SM11A-2002: Modeling the Forces in Saturn's Warped Magnetodisc

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Abstract

Observations from the *Cassini* spacecraft have established that Saturn's outer magnetospheric current sheet does not generally lie in the planet's rotational equatorial plane. Previous analyses have revealed that the current sheet adopted a 'bowl-like' shape, swept northwards of the equator, during the *Cassini* prime mission (southern summer solstice). In order to quantify the relationship between solar wind dynamic pressure, planetary dipole tilt, and the shape of the near-noon current sheet, we examine a simple model of magnetopause currents within systems where the planetary dipole / rotation axis is oriented at ~65 degrees (solstice) and 90 degrees (equinox) to the upstream flow direction of the solar wind. We use this simple model to compute the 'shielding field' for the UCL Magnetodisc Model. We show model predictions of the north-south asymmetry in the current sheet for varying dipole orientations and magnetopause sizes. We comment on the potential application of using observed magnetic signatures of current sheet displacement (relative to the equator) as an independent probe of solar wind pressure.

Introduction

- Analyses of *Cassini* magnetic field data have revealed that Saturn's magnetospheric current sheet is not planar under solstice conditions ('southern summer'), but 'bowl-shaped' and swept northwards of the rotational equator (e.g. Arridge et al. (2008b)).
- Empirical models have been constructed for the current sheet geometry, based on fitting the spatial locations of current sheet encounters (e.g. Arridge et al. (2008a), Arridge et al. (2011)).
- This 'warping' of the current sheet ('disc' to 'bowl'), is related to the non-orthogonality, at solstice, between the planetary dipole and the upstream solar wind flow. This configuration evidently requires a 'bowl-like' sheet geometry in order to maintain approximate force balance in the system.
- In this work, we modify an existing model of force balance in Saturn's magnetodisc, in order to quantify the relationship between magnetopause radius (equivalent to solar wind pressure) and current sheet curvature. We study only the 'bowl-like' geometry – we do not address the additional, quasi-periodic fluctuations in the current sheet location due to the 'camshaft' signal at Saturn (see e.g. Southwood & Kivelson (2007); Provan et al. (2009)).

Method

We use a semi-quantitative method for representing the magnetic field associated with the 'shielding currents' flowing on the magnetopause surface. This is a modification of the 'shielding field' employed by Achilleos et al. (2010a): A uniform, vertical field $\boldsymbol{B_S}$ (aligned with the planetary dipole) based upon a dayside, equatorial average of the analytical expressions by Alexeev et al. (2006). The modifications to $\boldsymbol{B_S}$ for the present work are:

- Restrict the averaging to the local time sector 10:00-14:00 hours, in order to use the model for near-noon sheet geometries. This produces a field $\boldsymbol{B_S^N}$, which is stronger than the full dayside average $\boldsymbol{B_S}$.
- Rotate the purely southward shielding field $\boldsymbol{B_S^N}$ by an angle λ, equal in magnitude to the subsolar latitude. This gives a new shielding field $\boldsymbol{B_S^N}(\lambda)$ with both southward and planetward components: $\boldsymbol{B_S^N}(\lambda) = -\xi B_S^N(\cos\lambda \boldsymbol{e_z} + \sin\lambda \boldsymbol{e_\rho})$, where $\boldsymbol{e_z}$ and $\boldsymbol{e_\rho}$ are respective unit vectors directed northward (parallel to planet dipole) and perpendicular-outwards from the planet's dipole / rotation axis. ξ is an adjustable constant, used for comparison with observations. We use $\xi = 5$ for this work, and compute new models – in force balance – which incorporate the new shielding field $\boldsymbol{B_S^N}$.

Table 1. Physical units used for 'normalized' outputs (Achilleos et al., 2010a).

Radius $\mathrm{R_S}$ or a (Distance)	Magnetic Field B_o	Magnetic Flux Unit $B_o a^2$	Pressure Unit B_o^2/μ_o	Angular Velocity ω_o
60280 km	21160 nT	77 GWb	0.00036 Pa	2π/10.78 h

