Magnetospheric Driving of Saturn's Thermosphere during Storm-Like Events

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Abstract

We present results of numerical experiments, using the UCL axisymmetric model of Saturn's thermosphere *(Smith et al., 2005)*, which reveal the following aspects of thermospheric flow during transient changes in the polar cap boundary and magnetospheric angular velocity:

1. The enormous inertia of the thermosphere introduces a delay of order one planetary day between the peak magnetospheric and peak thermospheric angular velocities.
2. This delay results in a period where thermospheric rotation exceeds magnetospheric, and the corresponding field-aligned currents transfer angular momentum from the magnetosphere to atmosphere, rather than the reverse situation which pertains in the steady state.
3. The thermospheric inertia also leads to flow speeds significantly more rapid (>10%) than the steady state, up to several planetary days after storm subsidence. A rich variety of auroral signatures are predicted by the modelling, including multiple auroral arcs in the vicinity of the quiescent oval.

Introduction

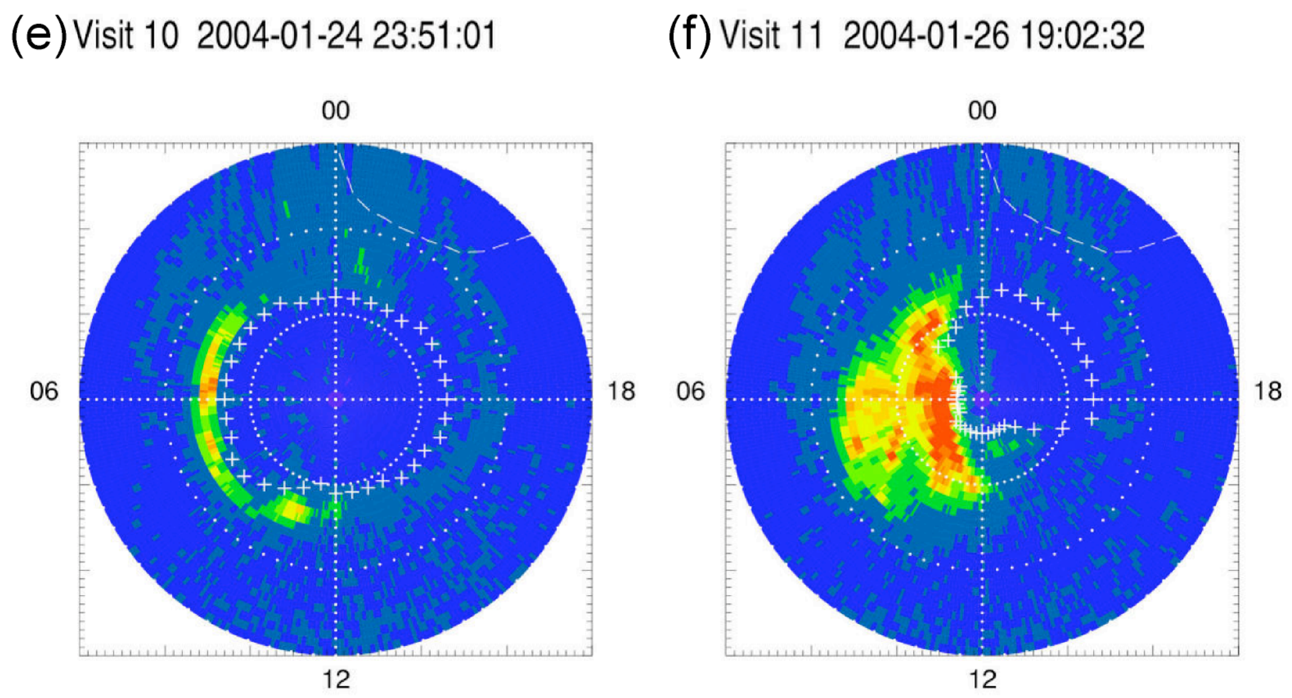

FIGURE 1: **Polar-Projected Auroral Images of Saturn:** These two ultraviolet images were derived from the larger set acquired by the Hubble Space Telescope (HST) and analysed by *Badman et al. (2005).* They show a dramatic 'filling in' or 'contraction' of the dawnside oval, interpreted as a response to a dramatic episode of magnetic reconnection in the magnetotail region. Earlier measurements by *Cassini* (then upstream of Saturn) indicated that a strong solar wind shock probably impinged on Saturn's magnetosphere at the time of the HST observations - consistent with such a scenario. The images suggest an upper limit of $\sim 2\,\mathrm{Earth\ days}$, or $\sim 4.5\,\mathrm{Saturn\ days}$, for the timescale for closure of an estimated $\sim 15\,\mathrm{GWb}$ of open magnetic flux.

