Learning about Earth's plasma processes from studies of other magnetospheres

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Why bother studying other magnetospheres?

- We have plenty of data from Earth's magnetosphere.
- The structure and dynamics of our magnetosphere can be described by magnetohydrodynamics (MHD) supplemented (in limited portions of the volume of interest) by kinetic theory or other intermediate approximations such as multifluid theory or Hall MHD.
- What more do we need?

We are physicists

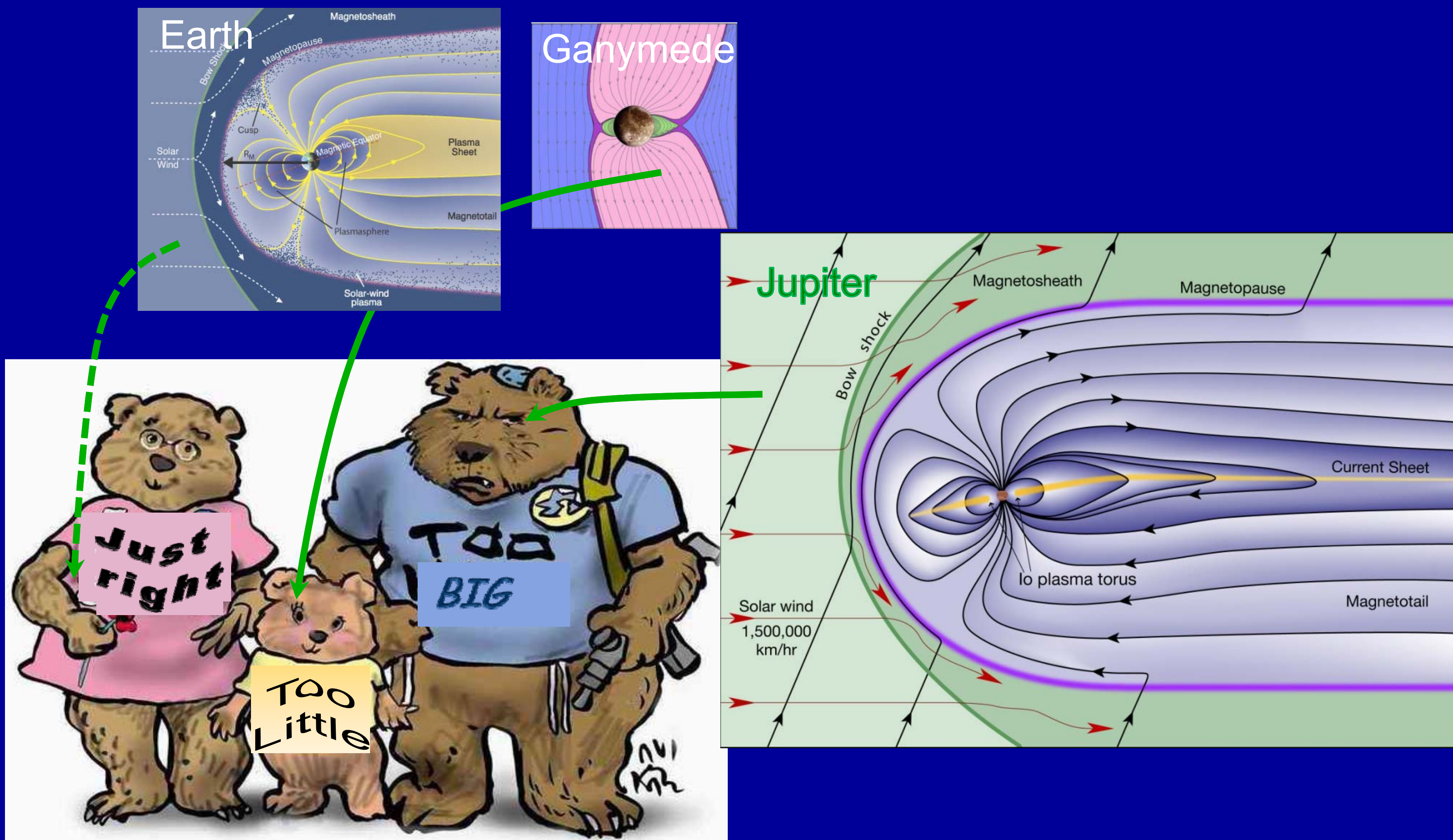
- Typical of the rigor of physics is the need to change the parameters governing the system studied in order to test whether behavior varies as predicted.
- Earth's magnetosphere experiences varying solar wind input, but other parameters such as the size of the central planet and its rotation rate, the rough magnitude of its internal field, and its plasma sources change little or not at all.
- Studies of planetary magnetospheres can be considered our experiments.

Processes to be discussed

- Selected as differing from those dominant at Earth.
- Selected to illustrate a range of possible behaviors.
  - Some may have arise in Earth's magnetosphere but may have escaped attention.
  - Others may have nothing to tell us about Earth but may interest you.

Planetary magnetospheres range from the small (Ganymede) to the large (Jupiter).

- Or as Goldilocks might say:



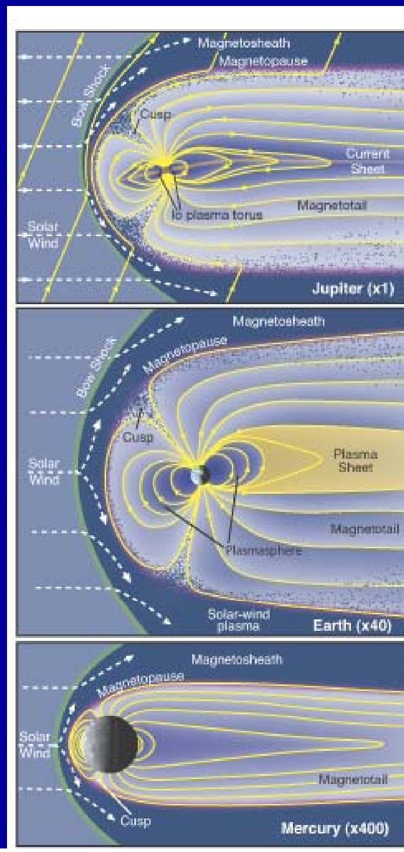
Indeed, size is the first thing that comes to mind

- But "big" and "small" require more scientific definitions.
  - Focus must be on ratios.
- All are big wrt ion scale lengths such as ion gyroradii, Debye lengths, . . .
  - MHD (usually) applicable.
- Some important ratios:
  - (Stand-off of nose)/ R_{planet}.
    - at Mercury: ~1
    - at Earth: ~10
    - at Jupiter: ~100
  - Not much room for radiation belts at Ganymede/Mercury.

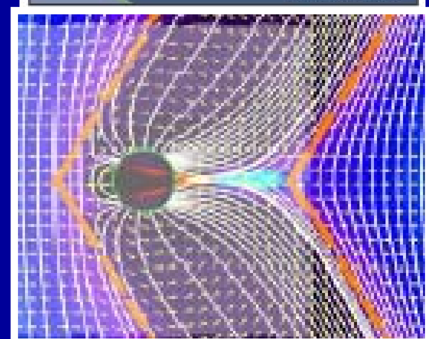
Jupiter

Earth
x 40

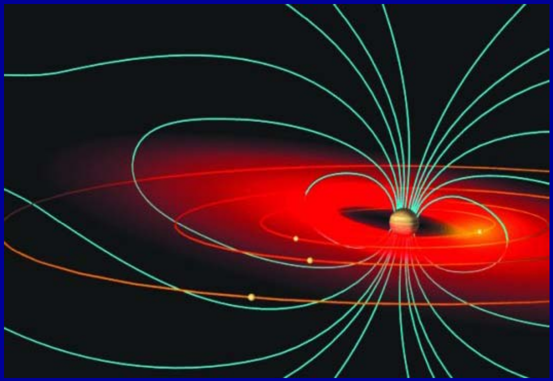
Mercury
x 400



Ganymede
x 400



Some properties that matter



- **Internal plasma sources.**
  - At Earth, the ionosphere;
  - at Jupiter mainly the moons, predominantly "heavy" ions arising from ionization of neutrals from Io;
  - at Ganymede, internal source (ionosphere) is weak.
- **Rotation rate**.
  - Jupiter's rotation period is 10 hours,
    Its equatorial surface rotates at a speed of 12 km/s.
    At Earth, the surface rotation speed is 0.46 km/s.
  - Jupiter's magnetosphere approximately corotates.
    Rotational stresses are far more significant at Jupiter than at Earth.
  - Ganymede is phase-locked to Jupiter, so it always keeps the same face to the upstream flow of Jupiter's magnetospheric plasma flow. Thus, relative to the magnetospheric symmetry axis or the flow direction (equivalent to $-x_{GSM}$), Ganymede's msf does not rotate.