Equinox and Solstice Magnetodiscs

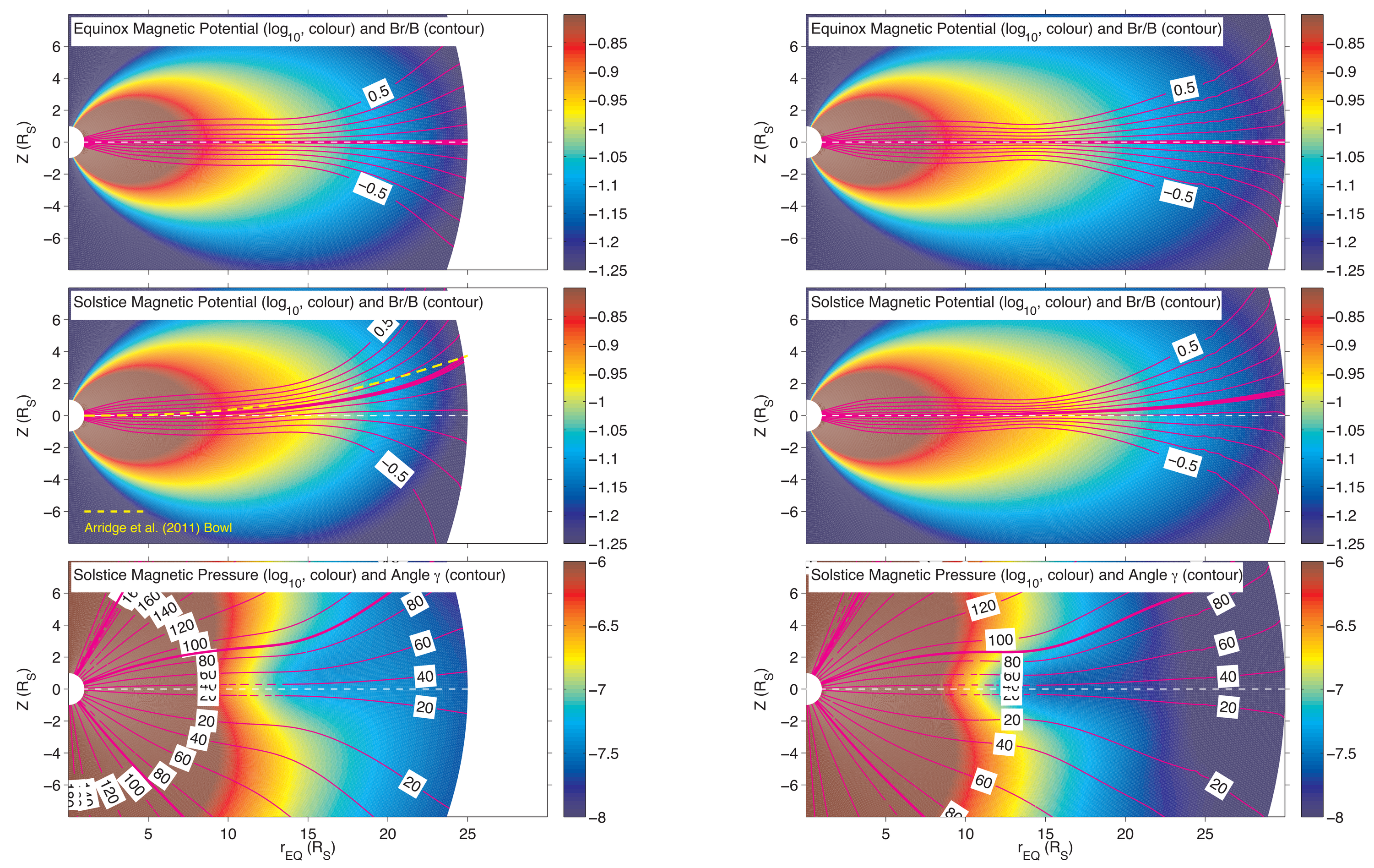

FIGURE 1: **Models with Magnetopause Radii $\mathrm{R_{MP}} = 25\mathrm{R_S}$ (left), and $30\mathrm{R_S}$ (right)** *Upper / middle panels*: Magnetic (Euler) potential on a colour scale for equinox ($\lambda = 0°$) and solstice ($\lambda = 25°$) disc models (magnetic field lines follow surfaces of constant magnetic potential). Coordinates are $\boldsymbol{r_{EQ}}$, equatorial radial distance, and $\boldsymbol{Z}$, vertical distance from equatorial plane. Magenta contours show constant B_r/B (ratio of radial to total field). Northward displacement of the current sheet centre ($B_r/B = 0$ contour) occurs, going from equinox to solstice. Displacement is weaker for a more expanded system, in accordance with the results of Hansen et al. (2010). *Bottom panel*: Normalized magnetic pressure on a colour scale, and contours of γ, the angle between the 'perturbation field' $\boldsymbol{\Delta B} = \boldsymbol{B_S^N}(\lambda) - \boldsymbol{B_S}$, and the total magnetic field for equinox. Note the north-south asymmetry between values of γ. For $\lambda = 25°$, a planar, equatorial disc would produce a higher magnetic pressure (smaller γ) for any southern location, when compared to its northern counterpart at the same r_{EQ} and same distance from the equatorial plane. The solstice 'bowl-shaped' current sheet arises from the 're-establishment' of force balance.

