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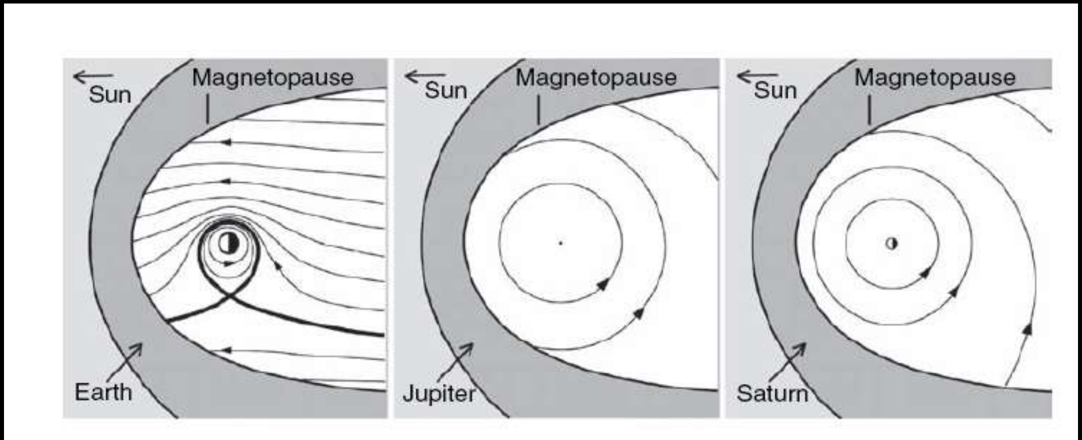
MAGNETOSPHERE: STRUCTURE AND DYNAMICS,

some intriguing issues

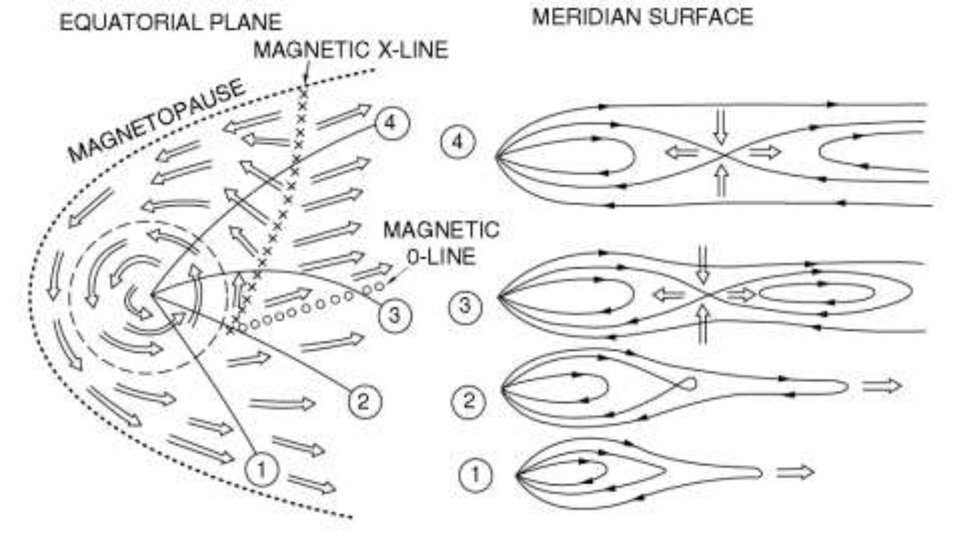
Margaret Galland Kivelson

Rotationally driven magnetospheres!

(*Mauk et al., (Saturn, Chapter 11*) state:
"while it is true that Saturn's magnetosphere is intermediate between those of Earth and Jupiter in terms of size (whether measured by R_P; R_{PP}, *or* R_{MP}), *it is not intermediate* in any meaningful dynamical sense. It is clearly rotationally driven like Jupiter's, not solar-wind-driven like Earth's."

