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► **To cite this version:**

V. Lainey, N. Rambaux, G. Tobie, N. Cooper, Q. Zhang, et al.. A recently formed ocean inside Saturn's moon Mimas. *Nature*, 2024, 626 (7998), pp.280-282. 10.1038/s41586-023-06975-9 . hal-04461691

HAL Id: hal-04461691

<https://hal.science/hal-04461691v1>

Submitted on 15 Oct 2024

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A recently-formed ocean inside Saturn's moon Mimas

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Moons potentially harboring a global ocean are tending to become relatively common objects in the Solar System¹. The presence of these long-lived global oceans is generally betrayed by surface modification owing to internal dynamics². Hence, Mimas would be the most unlikely place to look for the presence of a global ocean^{3,4}. Here, from detailed analysis of Mimas' orbital motion based on Cassini data, with a particular focus on Mimas' pericenter drift, we show that its heavily cratered icy shell hides a global ocean, at a depth of 20-30 km. Eccentricity damping implies that the ocean is likely to be less than 25 Myr old, and still evolving. Our simulations show that the ocean-ice interface reached a depth of less than 30 km only recently (< 2-3 Myr), a time span too short for signs of activity at Mimas's surface to have appeared.

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Analyzing the rotational motion of Mimas from Cassini ISS (Imaging Science Subsystem) images, a measured libration amplitude of -50.3 ± 1.0 arcmin was found for the Mimas orbital frequency⁵. It was deduced that Mimas should harbor either a highly elongated silicate core, or a global ocean. The libration measurement was based on the stereophotogrammetry control point network method⁵. Hence, Cassini ISS data were used to investigate the rotation of Mimas from its surface motion, only. In order to discriminate between the two interior models (a prominent distorted silicate core or a global internal ocean), it is necessary to have a further constraint on the internal state. However, these two interior assumptions imply very different gravitational potentials, corresponding to a rigid body in the case of the elongated scenario, or a body composed of different layers in relative motion in the case of the scenario with an ocean. Both models would induce a different gravitational pull received by Mimas from Saturn, implying a slightly different orbital trajectory over time. The study of such an orbital effect was proposed theoretically¹⁰, and recently applied with success to the inner Saturnian moons⁶.

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In the case of a completely solid body, the libration amplitude depends primarily on the gravity coefficient C_{22} for Mimas since the reasonable range of C/MR^2 is small, where C , M and R are the principal moment of inertia about the rotation axis, the mass and radius of Mimas, respectively. However, the orbital effect depends on both C_{22} and J_2 , where J_2 is the only other

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degree 2 gravity harmonic for Mimas if we assume rotational stability. Accordingly, the two measurements (libration and orbital change) can be used to solve for both J_2 and C_{22} provided the body is solid. The measured orbital shift is -9.4 ± 0.9 km over the duration of the Cassini mission (see Methods), and we find that this is compatible with both measurements provided J_2/C_{22} is of order 10. For a more typical J_2/C_{22} of order 3 (i.e. close to hydrostatic interior), the predicted orbital shift is about a factor of two larger in magnitude. Though unusually large, this ratio is a possible value if we assume that the silicate core component of Mimas takes the form of triaxial ellipsoid that is an elliptical pancake in the equatorial plane, elongated along the line to Saturn. The problem with such a solution is that the total volume of the silicate core is constrained by the mean density of Mimas, and a dramatically flattened shape can only satisfy this constraint along with the required large C_{22} , and even larger J_2 , if the elongation of the pancake causes its extremity to pierce the surface of Mimas. This is incompatible with observation (see Methods).

Since the solid Mimas hypothesis leads to a dead-end in terms of interior modelling, we tested the influence of a subsurface ocean. Starting from the one-layer formulation of the periapsis drift, we extended the theoretical approach⁷ to the case of a body containing an internal ocean. The derived expression is provided in the methods section. The new expression depends essentially on the flattening for each layer that controls the gravity coefficients and libration amplitude. Here, we took into account the libration amplitudes of the icy crust and silicate mantle^{5,8}. Fig. 1 shows the set of models explored as a function of the libration amplitude in longitude, and the periapsis drift. The librational model is based on three deformed layers⁸ where the outer ice shell is viscoelastic⁵. Here, the surface polar and equatorial flattenings are computed based on the best-fit ellipsoids⁹, and the interior interfaces are assumed to be at hydrostatic values. The intersection of the two sets of measurements (in grey) allows us to exclude several interior models and to constrain the ice sheet thickness at 20-30 km to be consistent with the measurements.

