Simulating Planetary Magnetospheres: An Example from Saturn

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Extending Limited Observations

- In situ spacecraft observations are limited to the trajectory.
- Need to place them in a global context.
- Remote sensing observations can provide a more global perspective.
- Auroral images provide information on closed/open field line regions and parallel currents.
- Large-scale models and simulations can be used to provide a global perspective.

Use auroral images and global MHD simulation to investigate magnetospheric and ionospheric convection and field aligned currents at Saturn.
Saturn - the Other Rapid Rotator

- Saturn rotates with a period of ~11 hours.
- Saturn’s magnetic axis is aligned with its rotational axis. (It is opposite in direction to the Earth’s.)
- The plasma in Saturn’s magnetosphere is driven toward co-rotation by the rotating atmosphere.
The Current System that Enforces Partial Corotation in Rotating Magnetospheres

• A frictional torque in the ionosphere accelerates the plasma to corotation.

• The ionospheric torque is transmitted to the magnetosphere via field-aligned currents that close through radial currents [Hill, 1979; Vasyliunas, 1983].

• \( \vec{j} \times \vec{B} \) in the magnetosphere is in the direction to accelerate the plasma while \( \vec{j} \times \vec{B} \) in the ionosphere is in the direction to slow the planet’s rotation.
Enceladus' Plasma Source

- Geysers on Enceladus provide water group neutrals that when ionized populate the magnetosphere.
- The source rate has been estimated to be between $3 \times 10^{27} \text{ H}_2\text{O s}^{-1}$ and $1.0 \times 10^{28} \text{ H}_2\text{O s}^{-1}$
Simulation Model - the Magnetosphere

- Solve the resistive MHD equations as an initial value problem.
- Solar wind parameters enter the simulation box at the upstream edge.
- Mirror boundary conditions are used at the equator.
- Free boundary conditions are used at the other edges.
- Corotation enforced at the inner boundary (5R_S).
- Enceladus source rate is a free parameter at the inner boundary – 5.5X10^{28} AMU/s
- (1802X1202X602) point grid with ΔX = 0.1R_S.
Simulation Model- the Ionosphere

• Solve the ionospheric current conservation equation

\[ \nabla \cdot \sum \cdot \nabla \Phi = -j_\parallel \sin I \]

where \( \sum \) is the conductance, \( \Phi \) is the electric potential, \( j_\parallel \) is the parallel current density, and \( I \) is the inclination angle.

• We assumed a Pedersen conductance of 1S and set the Hall conductance to 0.

• The velocity vectors are calculated from \( \mathbf{E} = -\nabla \Phi \) and \( \mathbf{V} = \mathbf{E} \times \mathbf{B} / B^2 \)

• The ionospheric parameters were calculated on a 200X200 point grid.
Observations of Saturn’s Aurorae

- View of Saturn’s auroral emissions looking from the north at the southern hemisphere.
- FUV aurora.
- HST-STIS
- Circles are $10^\circ$ in latitude

From Gérard et al., 2005
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B\textsubscript{Z} and Flow

• Solar wind – $\rho V^2 = 0.008$ nPa, $B\textsubscript{Z} = 0.4$ nT
• Waves on morning side present at 10 hours.
• Waves non-linear by 12 hours
• Waves form on afternoon side by 16 hours.
• Flow vortices in magnetosphere.
• Near-Saturn reconnection begins at about 16 hours.
**K-H Instability Criterion**

- For a tangential discontinuity between two incompressible plasmas with velocities $V_1$ and $V_2$, waves of frequency $\omega$ and wave vector $k$ are unstable only if

\[
[k \cdot (V_2 - V_1)]^2 > \frac{1}{\mu_0} \left( \frac{1}{\rho_1} + \frac{1}{\rho_2} \right) \left[ (k \cdot B_1)^2 + (k \cdot B_2)^2 \right]
\]

where $\rho_1$ and $\rho_2$ are mass densities and $B_1$ and $B_2$ are magnetic field vectors on the two sides of the boundary.