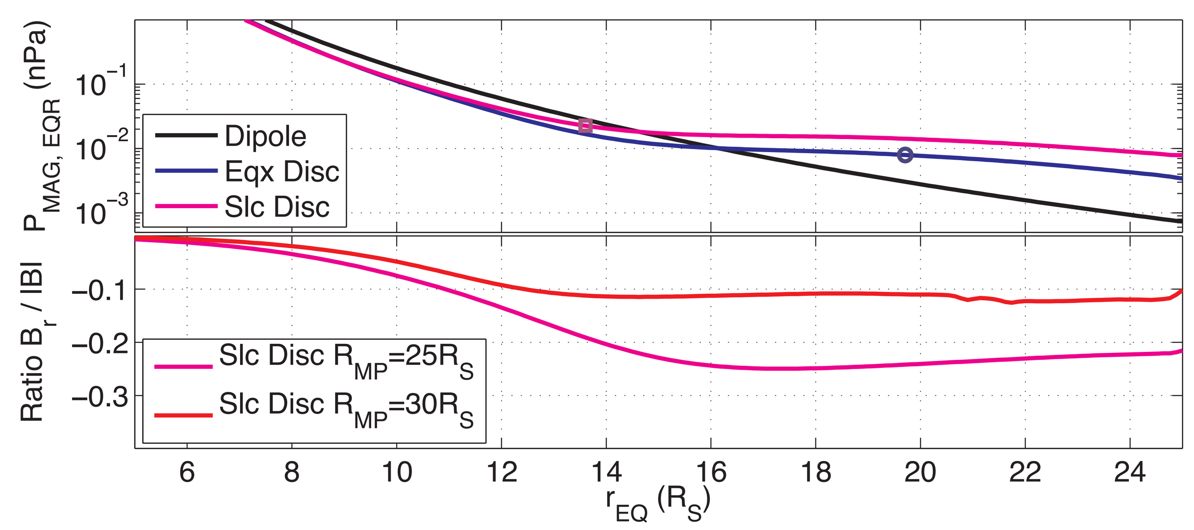

FIGURE 2: **Equatorial Magnetic Field Properties** *Upper Panel*: Equatorial profiles of magnetic pressure for pure dipole, equinox ('Eqx') disc, and solstice ('Slc') disc models (all have $\mathrm{R_{MP}} = 25\mathrm{R_S}$). Plotted symbols indicate the upstream solar wind dynamic pressure, computed from the maximum plasma-plus-magnetic pressure at the model's outer boundary; *Lower Panel*: Equatorial profiles of B_r/B for the solstice disc with $\mathrm{R_{MP}} = 25\mathrm{R_S}$ and $30\mathrm{R_S}$. This ratio is more sensitive, compared to the magnetic pressure profile, to changes in the disc radius $\mathrm{R_{MP}}$ and subsolar latitude λ.

