹ the shell and ocean thicknesses and densities. However, current state-of-the-art models rely on several critical assumptions of as-yet-uncertain validity: e.g., hydrostatic core, or that isostasy in the crust is isotropic⁵. If these assumptions are relaxed, it becomes impossible to separate crustal processes (e.g., freezing/melting of the shell, convection, impact cratering, tectonics) from processes occurring in the core. Separating the non-hydrostatic signal of the shell from that of the core could be achieved by mapping the shell thickness variations using a combination of topography, radar, and gravity data. Measuring the magnetic induction would provide a constraint on the ocean thickness and salinity. Improving the libration amplitude measurement at multiple frequencies ranging from hours to tens of days can be used to better constrain the shell structure, specifically moment of inertia differences. Accurate tracking of Enceladus' precession can also be used to determine the shell's polar moment of inertia. Finally, measuring the gravitational signal of the core-shell misalignment can eliminate the degeneracy.

Q2: Where is the heat generated and how is it transported?

A heat flux of 4.2 GW was observed from the SPT by the Composite Infrared Spectrometer (CIRS) onboard *Cassini*¹⁵. This heat flux is thought to be dominated by advection of heat in the Tiger Stripes. The heat flux away from the Tiger Stripes remains elusive. Current estimates on global heat flux (assuming a conductive shell) range from 25 to 40 GW [9]. Radiogenic heating within the rocky core can account for <0.3 GW [9], and is thus not sufficient to sustain the liquid water ocean. Recent astrometric efforts¹¹ indicate that Saturn may be more dissipative than previously thought, with a quality factor Q as small as $\approx 2,000$ at Enceladus' tidal frequency, permitting equilibrium tidal dissipation within Enceladus to be as much as ≈ 25 GW. Tidal heating is thus thought to provide an additional heat source, preventing quick freezing of the subsurface ocean²⁹.

The local instantaneous tidal heat generation is determined by the product of tidal stress and strain rate. The mutual relation between these two quantities is, in turn, set by the rheology of the material that is highly sensitive to temperature. Heat is likely generated in the warmer ice at the base of the shell or in the core, especially if the core is unconsolidated (e.g., sandy/muddy). Using a 3D model with a variable ice shell thickness including the SPT faults showed that dissipation in the ice shell cannot exceed 4 GW [30], implying that an additional heat source is needed. Over 10 GW can be generated by tidal friction inside the unconsolidated rocky core³⁴. Theoretical models predict that the ocean heat production is likely negligible^{31–33} because of Enceladus' low obliquity and thick ocean, although dissipation may be enhanced in narrow liquid-water conduits¹⁹.

The shell thickness directly affects the conductive heat flux. In order to determine the conductive heat flux to within 10%, the average shell thickness needs to be determined to within 2 km [9]. In the SPT, more precise ice shell thickness determination is required in order to constrain its dynamics and the implications for heat transport. For a fully conductive shell, the thickness derived from radar returns and from the other datasets such as the tidal Love numbers, libration amplitude or gravity-topography admittance should be comparable. The shell porosity affects the thermal conductivity and, therefore, the temperature and viscosity profiles. Thus, high-resolution gravity data would be complementary in assessing shell conductivity as the high-degree gravity-topography admittance is set by the density and porosity of the body's outer layer³⁵.

Distinguishing between convection and conduction is of great interest. Conduction is likely dominant in the outer part of the shell. Convection might dominate heat transport in the deepest part of the shell. Convection in the bottom shell makes the conductive region thinner and with a steeper temperature gradient, and therefore greater conductive heat loss. Efficient heat transport by convection might lead to quick ocean freezing. For a convective shell, radar reflections from the warmer bottom ice would result in a lower radar-derived shell thickness compared to that of the geodesy-based estimates. The low bottom shell viscosity would enable the relaxation of the isostatic roots affecting the gravity-topography admittance. Finally, vigorous convection can produce dynamically supported topography, which would also be reflected in the admittance.

Estimating the elastic thickness would provide a critical constraint on the heat transport within the shell. Elastic thickness can be derived either from the gravity-topography admittance³⁶ or by mapping flexural profiles of tectonic features that would require accurate topography knowledge⁴. A flexural profile amplitude of 120 m at ≈ 10 -km scale is predicted in the vicinity of Tiger Stripes⁹. Thus, measuring this flexural signal would require regional topography knowledge to at least an order of magnitude better (10 m). Deriving elastic thickness spatial variations and

cross-correlating them with the heat flow mapped in the thermal IR emission could help validate the dissipation pattern within the shell.