- Many features of the K-H instability in more realistic configurations reasonably well approximated by this [Kivelson and Pu, 1984]

- At about 10 hours the waves start at ~0900 LT. They go unstable when the criterion is met.
Velocity Vectors - Morning

T = 10 hours

T = 12 hours
Velocity Vectors – Afternoon

T = 12 hours

T = 16 hours
Parallel Component of Vorticity

- Enhanced vorticity in K-H waves.
- Enhanced vorticity in the magnetosphere.
- Vorticity changes throughout the simulation
Field Aligned Currents in MHD

• From the momentum equation and current continuity the field aligned currents in MHD are given by

\[ \nabla \cdot j_\parallel = \frac{\partial j_\parallel}{\partial s} = -\nabla \cdot \frac{1}{B^2} \left( B \times \left[ \rho \frac{d\mathbf{v}}{dt} + \nabla p \right] \right) \]

• If the inertial term is small

\[ \frac{j_\parallel}{B} (ion) - \frac{j_\parallel}{B} (eq) = -\frac{B_{eq}}{B^2} \left( \nabla p_{eq} \times \nabla V \right) \]

where \( V \) is the flux tube volume.

• If the pressure term is small

\[ B \frac{\partial}{\partial s} \left( \frac{j_\parallel}{B} \right) = \rho \frac{d\Omega_\parallel}{dt} \]

where \( \Omega_\parallel \) is the parallel component of vorticity.
Parallel Currents in the Ionosphere

- View is from the north looking through the Saturn to the south – most observations are of the southern aurora.
- Red is toward the ionosphere.
- Blue is away from the ionosphere.
- Expect discrete aurorae to be associated with away currents in analogy with the Earth.
Field Aligned Currents at $Z = 2R_s$

- Largest currents in KH vortices, along magnetopause and in the near-Saturn tail
- Inertial term ($\rho dV/dt$) was $>200$ times the pressure term ($\nabla p$).
• Isolated dayside currents map to KH vortices.
• Nightside currents map to region of enhanced vorticity Saturnward of the reconnection site.
Field Aligned Currents and Aurora

- The electrons associated with discrete aurora are associated with parallel electric fields.
- The field aligned voltage can be modeled by using the Knight relationship between magnetospheric plasma parameters and the minimum voltage
  \[ \Phi = \frac{kT_e}{e} \left[ \frac{j_{\|i}}{j_{\|0}} - 1 \right] \]
  where \( T_e \) and \( n_e \) are the electron temperature and number density in the magnetosphere, \( j_{\|0} = en\left(\frac{kT_e}{2\pi m_e}\right)^{\frac{1}{2}} \) and \( j_{\|i} \) is the ionospheric current density.
- The thermal energy flux is \( F_E = 2n_e kT_e \left(\frac{kT_e}{2\pi m_e}\right)^{\frac{1}{2}} \)
- The energy flux associated with the away currents is
  \[ F_{Ej} = \frac{F_E}{2} \left[ \left(\frac{j_{\|i}}{j_{\|0}}\right)^2 + 1 \right] \]
- The energy flux associated with the largest currents \( \sim 1 \text{ mW/m}^2 \)
- This gives about 70 GW of auroral power.
A Smoking Gun?

- Cassini FUV observations of Saturn aurorae from the UVIS instrument [Grodent et al., 2011].
- A panels show regions of interest. B show polar projections. C panel shows combined image.
- Small scale structures were found in the morning and afternoon – different events.
- Grodent et al., interpret these in terms of K-H waves.
Diffuse Aurora and Convection

- Convection dominated by rotation equatorward of 70° - 75°
- Large convection cell over pole.
- $F_E = \rho V_{th} = \sim 1 \text{ mW/m}^2$ for cusp aurora.
**Summary**

- Field aligned currents in Saturn’s magnetosphere are associated with changes in the flow vorticity.
- The largest currents are found associated with the KH vortices, along the magnetopause and in the near-tail.
- They map to high latitudes and may be responsible for Saturn’s main aurora.
- The auroral energy density can be > 1 mW/m²
- The K-H waves should be (are?) observable as localized spots of enhanced aurora.
- Enhanced thermal energy flux is found in the region of the polar cusp. This suggests that cusp aurora may be diffuse aurora.