EPSC Abstracts
Vol. 10, EPSC2015-292, 2015
European Planetary Science Congress 2015

Jupiter and Saturn: Two Classes of Planetary Magnetic Field

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Abstract

Saturn has a nearly axisymmetric field, a morphology that is believed to be the result of a stably stratified layer surrounding the dynamo source region in which non-axisymmetric components of the field are attenuated [11]. Here we demonstrate an important theoretical consequence of such a layer, namely that the secular variation of the axisymmetric field must be extremely slow. Observational evidence suggests that this may be the case for Saturn, a finding which is supported by numerical dynamo simulations. Jupiter on the other hand has a field with significant non-axisymmetric structure and is thus not subject to constraints on its secular variation. We propose the two planets represent two different classes of planetary magnetic field: the first has nearly axisymmetric fields with very slow secular variation; the second has non-axisymmetric fields with more rapid secular variation.

1. Introduction

Saturn's magnetic field, as first revealed by Pioneer 11 [1] and the Voyager I and II spacecraft [7, 8] and more recently by the Cassini spacecraft [6], is considerably more axisymmetric than the magnetic fields of the other planets in the Solar System. For example, its dipole tilt is less than $1°$ [4, 5, 10] and possibly less than $0.06°$ [3]. In comparison, the dipole tilts of Earth and Jupiter are about $10°$.

2. Secular Variation

The time-dependency of a dynamo-generated magnetic field results from one of two processes: advection of magnetic field lines by motions within the electrically conducting dynamo region and diffusion of magnetic field due to the finite electrical conductivity of the dynamo region. The effects of advection and diffusion are described by the magnetic induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B} \qquad (1)$$

where $\mathbf{u}$ and $\mathbf{B}$ are the flow field and magnetic field respectively, and η is the magnetic diffusivity.

In general, for dynamo action to occur, the ratio of these two effects (the magnetic Reynolds number) must be large; however, geometrical effects may result in the effects of advection on the time-dependency of the externally observed field being small, even though the magnetic Reynolds number in the interior is large. The fact that Saturn's magnetic field is nearly axisymmetric demands that the fluid flow near the top of the dynamo region must preserve the nearly axisymmetric nature of the field. Bullard and Gellman [2] in a pioneering study of the generation of magnetic fields by dynamo action, developed a formalism for understanding this interaction of fluid flow and the magnetic field.

If we assume that the fluid flow at the top of the dynamo is purely toroidal, as required by the presence of a stably stratified layer, then using the Bullard-Gellman formalism we can show that the flows that preserve the axisymmetric nature of the field do not change the axisymmetric part of the field. In other words, the flows that preserve axisymmetry do not create secular variation. Secular variation can then only result from either much slower diffusive processes or from the advection of very weak nonaxisymmetric field components. In either case, the secular variation will be weak. We note, however, that if some secular variation of a axisymmetric field were to be observed on a timescale shorter than the diffusive timescale then an estimate could be made of the nonaxisymmetric field.

3 Remarks

Based on this analysis we propose that there are two classes of planetary magnetic fields, axisymmetric fields with weak secular variation and nonaxisymmetric fields with strong secular variation. Saturn belongs to the first class (possibly alongside Mercury [9]) while Jupiter and Earth belong to the second class.

The Juno observations of Jupiter and the proximal Cassini observations of Saturn will provide an opportunity to test this theory.

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