Planetary Magnetospheres

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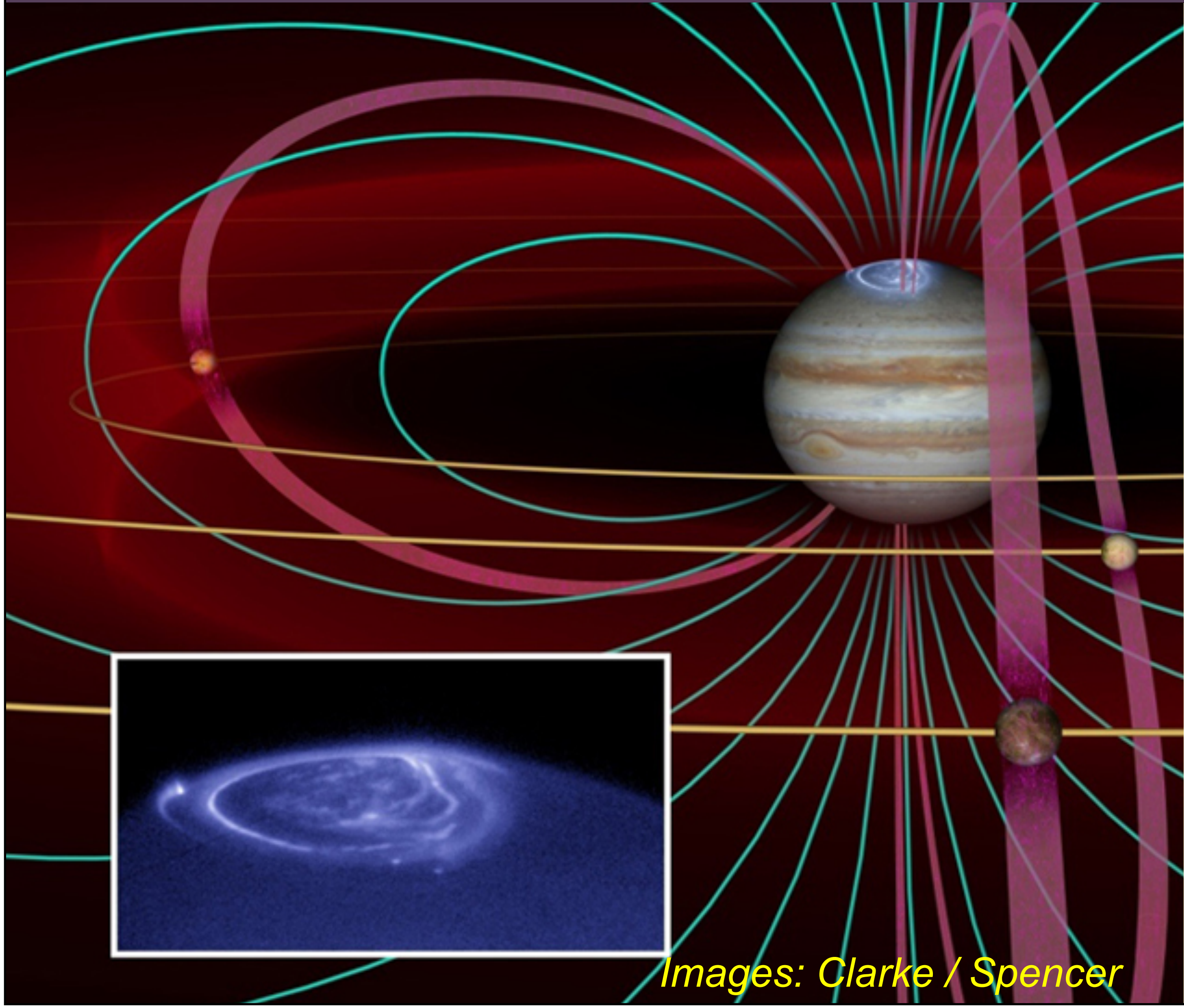
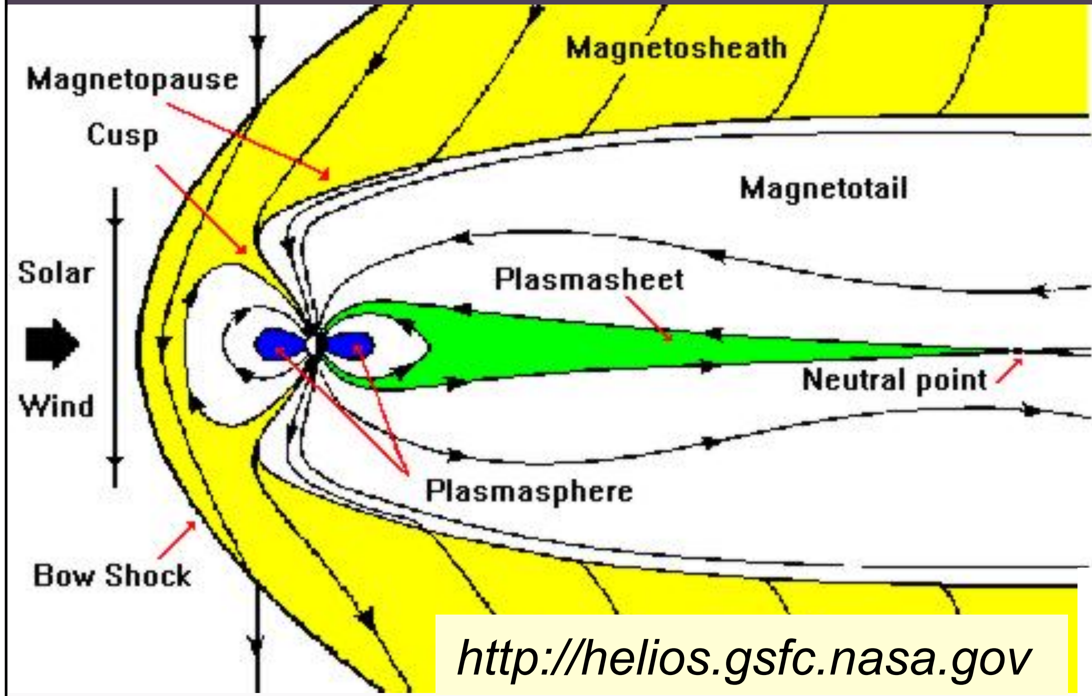
(Solutions to homework: www.ucl.ac.uk/~ucapnac)



- Interaction between *plasmas* and *magnetic fields*
- *Motion* of particles in magnetic fields - on larger 'fluid' scales ?
- Dominant type of plasma flow ?
- Compressibility?
- Solar wind versus 'internal' effects (rotation)
- Magnetosphere-ionosphere *coupling*

Overview: Solar Wind–Magnetosphere Interaction



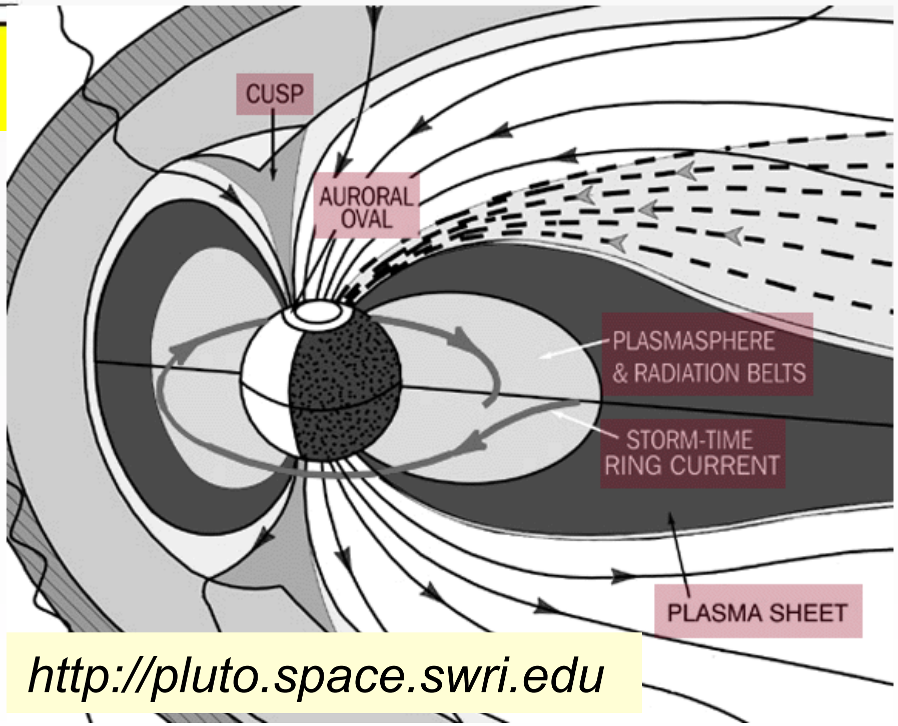
http://helios.gsfc.nasa.gov

🡐 Noon-midnight 'slice'.

- Boundaries *and* points of 'entry' for plasma (magnetic reconnection)
- Strong asymmetry in field structure.
- *Plasmasheet*: hot (~keV), low-density (~0.3 cm^{-3})
- *Plasmasphere:* cool (~1 eV), high-density (~10^3 cm^{-3}), flow is in sense of planetary *corotation*

'Close-up'.🡒

- *Ring current* region.
- *Auroral oval* associated with particles which impact neutral molecules in atmosphere.



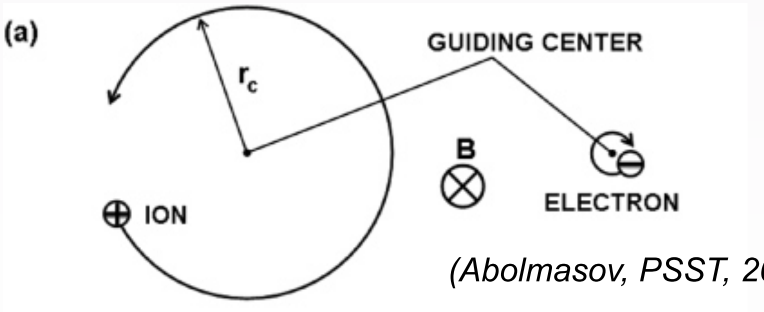
http://pluto.space.swri.edu

Starting Point: Particle Motion in a Magnetic Field

- **Lorentz Force:** For a particle of charge *q,* mass *m* and velocity **v** moving in electric field **E** and magnetic 'field' **B** (N.B. SI units):

$$\mathbf{F_L} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) = m\frac{d\mathbf{v}}{dt}$$

- **Motion:** If **E=0** and **B** = B $\mathbf{e_z}$ in Cartesian frame (uniform field along *z*), *xy* motion is *circular* (right-handed for *electrons*) with angular frequency
$\Omega_C = |q\,B/m|$ (cyclotron or gyrofrequency)
the radius of the circle is $r_C = |mv_\perp/(q\,B)|$ (also called Larmor radius)
where $v_\perp$ = speed perpendicular to **B**

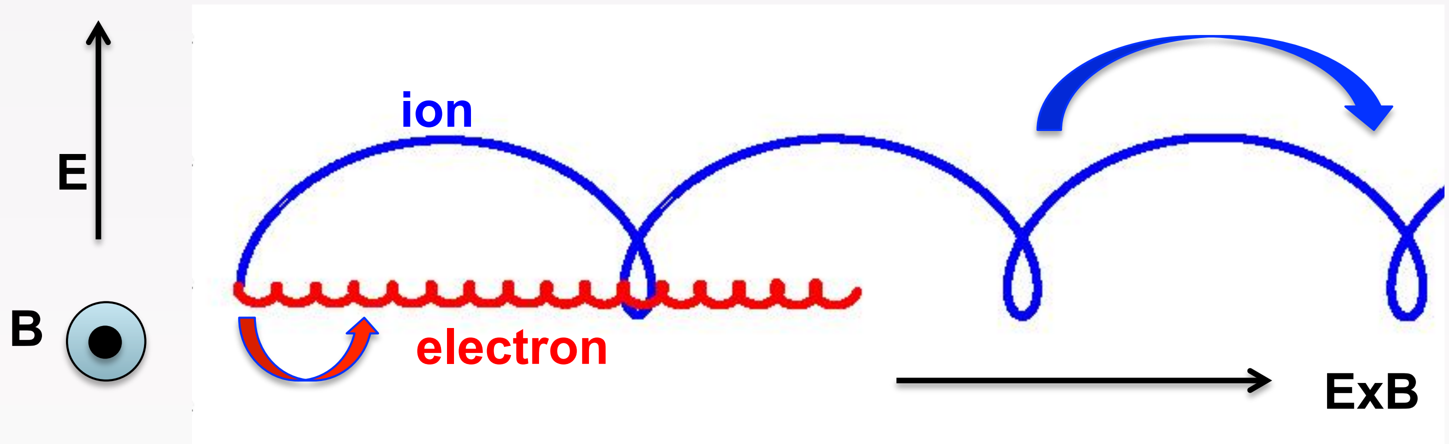


(Abolmasov, PSST, 2012)

- **Kinetic Energy:** Does not change, since force always acts perp. to **v**

'E x B' Drift

- **Now add E perpendicular to B:**



(relative gyroradii not to scale)

- **Motion:** **E** field accelerates particle for 'one half' orbit – increased $r_{c.}$
- Over 'other half' have decreased r_c - the two combined causes a 'drift' of the guiding centre.
- One can show that the drift velocity is: $\mathbf{u_E} = \mathbf{E} \times \mathbf{B}/B^2$
- Forces which depend on sign of charge do *not* generate drift currents.

Other Types of Drift

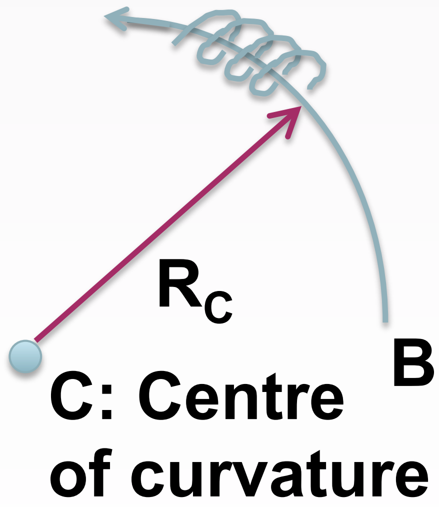
- **Guiding principle: Drift occurs when particle 'sees' significant changes in force during a single gyration.**

- **Gradient Drift:** *B* changes with spatial position.

$$\mathbf{u_g} = (W_\perp/(qB^3))\,\mathbf{B}\times\nabla B$$

- **Curvature Drift:** Particle whose g.c. moves along curved field line feels a centrifugal force.

$$\mathbf{u_c} = (2W_{||}/(R_c qB^2))\hat{\mathbf{n}}\times\mathbf{B}$$



- **'W' terms:** Kinetic energy

- $\hat{\mathbf{n}}$ Unit vector pointing out from C to particle

Question

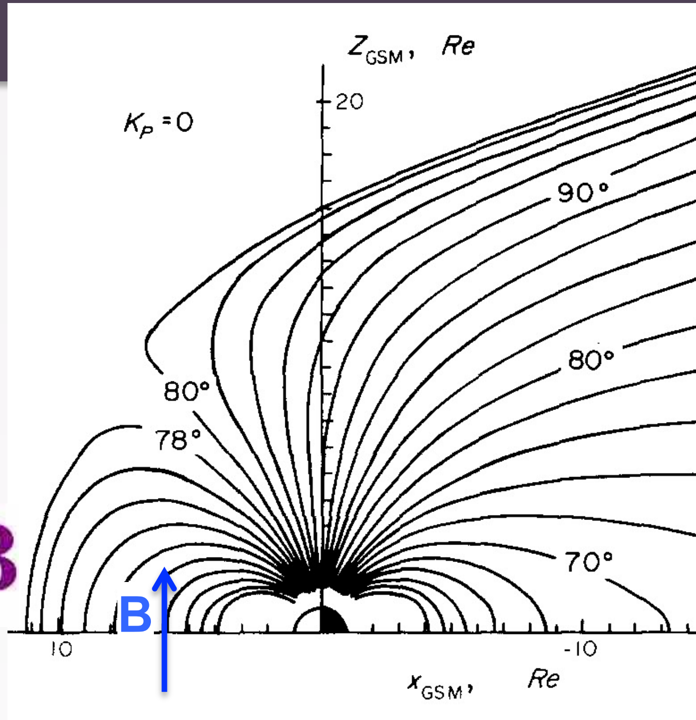
- **Gradient Drift:**

$$\mathbf{u_g} = (W_\perp/(qB^3))\,\mathbf{B} \times \nabla B$$

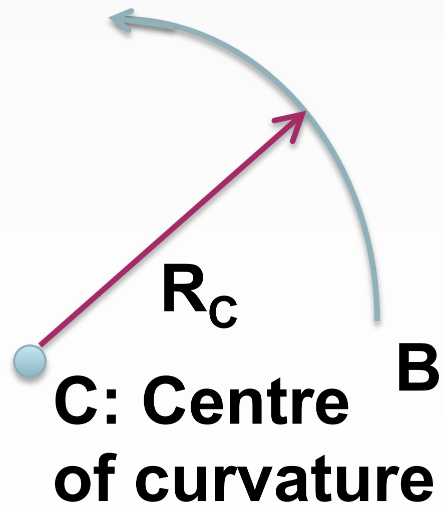
- **Curvature Drift:**

$$\mathbf{u_c} = (2W_{||}/(R_c q B^2))\hat{\mathbf{n}} \times \mathbf{B}$$

Q: Explain why these drifts contribute to a **westward** directed ring current (consider particle at the magnetic equator of the planet's dipole field) ?



adapted from Tsyganenko and Usmanov 1982



Answer

- **Gradient Drift:**

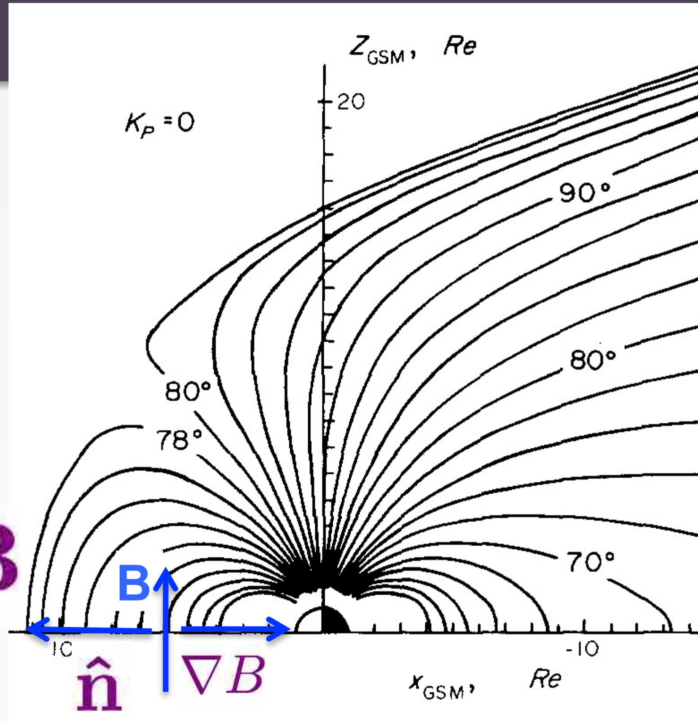
$$\mathbf{u_g} = (W_\perp/(qB^3))\,\mathbf{B} \times \nabla B$$

- **Curvature Drift:**

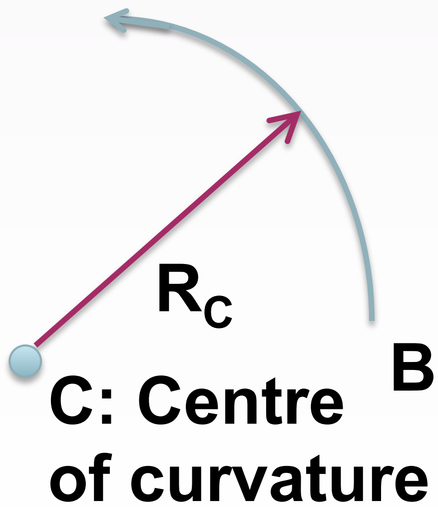
$$\mathbf{u_c} = (2W_{||}/(R_c q B^2))\hat{\mathbf{n}} \times \mathbf{B}$$

Q: Explain why these drifts contribute to a **westward** directed ring current (consider particle at the magnetic equator of the planet's dipole field) ?