Topics

- Role of centrifugal acceleration:
  - ballooning
  - spontaneous interchange
    - does this happen at Earth?
  - relation to plasma loss

- Reconnection in relation to steady/unsteady upstream conditions.
  - Ganymede and intermittency in the presence of steady upstream conditions
  - Scale length of Jupiter and possible consequences in relation to unsteady solar wind conditions.

- Alfvén wings from Ganymede to Earth.
  - a critical role for the ionosphere.

The magnitude of the planetary field matters

- Again – need to compare magnitude with something else.
  - The ratio of magnetic pressure to total pressure of external plasma determines size of magnetosphere.
    - Stress balance with external flowing sw gives

$$\rho_{sw} u^2 \approx B_o^2 / 2\mu_o (R_{\mathrm{nose}} / \mathrm{R_P})^6$$

  - $B_o^{1/3}$ controls a minimum stand off distance of the SW.
    - ρ_{sw} decreases with distance from Sun.
  - Magnetosphere size increases with both B_o and distance.
- But Jupiter's magnetosphere is even more inflated:
    - R_{nose} at Jupiter usually exceeds minimum estimate because of internal heavy ion plasma and rapid rotation (centrifugal stress helps push boundary outward).
- Ganymede is different. Its magnetospheric scale is unrelated to dynamic pressure of flowing plasma because the dominant pressure outside its magnetosphere is magnetic.

$$B_{ext}^2 / 2\mu_o \approx B_{o,G}^2 / 2\mu_o (R_{\mathrm{nose}} / \mathrm{R_G})^6$$

Effects of plasma rotation

- Rotation accelerates plasma outward. Pressure forces are also outward-directed. Only the curvature force pushes in.
- If rotation rate and density are sufficiently high, magnetic curvature force must increase to contain plasma → ballooning. Occurs when $\kappa \sim 1$.

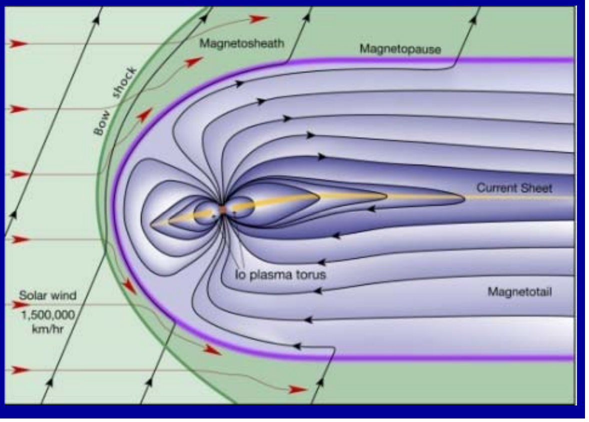
$$\kappa = \frac{\rho r \omega^2}{(B^2/2\mu_o)} \approx \frac{\mu_o \rho r^2 \omega^2}{3B^2} = \frac{1}{3}\left(\frac{v_\phi}{v_A}\right)^2 \geq 1$$

Near equator, assuming gravity is negligible.

- Rough estimates of κ at critical distances

	v_A(km/s)	v_{corot}(km/s)	κ and κ(L)
Jupiter (~20 R_J)	~130	12.5 L	0.003 L^2=1.2
Earth (~6 R_E)	~700	0.5 L	10^{-7} L^2=5×10^{-6}
Ganymede	~1000	**0**	**0**

- Extremes:
  - Ganymede plasma does not rotate relative to its magnetosphere - no ballooning.
  - Earth's rotates but m'sf balloons little.
  - Jupiter's m'sf balloons outside 20 R_J.

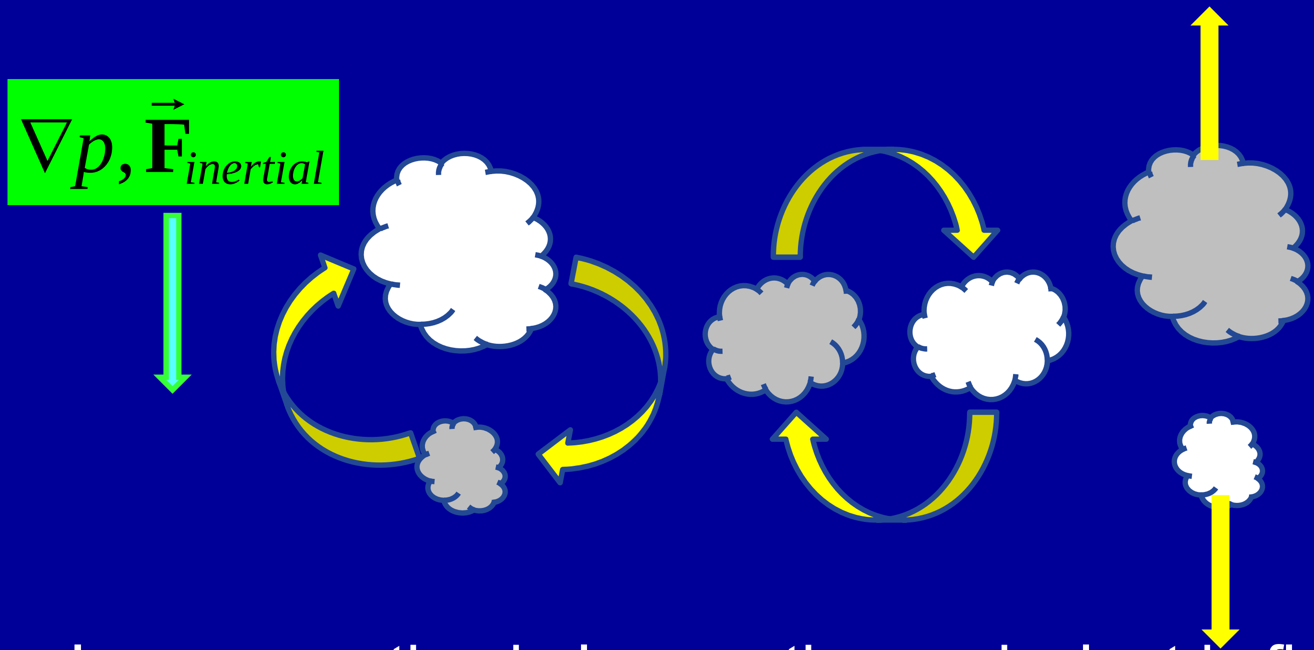


Plasma rotation rate also controls plasmapause distance

- Rotation modifies particle drift paths (establishes plasmapause).
- Extremes:
  - Ganymede plasma does not rotate relative to its magnetosphere. No plasmasphere. Plasma upwelling from the ionosphere gets swept to boundaries.
  - Earth's plasma rotates. Plasmasphere develops well within the magnetopause. Outer layers can be stripped off by convection to the magnetopause.
  - Jupiter's plasmapause beyond m'pause. Most drift paths are closed to encircle the planet. With strong plasma sources feeding the inner magnetosphere, loss mechanisms at Jupiter are not those typically observed at Earth.

Rotation can drive interchange instability

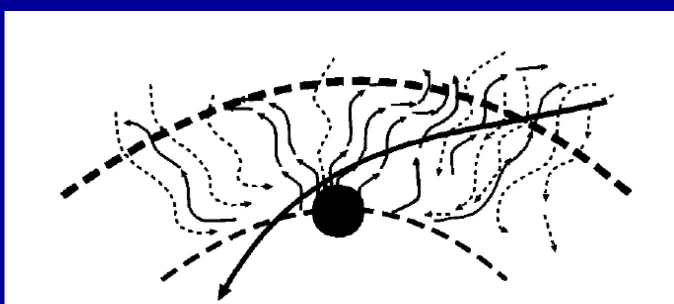
- Interchange familiar from studies of atmospheres.
  - 2 parcels of air at different altitudes change places
    - If then the parcel at lower altitude is denser than its surroundings, it will continue moving down in the gravitational field.

