EPSC Abstracts
Vol. 5, EPSC2010-525, 2010
European Planetary Science Congress 2010

OEDIPUS: numerical models for solid planetary bodies

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Abstract

OEDIPUS (Origin, Evolution and Dynamics of the Interiors of Planets Using Simulation) is a numerical method solving thermal convection in a spherical shell for a fluid with variable viscosity. We show why such programs are needed to describe the long-term internal evolution of solid planetary bodies. In order to compare models to measurements provided by spacecrafts (altimetry, gravimetry) or to include processes contributing to the heat budget of planetary bodies (e.g. tidal heating), specific modules are introduced.

Introduction

The internal evolution of solid planets and satellites is classically considered as resulting first from the extraction of heat buried deeply in these bodies. Primordial stages of the evolution might include the global melting of a significant part of the interior (due to the energy deposited by large impacts, for example, or caused by the conversion of gravitational energy during an early global-scale differentiation such as the core formation ‘event’ on the largest terrestrial planets). A fully molten silicate mantle is however a transient state since crystallization occurs rapidly compared to geological time scales. Most of the subsequent evolution thus involves solid-state heat transfer at least in the outer shells of the body (again, for terrestrial planets, a liquid metallic core might persist even at present day). Thermal convection driven by primordial heat sources or subsequent heating due to radiogenic decay or tidal dissipation probably characterizes most the solid planetary bodies during large parts of their history. Specific numerical tools designed to treat this problem are therefore needed: first these allow to derive generic scaling relationships for simplified processes ; moreover, since planetary bodies often resist generalization, more sophisticated scenarios, guided by such simple models, are required to compare with observations: these can only be obtained with numerical methods such as the one described in the following.

Thermal convection of a variable viscosity fluid in a spherical shell

Variable viscosity - The tool OEDIPUS solves the conservation equations describing thermal convection. The assumption of an infinite Prandtl number fluid, valid for a silicate mantle and, to a lesser extent, for icy layers, is done. The Boussinesq approximation is also adopted although more precise thermodynamical formulations should ultimately be used, mostly because viscous dissipation can become non negligible. Since the creep mechanisms associated to materials constituting these bodies provide strongly temperature-dependent rheologies (viscosity is expected to vary by several orders of magnitude), the numerical method should handle large viscosity gradients:

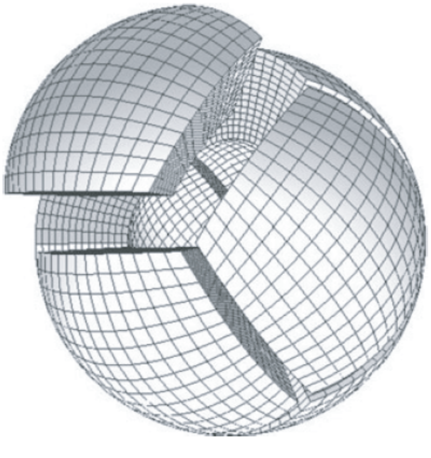

Figure 1: “Cubed sphere” mesh. A cube is projected on the circumscribed sphere leading to a decomposition into six identical blocks. Angular coordinates correspond to great circles in the two directions forming a quasi-uniform grid.

Discrete mesh - Numerical schemes that satisfy this requirement have so far only been found among grid based methods. Multigrid algorithms remain the fastest methods for such flow solvers although the efficiency decreases with increasing viscosity contrasts. These are also well suited for a parallel implementation. When a spherical numerical domain is considered, one caveat however, is that classical spherical coordinates introduce geometrical singularities at the poles. For this reason, the few recent programs that permit the numerical treatment of such problems have adopted specific grid meshes: the gridding technique used in OEDIPUS is derived from the "cubed sphere" idea [4] (cf. Fig. 1).

Other aspects

Topography and geoid - While seismic tomography is the most precise tool illuminating the Earth's interior, other planetary bodies (with the exception of the Moon) still lack such an efficient probe. In the absence of such data, the altimetry and gravimetry measurements provided by numerous spacecrafts on neighboring planets are the best geophysical observations to compare the models with: the gravity and topography of Venus and Mars, for example, are known very well and to a high spherical harmonic degree - it should be noted that distinguishing the deep dynamic component of topography from the one induced by lithospheric effects (isostasy, elastic support), is not a simple procedure (cf. e.g. [5]). We have included a precise computation of the geoid and dynamic topography induced by the viscous flows computed in our models [2]. This module has been carefully tested against very precise evaluations of kernels based on a spectral method. The last developments include the mechanical coupling of the convective layer with an overlying elastic shell in order to mimick the effect of a thick lithosphere.

Evolution of the spin-rate - We also propose to study the effect of thermal history on the evolution of the spin-rate and of the global shape. Technically, the ultimate goal of these developments will be to fully couple these aspects through the integration of Liouville equations describing the evolution of the rotation. A first application is the study of Iapetus, third largest moon of Saturn [3]: this body exhibits a strong flattening inconsistent with the small value of its current spin rate (synchronous rotation). We propose a scenario were this shape is inherited from the thermal evolution, controlling the viscosity profile: warm deep regions provide the dissipation required for the despinning (an initially fast rotating Iapetus is assumed) while the cold surface layer inhibits the complete relaxation of the flattened shape. The successful models imply a large amounts of short radionuclides thus favoring a very short time interval (3 Myr) between the formation of CAIs and the completion of Iapetus' accretion.

Tidal dissipation - A significant progress has also been accomplished in order to include the heterogeneous heating due to the viscous dissipation of tides. While this contribution to the heat budget is still the most prominent at present for several satellites of Jupiter and Saturn (e.g. Io, Europa, Titan, Enceladus) it is also likely that tidal heating played a major role in the evolution of terrestrial planets in the Solar System (Mercury, the Earth) and is potentially a major parameter for Earth-like bodies orbiting other stars that start to be discovered. Together with the viscous convection modelled by OEDIPUS, we propose a consistent description of the viscoelastic deformation induced by tides in the same spherical shell geometry [1]. This is achieved by a method combining spectral and grid-based spatial discretization. The thermally-activated rheologies controlling both processes imply that the temperature field provides a direct coupling. The first applications demonstrate (i) the existence of a strong feedback between the two processes, (ii) that earlier approaches assuming a radially layered models can significantly underestimate tidal heating (in the cases we performed, final differences up to 25 % are observed).

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