A: Check the relevant directions in the diagram – an ion would drift east-west while an electron would drift in the opposite direction. Do you know of any other types of current which may contribute to the *ring current* ?



adapted from Tsyganenko and Usmanov 1982



Constants of the motion: 'Invariants'

- **Guiding principle** **In collisionless plasmas, we may identify an 'invariant' if ΔB<<B over one gyration.**

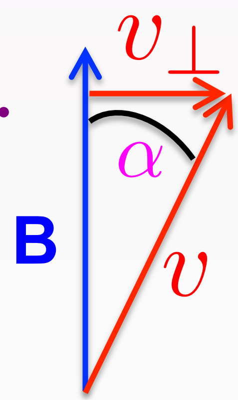
- **First adiabatic invariant - 'magnetic moment'** $\mu = W_\perp / B$

- **An effective force || B:** $\mathbf{F} = -\mu \dfrac{dB}{ds}$

- Particle moves to higher B, $v_{||} \downarrow, v_\perp \uparrow, v \,\mathrm{const.}$

- **Invariant** $\dfrac{\sin^2 \alpha}{B}$

- **<u>'Mirror point'</u>** $\alpha_M = \pi/2 \quad B_M = B/\sin^2\alpha$



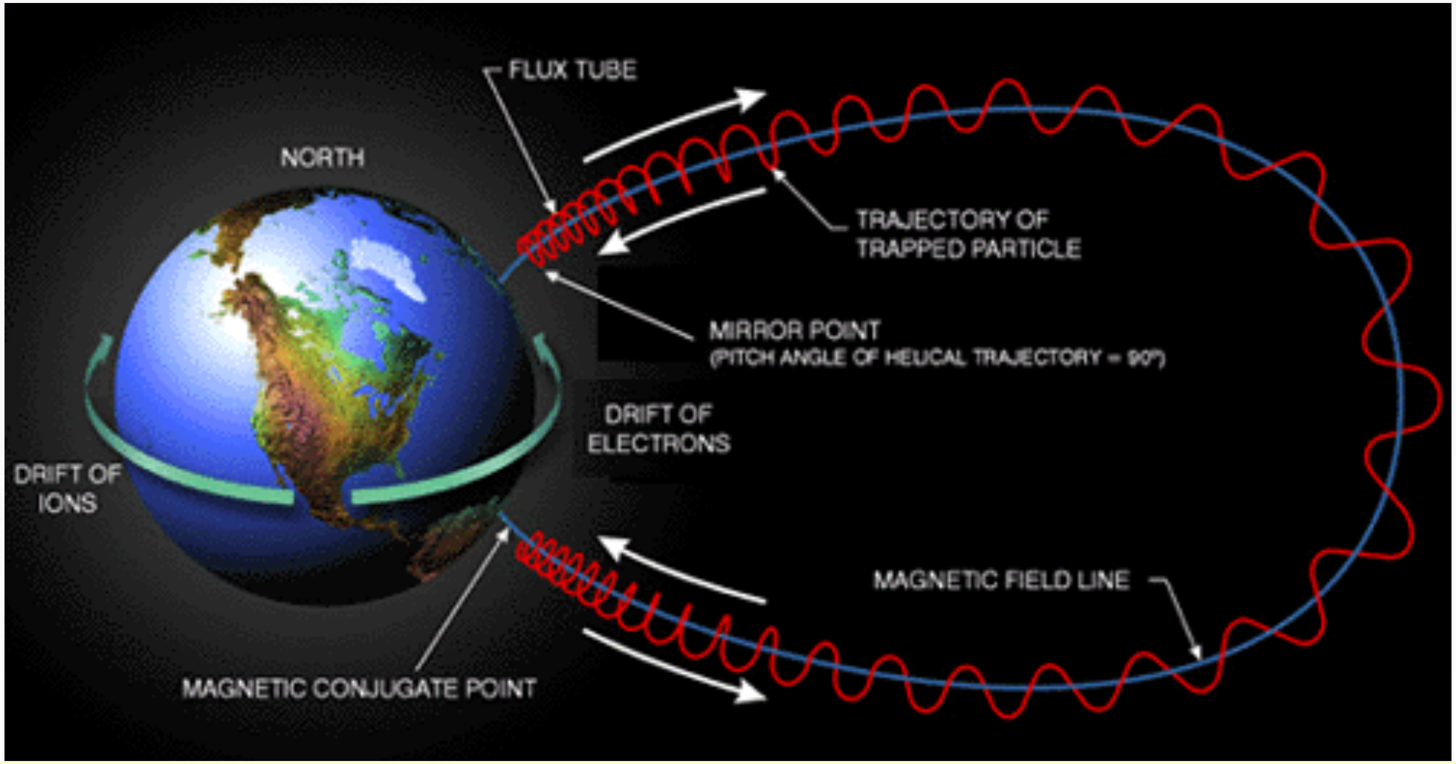
- Consider the situation $B_M > B_{\mathrm{SURF}} \rightarrow \sin^2\alpha < B/B_M$ where mirror field B_M exceeds that at planet's surface.

- Represents a ***loss cone*** at any location where particles are lost to atmosphere before they can mirror (maybe excite ***auroral emissions***)

Constants of the motion: ‘Invariants’

- **Guiding principle:**

Each **invariant** is linked to a certain type of **motion**, *provided* the field does not change appreciably over the corresponding timescale of that motion.



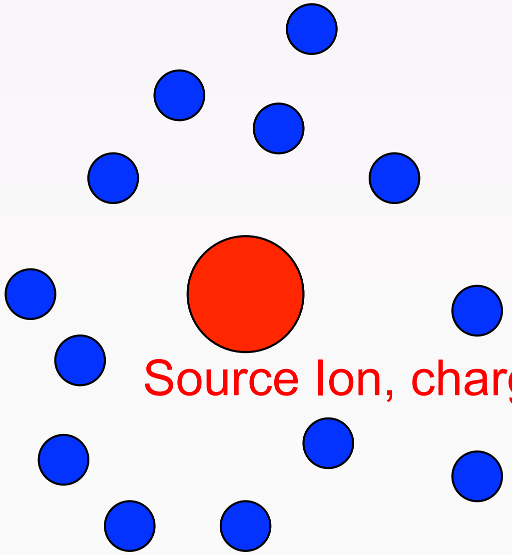
pluto.space.swri.edu/image/glossary/pitch.html, Based on Figure 5-10, "Handbook of Geophysics and the Space Environment," ed. A. S. Jursa (1985)

Types of motion: ***Gyration,*** ***Bounce,*** ***(Azimuthal) Drift***

➔ ***‘Drift shell’ concept***

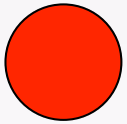
Collective behaviour: Debye 'shielding'

- 'Test' particles 'distant' from a given 'source ion (or electron) are 'shielded' from the source electric field.
- Mobile electrons form a neutralizing 'sheath' of charge.



Source Ion, charge q

'Shield' of electrons
Each of charge e



Test Ion does not 'feel' the full E-field of the source ion

The shielded potential Φ is characterised by the ***Debye length*** λ_D

$\Phi = (q / 4\pi\varepsilon_o r) \exp(-r / \lambda_D)$ 'cuts off' for $r \gg \lambda_D$

$\lambda_D = (\varepsilon_o k T_e / n_e e^2)^{1/2}$ colder, denser electrons are better 'shielders'

Assumes: quasineutrality ($n_e \sim n_i$) and lots of 'shielding particles' **i.e. for collective behaviour**

Plasma 'lambda' $\Lambda = n_e \lambda_D^3 \gg 1$

Properties of Various Plasmas in Nature

Plasma	Density (m^{-3})	Temp. (eV)	Debye Length (m)	Plasma Λ
Interstellar	10^6	0.1	1	10^6
Solar Wind	10^7	10	10	10^{10}
Solar Corona	10^{12}	10^2	10^{-1}	10^9
Magneto-sphere	10^7	10^3	10^2	10^{13}
Ionosphere	10^{12}	10^{-1}	10^{-3}	10^3
Fusion Expt.	10^{22}	10^5	10^{-5}	10^7

Based on Table 2.2 from 'Physics of Space Plasmas' by Kivelson, in 'Introduction to Space Physics' ed. Kivelson and Russell

Towards MHD

- Particle motions generate electromagnetic *fields*, but these same fields influence motion of neighbouring particles. A difficult problem.

- The ‘MHD’ (magnetohydrodynamic) approach combines a *fluid* approach for the plasma (treatment of many particles in terms of average properties) with Maxwell’s equations for the fields (with **J** = current density and non-relativistic flow).

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

Faraday’s Law

$$\nabla \times \mathbf{B} = \mu_o \mathbf{J}$$

Ampère’s Law

$$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B})$$

Ohm’s Law

Towards MHD

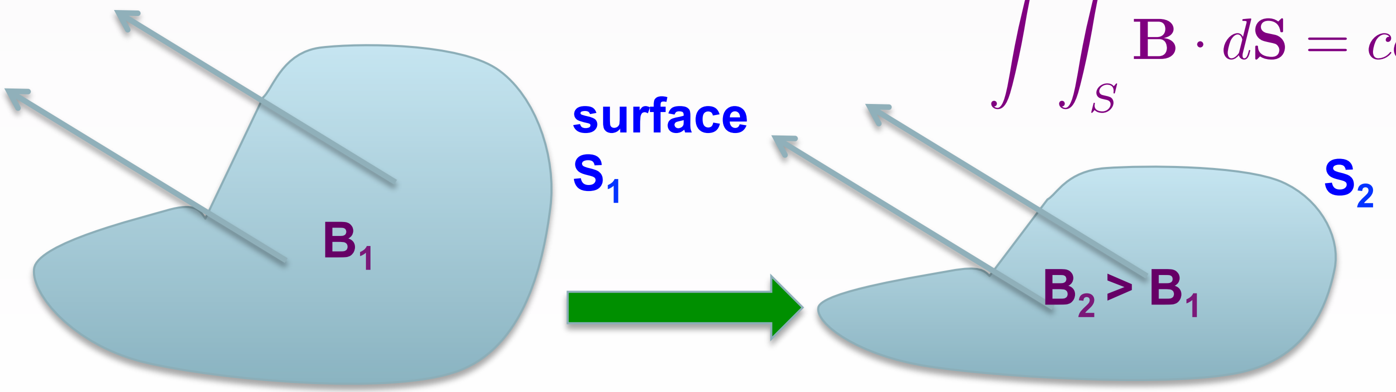
- Combining these gives the **induction equation** for the B field:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla^2 \mathbf{B}/(\mu_o \sigma) + \nabla \times (\mathbf{u} \times \mathbf{B})$$

- The first term is 'diffusive'. For collisionless plasmas ($\sigma \rightarrow \infty$) and / or adequately large length scales, this term will be negligible compared to the second *convective* term.

- If convective term dominates, one can show that the **frozen-in condition** applies and that the magnetic flux threading a moving 'blob' of plasma remains constant.

$$\int\int_S \mathbf{B} \cdot d\mathbf{S} = const.$$



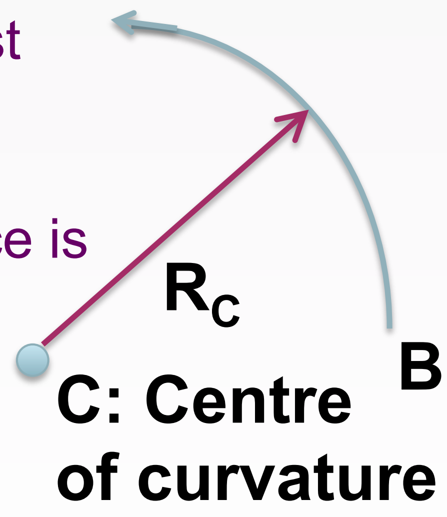
MHD concepts: Magnetic pressure and tension

Using Ampère's Law:

$$\mathbf{J} \times \mathbf{B} = \frac{1}{\mu_o}(\nabla \times \mathbf{B}) \times \mathbf{B} = -\nabla(B^2/(2\mu_o)) + (\mathbf{B} \cdot \nabla)\mathbf{B}/\mu_o$$

- Sum of a '**magnetic pressure gradient**' and a '**tension force**'
- The *field-parallel* components of these two terms must always add to zero (think of a vacuum dipole field)
- The *field-perpendicular* component of the tension force is related to field line curvature:

$$-(B^2/(\mu_o R_c))\hat{\mathbf{n}}$$

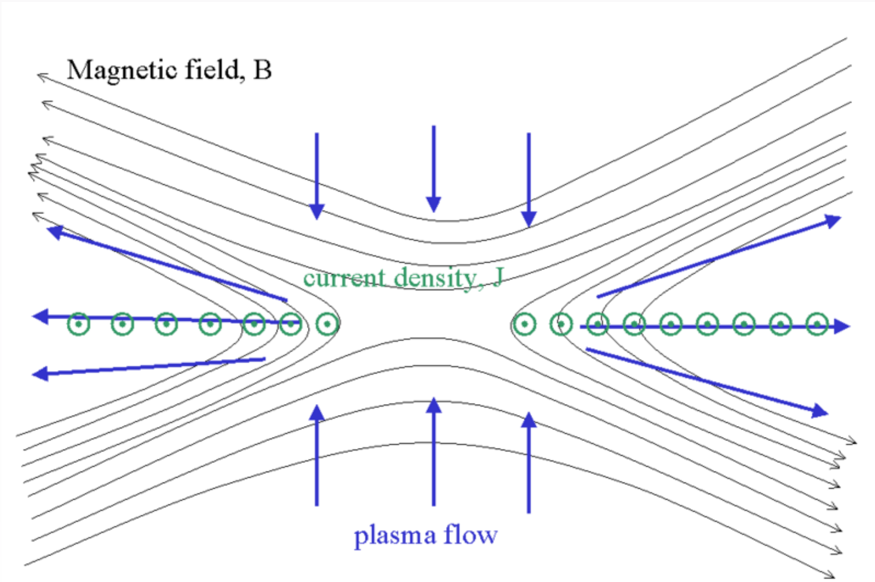


- In rapidly rotating, disc-like outer magnetospheres of Jupiter and Saturn, this *curvature force* (inward) balances (mainly) the strong *centrifugal force* plus *plasma pressure gradient* (outward)

Magnetic merging and reconnection

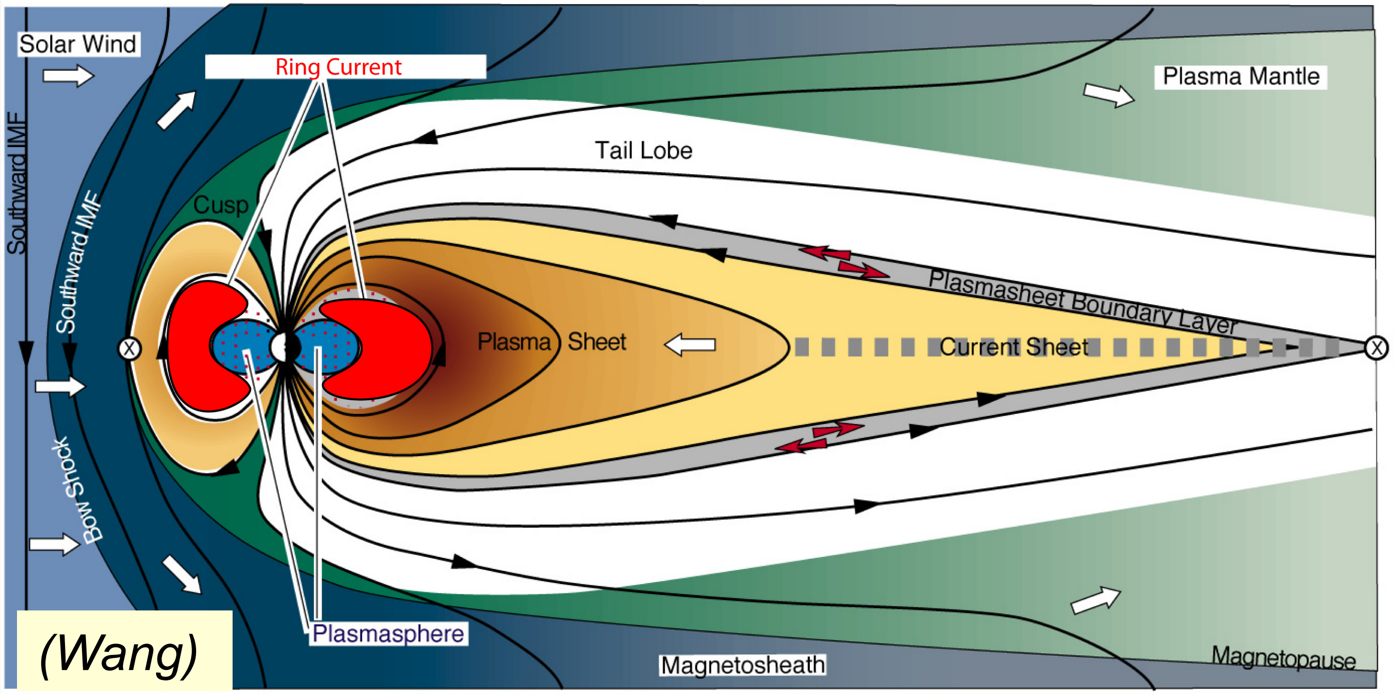
- In a simple 'dimensional' form, the Induction Equation is:
  $B / \tau = (1/\mu_o\sigma) B / L^2 + V_{perp} B / L$
  So ratio of convective to diffusive terms scales as
  $R_M = V_{perp} \mu_o \sigma L$ - known as the 'magnetic Reynolds number'
  It is high for *collisionless, fast-flowing* plasmas

- A *current sheet* with converging flows will show magnetic merging where $R_M \sim 1$ e.g. 'magnetic X line' at magnetopause



(Messer)

Different plasma 'regimes'



(Wang)

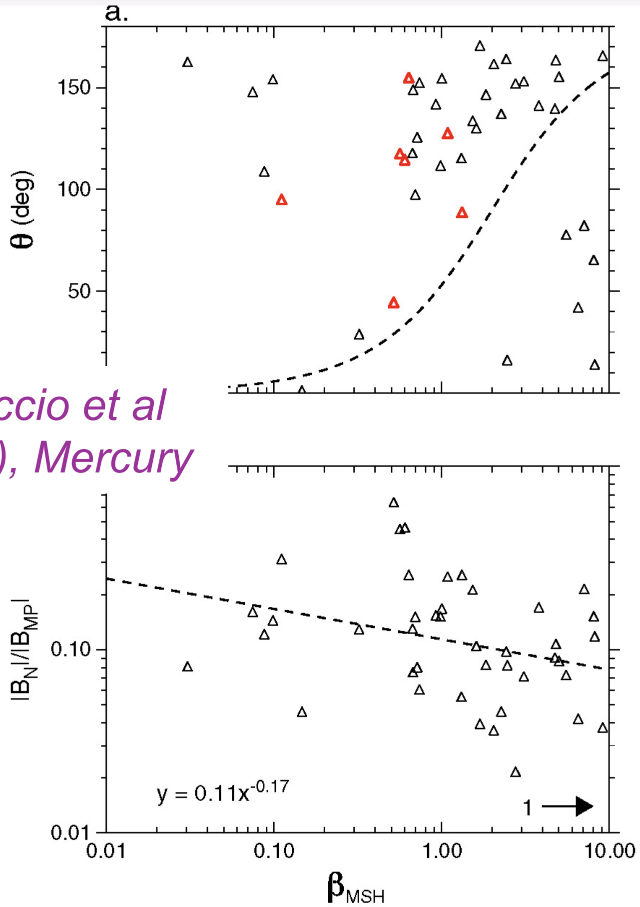
	Magneto-sheath	Tail Lobe	PS Boundary Layer	Central Plasma Sheet
n (cm^{-3})	8	0.01	0.1	0.3
T_i (eV)	150	300	1000	4200
B (nT)	15	20	20	10
β	2.5	0.003	0.1	6

(From chapter by Hughes in 'Intro to Space Phys')

- Tail Lobe: Open field
- PSBL: Prob. Closed field, thermal << flow energy
- PS: hot ~keV particles, flow<<thermal energy
- Reconnection: antisunward plasma streaming to thermal energy of PS
- More PS particles from ionosphere (O+) rel. to solar wind (H+) at 'active' times

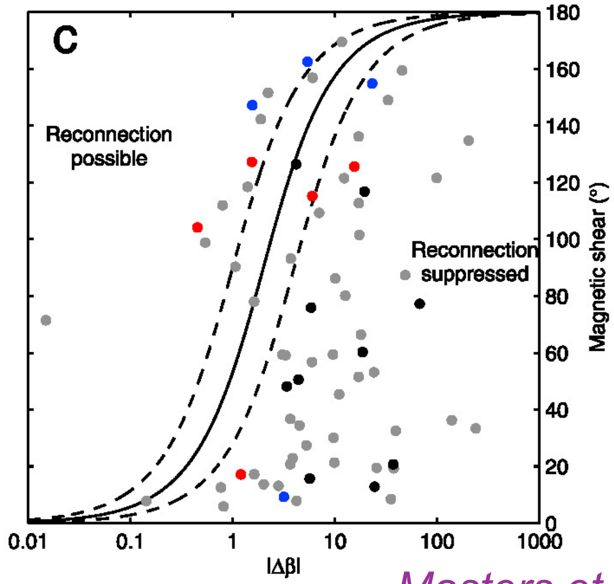
$\beta = P_{PLAS}/P_{MAG}$

… Aspects of Reconnection Elsewhere



DiBraccio et al (2013), Mercury

Figure 11. (a) Comparison of β to magnetic shear, together with the condition of *Swisdak et al.* [2010] for diamagnetic suppression of reconnection for $L = d_i$ (dashed line), to assess reconnection enhancements in the low-β environment. Black triangles are crossings with a reconnection rate of <0.25, and red triangles show reconnection rates of ≥0.25. (b) Evaluation of the correlation between β and the rate of reconnection with a power law fit (dashed line) to observations for the magnetopause crossings meeting the criteria of this study. One event with $\beta > 10$ is not shown on the plots.