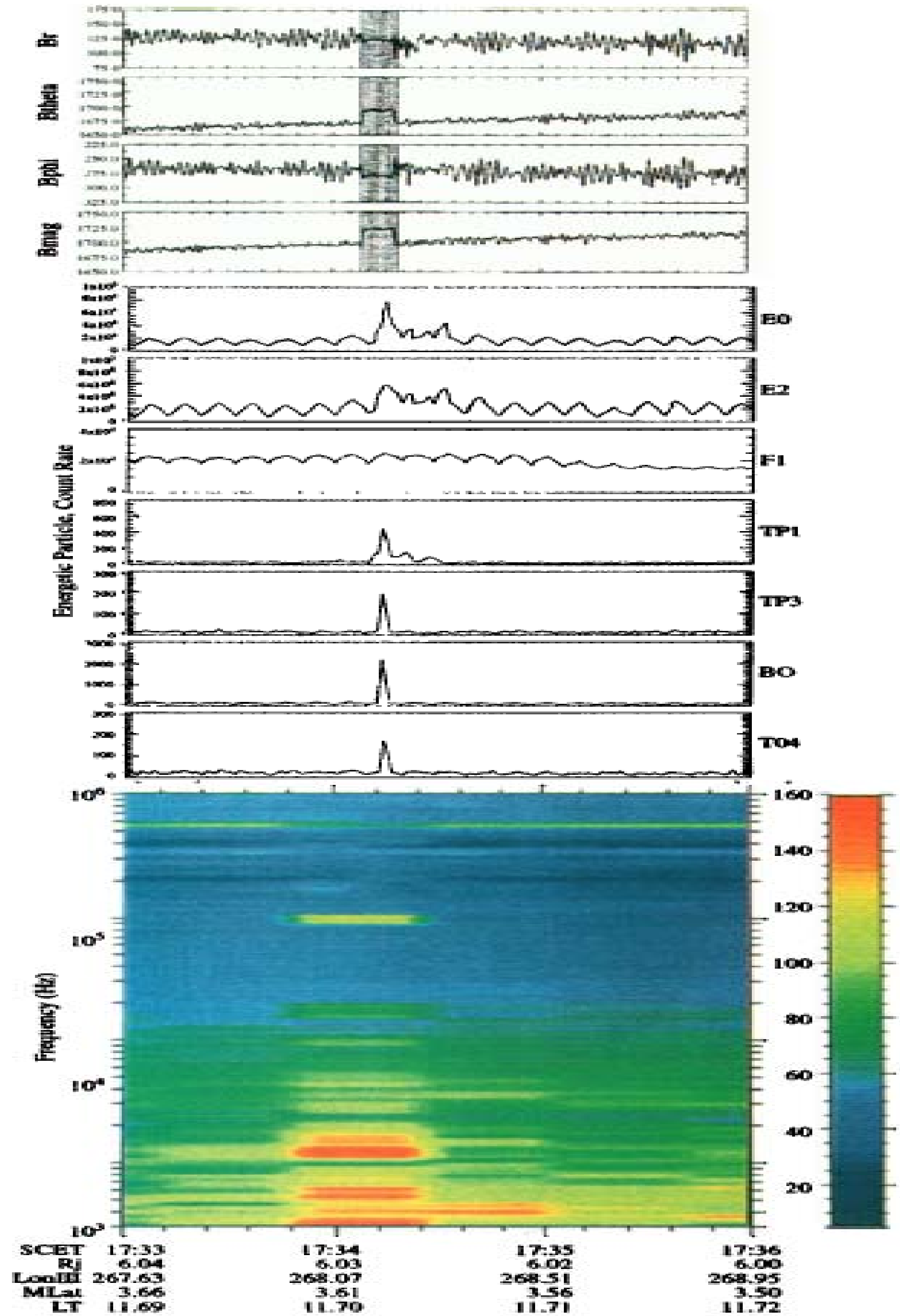


- In a magnetized plasma, the equivalent is flux tube interchange. Flux tubes loaded with cold, dense plasma may be unstable to motion in direction of inertial force, exchanging with flux tubes loaded with hot, tenuous plasma.

Interchange clearly identified at Jupiter (and Saturn)

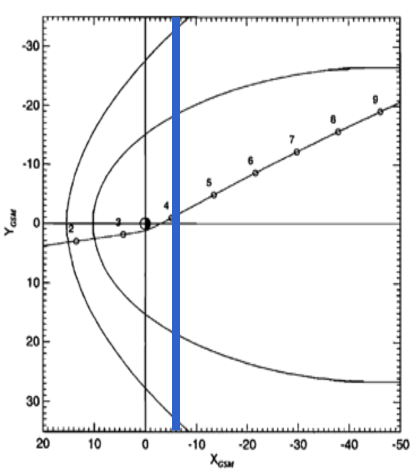
- In Jupiter's m'sphere beyond ~2 R_J, inertial response dominated by outward-directed centrifugal pseudo-force.
- Same principle as for Earth's atmosphere, but "heavy" flux tubes move out to be replaced by "hot, tenuous" flux tubes moving inward.

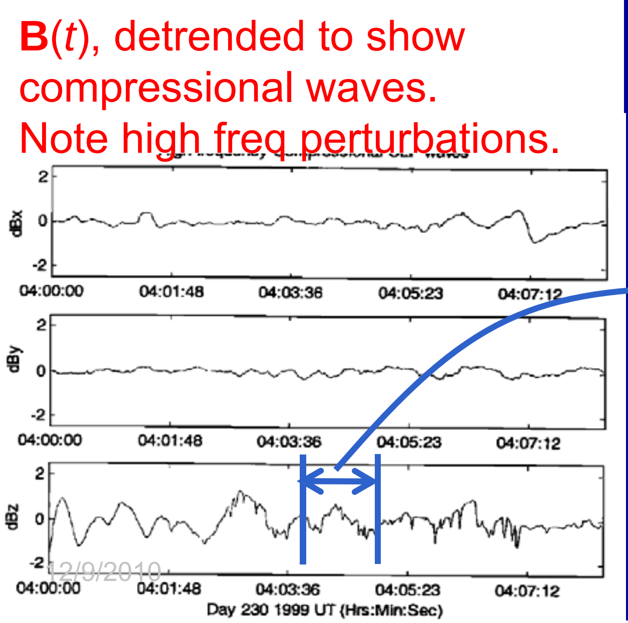


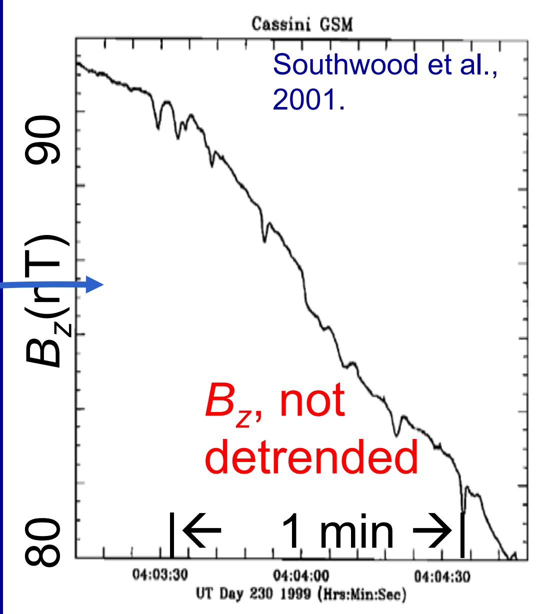


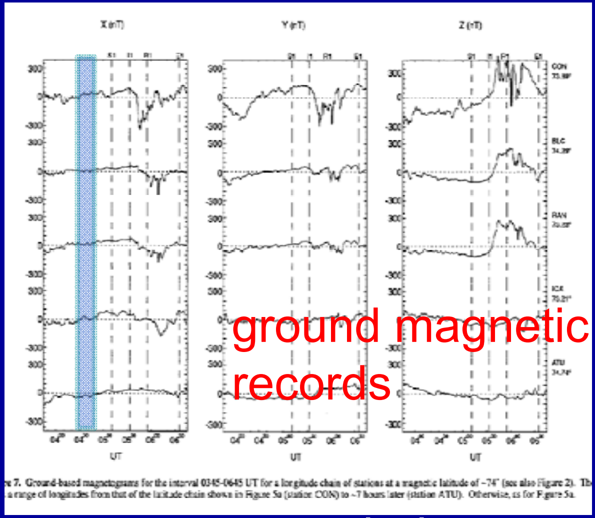
And at Earth?

- There has been discussion of "low entropy flux tubes" moving inward in the tail. Another possibility is of interest -
- Beyond geostationary orbit, outward rotational stress dominates inertial forces.
  - Outer edge of plasmasphere (cold, dense) could be interchange unstable (Richmond, 1973; Lemaire , 1974).
  - Plasmasphere must extend beyond ~6.6 R_E; sunward convection must be negligible (quiet time)
  - Appears to occur in data from Cassini flyby of Earth. (Time scale – sec - of drops is short.)









events occur during quiet conditions

Some loss from plasmasphere at quiet times could arise from interchange. Not clear how thoroughly this has been examined.