Finally, the rates of advective (volcanic) and conductive cooling appear to be similar in the SPT¹⁹. This contrasts both with the Earth's oceanic lithosphere, where conductive cooling dominates, and Io, where advective cooling dominates. The strong potential coupling between volcanism and tectonics highlights the importance of a high-resolution gravity and topography mapping within the SPT. For example, inferring the density of the upper crust from the gravity-topography admittance³⁵ could help distinguish whether the SPT is resurfaced by plume-fall (high porosity) or by intermittent surface flows (low porosity). Estimates of the elastic thickness from the flexural profiles collected in the vicinity of the cracks might be significantly different from the estimates using localized gravity-topography admittance if a significant advection of heat occurs in the cracks. Better constraints on the spatiotemporal pattern of eruptions¹⁷ might constrain the heat production within the Tiger Stripes and the plumbing system as well as tectonic mechanisms operating within the SPT^{19,35}.

Q3: Is Enceladus currently in a steady state?

The feedback between orbital and thermal evolution leads to two distinct kinds of a steady state. First, in the thermal steady state, the present-day heat production is equal to the present-day heat loss. Second, in an orbital steady state, damping of eccentricity due to dissipation within Enceladus is balanced by pumping of its eccentricity by the 2:1 e -Enceladus resonance with Dione (i.e., $de/dt=0$). If not in a steady state, Enceladus can exhibit a periodic behavior, in which energy is stored at one time and released at a later time (perhaps resulting in a cyclical ocean), or it might be in a net freezing or melting state. Both kinds of steady states critically depend on the tidal lag, which is characterized by the imaginary part of the potential Love number, or $\text{Im}(k_2)$. Larger values of $\text{Im}(k_2)$ correspond to larger internal tidal dissipation and faster tidal damping of eccentricity.

Understanding of whether or not Enceladus is in an orbital steady state requires precise knowledge of its ephemeris. However, the low accuracy of the current astrometry precludes a firm conclusion. Tidal phase lag can be derived in two ways. First, tidal phase lag would have an effect on the orbit on the spacecraft. Thus, it can be derived by radio-tracking of the spacecraft in the same way the gravity field is derived. Second, tidal phase lag has an effect on the orbit of Enceladus causing the damping of its eccentricity. Thus, it can be derived by building an accurate ephemeris model using ground- or spacecraft-based astrometry. Pursuing both ways of deriving the tidal phase lag would provide a robustness check. In addition, the change of eccentricity should be accompanied by the corresponding evolution of the Enceladus-Dione resonance libration angle, determination of which would require precise astrometry of both Enceladus and Dione.

In conclusion, long-baseline continuous ground-based astrometry at km level and future astrometry in the Saturnian system (20 years after Cassini) would be needed to constrain whether Enceladus is in the orbital steady state. Thermal IR mapping of Enceladus, including the conductive heat flux away from the Tiger Stripes, is critical for assessing if Enceladus is in the thermal steady state.

3) Measurement requirements

Geophysical measurement requirements can be derived in multiple ways as several combinations of measurements can yield identical accuracy for a recovered parameter (e.g., gravity and radar measurements can both yield shell thickness estimates). In addition, the measurement requirements might be dependent on the (yet unknown) value of the recovered parameter. For example, the thinner the decoupled shell, the more sensitive the libration amplitude is to the shell

thickness (because libration amplitude is an inverse function of shell thickness). In this report, we derive traceable measurement requirements with the Markov chain Monte-Carlo (MCMC) approach³⁷ using *a priori* central values for the internal structure parameters⁹ as the truth values.

The tidal deformation is 2-3 meters in the equatorial region, but can be amplified in the vicinity of the Tiger Stripes³⁸. Libration signal is larger (≈ 530 meters at the equator¹³) and, therefore, is easier to measure by optical imaging compared to tidal deformation. The combined measurement of the gravity-topography admittance and the libration amplitude at the orbital period can effectively reduce the shell thickness uncertainty. Finally, measuring obliquity and precession would require a sub-meter accuracy on the Enceladus orientation.

We find that improving the accuracy of the gravity-topography admittance to the level of 1 mGal/km up to degree 10 and libration amplitude to an accuracy of 6 meters can drive the uncertainty of the total shell thickness down to 2 km, which corresponds to a 10% uncertainty in the conductive heat flux. If k_2 is measured to an absolute accuracy of 10^{-2} , it would provide a constraint on shell rigidity, but would not provide a constraint on dissipation. We find $\text{Im}(k_2)$ to be in the range of $10^{-5} - 10^{-4}$ assuming a conductive shell. Thus, measuring k_2 to a 0.1% relative accuracy or better would be required for detecting tidal lag to constrain the dissipation in the interior. Finally, the recovery of h_2 and l_2 with the same accuracy as for k_2 can help mitigate the ambiguity of the ice rheology that arises when measuring k_2 only.