The thickness of Mimas's icy shell that we obtained is in close agreement with the one deduced recently¹⁰, assuming a realistic model for dissipation in the satellite. This confirms that Mimas may be close to thermal equilibrium at the present time. The amount of heat released at the surface of Mimas was estimated to be typically¹⁰ 25 mW/m^2 , corresponding to a total dissipated power of 12 GW. Nevertheless, such a large energy loss should be accompanied by a damping of Mimas's eccentricity, which, at this dissipation rate, should be reduced by a factor of two in 4-5 Myr.

In order to predict the recent past evolution of Mimas leading to the present date, we computed the tidal dissipation inside Mimas as the interior evolved, the ocean evolution owing to heat balance and the progressive evolution decay¹¹⁻¹² (see Methods). Fig. 2 shows the evolution of Mimas's eccentricity, tidal power, ice shell thickness and resulting surface heat flux, for end-member assumptions for the mechanical properties for the rocky core and the ice shell. For all tested cases, the initial eccentricity has been adjusted in order to match the present-day eccentricity value and to have an ice shell thickness ranging between 20 and 30 km. The initial eccentricity at the time of ocean initiation ranges between 2.3 times the current value for a very dissipative rocky core, comparable to Enceladus, to 2.9 for a rigid core. Tests performed at higher initial eccentricity values result in a very thin ice shell ($< 10\text{-}20$ km) and high surface heat flux ($> 50\text{-}100 \text{ mW.m}^{-2}$), incompatible with the lack of surface activity. Our simulations show that the ocean appeared between 25 Myr for the less dissipative case and only 2-3 Myr for the most dissipative case. In all cases, a rapid growth of the internal ocean occurs during the last Myrs. Interestingly, the most dissipative model results in the smaller surface heat flux,

owing to very rapid ocean melting and delay in the propagation of heat wave to the surface. As a comparison, the surface heat flux of 20-25 mW.m⁻² obtained here corresponds to the estimated surface heat flux in the oldest cratered terrains observed in the equatorial region of Enceladus¹³. Our results clearly indicate that an hydrothermally active porous core inside Mimas comparable to Enceladus is possible even in the absence of surface activity. Moreover, for an ice shell thickness ranging between 20 and 30 km, we predict a Love number k₂ of the order of 0.01, which might be measured by a future dedicated mission, thus confirming the presence of an ocean and its depth.

The origin of a larger eccentricity in the past may well be the consequence of a resonant encounter with another main Saturnian moon. While Mimas is currently in a mean motion resonance with Tethys, this interaction does not involve Mimas's eccentricity. Hence, Mimas may have passed through another resonant interaction involving its eccentricity in the past. As recently demonstrated¹⁴, such a resonance could involve three Saturnian moons, also. In particular, they could obtain a larger eccentricity for Mimas, up to 0.06, by considering a three-body resonance involving Mimas, Dione and Titan. Another possibility could be that Mimas crossed a resonant encounter, but without capture. Such a hypothesis was studied¹⁵⁻¹⁶ to explain the formation of the Cassini Division. However, for a past eccentricity of 2.3 to 2.9 times the present value, Mimas alone cannot explain the opening of the Cassini Division anymore, suggesting that Enceladus should have had a higher eccentricity as well, and thus a more intense heating during the last millions of years. More recently, it has been suggested that the loss of a Saturnian moon could explain Saturn's obliquity and young rings¹⁷ (with a typical age of 100 Myr). Under such a hypothesis, the mid-sized moon system might have been jostled allowing for slight changes in their orbital elements, with possible increases in eccentricity for some of them in the recent past. All these rapid changes in orbital dynamics are triggered by the strong tidal dissipation in Saturn¹⁸⁻²⁰. From that perspective, the temporary existence of Mimas' ocean is another manifestation of strong Saturnian tides.

Our results imply that Mimas has experienced during the last million years internal processes that may have been common in many icy worlds shortly after their formation. From this point of view, Mimas offers a unique opportunity to study ongoing melting-induced differentiation and extensive aqueous alteration driven by water-rock interactions. Mimas can thus provide a time window into the past evolution for Enceladus and other now-quiet icy worlds, including Uranian moons and Kuiper-Belt objects. Aqueous mineral alteration in icy worlds is known to be geologically rapid, typically of the order of millions to tens of millions of years²¹⁻²². Mimas would be one of the very few places where this could happen right now.

