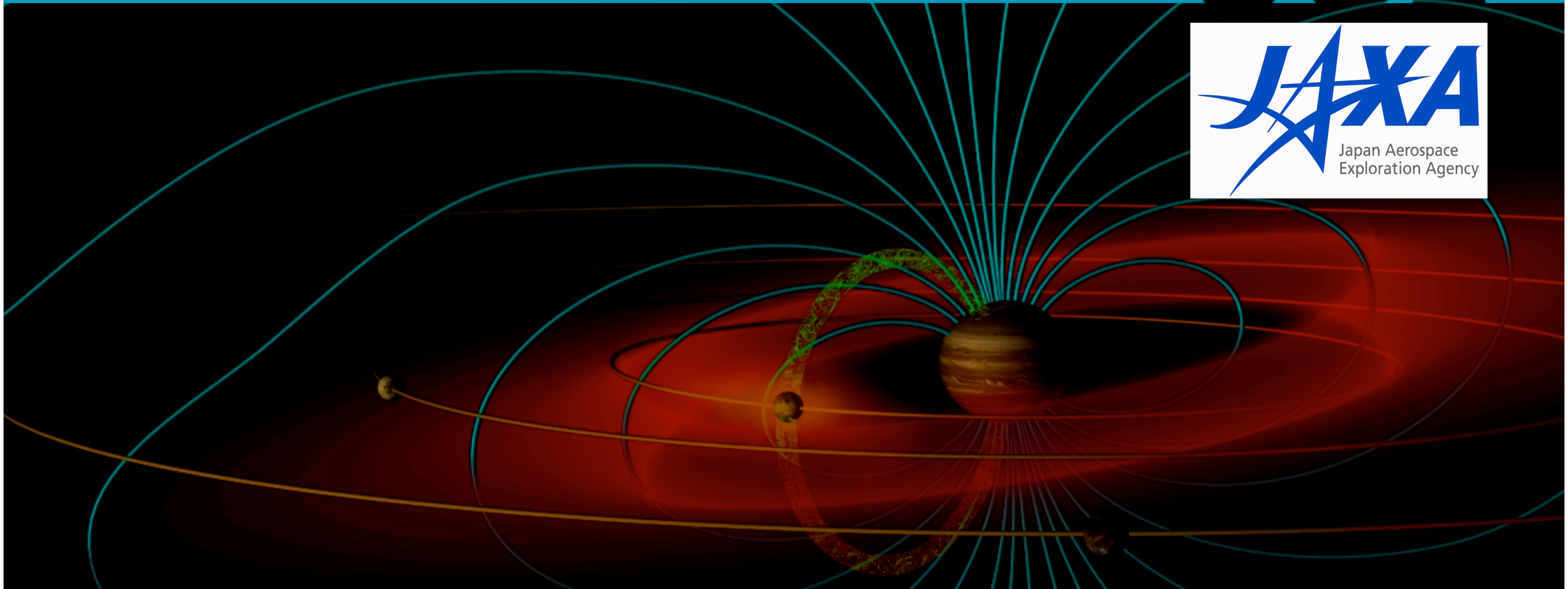
Comparing Auroral Processes at Different Planets



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(1: UCL Physics and Astronomy; 2: Japanese Aerospace Exploration Agency (JAXA / ISAS); 3: Mullard Space Science Laboratory; 4: UCL Centre for Planetary Sciences)

Some remarks of relevance, independent of planet:

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

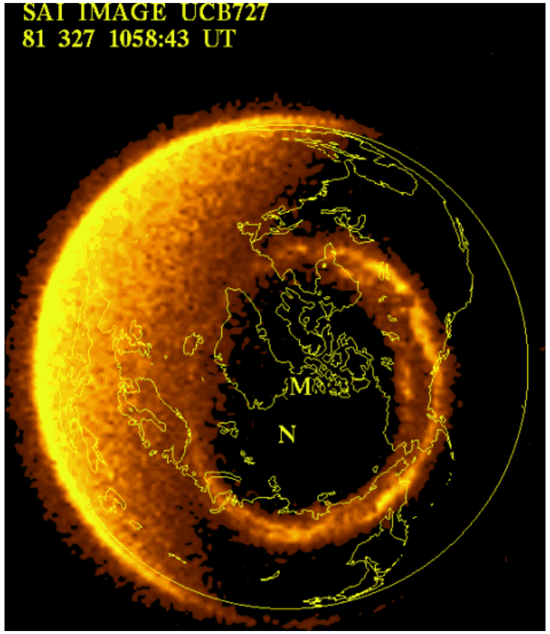
- Some auroral patterns arise from relatively steady *flows* (and *currents*) imposed on the planet's ionosphere through an interaction with some external 'energy source' or *driver*.

- 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.)

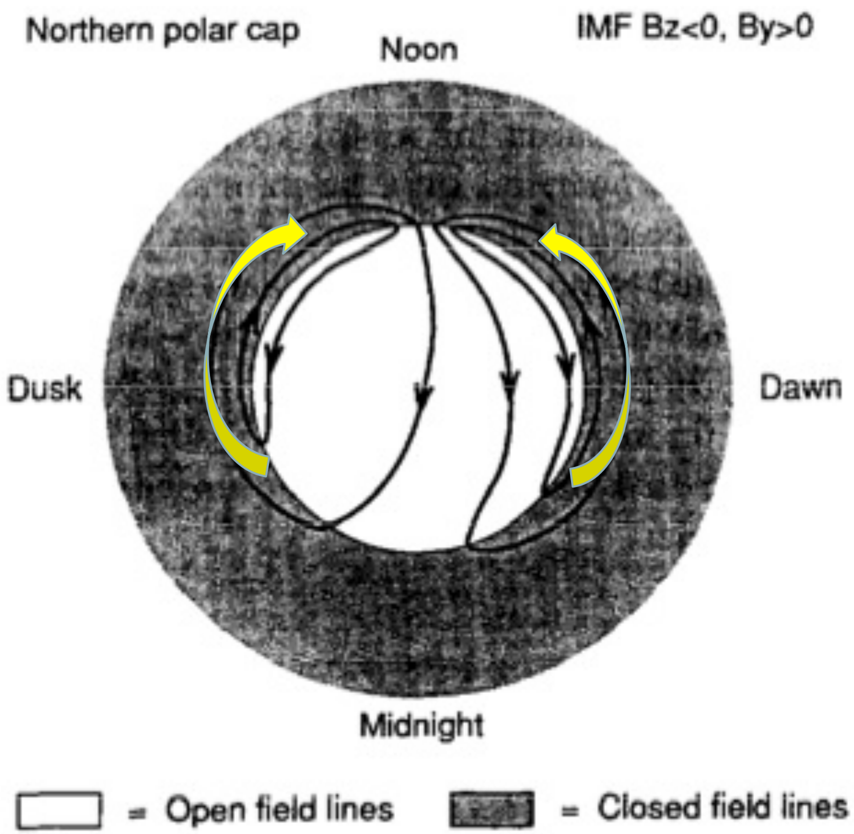


Fig. 1. A typical northern polar-cap convection pattern as observed for IMF $B_z < 0$, $B_y > 0$. Thick lines with arrowheads represent plasma flow streamlines. Antisunward convection occurs on open field lines (unshaded region) and sunward return flow on lower-latitude, closed field lines (shaded region).

From Hill (1994, JATP)

- 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 ?

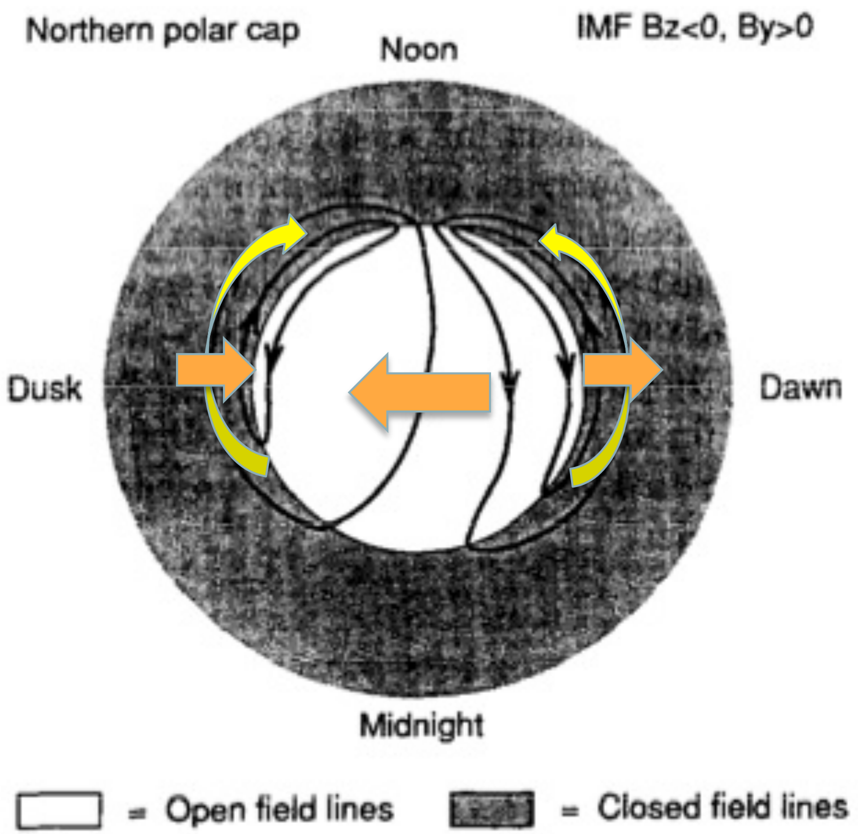


Fig. 1. A typical northern polar-cap convection pattern as observed for IMF $B_z < 0$, $B_y > 0$. Thick lines with arrow-heads represent plasma flow streamlines. Antisunward convection occurs on open field lines (unshaded region) and sunward return flow on lower-latitude, closed field lines (shaded region).

- *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 ➔ aurora.
- Example: Pedersen current – FACs at 'sharp' changes in **E**.

Auroral Oval: Earth

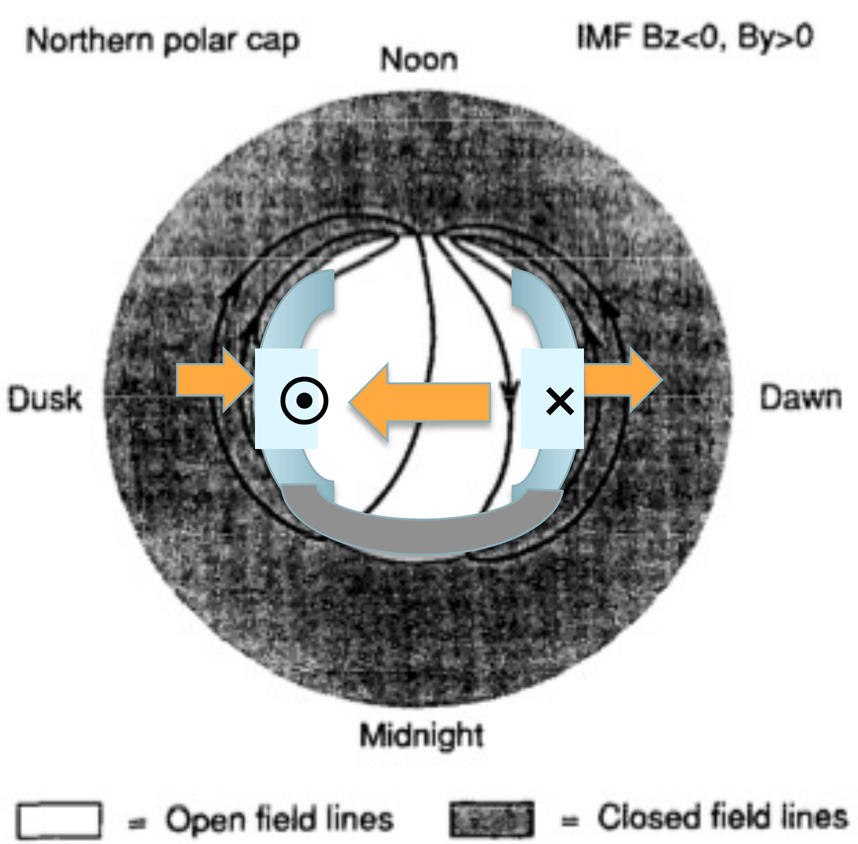
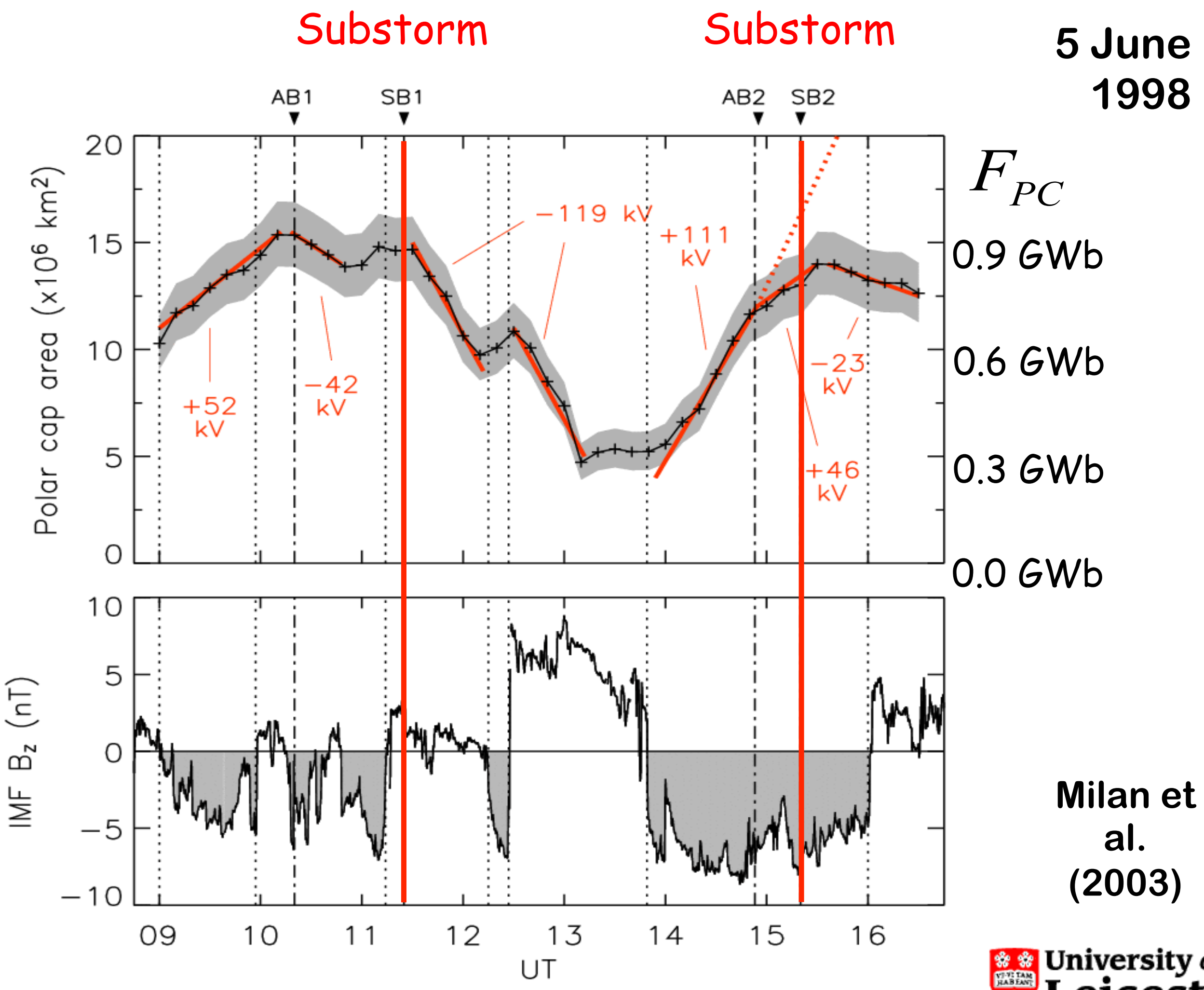


