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## TP6 abstracts

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# True polar wander of slowly rotating object and a case study of Venus

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## Abstract

A new semi-analytical method is established to calculate the true polar wander (TPW) of slowly rotating objects such as Venus. Compared with a previous study which is based on the quasi-fluid approximation [*Spada, G. et al* (1996)], a more accurate TPW path is obtained. More importantly, our method can include the coupling effect of the periodic (Chandler wobble) and non-periodic (TPW) terms when the rotation of the body is small. This effect is generally ignored for most of planets and moons such as Earth.

## 1. Introduction

In the body-fixed frame where the rotational axis aligns with the Z-axis, the linearized Liouville equation shows that the rotational perturbations in the X and Y directions are coupled (m-coupling). This means that in the body-fixed frame, a mass distribution imbalance in the X-Z plane would cause a rotational perturbation not only in the X-Z plane but also in the Y-Z plane. This coupling effect increases as the rotational speed of the object decreases and can turn TPW into a mega-wobble for objects such as Venus which rotate very slowly. Previous studies of TPW for this case applies the quasi-fluid approximation [*Spada, G. et al* (1996)] which can result in an inaccurate TPW path. More importantly, when the rotational speed is slow, the periodic response of the axis which is known as Chandler wobble and the non-periodic TPW is also coupled (p-coupling) and this effect has not been discussed yet.

## 2. Method

### 2.1 Moment of Inertia

The change in the inertia tensor for a centrifugally and tidally deformed body is given by

$$\Delta I_{ij}(t) = \frac{k^T(t)a^5}{3G} * [\omega_i(t)\omega_j(t) - \frac{1}{3}\omega^2(t)] \\ +\delta(t) + k^L(t)] * C_{ij}(t) \quad (1)$$

where $\boldsymbol{\omega}$ is the vector of centrifugal force. This equation can be solved analytically by linear change assumption or calculated numerically with a finite-element package. The analytical approach approximates the rotational axis as piecewise linear function with which the equation 1 can be solved analytically. The numerical approach has the potential to include the features such as non-linear rheology or lateral heterogeneity.

### 2.2 Liouville equation

With the information of the deformation, the reorientation is obtained by combining the perturbation of the rotational and tidal axes. Both can be obtained from a general linearized Liouville equation of non-periodic terms:

$$m_1(t) = \frac{\Delta I_{13}(t)}{C-A} + \frac{C\Delta\ \dot{I}_{23}\ (t)}{\Omega(C-A)^2} \quad (2a)$$

and periodic terms:

$$\bar{m}_1(t) = \frac{1}{(A-C)^2\Omega} \\ (\sin\left[\frac{A-C}{A}\Omega t\right]((A-C)\Omega\Delta I_{23} + C\Delta\ \dot{I}_{13}\ (t)) + \\ \cos\left[\frac{A-C}{A}\Omega t\right]((A-C)\Omega\Delta I_{13} + C\Delta\ \dot{I}_{23}\ (t))) \quad (3a)$$

Here $m_1$ and $\bar{m}_1$ are the non-periodic and periodic perturbation in the X-direction, respectively.

### 2.3 An iterative procedure

When the p-coupling is not considered, an iterative algorithm is applied in each time step [*Hu et al.* (2017)]

**Algorithm**

1. Assume that the step $i$ starts at time $t_i$ with the vector of the rotation being $\boldsymbol{\omega}^i = \Omega^i(\omega_1^i, \omega_2^i, \omega_3^i)$. and ends at time $t_{i+1}$ with the vector of the rotation $\boldsymbol{\omega}^{i+1}$. For the first iteration, we assume that the vector of the rotation does not change: $\boldsymbol{\omega}^{i+1} = \boldsymbol{\omega}^i$.

2. Obtain $\Delta\mathbf{I}$ and its derivative $\Delta\dot{\mathbf{I}}$ by solving equation 1. With $\mathbf{Q}$ the coordinate transformation matrix from the body-fixed coordinates to the local coordinates where the Z-axis aligns with the direction of the rotation, the inertia tensors in the transformed coordinates are obtained by $\Delta\mathbf{I}_1 = \mathbf{Q}^T\Delta\mathbf{I}\mathbf{Q}$ and $\Delta\dot{\mathbf{I}}_1 = \mathbf{Q}^T\Delta\dot{\mathbf{I}}\mathbf{Q}$.

3. Substitute $\Delta\mathbf{I}_1$ and $\Delta\dot{\mathbf{I}}_1$ into equation 2 and obtain $\boldsymbol{\omega}' = \Omega^i(m_1, m_2, 1 + m_3)^T$. We normalize this vector as $\boldsymbol{\omega}' = \Omega^{i+1}\bar{\boldsymbol{\omega}}'$ where $\bar{\boldsymbol{\omega}}'$ is the direction of the perturbed rotational axis in the local coordinate system which needs to be transformed back into the body-fixed frame to obtain $\boldsymbol{\omega}^{i+1} = \Omega^{i+1}\mathbf{Q}\,\bar{\boldsymbol{\omega}}'$ where $\Omega^{i+1}$ is the same as in the previous equation.

4. Substitute $\boldsymbol{\omega}^{i+1}$ into step 2 until the result converges.

# 3. Results

We load the Venus model with a point mass of $1 \times 10^{17}$ kg which is attached to the surface at 15 degree colatitude and 0 longitude, the rotational speed of the model is set to be 3 times larger than the current day speed of Venus. We compare our method with that of [*Spada, G. et al* (1996)] in figure 1. We simulate the model with increased speed in order to show the difference of the two methods, otherwise the results will be indistinguishable in the plot.

We can see that the result from previous method based on quasi-fluid approximation underestimates the speed of the TPW and gives a different path.
When the p-coupling is also considered, the step-size of our algorithm must be much smaller than the period of the Chandler wobble $\frac{2\pi A}{(C-A)\Omega}$ and equation 3 needs to be added in the iteration.

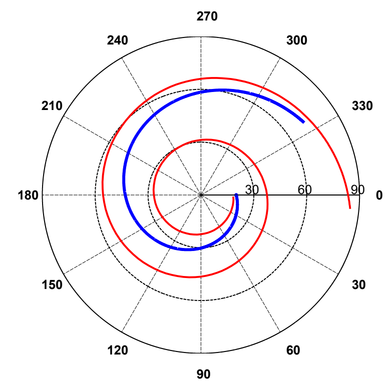


Figure 1: A top-down view of the body where the direction of the rotation is pointing upwards. The blue line is calculated with the quasi-fluid approximation while the red line is from our method

# Acknowledgements

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# $CO_2$ condensation can seriously limit the deglaciation of Earth-like planets

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## Context

It is widely believed that the carbonate silicate cycle [1,2,3] is the main agent (through volcanism, and when weathering ceases) to trigger deglaciations by $CO_2$ greenhouse warming on Earth and by extension on Earth-like planets when they get in frozen state.

We use a 3D Global Climate Model (the LMD Generic Model) to simulate the ability of planets initially completely frozen to escape from glaciation episodes by accumulating enough gaseous $CO_2$ [4]. The model includes $CO_2$ condensation and sublimation processes and the full water cycle.

