SM23C-1624 Magnetodisc Structure: Saturn versus Jupiter

N. Achilleos, C. S. Arridge and P. Guio

Atmospheric Physics Laboratory and Mullard Space Science Laboratory, Centre for Planetary Sciences, University College London, United Kingdom

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Email contacts: nick@apl.ucl.ac.uk, p.guio@ucl.ac.uk, csa@mssl.ucl.ac.uk

Abstract

We present some recent results of modeling studies undertaken with a dimensionless form of the Jovian magnetodisc model by Caudal (JGR,1986). We have calculated magnetospheric profiles of normalised current density, magnetic field and plasma pressure for reasonable representations of the conditions at Saturn and Jupiter, based on Cassini / Voyager observations. We present and discuss the following two important features which arise in the models: (i) The normalised equatorial current density at Saturn, over distances 5-16 planetary radii, actually exceeds that at Jupiter by factors $<\sim 5$. The kronian plasmadisc is thus expected to produce a stronger relative perturbation to the background dipole field of the parent planet. (ii) The Jovian outer plasmadisc is clearly a hot pressure-dominated structure, in terms of both force balance and current generation. However, the observed strong variability in hot plasma pressure at Saturn produces a characteristic region in its magnetosphere where the hot pressure gradient may become comparable to or exceed centrifugal force. The size of this region changes significantly according to the assumed mean global value of hot plasma beta.

Introduction: Model Elements and Scales

A recent study by Achilleos et al. (2009) adapted the original magnetic field and plasma model for Jupiter's magnetodisc by Caudal (1986), for use in analysing the plasmadisc of Saturn. Briefly, these models are based on the derivation of a magnetic field for which the plasma disc would obey the force balance condition:

$$\mathbf{J} \times \mathbf{B} = \nabla \mathrm{P} - n_i m_i \omega^2 \mathbf{e}_\rho \tag{1}$$

where $\mathbf{J}$ is current density, $\mathbf{B}$ is magnetic field and ρ is cylindrical radial distance from the dipole / rotation axis ($\mathbf{e}_\rho$ being the corresponding unit vector). Plasma properties are P (pressure, assumed isotropic), n_i (ion number density), m_i (ion mass) and ω (angular velocity). In an appropriate reference frame, this equation represents balance between magnetic body force, plasma pressure gradient and centrifugal force. The poloidal field components are expressed as the spatial gradients of an Euler potential α:

$$B_r = (1/r^2 \sin\theta)(\partial\alpha/\partial\theta)$$
$$B_\theta = (-1/r \sin\theta)(\partial\alpha/\partial r) \tag{2}$$

with θ denoting colatitude with respect to the planetary rotation axis, and r denoting radial distance from planet centre (in units of planetary radii). The unit of α in this 'normalized' system is $B_o a$, the product of the equatorial magnetic field at the planet surface and the planet radius a. The scales adopted by Achilleos et al. (2009) for relevant physical quantities are shown in Table 1 for Jupiter and Saturn.

Planet	Radius (Distance)	Magnetic Field B_o	Magnetic Flux Unit $B_o a^2$	Pressure Unit B_o^2/μ_o	Angular Velocity ω_o
Saturn	60280 km	21160 nT	77 GWb	0.00036 Pa	$2\pi/10.78$ h
Jupiter	71492 km	428000 nT	2187 GWb	0.146 Pa	$2\pi/9.925$ h

Table 1. Physical units used in the 'normalized' (dimensionless) system for both planets.

Disc Structure and Force Balance

Achilleos et al. (2009) used equatorial plasma observations by *Cassini* and *Voyager*, following the formalism of Caudal (1986), to calculate *global* magnetodisc models for Saturn and Jupiter **(observational plasma inputs were taken from Bagenal & Sullivan (1981); Kane et al. (2008); Krimigis et al. (1981); Sergis et al. (2007, 2009); Wilson et al. (2008))**. By investigating an axisymmetric 'toy model' of a rigidly rotating plasmadisc, characterised by constant plasma β for both hot and cold particle populations, these authors were able to derive the following **transition distance** ρ_T for the magnetosphere. This is the distance where the plasma pressure gradient and centrifugal force produce equal contributions to the azimuthal current density $\mathbf{J}$:

Transition Distance:

$$\rho_T = (2\chi\,\ell^2 \beta_h/\beta_c)^{1/2} = \mathrm{R_{MP}}(\chi\,\beta_h/\beta_{\mathrm{ROT,MP}})^{1/2}. \tag{3}$$

where χ is an index describing the variation of equatorial field strength with cylindrical radial distance ($B_{eq} \propto \rho^{-\chi}$, $\chi = 3$ for pure dipole); ℓ is a length scale associated with the centrifugal confinement of the cold disc plasma towards the equator; β_h and β_c are the plasma 'beta' parameters for the hot and cold components; $\mathrm{R_{MP}}$ is the magnetopause radius; and $\beta_{\mathrm{ROT,MP}}$ is a plasma 'beta' defined by the energy density of bulk rotation just inside the magnetopause. It follows that

$\rho \ll \rho_T$ is the region where plasma pressure determines disc structure, and
$\rho \gg \rho_T$ is the region where centrifugal force determines disc structure.

