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Zonal flow magnetic field interaction in the semi-conducting region of giant planets

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ABSTRACT

All four giant planets in the Solar System feature zonal flows on the order of 100 m/s in the cloud deck, and large-scale intrinsic magnetic fields on the order of 1 *Gauss* near the surface. The vertical structure of the zonal flows remains obscure. The end-member scenarios are shallow flows confined in the radiative atmosphere and deep flows throughout the entire planet. The electrical conductivity increases rapidly yet smoothly as a function of depth inside Jupiter and Saturn. Deep zonal flows will inevitably interact with the magnetic field, at depth with even modest electrical conductivity. Here we investigate the interaction between zonal flows and magnetic fields in the semi-conducting region of giant planets. Employing mean-field electrodynamics, we show that the interaction will generate detectable poloidal magnetic field perturbations spatially correlated with the deep zonal flows. Assuming the peak amplitude of the dynamo α-effect to be 0.1 mm/s, deep zonal flows on the order of 0.1–1 m/s in the semi-conducting region of Jupiter and Saturn would generate poloidal magnetic perturbations on the order of 0.01%–1% of the background dipole field. These poloidal perturbations should be detectable with the in-situ magnetic field measurements from the Juno mission and the Cassini Grand Finale. This implies that magnetic field measurements can be employed to constrain the properties of deep zonal flows in the semi-conducting region of giant planets.

1. Introduction

The giant planets in the solar system are natural laboratories for rotating convection and magnetohydrodynamics. The existence of deep convection inside all four giant planets are guaranteed by the measured large intrinsic heat flux (“large” here means larger than the heat flux that can be conducted along the adiabats) and the large-scale intrinsic magnetic fields. The dynamical details of the deep convection (e.g. amplitude, structure, and energy partitioning) and the coupling to the shallow atmospheric dynamics, however, remain largely unknown. In terms of observations, the gravity and magnetic field measurements from the Juno mission (Bolton, 2010) and the Cassini Grand Finale (Spilker et al., 2014) will provide an unprecedented opportunity to constrain the interior dynamics of Jupiter and Saturn.

Dynamics in the atmospheres of the solar system giant planets have been inferred from cloud tracking (Porco et al., 2003; Sanchez-Lavega et al., 2000; Vasavada et al., 2006; Baines et al., 2009; Sromovsky et al., 1993; 2001; Sromovsky and Fry, 2005; Hammel et al., 2005). The dominant features of the atmospheric dynamics of all four giant planets are the east-west zonal winds on the order of 100 m/s (Fig. 1). In the equatorial region, Jupiter and Saturn feature super-rotation, while Uranus and Neptune feature sub-rotation. Jupiter’s off-equatorial region features zonal winds with alternating directions, with the eastward flows being stronger than the westward flows when viewed in the System III corotation frame. Saturn’s off-equatorial region features zonal flows with varying speeds. The few minutes uncertainties in our understanding of Saturn’s deep interior rotation rate translate into uncertainties in the direction of the off-equatorial winds as well as the width of the equatorial super-rotation (Fig. 1). The off-equatorial region of Uranus and Neptune feature one broad super-rotation in each hemisphere. The latitude of transition from sub-rotation to super-rotation on the surfaces of Uranus and Neptune are affected by the uncertainties in our understanding of the deep interior rotation rates (Fig. 1).

Intrinsic magnetic fields have been detected for all four giant planets (Connerney, 1993; 2007; Cao et al., 2011; 2012). In terms of amplitude, the surface magnetic fields of Saturn, Uranus and Neptune are about 0.3 Gauss (30,000 nT), while the surface magnetic field of Jupiter is about 6 Gauss (600,000 nT). In terms of morphology, the magnetic fields of Jupiter and Saturn are axial dipole dominant, while the magnetic fields of Uranus and Neptune are