Fig. 1. A typical northern polar-cap convection pattern as observed for IMF $B_z < 0$, $B_y > 0$. Thick lines with arrow-heads represent plasma flow streamlines. Antisunward convection occurs on open field lines (unshaded region) and sunward return flow on lower-latitude, closed field lines (shaded region).

- Near-circumpolar sheets of FAC arise poleward ('Region 1') and equatorward ('Region 2') of the auroral oval.

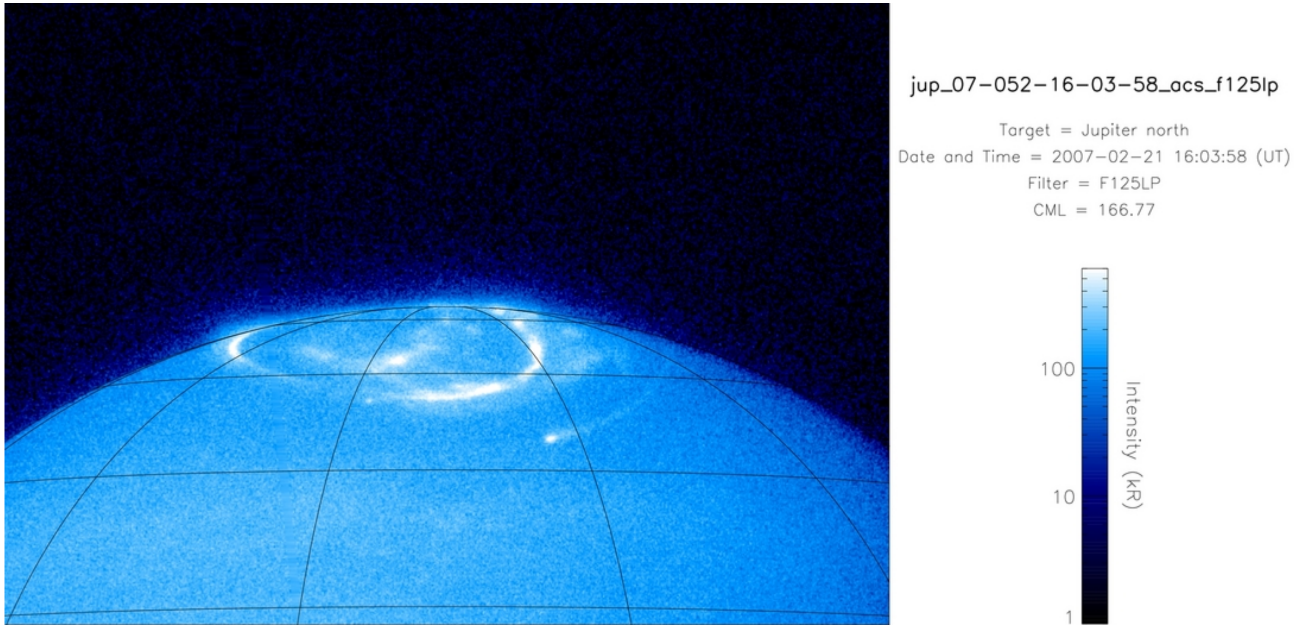
- Global auroral heat inputs, of order 10-100 GW (from particle precipitation and Joule heating).

- 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).

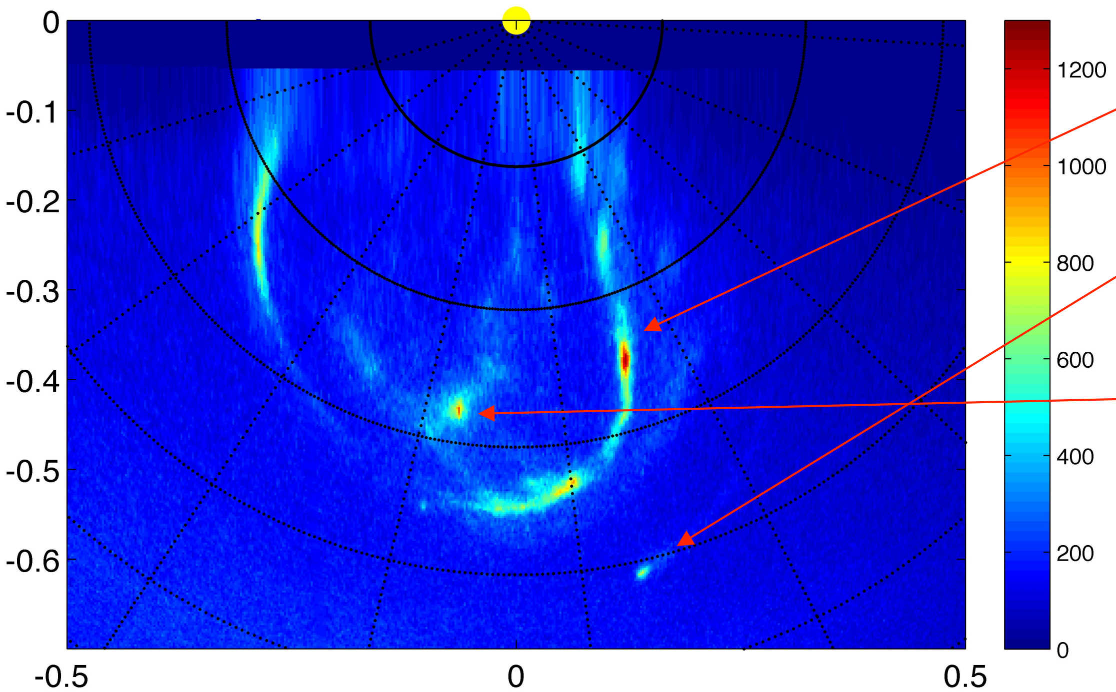


(Courtesy S. Milan)

Auroral Oval: Jupiter



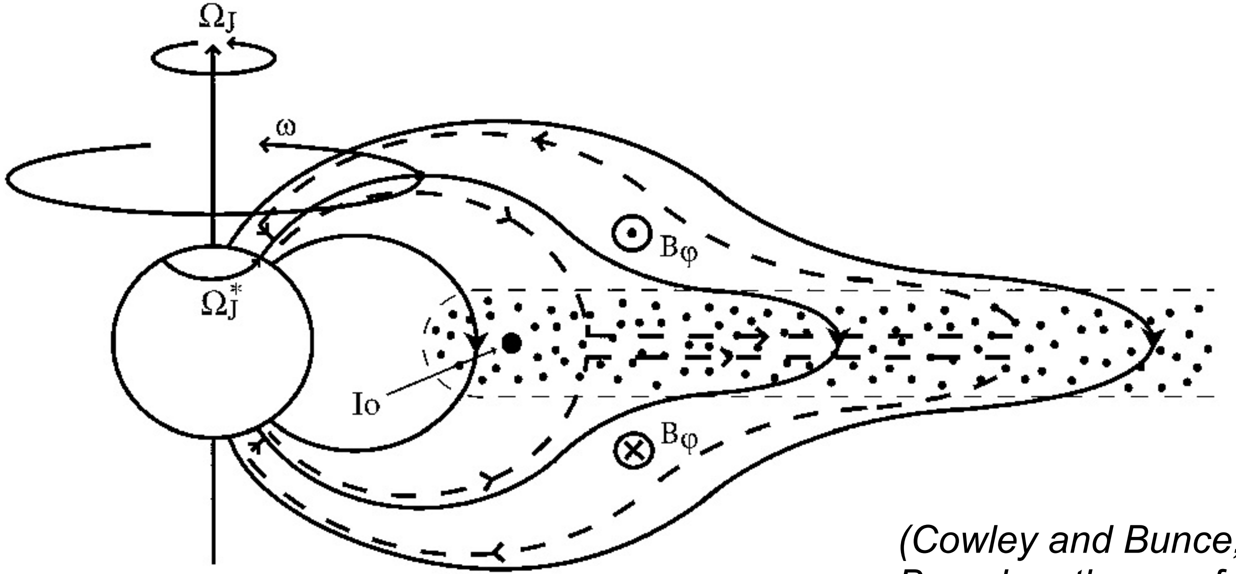
- UV image of Jupiter's aurora taken by HST ACS instrument.



Main oval – **corotates with the planet, it is not Sun-aligned.**

Io 'spot'

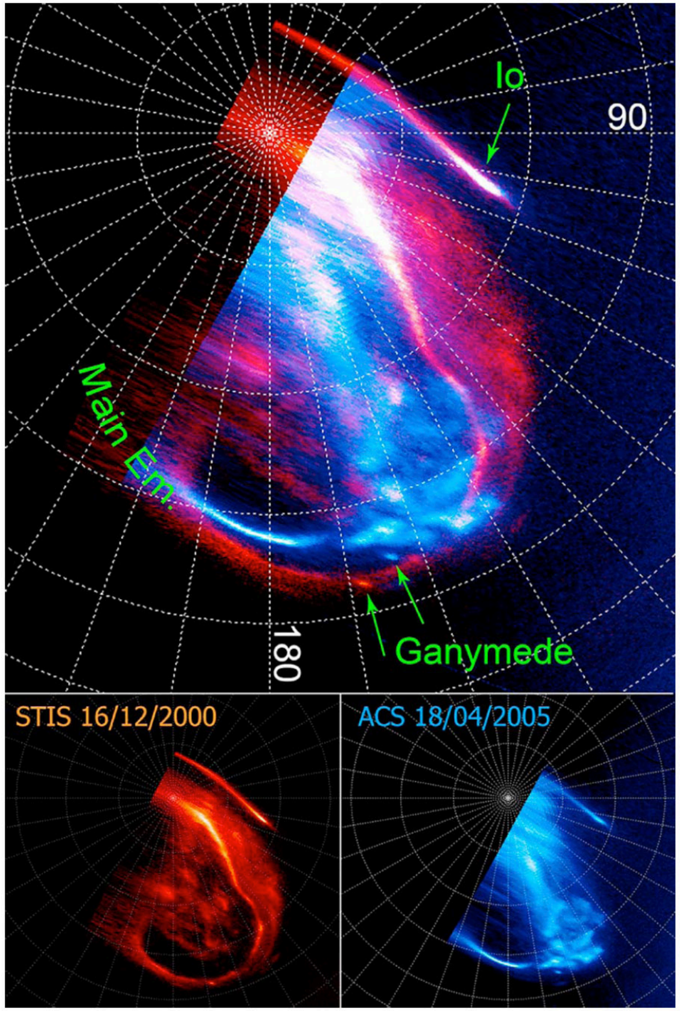
Cusp? (Talk by S. V. Badman, this meeting)