4) Mission Scenarios

Due to strong tidal perturbations from Saturn, a circular, polar orbit around Enceladus is practically impossible³⁹. Instead, a stable orbit around Enceladus with 60° inclination and periapsis and apoapsis altitudes of 150 km and 200 km, respectively, for 28 days is a viable mission scenario. Both poles can be covered with flybys prior to being placed into this stable orbit, depending on the science requirements. Based on this 60° inclination orbit, we have performed covariance analysis for two mission configurations to assess the expected accuracy of geophysical observables, such as Love numbers, gravity field, and libration amplitude.

Assuming a single orbiter with an X-band capability (range-rate accuracy of 0.1 mm/s at a 60-s count time), a gravity field up to degree ≈ 10 can be recovered; k_2 can also be recovered with an accuracy of $\approx 10^{-3}$. A high-resolution context imager with accurate pointing knowledge, such as the Advanced Pointing Imaging Camera⁴⁰ (APIC), can measure h_2 and l_2 with accuracies ≈ 0.01 and ≈ 0.002 , respectively. This corresponds to a relative uncertainty of 20-25%. The libration amplitude can be recovered with an accuracy of < 1 m at equator (a relative uncertainty of $< 0.2\%$). The accuracy of h_2 , l_2 , and libration amplitude can be improved with optimal distribution of crossover points⁴¹. Recovering h_2 can further be achieved by laser or radar altimetry in combination with stereo-imaging at crossover points²⁹. Equivalent measurements are already scheduled by the Ganymede Laser Altimeter³⁰ for Ganymede and the Radar for Europa: Ocean to Near-Surface¹⁵ in case of Europa.

Assuming the same orbit configuration, a GRAIL-like scenario (i.e., inter-satellite tracking at 0.01 mm/s range-rate accuracy) can improve the k_2 accuracy to $\approx 2 \cdot 10^{-5}$ (or relative accuracy of $\approx 0.1\%$) with gravity field determined to degree from 20 to 30, depending on the tracking accuracy and separation distance between spacecraft. This level of accuracy would allow a definitive determination of the tidal phase lag and total tidal dissipation within Enceladus. The core viscoelastic moduli remain virtually unconstrained for the mission configurations we studied. However, it would be possible to put a lower bound on the core viscosity from the Love numbers,

if they are measured to an accuracy of 0.1%. The core parameters could be constrained from the gravity effect of the core deformation (see White Paper by Vance et al.⁴²)

Advances in small radios based off the Iris transponder on the Mars CubeSat One mission and Artemis-1 CubeSats (e.g., software programmable Universal Space Transponder-Lite, or UST-Lite⁴³, ≈ 1 kg, ≈ 15 W, two-way Allan deviation of 10^{-14} at 1000 s) enable a GRAIL-like scenario at little resource cost to the primary mission, but with less accurate satellite-to-satellite ranging accuracy. The CubeSat can be carried to destination and network with the mothership via a deep space deployer providing power/thermal during cruise. This CubeSat would be enabled by new technologies in thermal management and propulsion subsystems.

5) Conclusions

We strongly advocate for a New Frontiers- or Flagship-class Enceladus Orbiter mission concept that can address the Priority Science Questions outlined in this report, as well as other compelling science questions (see White Papers by Vance et al.⁴², Cable et al.³, Byrne et al.⁴⁴).

Recommendation #1: Geophysical measurements should be an essential component of future Enceladus exploration. Geophysical data can shed light onto the mechanism of tidal dissipation and heat transport. Distinguishing between various locations of tidal dissipation can be achieved by mapping the variations of the total shell thickness, which can be further augmented by mapping the elastic shell thickness either by localizing gravity-topography admittance or by measuring flexural profiles at various locations. Thermal IR mapping away from the SPT is needed to understand the global heat flux. Measuring the magnetic induction response would provide a constraint on the ocean thickness and salinity. Laser or radar altimetry can be used to derive a high-resolution shape model and measure tidal deformations.

Recommendation #2: A GRAIL-like investigation can be added to New-Frontiers or Flagship-class mission concepts to Enceladus for little additional resource requirements by leveraging current and upcoming developments in CubeSat technologies and small radios. A GRAIL-like mission concept would be able to measure tidal lag and significantly improve the accuracy of the gravity-topography admittance. This would enable investigating the energetics of Enceladus, thus establishing a foundation for understanding Enceladus' long-term habitability³.

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