Masters et al (2012), Saturn

- Reconnection is influenced by change in plasma β across boundary (*Quest and Coroniti, 1981; Swisdak et al., 2003, 2010*). Observations from *MESSENGER* at Mercury indicate that reconnection rate is relatively *insensitive* to magnetic shear because of the relatively low Δβ, while the *opposite* has been found at Saturn with *Cassini.*

Magnetospheric Configuration: Field and Currents

adapted from Tsyganenko and Usmanov 1982

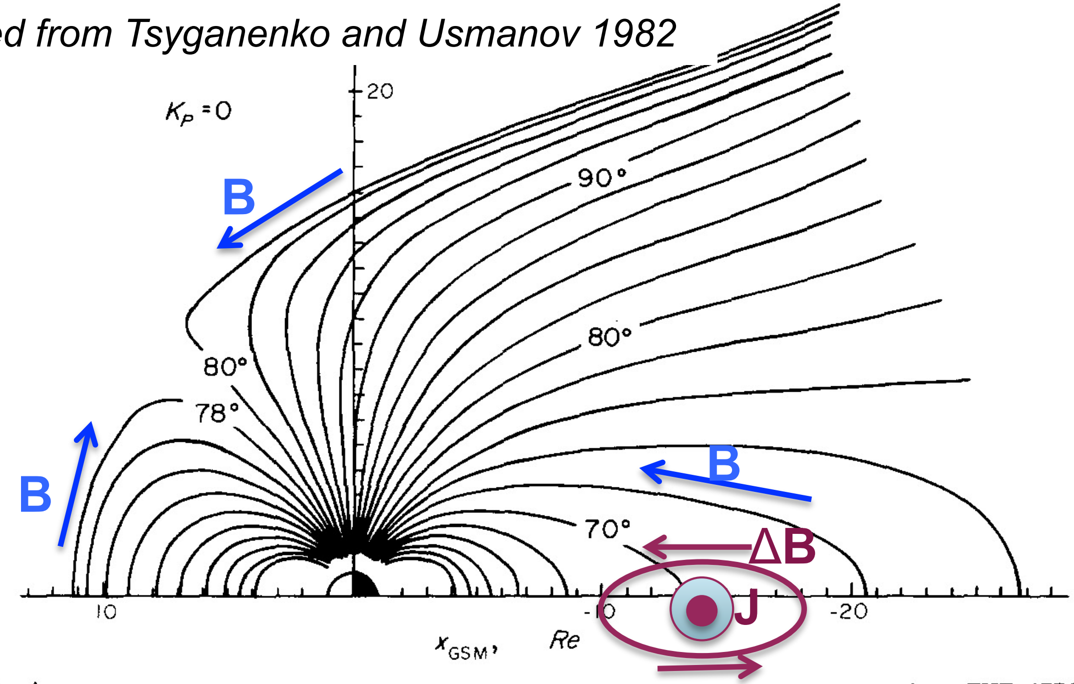
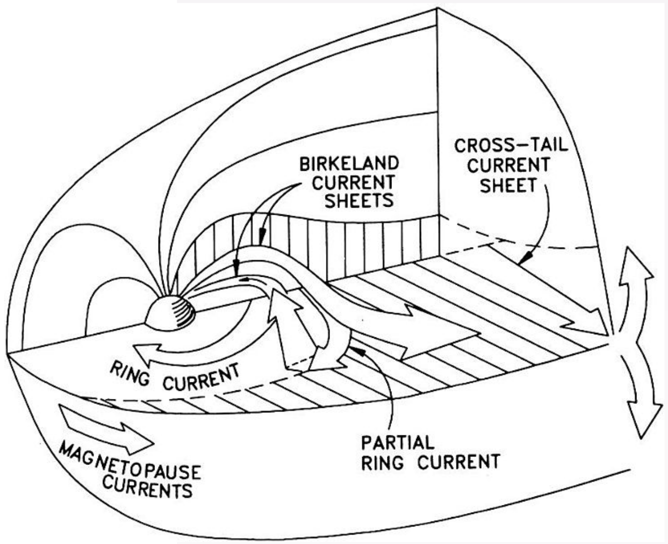


FIG. 8. A NOON–MIDNIGHT CONFIGURATION OF THE MODEL MAGNETIC FIELD LINES, IN THE VERSION WITH $K_p = 0$.

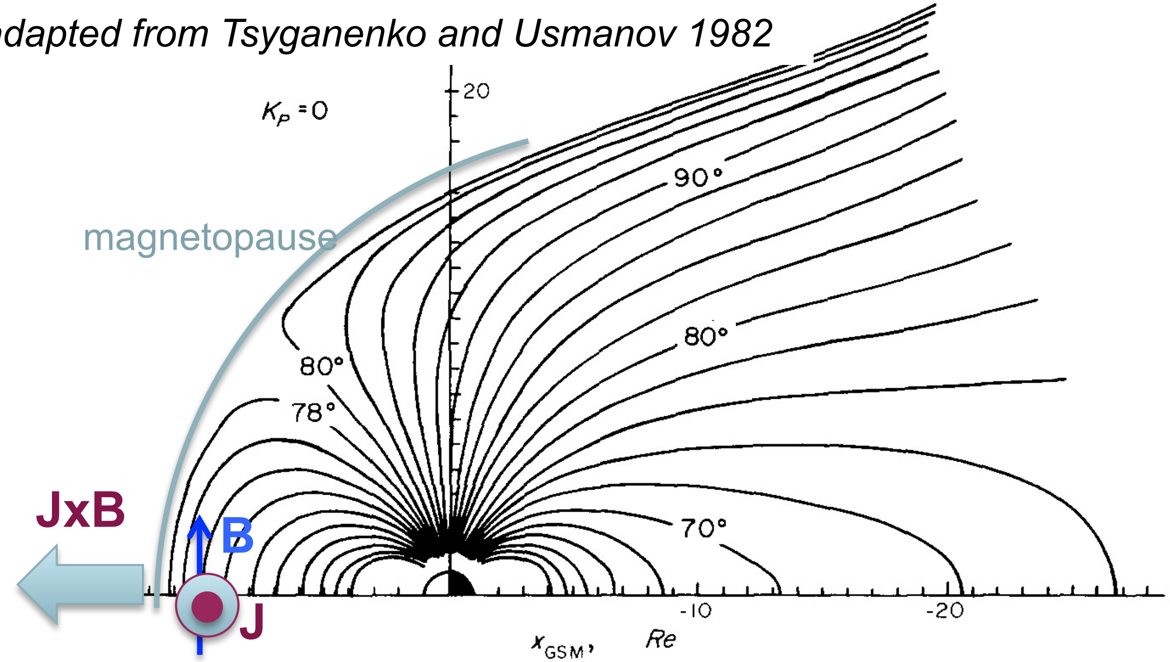


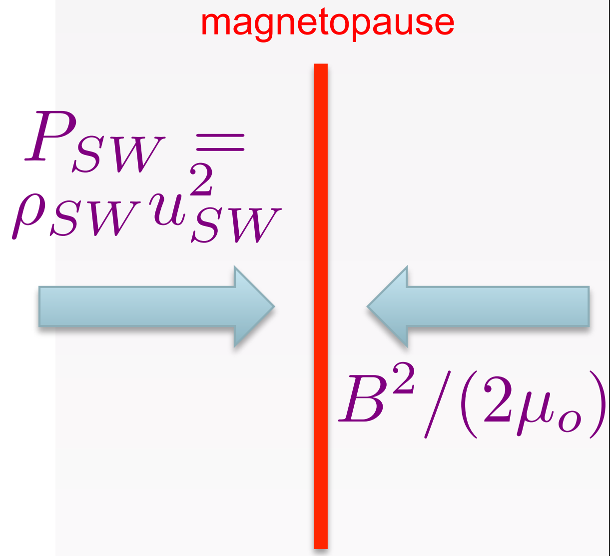
Stern 1994

- *External* field structures which depart from the internal field of the planet usually supported by **current distributions or sheets**.
- These currents modify the 'background dipole' in different ways – for example, the 'compression' of the dayside field associated with the magnetopause current.

Magnetospheric 'Pressure Balance'

adapted from Tsyganenko and Usmanov 1982





- Magnetopause currents act to 'hold off' the solar wind flow. At 'nose', the magnetic force is equivalent to an internal ***magnetic***, which balances the external solar wind ***dynamic pressure P***$_{SW}$.

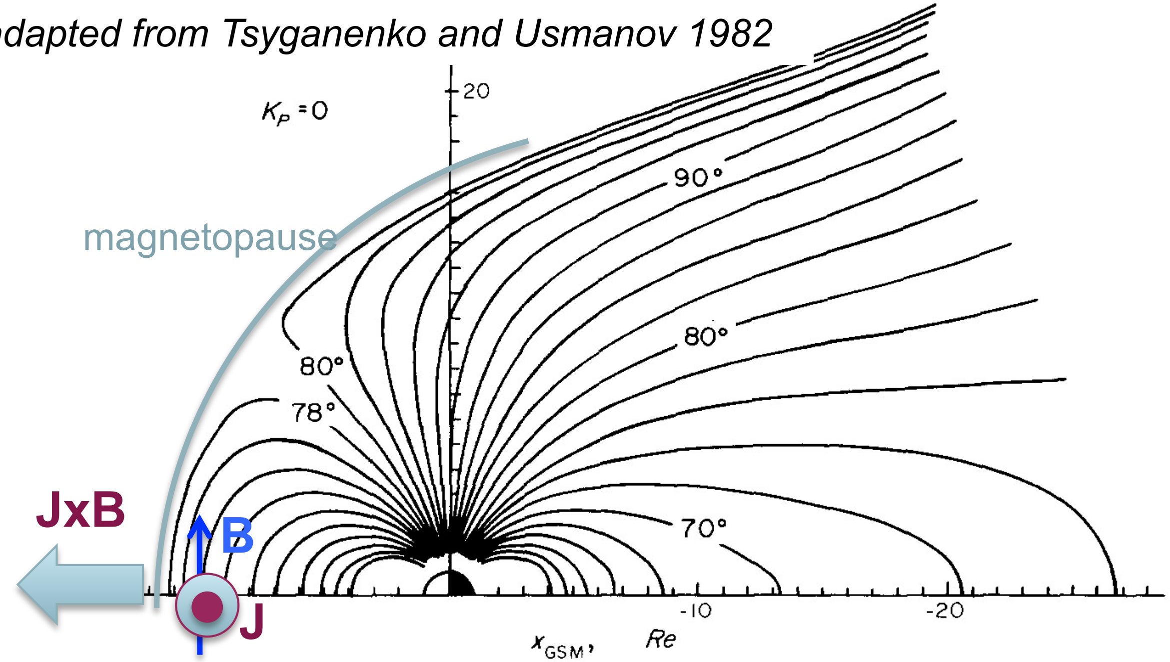
- If we simplify using dipole $B \sim 1/r^3$, then we expect subsolar location of MP to satisfy:

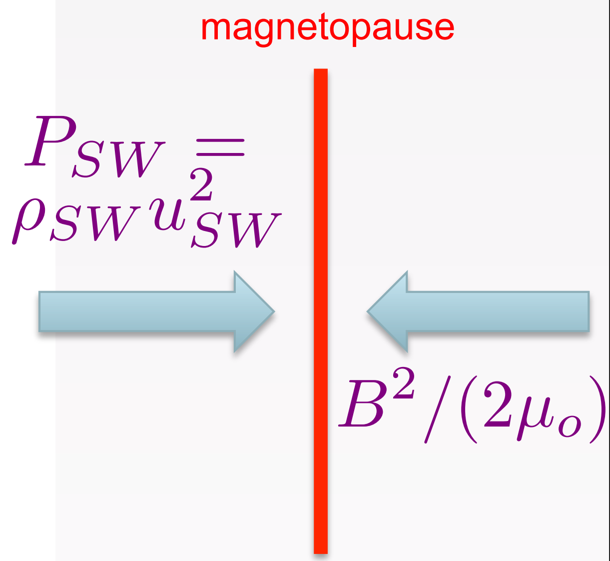
$$R_{MP} \propto P_{SW}^{-1/6}$$

- **Q: Why don't we consider curvature force in this balance condition?**

Magnetospheric ‘Pressure Balance’

adapted from Tsyganenko and Usmanov 1982





- Magnetopause currents act to ‘hold off’ the solar wind flow. At ‘nose’, the magnetic force is equivalent to an internal ***magnetic***, which balances the external solar wind ***dynamic pressure P_{SW}***.

- If we simplify using dipole B~1/r^3, then we expect subsolar location of MP to satisfy:

$$R_{MP} \propto P_{SW}^{-1/6}$$

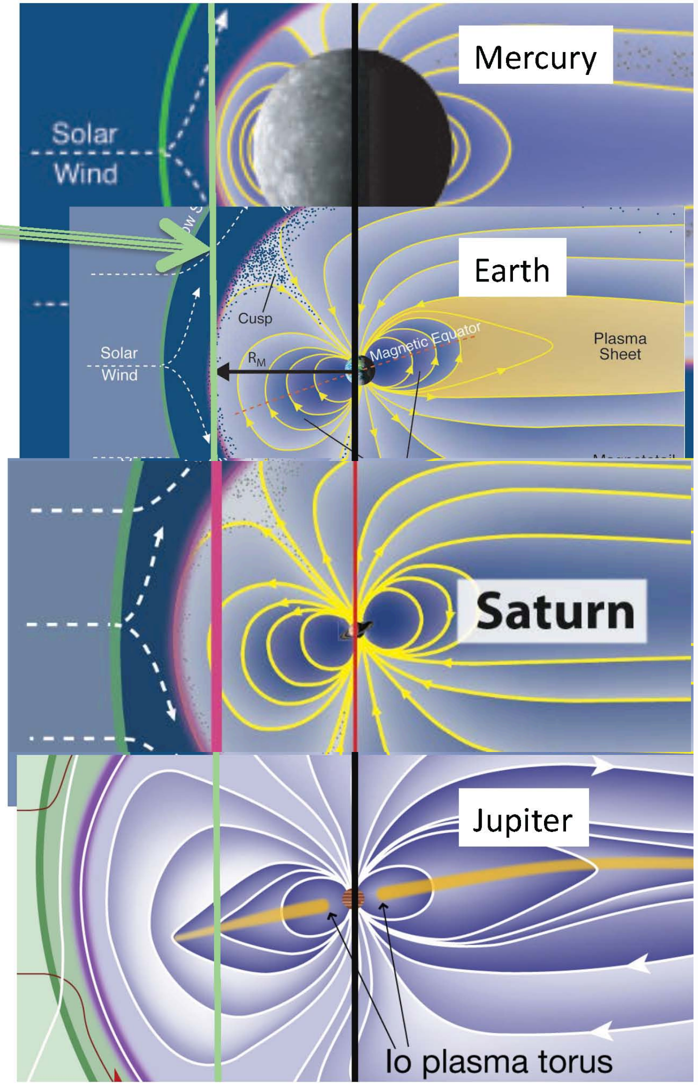
- **A: Compare the length scales: MPCL width << field line R_C**

Magnetospheres scaled by stand-off distance of dipole field

	M/M_E	MP_{Dipole}	MP_{mean}	MP_{Range}
Mercury	**~4x10^{-4}**	1.4 R_M	1.4 R_M	
Earth	1	10 R_E	10 R_E	
Saturn	600	20 R_S	24 R_s	22-27* R_S
Jupiter	20,000	46 R_J	75 R_J	63-92# R_J

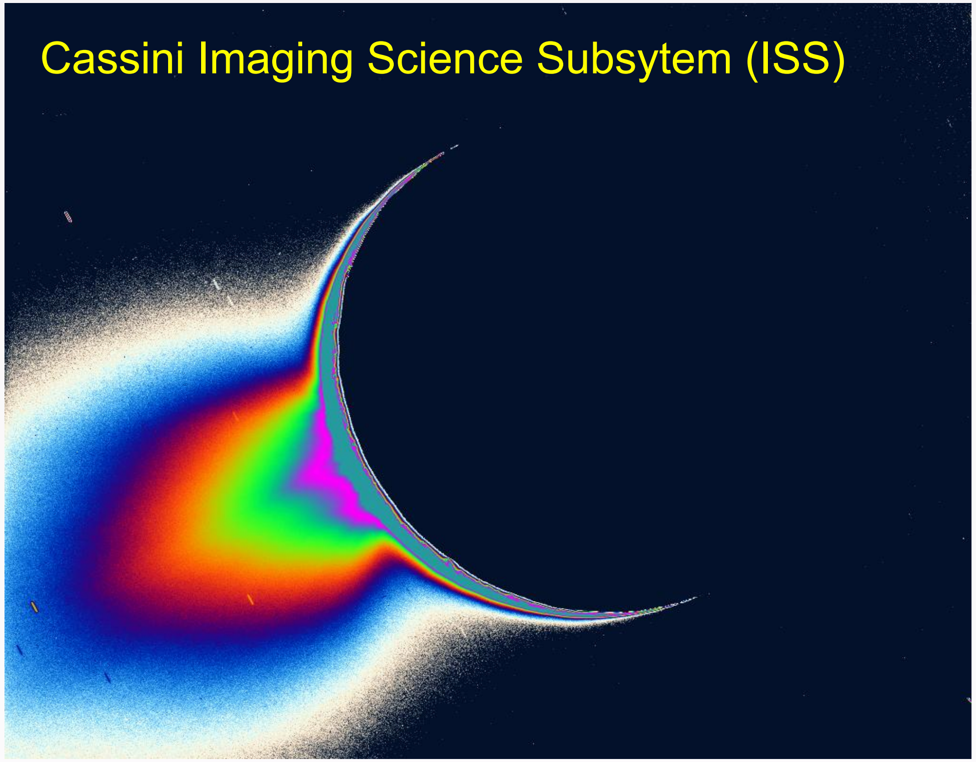
Inflated magnetospheres of Jupiter & Saturn due to HOT PLASMAS

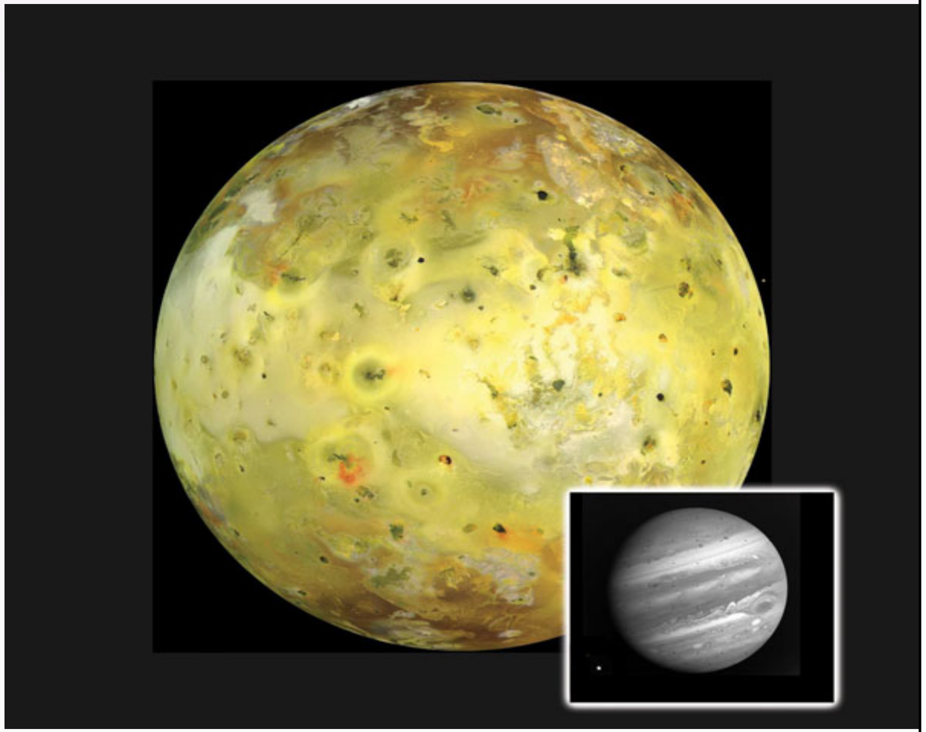
Note bimodal average locations
* *Achilleos et al. 2008* # *Joy et al. 2002*



Orig. Images / Text Credit: Bagenal / Bartlett
(Mercury mag. moment has been updated)

Internal mass sources: Moons

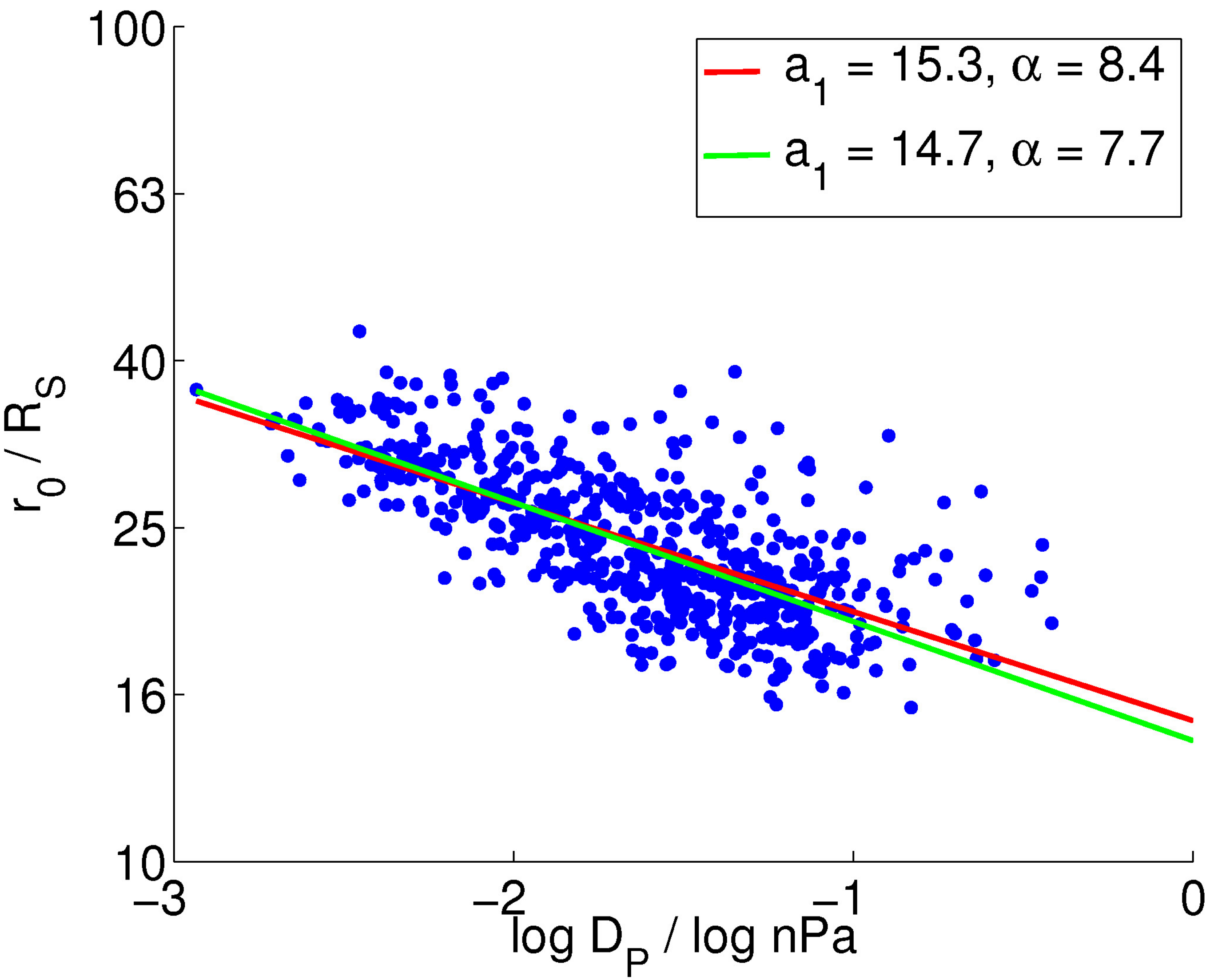




Enceladus (icy satellite): Mass source for Saturn's E ring, magnetosphere (~10-100 kg/s of plasma) **First discovered by MAG** *(Dougherty et al, Science, 2006)*