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Figure 1. Mimas measurements and ocean models. Here stands the amplitude of libration in longitude and periapsis drift variation for different internal structure models with an ocean. The colors represent the thickness of the ice crust. The grey areas correspond to the measured libration amplitude and perihelion longitude variation. The dispersion represents sensitivity to the crustal polar and equatorial flattenings (see additional tests in methods section).

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190 **Figure 2. Mimas's interior and orbital evolution.** The panels represent, from top left to
bottom right, time evolution of Mimas' eccentricity (normalized to the present value e_a), tidal
dissipated power, ice shell thickness, and surface heat flux for interior models with a rigid non-
dissipative core or with a unconsolidated dissipative core comparable to Enceladus. The pink
dashed lines indicate the upper and lower estimates of ice shell thickness at present. The grey
area indicates predicted time evolution during the next 5 Myrs. For the three tested values of
ice viscosity at the melting point, η_m , (10^{14} , 10^{15} , 10^{16} Pa.s), the initial eccentricity was adjusted
195 in order to match the present-day eccentricity value and the estimated ice shell thickness. For a
rigid core and $\eta_m = 10^{16}$ Pa.s, no solution could match the ice shell thickness estimate and
therefore no result are shown.

200 **Extended Data Figure 1. Reprocessing of Mimas astrometry.** Here most of the satellite edge
can be used for determining the center of figure of Mimas. The purple dots are the detected
edge points on the image, while the turquoise ones represent the expected shape from spherical
harmonics computation. The orange curve represents Mimas's equator. Using 3-D complex
shape modelling allows to obtain a more accurate center of figure on the image.

205 **Extended Data Figure 2. Core radius for solid model.** Solutions for the 3-D geometric axes,
polar radius (r_p) and equatorial radius at longitude = $\pi/2$ (r_{e2}) as function of the equatorial
radius at longitude = 0 (r_{e1}). Each point represents an interior model where the core and mantle
densities vary from [920-1100] kg m^{-3} and [1200-3600] kg m^{-3} . In all cases, r_p or r_{e2} is negative.
210 For this figure, Stoke's coefficients are $C_{20} = -0.101$ and $C_{22} = 0.0093$.

Extended Data Figure 3. Sensitivity of shape parameters. This figure shows the Mimas'
libration and periapsis drift solutions for various ranging of equatorial and polar flattenings.

215 **Extended Data Table 1. Estimation of Mimas gravity field.** Error bars are at 3 sigma level.
The value of 50.3 arcmin in column 4 is from the control point network measurement⁵. When
not solved for with all other parameters, expression of C_{22} coefficient was computed from
 $C_{22} = CA/24eMR^2$ where C , e , M and R are the largest moment of inertia, Mimas' eccentricity,
mass and radius, respectively. On row 5, the orientation of Saturn was forced to the one of
French et al. (2017). On the next line, we introduced the nutations of Saturn estimated from the
JPL kernel sat427. The last line corresponds to the ocean case, where Mimas gravity field was
set to its mean expected value under our ocean interior model, while no constraints was applied
on the Mimas physical libration.

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Methods

230 **New astrometric reduction of Mimas and Tethys ISS images using 3-D complex shape
modeling**

To benefit from the most accurate astrometric data from ISS images, we reprocessed close
images of Mimas and Tethys, using complex shape modeling. Previously, all ISS data were
235 astrometrically reduced using an ellipsoidal shape model. But the limitation of using such a

simple shape modeling approach has recently been demonstrated²³. Here, we used a spherical harmonic representation for the topography of both moons, using a method developed last year²⁴. The data were then split into two different subsets depending on the extension of the limb detection on the image. In Extended Data Fig. 1, most of the satellite edge is detectable on the image, with now a proper modeling of Herschel crater. The typical difference between ellipsoidal shape models versus those derived using spherical harmonics was found to be few tenths of a pixel. In addition, we looked for images that were acquired with a different filter combination than CL1/CL2 (clear filters). This allowed us to add several tens of extra images. No biases were found from the use of non-clear filters. All our new observations and astrometric residuals are fully available on request.