Role of the Thermosphere: A rapid contraction of Saturn's polar cap (area bounded by the auroral oval), as observed, would affect dynamics of slowly rotating thermospheric gas, poleward of the nominal latitude of the quiescent oval $\sim 75°$. During the reconnection event, neutrals would collide with ionospheric plasma, whose angular velocity Ω_M would be expected to change between observed 'polar cap' values of $\sim 0.3\Omega_S$ *(Stallard et al., 2004)* (pre-reconnection) and $\sim 0.8\Omega_S$ (typical values in the outer, closed magnetosphere; post-reconnection). Here Ω_S is the planetary angular velocity, which we have taken to be $1.6236 \times 10^{-4} s^{-1}$ (period 10.75 hr). Because the thermosphere represents a considerable 'load' from the magnetosphere's point of view, we do not expect it to respond instantly to changes in Ω_M. Highly disturbed aurorae would thus be expected to arise, relative to quiescent conditions.

Model

Here we show results of a relevant, simple 'numerical experiment' where the magnetospheric angular velocity (Ω_M) profile, used to drive the UCL 2-D (axisymmetric) Saturn Thermosphere Model, has been varied in both time and latitude. More details of this model are given by *Smith et al. (2005).* The main modification we have made is to incorporate the 1D model of auroral precipitation at Saturn presented by *Tao et al. (2010), (Icarus, in press, 2011).* The Figures show the results of this semi-qualitative simulation of a reconnection event, in terms of its effect on neutral and magnetospheric dynamics, and energy flow. The model has time-dependent values of both (i) latitude of the polar cap boundary; and (ii) Ω_M value in the 'active region' between the assumed latitudes of the quiescent (76.8°) and most contracted (80.5°) polar cap boundaries. The chosen latitudes correspond to a magnetic flux interval of $\sim 9\,\mathrm{GWb}$ per radian, similar to the observed levels of flux closure. This time-dependence is proportional to a simple, analytic 'storm function' which changes on a time scale of $\tau_S = \sim 0.4$ planetary days - in future studies we will further explore the consequences of varying τ_S.