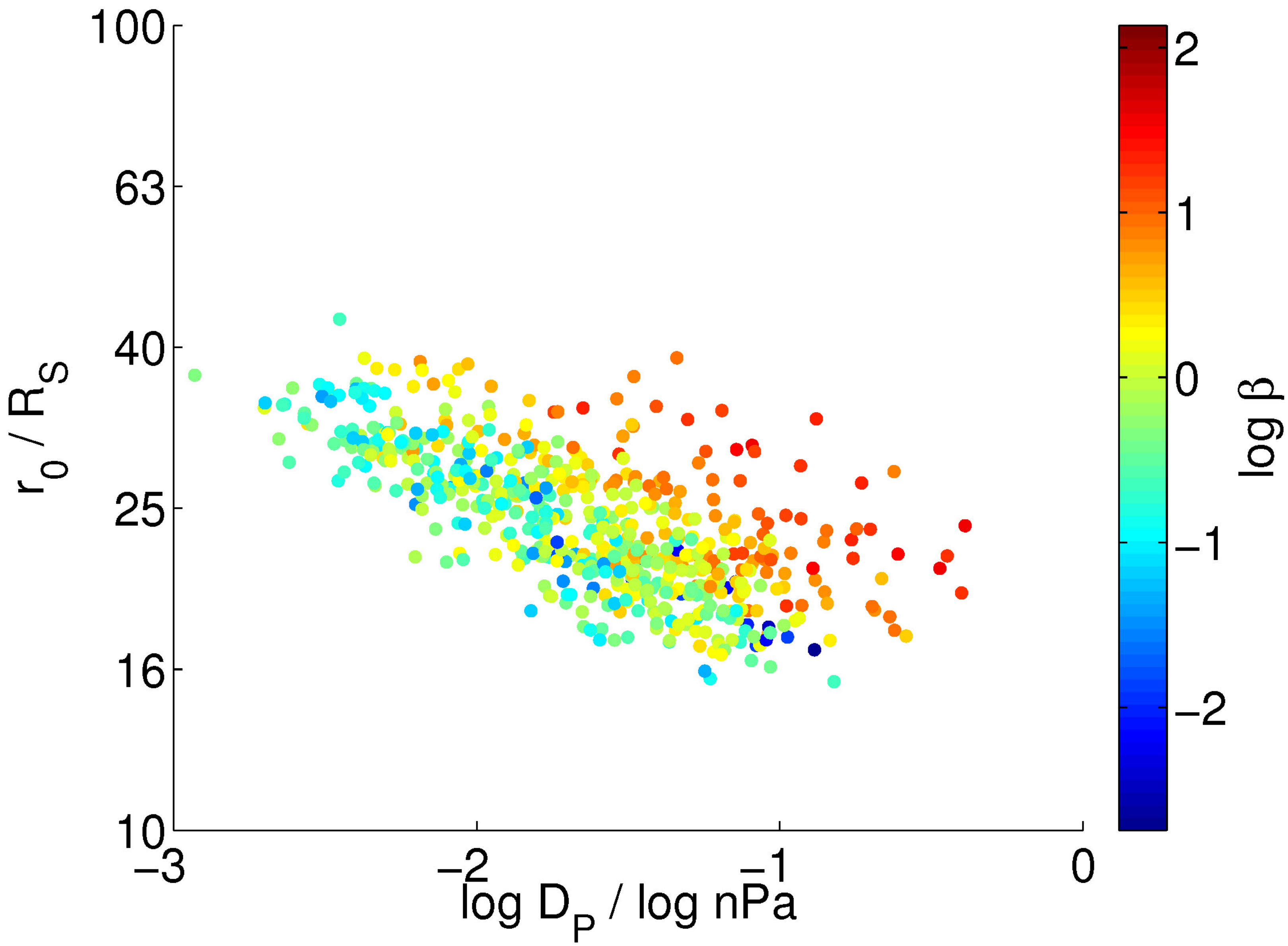
Io: Mass source for Jupiter's magnetosphere (~1000 kg/s of plasma)

Magnetospheric 'Compressibility': Saturn 'case study'



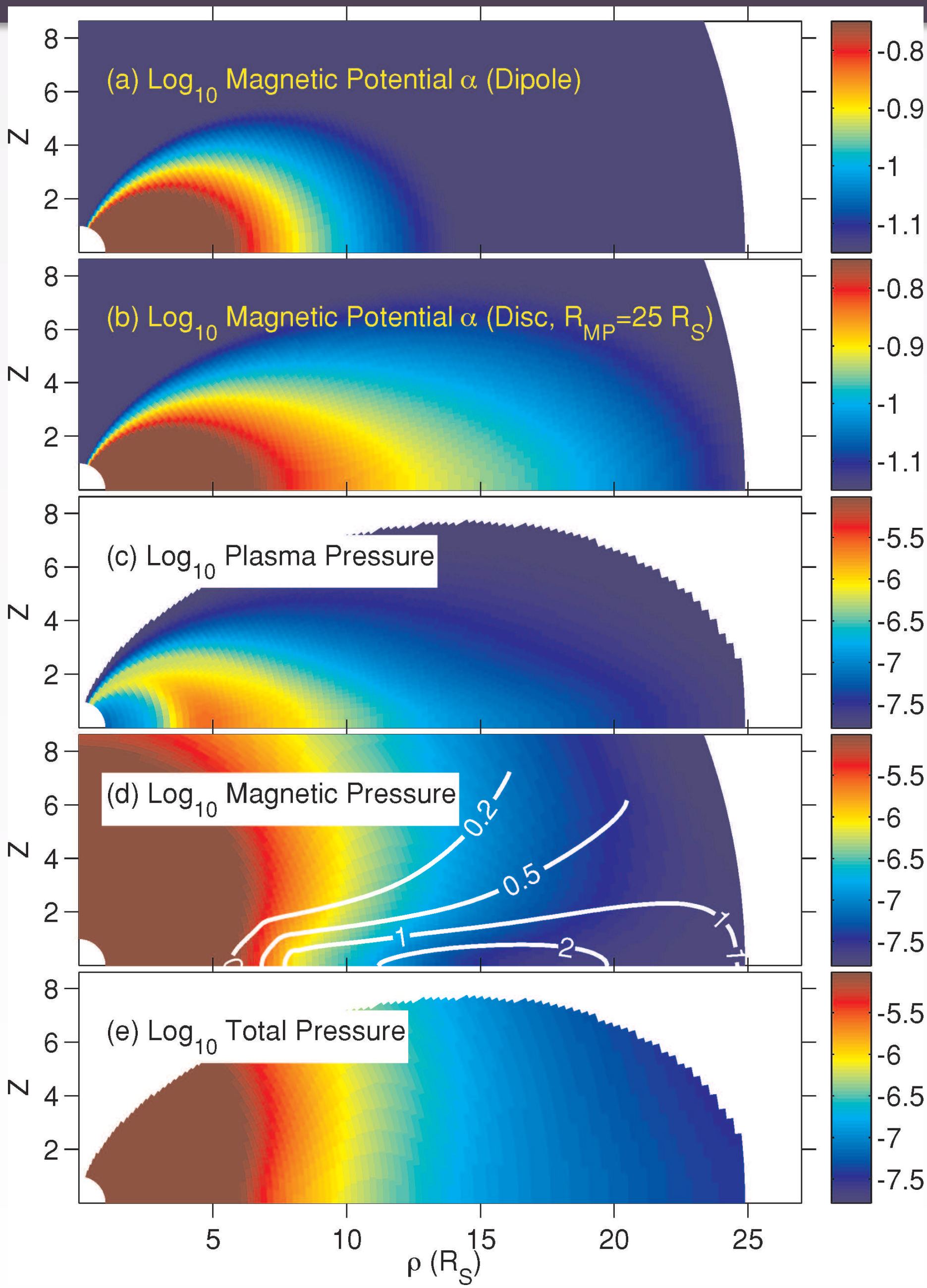
- From *Pilkington et al. (JGR submitted)*
- Fitting a global surface to *Cassini* magnetopause crossings
- Compressibility indicated by index of $r_0 = a_1 D_P^{-1/\alpha}$
- Much scatter
- ***α*** *large compared to previous (~4.3 Arridge et al 2006, ~5.0 Kanani et al 2010)*

Magnetospheric ‘Compressibility’: Saturn



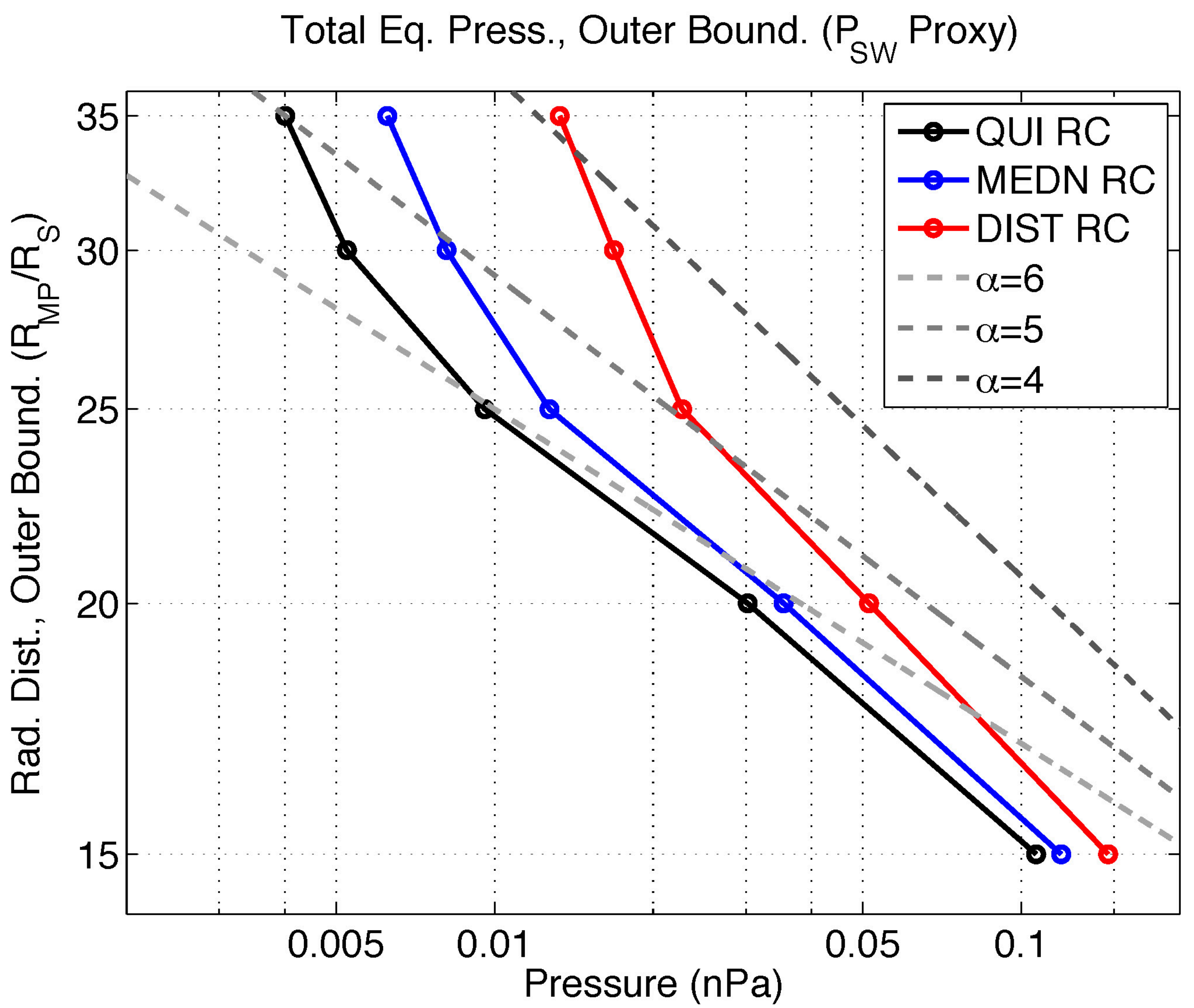
- When crossings are coded by plasma ‘beta’ parameter, r_0 at fixed D_P is well-correlated with β

Magnetodisc Model



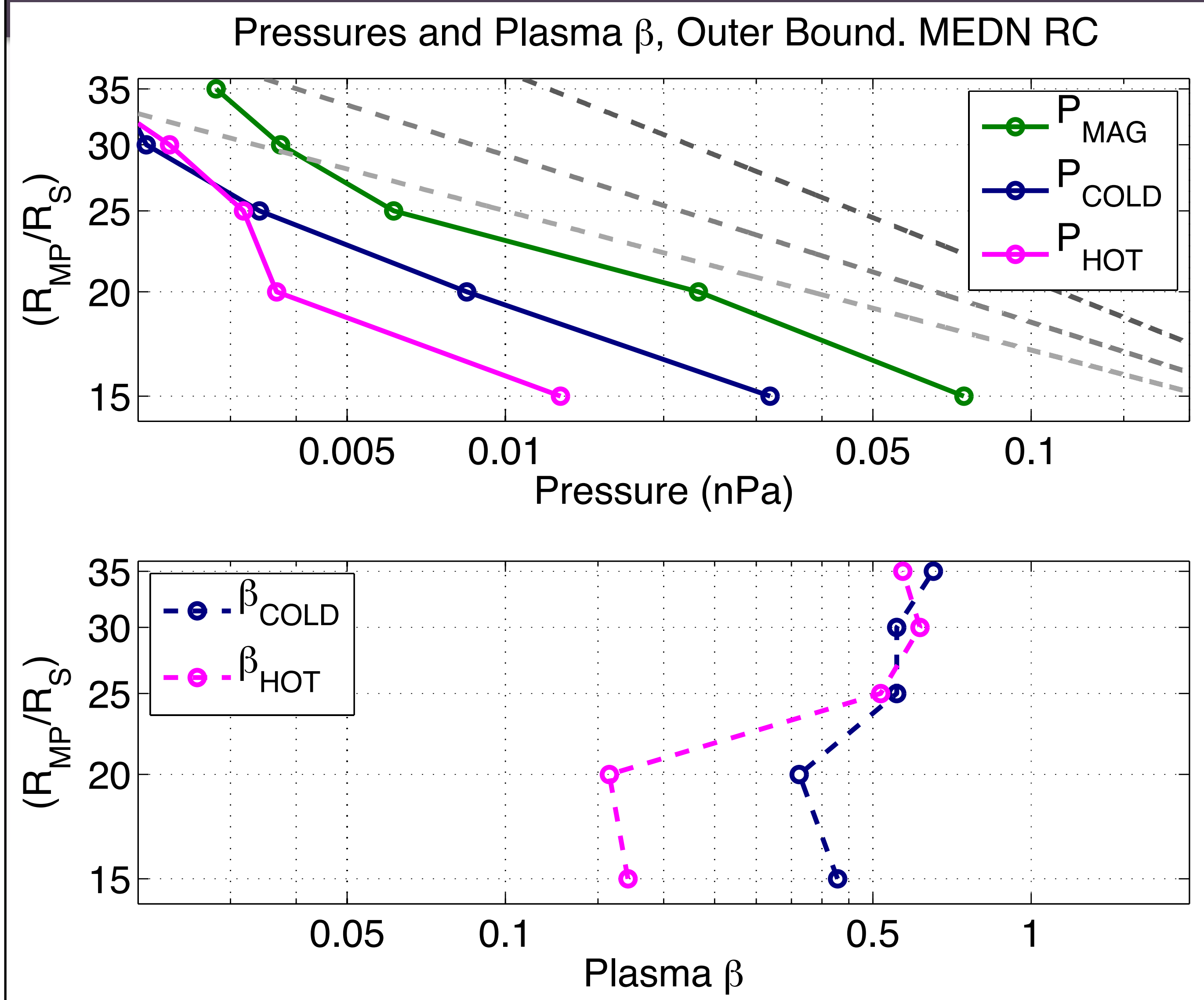
- *Can model Saturn's magnetodisc with UCL Magnetodisc Model (Achilleos, Guio and Arridge 2010, MNRAS; Achilleos et al 2010, GRL)*
- *Example outputs shown here of magnetic field and plasma distribution – based on a balance between centrifugal force, plasma pressure gradient and magnetic **'JxB'** force.*
- *Can take total pressure at outer boundary as a 'proxy' for solar wind dynamic pressure D_P*
- *Two main parameters:*
  Magnetopause radius (external)
  Hot plasma content (internal)

Compressibility Calculations



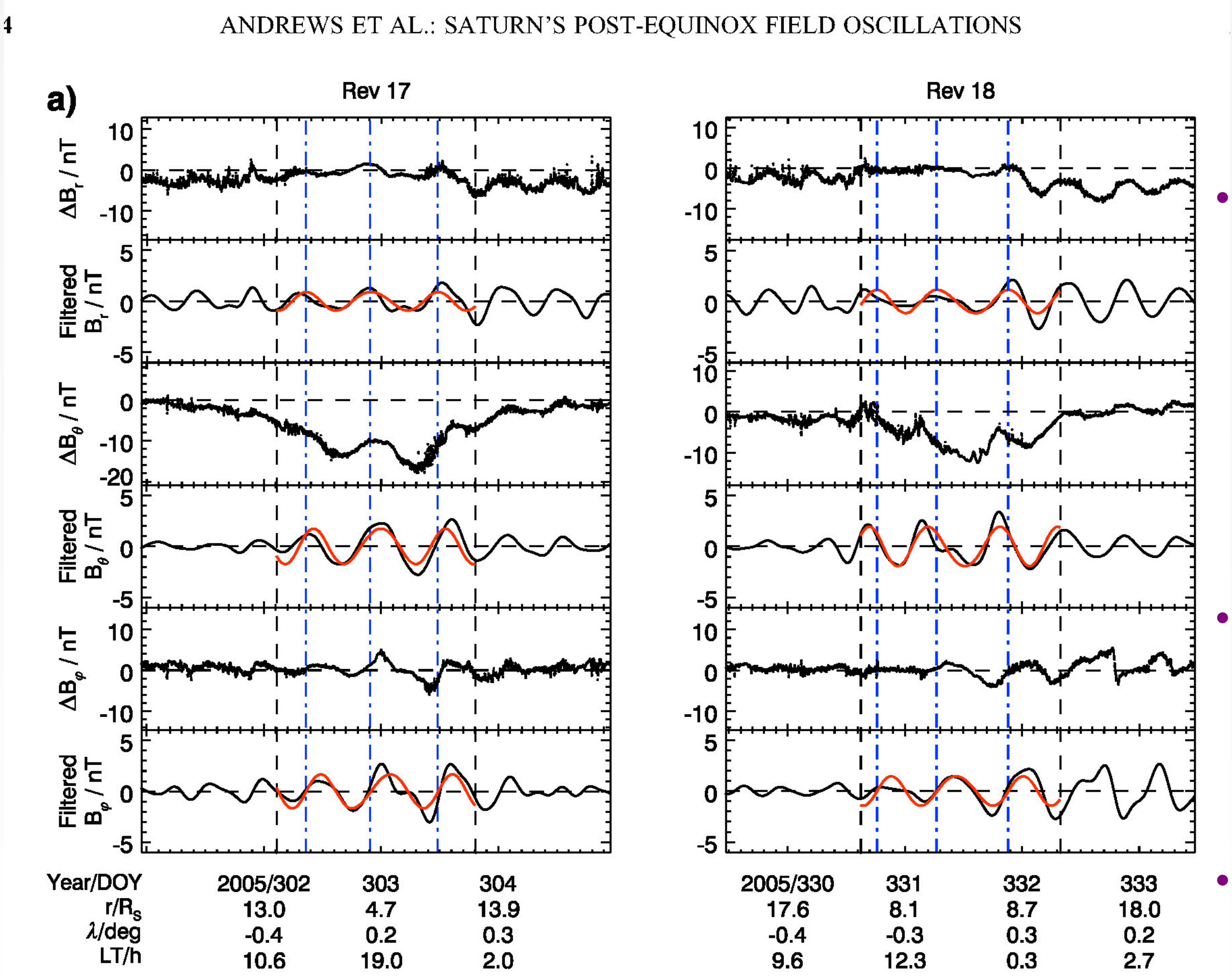
- *R_{MP} (r_0) can change by <~10 R_S at fixed D_P, when going from quiet to disturbed ring current (hot plasma) state.*
- *Note that compressibility* ***α*** changes with system size – in agreement with behaviour modelled by *Bunce et al (2007, JGR)*

Behaviour of Pressure Components



- *'Median' ring current model*
- *Hot plasma pressure and magnetic pressure show different 'slope' of variation with system size*
- *Near ~20 RS is artefact of how we parameterise hot pressure*

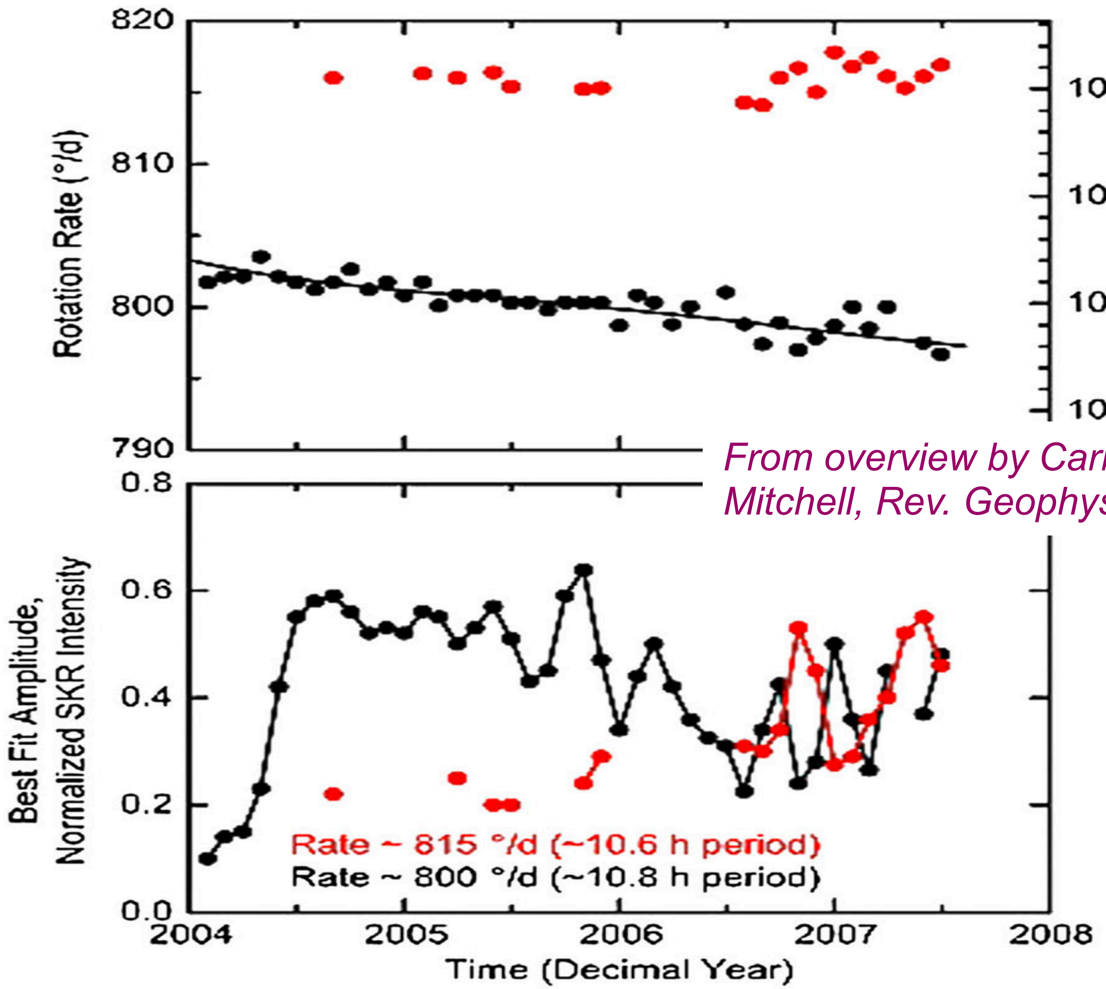
Magnetospheric Field Oscillations at Saturn



(Andrews et al, JGR, 2012)

- *Cassini* observations of global magnetic oscillations at Saturn
- A 'core' region has special 'phase relations' between the residual radial (Br) and azimuthal (BΦ) components of the field.
- This pattern must be supported by a rotating pattern of *current*.
- Drive oscillations in position of *magnetopause* (e.g. *Clarke et al. 2006*)

SKR and ENA Oscillations



From overview by Carbary and Mitchell, Rev. Geophys. 2013

Figure 4. RPWS measurements of variations in Saturn's SKR period during the Cassini mission. The black dots and black trace show the data used to extend the SLS2 longitude system to make the SLS3 system. The red dots and red traces show the emergence of a new, second period [from *Kurth et al.*, 2008].

