Comparing Auroral Processes at Different Planets

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Some remarks of relevance, independent of planet:

- **Aurorae** are radiative *emissions*, excited through the impact of precipitating *particles* onto the upper atmosphere.

- Some auroral patterns arise from relatively steady *flows* (and *currents*) imposed on the planet’s ionosphere through an interaction with some external ‘energy source’ or *driver*.

- Other auroral features are *transient*, and are often a signature of time-dependent changes in this driver.
Some remarks of relevance, independent of planet:

• The most striking difference between planets is which driver produces the brightest, most persistent emission, i.e. the *auroral oval*.

  • **Earth:** Magnetosphere-solar wind interaction  
  • **Jupiter:** Planetary rotation (source is inside)  
  • **Saturn:** Arguably Earth-like, with ‘secondary’ features.

(Image taken by the Spin-Scan Auroral Imaging instrument on board Dynamics Explorer - 1. Courtesy L. Frank, the University of Iowa, and NASA.)
Auroral Oval: Earth

• Schematic view of flows across Northern polar cap, similar to those first proposed by Dungey (1961, PRL).
• Aurora occurs near the boundary between open and closed field lines, typically ~70 deg magnetic latitude.
• Precipitating electrons correspond to upward, field-aligned currents.
• How do such currents arise in this picture?

From Hill (1994, JATP)
- **Horizontal gradients in flow** correspond to similar gradients in *E-field* (arrows), and current density $J_{HORIZ}$ in the ionosphere.

- To ‘close’ the current, we require FAC $\rightarrow$ aurora.

- Example: Pedersen current – FACs at ‘sharp’ changes in $E$. 
• Near-circumpolar sheets of FAC arise poleward (‘Region 1’) and equatorward (‘Region 2’) of the auroral oval.

• Global auroral heat inputs, of order 10-100 GW (from particle precipitation and Joule heating).
• Changes in oval morphology due to changes in open magnetic flux (polar cap). How?

• Dayside reconnection

• Substorms: episodes of tail reconnection (~0.3 GWb closure).

(Courtesy S. Milan)
Main oval – **corotates with the planet, it is not Sun-aligned.**

Io ‘spot’

Cusp? (Talk by S. V. Badman, this meeting)

- **UV image of Jupiter’s aurora taken by HST ACS instrument.**
• Jupiter’s main oval is also linked to flow shear – but here, that ‘shear’ arises from the different rotation periods of the planet (~10 hr) and the plasma disc (~10 down to ~3 hr).
• The source of disc plasma for the disc is the moon, Io – adds ~500-1000 kg/s of sulphur / oxygen plasma (e.g. Bagenal and Sullivan, 1981, JGR).
• The diagram shows the general sense of the currents.
• Usually, main oval emissions map to ~20-30 RJ in the equatorial plane, which is also the location of the strongest gradient in rotation rate (‘breakdown in corotation’ of plasma).
• Global energy dissipated is typically 90-200 TW (Joule heating + precip’n), roughly 1000 times the energy range for the Earth.
Does the Jovian oval morphology change?

• Does Jovian oval morphology ever change? Here’s an example (Grodent et al (JGR, 2008), see also Bonfond et al (GRL, 2012))

• Main emission in the ‘red’ image is ‘displaced’ equatorward by up to ~5 deg, at least as far as the satellite footprint of Ganymede.

• Io footprint unaffected - it is in the ‘rigid’ field of the inner magnetosphere.

• Nichols’ (2011) results show that increased mass-loading of the disc is one way to displace both these features equatorward, but even very high mass-loading rates (4000 kg/s!!) cannot make them coincide.

• Work in progress by Achilleos et al. (2012) indicates that hot particle population enhancement, combined with mass loading increase, may work.
HST images of Saturn’s southern UV aurora presented by Badman et al (JGR, 2005).
- Concurrent observations by Cassini → planet’s auroral response to the passage of a solar wind compression / shock.
- Polar cap boundary (main oval) strongly contracts to higher latitudes, an ‘Earth-like’ response.
- Compression → magnetic reconnection on the nightside, which closes of order 10 GWb of open magnetic flux (~20x Earth value).
• **Badman et al (JGR, 2005)** used the conceptual model shown here. Configuration: concurrent nightside and dayside reconnection.

• In contrast to the Earth, the flows are dominantly *rotational*, even across the nominal polar cap.

• ‘Quiescent’ oval can be modelled through gradients in flow velocity between outer magnetosphere (~0.8 $\Omega_S$) and polar cap (~0.3 $\Omega_S$) (*Cowley et al, JGR, 2008*). The energy dissipated is ~10-20 TW.