## Results

We find that initially completely frozen planets that accumulate $CO_2$ through volcanism can evolve in three different climate regimes:

**1)** The greenhouse effect of $CO_2$ is too weak to trigger a deglaciation. The planet stays in a snowball state but keep accumulating $CO_2$ in the atmosphere.

**2)** The greenhouse effect of $CO_2$ is sufficient to raise the surface temperatures in equatorial regions above the melting temperature of water ice. The planet escape from glaciation.

**3)** The greenhouse effect of $CO_2$ is too weak to raise the surface temperatures of the poles above the condensation temperature of $CO_2$ . In this case, the gaseous $CO_2$ collapses and the planet is locked in a global glaciated state, with two permanent $CO_2$ polar ice caps.

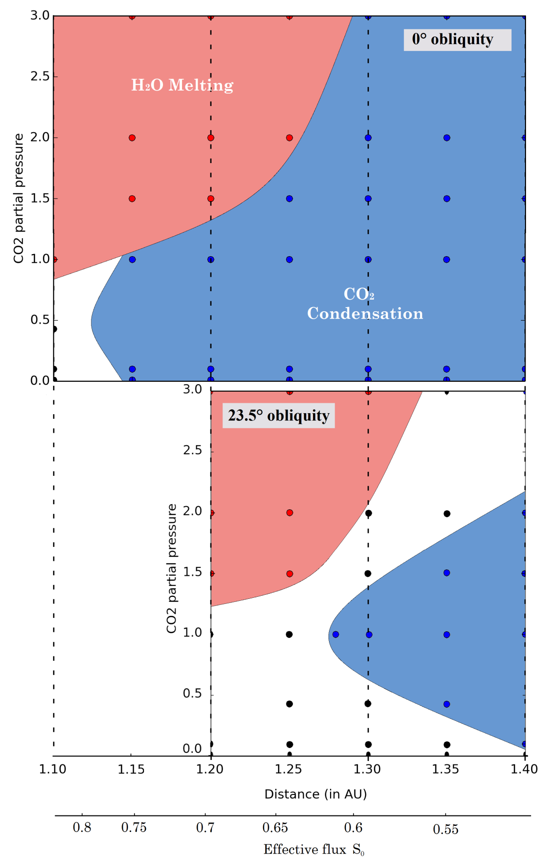


*Figure 1: Climate regimes reached as function of the equivalent distance from a Sun-like star (in AU) and the $CO_2$ partial pressure, assuming a cold start (i.e. snowball state without permanent $CO_2$ ice deposits). Figures correspond to Earth-like planets with 0° (top panel) obliquity or 23.5° obliquity (bottom panel). The red color roughly depicts the region where deglaciation is observed. The blue region represents glaciated states where $CO_2$ collapses permanently. The white region describes cases where none of this two previous conditions were reached.*

Quantitatively, and as illustrated on Fig. 1, we find that planets with Earth-like characteristics (size, mass, obliquity, rotation rate, ...) orbiting a Sun-like star may never be able to escape from a glaciation era if their orbital distance is greater than ∼ 1.27 Astronomical Units (Flux < 847 W $m^{-2}$ , $S_{eff}$ < 0.62), because $CO_2$ would condense at the poles – here the cold traps – forming permanent $CO_2$ ice caps. This limits the amount of $CO_2$ in the atmosphere and thus its greenhouse effect.

Furthermore, our results indicate that for (1) high planetary rotation rates ($P_{rotation}$ < 24 h), (2) low obliquity (< 23.5°), (3) low background gas partial pressures (< 1bar), and (4) high water ice albedo (> 0.6), the $CO_2$ polar condensation could occur for significantly lower orbital distance.

For each possible configuration, we show that the amount of $CO_2$ that can be trapped in the polar caps depends on the efficiency of $CO_2$ ice to flow laterally as well as its gravitational stability relative to subsurface water ice. The flow of $CO_2$ ice from polar regions to the equator is mostly controlled by the bottom glacier temperature, and hence by the internal heat flux of the planet. We find that a frozen Earth-like planet located at 1.30 AU of a Sun-like star could store as much as 1.5/4.5/15 bars of dry ice at the poles, for internal heat fluxes of 100/30/10 mW $m^{-2}$.

But these amounts are in fact lower limits. For planets with a significant water ice cover, we show that $CO_2$ ice deposits should be gravitationally unstable. They get buried beneath the water ice cover in very short timescales of $10^2$ -$10^3$ yrs, mainly controlled by the viscosity of water ice. For water ice cover exceeding ~ 300 meters (or geothermal heat flux lower than ~ 0.4 W $m^{-2}$, respectively), we show that the $CO_2$ would be permanently sequestered underneath the water ice cover, in the form of $CO_2$ liquids, $CO_2$ clathrate hydrates and/or dissolved in subglacial water reservoirs. This would considerably increase the amount of $CO_2$ trapped and further reduce the probability of deglaciation.

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# Reorientation Histories of Mercury, Venus, the Moon, and Mars

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## Abstract

The spins of planets are not stagnant with time; they continuously evolve in response to both internal and external forces. One mechanism for changing the spin of a planet is true polar wander (TPW). TPW is the reorientation of the bulk planet due to some redistribution of mass on, or within, the planet. This processes can have important consequences for the climate, tectonics, and geophysics of the planet. Yet, despite its potential importance, it has been difficult to constrain the TPW histories of solar system worlds beyond the Earth. In this work, we present the first comprehensive, data-driven investigations into the reorientation histories of the terrestrial worlds: Mercury, Moon, Venus, and Mars. The technique utilizes the high resolution global gravity fields now available for these worlds. The methodology developed here is completely general, and can be applied to future investigations of other solar system worlds (e.g. ocean worlds).

## 1. Introduction

The dynamics of a planet's spin is controlled by the planet's inertia tensor. In a minimum energy rotation state, planets spin about the maximum principal axis of inertia. Yet, the magnitudes and orientation of these principal axes of inertia are not always constant with time. The redistribution of mass within the planet due to both interior processes (e.g. mantle convection) and surface processes (e.g. extrusive volcanism and impacts) can significantly alter the planet's inertia tensor, resulting in the reorientation of the planet with respect to its principal axes of inertia. This form of reorientation is known as true polar wander (TPW).

TPW can have dramatic implications for the geology of a planet. For example, TPW can change insolation geometry, altering climate and volatile stability; generate tectonic stresses; and modify the planet's magnetic field. Yet, despite its significance, the TPW histories of most solar objects are not well constrained. Here, we present the first systematic, data-driven investigation of TPW of the terrestrial worlds: Mercury, Venus, Moon, and Mars.

## 2. Methods

The orientation of a planet is controlled by the differences by the non-spherically symmetric component of the planet's inertia tensor. This non-spherically symmetric component can be directly related to a planet's spherical harmonic degree and order 2 gravity field (1). It is often assumed that the majority of a planet's degree-2 gravity field (and shape for that matter) arise from the combination of tidal and rotational deformation. This tidal and rotational deformation can have contributions both from the present-day tidal and rotational potential (often referred to as the "hydrostatic" figure), and from a past tidal and rotational potential that has been preserved by the presence of an elastic lithosphere (often referred to as the "fossil" or "remnant" figure). While tidal and rotational deformation often dominate the degree-2 gravity field of a planet, they are not the only important factor. Impact basins, volcanoes, and other smaller-scale geologic structures (henceforth, "mass anomalies") can contaminate the degree-2 gravity field—and thus the inertia tensor—of a planet.