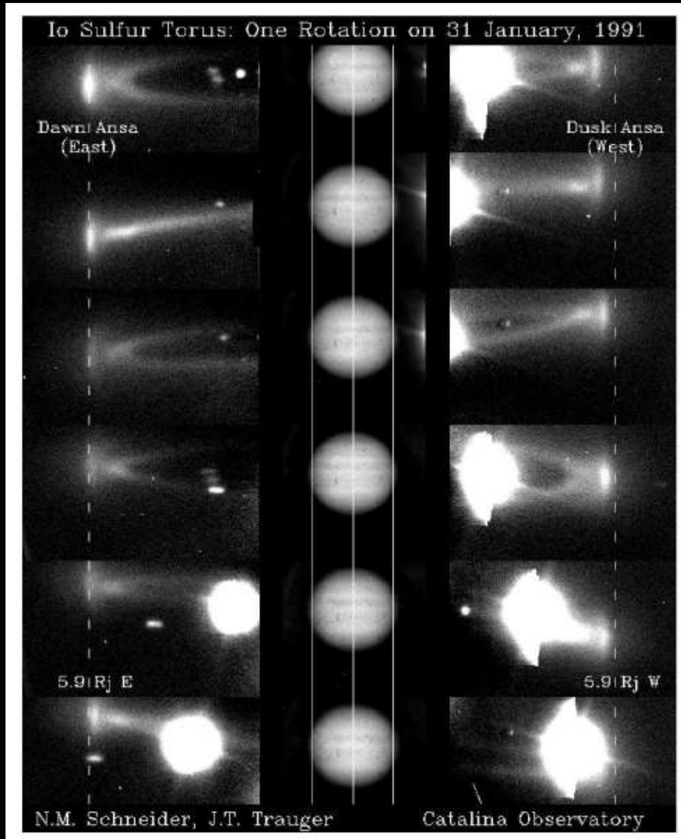


Dynamics

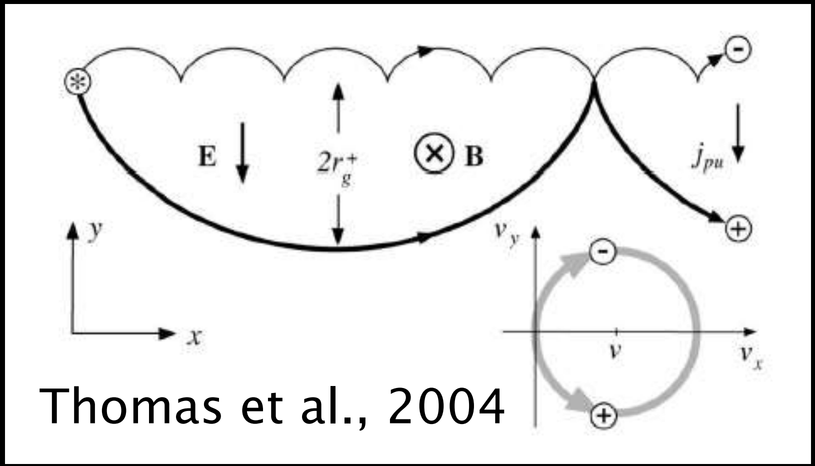


- This Vasyliunas (1983) diagram is a necessary element of any discussion of the magnetospheres of gas giants!
- It captures some critical features implicitly or explicitly:
  - A significant source of heavy plasma deep within the magnetopause (Io, Enceladus) is spun up to some fraction of corotation speed by field-aligned currents coupling magnetosphere and ionosphere.
  - Rotation dominates the dynamics – drives plasmoid releases down the tail.
  - Solar wind shapes the boundaries but does not dominate the dynamics.