• Note that Saturn does have a ‘Jupiter-like’ aurora formed by internal rotation, but it is not the main emission (~20% of main oval) (*Stallard et al, Nature 2008*).
## Summary

<table>
<thead>
<tr>
<th></th>
<th>Earth</th>
<th>Jupiter</th>
<th>Saturn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole moment</td>
<td>$1 \mu_E$</td>
<td>$18000 \mu_E$</td>
<td>$550 \mu_E$</td>
</tr>
<tr>
<td>M’pause standoff distance $R_{MP}$</td>
<td>$1R_{MP,E}$</td>
<td>$80R_{MP,E}$</td>
<td>$20R_{MP,E}$</td>
</tr>
<tr>
<td>$P_{ROT}/(R_{MP}/V_{SW})$</td>
<td>$\sim500$</td>
<td>$\sim2.5$</td>
<td>$\sim8$</td>
</tr>
<tr>
<td>Auroral energy dissipated</td>
<td>$\sim10$s of GW</td>
<td>$\sim100$ TW</td>
<td>$\sim20$ TW</td>
</tr>
<tr>
<td>Main auroral ‘oval’ due to:</td>
<td>Solar wind-driven</td>
<td>Planetary rotation</td>
<td>Solar wind-driven*, with fainter rot’n oval</td>
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All main ovals involve spatial gradients in plasma flows

| Other examples of transient aurora | Transpolar arc (*change in IMF $B_Y$*) (e.g. Milan et al, 2005) | Polar dawn ‘spots’ (*tail reconn.*) (Radioti et al, 2010) | Oscillations in oval location (*camshaft’ currents*) (Nichols et al. 2010) |
• Footprint locations, relative to the oval, are of interest because of this observation by *Grodent et al (2008)* (see also *Bonfond et al (GRL, 2012)*)

• The main emission in the ‘red’ image is ‘displaced’ equatorward, at least as far as the satellite footprint of Ganymede.

• Io footprint unaffected - it is in the ‘rigid’ field of the inner magnetosphere, which is relatively ‘undistorted’ by the ring current.

• *Nichols’ (2011)* results show that increased mass-loading of the disc is one way to displace both these features equatorward, but even the *highest* mass-loading rates (4000 kg/s!!) cannot make them coincide.

• Can something else ‘internal’ be changing? (Note the emission between Io footprint and main oval)
A ‘hot population’ of plasma

- The Voyager and Galileo observations were compared by Mauk et al. (JGR 1996) who described a ‘ring current depletion’ in the Galileo era.

- We have extended the Voyager profile as shown in order to provide input to the UCL Magnetodisc Model (Achilleos et al, MNRAS, 2010)

- We have calculated disc models for ‘Voyager-like’ and ‘Galileo-like’ conditions, as well as different Io mass-loading rates.

- The model solves for magnetic field structure and plasma rotation rate in a self-consistent manner (see also Caudal, JGR, 1986).
Rotation Model: ‘Hot’ Disc (Voyager)

• Note the broad local minimum in magnetic field strength and angular velocity - why?
Field Model: ‘Cold’ Disc (Galileo)

- Constant colour surfaces are ‘shells’ of magnetic field lines
- Colour can be interpreted as the location of that field line’s ionospheric footprint
A global increase in hot pressure ‘inflates’ flux tubes, and pushes them outwards, until force balance with the magnetic field is re-established.
Auroral Current: ‘Cold’ Disc (Galileo)

- Unusually high mass-loading shifts aurorae equatorward, but not to the level where main oval and Ganymede spot coincide.
‘Easier’ to make auroral features coincide with a global increase in hot plasma pressure. *Note* the ‘filling in’ emission between Io footprint and main oval is consistent with such an event.
Conclusions

• Jupiter’s auroral features - ‘main oval’ and satellite footprints - are a diagnostic of magnetic field structure and plasma content of the system.

• Both of these properties influence the rate of rotation of the plasma, which in turn determines strength and location of main oval and satellite ‘spot’ aurorae.

• Models indicate that, if a global increase in hot plasma pressure accompanies a ‘realistic’ increase in Io mass-loading, this could explain the unusual ‘coincidence’ of the oval and the Ganymede footprint.

• Observations are consistent with a hot plasma increase (but not uniquely so).

• Increased Io mass-loading would plausibly require ‘stronger’ episodes of mass loss from the system (‘mass balance’) - we know that such episodes can be triggered by magnetic reconnection on the night side, which strongly heats the remaining plasma.