We have developed a technique for using higher resolution gravity data to isolate the contribution of mass anomalies to the degree-2 gravity field of solar system objects (2). Most large mass anomalies (e.g. impact basins) are axisymmetric at long-wavelength. We model their gravity fields using a linear combination of concentric, uniform density spherical caps. The gravity anomaly of these caps scales linearly with the single (scalar) surface density of each cap. For each mass anomaly, we determine the best fitting linear combination of surface densities for each spherical cap. We perform these fits from spherical harmonic degree and order 3 and above, in order to prevent directly fitting any underlying tidal and rotational figure. Since the spherical harmonic gravity coefficients of a spherical cap scale linearly with the surface density of the cap, we can determine the degree-2 contribution by scaling the analytically-derived degree-2 gravity coefficients of the cap by the best-fit surface density determined from fitting higher degrees and orders. The inertia tensor perturbations arising from each mass anomaly can then be determined (1).

## 3. Results

Thanks to many robotic exploration missions, we now have sufficiently high resolution gravity data to perform this reorientation for a variety of solar system worlds, including Mercury, Venus, Moon, and Mars. Preliminary TPW chronologies for these terrestrial worlds are shown in Figure 1. In these chronologies, we use perform our mass anomaly fitting routine outlined above, and sequentially remove the inertia tensor perturbations of major mass anomalies from the present-day, non-hydrostatic inertia tensor of each planet. The chronologies are relative, and are not well constrained on many worlds. This technique is only capable of constraining reorientations driven by mass anomalies that are preserved in the present-day gravity fields of these worlds.

The reorientation histories for the Moon and Mercury are similar. The orientation of both planets is strongly controlled by the presence of a large remnant bulge. On the Moon, this bulge is predominantly a fossil tidal and rotational bulge; on Mercury, this bulge likely has a significant thermal component, arising from Mercury's proximity to the Sun and its unique spin-orbit resonance (3). Nonetheless, large impact basins and volcanic events have significantly altered the orientation of these worlds—resulting in 10-30° of total reorientation after their formation. The South Pole-Aitken impact basin on the Moon resulted in one of the single largest reorientation events on any planet studied here. Asymmetric thermal evolution may further alter the orientation of the Moon (4).

Mars has also experienced large reorientation events, but due primarily to the formation of the hemispheric dichotomy and Tharsis volcanic rise. Large impact basins contribute less to the planet's total inertia tensor than comparably sized impact basins on the Moon and Mercury.

Venus's slow rotation results in a very small tidal and rotational bulge, making it extremely prone to dramatic reorientation events (4). Our analysis of the inertia tensor perturbations of Venus's large volcanic provinces seems to agree with this notion. Individual, regional volcanic provinces can reorient Venus by as much as 60°. However, the exact reorientation chronology on Venus is by far the least well constrained.

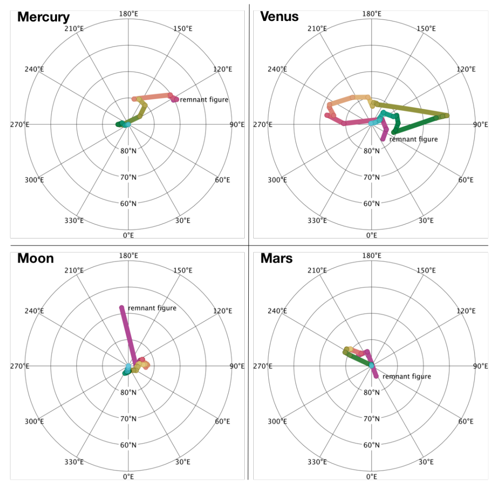


Figure 1: Preliminary TPW chronologies for the terrestrial planets. Each point in these plots indicates the location of the spin pole after the formation of some large geologic feature, relative to the present-day coordinate system. TPW paths start at a presumed remnant figure (purple) and migrate to the present-day spin pole (blue).

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# Coupling giant impacts and long-term evolution models

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## Abstract

The crustal dichotomy [1] is the dominant geological feature on planet Mars. The exogenic approach to the origin of the crustal dichotomy [2-6] assumes that the northern lowlands correspond to a giant impact basin formed after primordial crust formation. However these simulations only consider the impact phase without studying the long-term repercussions of such a collision.

The endogenic approach [7], suggesting a degree-1 mantle upwelling underneath the southern highlands [8-11], relies on a high Rayleigh number and a particular viscosity profile to form a low degree convective pattern within the geological constraints for the dichotomy formation. Such vigorous convection, however, results in continuous magmatic resurfacing, destroying the initially dichotomous crustal structure in the long-term.

A further option is a hybrid exogenic-endogenic approach [12-15], which proposes an impact-induced magma ocean and subsequent superplume in the southern hemisphere. However these models rely on simple scaling laws to impose the thermal effects of the collision.

Here we present the results of impact simulations performed with a SPH code serially coupled with geodynamical computations performed using the code I3ELVIS to improve the latter approach and test it against observations. We are exploring collisions varying the equation of state, impact angles and target body properties, and are gauging the sensitivity to the handoff from SPH to I3ELVIS.

As expected, our results indicate the formation of a transient hemispherical magma ocean in the impacted hemisphere, and the merging of the cores. We also find that impact angle has a strong effect on the post-impact crustal pattern.

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# Constraints on the interior structure of Mars from nutations

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## Abstract

Studying the rotation of Mars provides knowledge about its interior structure and global scale atmosphere dynamics. In particular, observing Mars' nutation by the forthcoming RISE and LaRa experiments on InSight and ExoMars, allows to infer information about its core. Nutation amplitudes can be resonantly amplified if the planet's core is liquid, thus the state of the core can be determined from the response induced by the precisely known tidal forcing of the Sun acting on Mars. The response to the external forcing does not only depend on the core state but also on its polar moment of inertia, figure, and capacity to deform. By combining measured nutation amplitudes with the already well known polar moment of inertia and tidal Love number $k_2$ the size of the core and its material properties can be determined more precisely than from the latter quantities alone. Also the polar moment of the mantle can then be determined from which constraints on the mantle's composition and thermal state be obtained.

In this study, we first reconsider the study of the nutations of a rigidly rotating Mars. Next, we use interior structure models of Mars that are consistent with the most recent estimates of the moment of inertia, tidal Love number $k_2$, and global dissipation in order to model the nutations of the real Mars. The models have been constructed from depth-dependent material properties about mantle minerals and use thermoelastic and melting properties of core constituents (iron and sulfur). For each model we compute nutation amplitudes and then assess the constraints on the interior structure of the core that can be expected by measuring nutations with RISE and LaRa.