(Cowley and Bunce, PSS, 2001)
Based on theory of ***Hill (JGR, 1979)***

- 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 Jovian oval morphology ever change ? Here's an example (*Grodent et al (JGR, 2008), see also Bonfond et al (GRL, 2012)*)



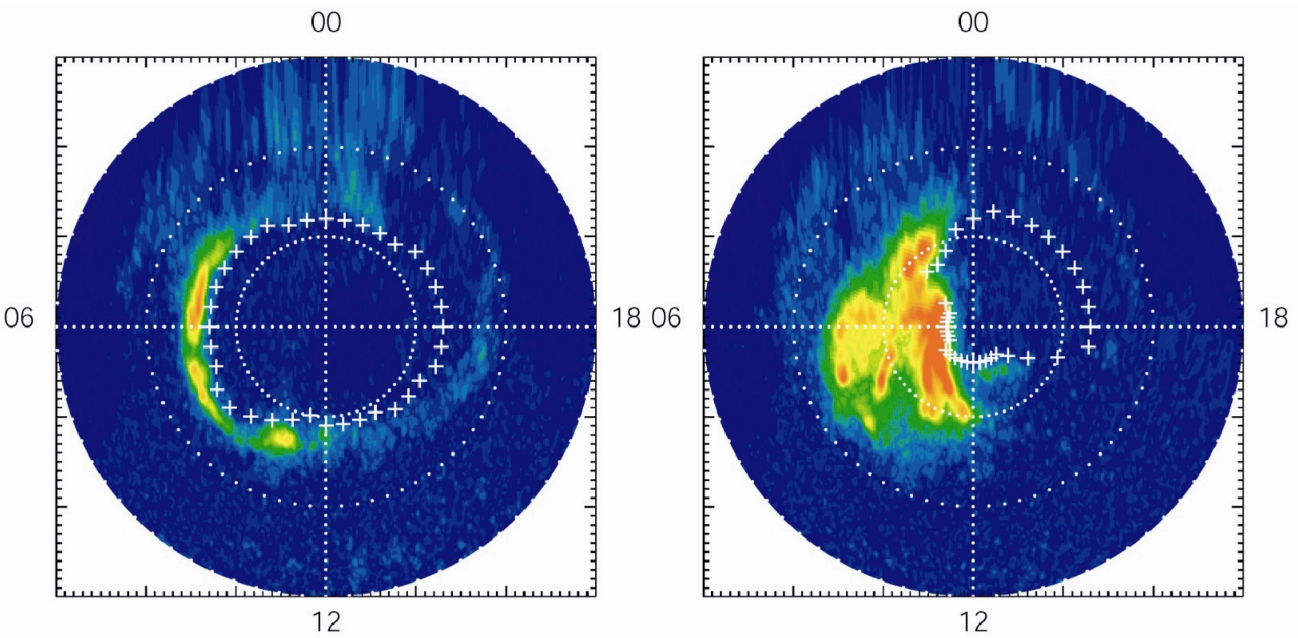
- Main emission in the 'red' image is 'displaced' equatorward by up to ~5 deg, at least as far as the satellite footprint of Ganymede.

- 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.

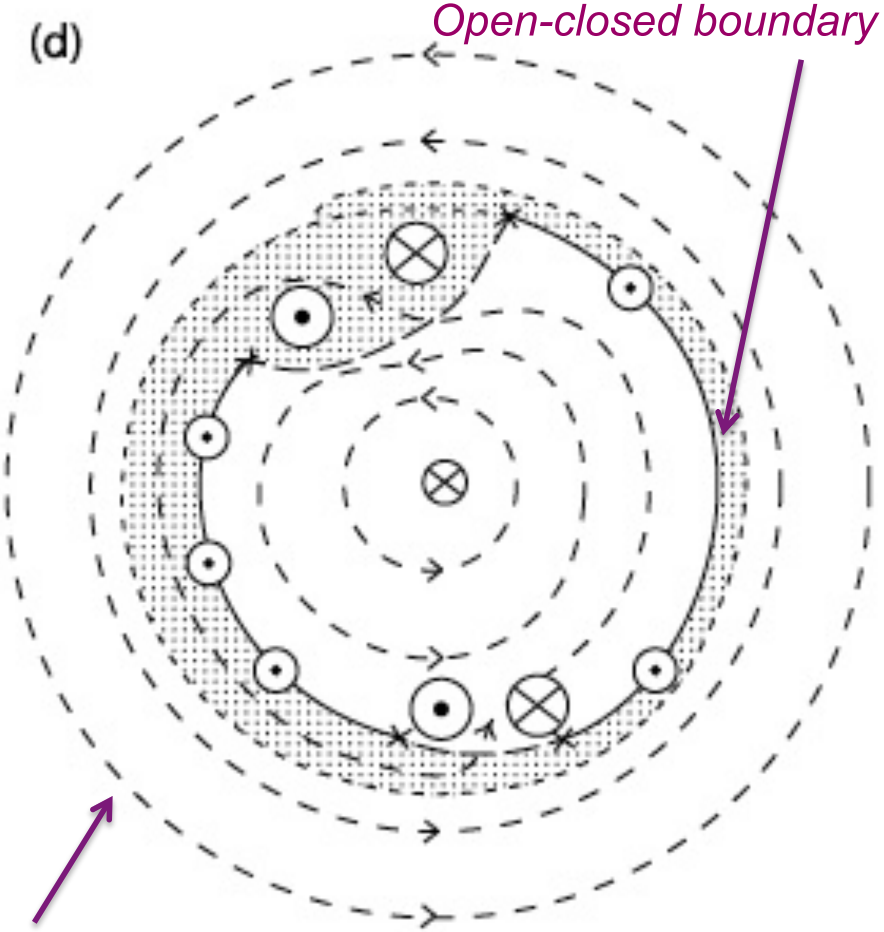
- Work in progress by *Achilleos et al. (2012)* indicates that hot particle population enhancement, combined with mass loading increase, may work.

Auroral Oval: Saturn



30 hours before SW shock *10 hours after SW shock, up to 50 kR emissions*

• 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).



Ionospheric flows out to 30 deg co-latitude

• *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 Ω_S) and polar cap (~0.3 Ω_S) *(Cowley et al, JGR, 2008)*. The energy dissipated is ~10-20 TW.

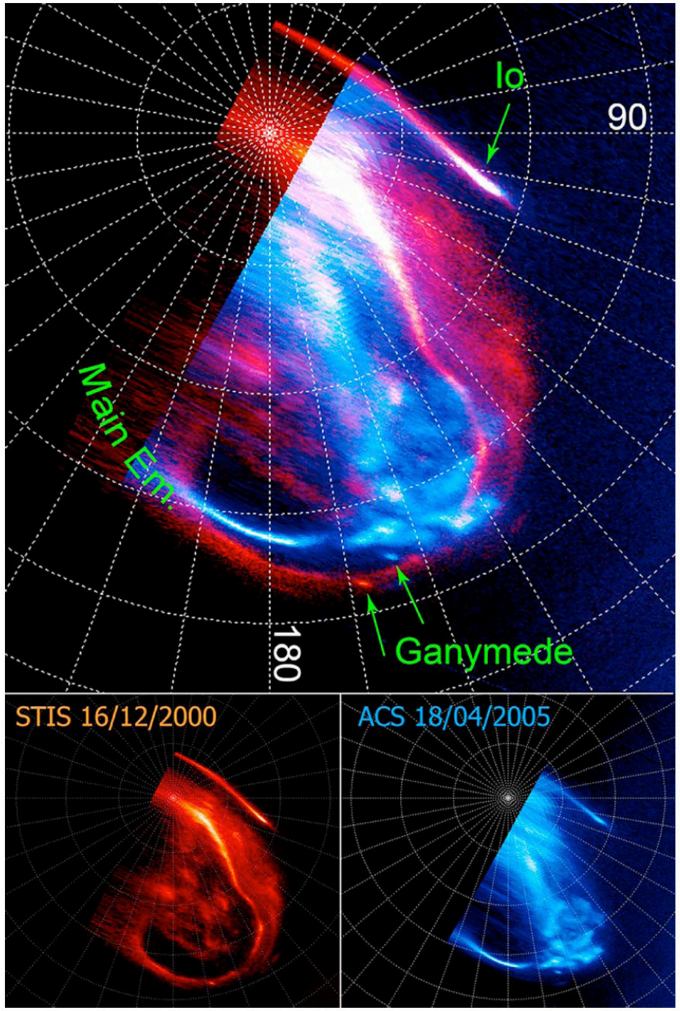
• Note that Saturn does have a 'Jupiter-like' aurora formed by internal rotation, but it is not the main emission (<~20% of main oval) *(Stallard et al, Nature 2008)*

Summary

	Earth	Jupiter	Saturn
Dipole moment	$1\mu_E$	$18000\mu_E$	$550\mu_E$
M'pause standoff distance R_{MP}	$1R_{MP,E}$	$80R_{MP,E}$	$20R_{MP,E}$
$P_{ROT}/(R_{MP}/V_{SW})$	~500	~2.5	~8
Auroral energy dissipated	~10s of GW	~100 TW	~20 TW
Main auroral 'oval' due to:	Solar wind-driven	Planetary rotation	Solar wind-driven*, with fainter rot'n oval
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)*

Auroral Features: Footprints

- 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))*



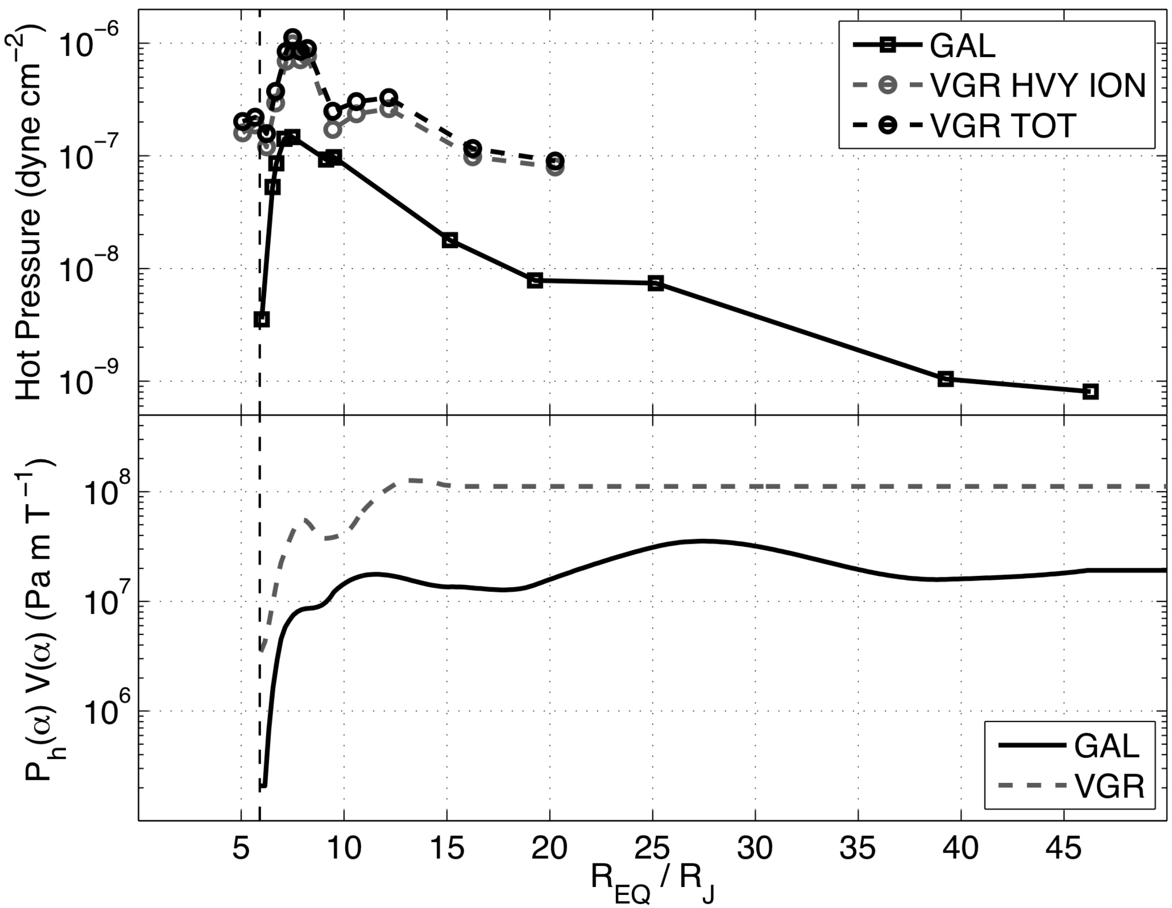
• The main emission in the 'red' image is 'displaced' equatorward, at least as far as the satellite footprint of Ganymede.