Plasma and Total Pressure

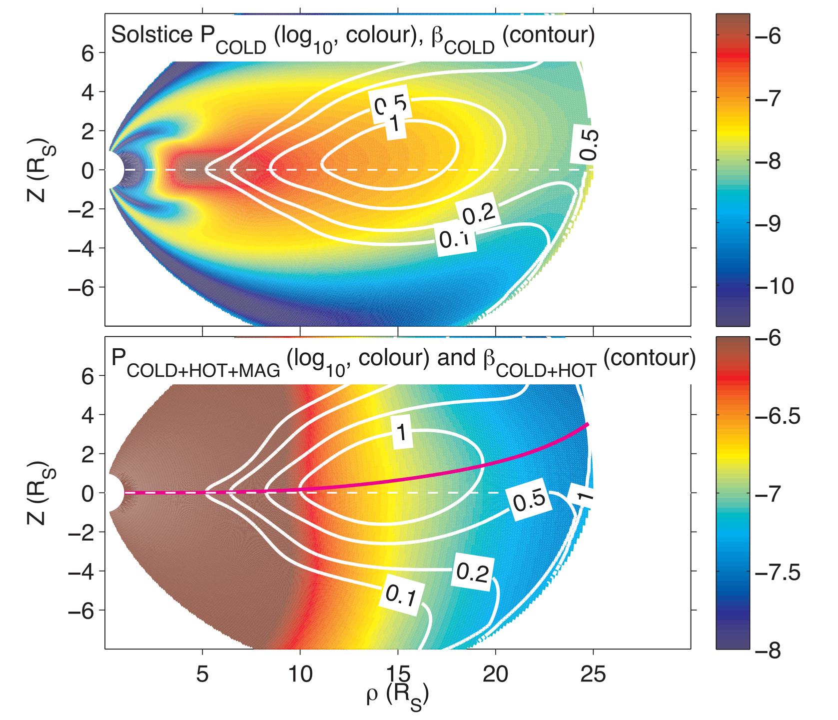

FIGURE 3: **Pressure Distributions** *Upper Panel*: Colour scale shows logarithm of cold plasma pressure, with superposed white contours showing corresponding plasma β for solstice. The 'bowl shape' (concave towards north) and current sheet tilt is evident. *Lower Panel*: Colour scale shows logarithm of total (magnetic plus plasma) pressure, with superposed white contours showing corresponding plasma β (hot plus cold population) for solstice. The magenta contour shows the current sheet centre ($B_r = 0$) for reference.

Comparison with Observations

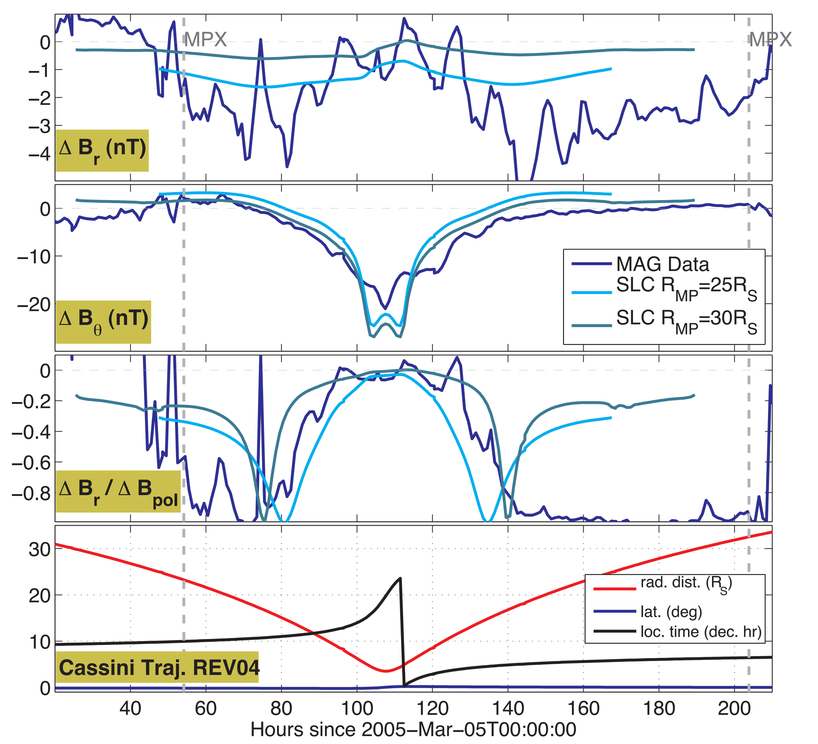

FIGURE 4: **Observed and Modelled Perturbation Field** The top two panels show radial and meridional perturbation fields for *Cassini* Revolution 4 as observed by the spacecraft, and as predicted by the solstice disc models. These fields have been obtained by subtracting an internal field model (Burton et al., 2010) from the magnetic data, and subtracting the planetary dipole from the magnetodisc model field. The third panel shows the ratio between the radial and total, poloidal field perturbations. The bottom panel shows the *Cassini* trajectory. 'MPX' denotes magnetopause crossing.

Summary

- Our simple shielding field produces a current sheet distortion in qualitative agreement with the observed northward 'bending' of the current sheet at southern summer solstice.
- Quantitatively, the models give best agreement with the ratio $\Delta B_r/\Delta B$ (see *Fig. 4*) over a 'middle magnetospheric' region, between ~ 4–$20\mathrm{R_S}$. Our model does not address the quasi-periodic fluctuations in the field due to the 'camshaft' signal. For the outer magnetospheric regions $> 20\mathrm{R_S}$, our model predicts a smaller radial fraction of the poloidal perturbation field than that observed. This discrepancy is probably dependent on both our assumed form of shielding field, and the global hot plasma content of the magnetosphere. This latter quantity has been demonstrated to affect the degree to which outer magnetospheric field lines are radially 'stretched' (Achilleos et al., 2010b).
- Additional investigation is thus required, for example: (i) The influence of the 'scaling factor' ξ; (ii) The effects of changing $\mathrm{R_{MP}}$ and the internal plasma content of the system (e.g. the 'plasma index' of Achilleos et al. (2010a)); and (iii) ultimately, a more realistic treatment of the shielding field due to the magnetopause currents (e.g. Maurice et al. (1996)).

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