## Acknowledgements

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# Constraining mantle convection models with palaeomagnetic reversals record and numerical dynamos

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## Abstract

We present numerical models of mantle dynamics forced by plate velocities history in the last 450 Ma. The lower-mantle rheology and the thickness of a dense basal layer are systematically varied and several initial procedures are considered for each case. For some cases, the dependence on the mantle convection vigor is also examined. The resulting evolution of the CMB heat flux is analyzed in terms of criteria known to promote or inhibit reversals inferred from numerical dynamos: (1) mean value of CMB heat flux $q^0$, (2) amplitude of heat flux heterogeneities $q^*$, (3) polar vs. equatorial cooling (measured by harmonic coefficient $q_2^0$), (4) equatorial symmetry of the heat flux pattern.

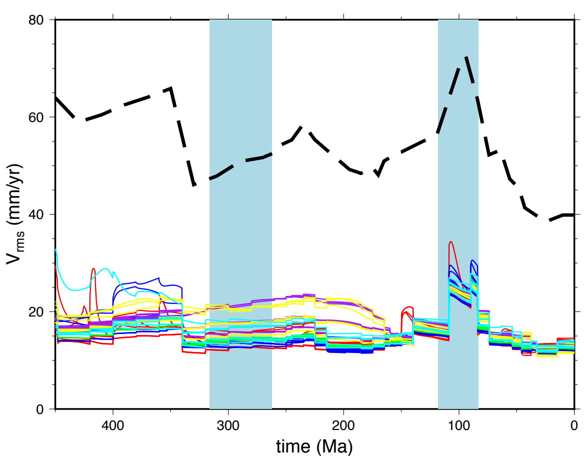


Figure 1: Time evolution of the surface average prescribed plate velocity model (thick dashed line) as well as the volume average velocity for 54 numerical mantle convection models (colored lines). The two light blue rectangles indicate the Kiaman Reverse Superchron (KRS) and the Cretaceous Normal Superchron (CNS).

Most models present a rather dynamic lower mantle with the emergence of two thermochemical piles towards present-day. Only a small minority of models present two stationary piles over the last 450 Myr. At present-day, the composition field obtained in our models is found to correlate better with tomography than the temperature field. In addition, the temperature field immediately at the CMB (and thus the heat flux pattern) slightly differs from the average temperature field over the 100-km thick mantle layer above it.

The evolution of the mean CMB heat flux or of the amplitude of heterogeneities seldom presents the expected correlation with the evolution of the palaeomagnetic reversal frequency suggesting these effects cannot explain the observations. In contrast, our analysis favors either inertial control on the geodynamo associated with polar cooling and in some cases break of Taylor columns in the outer core as sources of increased reversal frequency. Overall, the most likely candidates among our mantle dynamics models involve a viscosity increase in the mantle equal or smaller than 30: models with a discontinuous viscosity increase at the transition zone tend to agree better at present-day with observations of seismic tomography, but models with a gradual viscosity increase agree better with some of the criteria proposed to affect reversal frequency.

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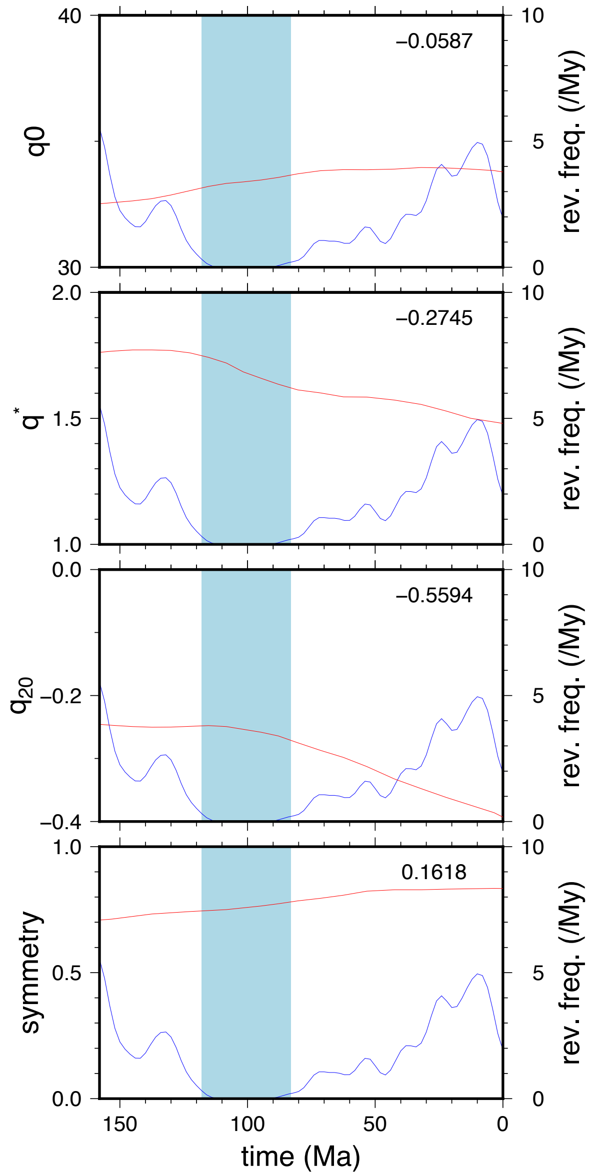


Figure 2: Time evolution of the values associated with the four criteria on CMB heat flux for one model (red) vs. reversal frequency (blue). The CNS is highlighted in light blue.

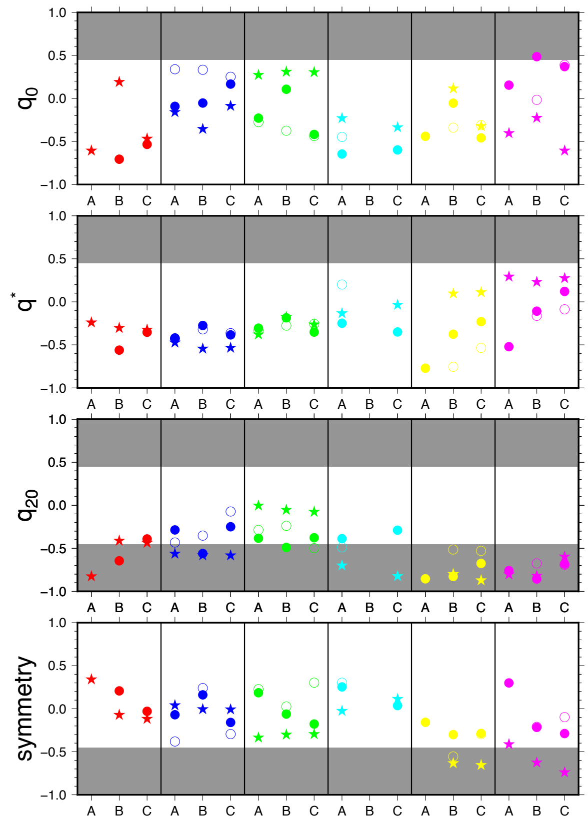


Figure 3: Linear correlation coefficient between the time evolution of reversal frequency and the time evolution of criteria for the CMB heat flux. The various colors, symbols and letter (A,B,C) denote various rheological models, initial procedure and thickness of the dense layer at the base of the mantle, respectively. Only models whose present day composition field correlates sufficiently well with tomography (with at least a 90 % confidence), are presented here. Shaded rectangles denote statistically significant correlation/anticorrelation (a 95 % confidence for the number of degrees of freedom considered, approx. 20). For example, a minimal heat power $q^0$ or a pattern presenting larger equatorial symmetry is expected during the CNS, thus a positive correlation is expected for $q^0$ and a negative one for symmetry.