Orbital modeling and astrometric fitting

We challenged the elongated silicate core hypothesis for Mimas's interior by measuring the feedback of the associated physical libration on Mimas's orbital motion. Analytical estimation suggests that the periapsis of Mimas should drift by 20.1 km over the 13 years of Cassini data (see methods section), which is large enough compared to the ISS astrometric precision to be detectable. We used all the Cassini ISS astrometric data already considered in former work²⁰. Moreover, we reprocessed all the close images of Mimas and Tethys, introducing an improved modeling of their shapes²⁴ to increase the accuracy of our measurements (see former section). Similarly, we improved the astrometric reduction of the small moons²⁵, especially Methone and Anthe, whose motions are affected by commensurabilities with Mimas. Our model solved the equations of motion of the eight main moons of Saturn, with the addition of the five inner moons, the four Lagrangian moons of Dione and Tethys, as well as Methone, Anthe and Pallene. In addition to the initial state vectors of the moons, we fitted the masses of the moons and their primary, the gravity field of Saturn up to order 10, the orientation and precession of Saturn's pole, the Saturnian Love number k_2 and the physical libration of Prometheus, Pandora, Janus and Epimetheus. Mimas's gravity field by means of the two gravity coefficients C_{20} and C_{22} and Mimas' physical libration were simultaneously solved for, along with the physical parameters described above. The development was limited to degree 2 in shape, as the influence of higher terms is small on C_{20} , C_{22} coefficients⁹. During the fitting procedure, Saturn's gravity field was constrained to remain within the radio-science data solution²⁶, while Mimas's physical libration was constrained to be consistent at a one sigma level with the direct measurement from Cassini images⁵.

Our results are shown in Extended data Table 1. Most of the parameter space for C_{20} and C_{22} is unphysical, since it implies positive C_{20} and negative C_{22} . It appears that a solution remains possible allowing for negative C_{20} and positive C_{22} . Due to the tremendous anti-correlation between Mimas' C_{20} and C_{22} at a 99% level, we double-checked the validity of our analysis by setting to a fixed value the C_{22} and solving for the C_{20} , only. In such a way, no significant correlation is present anymore among all fitted parameters. Starting from two very low polar moment of inertia value, we computed C_{22} values (Extended Data Table 1) and restarted the fitting process. It should be noted that the chosen values of moment of inertia are small compared to other icy satellites (Titan²⁷ 0.3431, Enceladus²⁸ 0.335), and are closer to the gas giant planet Jupiter's value²⁹ ($C/MR^2 = 0.26939$). Such low values are required to avoid too low a negative C_{20} value. Our two estimations of C_{20} followed perfectly the more general solution where both C_{20} and C_{22} were solved for. This indicates that the gravity field of Mimas inferred from its orbit and rotational motions, and assuming a rigid interior, must have an extremely large ratio C_{20}/C_{22} of about 10, which is three times larger than the hydrostatic case²⁸.

Extra tests were performed, using different dynamical modelling and adding HST data³⁰, confirming the robustness of our results (see methods section). We determined the periapsis drift, $\Delta\varpi$, associated with Mimas's libration to infer an orbital signal (see methods section) of -5.4 ± 0.5 (10^{-7} rad/day, 3σ). This translates to -9.4 ± 0.9 km over the whole duration of the Cassini mission, a value which is smaller by a factor of two than that expected from the silicate elongated core hypothesis (-20.1 ± 0.2 km).

To test the robustness of our solution under slightly different modeling scenarios, we performed many tests. In Extended Data Table 1, we also show the variation of the Mimas gravity field under a few extra different modeling assumptions.

In addition, using, potential theory⁸, we have estimated the possible values of the core-mantle interface shape coefficients d_{20c} , d_{22c} from the C_{20} , C_{22} estimated. We looked at the strong values obtained translated in terms of polar and equatorial radii. Despite the fact that too large radii appeared often, all solutions imply one radius to be negative (see the Extended Data Figure 2).

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Periapsis drift for a fully rigid Mimas

As already pointed out in 1990⁷, the physical libration introduces a specific extra secular term in the precession of the periapsis, that can be barely masked within the fitting procedure. This term is equal to³¹:

$$\Delta\varpi = \frac{3}{2} \left(\frac{R}{a}\right)^2 \left[J_2 - 2C_{22} \left(5 - \frac{4A}{e} \right) \right] nt$$

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In other words, the most important orbital signal that allows us to determine the physical libration of a moon from astrometry is this extra periapsis drift. As already experienced³², using the periapsis drift estimation above is a pretty convenient way to infer the physical libration A of a spinning/orbiting celestial object for any set of J_2 ($-C_{20}$) and C_{22} values, and vice versa i.e. any combination of the physical libration A , gravity parameters J_2 and C_{22} should be consistent with the periapsis drift estimation. Once this periapsis drift and its uncertainty are determined from a fit of Mimas' C_{20} , C_{22} assuming the physical libration value from ISS data⁵, we were then able to use it for discriminating between the various global ocean models.