• 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



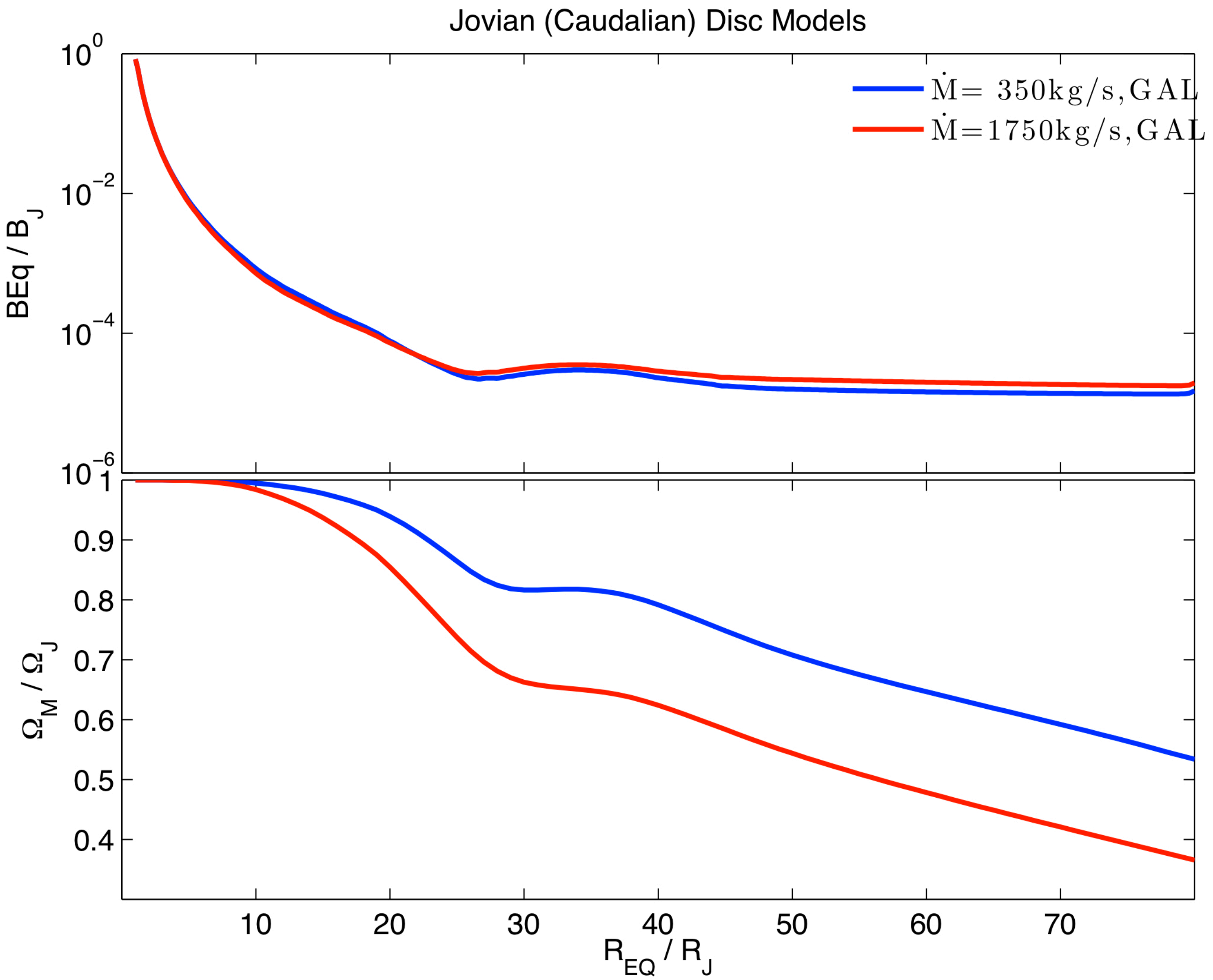
- The Voyager and Galileo observations were compared by *Mauk et al. (JGR 1996)* who described a 'ring current depletion' in the Galileo era.

- 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.

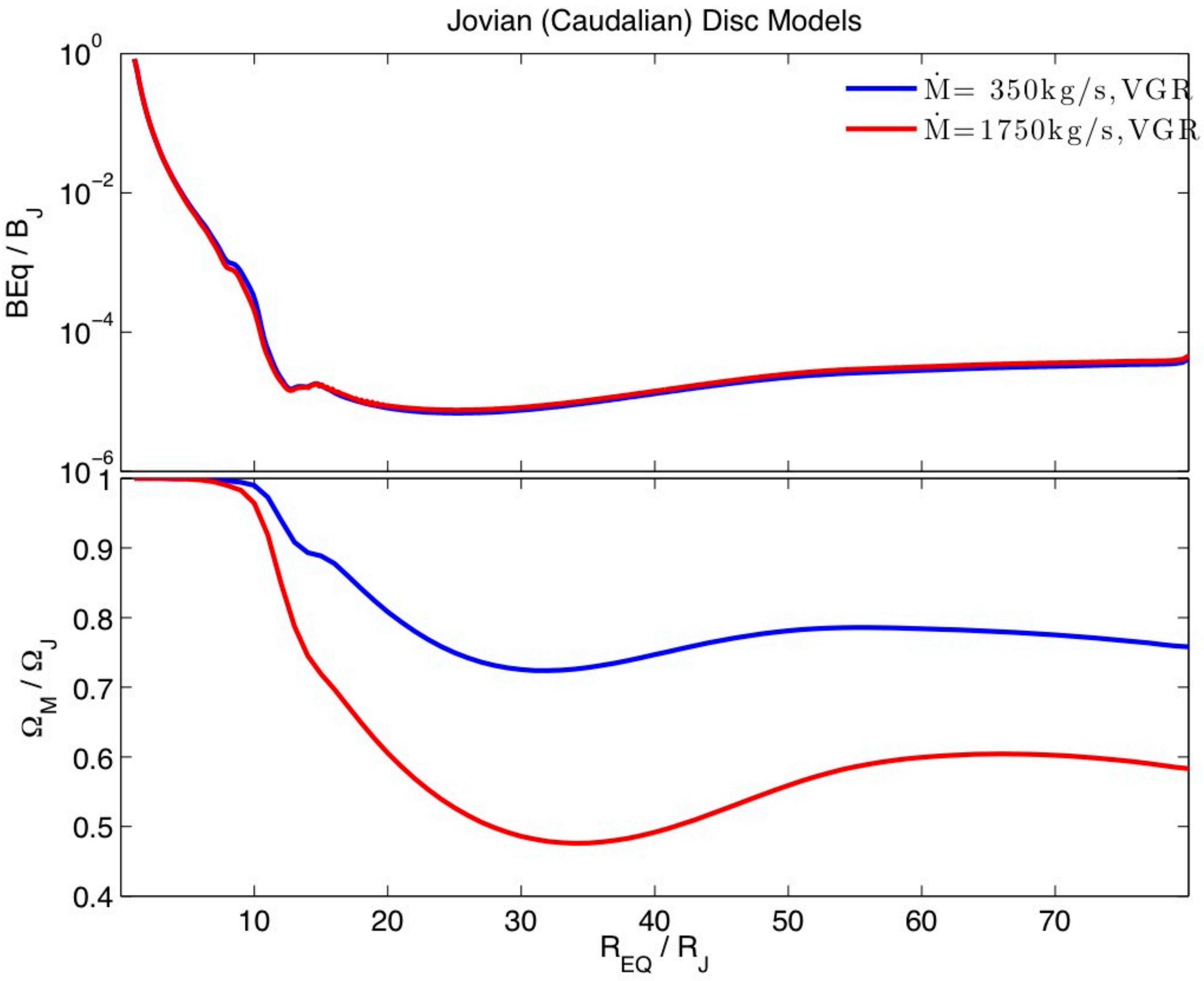
- The model solves for magnetic field structure and plasma rotation rate in a self-consistent manner (see also *Caudal, JGR, 1986*).

Rotation Model: ‘Cold’ Disc (Galileo)



Rotation Model: ‘Hot’ Disc (Voyager)

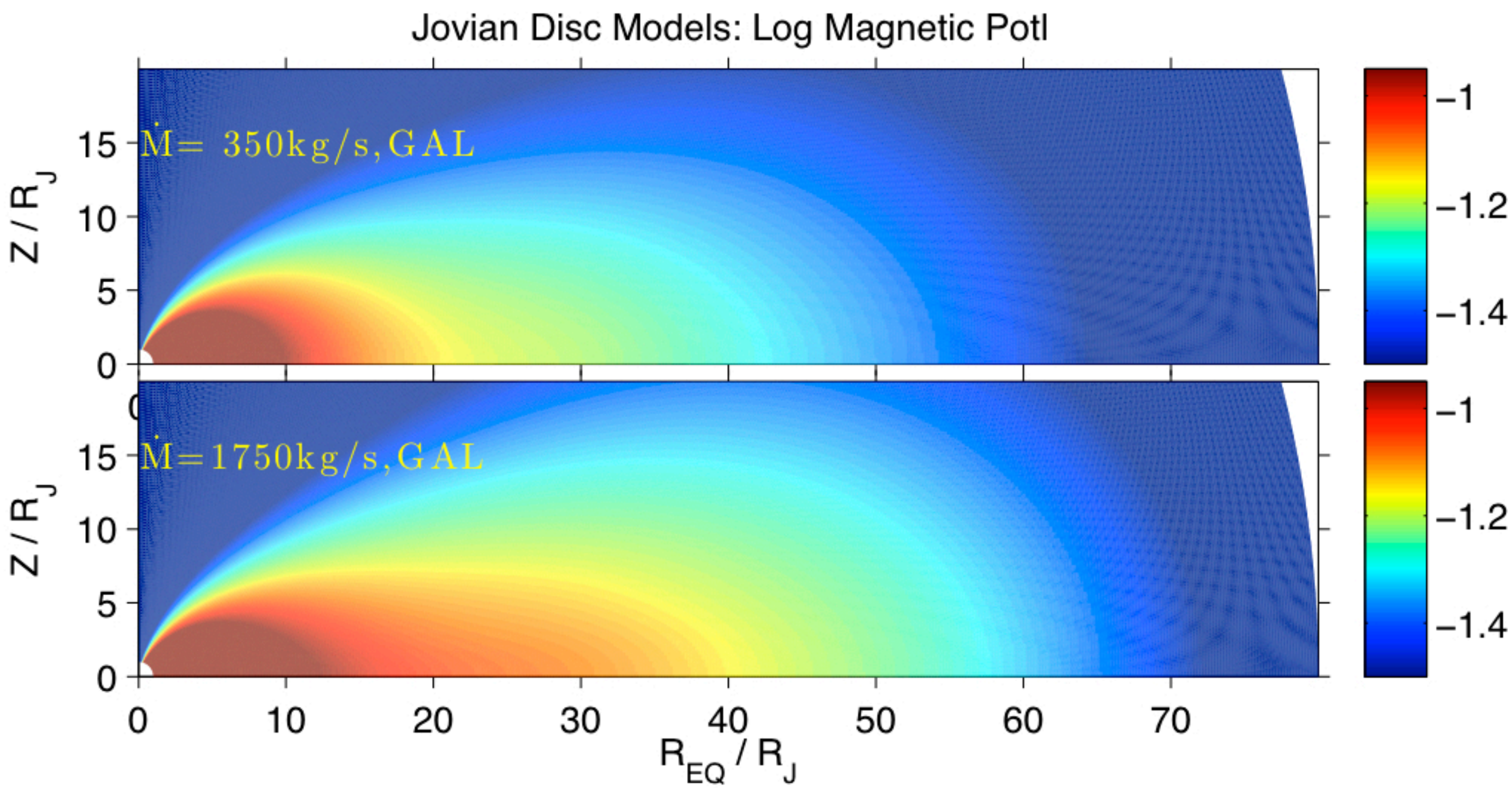
UCL



• Note the broad local minimum in magnetic field strength and angular velocity - why ?