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# Interior and surface evolution paths of rocky exoplanets

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## Abstract

In this study, the thermal and chemical evolution of rocky exoplanets is modelled, using a Monte-Carlo method to study the influence of randomly selected values for unknown parameters like composition-related or thermal parameters. Evolution scenarios can be diverse depending on the parameter assumptions for small-massive planets (with masses of up to few Earth masses).

## 1. Introduction

Thousands of exoplanets have been discovered in the past decade, revolutionizing our way of scientific thinking both in the direction of formation and evolution of planets, as well as in the direction of exotic places where life may evolve and flourish in non-Earth-like environments. However, identification of possible atmosphere bio-signatures or models of the evolution of exoplanets are typically based on Earth models - which is a natural first step to understand processes on possibly habitable planets, especially since we are more prone to detect exo-life (if it exists) on Earth-like planets than on other planets due to our detection bias.

Several studies for example extrapolated Earth models to other planet properties (e.g. mass, radius, core size, see Fig. 1 from [1]) to predict how basic planetary processes (like mantle convection or plate tectonics) are affected by these parameters. However, even if a planet is discovered with a density hinting at a rocky planet, it may be quite non-Earth-like for example in terms of composition, mineralogy, core formation, volatile content, etc. Within the range of uncertainties and with the current observation techniques, it is impossible to differentiate remotely between a planet like Earth with continents and oceans at the surface, or a dry one-plate planet, or an ocean planet, or other, exotic planets.

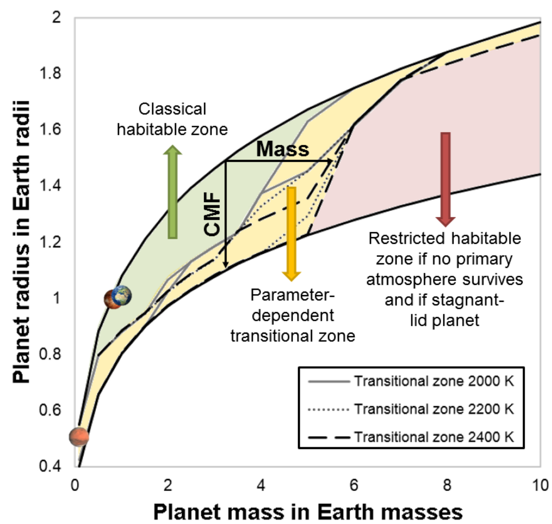


Figure 1: Sketch of a mass-radius diagram indicating the mass-radius range, where the classical HZ definition can be applied (green area), the range where the HZ may be restricted due to limited outgassing (red area) and the transitional regime in-between (yellow area) for planets of Earth-like composition and structure without plate tectonics. From [1]

It is therefore necessary to study how the evolution of a planet may be affected by the unknown planet's properties as well as its formation and evolution history, and to better understand possible restrictions for surface or subsurface habitability.

## 2. Convection simulations

The evolution of the mantle of rocky exoplanets is modelled using the truncated anelastic compressibility approximation (for specifics on the code implementation, please look at [2]). For given planet mass and pre-defined mantle composition, radial profiles are derived for the thermodynamic properties depending on an adiabatic temperature profile.

The composition of the mantle has a strong influence on the mantle convection (and possibly plate tectonics initiation or maintenance), as well as on the crust and atmosphere evolution (for example via volatile-dependent melting temperatures and melt compositions). The influence of the mineralogy of the mantle (depending for example on the Fe/Si and Mg/Si ratio as well as on volatile contents) and initial parameters (as for example initial upper mantle and core temperatures and radioactive heat sources) on convective behavior, surface processes and outgassing of greenhouse gases such as $CO_2$ and $H_2O$ [3] is investigated.

## 3. Preliminary results

Thermal initial parameters can strongly influence the efficiency of mantle convection and therefore have a major effect especially on outgassing results.

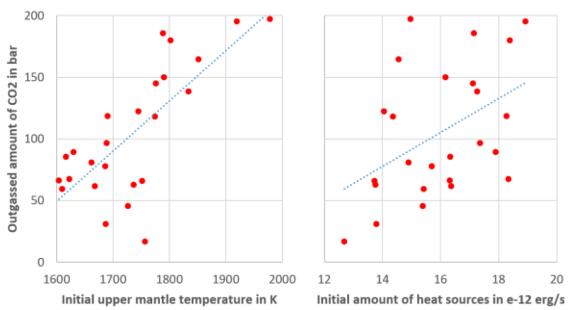


Figure 2: Example outgassed amount of $CO_2$ depending on initial upper mantle temperature (left) and initial amount of radioactive heat sources (right).

Figure 2 shows an example outgassing result for a rocky planet of 1.3 Earth masses with an Earth-like core-mass fraction and assuming here a pure silicate mantle and pure iron core. A clear increasing trend can be observed between outgassing efficiency and initial upper mantle temperature (influencing the entire adiabatic temperature), whereas a less strong but still increasing trend can be observed with respect to the initial amount of radioactive heat sources.

Further investigations will include for example the influence of composition (e.g. magnesium number in mantle minerals), initial mantle volatile content, non-linear partitioning of volatiles into the melt, and volatile influences on melting temperature.

## 4. Summary and Conclusions

Monte-Carlo models of possible planet post-formation thermal states and planet compositions are used in this study to predict the range of possible evolution trends for specific rocky planets. Initial parameters for the thermal profile as well as radioactive heat sources have a strong influence on outgassing of greenhouse gases and therefore possible surface habitability (see also [4]). The mass in addition strongly affects the convective behavior in the interior and therefore also the effectiveness of outgassing.

Monte-Carlo models with randomly chosen parameters for planet properties and initial values as reported here can be used to obtain a statistical probability of specific surface processes (e.g. sufficient greenhouse outgassing at the outer boundary of the habitable zone, [1]). This can be used to help identifying exoplanets of higher (or lower) interest to expensive follow-up observations.

## Acknowledgements


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# A scaling law for impact-induced melt volume

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## Abstract

During the late stages of planetary accretion, protoplanets experience a number of giant impacts and extensive mantle melting. Understanding the melt volume is important because it determines elemental abundances in the planetary core and mantle. Here, we develop a scaling law for melt volume based on giant impact simulations using smoothed particle hydrodynamics (SPH) as a function of the total mass, impact angle, impact velocity, and impactor-to-total mass ratio. We find that the law is most sensitive to the impact velocity and angle.

## 1. Introduction

Giant impacts play an essential role for determining the starting conditions of terrestrial planets. A large impact melts the outer part of the planetary mantle and delivers the impactor's iron to the planet. During descent of the iron through the molten part of the mantle (magma ocean), the iron, at least partly, experiences metal-silicate equilibration with the magma ocean [e.g., 1]. The sinking iron gains some light elements and eventually merges with the planetary core. An important parameter here is the magma ocean depth; element partitioning between silicate and iron depends on the equilibrium pressure and temperature, which are often considered as the ones at the base of the magma ocean. Thus, magma ocean depth is highly important for determining the planetary core and mantle compositions. Many insightful studies have been conducted to estimate mantle melt volume by impact [e.g., 2], but some of these studies have focused on cratering impacts and they do not consider self-gravity and geometry, which can play an important role during a giant impact. Here, we derive a scaling law for melt volume-based on impact simulations.

