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Interaction of Saturn's dual rotation periods

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ABSTRACT

We develop models of the interaction of Rossby wave disturbances in the northern and southern ionospheres of Saturn. We show that interhemispheric field-aligned currents allow the exchange of vorticity, modifying the background Rossby wave propagation speed. This leads to interaction of the northern and southern Rossby wave periods. In a very simple symmetric model without a plasma disk the periods merge when the overall conductivity is sufficiently high. A more complex model taking account of the inertia of the plasma disk and the asymmetry of the two hemispheres predicts a rich variety of possible wave modes. We find that merging of the northern and southern periods can only occur when (i) the conductivities of both hemispheres are sufficiently low (a criterion that is fulfilled for realistic parameters) and (ii) the background Rossby wave periods in the two hemispheres are identical. We reconcile the second criterion with the observations of a merged period that also drifts by noting that ranges of Rossby wave propagation speeds are possible in each hemisphere. We suggest that a merged disturbance in the plasma disk may act as an 'anchor' and drive Rossby waves in each hemisphere within the range of possible propagation speeds. This suggestion predicts behaviour that qualitatively matches the observed merging and splitting of the northern and southern rotation periods that occurred in 2013 and 2014. Low conductivity modes also show long damping timescales that are consistent with the persistence of the periodic signals.

1. Introduction

Various phenomena in Saturn's magnetosphere exhibit ∼10.7-h oscillations that are related to the rotation of the planet, a situation summarised by Carbary and Mitchell (2013). One of the most puzzling aspects of the observations is the presence of two separate periodicities in the northern and southern hemispheres. The dual periodicity was first detected in Saturn kilometric radiation (SKR) emissions (Gurnett et al., 2009), and has subsequently been observed in magnetic field perturbations (Andrews et al., 2010) and in both ultraviolet and infrared auroral emissions (Nichols et al., 2010; Badman et al., 2012).

Recent analysis of the periodicities observed in SKR emissions and magnetic field perturbations (Fischer et al., 2015; Ye et al., 2016; Provan et al., 2016; Carbary, 2017) does not produce complete agreement between the two datasets. However, what seems to be clear is that there are indeed two independent current systems with different rotation periods, one concentrated in the northern hemisphere and one in the southern hemisphere. Within each system, currents flow through the ionosphere and then out along field lines, gradually closing via cross-field line currents throughout the magnetosphere (Hunt et al., 2015). The rotation periods of these current systems vary slowly with time. Provan et al. (2016) showed that in 2013, after a long timeframe during which the northern hemisphere had shown a slightly shorter rotation period, the periods merged and became 'locked' together for about ∼1 year. They then separated in mid-2014, so that the northern hemisphere now shows a slightly longer rotation period.

The idea that the magnetospheric periodicities may be driven by a vortex-like structure in the neutral atmosphere was first proposed by Smith (2006). Smith (2011) investigated this further and showed that asymmetric heating in the thermosphere could drive appropriate field-aligned currents. Smith and Achilleos (2012) extended this model, proposing that a feedback effect in the auroral ionosphere could permanently break the symmetry of the thermosphere, driving a persistent asymmetry. However, both these studies concluded that the energy required to sustain magnetic perturbations of the observed magnitude was improbably large. Smith (2014) partially solved this problem by proposing that the northern and southern twin vortices driving the field-aligned currents (Southwood and Cowley, 2014) were located not in the ther-

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mosphere but in the upper stratosphere, around an altitude of ~750 km above the 1-bar level. Smith et al. (2016) developed this proposal further, describing a detailed model of Rossby waves in the upper stratosphere. This model predicted waves drifting westwards at ~0.3% of the background angular velocity, the same order of magnitude as the variation in the observed periodicities.

A complementary approach to the same conceptual model (Jia et al., 2012; Jia and Kivelson, 2012; Kivelson and Jia, 2014; Ramer et al., 2017) imposes twin-vortex flows directly on the ionospheric plasma and calculates the detailed implications for the magnetosphere, using a magnetohydrodynamic model of this region. This approach has been shown to reproduce many of the observed phenomena, but the flow speeds prescribed by the model are as large as 3000 m s^{-1}. These are implausibly large for two reasons: first, they are ~100 times greater than the typical non-axisymmetric flow speeds predicted by thermosphere models (Smith, 2011); second, they would have easily been detected in Doppler observations of the ion flow speed (e.g. Stallard et al., 2008), which instead show consistent subrotational flows.

An important alternative model of the periodicities is the idea of a persistent two-cell convection pattern or 'plasma cam' in the middle magnetosphere (Gurnett et al., 2007; Goldreich and Farmer, 2007). A key virtue of this model is that the asymmetric distribution of plasma required has been observed (Burch et al., 2009). Its key difficulty is that it offers no simple explanation for the different periods in the northern and southern hemispheres.

The purpose of this paper is to attempt to understand the merging and splitting observed by Provan et al. (2016) in terms of an atmospheric driver for the periodicities. We will abandon detailed consideration of the exact altitude and magnitude of the atmospheric wave structures, and instead examine the consequences of coupling the wave structures in opposite hemispheres to each other, and to the plasma disk. In Section 2 we describe a minimal wave model in one hemisphere. In Section 3 we couple two such models together via interhemispheric currents, including limited hemispheric asymmetries, and in Section 4 we add further hemispheric asymmetry and coupling to the equatorial plasma disk. In Section 5 we compare our calculations to estimates of realistic parameters at Saturn, and in Sections 6 and 7 we discuss the implications of the study and summarise our conclusions. Symbols used in this paper are listed in Table 1.

