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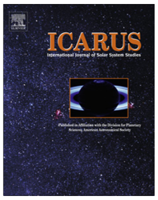

A planetary wave model for Saturn’s 10.7-h periodicities

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ABSTRACT

A proposed resolution of the unexplained 10.7-h periodicities in Saturn’s magnetosphere is a system of atmospheric vortices in the polar regions of the planet. We investigate a description of such vortices in terms of planetary-scale waves. Approximating the polar regions as flat, we use theory developed originally by Haurwitz (Haurwitz, B. [1975]. Geophys. Bioklimatol. 24, 1–18) to find circumpolar Rossby wave solutions for Saturn’s upper stratosphere and lower thermosphere. We find vertically propagating twin vortex solutions that drift slowly westwards at <1% of the deep planetary angular velocity and are thus ideal candidates for explaining the observed periodicities. To produce integrated field-aligned currents of the order of 1 MA we require wind velocities of $\sim 70\ \mathrm{ms}^{-1}$. A particular class of vertically propagating solutions are potentially consistent with wave energy being ‘trapped’ between the deep atmosphere and lower thermosphere, at altitudes suited to the production of the necessary field-aligned current systems.

1. Introduction

The ∼10.7-h modulation of various phenomena in Saturn’s magnetosphere (see review by Carbary and Mitchell, 2013) has yet to be fully explained. The idea of a vortex-like structure in the neutral atmosphere driving magnetospheric periodicities was first proposed by Smith (2006) and investigated further by Smith (2011) and Smith and Achilleos (2012). The conclusion of these studies was that a thermospheric vortex could drive approximately the observed magnetic perturbations in the magnetosphere, but that the energy required to sustain magnetic perturbations of the observed magnitude was improbably large.

A complementary approach to the same conceptual model (Jia et al., 2012; Jia and Kivelson, 2012) imposed twin-vortex flows directly on the ionospheric plasma and calculated the detailed implications for the magnetosphere, using a magnetohydrodynamic model of this region. This approach reproduced many of the observed phenomena, but the thermospheric flow speeds prescribed by the model as a boundary condition were implausibly large. More recently, Southwood and Cowley (2014) presented a qualitative model of twin vortices in both northern and southern polar ionospheres, able to explain the ‘mixed’ northern and southern signals observed on closed field lines and the ‘pure’ northern and southern signals observed on open field lines.

Most recently, Smith (2014) synthesised the Southwood and Cowley (2014) model with lessons learnt from thermosphere modelling (Smith et al., 2005; Müller-Wodarg et al., 2006; Smith and Aylward, 2008; Smith, 2011; Smith and Achilleos, 2012), proposing that the vortices are located not in the thermosphere but in the upper stratosphere, around an altitude of ∼750 km above the 1-bar level. Two reasons were given for this suggestion. First, the polar thermosphere substantially subcorotates and so cannot sustain a vortex system with a steady ∼10.7-h rotation period. Second, a thermospheric vortex system of the required magnitude would entail an unrealistically large thermal energy input, the heating effect of which would produce thermospheric temperatures far greater than those that are observed.

A vortex system located in the upper stratosphere would interact with the ionisation produced at these altitudes by the particle precipitation associated with the main auroral oval, thus generating horizontally divergent currents that flow into and drive the magnetosphere. This scenario is sketched in Fig. 1. Panel (a) shows a simple twin-cell vortex system. Panels (b) and (c) then indicate the currents driven by the interaction between these vortices and a region of enhanced conductance (indicated by the shaded regions). Panel (b) shows Pedersen currents and panel (c) Hall currents.

A number of studies have also examined empirical evidence for a neutral atmosphere source. Cowley and Provan (2013) examined

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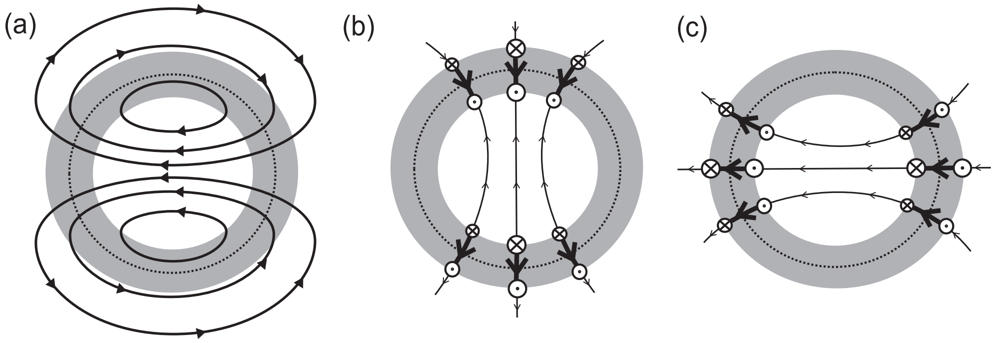