## 2. Method & Model

We perform impact simulations using a particle method called smoothed particle hydrodynamics (SPH) considering self-gravity. We develop a simple scaling law for melt volume based on SPH simulations. We use entropy of the mantle to determine the extent of mantle melting. We assume the pre-impact mantle temperature is close to solidus [3] and use M-ANEOS equation of state to describe the mantle materials.

## 3. Results

We derive a scaling law for mantle melting based on 80 impact simulations with various impact velocities $V_{\rm imp}$ (1-2 $V_{\rm esc}$ where $V_{\rm esc}$ is the mutual escape velocity), impact angle $\theta$ (0-90°), impactor-to-total mass ratio $\gamma$ (0.03-0.5), and the total mass $M_{\rm T}$ (1-6.5 Mars mass). Our preliminary results indicate that the mass fraction of molten mantle $f$ in this parameter range is approximately expressed as

$$f \sim \frac{M_T\gamma(1-\gamma)V_{\rm imp}^2}{2M_mL}\left(\frac{V_{\rm imp}}{V_{\rm esc}}\right)^{-1.2}\sin^{0.86}\theta(1-\cos\theta)^{1.66(V_{\rm imp}/V_{\rm esc}-1)},$$

where $M_m$ is the mantle mass and $L$ is the latent heat. In this parameter range, the standard deviation between SPH and this fitting model is smaller than 0.20. We also find that self-gravity plays an important role in a large impact by converting potential energy into heat. Likewise, geometry needs to be taken into account for precise melt volume estimates.

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# Formation of continental crust by intrusive magmatism

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## Abstract

We investigate the creation of proto-continental crust (TTG rocks) employing fully self-consistent numerical models of thermo-chemical convection on a global scale at the Archean, after crystallization of the magma ocean. We show that intrusive magmatism is the key process to reach the pressure-temperature conditions of TTG formation. Full eruptive magmatism produces a too cold lithosphere in our self-consistent models. Our simulations show that the Archean Earth might have gone through various convection regimes before the stabilisation of plate tectonics: eclogite dripping events, stagnant episodes and resurfacings.

## Introduction

We solve the equations of compressible mantle convection, employing fully realistic rheological parameters [3] using the convection code StagYY [7] in 2D spherical annulus geometry for a period of one billion years.

Starting from a pyrolytic composition and an initially warm core (6000K), when the temperature exceeds the solidus temperature, our simulations first generate oceanic crust and depleted residue (harzburgite) in the upper mantle. In our model, basaltic material can be both erupted (cold) at the top of the domain and intruded (warm) at the base of the crust following a predefined partitioning. At all times, water concentration is considered fully saturated in the top 10 km of the domain, and it is simply advected elsewhere.

Second, we track the pressure-temperature conditions of the newly formed hydrated basalt and check if it reaches the conditions necessary for the generation of primordial continental crust [5]. We systematically investigate the influence of volcanism (eruption, also called "heat pipe") and plutonism (intrusive magmatism) on the time-dependent geotherm in the lithosphere.

## Results

We show that the "heat-pipe" model (assuming 100% eruption and no intrusion) proposed to be the main heat loss mechanism during the Archean [4] is not able to produce continental crust as it forms a too cold and thick lithosphere [6]. We also systematically test different mechanical properties of the brittle domain (friction coefficients). With this parameter study, we are also able to show that an intrusion fraction higher than 60% (in agreement with [1]) combined with a friction coefficient greater than 0.1 can generate the expected amounts of the three main petrological TTG compositions previously reported in field studies [5]. Figure 1 illustrates the impact of intrusion efficiency on the geotherm in the lithosphere.

This result seems robust as the amount of TTG rocks formed varies over orders of magnitude. A fully eruptive model can result in up to 100 times less felsic crust production than in a plutonic simulation using the same rheological parameters. However, our simulations are unfortunately not yet able to produce depleted continental roots, which might significantly modify the thermal profile of the lithosphere.

Despite such limitations, our models might also provide an explanation for the transition in convection regime previously suggested around 3.6 Ga, where mantle activity could have temporarily decreased [8]. Widespread felsic magmatism has been reported over hundreds of millions of year in localised regions, suggesting a possible fixity of mantle upwellings [2]. Our models show that such surprising observation can be reproduced after the initial vigorous stages in which tremendous amounts of eclogite drip from the lithosphere due to extensive melting and crust production. Since this mafic material is denser than the ambiant mantle, it sinks and stabilizes above the core mantle boundary. Hundreds of millions of year of relative convective stability are then often observed in our models. Moreover, massive catastrophic overturns sometimes follow this quiescent phase, which might have a geochemical signature similar to what the onset of plate tectonics could have produced.

# 1. Summary and Conclusions

We demonstrate that crust production has a major influence on the convection regime on terrestrial planets, as previously reported in [4]. We show that both eruptive and intrusive magmatism are required to form continental material in self-consistent numerical simulations of mantle convection.

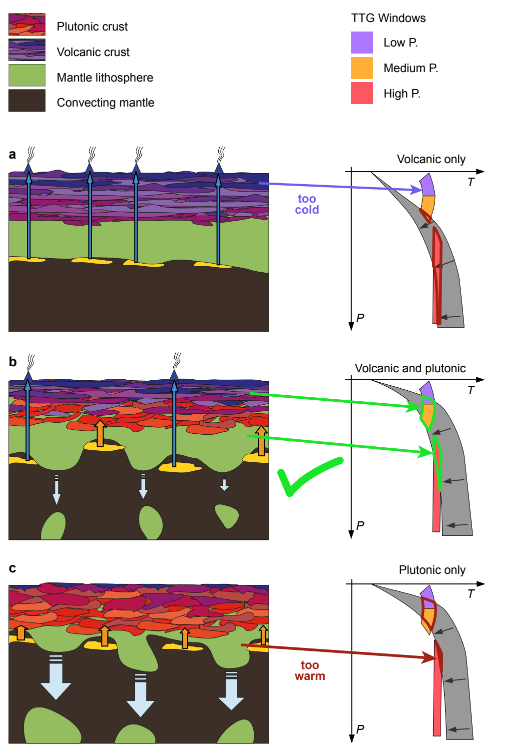


Figure 1: Intrusive vs eruptive magmatism and its impact on the geotherm of the early Earth [6].


# Acknowledgements

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# Extrusive and Intrusive Magmatism Greatly Influence the Tectonic Mode of Earth-Like Planets

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## Abstract

Plate tectonics on Earth-like planets is typically modelling using a strongly temperature-dependent visco-plastic rheology. Previous analyses have generally focussed on purely thermal convection. However, we have shown that the influence of compositional heterogeneity in the form of continental [1] or oceanic [2] crust can greatly influence plate tectonics by making it easier (i.e. it occurs at a lower yield stress or friction coefficient). Here we present detailed results on this topic, in particular focussing on the influence of intrusive vs. extrusive magmatism on the tectonic mode.