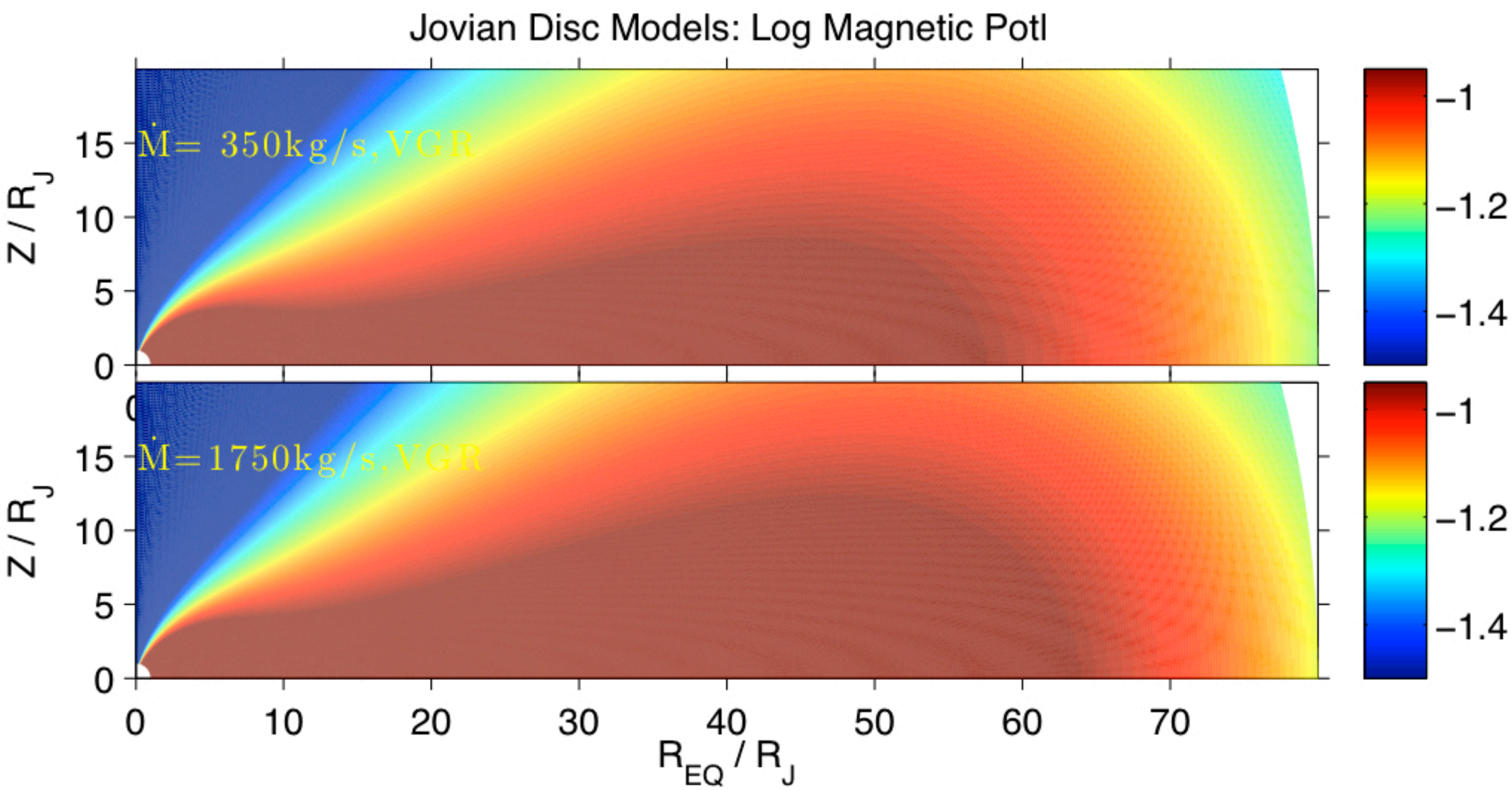
Field Model: ‘Cold’ Disc (Galileo)

UCL



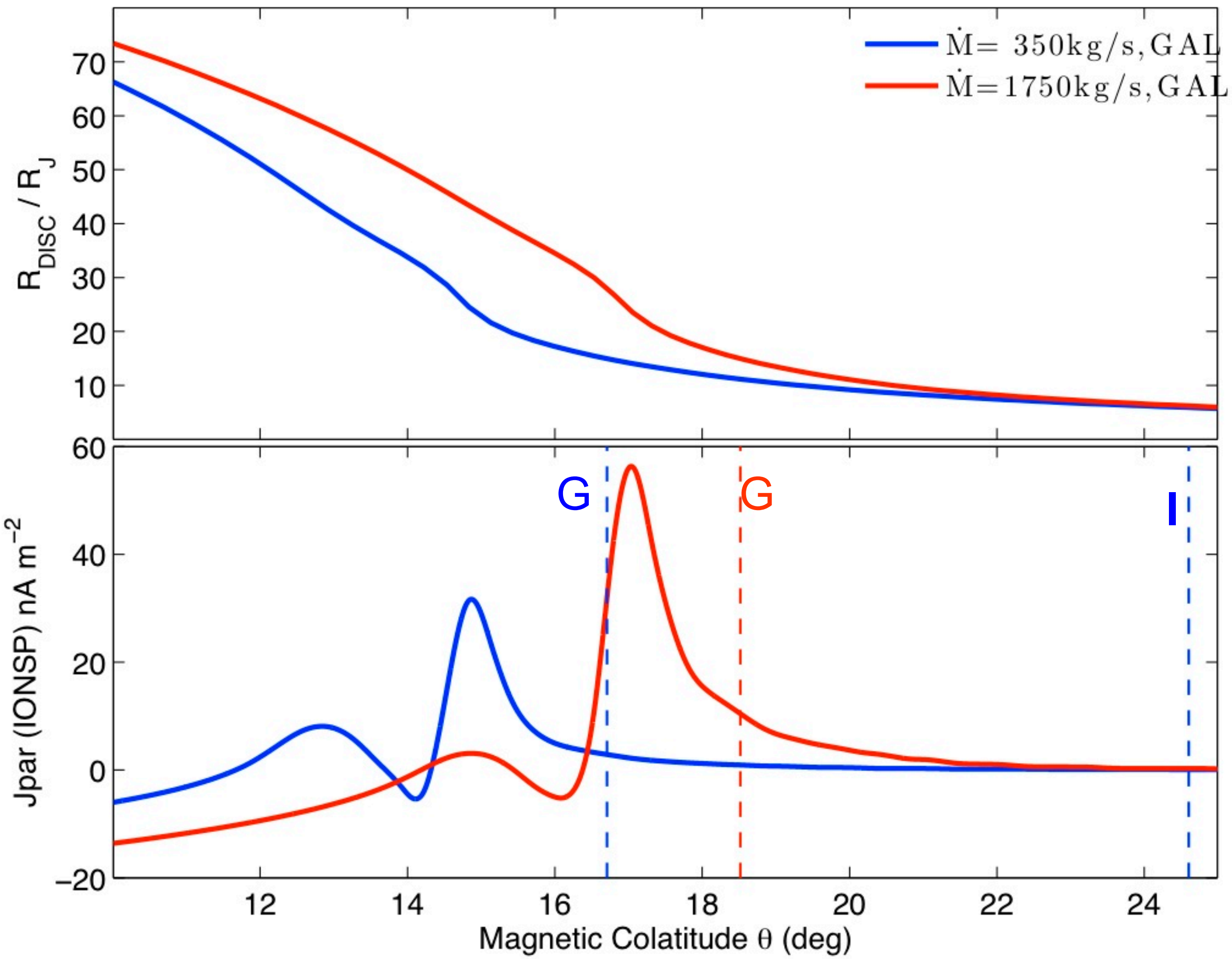
- ‘Constant colour’ surfaces are ‘shells’ of magnetic field lines
- Colour can be interpreted as the location of that field line’s *ionospheric footpoint*

Field Model: 'Hot' Disc (Voyager)



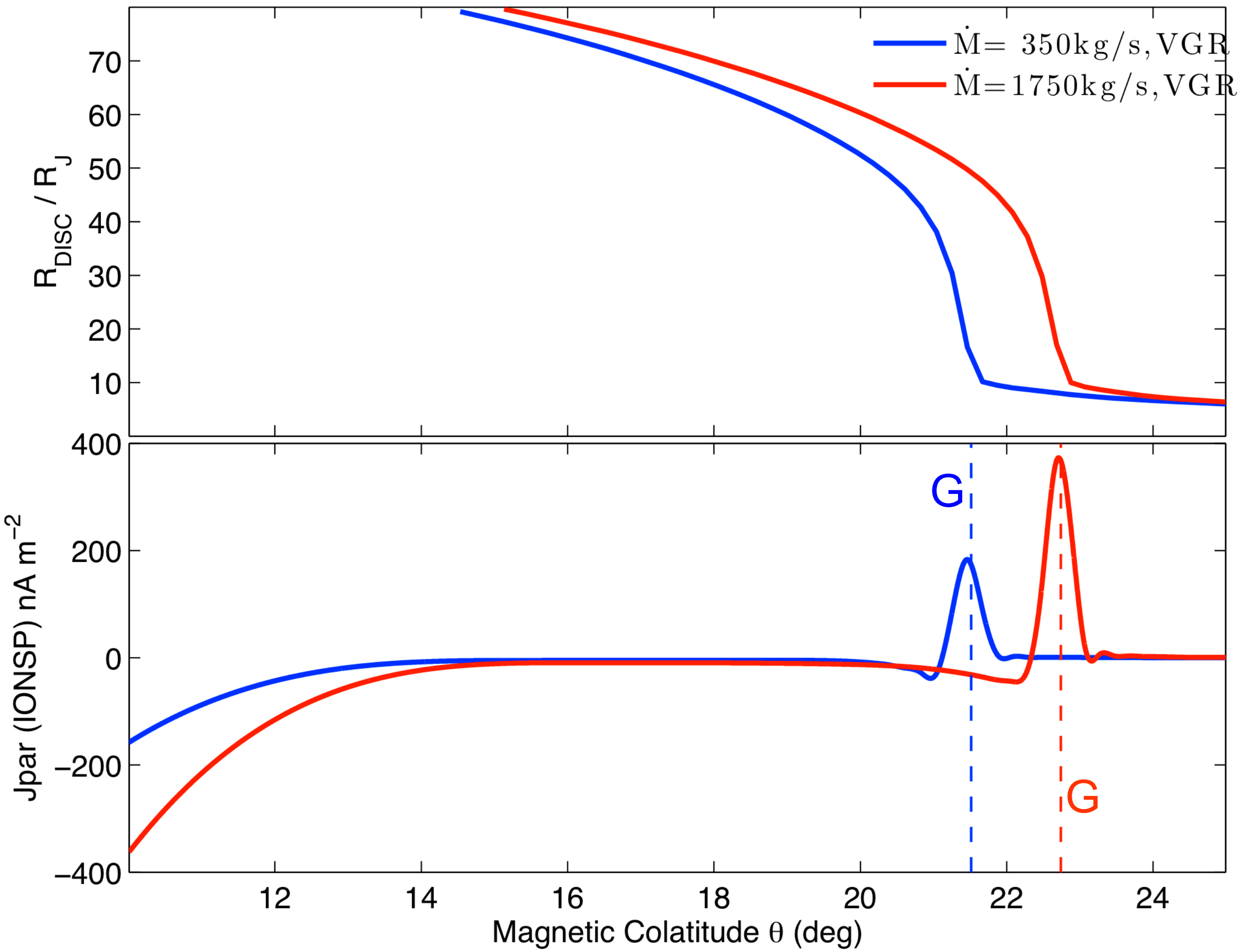
• A *global* increase in hot pressure 'inflates' flux tubes, and pushes them outwards, until *force balance* with the magnetic field is re-established.

Auroral Current: ‘Cold’ Disc (Galileo)



- Unusually high mass-loading shifts aurorae equatorward, but not to the level where main oval and Ganymede spot coincide.

Auroral Current: ‘Hot’ Disc (Voyager)



- ‘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.

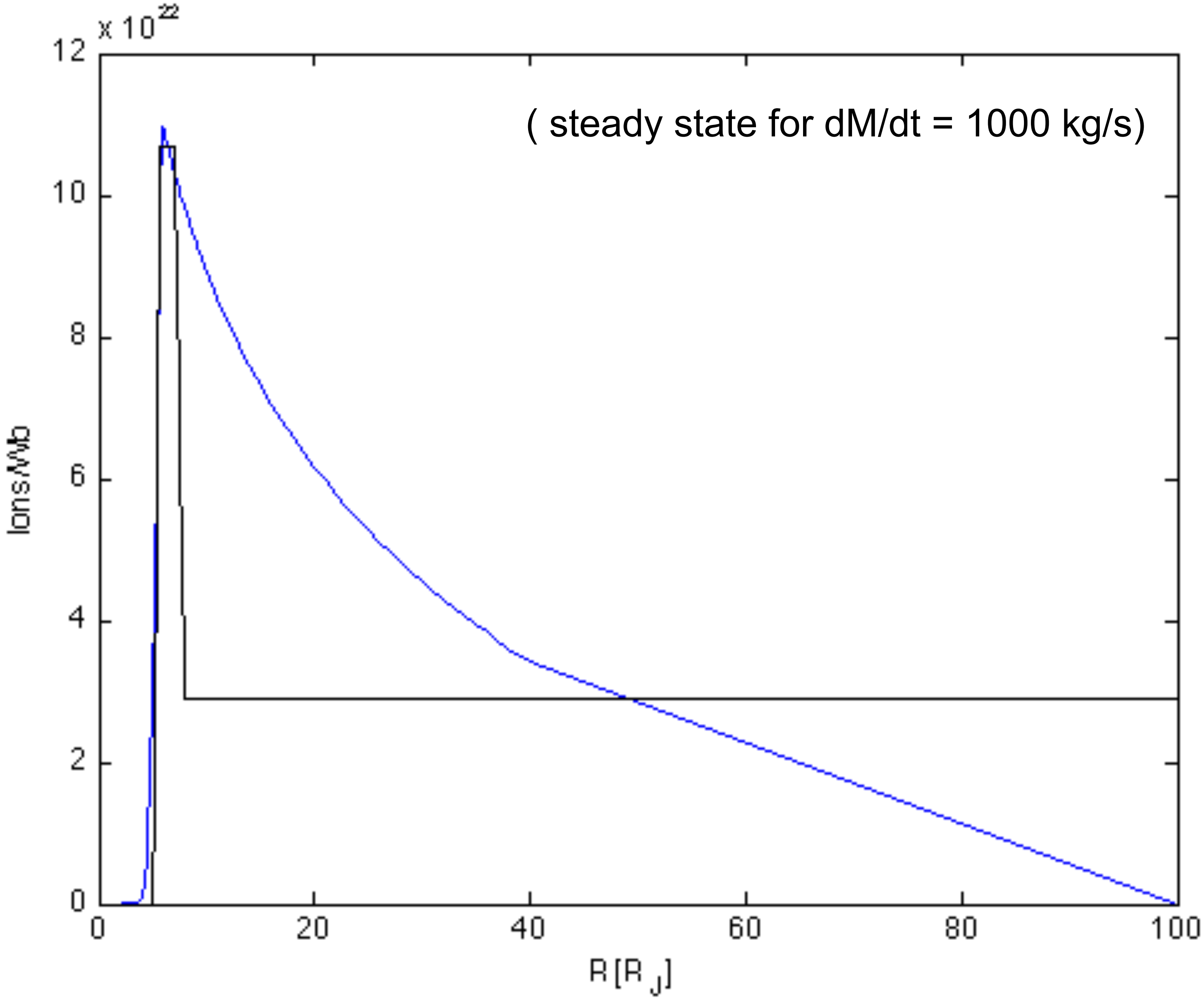
• Could additional modelling constrain changes in mass-loading, hot plasma *as a function of 'auroral shift'* (?)

