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Connecting Jupiter’s atmosphere and magnetic field: Wind-driven advection of the Great Blue Spot

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Abstract

Jupiter’s magnetic field is the strongest planetary dynamo in the Solar System, and so studying this field is essential to understanding the fluid interiors of Giant Planets and magnetic fields more broadly. Recently, it has been shown that Jupiter’s atmospheric zonal winds may extend ~3000km deep into the planet [1-2], to regions where the planet’s atmosphere retains significant conductivity [3]. Thus zonal wind motion at this depth may affect Jupiter’s magnetic field [4]. Here we discuss these connections between the atmosphere and magnetic field, specifically focusing on atmospheric interactions with Jupiter’s Great Blue Spot, with implications for the dynamics of Jupiter’s atmosphere and generation of the dynamo field.

1. Introduction

Jupiter’s interior is primarily composed of hydrogen and helium. At high pressures and temperatures (~0.85-0.9 Jupiter Radii (RJ)), hydrogen undergoes a phase transition to an electrically conductive liquid metal. The convection of this metal is responsible for generating Jupiter’s magnetic field (dynamo). However, as this phase transition is believed to be smooth, significant portions of Jupiter’s atmosphere are likely to be semi-conducting. Thus, wind motion in this semi-conducting region should advect Jupiter’s magnetic field, generating a time-dependent signal potentially observable by a spacecraft.

1.1 Simple model of zonal wind advection

We produce a simple forward model of the expected time-variation (secular variation) due to zonal wind advection of the magnetic field (hereafter called the ZWA model). To do this, we project Jupiter’s observed surface winds downwards parallel to the rotation axis onto a surface at 0.95 RJ. Mathematically, the effects of zonal wind advection will be the strongest where the fastest winds are acting on the highest-magnitude regions of (non-axisymmetric) radial magnetic flux. For Jupiter, this should occur near the Great Blue Spot, a region of equatorial, intensely concentrated negative flux (see the large blue spot in Figure 1b-d). Currently this spot is being sheared by the alternating zonal winds, and may be ripped apart entirely within the next few decades (Figure 1). Understanding the dynamics of the Great Blue Spot is thus key to understanding Jupiter’s time-varying magnetic field.

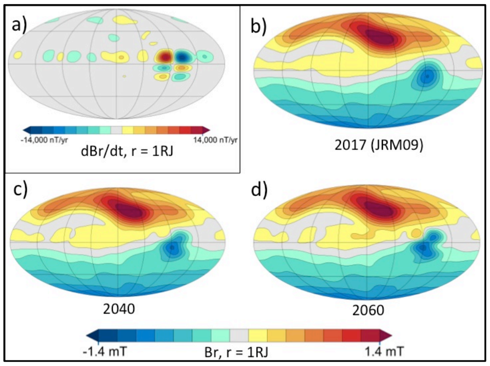

Figure 1: a) Time-variation of Jupiter’s radial magnetic field from our zonal wind advection model (ZWA [4]), at 1 RJ. b-d) Predicted changes in Jupiter’s radial magnetic field from 2017-2060.

1.2 Detection of atmosphere-magnetic field interactions

We also report a definitive, data-based detection of time-variation (secular variation) in Jupiter’s magnetic field [4], found by comparing past spacecraft observations to a recent magnetic field model from Juno (JRM09) [5]. Interestingly, we find that Jupiter's secular variation over the past 40 years can be almost entirely explained by the zonal wind advection of the magnetic field. That is, Jupiter's secular variation can be explained wholly by an independent model of atmosphere-magnetic field interactions, with no need to invoke time-variation in Jupiter's main dynamo field. This implies one of three processes are at play; either:

1) Unlike Earth, Jupiter's main dynamo field has not changed significantly on a decadal scale

2) The changes in the dynamo field are at extremely small length-scales, and not observable at altitude

3) The patterns of flow inside the dynamo region are similar to the deep wind geometry used in our model of zonal wind advection.

To better understand the dynamics of Jupiter's dynamo, we extend the results of our simple ZWA model [4] here, and perform more complex modeling of magnetic field-zonal wind interactions in the vicinity of the Great Blue Spot.

2. Numerical modelling

The time-variation of a magnetic field ($\vec{B}$) can be described by the magnetic diffusion equation, which is derived by combining Maxwell's Equations and Ohm's Law.

$$\frac{\partial \vec{B}}{\partial t} = \nabla\times\left(\vec{u}\times\vec{B}\right) - \frac{1}{\mu_0}\nabla\times\left(\frac{1}{\sigma}\nabla\times\vec{B}\right) \quad (1)$$

where $\vec{u}$ is the wind velocity, μ_0 is the magnetic permeability of free space, and σ is the electrical conductivity. Equation (1) can also be written in terms of a magnetic vector potential, $\vec{A}$ (where $\vec{B} = \nabla\times\vec{A}$):

$$\frac{\partial \vec{A}}{\partial t} = \vec{u}\times\left(\nabla\times\vec{A}\right) + \frac{1}{\sigma\mu_0}\nabla^2\vec{A} \quad (2)$$

In this study, we solve Equation (2) using a 3-D box geometry, for conditions relevant to Jupiter's deep winds acting on the Great Blue Spot. We use a pseudo-spectral Crank-Nicolson method.

3. Summary and Conclusions

Here we study the complex interactions of Jupiter's atmosphere and magnetic field. We predict these interactions are dominated by Jupiter's zonal winds shearing apart the Great Blue Spot. By performing a detailed, local model of the advection and diffusion of the Great Blue Spot, we can better understand the processes involved in generating Jupiter's magnetic field and sustaining the Great Blue Spot. These models can be compared with future Juno magnetometer observations, to compare sources of secular variation due to zonal wind advection with that from Jupiter's main dynamo. Ultimately, this will improve our understanding of the dynamics of Jupiter's fluid interior.

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