Fig. 1. Sketches of the proposed vortex system. In each sketch the dotted line indicates the central line of the main auroral oval, and the shaded region the zone of enhanced ionisation associated with auroral electron precipitation. (a) Sketch of twin vortex flows. (b) Sketch of Pedersen currents. (c) Sketch of Hall currents.

the rotation periods of a number of neutral atmospheric features and searched for correlations with the observed periodicities in the magnetosphere. They found no convincing correlation that might indicate a direct causal link. Fischer et al. (2014) investigated a possible correlation between the presence of the Great White Spot in the northern hemisphere and a pronounced shift in the period of the 10.7-h signal, but were unable to find a physical link between the two phenomena. Whilst both of these studies were inconclusive, they dealt with tropospheric and lower stratospheric phenomena. They thus in no way rule out a source in the upper stratosphere or thermosphere. A different type of evidence was presented by Hunt et al. (2014) who analysed observed field-aligned currents in the southern auroral region, concluding that they provide evidence for energy flow outwards from the planet. This indicates an atmospheric location for the original source of energy. All of this evidence taken together – no evidence for a lower atmosphere source but positive evidence for an atmospheric source – points towards an upper atmosphere source as proposed by the recent theoretical studies referenced above (Jia et al., 2012; Southwood and Cowley, 2014; Smith, 2014).

Despite this evidence, as yet there has been no detailed model of how a twin vortex system could be generated or sustained in the upper atmosphere. A possible description of such a global vortex system is in terms of planetary-scale waves. The purpose of this paper is to explore such a description of the required vortices in terms of circumpolar Rossby waves. In Section 2 we will outline how the properties of Rossby waves make them suitable candidates. In Section 3 we will then develop a theoretical description of circumpolar Rossby waves using the work of Haurwitz (1975). In Section 4 we will then analyse explicit solutions of our equations, including predictions of the magnitude of magnetospheric current systems produced. Finally, in Section 5 we will summarise and conclude.

2. Outline of model

In a rigidly rotating atmosphere, the restoring force mechanism for Rossby waves arises from the variation of the Coriolis parameter with latitude. In these circumstances they propagate westwards in the corotating frame at a small fraction of the planetary rotation velocity (e.g. Houghton, 1986). Rossby waves are thus good candidates for explaining the ~10.7-h periodicities because, provided the background atmosphere on which they propagate is almost in rigid corotation with the deep atmosphere, they will also almost corotate with the deep atmosphere.

Furthermore, there is evidence that the ~10.7-h periodicities correspond to angular velocities slightly slower than the deep rotation velocity of the planet (Gurnett et al., 2010), consistent with a small westwards propagation velocity. The westwards motion of Rossby waves in these circumstances also suggests that Rossby waves in the already strongly subcorotating thermosphere region are unlikely to be responsible for the periodicities: a westwards-propagating Rossby wave superimposed on the already westwards-flowing gas at these altitudes would not have a ~10.7-h period.

If the atmosphere is not rigidly rotating – i.e. if the zonal winds vary rapidly with latitude – then these attractive properties of Rossby waves break down. For example, within a strongly curved eastward jet Rossby waves may propagate with an eastwards phase velocity. We require a structure that slowly moves westwards, and therefore suitable ~10.7-h Rossby waves must be located in regions where there are no strong jet curvatures and where the atmosphere is close to rigid rotation.

The troposphere and lower stratosphere are most certainly not suitable locations, with strongly curved jet structures observed at pressures higher than 100 Pa (e.g. Read et al., 2009b). However, the altitudes of interest here, in the upper stratosphere and lower thermosphere, are at pressures around 0.01 Pa or less, or ~10 pressure scale heights higher than the observed jets. We would not expect these jet structures to penetrate to such high altitudes. For example, Conrath et al. (1990) calculated mean flows in the stratosphere using a simple model that was forced by tropospheric jets as a lower boundary condition. The magnitude of the jets decayed with altitude – roughly in proportion to the pressure – indicating that their magnitude will be negligible in the upper stratosphere.

Instead, we would expect the dominant process forming zonal winds in the polar regions of the lower thermosphere and upper stratosphere to be the steady westwards drag of the magnetosphere on the thermosphere. This causes a continuous input of westwards momentum that must be transferred downwards to the deep atmosphere. This implies a vertically sheared structure to the zonal flow, with the shear weakening with depth.

As a first approximation, we will assume that this shear is consistent with rigid rotation at each altitude. This means that at each altitude we treat the atmosphere as a rigidly rotating shell, with the westwards angular velocity of this shell decreasing with decreasing altitude. There are no direct measurements of neutral winds to support this model, however Doppler observations of the ion flows (e.g. Stallard et al., 2004) indicate approximately linear variation of the zonal ion flows as a function of latitude, consistent with rigid rotation. These rigidly rotating zonal ion flows then directly drive the zonal neutral winds, and so it is likely that they will also be close to rigid rotation.

There is expected to be some localised curvature of the zonal flows close to the main auroral oval (Cowley et al., 2008) that will certainly violate the assumption of rigid rotation in the