Magnetodisc Models: Force Balance & Azimuthal Currents

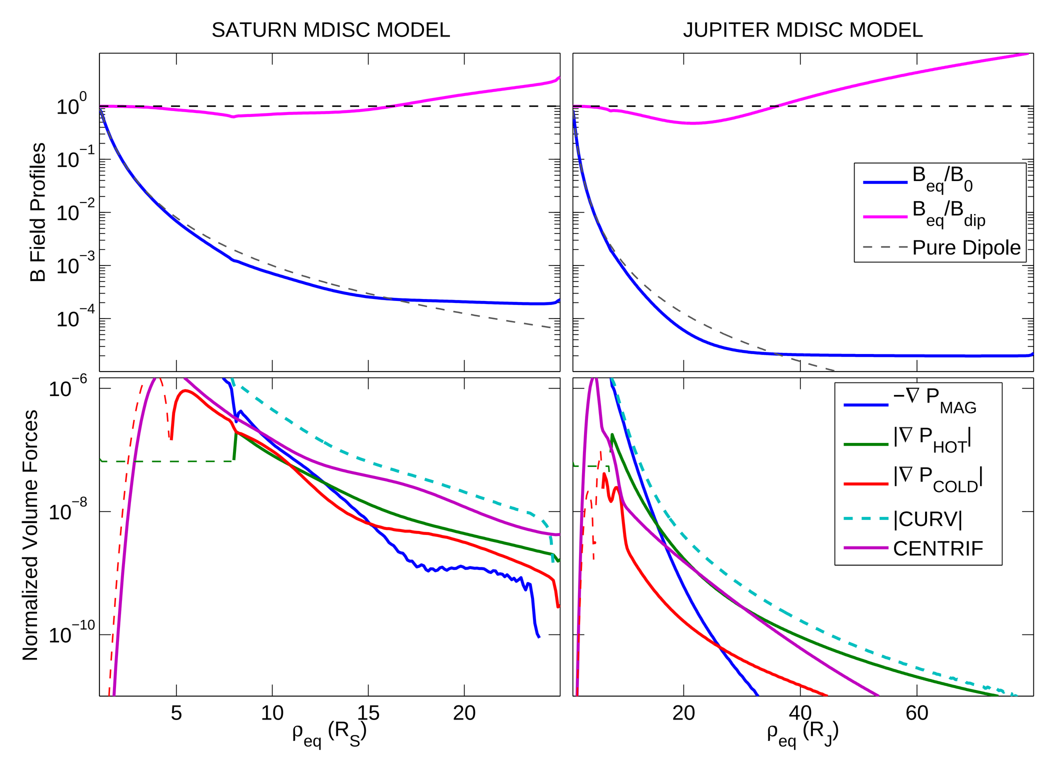

FIGURE 1: *Top panels*: Model calculations of the magnetic field in the equatorial plane of both planets. We show the normalized field strength B_{eq} as a function of ρ for the models (dipole plus disc) and for the pure planetary dipole. The ratio of the model to dipole field is also shown. *Bottom panels*: The normalized volume forces in the equatorial plane due to plasma pressure gradient, magnetic pressure gradient, magnetic curvature and centrifugal force (see legend colour codes). Solid (dashed) curves indicate outward (inward) directed force. Note that it is centrifugal force which mainly balances curvature for Saturn's outer magnetosphere, while for Jupiter's analogous region it is hot plasma pressure which provides the strongest outward force. Achilleos et al. (2009) showed that these results were consistent with the Saturn model's values of transition distance ρ_T between 12–22$\mathrm{R_S}$ (well within the magnetosphere), while the Jovian ρ_T values lie well beyond the magnetopause radius.