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Periapsis drift for three-layer Mimas

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In this section, we present the model used to compute the periapsis drift for a three-layer Mimas. The potential is calculated using former approach³¹, but extended to a body containing a solid crust, fluid layer and a solid mantle. The solid crust and mantle are free to librate at different

335 amplitudes. The librations are computed using the usual formalism³³⁻³⁵. The ocean potential has been computed following the method developed for the Earth³⁶. The final expression is

$$\Delta\varpi = \frac{3}{2} \left(\frac{R}{a}\right)^2 \left[(J_2^s - 2 C_{22}^s) \left(5 - \frac{4A_s}{e}\right) + (J_2^o - 2 C_{22}^o) \left(5 - \frac{4A_s}{e}\right) \left(1 - \frac{\rho_s}{\rho_o}\right) + (J_2^m - 2 C_{22}^m) \left(5 - \frac{4A_m}{e}\right) \left(1 - \frac{\rho_o}{\rho_m}\right) \right] nt$$

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This expression depends on the librational amplitude of the shell A_s and mantle A_m , the density of each layer the shell ρ_s , the ocean ρ_o , the mantle ρ_m , and of the stokes coefficients of each layer that can be determined from the mean radii, densities, and geometric flattening of each layer

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$$J_2^k = \frac{8 \pi}{15} (r_k^5 \alpha_k - r_{k-1}^5 \alpha_{k-1})$$

$$C_{22}^k = \frac{2 \pi}{15} (r_k^5 \beta_k - r_{k-1}^5 \beta_{k-1})$$

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the index k represents the current layer and $k-1$ is the layer below the current layer where r_k , α_k , β_k are the radius, polar flattening and equatorial flattening of the layer. The Extended Data Figure 3 shows the sensitivity of the periapsis drift to the variation of the geometric flattening. The main impact is from the α and β of the surface and then β of the ocean. The other parameters have negligible contribution. Here, we use extrema values of 7, 8% for α and β of the crust and 10% for the other interfaces. The first two uncertainties were derived using the uncertainties on the shapes³⁷.

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Tidal dissipation and thermo-orbital evolution of Mimas

Interior structure and rheology: Mimas' interior is divided in three layers, from the centre to the surface: a rock-rich core assumed either rigid and non-dissipative or water-saturated unconsolidated dissipative core (similar to Enceladus³⁸), an inviscid water ocean and a viscoelastic conductive ice shell. For simplicity, the rock core is assumed to have constant and uniform densities and mechanical properties (shear modulus and viscosity). In the outer ice layer, the viscosity is computed for the temperature profile solved assuming thermal diffusion only (no thermal convection). In the rock core, the complex shear modulus, μ_c , is determined from the effective shear modulus μ_{eff} , equal to the norm of μ_c and the dissipation function Q_μ^{-1} equal to the ratio between the imaginary part and the norm of μ_c . Values between 10^7 and 10^9 Pa and between 0.2 and 0.8 are tested for μ_{eff} and Q_μ^{-1} , respectively. For the outer ice shell, an Andrade rheology³⁹ is considered, characterized by constant values of elastic modulus, μ_E , and temperature-dependent viscosity, $\eta(T)$. The thicknesses of the ice shell and ocean are computed from heat thermal balance.