- 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.

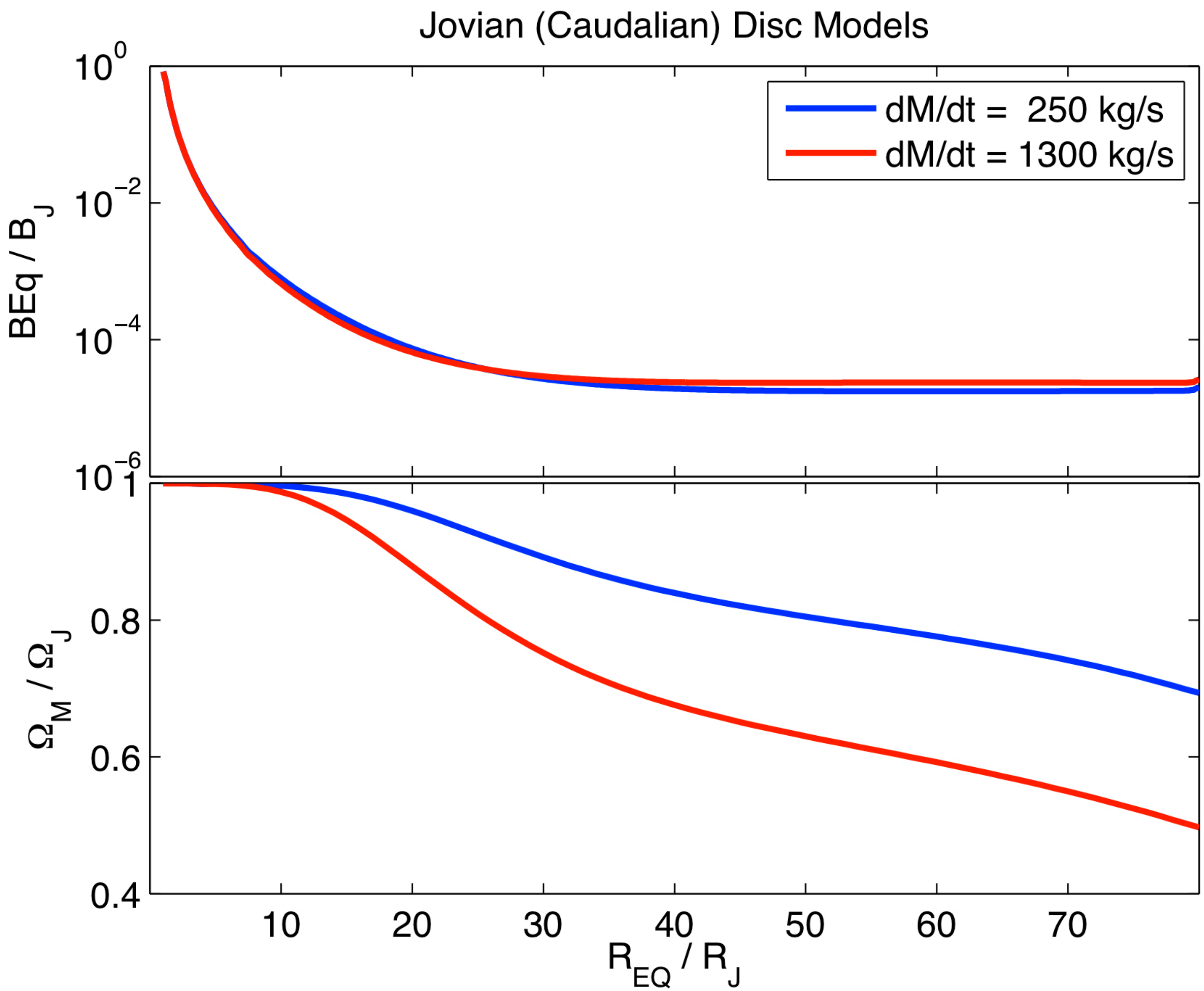
$$\frac{\partial(NL^2)}{\partial t} = L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial(NL^2)}{\partial L}\right) + SL^2$$

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

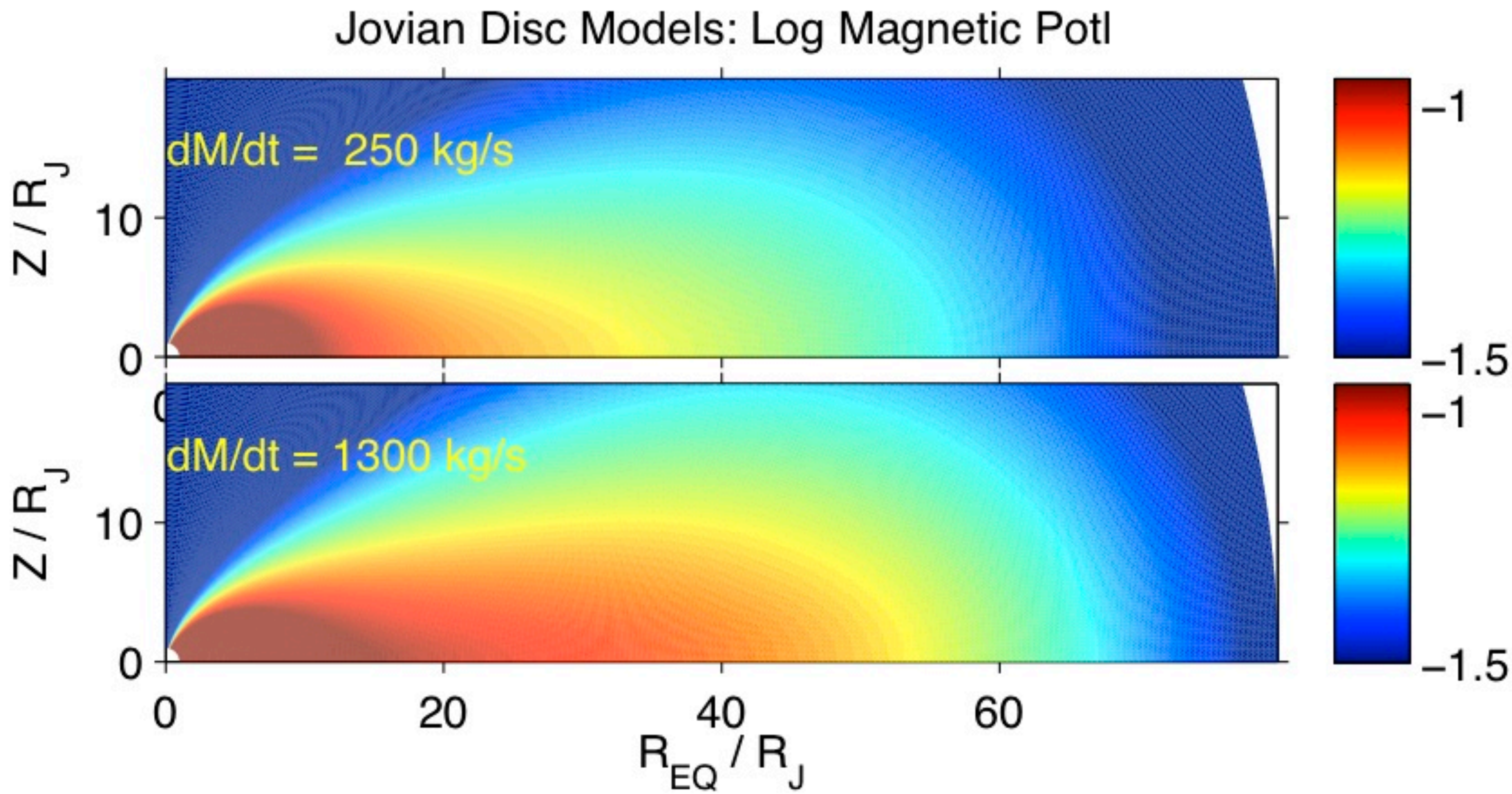


Preliminary Results

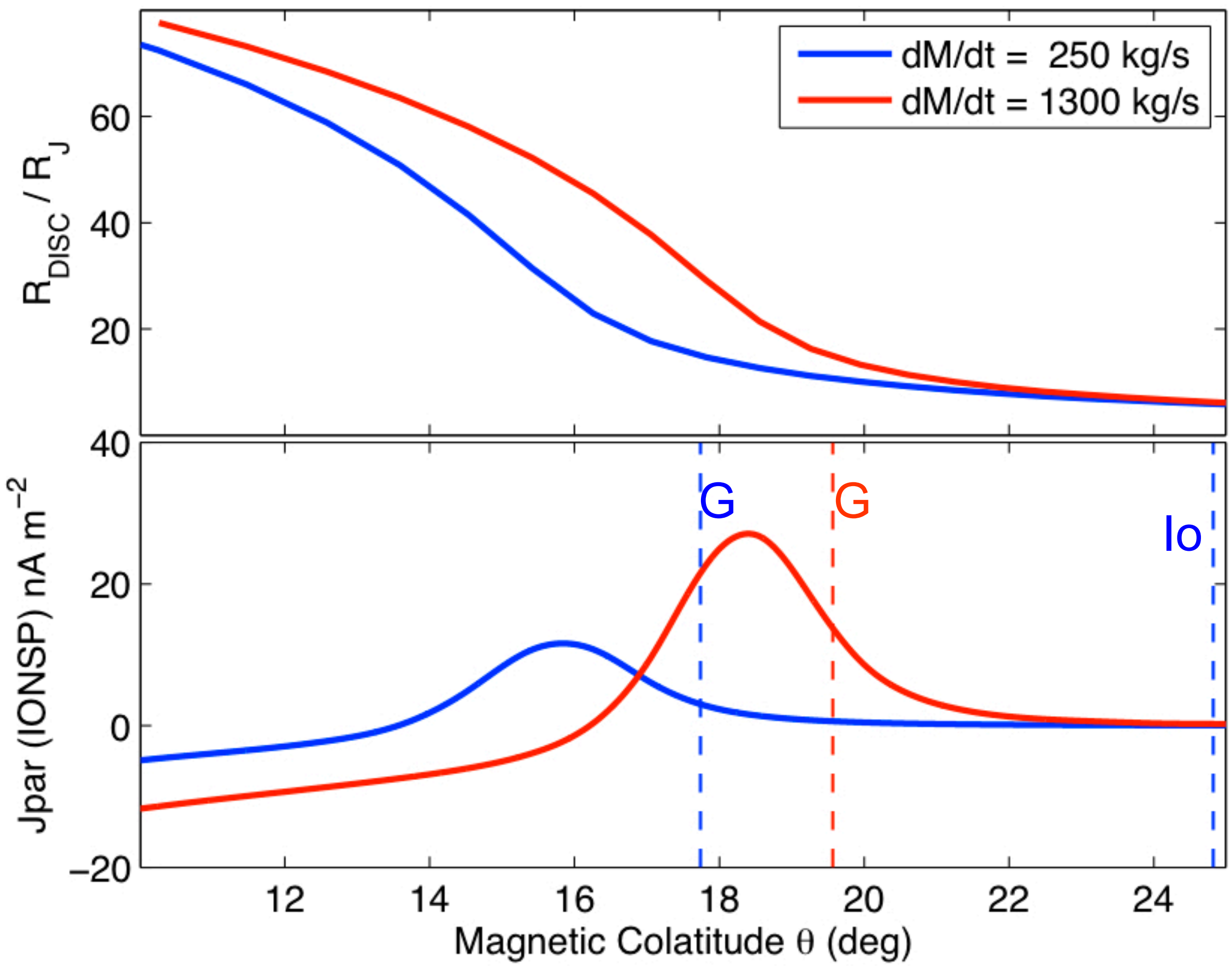


(Results have converged within a maximum 'tolerance' of ~5%)