- The situation is even more complicated. *Two* rotating patterns of field, similar to 'transverse dipoles', one in the north, one in the south.Each similar to the pattern of Southwood and Kivelson (2007)
- Rotate at periods close to the corresponding SKR modulations.
- These periods are *not fixed*, hence the relative phase between the N and S oscillation can change.
- **What drives the underlying current system ?**

Some Proposed Models…

- **'Internal':** Rotating magnetic anomaly, which launches a 'wave' into the magnetosphere (e.g. 'camshaft signal' - Espinosa et al (2003)) – but what about the seasonal modulation of the periods ?
- **'External':** Pre-existing magnetospheric structures, which rotate (e.g. rotating plasma 'convection cells' of Goldreich and Farmer (2007); - but what about the distinct northern and southern signals ?
- **'Atmospheric':** Thermospheric flows can modulate currents. A flow pattern ('vortex') which 'breaks' the azimuthal symmetry of a global rotation would underpin a rotating current system (*Smith and Achilleos 2012 – qualitative agreement*).
- **Imposing an assumed ionospheric flow** as a 'boundary condition' for a MHD model works well for quantitatively explaining the oscillations, as found by *Jia et al (JGR,2012)*. Requires a strong flow shear of 6 km/s over the 65-75 deg. interval of latitude.
- *Southwood and Cowley (2014)*: field-aligned currents at **polar cap boundaries**.

Jupiter: A Rapidly Rotating Magnetosphere

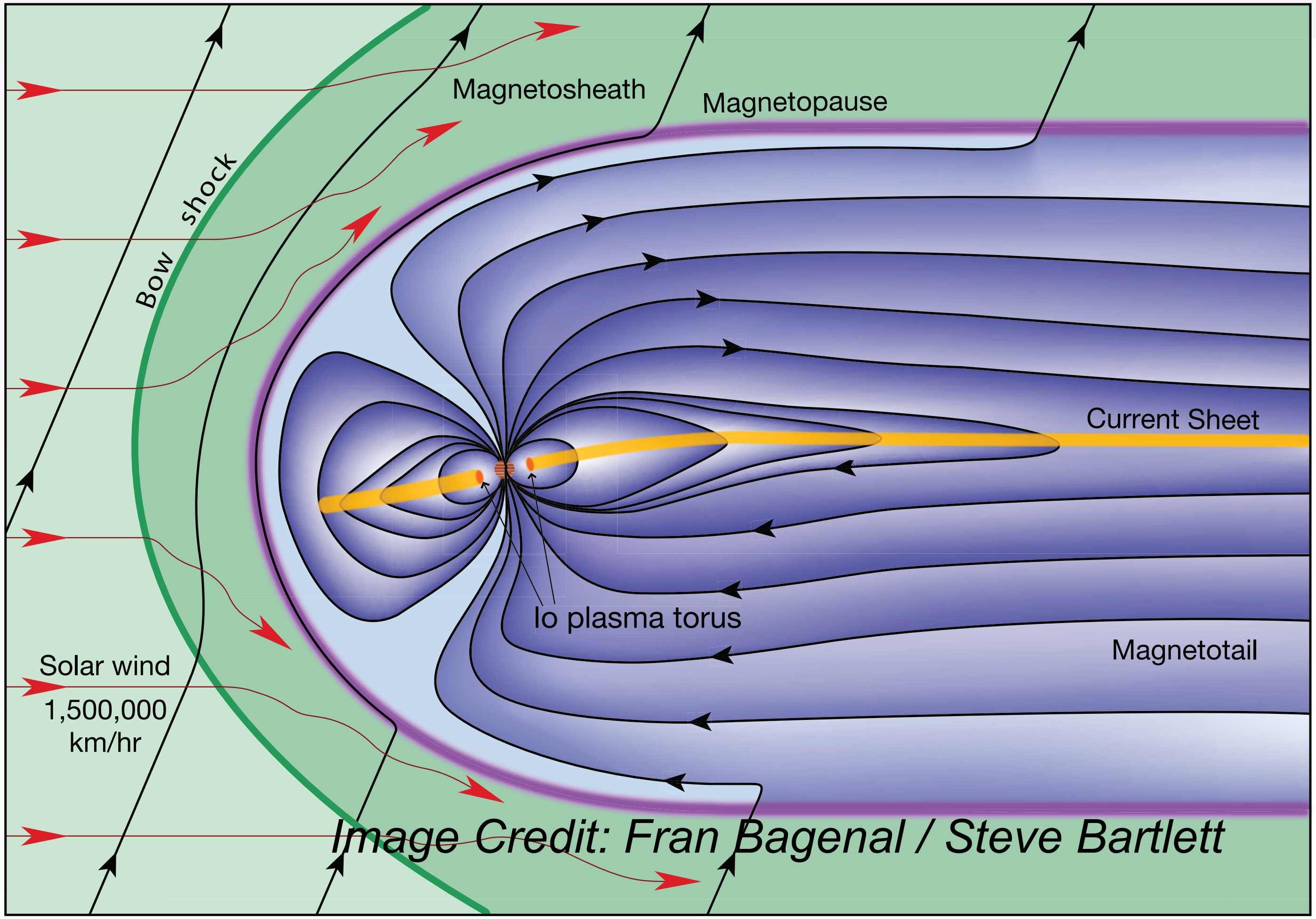


Image Credit: Fran Bagenal / Steve Bartlett

- P_{ROT}~9.9 hr
- R_J ~ 71500 km ~ 11 R_E
- $B_{J,EQ}$ ~ 428000 nT ~ 14 $B_{E,EQ}$
- $\mu_J = B_{J,EQ} R_J^3$ ~ 18000 μ_E
- A 'cavity' in the solar wind.
- Boundaries in field / flow
- Magnetopause on dayside extends to 60-90 R_J (c.f. Earth, 10 R_E ~ 1 R_J)

Jupiter: A Rapidly Rotating Magnetosphere

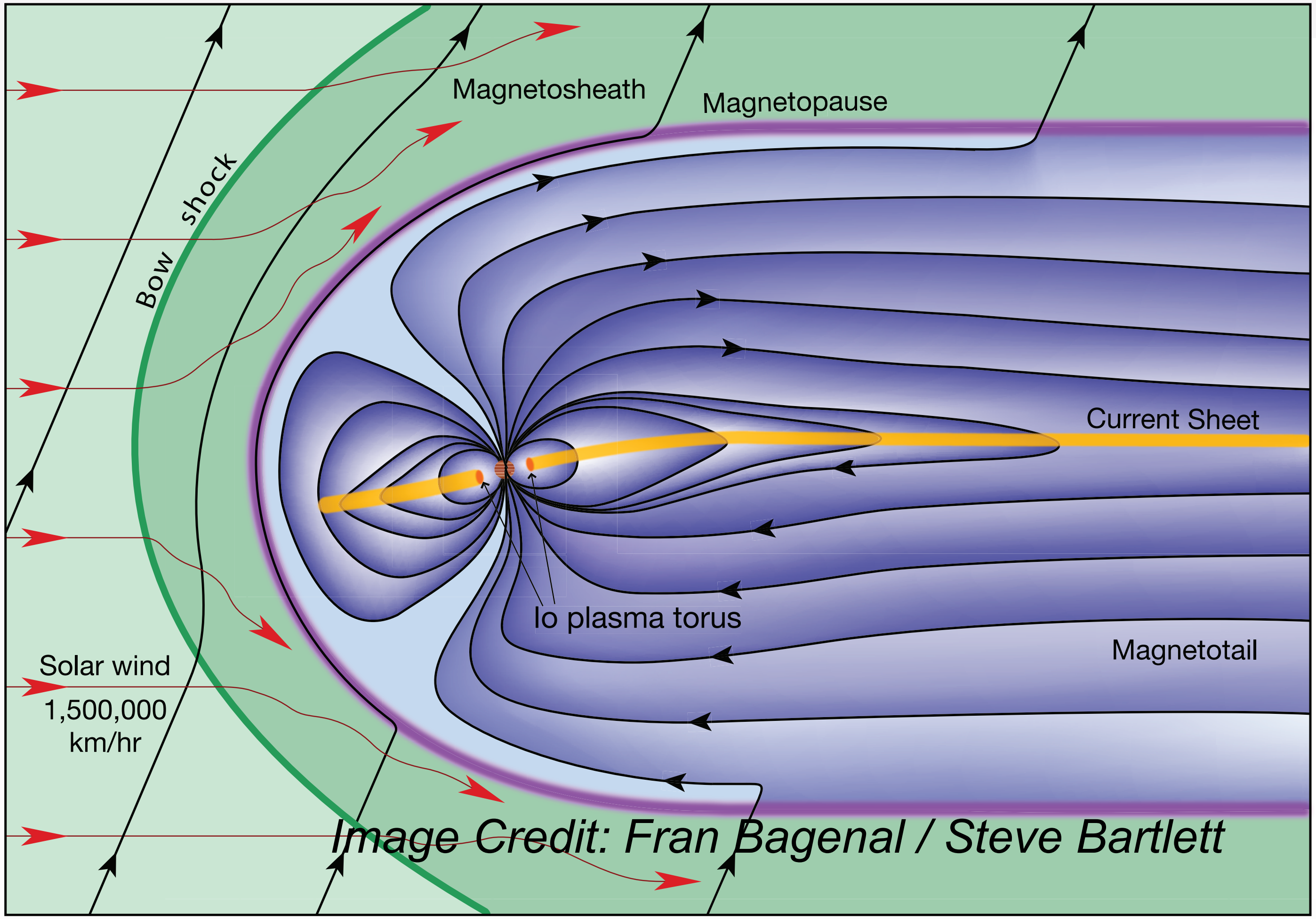


Image Credit: Fran Bagenal / Steve Bartlett

- Subsolar MP location pressure balance

$(1+\beta)\, B^2/2\mu_O \sim \rho_{sw}\, v^2_{sw}$

- Large μ_J and plasma β – large magnetosphere
- 'Disc-like' field- Jovian system 'squishy' $R_{MP} \sim P_{SW}^{-1/4}$ cf Earth $P_{SW}^{-1/6}$
- Disc-like obstacle – 'polar-flattened shape' (e.g.Saturn: *Pilkington et al JGR 2014*)

Jupiter: A Rapidly Rotating Magnetosphere

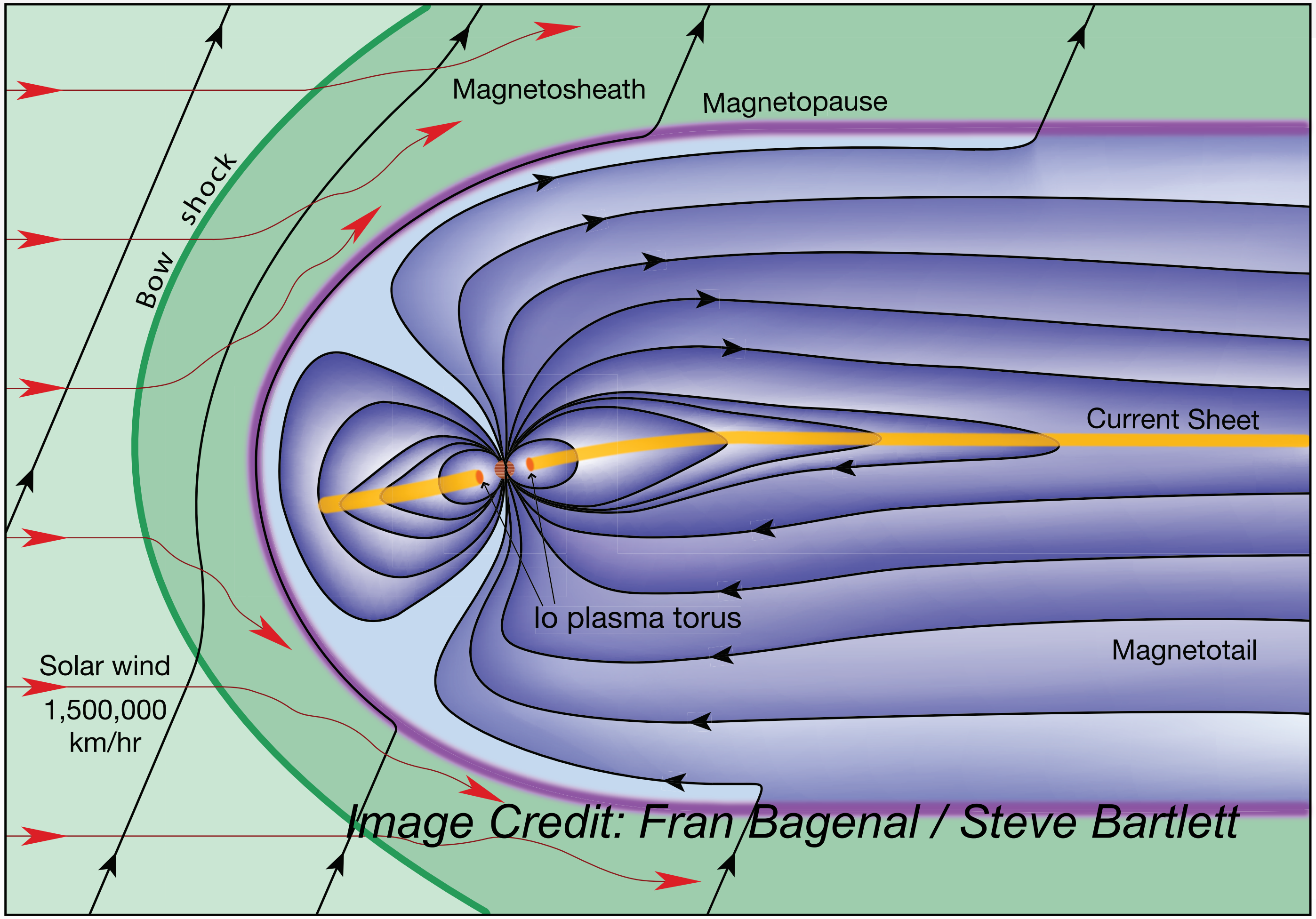
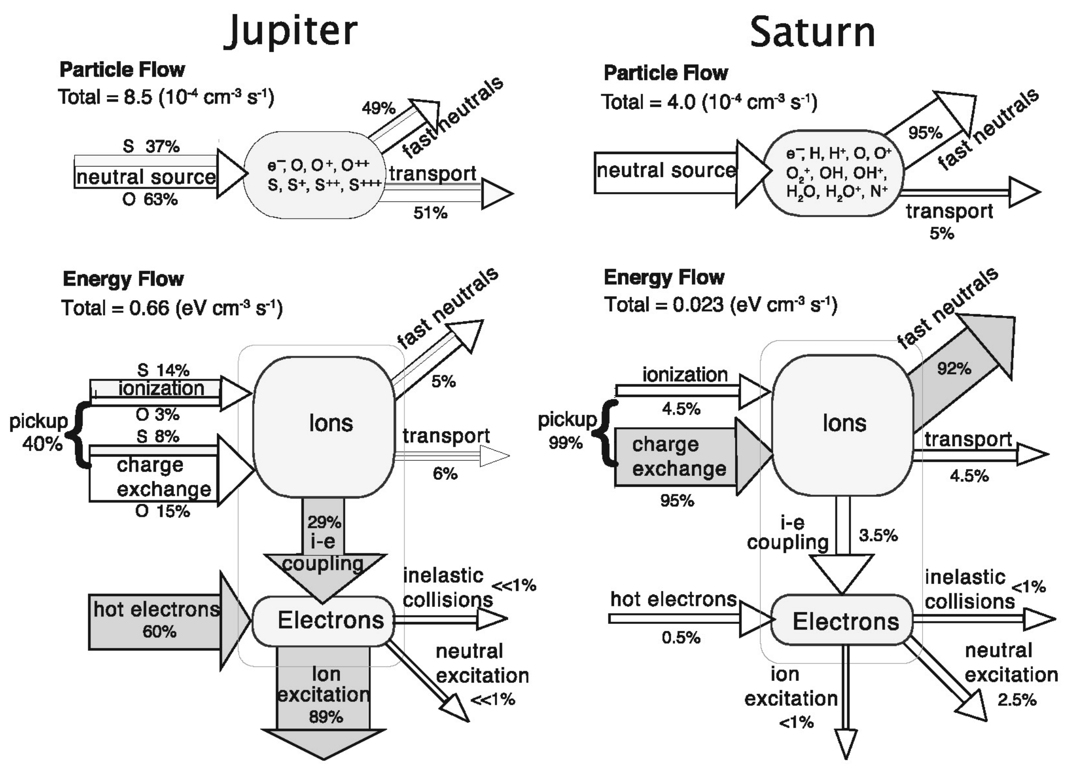


Image Credit: Fran Bagenal / Steve Bartlett

- An **internal** plasma source: Io
- Adds ~500-1000 kg/s of sulphur and oxygen plasma to the system
- The plasma does not 'build up' indefinitely – radial transport

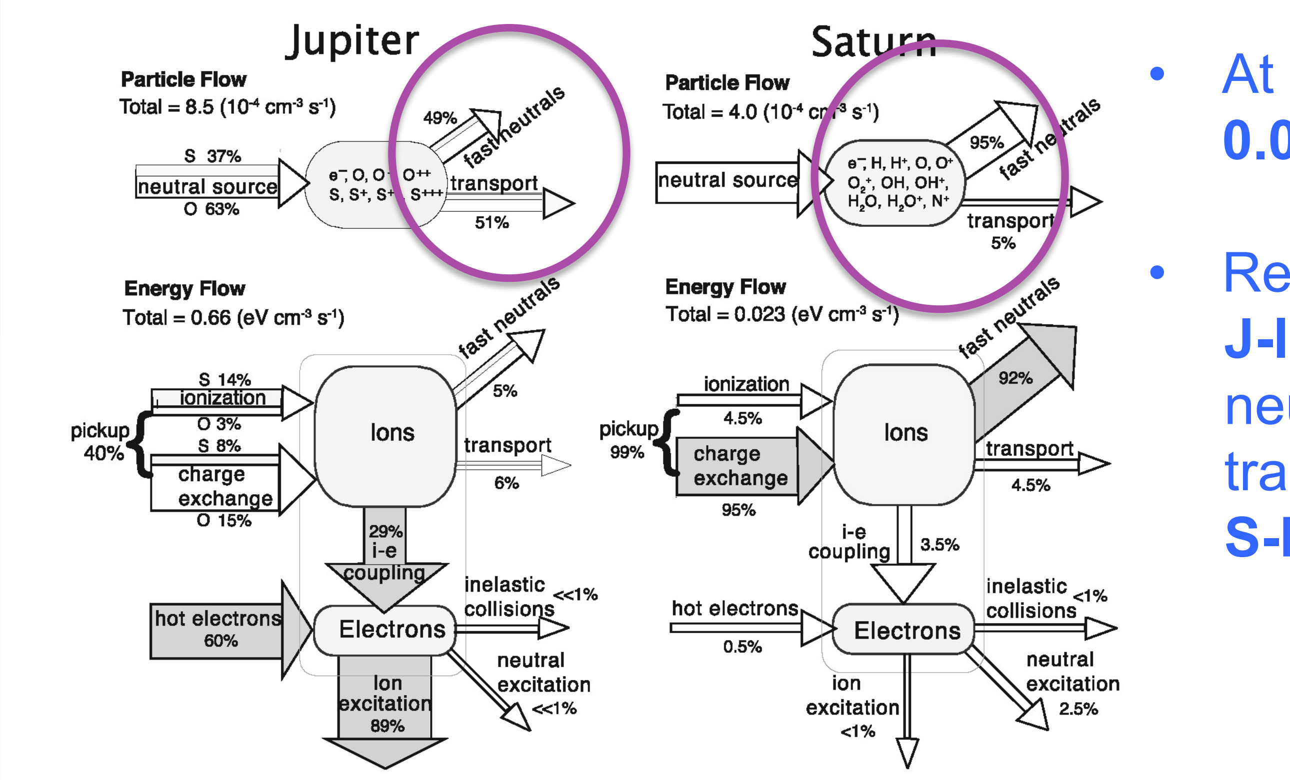
Tori at Jupiter and Saturn



1. Mass and energy flow for (left) the S,O-based Jupiter model and (right) the O-based Saturn model (see Table 1 ues). At Jupiter energy flows primarily from ion pickup and hot electrons to UV radiation (ion excitation), while at energy flows primarily from ion pickup to fast neutral escape.