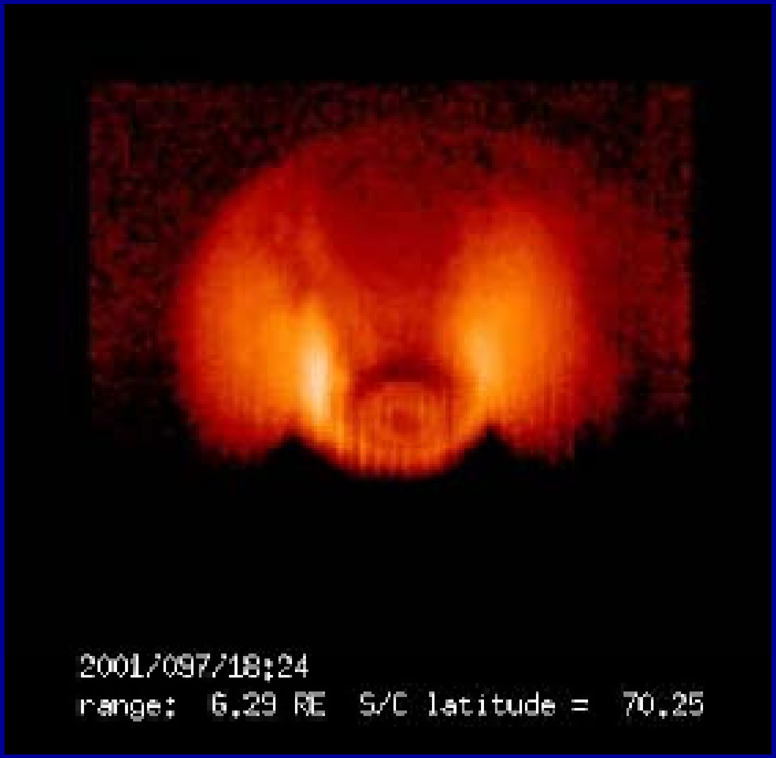


Image video.
(Decorative but not intended to be illustrative because not from quiet time.)

Plasma plumes probably dominate loss, but the outer edge pre-midnight may at times be interchange unstable.
This may be worth some attention but requires high time resolution data.

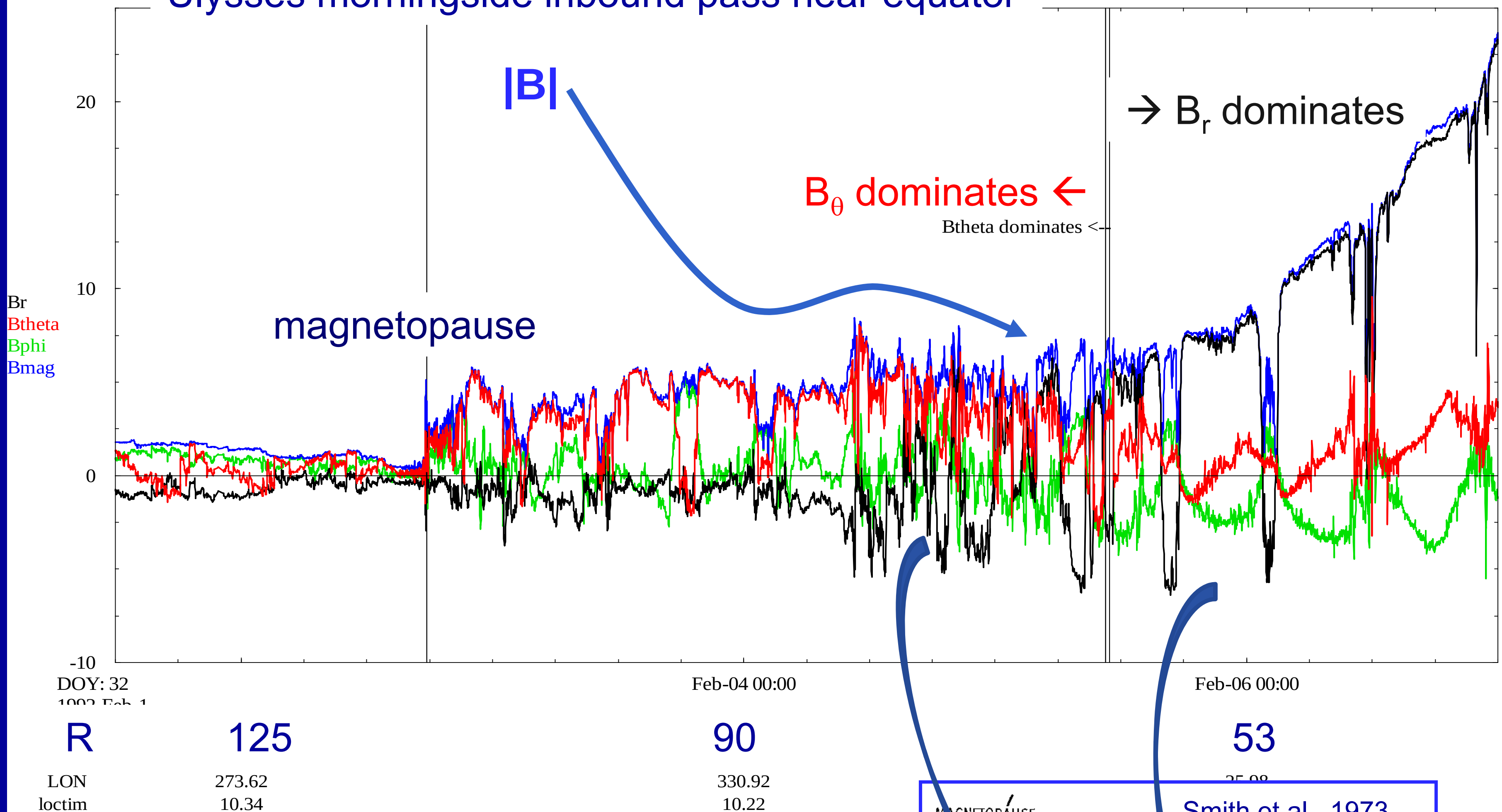
Another consequence of rapid rotation

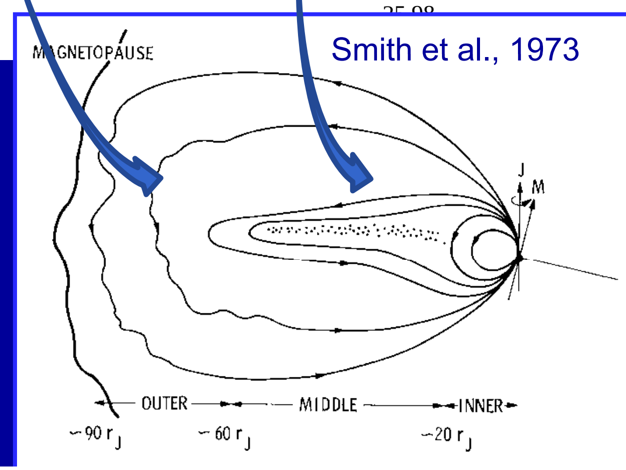
- Rotational stresses can produce not only ballooning but can lead to plasma losses. Containment becomes marginal when $\rho\Omega^2 r\sin\theta \approx B^2/\mu_o R_c$ (or alternatively when $p_{||}/p_{\perp}$ becomes sufficiently large). Containment requires

$$n_i \leq B^2/20 m_p \mu_o R_c \Omega^2 r$$

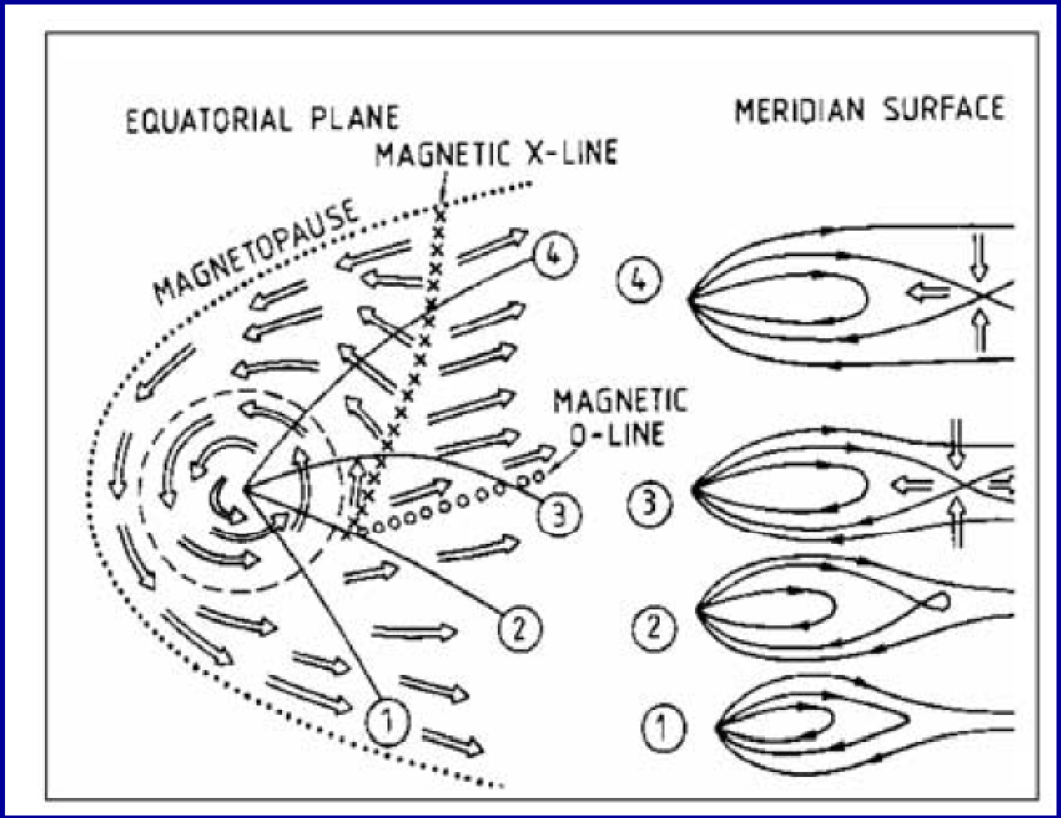
  - With r ~60 R_J, B ~2.5 nT, R_c~2 R_J, Ω=2π/36000, ρ_ι =20m_p n_i(cm^3) x10^6; equality → n_i ~ 0.01 cm^{-3} which is of order measured.
- Field may no longer be able to contain plasma, especially if magnetopause is moving outward.
- Mechanism? Drizzle? Or bubbles break off?
- Change of magnetic structure systematically observed in the outer morning magnetosphere at Jupiter where there is a sharp transition from disk-like to dipole-like in a region where rotational stresses (or possibly non-adiabaticity) enable plasma to escape confinement by curvature forces.