• Could additional modelling constrain changes in mass-loading, hot plasma as a function of ‘auroral shift’ (?)
• These results raise the intriguing possibility of using the auroral emission and satellite footprints as a ‘monitor’ of the time-dependent history of mass-loading.
• Additional ‘refinement’ is a treatment of the radial plasma transport.
• Calculations by Arridge (2012) use a diffusion equation (e.g. Thorne, in ‘Physics of the Jovian Magnetosphere’, 1981) to simulate profiles of cold plasma density (flux tube content), controlled by diffusion from a simulated source near Io.

\[
\frac{\partial(NL^2)}{\partial t} = L^2 \frac{\partial}{\partial L} \left( \frac{D_{LL}}{L^2} \frac{\partial(NL^2)}{\partial L} \right) + SL^2
\]

Where:
- \(NL^2\) indicates number of ions per unit magnetic flux
- \(D_{LL}\) is the diffusion coefficient, e.g. Delamere and Bagenal (2005) \((D_{LL} \sim L^{-5.6})\)
- \(S\) is the Iogenic source rate (ions/s)
- (Use ions per unit magnetic flux for ‘Caudalian’ disc)
Flux tube content compared with Caudal

( steady state for dM/dt = 1000 kg/s)
Preliminary Results

As expected, the more mass-loaded disc rotates more slowly.

(Results have converged within a maximum ‘tolerance’ of \(~5\%)\)
Jovian Disc Models: Log Magnetic Potential

dM/dt = 250 kg/s

dM/dt = 1300 kg/s
• Simulation of Jovian plasma disc, using the indicated Io mass-loading rates.
  
(G=Ganymede footprint)

• Quantitatively similar to Nichols (2011) - footprints for ‘loaded’ state extend 0.5-1 deg further in the UCL model.

• If mass-loading only is responsible for shift, need enormous dM/dt to make Ganymede and ‘main auroral’ footprints ‘touch’ (as indicated by recent, unusual HST observations)!
• *Mauk et al (JGR, 2004)* examined the hot plasma pressure measurements of *Voyager* and *Galileo* - ‘ring current depletion’ in region <~ 15 RJ, possibly due to increased Io neutral loading, charge exchange.

• We also show a ‘fake’ profile, labelled ‘VGR +’, to use as an additional ‘test case’.

The data points represent many orbits, etc…
Voyager / Galileo Comparison

- Higher mass-loading produces a more slowly rotating disc.
- For these choices of \(\frac{dM}{dt}\), relatively small change in equatorial field strength.
As expected, higher mass-loading increases the radial ‘stretch’ of the field lines.

For these models, main emission shifts by 2 deg but Ganymede footpoint by <1 deg. Note Ganymede orbit is just outside the ‘bump’ in hot pressure.
Here, dM/dt is fixed but hot pressure is enhanced in VGR+.

Disc rotation not changed appreciably - most mass is in the cold population, slight change due to hot pressure affecting field line shape.
- Hot pressure effect on field line mapping.

- Main emission shift is ~1 deg, but now Ganymede footpoint shifts by > 2 deg.

- Iogenic mass loading good for main emission shift.

- Hot pressure enhancement good for shifting Ganymede footpoint.
Time-dependent studies

Model-derived animation, courtesy C. S. Arridge:
The main Jovian auroral emission can ‘shift’ in location - this shift is observable (e.g. Grodent et al (JGR, 2008), Bonfond et al (GRL, 2012)).

Using models such as Nichols et al (2011), we can obtain information about the ‘interior state’ of the magnetosphere from such shifts.

Preliminary calculations show that the observations may be due to the combination of an increase in Io mass loading, combined with hot pressure enhancement - particle energization?

**Have not mentioned:**
- Progress beyond axisymmetry - local time effects? Can use a 2D model as a ‘local time sector’, e.g. Achilleos et al (GRL, 2010)
- Progress beyond isotropic pressure - ‘stability’ of disc structure? (e.g. Kivelson and Southwood, JGR, 2005)
- Influence of large field-aligned potential drops on M-I currents (e.g. Ray et al (JGR, 2010; JGR, 2012))
Time-dependent studies

• The logenic source rate can be varied, and the consequent effect on magnetodisc field can be calculated (Arridge, 2012, in prep.)

• Example below: Double the source rate between days 300 and 310.

• A full, time-dependent treatment of disc structure (field and plasma) would need to use time-dependent / modified form of Hill-Pontius equation.

• Would observable auroral ‘modulations’ arise in response to a ‘history’ of mass-loading?