Results

Atmospheric Dynamics and Aurora

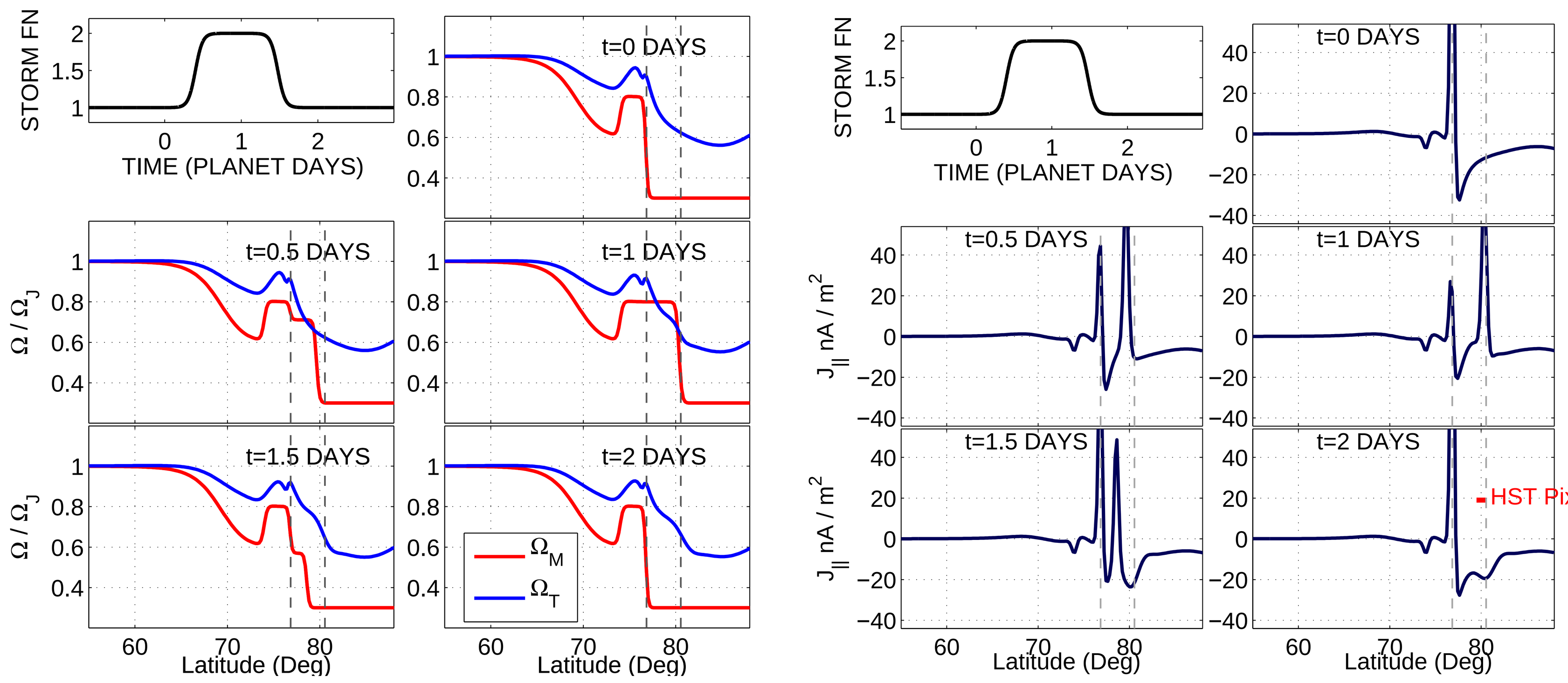

FIGURE 2: **Ascending 'Storm' Dynamics:** The left-hand set of plots shows the angular velocities of the magnetosphere (Ω_M, coloured red) and thermosphere (Ω_T, coloured blue) during the simulation, as a function of time. The 'storm function' indicates the qualitative 'phase' of the storm event, and controls the changes in: (i) the polar cap boundary location; and (ii) magnetospheric Ω_M in the 'active region' (latitudes 76–$80°$, shown as vertical dashed lines). Ω_T is a weighted average over the pressure levels in the model, which corresponds to an equatorward Pedersen current $J_\theta \propto (\Omega_T - \Omega_M)$. The quiescent system ($t$=0 days) has been allowed to approach steady state over 6 planetary days – this pre-storm state shows the expected steady-state behaviour $\Omega_M < \Omega_T$ at all latitudes. At t=0.5 days ('ascending phase'), Ω_M in the active region has increased above Ω_T – the thermosphere's enormous inertia prevents Ω_T from responding instantly to this imposed Ω_M, thus we see a reversal in the usual ordering, i.e. $\Omega_M > \Omega_T$.

Descending 'Storm' Dynamics: This reversal persists at the 'peak phase', t=1 days, where we see evidence of the delayed response of the thermosphere (increased Ω_T). The 'descending phase', t=1.5 days, sees the restoration of the steady-state ordering, although the profiles are quite disturbed compared to the quiescent phase. Finally, the 'post-storm' phase, t=2 days (∼0.5 days after storm subsides), shows the system returning to quiescence – although clear differences in active region Ω_T are still apparent.

Aurora: Right-hand plots show the corresponding auroral (field-aligned) current profiles at each phase. The change in Ω_M and Ω_T profiles produces a rich variety of auroral forms, some of which would correspond to obervations of multiple auroral arcs. The angular size of an HST ACS pixel is shown for comparison.