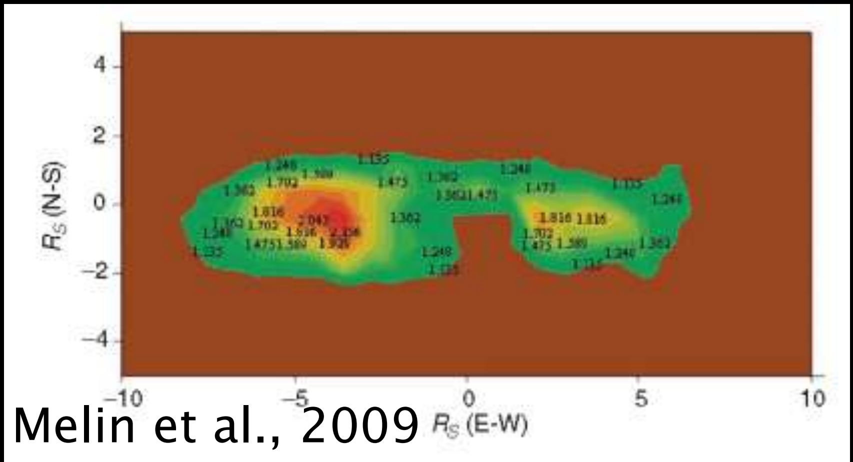
The source of the heavy ion plasma – neutrals from Io or Enceladus



Schneider and Trager, 1995



Thomas et al., 2004



Melin et al., 2009

- In the pickup process, ions acquire perp. thermal speed of local rotation speed.
- $$\text{Energy added} \propto \dot{N}_{pu} m(\Omega\rho)^2$$
- Pickup energy is shared with background plasma.
- Typically heats plasma.

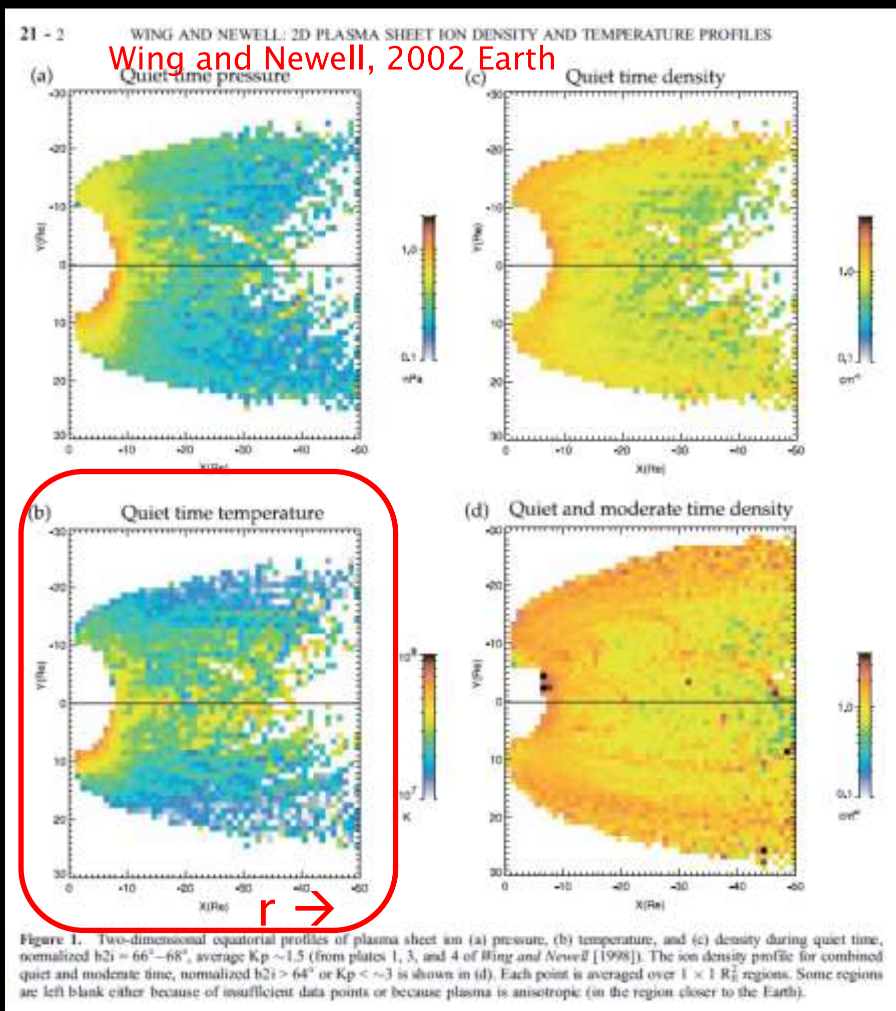
Giant planets spin up plasma, heat it, and jet it out, but details are complex