## 1. Modelling results

### 1.1 Extrusive magmatism

In this study, reported in [2], we use numerical simulations to address the question of whether melting-induced crustal production changes the critical yield stress needed to obtain mobile-lid behaviour (plate tectonics). Our results show that melting-induced crustal production strongly influences plate tectonics on Earth-like planets by strongly enhancing the mobility of the lid, replacing a stagnant lid with an episodic lid, or greatly extending the time in which a smoothly evolving mobile lid is present in a planet. Finally, we show that our results are consistent with analytically predicted critical yield stress obtained with boundary layer theory, whether melting-induced crustal production is considered or not.

### 1.2 Intrusive magmatism and Plutonic Squishy Lid mode

Volumes of intruded magmas are observed to be ~4−9 times larger on Earth than erupted magmas. Therefore, intrusive magmatism is thought to play a role in the dynamics of the lithosphere. In this study reported in [3], we use thermo-chemical global mantle convection numerical simulations to systematically investigate the effect of plutonism, in conjugation with eruptive volcanism. Results reproduce the three common tectonic/convective regimes usually obtained in simulations using a visco-plastic rheology: stagnant-lid (a one-plate planet), episodic (where the lithosphere is unstable and frequently overturns into the mantle), and mobile-lid (similar to plate tectonics). At high intrusion efficiencies, we observe and characterise a new additional regime called "plutonic-squishy lid". This regime is characterised by a set of strong plates separated by warm and weak regions generated by plutonism. Eclogitic drippings and lithospheric delaminations often occur around these weak regions. These processes lead to significant surface velocities, even if subduction is not active. The location of the plate boundaries is strongly time-dependent and mainly occurs in magma intrusion regions. This regime is also distinctive because it generates a thin lithosphere, which results in high conductive heat fluxes and lower internal temperatures when compared to a stagnant lid. The plutonic-squishy-lid regime has the potential to be applicable to the Archean Earth and Venus, as it combines elements of both protoplate tectonic and vertical tectonic models, such as horizontal plate motion and reprocessing of the lithosphere for the former, and lithospheric diapirism, volcanism, and basal delamination for the latter.

## 2. Summary and Conclusions

Magmatism makes a first-order difference to the scaling of plate tectonics on Earth-like planets. It facilitates plate tectonics, and large amounts of intrusive magmatism may result in a new "Plutonic-squishy-lid" tectonic mode that may be important in early Earth and on Venus. In recent results reported in [4] and presented separately, the plutonic-squishy-lid mode is shown to facilitate the formation of

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# Induction heating of planetary interiors

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## Abstract

We present a calculation of the energy release in planetary interiors caused by induction heating. If an exoplanet orbits a host star with a strong magnetic field, it will be embedded in periodically varying magnetic environment. In our work, we consider only a dipole field of the host star and assume the dipole axis to be inclined with respect to the stellar rotational axis, which causes the magnetic field to vary. In this case, the varying magnetic field surrounding the planet will generate induction currents inside the planetary mantle, which will dissipate in the planetary interiors. We show that this energy release can be very substantial and in some cases even lead to complete melting of the planetary mantle over geological timescales, accompanied by the enhanced magnetic activity.

## 1. Introduction

Unlike the Sun, low-mass M dwarfs often are observed to have strong magnetic fields of a few hundred Gauss or more. We consider TRAPPIST-1 system as an example and calculate the induction heating of planetary mantles of the seven TRAPPIST-1 planets. In the Solar system, the environmental conditions differ substantionally from the TRAPPIST-1 system, with the only exception of the Galilean moons. The Galilean satellites are embedded in the magnetic field of Jupiter, varying due to Jupiter's rotation and the dipole axis inclination of $\approx 10^{\circ}$. Although the magnetic field of Jupiter is not strong enough to heat the interiors of the Galilean satellites, it leads to generation of induced dipole fields inside the moons. Observation of these induced fields allowed to discover salty water oceans under the surfaces of Europa and Callisto [1, 2].

## 2. Method

First, we calculate the magnetic field inside the planetary mantle embedded into varying external magnetic field. We apply the formulas for the magnetic field components for a sphere with non-homogeneous conductivity presented by [3]. We divide the planetary mantle into layers assuming the conductivity to be constant inside a layer and solve the induction equations for the magnetic and electic fields and for the current inside every layer and in the central part of the sphere. Knowing the current in every layer, one can easily calculate the energy release in it. Then, we use the code CHIC [4] to model the corresponding magmatic effects in the planetary mantle. We calculate the amount of melt in the mantle, and the amount of the induction heating-triggered volcanic outgassing.

## 3. Results

Fig. 1 presents an example of our calculation for the planet TRAPPIST-1c, which has a radius close to the one of the Earth. Since the masses of the TRAPPIST-1 planets have not been measured yet with a high precision, we assume an Earth-like composition in our calculations. We also assume an Earth-like conductivity profile (shown in Fig. 2). Fig. 1 shows energy release rate inside the planet depending on the depth. Total energy release inside the planet equals approximately $10^{22}$ erg/s. We assume the dipole field strength of TRAPPIST-1 equal to 600 G. As one can see, energy release peaks at about 0.9 planetary radii. Below approximately 0.8 planetary radii magnetic field already substantionally declines, leading to insignificant energy release. On the other hand, in the upper part of the mantle above 0.9 planetary radii energy release is weak due to low conductivity (see Fig. 2).

We modelled corresponding magmatic effects in

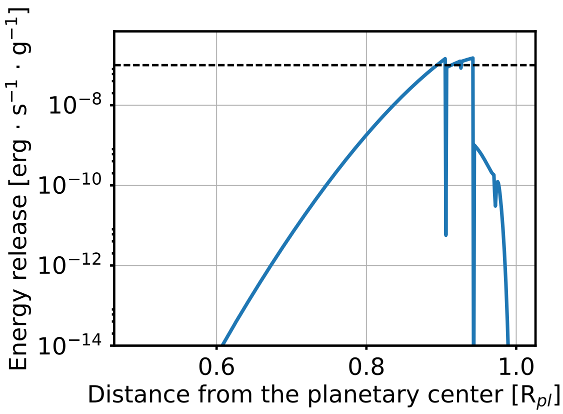


Figure 1: Energy release rate in the mantle of the exoplanet TRAPPIST-1c. The dashed line indicates approximate level of the local heat necessary to melt the mantle and create a magma ocean.

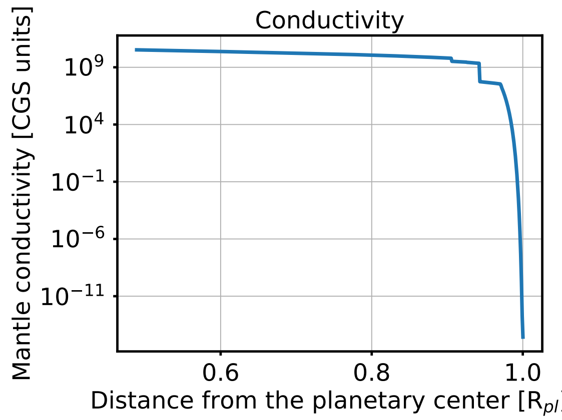


Figure 2: Elecrical conductivity profile of the planetary mantle for TRAPPIST-1c, assumed for calculations.

planetary interiors using the code CHIC. Our results show, that in case of TRAPPIST-1c a magma ocean is formed beneath the planetary surface, similar to the one of Io. Therefore, similar to Io, one can expect volcanic activity at this planet to be strong.