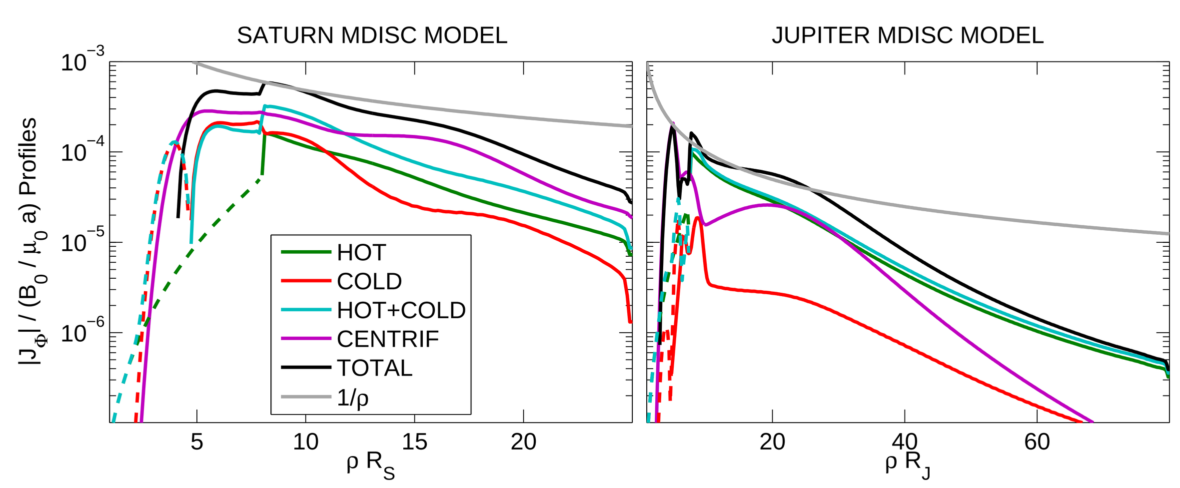

FIGURE 2: Model calculations of the (normalized) azimuthal current densities in the equatorial plane of both planets. We show colour-coded contributions to the total J_Φ associated with the various magnetospheric forces / populations, namely: Hot plasma current linked to the drifts arising from the hot population's thermal energy; Cold plasma current from the analogous drift of the cold population; Inertial current linked to centrifugal force in the non-inertial frame corotating with the local flow of the cold plasma. Solid (dashed) curves indicate azimuthal current directed parallel (antiparallel) to planetary rotation. Note that the strong variability in the hot pressure at Saturn (Sergis et al., 2007, 2009) suggests that the region where plasma current exceeds inertial may also vary greatly in radial extent, perhaps even disappearing at times. As expected from the force calculations in Fig 1, the centrifugal and hot plasma currents are the largest respective contributions for the outer Kronian and Jovian magnetospheres.