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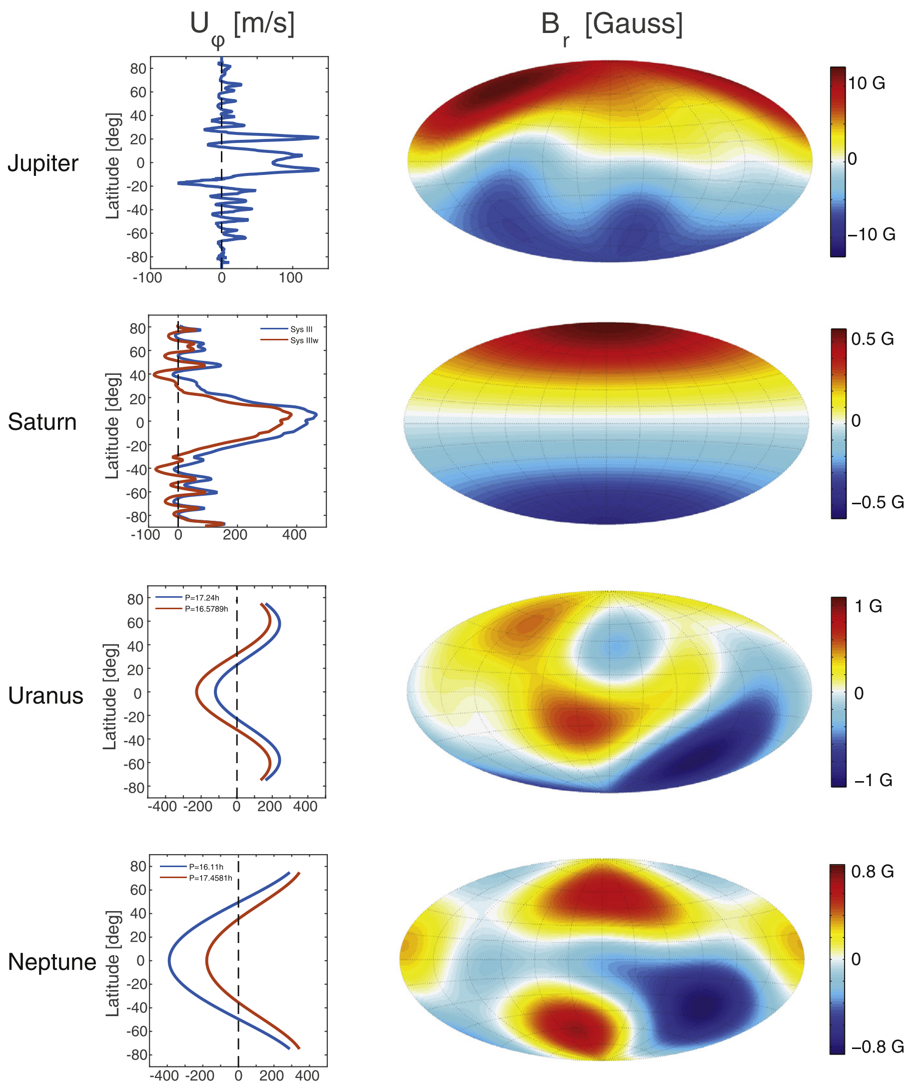

Fig. 1. Observed surface zonal wind and magnetic field profile for solar system giant planets. The zonal wind profile for Jupiter and Saturn shown here are from Cassini and Voyager observaions (Porco et al., 2003; Sanchez-Lavega et al., 2000; Vasavada et al., 2006; Baines et al., 2009), while the zonal wind profile for Uranus and Neptune shown here are the empirical fits to Hubble Space Telescope (HST) and Voyager 2 observations (Sromovsky et al., 1993; 2001; Sromovsky and Fry, 2005; Hammel et al., 2005). Not many observational constraints exist for zonal winds on Uranus and Neptune at latitude beyond 75° north and south, but the winds likely decrease to zero smoothly towards the poles. The uncertainties in our understanding of the deep interior rotation rates of Saturn, Uranus and Neptune affect the details of the surface zonal wind profiles. The surface magnetic field profiles are based on the Galileo 13 model for Jupiter (Yu et al., 2010), Cassini 5 model for Saturn (Cao et al., 2012), Umoh model and Nmoh model truncated at degree and order 3 for Uranus and Neptune (Holme and Bloxham, 1996).

non-axial and multipolar. Jupiter's magnetic dipole axis is tilted about 10° from the spin axis, while Saturn's magnetic dipole axis is aligned with the spin-axis to within 0.06° according to the latest Cassini measurements (Cao et al., 2011).

Electrical conductivity inside Jupiter and Saturn increases rapidly yet smoothly from $< 10^{-7}$ S/m near the 1 bar level to $10^5 - 10^6$ S/m near the $1 - 3$ Mbar level (Weir et al., 1996; Nellis et al., 1996; Liu et al., 2008; French et al., 2012). The high electrical conductivity in the deep interior is likely due to pressure ionization of hydrogen. The alkali metals with solar composition would be the main contributor to the electrical conductivity in the low pressure region. Electrical conductivity inside Uranus and Neptune is uncertain due to two unknowns: the abundance of ice (water, methane, ammonia) in the hydrogen-helium envelope and the abundance of hydrogen in the ice layer. The electrical conductivity inside an ice giant planet would only reach 10^3 S/m in the ice layer without significant mixing of hydrogen (Nellis et al., 1997), and would remain below 1 S/m in the hydrogen-helium envelope if the ice mixing ratio in the envelope is below 10% (Liu, 2006).

The highly conducting region of giant planets with electrical conductivity greater than 1000 S/m likely feature zonal flows on the order of 1 cm/s or less, based on Jovian magnetic secular variation measurements (Yu et al., 2010; Ridley and Holme, 2016). The magnetic secular variation measurements are not straightforward to interpret for giant planets for two reasons. First, the rotation rate of the deep interior of giant planets is defined by the observed rotation rate of non-axisymmetric magnetic fields. Thus only the spatial variation of the drifts in the non-axisymmetric magnetic fields (e.g., caused by spatial variation of steady deep zonal flow) and the time variations of the drifts (e.g., caused by the time variations of deep zonal flow) can be straightforwardly detected. Second, the forward problem of observable magnetic secular variations for a given deep flow structure has not been solved for a planet with radially varying electrical conductivity. We will address the second problem in detail in a separate paper. For now, we interpret the inferred Jovian magnetic secular variation loosely as representing flows in regions with magnetic Reynolds number (Rm) greater than 10. We choose $Rm = 10$ as the threshold to en-