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Paving the Way for Future Space Missions in the Context of High Tidal Dissipation in the Saturnian System

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Abstract

The recent discovery of strong tidal dissipation in Saturn's interior has radically changed our view of the Saturnian system. While some questions are naturally answered by the new paradigm, others are emerging and require further measurement. This article presents the next key questions to be addressed by future space missions and analysis. Suggestions for space measurements to discriminate between different scenarios concerning the formation, evolution and internal state of the Saturnian system are given.

Keywords Saturnian system · Future space missions · Tides · Dynamics · Cassini mission

1 What Physical Mechanisms Drive the High Dissipation Observed in Saturn?

One of the great surprises of the Cassini mission was certainly the discovery of the intense tidal energy dissipation in Saturn (Lainey et al. 2012, 2017). Successive measurements revealed that the frequency dependence of the amount of energy dissipated was very different from the usual models that were based on a constant quality factor Q or delay time Δt. As described in Fuller et al. (2024) and summarized below, while there are several mechanisms that could lead to significant tidal loss of mechanical energy (Ogilvie and Lin 2004; Remus et al. 2012; Terquem 2021; Barker and Astoul 2021; Dewberry 2024), the mechanism proposed by Fuller et al. (2016) is currently the only one to explain the observed frequency variation of Q (Lainey et al. 2025). This mechanism is based on the excitation of the planet's internal eigenmodes by the tidal forces associated with the moons. When a resonance is encountered, a large amount of mechanical energy is dissipated as heat via turbulence in the fluid part of the planet. As the planet cools and its structure and rotation rate evolve, the frequencies of the eigenmodes vary with time. As a result, the moons all have a high probability of encountering resonances with the planet's modes. Hence, because of the intense internal friction generated, the moons are then pushed outwards from the planet via an exchange of angular momentum between Saturn's rotation and the moons' orbits. The result is a dynamic equilibrium in which each moon migrates outwards as its resonant eigenmode evolves. Thus, according to the mechanism developed by Fuller et al. (2016), the commonly

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Extended author information available on the last page of the article used physical parameter Q must be replaced by analysis of the parameter t_{tide} equal to the ratio $\frac{a}{\dot{a}}$. According to the resonance locking model, each moon raises a tidal wave whose frequency is resonant with a normal mode, causing the moon to migrate outwards at a rate dictated by t_{tide}.

However, several questions remain to be addressed. Firstly, Jacobson (2022) obtained an orbital expansion for Titan that disagrees with that published by Lainey et al. (2020). Specifically, when combining the radiometric and astrometric data, Jacobson (2022) obtain a tidal Q of Saturn at Titan's forcing frequency that is about an order of magnitude larger than both results (one from astrometric data, one from radiometric data) of Lainey et al. (2020), while they obtain a statistically consistent result when omitting the Voyager and Cassini tracking data from their analysis. A fuller discussion of this is described in Fuller et al. (2024). As Titan's orbital expansion is, along with that of Rhea, the most important piece of information for asserting the existence of a resonance locking mechanism between the satellites' orbital evolution and Saturn's evolving internal oscillation modes (Fuller et al. 2016), this conflict between different results needs to be resolved. Since the solution for the orbital evolution depends on a combination of astrometric and radiometric data, a global re-analysis is necessary, with a particular focus on how uncertainties in the data and models propagate to uncertainties in Saturn's dissipation. Ideally, an independent team should reanalyze the radio-science data from Cassini's flybys of Titan, and help to confirm or deny the presence of such a rapid orbital expansion (11 ± 2 cm/year) of Titan's orbit (Lainey et al. 2020). Such an analysis is now underway (Hener et al. 2025)

Another open question is that of dissipation within Saturn's core. Work focusing on this question has suggested that a significant fraction of the system's mechanical energy may be dissipated in Saturn's core (Remus et al. 2012). In theory, accurate measurements of the inner moons' migration rates may allow us to separate the fraction of energy dissipated in the core by viscoelastic dissipation from that dissipated by resonant modes in the fluid envelope. In practice, however, orbital expansion measurements are still subject to large error bars. Moreover, the exchange of angular momentum between Mimas and the Saturnian rings may be significant due to the 2:1 resonance (Lissauer and Cuzzi 1982), inducing an orbital expansion of Mimas, similarly to tides. Last, Mimas' orbital expansion is very weakly constrained (Lainey et al. 2020) with a da/dt of 25.3 ± 20.9 cm/year (at 3-sigma) leaving only five truly constraining measurements, associated with the moons Enceladus, Tethys, Dione, Rhea and Titan. Thus, it is desirable that future space missions add further constraints on the orbital expansions of these moons via astrometry and radio-science during future flybys, orbit phases or landers. Measurements of the orbital expansion of Mimas will especially be important.