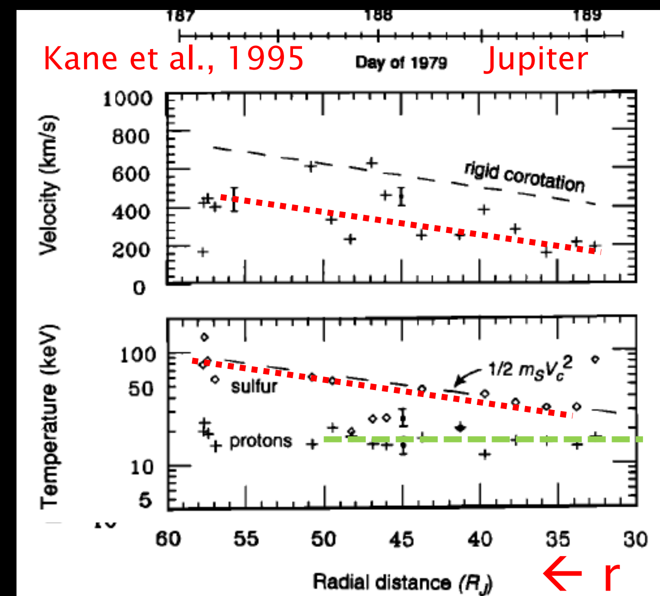
- Much is well established, but puzzles remain.
- Discuss a few features
  - energy density of plasma and why it changes
    - vs. radial distance,
    - vs. local time,
  - periodicities,
  - Anomalies in regions of high dust density.

Thermal energy variation with ρ?
(ρ is distance from spin axis)

At Earth, temperature (more correctly thermal energy per particle) decreases with ρ but not at Jupiter or Saturn.

Below a plot from Kane et al (1995) of Voyager data at Jupiter, modeled as kappa distributions



