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Numerical Modelling of Planetary Dynamos

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Abstract

We review the present state of knowledge of numerical modelling of planetary dynamos. We focus on simulations that have been tailored for specific planets or have explained non-Earth-like features of various planetary magnetic fields.

1. Introduction

Magnetic field observations by spacecraft missions have provided vital information on planetary interiors and evolution. The four giant planets as well as Earth, Mercury and Ganymede have active dynamos generating magnetic fields. In contrast, Moon and Mars only have remanent crustal fields from dynamo action in their early histories. There is no unambiguous detection of dynamo-generated fields on any other solar system planetary body.

Three-dimensional, self-consistent numerical simulations of planetary dynamos have flourished over the past two decades. These simulations began with attempts to reproduce specific characteristics of the Earth's magnetic field, however, within the last decade, numerical dynamo models of other planetary bodies have increased in popularity.

Here we review numerical dynamo simulations of planetary bodies. We focus on planets other than Earth, however will appeal to Earth in a comparative sense. Although there are various studies of general dynamo characteristics involving relatively large regions of parameter space, we choose to concentrate on models that have been tailored for specific planets or have addressed non-Earth-like magnetic field characteristics.

2. Methods

All planetary dynamo simulations essentially solve the same magnetohydrodynamic (MHD) equations, although they may use different approximations, boundary conditions and numerical methods. One thing they have in common is that none can work in the appropriate parameter regime of any planetary core. Specifically, numerical resolution issues limit the Ekman number and magnetic Prandtl number to be much larger in simulations than in planets and the Rayleigh number to be much smaller in simulations than in planets. This means that making a numerical model of a particular planet does not reduce to calculating the specific non-dimensional governing parameters for that planet and running simulations with those values. Indeed, numerical models of Earth's and Jupiter's dynamos may be very similar in parameter values even though the physical planetary properties are very different.

Instead, modellers focus on first-order characteristics that they can model more accurately in order to simulate a specific planet. For example, the core geometry (i.e. fluid shell thickness), buoyancy stratification, boundary conditions and influences of the mantle or other external agents are modified from Earth-like conditions. If the resulting magnetic field morphology depends strongly on these characteristics, then its possible to determine planetary interior properties from these models.

3. Planetary Models

3.1. Mercury

Hermean dynamo models have focused on trying to explain the anomalously weak observed dipole field. Numerical models guided by observational, experimental and theoretical constraints on Mercury's interior have been able to reproduce the weak observed field by invoking a non-Earth-like fluid core shell thickness, the presence of stably-stratified layers or magnetospheric feedback mechanisms (for a review, see [1]). Indeed, the issue now is discriminating between the models. MESSENGER data may resolve the issue by providing details on the secular variation or power spectrum of the magnetic field.

3.2. Jupiter and Saturn

The magnetic fields of the gas giants are axially-dipolar dominated with expected field strength. Numerical models have investigated the effect of radially varying material properties such as density and electrical conductivity (more stratified than in the terrestrial planets) on the generated magnetic fields [2, 3] as well as being able to reproduce the banded zonal flows in the outer layers of the planets. The anomalously perfect axisymmetry of Saturn's observed field has also been studied [4, 5].

3.3. Uranus and Neptune

The ice giants are unique in that their magnetic fields are not dominated by axially-dipolar components. Appealing to the low observed heat flows from these planets [6], models with thin convecting shells surrounding stably-stratified interiors were able to produce Uranus and Neptune-like fields [7]. Models with radially varying electrical conductivity have also been generated [8].

3.4. Ganymede

Due to the sparsity of data, there are currently no anomalous features of Ganymede's magnetic field, i.e an appropriately scaled Earth-like model can explain the observations. However, it is possible that exotic buoyancy sources and alternative driving mechanisms are required for Ganymede's dynamo.

3.5. Mars and Moon

The crustal magnetic fields on Mars and Moon are most likely the result of past dynamo action. For Mars, models have shown that the anomalous spatial distribution of the crustal fields may be explained by a hemispheric dynamo resulting from the crustal dichotomy formation mechanism [9]. The death of the martian dynamo has also been explored using dynamo models with shock-heating due to a large impact [10] and sub-critical dynamo action [11].

Perhaps unfairly, the Moon's crustal field has received the least study via dynamo models. However, recently, thermal core-mantle interactions have been invoked to explain the spatial distribution of the crustal fields [12] and alternative driving mechanisms such as tidal forcing may be significant.

4. Conclusions

As dynamo models improve due to better understanding of planetary interiors and more sophisticated computational resources, planetary magnetic fields will continue to be an important resource in our study of the planets.

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