Ulysses morningside inbound pass near equator



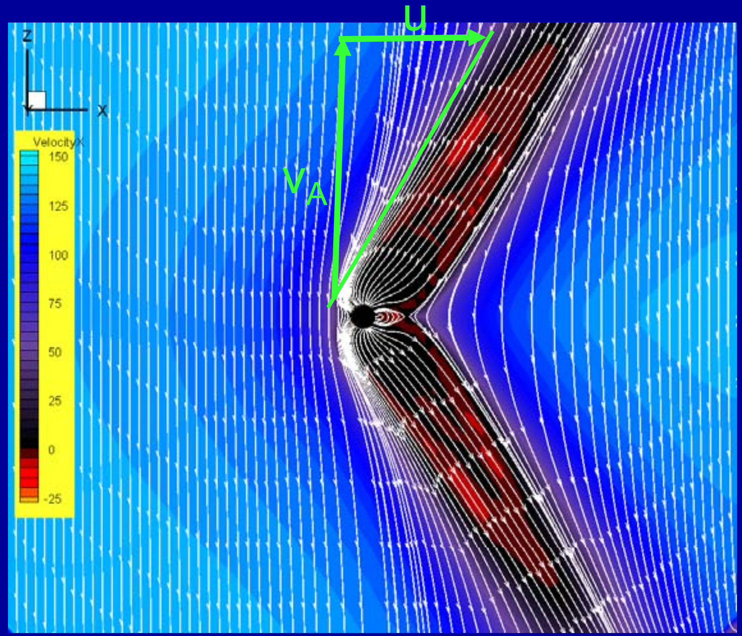


Loss of plasma down the tail may also arise through release of plasma bubbles as flux tubes stretch while rotating through the night side
(Vasyliūnas, 1983; Kivelson and Southwood, 2005)



Shifting gears: Reconnection with steady upstream plasma flow

- Ganymede is of particular interest here.
- Special case:
  - Embedded in rotating plasma of Jupiter's magnetosphere: sub-magnetosonic flow, steady, v e r y slowly varying conditions.
    - no upstream shock
    - "lobes" directed up-down at Alfvén wing angle instead of folding over as when $u \gg v_{ms}$
- How does reconnection function when upstream conditions are effectively steady for times long compared with time to flow across the magnetosphere?
- Use simulation results from Xianzhe Jia.



RIGOROUSLY TESTED SIMULATIONS

Jia carried out MHD simulations for all 6 flybys of Ganymede.

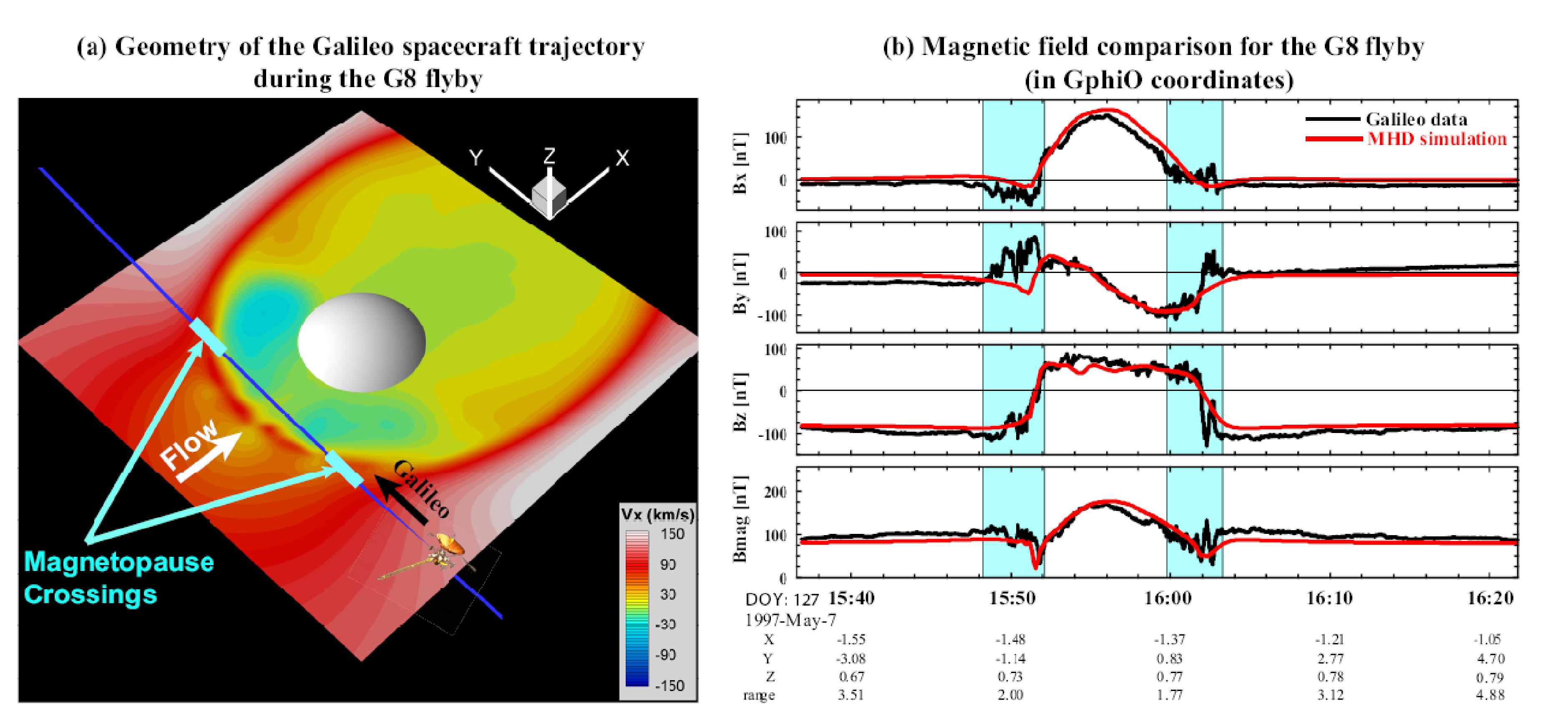
Upstream conditions are known. No wiggle room there!

Tweaks carried out on only one pass. Results were *very* sensitive to bc in ionosphere.

Once data reproduced on one pass, only upstream conditions modified for others.

All cases gave excellent agreement with measured B and plasma properties

-except for boundary disturbances. Waves?



Temporal changes result from bursty reconnection on the magnetopause.

- Diagram shows amplitude of field-aligned flows away from equatorial plane.
- One plot every 30 seconds.
- Flow direction, speed and magnetic connectivity demonstrate bursty reconnection.