- *Delamere et al (2007)* modelled physical chemistry under conditions within Io, Enceladus tori.
- 'Destiny' of ions 'injected' into the system with gyro-energies ➔ 57 km/s (***150 eV***, J-I), 26 km/s (***37 eV***, S-E)
- Model includes energy input from hot electrons; Coulomb heating of electrons by ions

Tori at Jupiter and Saturn



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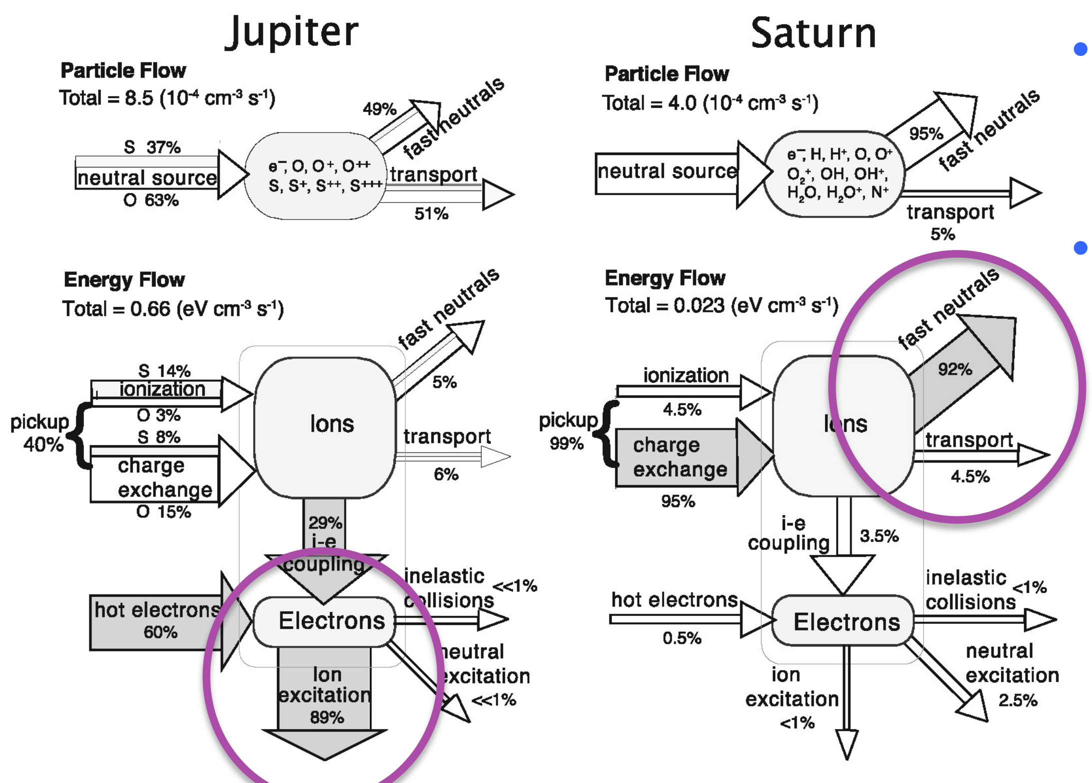
- At Saturn, No / Ni ~ **12**, c.f. **0.012** for 'S/O Jupiter'
- Reflected in particle losses: **J-I: 'Half and half'** fast neutral escape / radial transport **S-E: 95% neutral escape**

Tori at Jupiter and Saturn



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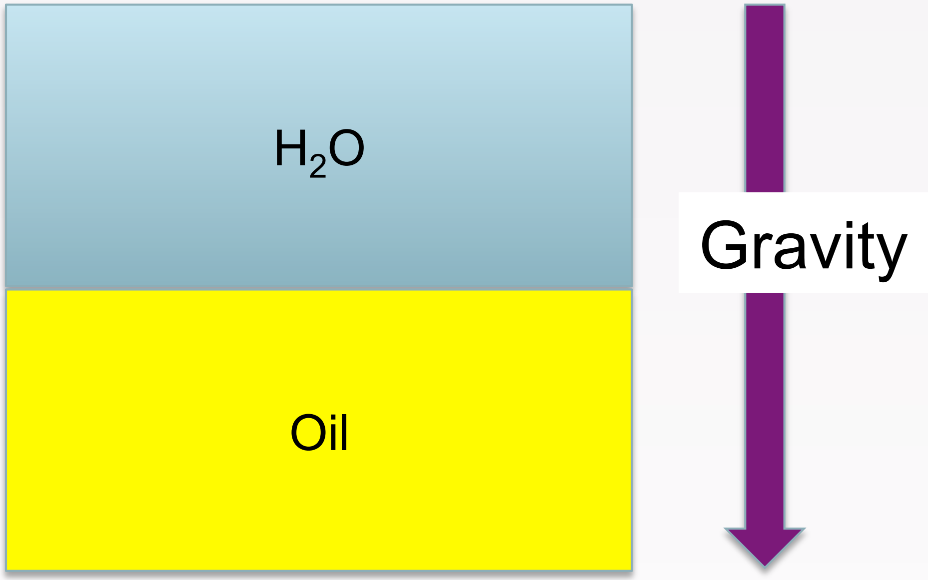
- At Saturn, No / Ni ~ **12**, c.f. **0.012** for 'S/O Jupiter'
- Also reflected in output of energy:
  J-I: Ion excitation (subsequent radiation) **89%**
  S-E: 92% energy carried away by fast neutral escape

Radial Transport of Plasma in the Jovian Disc

Some simple considerations:

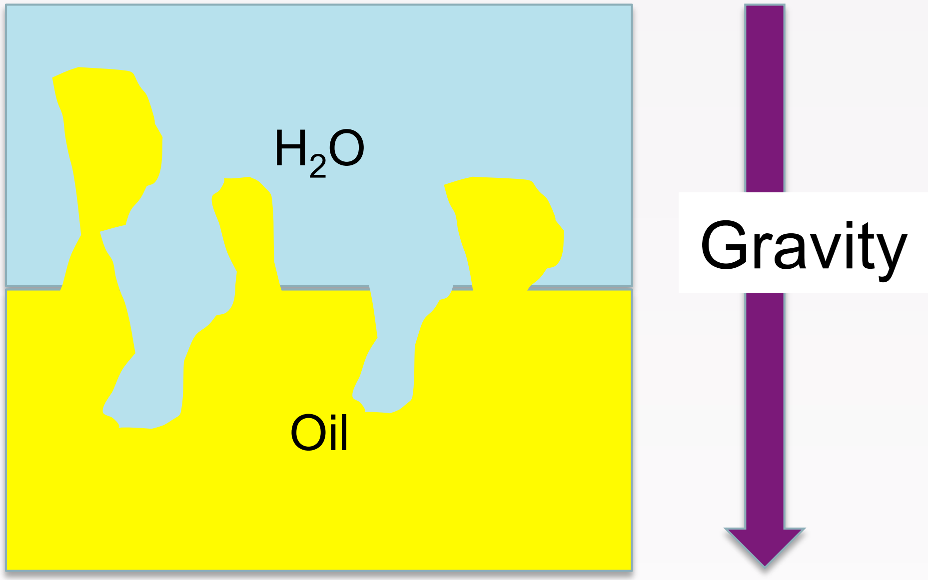
- The 'average' Jovian configuration is a plasma concentrated into a relatively thin, near-equatorial sheet.
- In an average sense, of order ~1 tonne/s of plasma must be lost from the system, to balance the Iogenic source.
- The net transport of this material from Io orbit must be achieved in the *'quasi-dipolar'* region (r <~ 10-15 RJ), where the field strongly resists 'deformation'.
- Thus we need a 'mode' of transport where plasma mass is displaced, but magnetic flux is not ➔ 'interchange' – a process which relies on the development of '**texture**'

Radial Transport Simple Picture: Rayleigh-Taylor instability



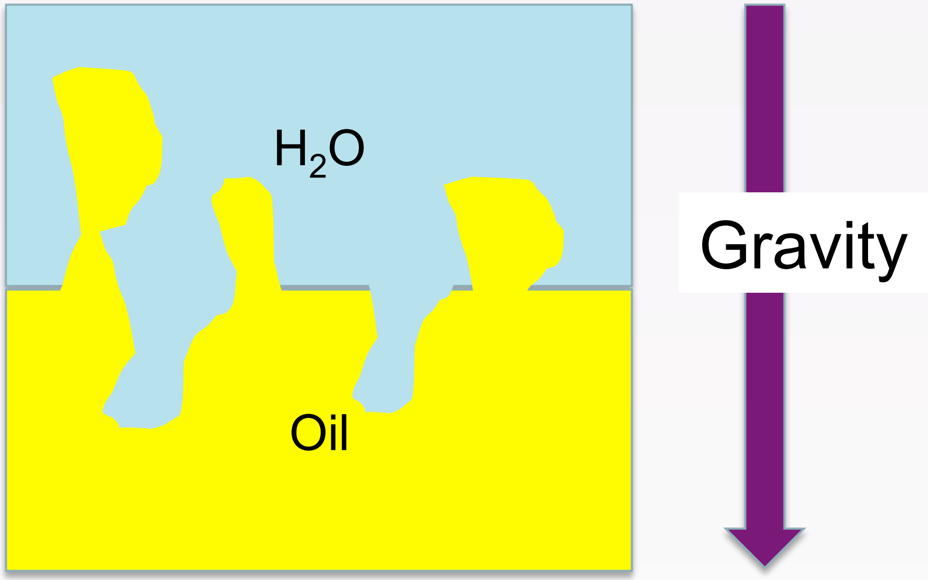
- An *unstable* equilibrium
- Density gradient opposes the ‘driving force’

Radial Transport Simple Picture: Rayleigh-Taylor instability



- The system evolves to a more stable equilibrium, characterised by minimum *potential* energy.
- Concept of 'fingers' or 'droplets' to achieve this.

Radial Transport Simple Picture: Rayleigh-Taylor instability



- For the Jovian magnetosphere:
- Replace H2O by the colder, dense plasma injected by Io.
- Replace oil by hotter, more tenuous plasma.
- Replace gravity by centrifugal force.
- The decrease in centrifugal potential must more than compensate the heating of inward-moving flux tubes.
- Gradients in cold plasma – ions per unit flux must decrease with distance

Radial Transport: Observations

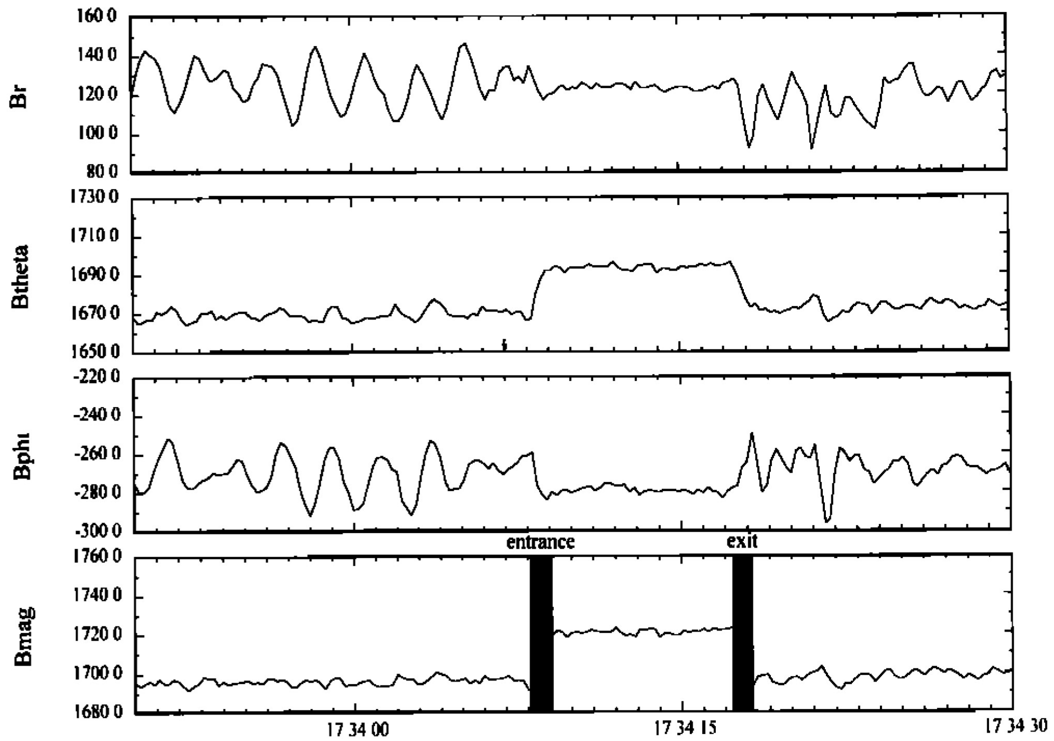
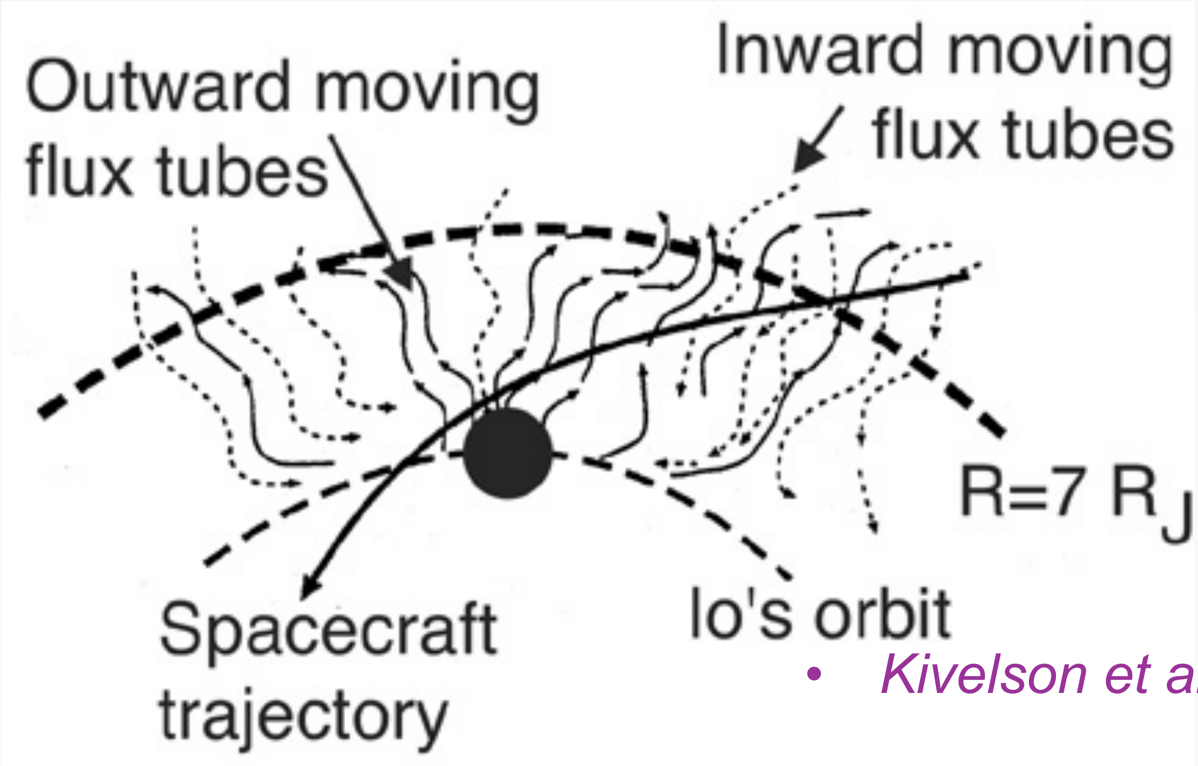


Figure 4. The field magnitude and components in the interval of enhanced field at ~17:34 UT. Shading emphasizes the 1 s intervals during which the field increased and decreased abruptly. The marked decrease of the power in the ion cyclotron waves during the interval of interest is evident.

- *Galileo* observed field enhancements of 1-2% (10-25 nT) over 6-7.7 RJ *(e.g. Kivelson et al, GRL, 1997)*
- Event shown is at 6.03 RJ, lasts 10s, has density depletion Ni/No >~ 0.53
- Estimated distance of origin: 7.2 RJ
- Note also disappearance of ion-cyclotron waves: consistent with Vr~100 km/s to ‘avoid’ growth due to ion pickup *(Russell et al, 1997)*

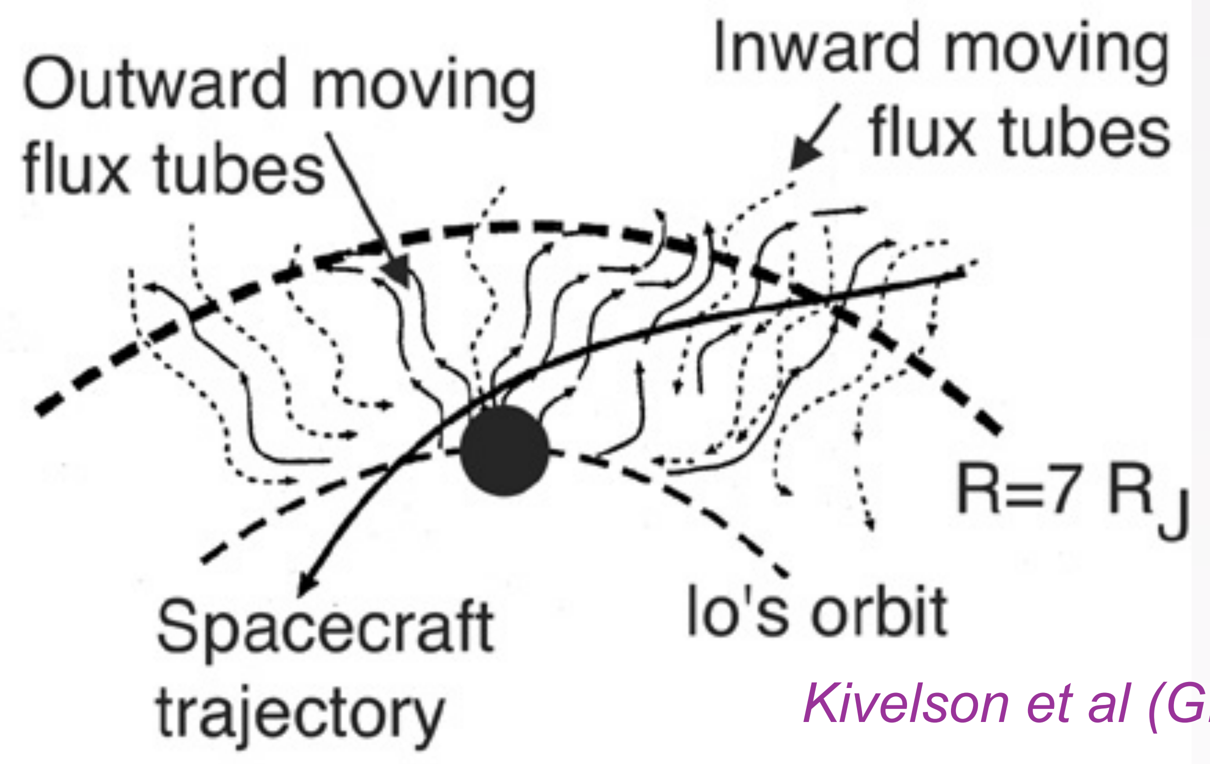
Interchange Properties



- *Kivelson et al (GRL, 1997)*

- Heavier tubes are outward-moving.
- Close to Io, magnetic data indicates outward motions dominant (balanced by inward motions at other longitudes)
- Further away, motions 'balance'

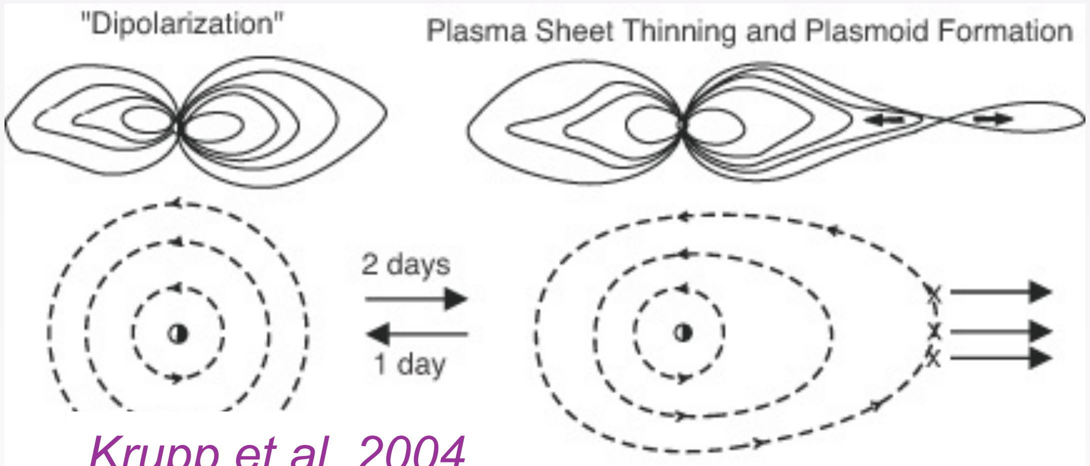
Interchange Properties



Kivelson et al (GRL,1997)

- Interchange concept first proposed by *Ionnadis and Brice (1971)*, further developed by e.g. *Siscoe and Summers (1981)*, *Southwood and Kivelson (1987)*, *Yang et al (1994).*
- *More recently e.g. André and Ferrière (2008, JGR, effect of pressure anisotropy); Kidder et al (2009, JGR, Saturn multifluid model, effect of Enceladus and solar wind****)****; Observations by* Cassini *at Saturn* (e.g. *Hille et al 2005, Rymer et al 2009*)

What goes in must (eventually) come out



Krupp et al, 2004

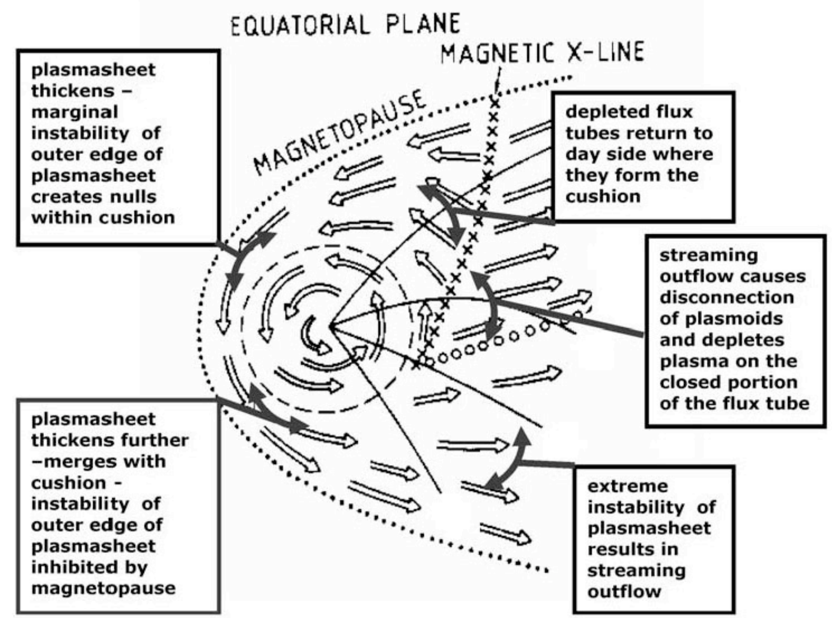


Figure 8. The equatorial plane of Jupiter's magnetosphere as represented by *Vasyliunas* [1983]. Labels indicate the interpretation of the dynamics in the schematic in terms of the processes discussed in this paper.