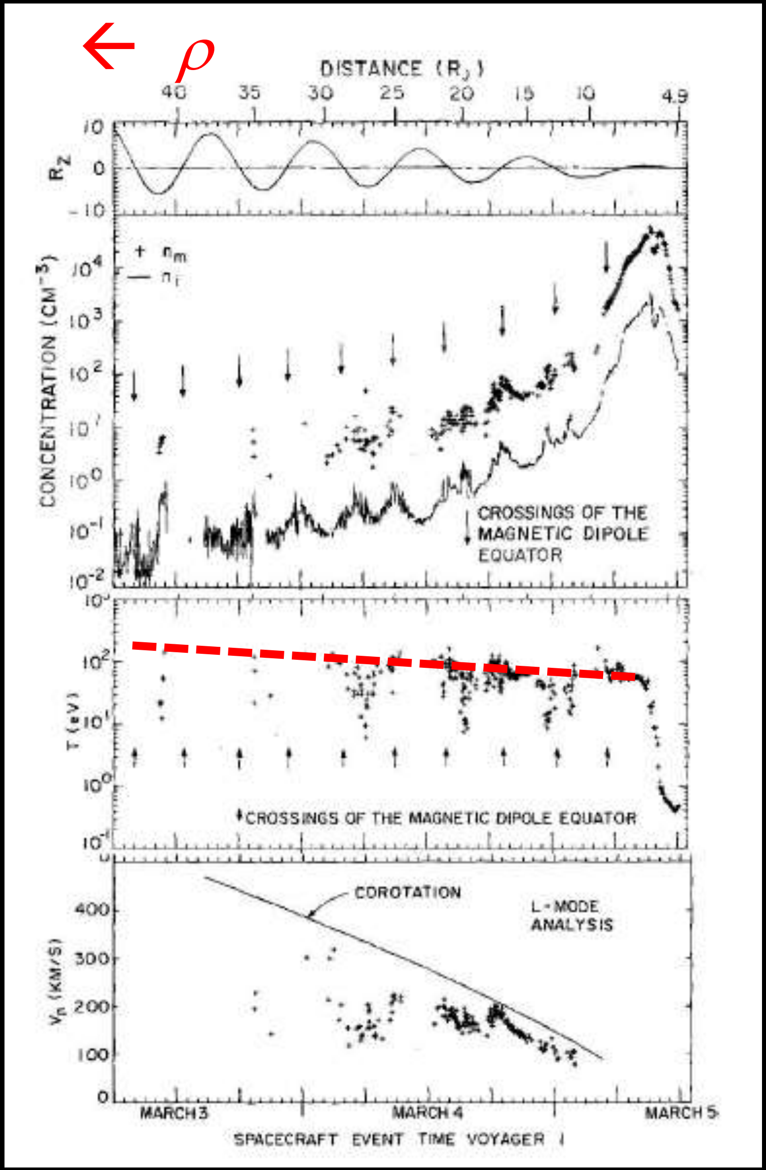


Proton temperature remains nearly constant (20 keV) on day side. Heavy ion temperature increases with ρ proportional to corotation energy.

WHY?

Pickup energy increases with rotation speed. Can that account for increase of T with ρ?

- For <6 keV ions (measured by PLS at Jupiter), temperature shown in figure changes little between 10 and 40 R_J. Pickup as heat source not ruled out.
- The >30 keV heavy ions shown for Jupiter in previous slide require v_{th} >~500 km/s, which exceeds rotation speed. (Also, each new ion must share pickup energy with ambient ions).
- Not plausible that pickup is the primary heat source for energetic heavy ions.



From Khurana et al., 2004
Voyager 1 inbound, warm plasma

Why is increase like $\frac{1}{2}\rho^2\Omega^2$? Insight into the tricky physics of rotating magnetospheres comes from e.g., Northrop and Birmingham, 1982

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Adiabatic Charged Particle Motion in Rapidly Rotating Magnetospheres

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When the $c\mathbf{E} \times \mathbf{B}/B^2$ drift velocity is large enough to exceed the particle gyro velocity, a theory becomes more complicated and less useful: more complicated because there are five addition to the $\mathbf{E} \times \mathbf{B}$, gradient, and line curvature drifts and three more terms in the parallel equ motion; less useful because the second and third invariants J and Φ are no longer valid in mirror g due to the rapid drift across field lines that destroys any semblance of periodicity in the bounce (Approximate periodicity is necessary to have an adiabatic invariant.) But the special case of a rotating rigid magnetic field, with $E_\parallel = 0$, is an exception. If the field at any time is merely a rotatio at an earlier time, the drift and parallel equations simplify, and even better, the second invariant valid. The drift equation now has two rather than five additional terms—a Coriolis drift and a ce drift. Just as in a slowly or nonrotating mirror system, the second invariant now provides a rotating) drift shell to which the guiding center is confined. The particle kinetic energy in the frame, minus the centrifugal potential, is an exact constant of motion in a rigid rotator. This co well known but does not by itself put limits on radial motion toward or away from the rotation axi it does not limit particle energy changes. But the drift shell does limit and make periodic an excursions, and this is why previous studies of particle motion, in particular examples of rigid have shown that particles experience no steady energy gain or loss.

$$H = \frac{m}{2}(v^2 - \rho^2\Omega^2)$$

is an exact constant of the motion for observer in rotating frame <u>if the field in that frame is static.</u>