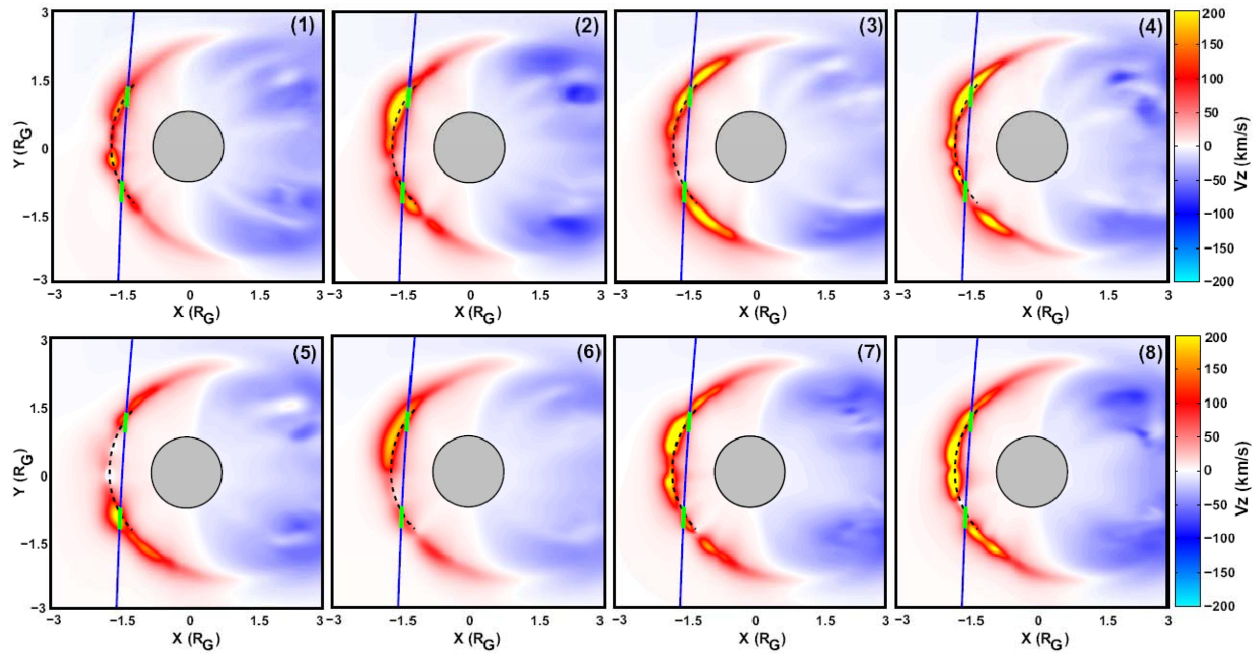


Figure 8. Color contours of V_z in an XY plane (at Z= 0.7 R_G) in which the Galileo spacecraft trajectory (blue trace) lies during the G8 flyby. Results at different time steps are shown. The time interval between consecutive subplots is 30 seconds. In each plot, two green bars mark the regions along the Galileo trajectory where large magnetic field fluctuations were observed during the inbound and outbound magnetopause crossings.

Amplitude, periodicity, and spatial extent of the FTE signatures reproduce the magnetic fluctuations at boundary observed in data. Not waves!

Bursty reconnection → FTEs compared

	Duration	Recurrence rate	Size (km)	Size (R_{body}[1])	Size(L_{MP}[2])	M_A
Jupiter[3]	< 1 min	~ 4 min	~ 7000	~ 0.1	$< 0.1\%$	~ 8
Earth[4]	$1 \sim 4$ min	~ 8 min	~ 6000	~ 1	5%	~ 6
Mercury[5]	$1 \sim 4$ sec	~ 1 min	$360 \sim 1200$	$0.15 \sim 0.5$	10%	~ 2
Ganymede	$5 \sim 10$ sec	$10 \sim 30$ sec	~ 400	~ 0.15	5%	~ 0.7

1 R_{body} denotes the radius of the body.

2 L_{MP} denotes the width of the magnetopause.

3 *Walker and Russell* [1985]

4 *Rijnbeek et al.* [1984]

5 *Russell and Walker* [1985]; *Slavin et al.* [2008]

Valuable for FTE studies.
Have we underestimated the size of FTEs at Jupiter?
Underestimated the recurrence rate at Earth?
What establishes the characteristics of FTEs?

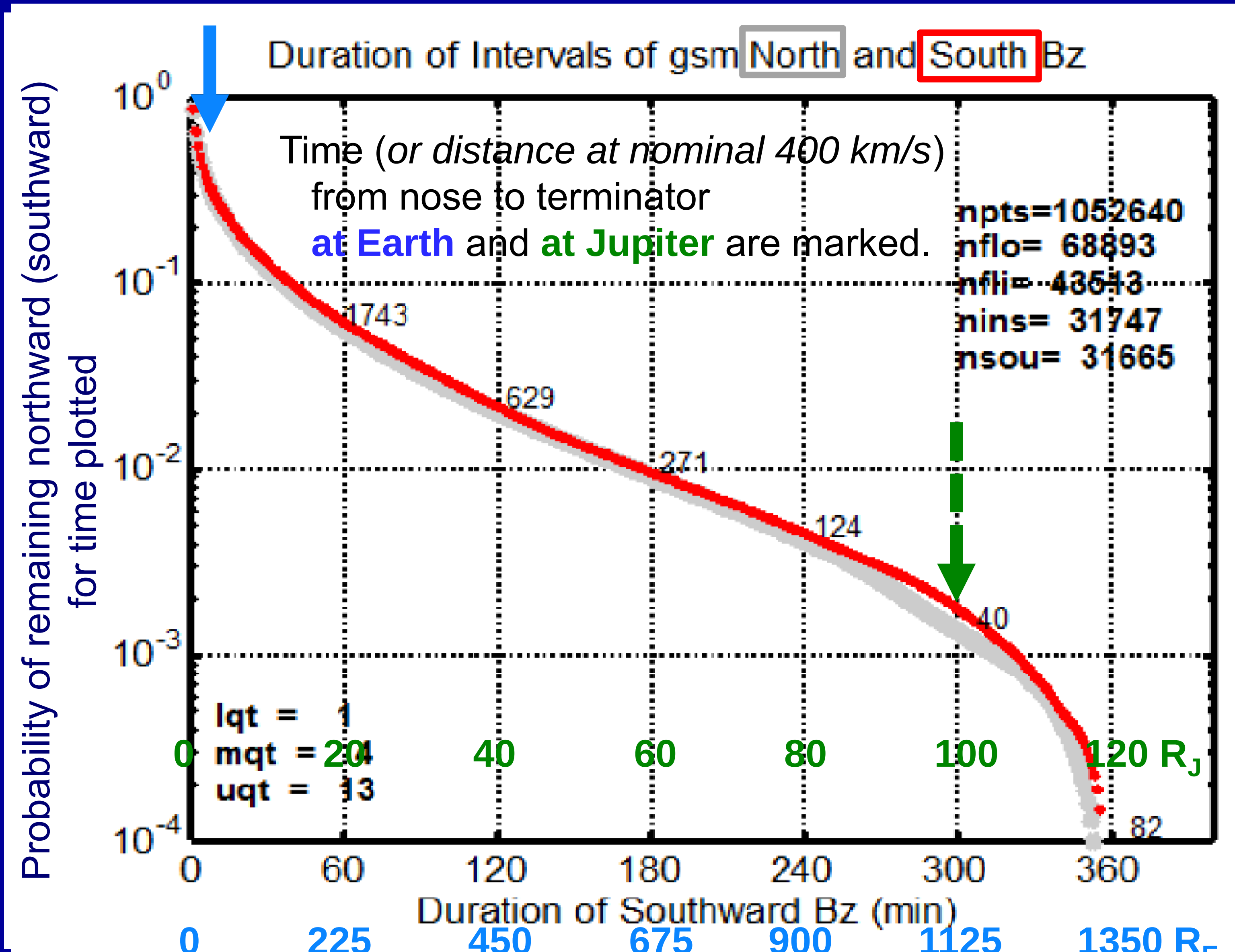
Of particular interest is that for steady upstream conditions, reconnection at Ganymede's magnetopause is intermittent.

At Ganymede, emphasized uniqueness of steady upstream conditions. Now look at reconnection for unsteady upstream conditions

- It takes about 4 minutes for plasma to flow across Ganymede's during which time neither plasma nor field incident on system change significantly.
- At Earth, it takes the solar wind ~ 30 min to reach the distant neutral line.
- At Jupiter it takes the solar wind ~ 5 hours to reach the terminator, and probably about 50 hours to reach the putative distant neutral line.

- Let's consider how steady the solar wind is over such time scales.