Joule Heating

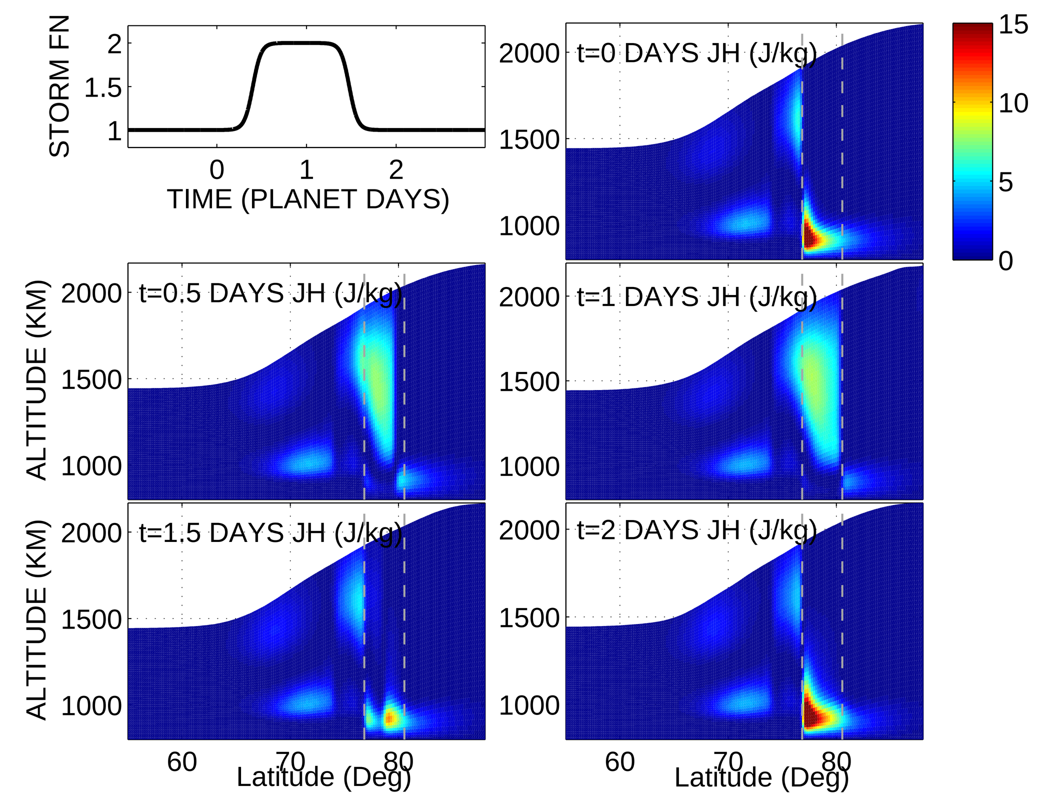

FIGURE 3: Colour scale shows Joule heating predicted by the model as a function of latitude and altitude above the 1-Bar pressure level. The quiescent phase shows the maximum corresponding to the auroral ionization peak near $\sim 76°$, 1000 km. Other phases show a great variety of heating profiles, corresponding to results from Figure 2.

Temperature

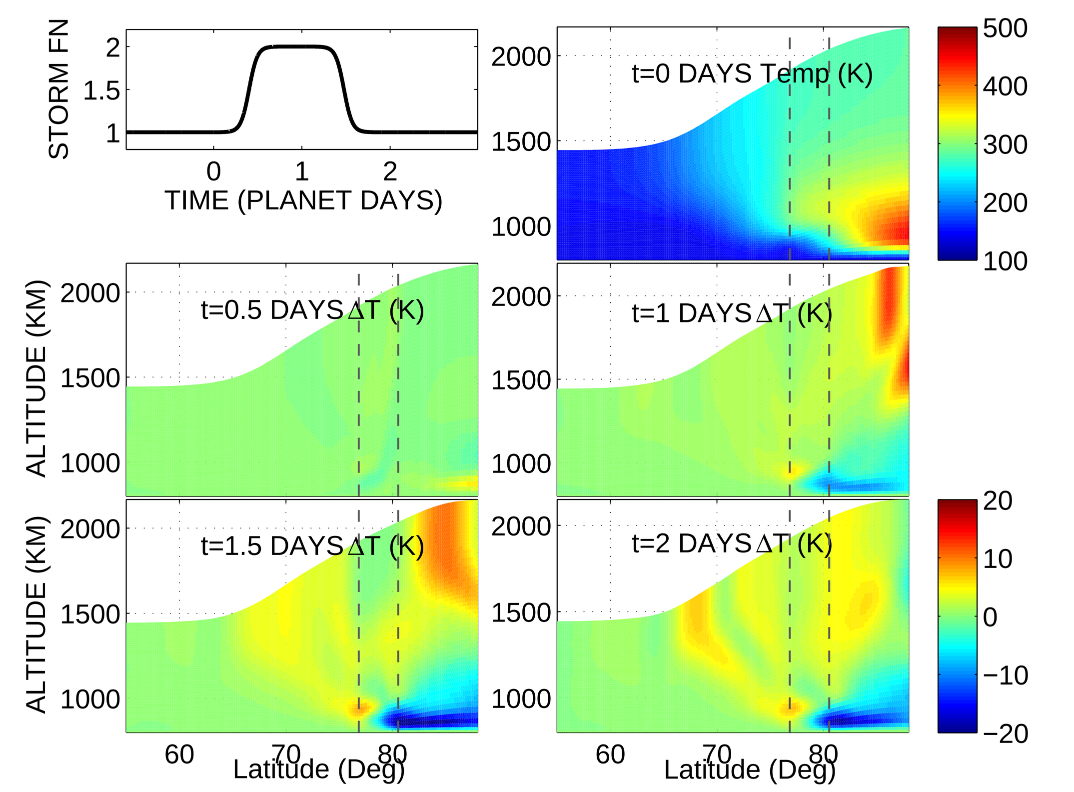

FIGURE 4: Colour scale indicates quantities derived from neutral temperature, as a function of latitude and altitude; active region boundaries are shown by vertical dashed lines. For quiescent phase (t=0 days), total neutral temperature is indicated – the increased temperature in the polar cap region is produced by advection of heat energy from the auroral region (see the Joule heating distribution in Figure 3). Other phases show temperature *differences* relative to quiescent. Global fluctuations in temperature are transported by winds from the auroral regions, both poleward and equatorward of the active region. Fluctuations up to ~ 20K are evident in the high-altitude polar cap. Cooling is evident near the lower altitude boundary of the polar cap region, associated with strong upwelling. A future study will examine the correlation between atmospheric flows and these global temperature fluctuations.

References

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