TABLE [illegible]ummary of Equations for a Rigid Rotator

Type of Equation	For Observer Rot[illegible]ith the System	For a Nonrotating Observer Looking at the Rotating System
Exact particle equation of motion	$\left(\frac{d\mathbf{w}}{dt}\right)_c = -\nabla\frac{1}{2}\rho^2\Omega^2 + \frac{e}{mc}\mathbf{w}$ [illegible] $(\mathbf{r}) + \frac{2mc}{e}\boldsymbol{\Omega}\Big]$	$\frac{d\mathbf{v}}{dt} = \frac{e}{m}\left[\mathbf{E}(\mathbf{r}, t) + \frac{\mathbf{v}}{c} \times \mathbf{B}(\mathbf{r}, t)\right] = \frac{e}{mc}(\mathbf{v} - \rho\Omega\hat{\boldsymbol{\phi}}) \times \mathbf{B}(\mathbf{r}, t)$
Exact constant of the motion	$\boxed{H = \frac{1}{2}(w^2 - \rho^2\Omega^2)}$	$H = \frac{v^2}{2} - \rho\Omega\mathbf{v}\cdot\hat{\boldsymbol{\phi}}$
Vlasov equation	$\frac{\partial f}{\partial t}(\mathbf{w}, \mathbf{r}, t) + \mathbf{w}\cdot\nabla f + \left[\nabla\frac{1}{2}\rho^2\Omega^2 + \frac{e}{mc}\mathbf{w} \times \left(\mathbf{B} + \frac{2mc}{e}\boldsymbol{\Omega}\right)\right]\cdot\nabla_w f = 0$	$\frac{\partial f}{\partial t}(\mathbf{v}, \mathbf{r}, t) + \mathbf{v}\cdot\nabla f + \frac{e}{mc}(\mathbf{v} - \rho\Omega\hat{\boldsymbol{\phi}}) \times \mathbf{B}\cdot\nabla_v f = 0$
Guiding center equation of motion	$\ddot{\mathbf{R}}_c = \nabla\frac{1}{2}\rho^2\Omega^2 + \frac{e}{mc}\dot{\mathbf{R}}_c \times \left(\mathbf{B} + \frac{2mc}{e}\boldsymbol{\Omega}\right) - \frac{M}{m}\nabla B$	$\ddot{\mathbf{R}} = \frac{e}{m}\left(\mathbf{E} + \frac{\dot{\mathbf{R}}}{c} \times \mathbf{B}\right) - \frac{M}{m}\nabla B = \frac{e}{mc}(\dot{\mathbf{R}} - \rho\Omega\hat{\boldsymbol{\phi}}) \times \mathbf{B} - \frac{M}{m}\nabla B$
Guiding center drift velocity	$\dot{\mathbf{R}}_{c\perp} = \frac{mc}{eB}\hat{e}_1 \times \left(-\nabla\frac{1}{2}\rho^2\Omega^2 + \frac{M}{m}\nabla B + u_c^2\frac{\partial\hat{e}_1}{\partial s} + 2u_c\boldsymbol{\Omega} \times \hat{e}_1\right)$	$\dot{\mathbf{R}}_\perp = \dot{\mathbf{R}}_{c\perp} + \frac{c\mathbf{E} \times \hat{e}_1}{B} = \dot{\mathbf{R}}_{c\perp} + \rho\Omega(\hat{\boldsymbol{\phi}} - \hat{e}_1\hat{\boldsymbol{\phi}}\cdot\hat{e}_1)$ where u_c in $\dot{\mathbf{R}}_{c\perp}$ is to be replaced by $v_\parallel - \rho\Omega\hat{\boldsymbol{\phi}}\cdot\hat{e}_1$
Guiding center parallel equation of motion	$\frac{du_c}{dt} = -\frac{M}{m}\frac{\partial B}{\partial s} + \frac{\partial}{\partial s}\frac{1}{2}\rho^2\Omega^2 - \frac{2Mc}{e}\boldsymbol{\Omega}\cdot\frac{\partial\hat{e}_1}{\partial s} - \frac{mc}{eB}\hat{e}_1 \times \left(u_c\frac{\partial\hat{e}_1}{\partial s} + \boldsymbol{\Omega} \times \hat{e}_1\right)\cdot\nabla\left(\frac{MB}{m} - \frac{1}{2}\rho^2\Omega^2\right)$	$\frac{dv_\parallel}{dt} = -\frac{M}{m}\frac{\partial B}{\partial s} + \frac{\partial}{\partial s}\frac{1}{2}\rho^2\Omega^2 + (v_\parallel - \rho\Omega\hat{\boldsymbol{\phi}}\cdot\hat{e}_1)\frac{\partial}{\partial s}(\rho\Omega\hat{\boldsymbol{\phi}}\cdot\hat{e}_1)$ plus a first order in gyroradius term (see equation (30))
Lowest order constant of the parallel motion	$\frac{K_c}{m} = \frac{1}{2}(u_c^2 - \rho^2\Omega^2) + \frac{MB}{m}$	$\frac{\dot{K}_c}{m} = \frac{1}{2}(v_\parallel - \rho\Omega\hat{\boldsymbol{\phi}}\cdot\hat{e}_1)^2 - \frac{1}{2}\rho^2\Omega^2 + \frac{MB}{m}$
Rate of change of K_c	$\frac{\dot{K}_c}{m} = -\frac{2Mc}{e}u_c\boldsymbol{\Omega}\cdot\frac{\partial\hat{e}_1}{\partial s}$	$= -\frac{2Mc}{e}(v_\parallel - \rho\Omega\hat{\boldsymbol{\phi}}\cdot\hat{e}_1)\boldsymbol{\Omega}\cdot\frac{\partial\hat{e}_1}{\partial s}$
Gyro average total energy (kinetic + potential)	$H = \left\{\frac{w^2}{2}\right\} - \frac{\rho^2\Omega^2}{2}$	$H = \left\{\frac{v^2}{2}\right\} - \rho\Omega\hat{\boldsymbol{\phi}}\cdot\dot{\mathbf{R}}_c - \rho^2\Omega^2$ where $\dot{\mathbf{R}}_c = u_c\hat{e}_1 + \dot{\mathbf{R}}_{c\perp}$, with $u_c = v_\parallel - \rho\Omega\hat{\boldsymbol{\phi}}\cdot\hat{e}_1$
Second adiabatic invariant	$J_c = m\oint ds\left[\frac{2}{m}(K_c - MB) + \rho^2\Omega^2\right]^{1/2}$	same as for rotating observer