## 4. Summary and Conclusions

We have shown that induction heating is substantial in the interiors of planets orbiting strongly magnetized M dwarfs. Sometimes the heating is strong enough to melt the planetary mantle and produce an Io-like magma ocean under the planetary surface. In case of weaker heating, it still leads to enhanced volcanic activity and increased outgassing of greenhouse gases. Our results indicate that induction heating should be taked into consideration among other effects when studying the evolution of exoplanets orbiting M dwarfs, especially for close-in planets, but also for some planets in the habitable zones of M dwarfs. Our results are summarised in [5].

## Acknowledgements


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# Present-day heat flow and seismicity of Mars as predicted from convective thermal evolution models

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## Abstract

The InSight (Interior exploration using Seismic Investigations, Geodesy and Heat Transport) Discovery-class mission, to be launched in 2018, will perform a comprehensive geophysical investigation of Mars using a seismometer and a heat flow probe as well as precision tracking. The seismic and heat flow data are ultimately important to constrain the present-day interior structure and heat budget of the planet, and, in turn, offer constraints on its thermal and chemical evolution [1]. As the InSight lander will perform its measurements at a single location, in the Elysium Planitia region [2], numerical simulations of the dynamics of the interior can greatly help to interpret the data in a global context. In this study we present 3D numerical thermal evolution models of Mars and focus on the present-day state. Furthermore, we compare our results with available estimates of elastic lithosphere thickness and seismicity.

## 1. Introduction

At present, the Moon is the only body beside the Earth for which globally significant heat flow and seismic measurements are available. For Mars, indirect estimates from lithospheric loading models are used to infer the surface heat flow. However, the only available estimate of the present-day lithosphere thickness suggests a value larger than 300 km at the north pole [3]. This value corresponds to a heat flow smaller than 15 mW/m$^2$, which, if globally representative, is significantly lower than that predicted by numerical simulations [4, 5] employing the well accepted compositional model of [6]. This discrepancy led to speculations that the concentration of heat producing elements in the interior of Mars may be subchondritic or that the secular cooling of the planet could be smaller than predicted. Instead, we show that mantle plumes can introduce significant variations in the average surface heat flow [7]. Assessing the extent of surface heat flow variations is particularly important since one of the main goals of the InSight mission is to constrain the average surface heat flow from one single measurement. Together with the Urey ratio (i.e., the heat production rate divided by the rate of heat loss) as obtained from numerical models, the average surface heat flow can be used to constrain the heat production rate in the Martian interior [8].

Previous seismic measurements on Mars have been performed in the mid 1970's by the Viking seismic experiment. However, the instrument's poor coupling to the ground led to a high noise level produced by the wind-induced lander movements, making it difficult to identify events of seismic origin [9]. Yet estimates of present-day seismicity based on the analysis of surface faults predict values between those obtained for the Earth and the Moon [10, 11], even though it remains rather uncertain which of the faults are currently active on Mars. In this study, we use thermal evolution models to derive the amount and distribution of Mars' seismicity.

## 2. Model

We employ the mantle convection code GAIA [12] to compute the thermal evolution of Mars in a 3-D spherical geometry. Our models assume a fixed crust with a variable thickness as inferred from gravity and topography data, which is enriched in radiogenic heat sources according to the surface abundances inferred from gamma-ray measurements. We vary the mantle reference viscosity as well as the depth-dependence of the viscosity, consider constant and variable thermal expansivity, vary the crustal thermal conductivity, and the size of the core.

## 3. Results

The surface heat flow pattern is dominated by the crustal structure. However, upon considering a viscosity increase with depth of about two orders of magnitude, the signature of mantle plumes becomes visible on the surface heat flow map (Fig. 1). Such heat flow anomalies introduced by mantle plumes remain confined to narrow regions and are unlikely to affect the InSight measurement. Moreover, north and south pole elastic lithosphere thicknesses based on the thermal structures obtained from our models are consistent with the available present-day estimates.

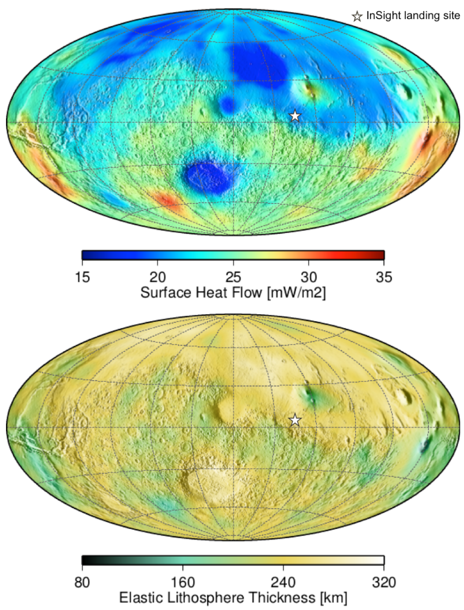


Figure 1: Distribution of the surface heat flow (top) and elastic lithosphere thickness (bottom) after 4.5 Gyr of thermal evolution (case 3 from [7]).

Furthermore, we derive the amount and distribution of present-day seismicity from the 3D thermal evolution models. We find similar but spatially anticorrelated seismic moments produced by convective stresses and stresses caused by cooling and planetary contraction, and consequently a relatively homogeneous distribution of the sum of seismic moments. Our results predict an annual moment release between $10^{16}$ Nm and $10^{19}$ Nm, similar to the values presented previously in [10] and [11]. However, while [11] used a mapping of tectonic surface faults to predict the spatial distribution of epicenters, we derive the distribution from the thermal evolution (Fig. 2). Besides the Null-Hypothesis of a uniform distribution and the model of [11], this provides a new, self-consistent, competing hypothesis for both the amount and distribution of seismicity on Mars.

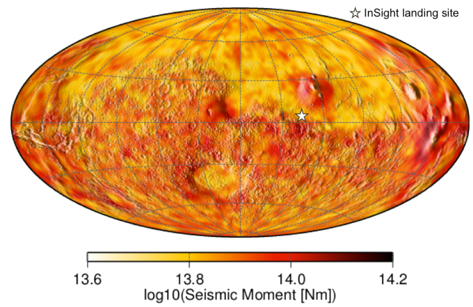


Figure 2: Distribution of the cumulative seismic moment obtained by adding the contributions from convective stresses and stresses produced by planetary contraction. The map shows the median of more than 10 models averaged on a 3×3° grid to filter out small scale structures that may be model dependent.

## 4. Conclusions

The 3D thermal evolution models we present allow estimating the global heat flow from a single-point measurement with InSight. The presence of plumes resolves the polar lithosphere thickness paradox. Additionally a new, self-consistent seismicity distribution model can be derived.

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