Another important point is the amplitude of tidal effects in the moons themselves. As the dissipated energy is taken from the orbital energy, the tides in the moons decrease their eccentricities and semi-major axes. The orbital expansion measurements obtained by Lainey et al. (2020) assumed that tidal dissipation in Enceladus was in the range 3-55 GW. This is consistent with observationally constrained upper limit of 54 GW (Miller et al. 2024). Because of the degeneracy between tidal migration driven by Saturn and that driven by dissipation within Enceladus, error bars on dissipation in Saturn at the frequency of Enceladus and Dione are very large.

Furthermore, no significant dissipation in the other moons was modeled, on the assumption that this would be negligible within the error bars of the measurements. Nevertheless, Lainey et al. (2024) recently showed that Mimas could be the center of intense tidal effects due to the inferred presence of a young ocean beneath its ice pack. This suggests that the interpretation of orbital expansion measurements could be revised, at least for Mimas, and potentially for other moons (see Sect. 5).

Finally, testing the resonance locking mechanism within a system other than Saturn is more than desirable. For example, Fuller et al. (2016) predicted that if this mechanism were to take place within Jupiter, Callisto should exhibit a significant orbital expansion. Such a measurement will be conceivable with the arrival in the Jovian system of the next generation of space missions, such as JUICE and Europa Clipper (Magnanini et al. 2024; Fayolle et al. 2024).

2 Determining the Formation Process and the Age of the Main Moons

With the observed fast outwards migration of Saturn's regular satellites, the question of their origin must be addressed from a new perspective. In particular, it is not clear that the currently observed moons formed in a circum-planetary disk, close to where they currently orbit. The highly variable composition of the mid-sized moons, from 7 to 70% silicates with no apparent radial gradient, also suggests some stochasticity in their formation process. Meanwhile the low density and pure water ice composition of the small moons suggests a connection to the rings. Therefore, the idea has emerged that the regular satellites might come from the spreading of the rings beyond the Roche radius, where the material naturally agglomerates under the effects of self-gravity (Charnoz et al. 2010), and then migrated outwards by interaction with the rings and with Saturn itself. The fast outwards migration, with a constant Q model, allows to form by this mechanism all the mid-sized moons inside the orbit of Titan within the age of the Solar System (Charnoz et al. 2011). Moving to the resonance-locking mechanism makes it possible to add Titan in the list of the satellites formed by the spreading of a massive primordial ring beyond the Roche radius (Crida 2020). However, Iapetus does not fit in this frame, and most likely was formed in the circum-planetary disk. So was the progenitor of the massive rings in the model by Canup (2010), leading to a hybrid satellite formation scenario around Saturn: a primordial satellite is the progenitor of the rings, who are the progenitors of most satellites observed today. The theories on the formation of Saturn's satellites are reviewed in Blanc et al. (2025).

Details in this global picture are still to be understood however. It is expected that merger events occur in the so-called pyramidal regime (Crida and Charnoz 2012), so that the age of an object may not be so clearly defined. The age of the surfaces imposes a lower limit of the time of the last major collision these moons suffered. Impacts with debris from a catastrophic collision in the system may perturb the age estimated from the cratering rate (Asphaug and Reufer 2013). Other constraints can potentially be derived by the surface ice amorphous/crystalline ratio (Dalle Ore et al. 2015).

The dynamical interactions between the moons and their exact orbital parameters place constraints on their relative migration history. Whether the moons migrate outwards following a classical constant Q model or following a resonance locking model completely changes their relative migration velocity, and hence their resonant interactions. The presence of current mean-motion resonances between three pairs of moons (Mimas-Tethys, Enceladus-Dione and Titan-Hyperion) requires current (or recent) convergent migration in each of these pairs. While convergent migration is possible in resonance locking, especially when only the inner moons are caught in resonance locks, divergent migration is also possible and the dynamics can be quite complex. More detailed planetary and tidal evolution models are needed to predict how often convergent vs. divergent migration occurs. Additionally, classical tides are a stronger function of distance than the resonance-lock tides, so, depending on the satellite masses and the Q factor at relevant frequencies, classical tides may even dominate migration of sizable moons close to the planet.