Here e stands for the total charge on the particle ($e < 0$ for negative charge); argument of $\mathbf{B}$, $\hat{e}_1$, ρ, $\hat{\boldsymbol{\phi}}$, etc., is $\mathbf{R}$ (the guiding center position) in a guiding center equation, and $\mathbf{r}$ (particle position) in a particle equation; and subscript c indicates as seen in corotating system. For example, $d\mathbf{w}/dt$ seen from nonrotating system $= ((d\mathbf{w})/(dt))_c + \boldsymbol{\Omega} \times \mathbf{w}$.

- Data provide T vs. ρ
- *(axial radial distance)*.

- T gives mean particle kinetic energy in fluid rest frame, i.e. in rotating frame.

$$H = \tfrac{m}{2}(v^2 - \rho^2\Omega^2)$$

is constant in the corotating frame *and* the field is constant in that frame. In the corotating frame, for a collection of particles, the bounce-averaged particle energy is $\frac{3}{2}kT$ so

$$kT = <\tfrac{2}{3}(H + \rho^2\Omega^2)>$$

- For simple rotation, the increases and decreases of T cancel out over a rotation.
- If flux tubes interchange, there can be net energization.
- Efficient: the full distribution changes energy with ρ.

Implications

- Possibly this type of acceleration contributes to observed temperature increase of both high and low energy ions with radial distance at Jupiter.
- Many other processes need to be considered.
- Concern: Temperature (T) is measured in plasma rest frame, which is not fully corotating, but we assume that it is close enough for the relation to be valid as it seems to work for Jupiter.
- What about Saturn?

Saturn also shows temperature increasing like $\Omega^2\rho^2$, although again plasma not fully corotating.