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



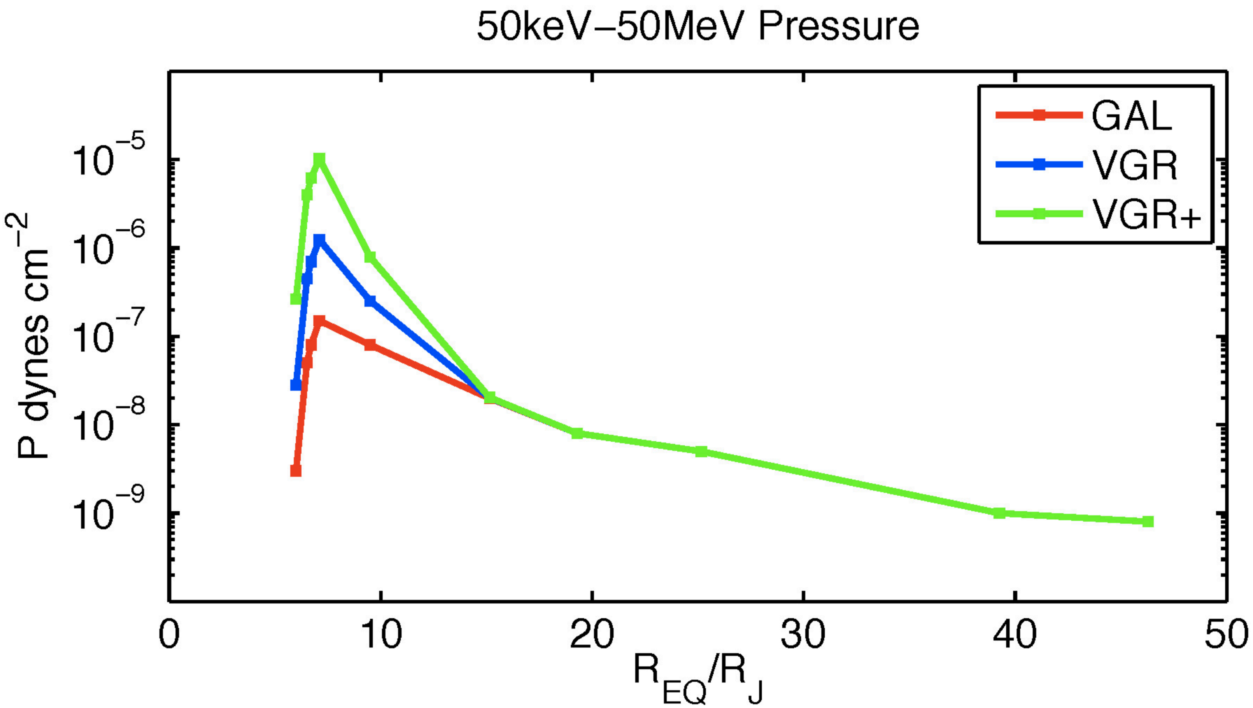
Jovian Disc Models: Log Magnetic Potl
dM/dt = 250 kg/s
dM/dt = 1300 kg/s
Z / R_J
10
0
20
40
60
R_EQ / R_J
−1
−1.5



- 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.

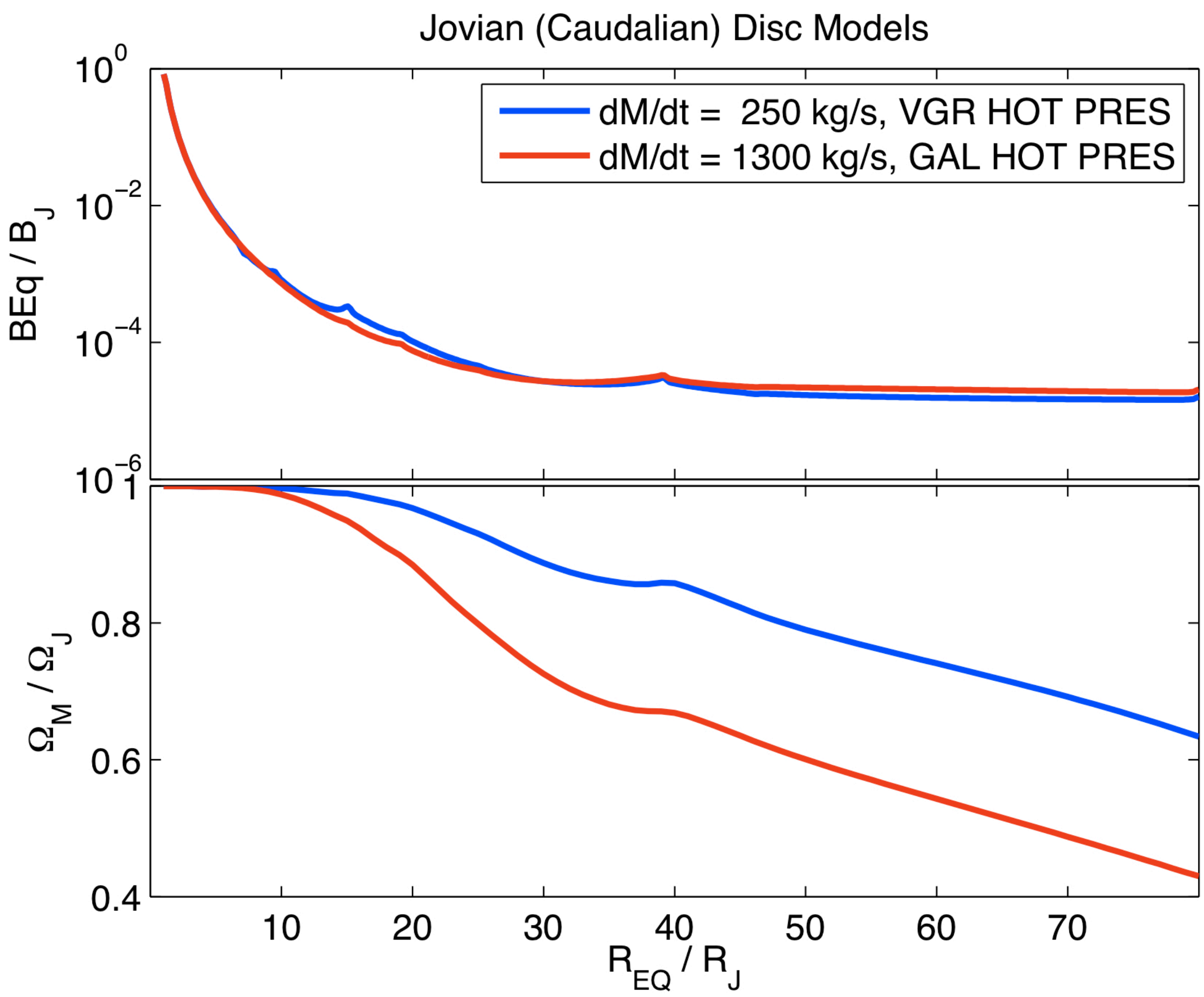
- If mass-loading only is responsible for shift, need enormous dM/dt to make Ganymede and 'main auroral' footprints 'touch' (as indicated by recent, unusual HST observations) !



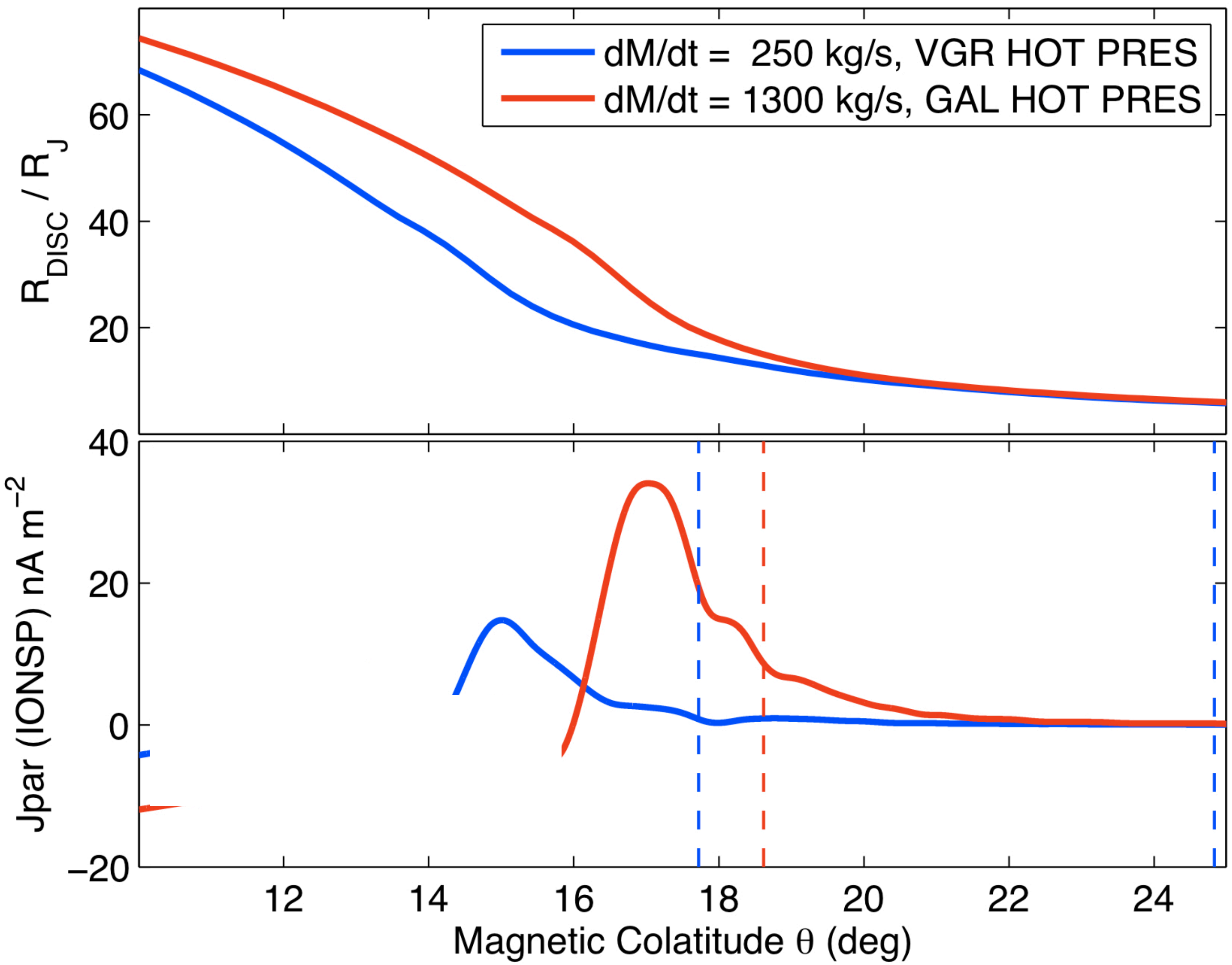
- *Mauk et al (JGR, 2004)* examined the hot plasma pressure measurements of *Voyager* and *Galileo* - 'ring current depletion' in region <~ 15 RJ, possibly due to increased Io neutral loading, charge exchange.

- We also show a 'fake' profile, labelled 'VGR +', to use as an additional 'test case'.

The data points represent many orbits, etc…



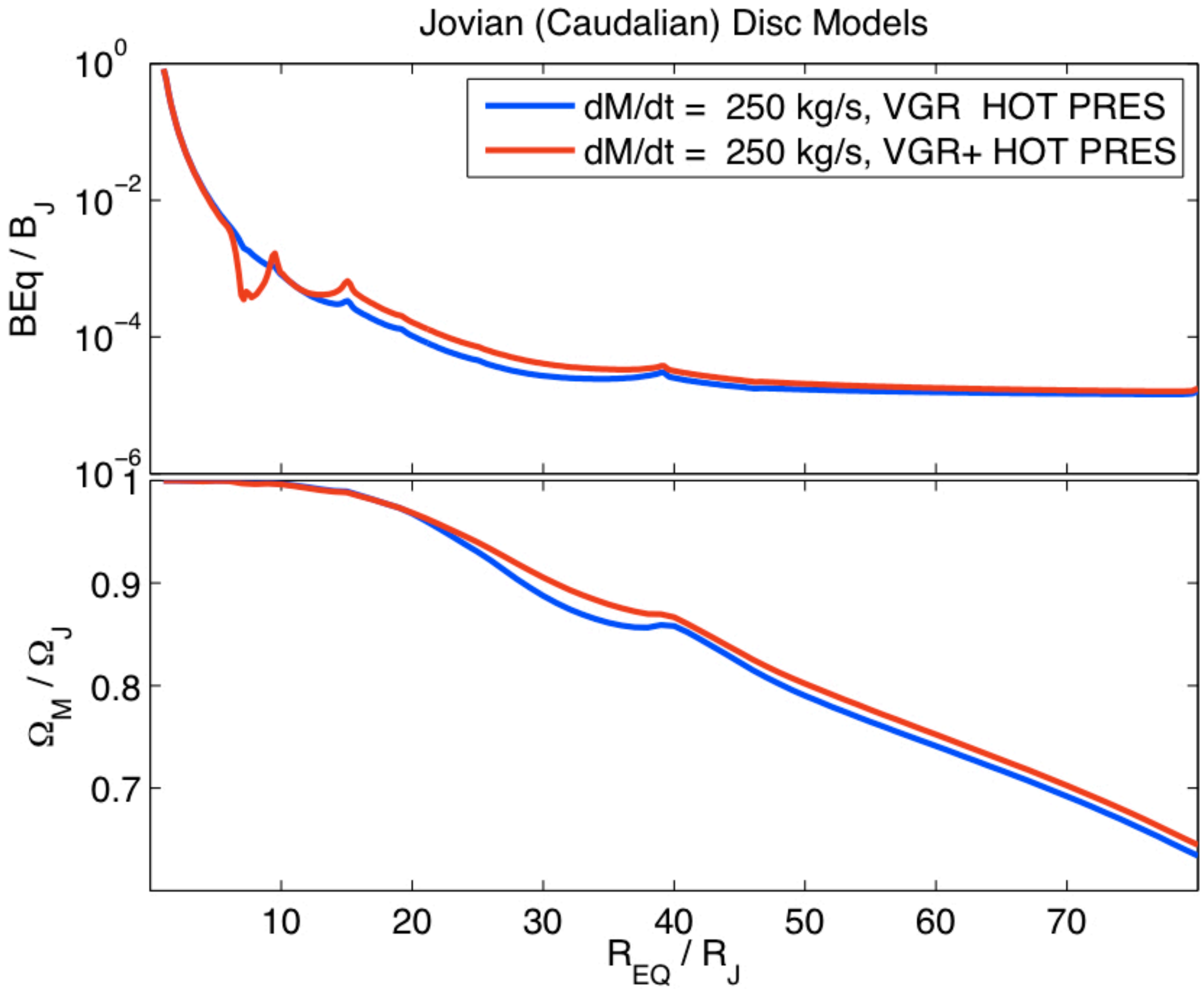
- Higher mass-loading produces a more slowly rotating disc.
- For these choices of dM/dt, relatively small change in equatorial field strength.