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Computation of tidal dissipation: The viscoelastic deformation of Mimas under the action of periodic tidal forces is computed following the method of Tobie et al.¹². The Poisson equation and the equations of motion are solved for small perturbations in the frequency domain assuming a compressible viscoelastic rheology. The potential perturbation, associated displacement and stress are computed as a function of radius by integrating the radial functions associated with the radial and tangential displacements (y_1 and y_3 , respectively), the radial and tangential stresses (y_2 and y_4 , respectively), and the gravitational potential (y_5), and a sixth radial function (y_6) to account for the continuity of the gravitational potentialⁱ in the elastic equivalent problem. For the deformation of the inviscid water ocean, the static simplified formulation⁴⁰ is adopted relying on two radial functions, y_5 and y_7 . The solution in the solid part (porous core and ice shell) is expressed as the linear combination of three independent solutions ($y_i = Ay_{i1} + By_{i2} + Cy_{i3}$), which reduces to one solution in the liquid part. The integration of these three solutions is initiated at the centre using the analytical solutions of spheroidal oscillations for a compressible homogeneous sphere (equations 98, 99 and 100 in Takeushi and Saito⁴¹). The system of six differential equations is solved by integrating the three independent solutions using a fifth-order Runge-Kutta method with adjustive step size control from the centre ($r=0$ km) to the surface ($r=252$ km). The three coefficients, A , B and C , are determined at the surface by imposing the boundary conditions appropriate for forcing by an external tidal potential. The solutions for the six radial functions are then computed using the coefficients and the appropriate relationship at each liquid/solid interface.

From the radial functions, y_1, y_2, y_3 and y_4 , and the degree-2 tidal potential at the surface, the tidal heating rate as a function of depth is computed. The global dissipation in each layer (P_{core}, P_{ice}) is then determined by integrating over the entire layer the dissipation rate computed at each radius. In addition, we also determine the global dissipation directly from the imaginary part of the complex Love number, k_2^c (defined from the potential radial function, y_5 , at the surface ($r = R_s$): $k_2^c = y_5(R_s) - 1$) using the classical formulation: $\dot{P}_{tide} = -\frac{21}{2}\Im(k_2^c) \frac{(\omega R_s)^5}{G} e^2$. The two approaches are used simultaneously to ensure that the computation is consistent.

Heat balance and ocean evolution: The melting/cooling of the internal ocean is controlled by heat production by tides in the interior and the heat transfer through the outer ice shell. The heat is transported by thermal diffusion through the outer ice shell, as conditions for the onset of convection is not met during the melting phase. Conductive heat transfer through the ice shell is computed using temperature-dependent thermal conductivity and tidal heating. Tidal heating is self consistently computed from the viscosity profile determined from the temperature profile, for viscosity values ranging between 10^{14} and 10^{16} Pa.s and activation energy equal to 50 kJ.mol⁻¹. The evolution of the ice/ocean interface is determined from the balance between heat flux from the rocky core (including tidal heating) and heat flux through the outer ice shell. The melting temperature takes into account the ammonia fraction in the liquid whose concentration involved with the ocean volume, following the parameterization of Grasset and Pargamin⁴². The initial ice shell thickness is set to 100 km and the rock core radius to 95 km. The ammonia mass fraction relative to the total water mass is set to 1%, comparable to the value observed in Enceladus' plume⁴³.

Orbital eccentricity evolution: The reduction in orbital eccentricity, e , due to tidal dissipation is computed from the total dissipated power \dot{P}_{tide} as:

$$\frac{de}{dt} = \frac{-a(1 - e^2)}{eGM_S M_M} P_{diss}$$

425 with a the semi-major axis, M_S Saturn's mass, M_M Mimas' mass and G the gravitational constant.

430 **Data availability:** Most astrometric data are already available from Lainey et al. (2023), Cooper et al. (2018) and references therein. The extra astrometric data of Mimas and Tethys that were obtained from 3-d complex shape modeling are available on IMCCE FTP server: <ftp://lainey@ftp.imcce.fr/pub/psf>.

435 **Code availability:** All Astrometric data derived from ISS-images can be reproduced using our CAVIAR software available under Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International. License here: www.imcce.fr/recherche/equipements/pegase/caviar
An access to NOE code is possible upon reasonable request to the first author.

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Acknowledgments: VL and NR thank the FP7-ESPaCE European program for funding under the agreement No. 263466. GT acknowledges support from the ANR COLOSSE project. QZ is supported by the Joint Research Fund in Astronomy (No.U2031104) under cooperative agreement between the National Natural Science Foundation of China (NSFC) and Chinese Academy of Sciences (CAS).

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Author contributions: V.L. developed and fitted to the observations the full numerical model presented for the astrometric approach. N.R. developed the librational model and provided the solutions as function of interior structure. G.T. developed the thermo-orbital model of Mimas and performed the simulations of past evolution. N.C., V.L. and Q.Z. provided extra astrometric data. B.N. ran the N-body simulations involving a high eccentric Mimas. All authors contributed to the writing of the manuscript.

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Competing interests: Authors declare that they have no competing interests.

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