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Dynamos in the Earth and other planets

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Numerical simulations are an important tool for understanding convection in the silicate mantles of terrestrial planets and convection and magnetic field generation in the fluid and electrically conducting cores of solid or gaseous planets. Mantle convection models have been studied for more than 40 years now, whereas successful models for the geodynamo are more recent. This presentation will highlight the progress in understanding planetary dynamos for an audience whose background is in solid Earth geodynamics. The dynamo problem is more complex than the basic model for mantle convection and some of the control parameters in dynamo simulations fall short of their Earth values by many orders of magnitude. Most importantly, the viscosity in the model is typically taken some ten orders of magnitude larger than that of liquid iron in order to suppress small-scale eddies in the flow that cannot be resolved numerically. On the other hand, in contrast to mantle convection, complex material behavior plays no major role for the geodynamo. The mantle and the core are one coupled system and the slowly changing conditions in the lower mantle exert an important influence on the dynamo.
Given the mismatch in control parameters, the success of the dynamo models in matching geomagnetic field properties seemed somewhat surprising. Many models reproduce the geomagnetic spatial power spectrum and the basic magnetic field morphology. Some models exhibit dipole reversals whose temporal behavior agrees with what is known for geomagnetic reversals from the paleomagnetic record. Systematic modeling studies that vary the essential control parameters within the numerically accessible range have improved our understanding of where in parameter space Earth-like dynamo solutions are found and have established scaling laws that quantify the dependence of magnetic field strength, flow velocity and heat transport on the input parameters. They have also increased our confidence that despite their shortcomings current models do in fact capture the essential physics of the geodynamo.

Sluggish convection in the Earth's mantle imposes effectively a heat flux condition on the upper boundary of the convecting core. The flux is spatially non-uniform and varies slowly with time. This so-called thermal core-mantle coupling has been studied in several dynamo models. It can explain persistent pattern in the geomagnetic field of the past few thousand years and possibly the secular change in the frequency of geomagnetic reversals on time scales of 100 million years.
The magnetic fields of the various planets in the solar system differ greatly in strength and morphology. A general theory of planetary dynamos is still in its infancy and perhaps a case-by-case treatment is necessary, but hampered by our very scanty knowledge of conditions in the interior of other planets. The weakness of Mercury's magnetic field, which has only 1% of Earth's field strength, is difficult to explain by a geodynamo-like model. The perfect axisymmetry, within observational uncertainty, of Saturn's magnetic field defies a fundamental theorem in dynamo theory that forbids such field geometry. The possible existence of a stably stratified and electrically conducting layer above the dynamo region might explain the particular field properties of these two planets. The cessation of the Martian dynamo around 4 billion years ago must be linked to the thermal evolution history of Mars. Magnetic field observations at different planets can therefore be used to put constraints on their internal structure and evolution.

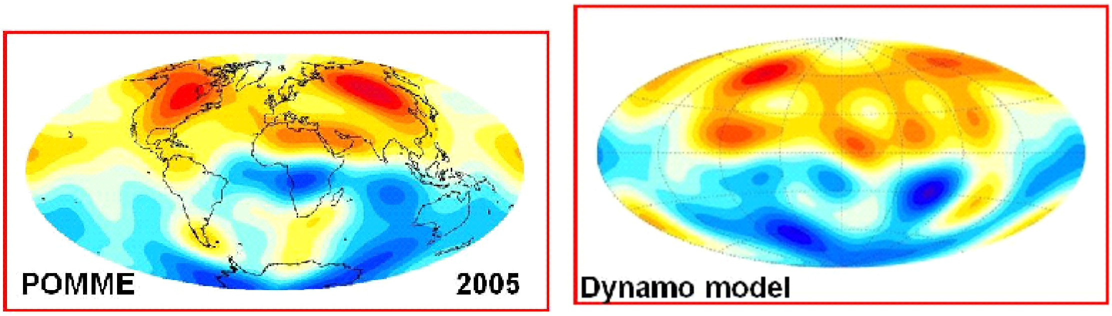

Figure 1: Radial component of the magnetic field up to spherical harmonic degree eight. Left: geomagnetic field at the core-mantle boundary. Right: field at outer boundary of a geodynamo model.