While the ring-spreading satellite-formation model that implicitly assumes the fragmentation of a big moon opens the way for a highly variable density of the produced moons due to the stochastic nature of the formation of silicate chunks in the rings and of the accretion history (Charnoz et al. 2011, Sect. 4), it does not address the short tidal evolution timescales obtained if Q is assumed to be constant. However, in the resonance-locking model, Q is not constant and ancient formation of the midsize moons is fully compatible with their present-day orbital expansion (Fuller et al. 2016). As a consequence, models for the early formation of the midsize moons that can date back to a primordial disk are not ruled out. Still, it should be kept in mind that there are several other comparably-short-timescale indications associated even with Titan itself (such as its eccentricity damping timescale and lifetime of atmospheric CH_4) which need more study (Nixon et al. 2018). One possibility is that the system was dynamically excited recently, for instance by a mid-sized satellite becoming destabilized and ultimately colliding with Saturn (Wisdom et al. 2022).

The age of the surfaces of the midsize moons probably contains the best clues to the time and mode of their formation (or re-formation). Unfortunately, obtaining absolute ages for satellite surfaces depends on what model of impactor flux is used (Zahnle et al. 2003), so they cannot be used as a test of such models. Traditional assumptions of heliocentric impactors lead to ancient ages but may not be fully consistent with the observations in several ways (Rhoden et al. 2024). Indeed, some of the observations are better fit by a Saturn-unique planetocentric population operating over a shorter period of time. Certainly, more effort along the lines of crater analyses is extremely important (Bottke et al. 2024). Other constraints may be derived from the surface ice amorphous/crystalline ratio; here, more laboratory or experimental work may be needed to characterize the conversion rates. It was also recently proposed that hypervelocity dust impacts may efficiently clean icy surfaces (Hyodo et al. 2025), potentially explaining young-looking terrains without requiring recent formation.

3 Constraining the Evolution and Age of the Ring System

The origin and age of Saturn's ring system is the prominent topic of this special issue. Crida et al. (2025) discuss the hypotheses behind the "primordial" and the "recent" ring formation scenarios that are, so far, the two main families of formation models proposed to explain a range of observations, including several critical new ones by Cassini: the rings' bulk composition, the interplanetary micrometeoroid bombardment rate, and the rings' mass.

In the "primordial" age scenarios the rings are billions of years old and are either the in-situ remnants of the planetary subnebula from which the entire planetary system formed, or the product of the destruction of a large close-in differentiated moon - either by tides or by late-heavy-bombardment interlopers. Since then, the dissipative dynamical processes occurring within the disk generated the regular icy satellites, which were sequentially expelled from the disk itself, causing its progressive loss of mass and explaining the regular moons' mass-distance distribution (Charnoz et al. 2011; Crida and Charnoz 2012). The last satellites to be formed were the small ring satellites that share a composition similar to the main ring particles (Charnoz et al. 2010; Ciarniello et al. 2024), and the rings naturally reach the present mass in $\sim$4 Gyrs of evolution (Salmon et al. 2010).

Conversely, the "recent" age scenarios are motivated by a combination of compositional and structural arguments suggesting an age of a few hundred million years. The rings could have formed recently in two different dynamical scenarios. First, the eccentricity of an outer moon may increase following its capture in resonance with the rapidly outward migrating

Titan. By passing through pericentre within the planet's Roche limit, this moon may have undergone a rapid disintegration caused by tidal forces before escaping, and its remnants are assumed to have formed the ring disk (Wisdom et al. 2022). Second, inner moons and the rings could have originated or been reconfigured in a collision between moons interior to Titan that was induced by the evection resonance between a moon and the Sun (Cuk et al. 2016; Teodoro et al. 2023).

Crida et al. (2025) review the pros and cons of these two types of scenarios. The temporal evolution of the Saturn system is discussed in order to determine the ring age with respect to the *exposure* to the micrometeoroids bombardment flux, to the stability of the ring dynamical *structures* (e.g. orbital resonances) and to the *dynamical* evolution of the disk through orbital energy and angular momentum conservation laws. Reflecting the open debate in the community, the authors do not agree on some of the implications, so the interested reader is encouraged to read the chapter carefully and make up their own mind based on the balance of the evidence.