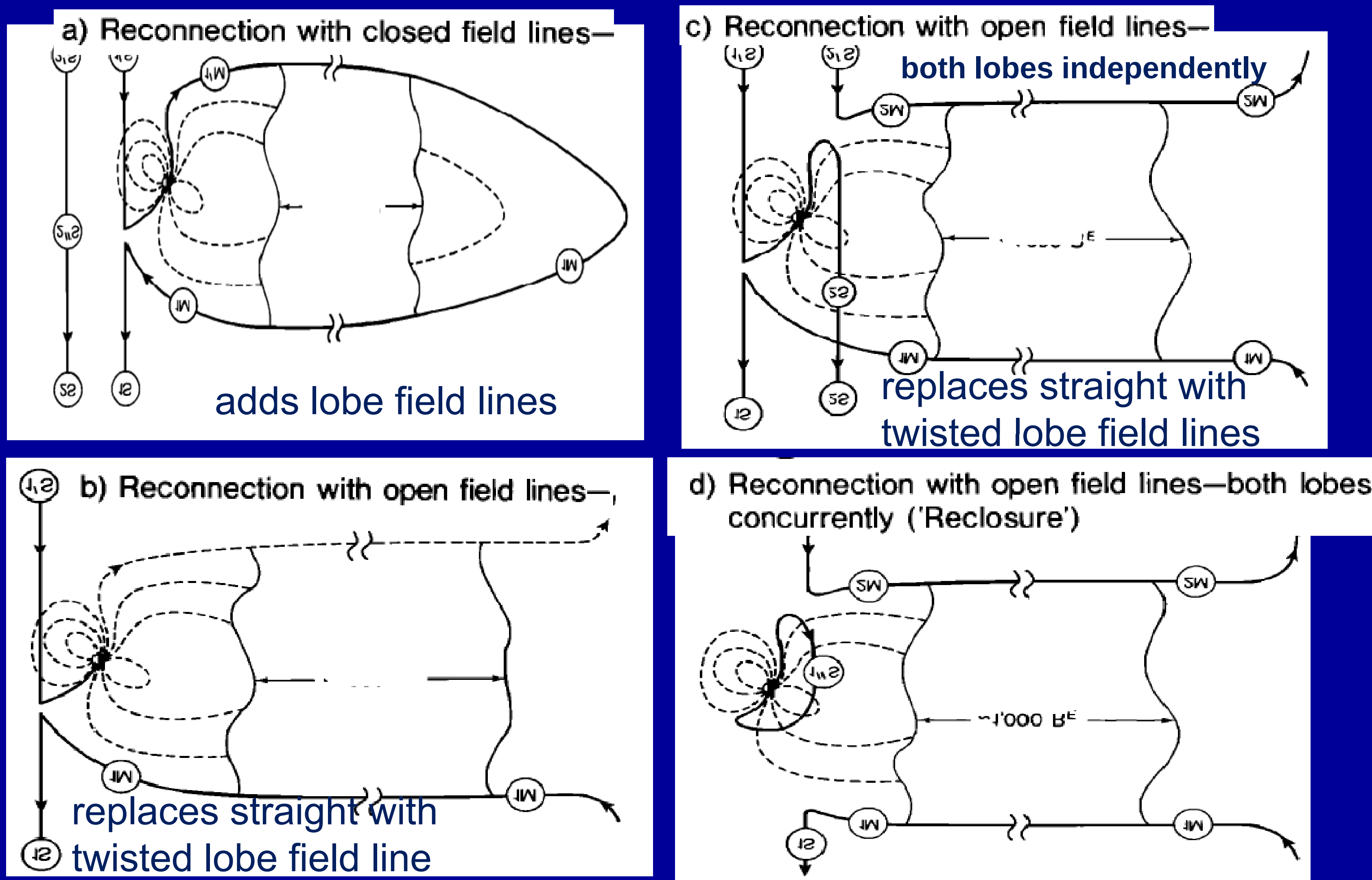
Data from solar wind at 1 AU. Thanks to Bob McPherron



What does a reconnecting magnetosphere look like if $B_{z,\ sw}$ keeps changing sign?

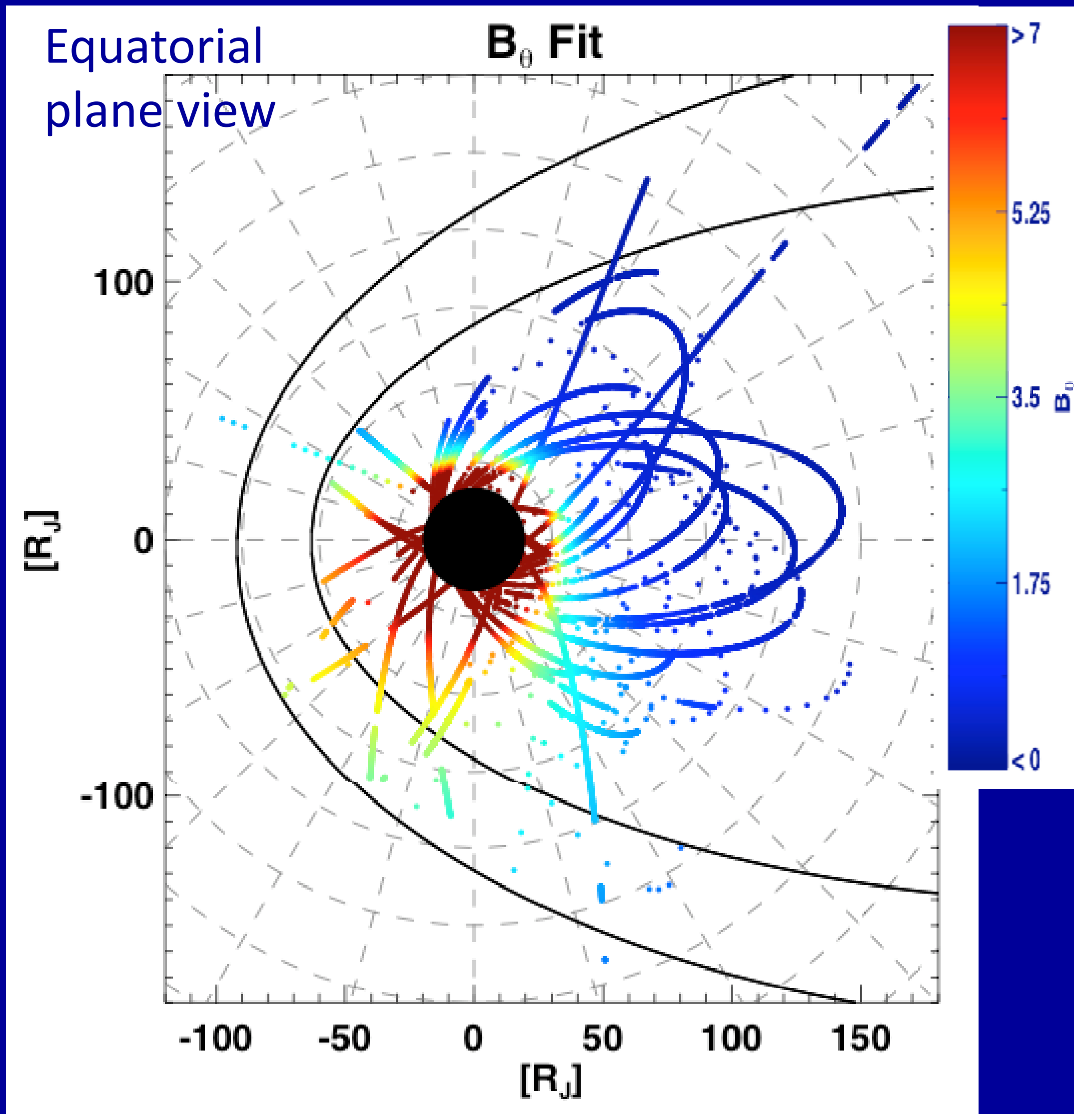
- The famous "Dungey magnetosphere" becomes a highly unlikely configuration if external field does not maintain a ~steady orientation.
- McComas and Bagenal (2007) suggest that at Jupiter the flip-flop of the external field will allow "re-reconnection" and make it unlikely that there is a significant region of open field lines.

At Jupiter: reconnection with northward field increases open flux but reconnection with a southward field can increase, decrease, or leave unchanged the open flux.



What does a reconnecting magnetosphere look like if $B_{z,\ sw}$ keeps changing sign?

- Possibly pretty messy, but likely to have regions of open flux.
- Our recent work (Vogt et al., 2009) relating the magnetic field in the equator to the field in the ionosphere and comparing with auroral emissions supports the idea that there is a significant region of open flux in the polar cap.



From this data-based model of the magnetic field, one determines the flux crossing the equatorial current sheet in any $r\ dr\ d\phi$ bin.

In the auroral ionosphere, the "foot of the Ganymede flux tube" can be identified through a localized glow. Thus the mapping of a ring at 15 R_J is known.