2. Minimal Rossby wave model

Smith et al. (2016) described a complex model of Rossby waves across the whole of the polar regions, using a simplified circular geometry. For the arguments employed here we use a further simplified two-dimensional Rossby wave model on a beta-plane (e.g. Houghton, 1986), with the effects of ionospheric currents also included. This model assumes a constant density atmosphere with no vertical motion, and so the density ρ is height-integrated, i.e. it represents mass per unit area. Considering the northern hemisphere, we take x to be north and y to be west. We choose these coordinates because the zonal flows at high latitudes are frequently westwards, and the phase velocities of Rossby waves are always westwards. In the southern hemisphere we obtain identical equations by taking x to be south and y to be west, so that our coordinate system maps along the magnetic field lines.

The basic momentum equation is:

$$\frac{D\boldsymbol{u}}{Dt} + \frac{1}{\rho}\nabla P - \boldsymbol{u} \times \boldsymbol{f} - \frac{1}{\rho}\boldsymbol{J} \times \boldsymbol{B} = 0 \quad (1)$$

where $\boldsymbol{u}$ is the horizontal wind, P is the height-integrated pressure, $\boldsymbol{f} = f\boldsymbol{k}$ is the Coriolis parameter expressed as a vertical vector, $\boldsymbol{J}$ is the height-integrated horizontal current and $\boldsymbol{B} = B\boldsymbol{k}$ is the magnetic flux density, assumed to be vertical. We use a standard beta-plane approximation, in which we approximate as linear the variation of the Coriolis parameter with latitude:

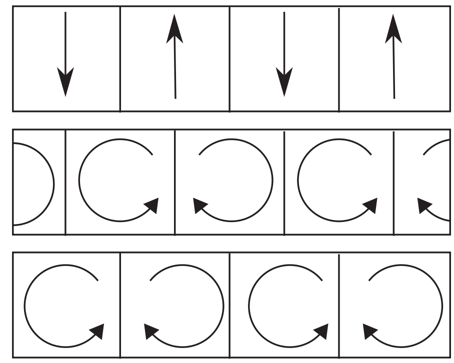

Fig. 1. Sketch of mechanism to produce westwards drift.

$$f = f_0 + \beta x \quad (2)$$

This approximation is typically used for mid-latitude studies. It becomes less accurate with increasing latitude. However, we are principally interested in understanding the basic physics of the situation, rather than in constructing a precise physical model: the beta-plane approximation is more than adequate for this purpose.

Eq. (1) can be simplified by insisting on continuity ($\nabla \cdot \boldsymbol{u} = 0$) and splitting the horizontal wind into a uniform zonal flow $\bar{\boldsymbol{u}} = \bar{v}\boldsymbol{j}$ and a perturbation $\boldsymbol{u}'$. We represent this perturbation using a stream function $\boldsymbol{\psi} = \psi\boldsymbol{k}$ such that $\boldsymbol{u}' = -\nabla \times \boldsymbol{\psi}$. Taking the curl of Eq. (1) and expanding the first term, it reduces with a little manipulation to:

$$\left(\frac{\partial}{\partial t} + \bar{v}\frac{\partial}{\partial y}\right)\nabla^2\psi - \beta\frac{\partial \psi}{\partial y} + \frac{B}{\rho}\nabla \cdot \boldsymbol{J} = 0 \quad (3)$$

This equation represents conservation of absolute vorticity. Absolute vorticity is the sum of vorticity due to motion of the gas and vorticity due to the planetary rotation. In the beta-plane approximation the latter is encoded in the term that involves β. We can therefore interpret the terms as follows: the first term is advection of vorticity by the zonal winds; the second term is a torque acting on the meridional winds due to the variation of the Coriolis parameter with latitude; and the final term is the torque due to horizontal currents.

In a situation where one hemisphere is completely isolated, current must be conserved locally, and so $\nabla \cdot \boldsymbol{J} = 0$. Solutions of the resulting equation exist for $\psi \propto \exp i(lx + ky - \omega_R t)$ with phase speed c westwards relative to the frame of the planet:

$$c = \frac{\omega_R}{k} = \bar{v} + \frac{\beta}{k^2 + l^2} \quad (4)$$

Thus the Rossby waves move westwards with a component due to the background westwards wind and a second component related to the wave properties.

A physical interpretation of the westwards drift of Rossby waves is that the β term represents a torque that is out of phase with the existing vorticity. This out of phase torque causes the pattern of vorticity to shift westwards while conserving the total absolute vorticity. This is sketched in Fig. 1 for a wave in the northern hemisphere. The top panel shows a wave with $l = 0$, showing alternating regions of northward and southward flow. The pattern of vorticity, shown in the middle panel, shows maxima that are a quarter cycle out of phase with the maxima in the patterns of the winds. However, the torque due to the β term, shown in the bottom panel, is in phase with the winds. This arises because the Coriolis force in the northern hemisphere acts to deflect winds to