In the future, further efforts are necessary to better describe the current rings environment within the two proposed scenarios. More studies of crater and impact statistics across the Saturn system (compared to other outer planet systems) will be useful. The comparison with the other Outer Planets ring systems is one necessary advance because some common mechanisms may drive the origin and successive evolution of planetary rings. Why are Saturn's rings so massive and extended with respect to the ones encircling Jupiter, Uranus and Neptune? What can we learn from recently discovered rings around the Centaur (10199) Chariklo (Braga-Ribas et al. 2014), and trans-Neptunian objects (136108) Haumea (Ortiz et al. 2017), and (50000) Quaoar (Morgado et al. 2023; Pereira et al. 2023)? Additional efforts must also resolve the compositional differences within Saturn's system of rings and satellites. Why are the rings and inner satellites almost depleted in organic matter while the satellites orbiting beyond Titan organic-rich (Filacchione et al. 2010)? Is this difference inherited from a radial compositional gradient within the circumplanetary disk from which they formed? Does it reflect a successive evolution? Or is it a strong indication that the inner satellites formed from the spreading of the rings, while the ones beyond Titan were born in the circum-planetary disk? Early intense bombardment and satellite disruption could have mixed or buried early-delivered organics, complicating interpretations of present-day surface compositions. Resolving the entire ring formation and evolution scenario will remain a challenging task for future planetary scientists.

4 When Did the Ocean of Enceladus Form?

This is a hard question to answer. Currently, there are really only two constraints: one is from orbital dynamics, which might bound the age of Enceladus or the 2:1 Enceladus:Dione resonance; the other is from a combination of crater counts and heat flux estimates. Neither gives an answer in which one can be very confident.

The current orbital migration rate of Enceladus is known (e.g. Lainey et al. 2020). In principle, one could track Enceladus's position back in time based on the current rate, and derive an age. If one assumes that Saturn's dissipative properties (as parameterized by the dissipation factor Q) are constant, one gets an Enceladus age of order 1 Gyr. However, there is no reason to think that Q is constant. On the contrary, the resonance locking mechanism (Sect. 1; Fuller et al. 2016, 2024) has observational support, and implies that Q is time-variable and is potentially consistent with a several Gyr age for Enceladus. The issue of resonance-locking is discussed in some detail in Nimmo et al. (2023) and Ćuk et al. (2024).

An important consequence of the resonance locking mechanism is that it implies roughly constant tidal heating inside Enceladus for as long as the Enceladus-Dione resonance has existed (Nimmo et al. 2023). Furthermore, although the magnitude of this heating is uncertain, the best guess is close to the estimated global heat loss rate derived from shell thickness measurements (Hemingway and Mittal 2019). This means that Enceladus has likely been in steady-state for as long as the resonance has lasted, which also means that the present-day ocean is a long-lived feature (Nimmo et al. 2023).

The orbital evolution of the Saturnian satellites prior to the present day is poorly understood (Ćuk et al. 2024); there are no orbital constraints on the age of the Enceladus-Dione resonance. However, there are hints that it is old based on heat flux inferences and crater counts, even though recent analyses make this far from certain (Rhoden et al. 2024).

Some geological features on Enceladus, such as flexural uplift at rifts and viscously-relaxed craters, allow the heat flux at the time of deformation to be inferred (Nimmo et al. 2023). These heat fluxes are typically high (of order 100 $\mathrm{mW/m^2}$), comparable to the present-day heat fluxes at the South Polar Terrain. However, the geological features are located in other, older regions of Enceladus, suggesting that high heat fluxes have been a prominent feature of Enceladus's history. Since tidal heating is the only plausible energy source, these older features suggest that either the Enceladus-Dione resonance or some prior resonance was operating in Enceladus's past. However, estimating the actual age of these features is not easy (Rhoden et al. 2024).

Enceladus possesses regions with large variations in crater densities, some of which (e.g. high northern latitudes) are heavily cratered and appear "old" (Patterson et al. 2018). Converting crater densities to actual ages requires a model of the impact flux, which has already been partly constrained by New Horizons observations (Doner et al. 2024) and will be further refined by JUICE and Europa Clipper. Assuming heliocentric impactors, both Zahnle et al. (2003) and Bottke et al. (2024) find some Enceladus regions are older than 4 Gyr, and Giese et al. (2008) obtained an age of 3.5 Gyr for a flexurally-uplifted rift. At face value, these derived ages support the argument that Enceladus itself is old and that tidal heating is also ancient. However, one complication noted by Bottke et al. (2024) (see also Rhoden et al. 2024) is that the impact flux in the Saturnian system may include planetocentric impactors (Ferguson et al. 2022). If this is the case, then the current age estimates are likely too old.

Of course, tidal heating might be episodic (e.g. driven by different resonances). The freezing timescale for an ocean that extends to depths of $\sim$80 km is about 200 Myr, so one could in principle imagine a situation in which multiple oceans are created, each one during a different pulse of tidal heating. Given the fragmentary record of tidal heating on Enceladus, episodic heating is possible but not required. However, once a subsurface ocean fully freezes, restarting it through tidal heating alone is difficult, somewhat favoring scenarios with long-lived or persistent oceans.