Influence of Hot Plasma Pressure

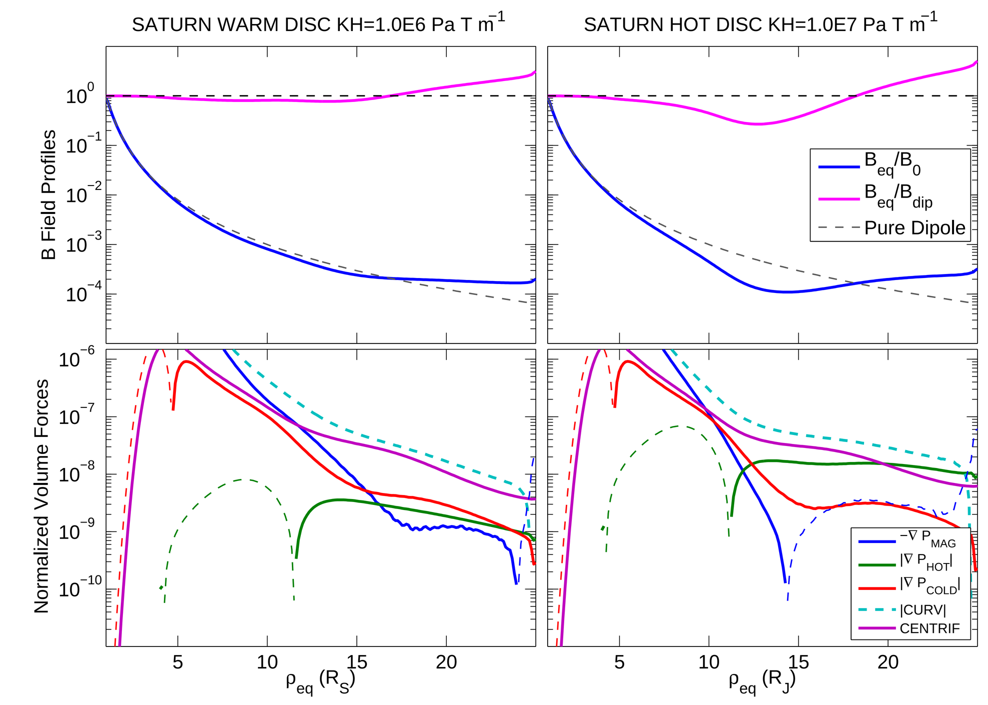

FIGURE 3: Equatorial magnetic and force profiles for two different values of 'hot plasma index' K_h. This parameter is the product $P_h V_\alpha$ of hot plasma pressure and unit flux tube volume in the outer magnetosphere. Following Caudal (1986), it was used by Achilleos et al. (2009) to simply characterise the hot plasma pressure at Saturn, in a manner consistent with the observations of Sergis et al. (2007, 2009). For the left panel, $K_h = 10^6$ Pa T m^{-1} consistent with 'average' ring current activity, while for the right panel $K_h = 10^7$ Pa T m^{-1}, used to represent the maximum levels of hot pressure that have been observed with Cassini's MIMI instrument. Our previous Figures show Kronian models with $K_h = 2 \times 10^6$ Pa T m^{-1} and a 'sharper' decrease in hot pressure for $\rho < 8\mathrm{R_S}$, as used in the original calculations by Achilleos et al. (2009)).

The modeled increase in hot plasma pressure produces three main changes to disc structure: **(i)** A strong reversal in magnetic pressure gradient beyond 14$\mathrm{R_S}$, associated with a field strength which is significantly *lower* (relative to the planetary dipole field) than in the Jovian model of Figure 1; **(ii)** 'Piling up' of flux tubes in the outer magnetosphere, giving the increase in curvature force needed to maintain equilibrium; **(iii)** Outer disc structure where the main force balancing magnetic curvature is hot pressure gradient, rather than centrifugal force (latter prevails for more typical conditions at Saturn).

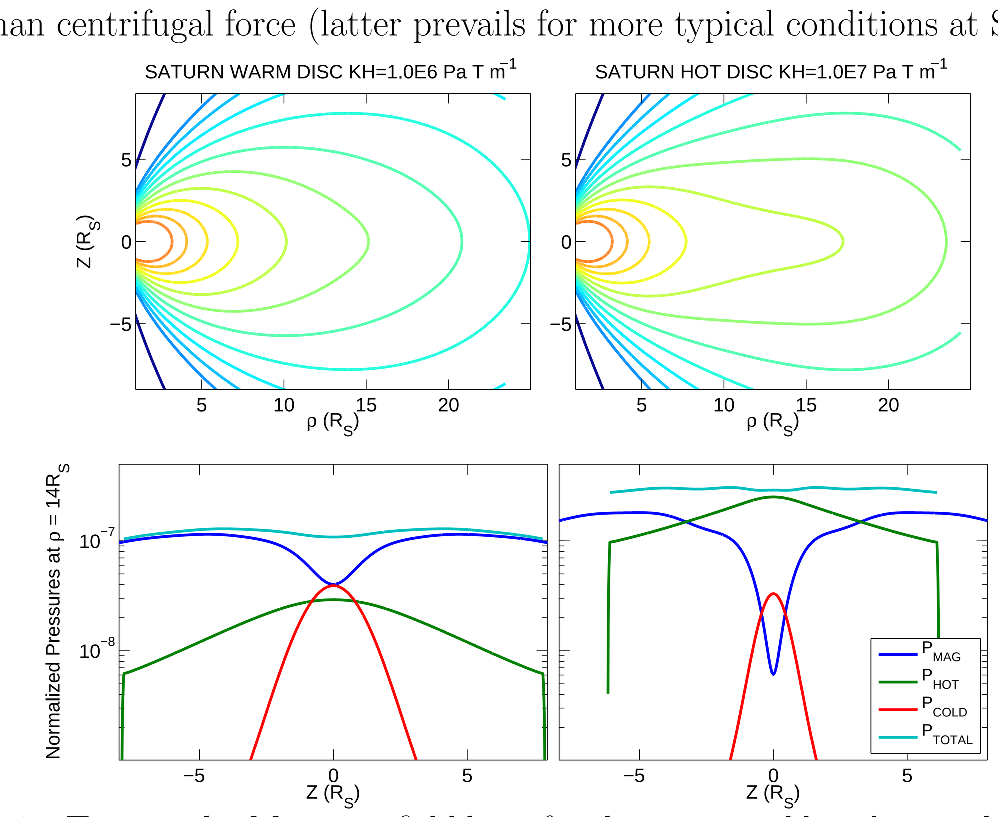

FIGURE 4: Top panels: Magnetic field lines for the warm and hot disc models in Figure 3 (cylindrical coordinates). Bottom panels: Corresponding vertical profiles of magnetic and plasma pressure at radial location $\rho = 14\mathrm{R_S}$ (Z denotes distance above / below equator). Note that the hot disc configuration is associated with a thinner plasma / current sheet, and higher equatorial value of plasma β.

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