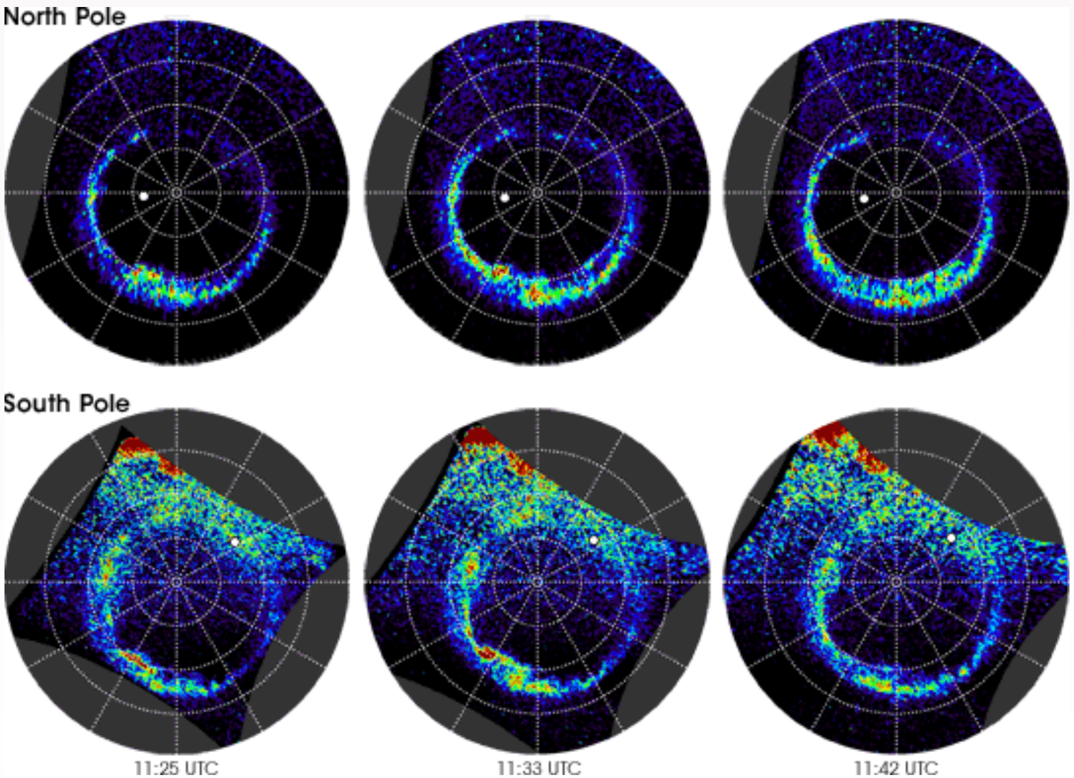
Kivelson and Southwood 2005

- Flux tubes cannot maintain integrity
- The process of mass-loading leads to strong radial expansion of tubes in the tail region
- Formation of plasmoids, dipolarizations – à la *Vasyliunas (1983)*
- Importance of *Kivelson and Southwood (2005)* analysis: **Must combine MHD and kinetic framework**
- ~1 keV heavy ions can 'pick up' ~20 keV from centrifugal acceleration, moving 45-50 RJ in cyl. radial dist.
- Combined with significant rotation / expansion of tube during bounce period - unstable plasma sheet.

Magnetosphere-Ionosphere Coupling / Aurorae

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: Earth-like, with 'secondary' features.



Examples of Earth UV auroral images

Image credit: T. J. Stubbs / NASA

Auroral Oval: Earth

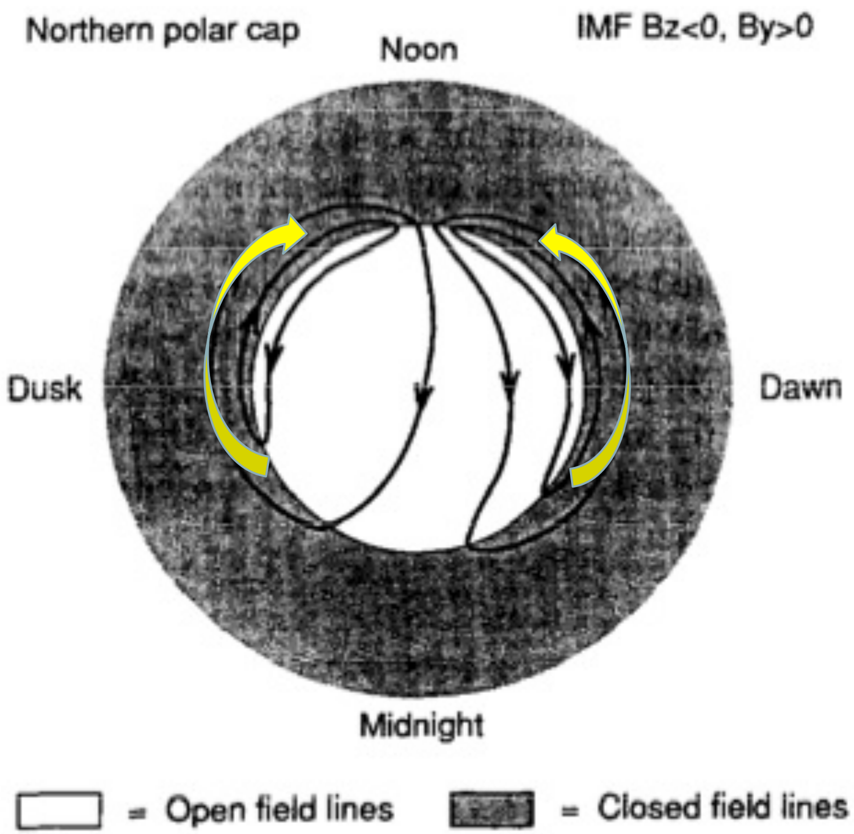
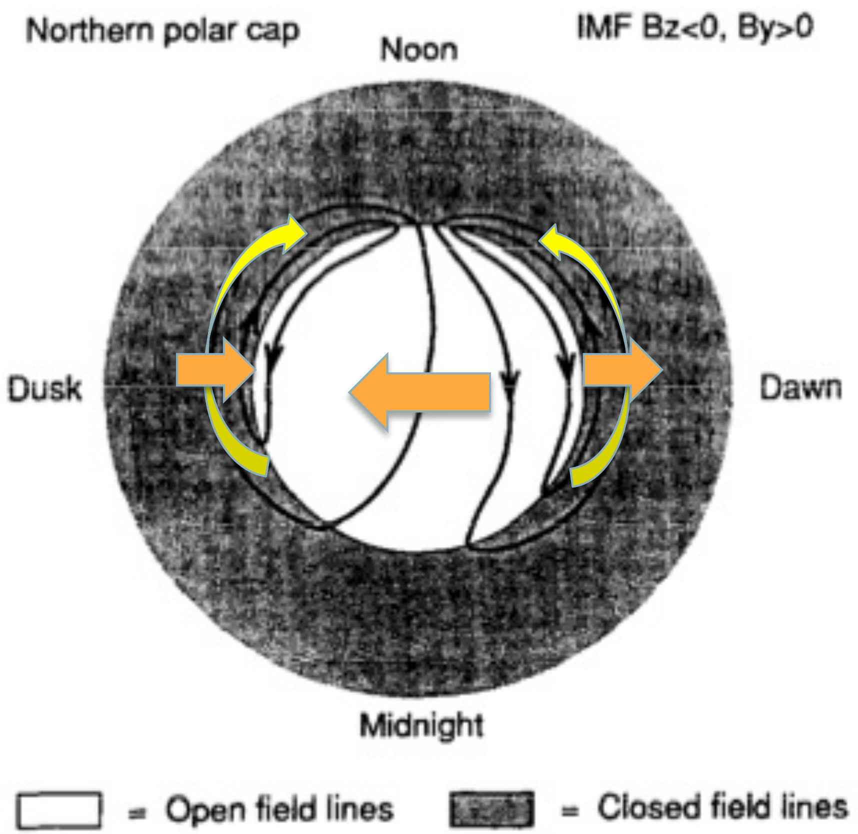


Fig. 1. A typical northern polar-cap convection pattern as observed for IMF $B_z < 0$, $B_y > 0$. Thick lines with arrowheads represent plasma flow streamlines. Antisunward convection occurs on open field lines (unshaded region) and sunward return flow on lower-latitude, closed field lines (shaded region).

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 ?

Auroral Oval: Earth



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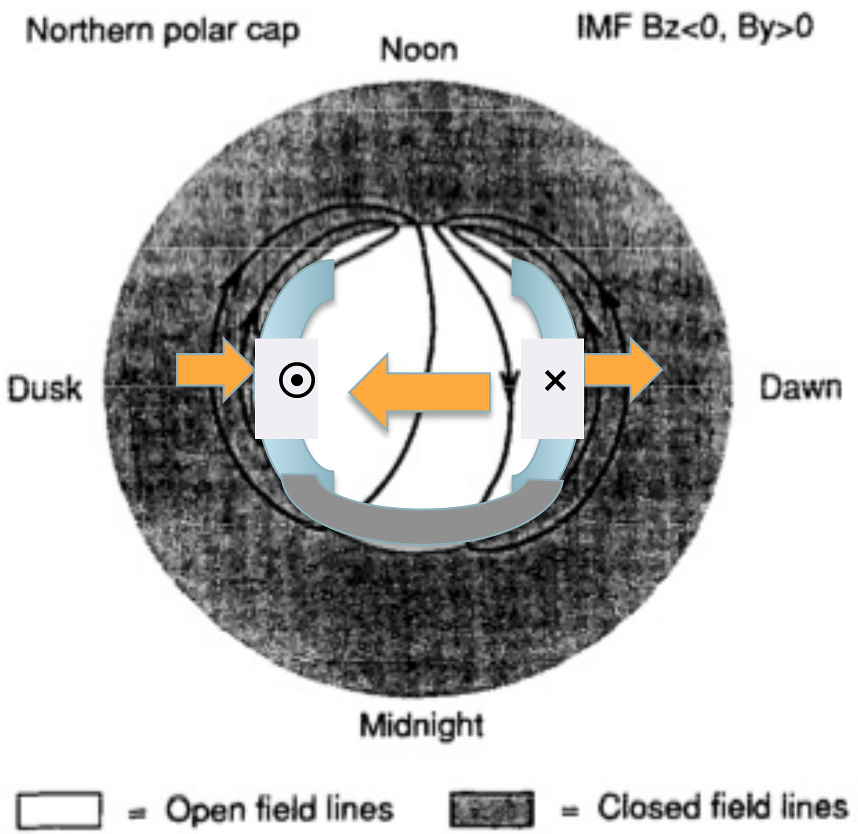
- *Horizontal gradients in flow* correspond to similar gradients **in *E-field* (arrows)**, and current density J_{HORIZ} in the ionosphere.
- To 'close' the current, we require FAC ➔ aurora.
- Example: Pedersen current – FACs at 'sharp' changes in **E**.

Auroral Oval: Earth



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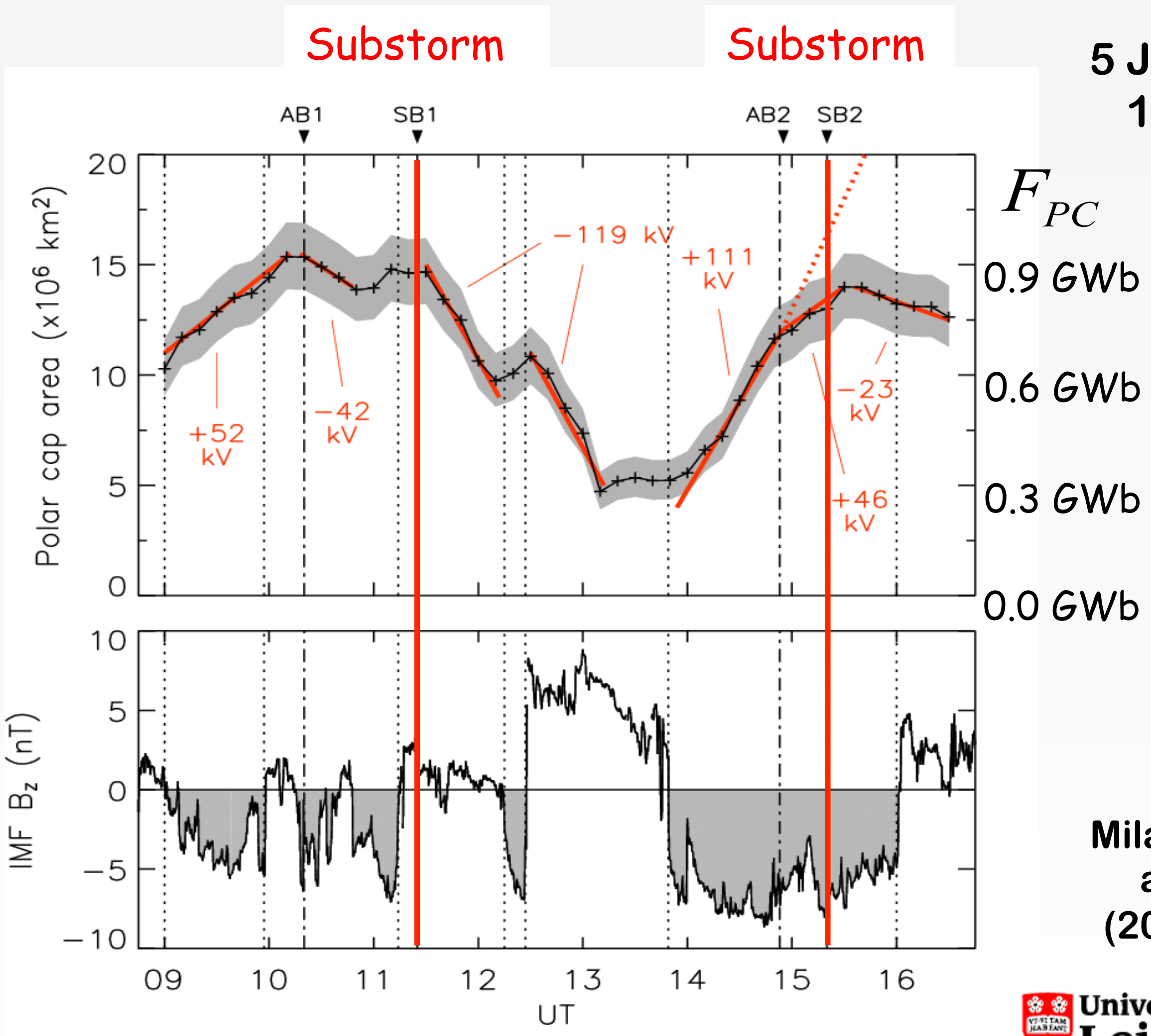
- Near-circumpolar sheets of FAC arise poleward (‘Region 1’, shown) and equatorward (‘Region 2’) regions near the polar cap boundary.
- Global auroral heat inputs, of order 10-100 GW (from particle precipitation and Joule heating).

Auroral Oval Changes: Earth

- 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).

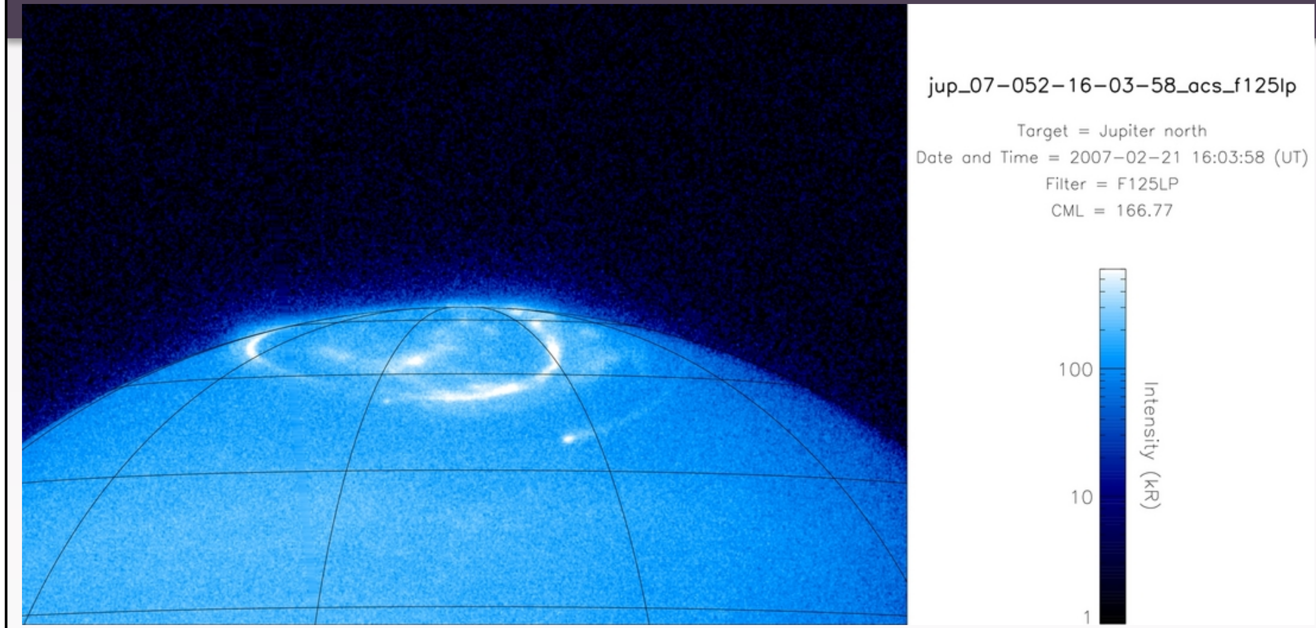


Milan et al. (2003)

(Courtesy S. Milan)