At present, the answer that requires fewest deviations from the inferred histories of other satellite systems appears to be that Enceladus is old ($\sim$ 4 Gyr) and its ocean equally old. Tidal heating has probably been operating at least episodically since early in Enceladus's history, and the power supplied by tidal heating via resonance locking is sufficient to maintain an ocean over 4 Gyr. However, these conclusions are not secure. In particular, episodic heating intervals with periods of a mostly- or totally-frozen Enceladus in between are conceivable, as is a relatively recent resetting event; and the impact fluxes on which absolute age determinations are based could be incorrect.

Despite the successes of astrometry, dynamical models or observations are unlikely to solve this particular problem. The real key is to develop better impact flux models. A good start would be estimates of the present-day outer solar system impact flux, which will probably be provided by JUICE and Europa Clipper. However, such constraints may only be of limited use if the Saturnian system experienced impacts from a population of planetocentric bodies that no longer exists.

5 Probing the Presence of Other Possible "Ocean World" Moons

To date, three of Saturn's moons are thought to host a global ocean beneath their surface: Titan, Enceladus and perhaps Mimas (Iess et al. 2012; Thomas et al. 2016; Lainey et al. 2024).

In the case of Titan, the original arguments for an ocean on the basis of the tidal response (Iess et al. 2012) and obliquity (Baland et al. 2011) have recently been re-examined and the data re-interpreted as indicating an *absence* of a subsurface ocean (Petricca et al. 2025). This is a surprising result and will certainly lead to further analyses of the available observations.

In the case of the latter two moons, their small size seemed to be a considerable challenge to the existence of an ocean present beneath the entire surface. Indeed, the surface-to-volume ratio of these small moons implies that internal heat is released very rapidly, with the expected corollary that any ocean must freeze quickly if not maintained by active heating. From this point of view, the presence of a global ocean on Enceladus was already unexpected; it has been subsequently explained by the discovery of intense tides in Saturn that maintain Enceladus' eccentricity over a long period of time (e.g. Fuller et al. 2016).

The apparent discovery of an ocean beneath the entire surface of Mimas is even more astonishing, given the absence of resurfacing. However, it should be noted that evidence for this claim is not definitive. In particular, the requirement that the ocean form within the last few tens of Myr requires some kind of recent heating episode of unknown origin. Second, formation of such an ocean should result in large global compressive stresses, of which there is no evidence (McKinnon and Schenk 2025).

If it is actually the case that Mimas possesses a subsurface ocean, this raises the question of whether other moons might conceal a global ocean beneath their surface. Radio-science measurements associated with flybys of Dione by the Cassini probe raise the possibility that this moon too could hide a global water ocean (Zannoni et al. 2020). Indeed, the combined analysis of Dione's gravitational field and its topography reveals a significant deviation from hydrostatic equilibrium. One possible interpretation is the presence of a thin global ocean beneath a thick layer of ice. Could the other medium-sized moons be hiding global oceans? For the time being, radio-science data have not yielded gravitational fields precise enough to tell us more. Interestingly, isostatic modeling minimizing crustal stresses supports the presence of an ocean for Dione as well (Beuthe et al. 2016).

As a result, future space missions will have to consider close flybys of these moons, with one of their objectives being to test the possibility of the presence of a global ocean beneath their surface. Experience has shown that the absence of resurfacing does not always indicate the absence of liquid water beneath the surface, the type example being Callisto, although the presence of an ocean there is not definitively established either (e.g. Cochrane et al. 2025).

In practice, the presence of an ocean can be determined by geophysical measurements such as topography, gravity and magnetic fields, including tidal Love numbers, or derived from rotational dynamics, including obliquity and physical librations. Future measurements at target satellites should include precise radio science tracking of the spacecraft, magnetometer, altimeter and a camera to characterize satellite rotation (or a radar for Titan). The global inversion of all available data would then allow us to precisely characterize the interior of the moon, including depth and density of a liquid ocean layer.

6 Conclusion

Far from existing exclusively in the Galilean system, ocean moons are just as present in the Saturnian system. While this conclusion would not have been possible without the data from the Cassini mission (including the discovery of high tidal dissipation inside Saturn), many questions remain as to their number, formation and evolution. Similarly, the age of Saturn's moons and rings remains uncertain in spite of multiple indications of short timescales for the rings and Titan, at least. Finally, the physical mechanism responsible for the intense tides in Saturn has yet to be confirmed. For this reason, further work, including measurements from a future space mission, are required. In the present article, we have attempted to put together a set of thoughts that could feed into future space projects, hoping this will inspire future space mission proposals.

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Declarations

Competing Interests The authors declare no competing interests.

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