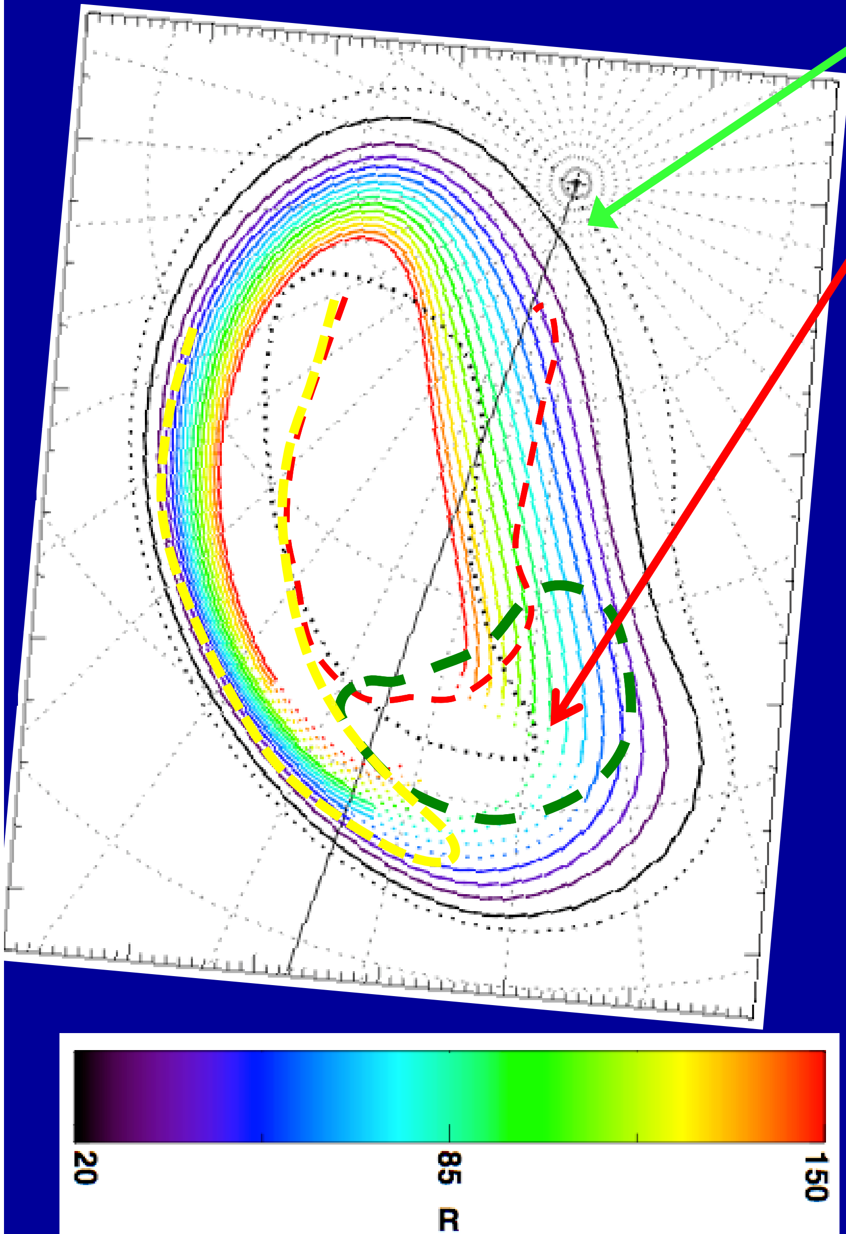
Thereafter match flux in equator in each pixel to flux in ionosphere to establish where rings at 15 $+n5R_J$ map.

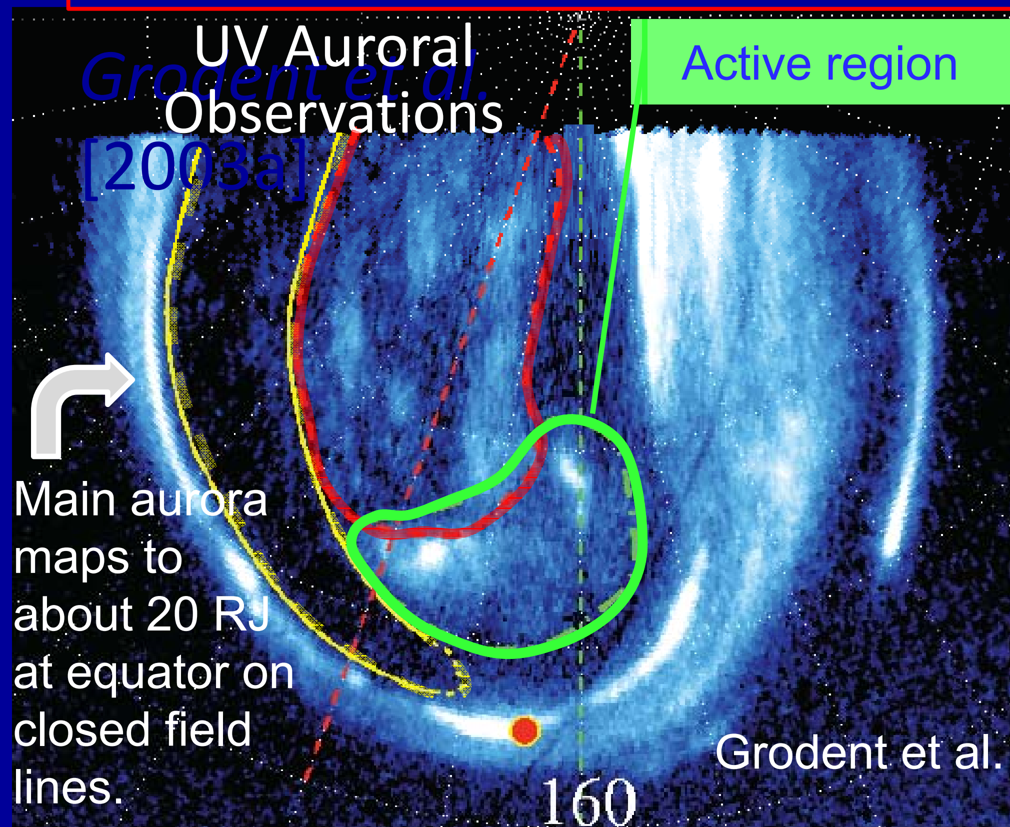
Equatorial field strength from data analysis:

- field stronger on day side/dusk than night side/dawn
- fall off ~R^{-3} or slower and no closed field lines outside magnetopause.

Mapping Results: 160° CM 15 R_J tracing reference contour (dashed line) and 5 R_J increments

Curves end when the equatorial circles encounter the magnetopause, roughly at the boundary of the "active region". Field lines poleward of the magnetopause must link to the cusp. We find that unmapped region contains flux equal to tail "lobe"





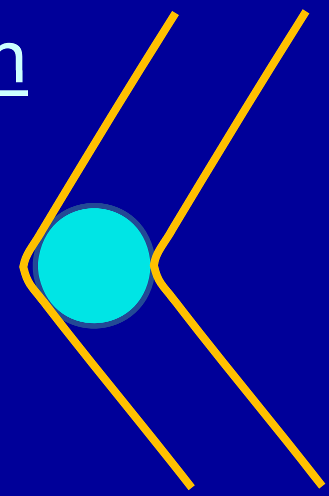
For Jupiter it seems that:

- Open-closed field line boundary has no clear signature in the aurora.
- Active region maps to dayside polar cusp where field lines recently reconnected with sw would be found.
- Umapped region has ~same flux as very low plasma density region of tail that bounds the nightside plasma sheet and is threaded by a steady quiet magnetic field that looks like the terrestrial lobe.
- This does not prove that those field lines are open, but it does seem likely.

At Jupiter, magnetotail structure (region of open field lines ??) is disputed, as is the question of whether magnetic activity is primarily driven by rotational stresses or by Dungey-type reconnection.

- For this audience, there is a related question for Earth and terrestrial substorms.
  How does geomagnetic activity differ between
  - events for which the IMF has southward component that remains a fairly steady during the growth phase (i.e., ~the time needed to convect to the distant neutral line)
  - events for which the IMF flip-flops during the growth phase.
- What to look for in data? Significantly bent lobe field lines? Inconsistent field orientations? Different time scales?

A few words on the application of Alfvén wing theory applied to Earth



- At Ganymede, it is natural to discuss the magnetic structure in terms of Alfvén wing theory. The theory has been developed for the moons of Jupiter, but it also applies at Earth.
- That AWs are part of magnetospheric structure is not usually noted, but the principle applies.
- In the presence of reconnection, the magnetopause flares at an Alfvén wing angle because the perturbations imposed on the reconnected field line are carried from the magnetopause into the magnetosheath by Alfvén waves.
- With v_A/u_{sw} <<1, the fold-back at Earth is extreme with two wings coming together in the center of the tail.
- Associated FACs flow between the solar wind and the ionosphere. They must close in the bounding plasmas.
- Differences in conductance of the sw and ionosphere present a problem.
- Sometimes only part of the incident signal can penetrate the ionosphere. This can explain the saturation of the cross polar cap potential.

I have not left time to discuss the application of Alfvén wing theory applied to Earth

- Suffice it to say that it can account for saturation of the cross polar cap potential during storm times.

Lots more good stuff out there

- Take away message:
  - There is a lot to learn about odd features of other magnetospheres.
  - Looking at how things work out in other domains may give you ideas to explore in studying the terrestrial magnetosphere.