University of Leicester

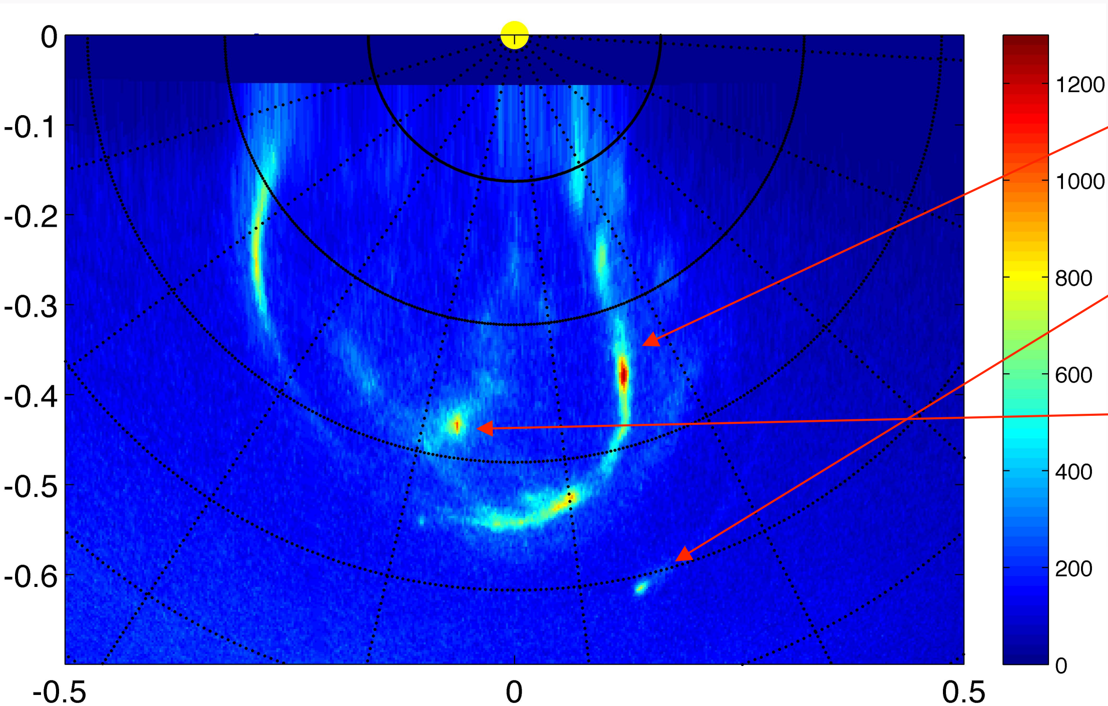
Auroral Oval: Jupiter



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

[Youtube Jupiter UV movie](https://www.youtube.com/watch?v=oFsoXjFoKf4)

https://www.youtube.com/watch?v=oFsoXjFoKf4

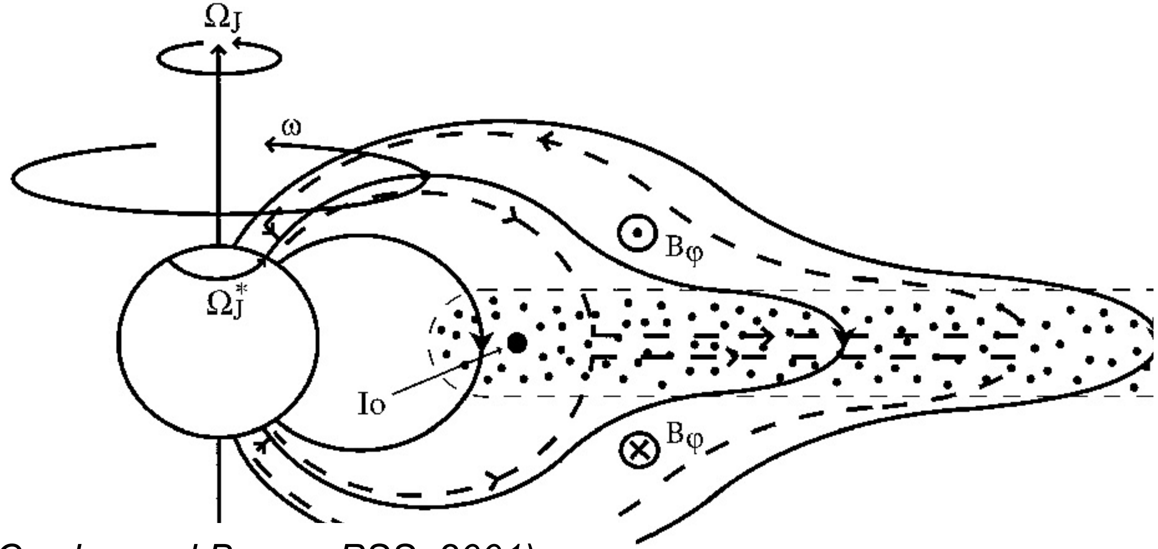


Main oval – **corotates with the planet, it is not Sun-aligned.**

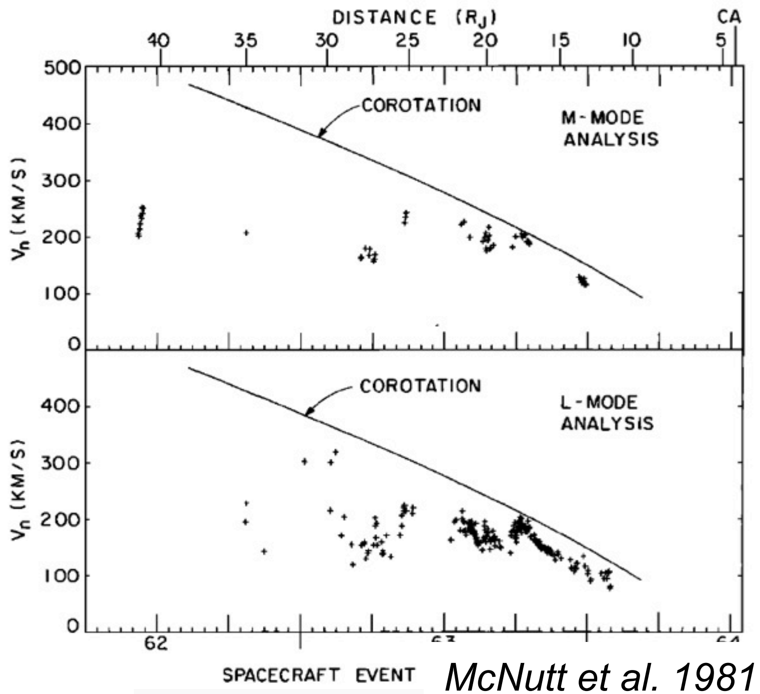
Io 'spot'

Cusp?

Auroral Oval: Jupiter



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

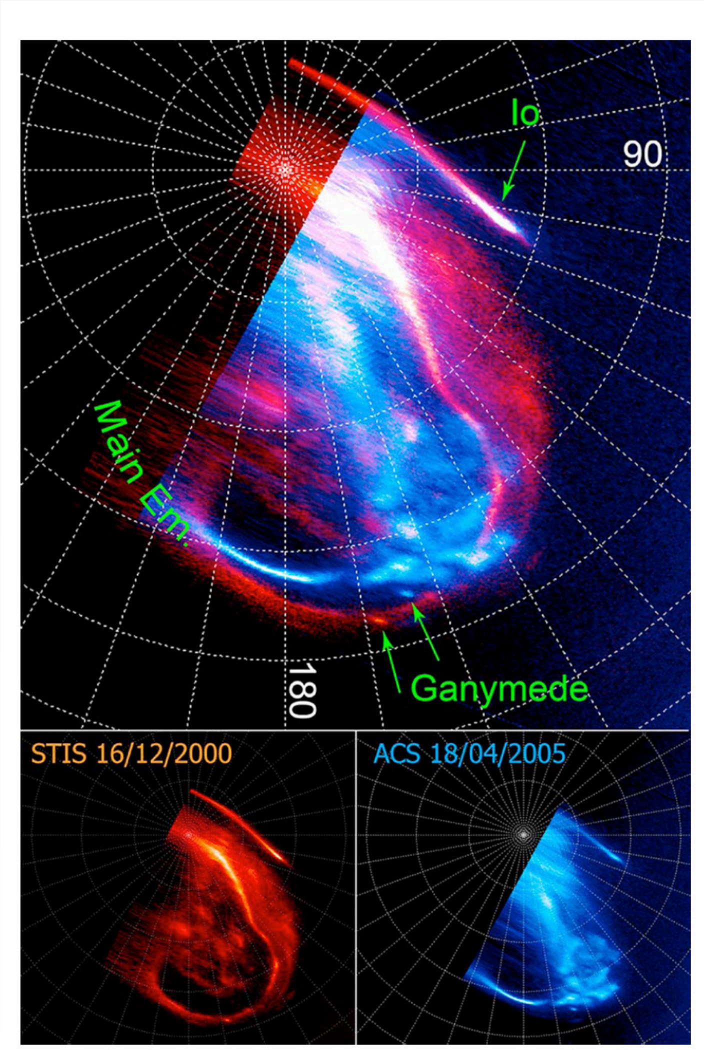


McNutt et al. 1981

- Jupiter's main oval 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 up to ~30 hr).
- Source of disc plasma is the moon, ***Io*** – adds ~500-1000 kg/s of sulphur / oxygen plasma (e.g. *Bagenal and Sullivan, 1981, JGR*).
- Diagram shows the general sense of the ***currents***.
- Usually, main oval emissions map to ~20-30 RJ in the equatorial plane – location of 'breakdown in corotation' of plasma.
- Global energy dissipated is **~90-200 TW** (Joule heating + precip'n), ~1000 times the energy range for the Earth.
- *Ray et al* (e.g. *JGR*, *2010*) considered effect of field-aligned **E**

Does the Jovian oval morphology change ?

- Yes. Here's an example (*Grodent et al (JGR, 2008), see also Bonfond et al (GRL, 2012)*)



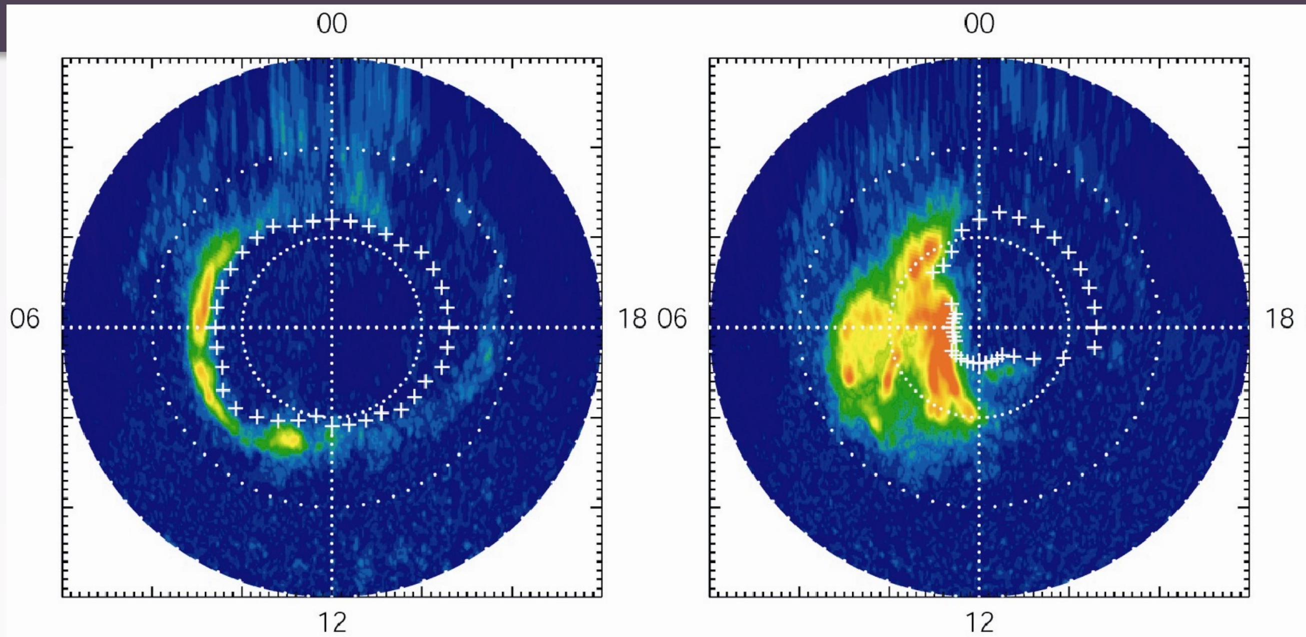
- Main emission in the 'red' image is 'displaced' equatorward by up to ~5 deg, coinciding with the footprint of Ganymede.

- 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 *Nichols et al. (2015)* indicates that hot particle population enhancement, combined with pressure *anisotropy*, can 'work'.

Auroral Oval: Saturn

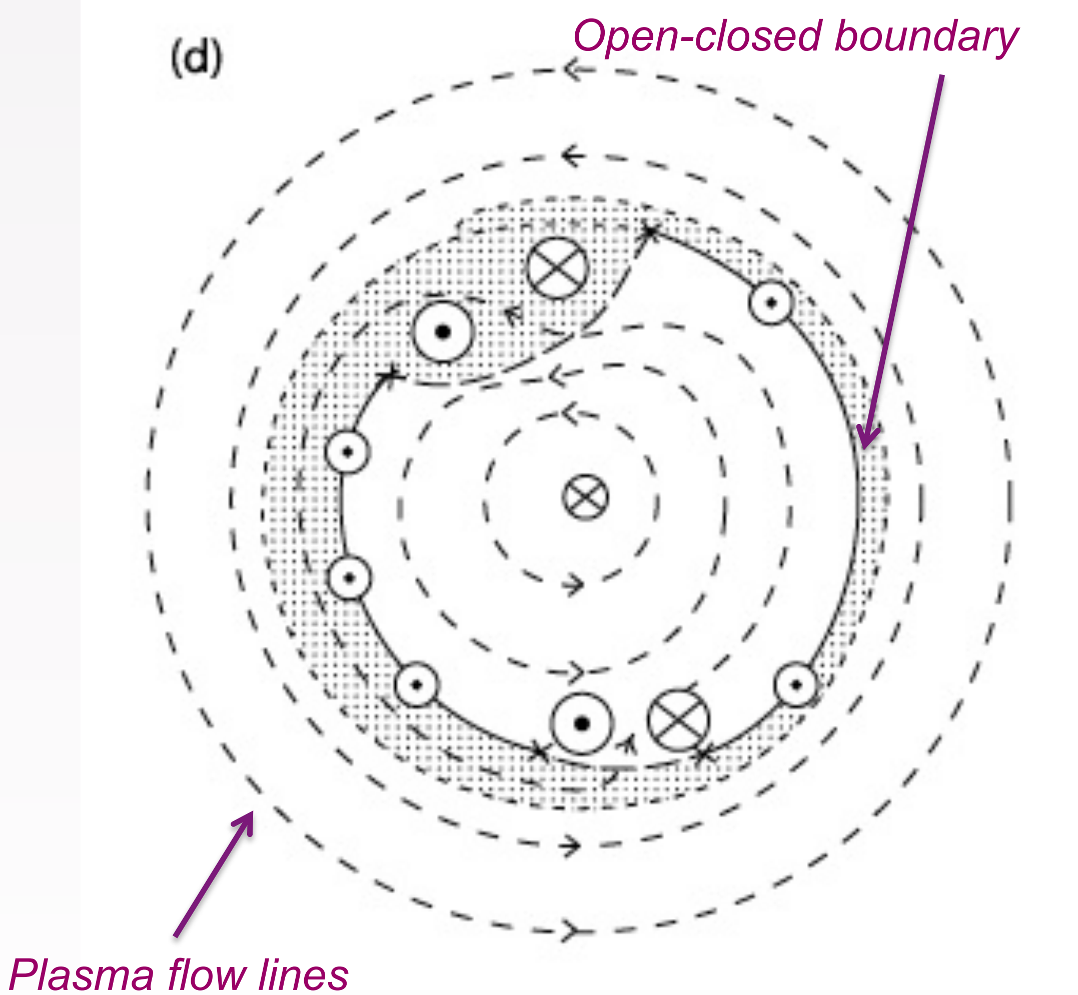


30 hours before SW shock

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).

Auroral Oval: Saturn



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, flows are dominantly *rotational*, even across the nominal polar cap.

- 'Quiescent' oval from 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)*

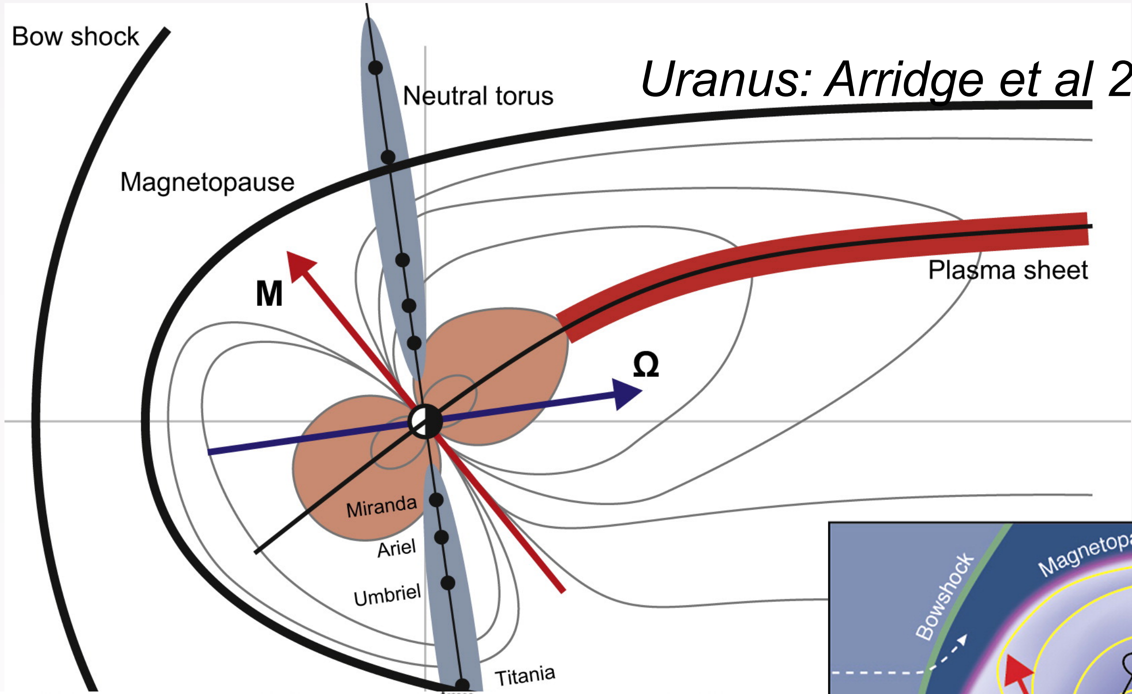
Summary

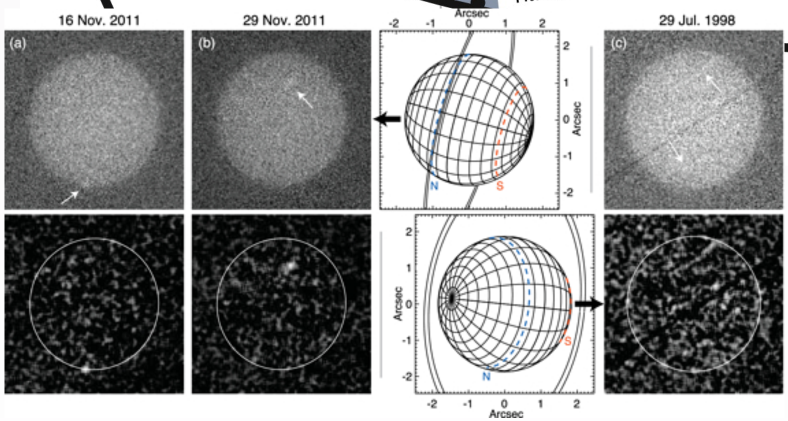
	Earth	Jupiter	Saturn
Dipole moment	$1\mu_E$	$18000\mu_E$	$550\mu_E$
M'pause standoff distance R_{MP}	$1R_{MP,E}$	$80R_{MP,E}$	$20R_{MP,E}$
$P_{ROT}/(R_{MP}/V_{SW})$	~500	~2.5	~8
Auroral energy dissipated	~10s of GW	~100 TW	~20 TW
Main auroral 'oval' due to:	Solar wind-driven	Planetary rotation	Solar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

‘Ice Giants’

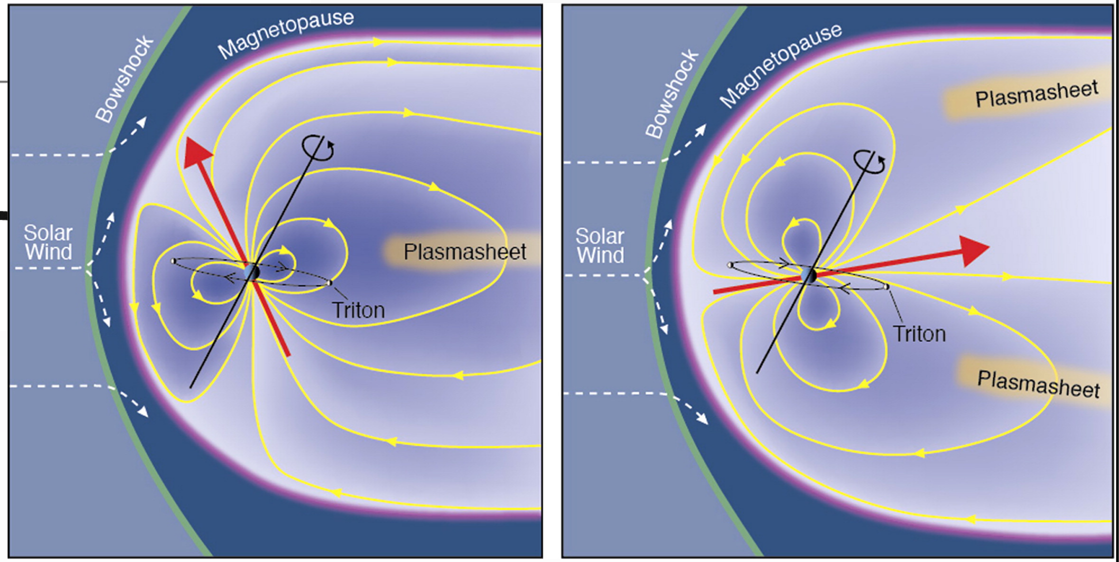
- ***Complex*** B-fields
- Large dipole-rotn axis angles predict dramatic magnetospheric ‘reconfigurations’

Uranus: Arridge et al 2014





Uranus Aurora: Lamy et al 2012



Neptune: Bartlett / Bagenal, Masters et al (2014)

Summary

- Magnetospheres are natural laboratories for ***plasma physics***.
- We may describe plasma motion in terms of individual particle *drifts*.
- When we consider **collective behaviour**, MHD provides a framework for treating the plasma as a *fluid* permeated by electromagnetic *fields.* Concepts of **magnetic 'pressure' and 'tension'** are useful.
- The magnetic field structure plays an important role in ***force balance*** and ***plasma transport and dynamics***. Reconnection is an important means of 'solar wind – magnetosphere coupling'.
- **Magnetosphere-ionosphere *coupling*** 'transmits' energy and momentum by means of *field-aligned current* systems. These are often associated with ***auroral emissions***.
- **MISSIONS to Jupiter: Juno** (JOI 2016), **JUICE** (JOI planned 2030)

- *Further reading (not exhaustive!):*

- *'Heliophysics' series (ed. Schrijver / Siscoe / Bagenal / Sojka);*
- *'Introduction to Space Physics' (ed. Kivelson and Russell);*
- *'Basic Space Plasma Physics' (Baumjohann / Treumann);*
- *'Jupiter' book (ed. Bagenal, Dowling, McKinnon);*
- *'Physics of the Jovian Magnetosphere' (ed. Dessler)*
- *Special issue of SSR / ISSI book 'Giant Planet Magnetodiscs and Aurorae' (ed. Szego et al)*