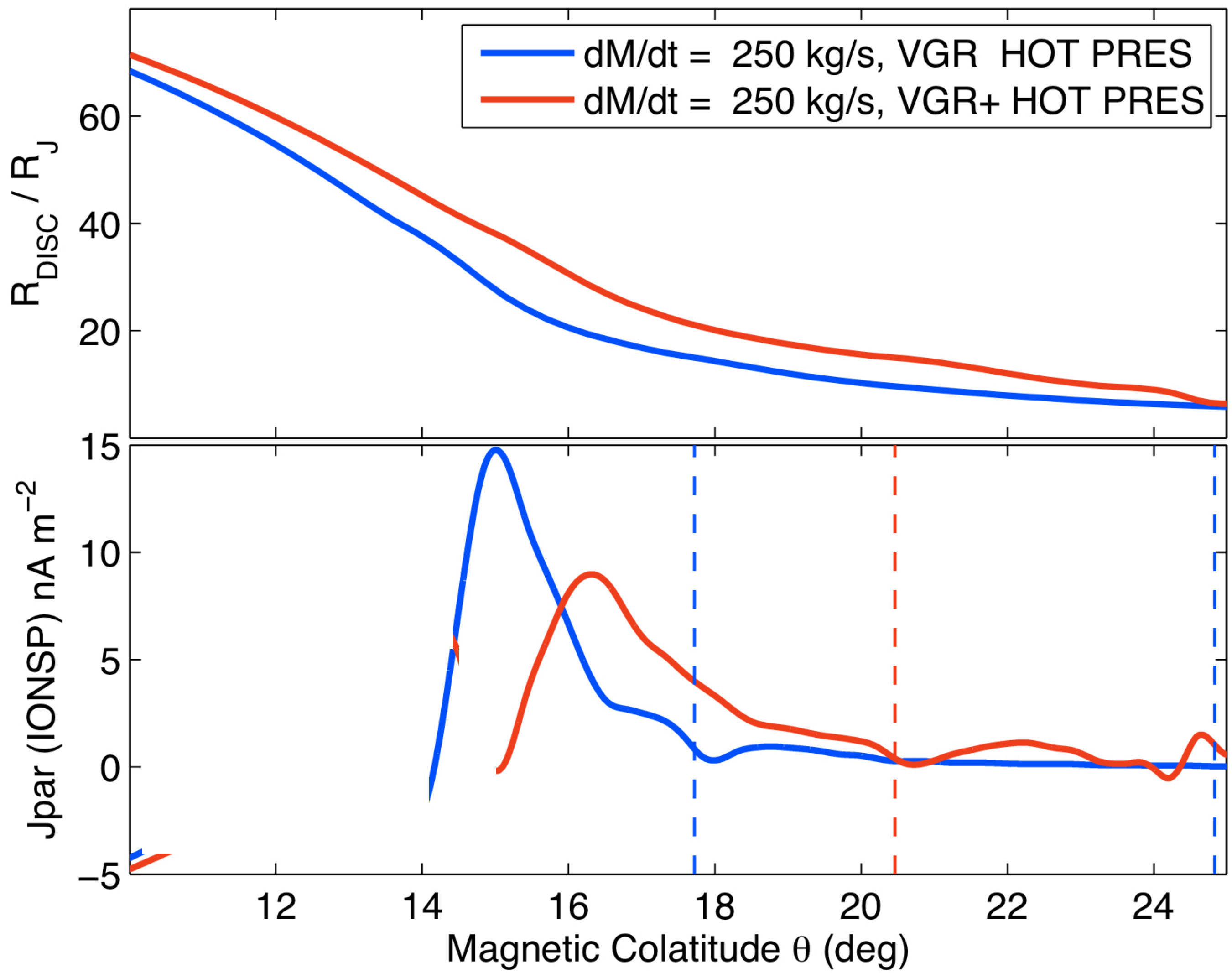
- As expected, higher mass-loading increases the radial 'stretch' of the field lines.

- 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.*

Voyager / 'Voyager +' Comparison



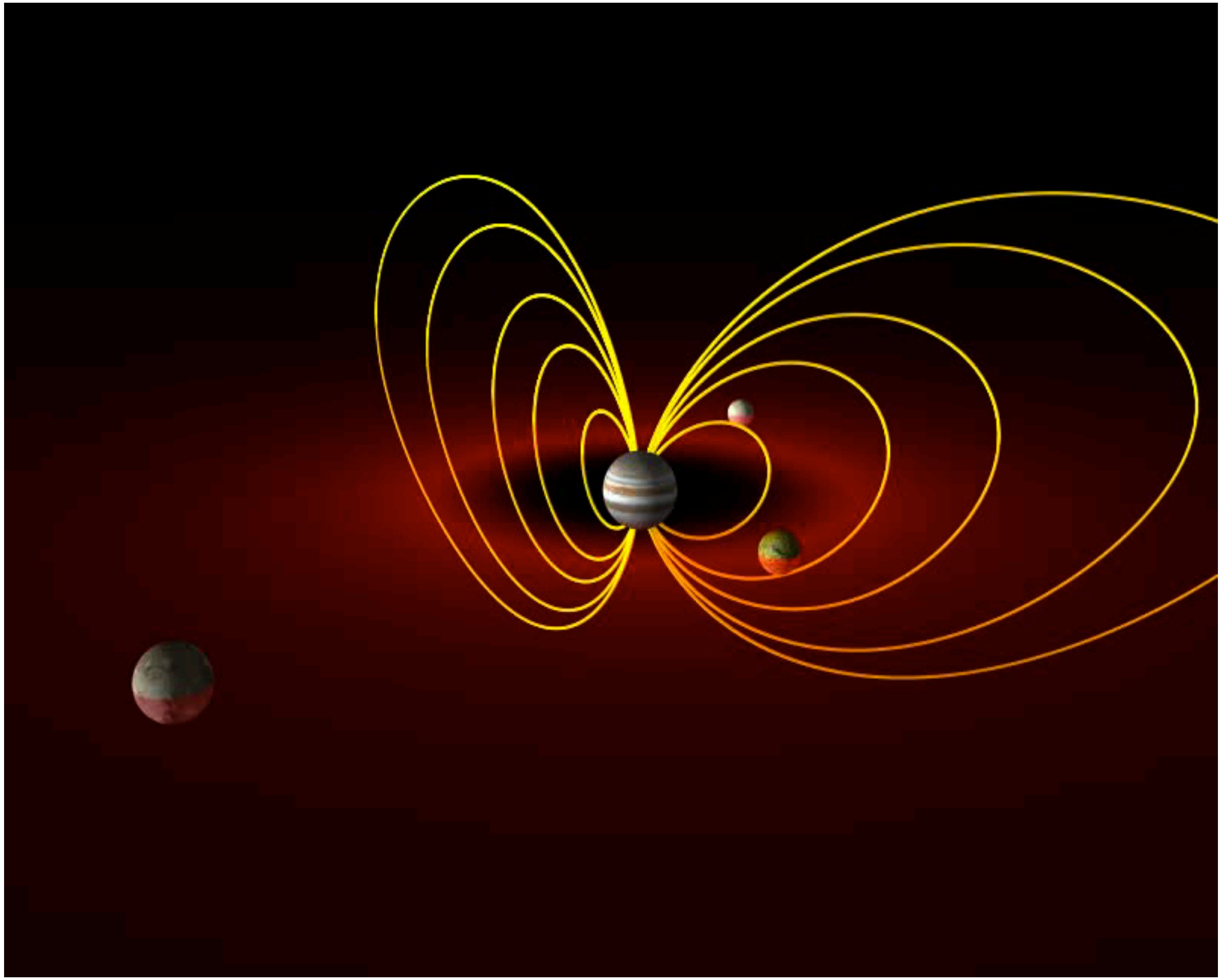
- Here, dM/dt is fixed but hot pressure is enhanced in VGR+.
- Disc rotation not changed appreciably - most mass is in the cold population, slight change due to hot pressure affecting field line shape.



- 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:



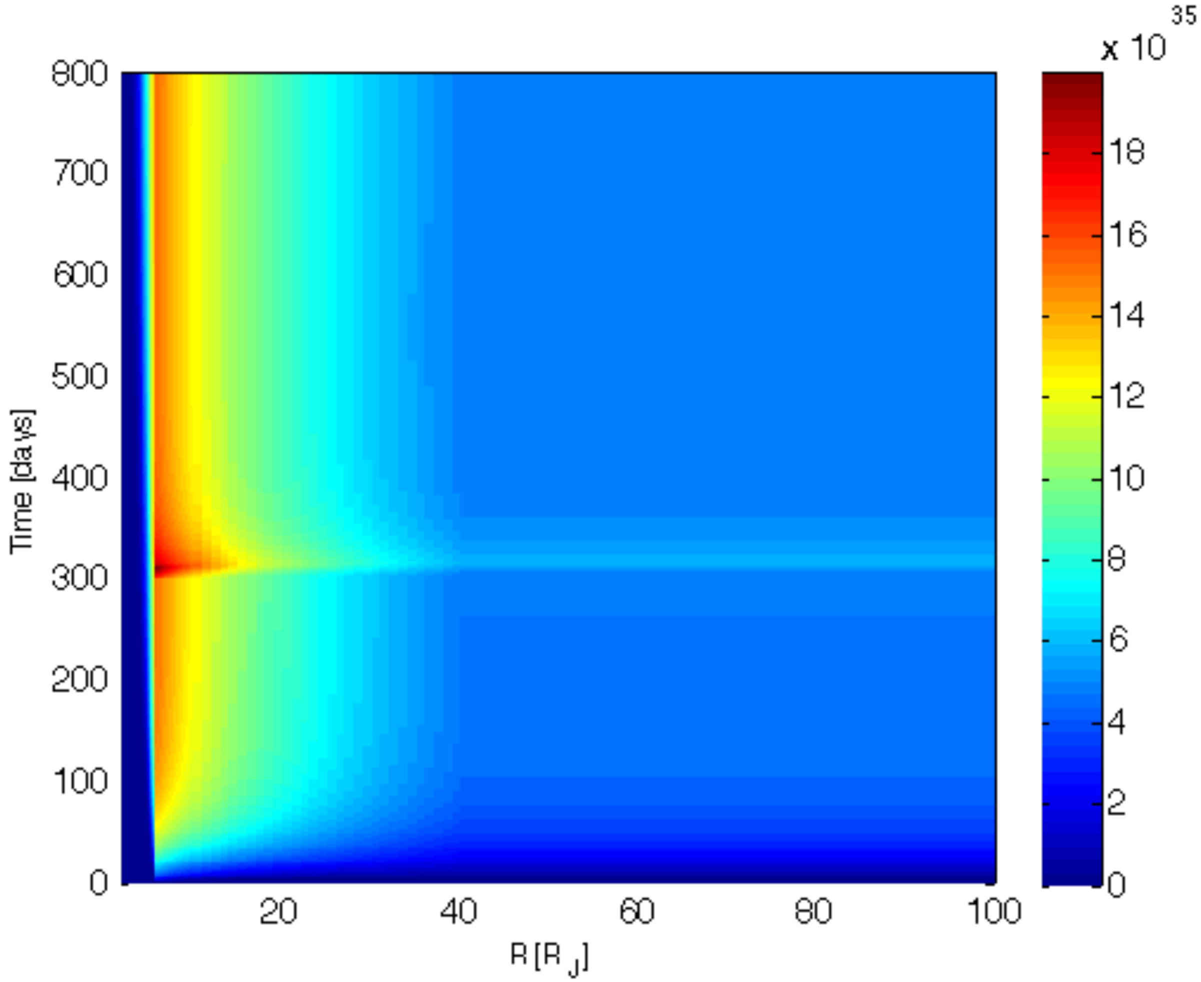
Summary

- 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 Iogenic 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 ?