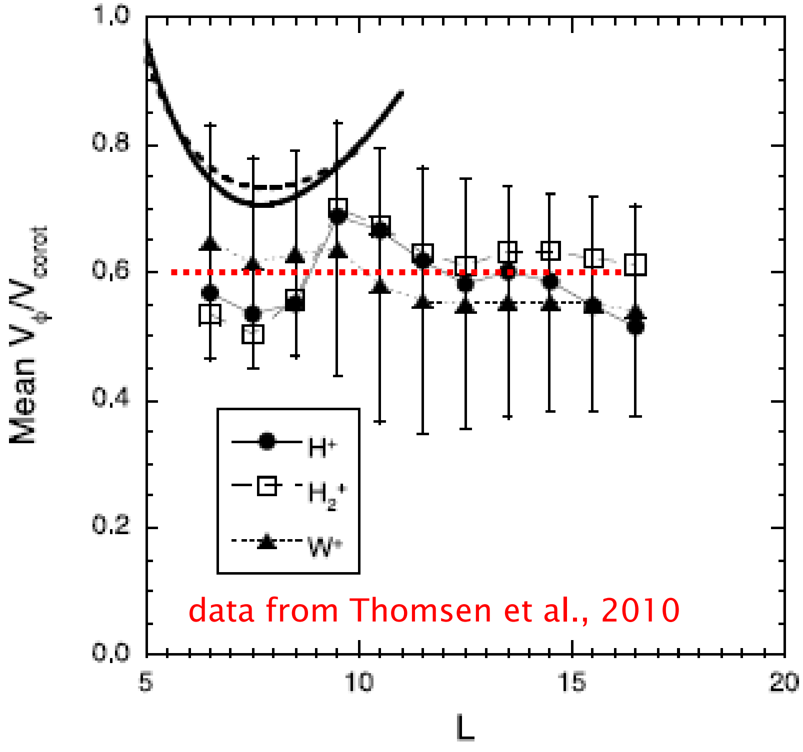


Figure 16. Mean values of the normalized flow speeds shown in Figure 15, from 1-R_S bins in L. The means are plotted at the center L of the corresponding bins. The error bars show the standard deviations in the means for the W^+ population. The heavy dashed line is the quadratic fit to V_ϕ reported by *Wilson et al.* [2008] for a carefully selected set of inner magnetospheric observations, and the heavy solid line is a similar fit to the numerical moments obtained in the same set of intervals.

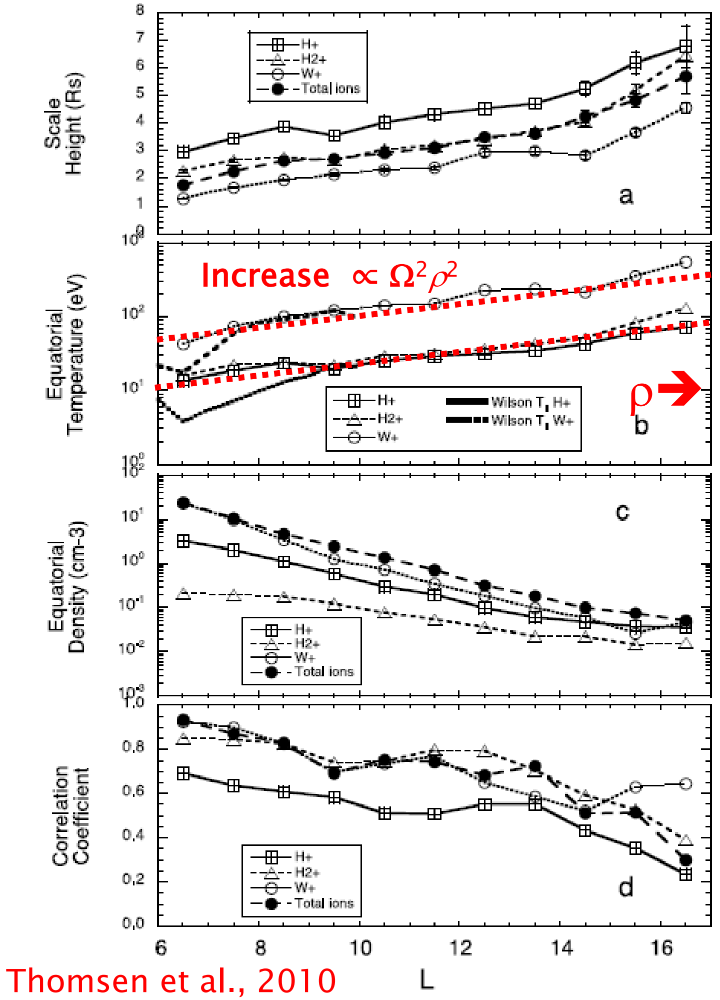
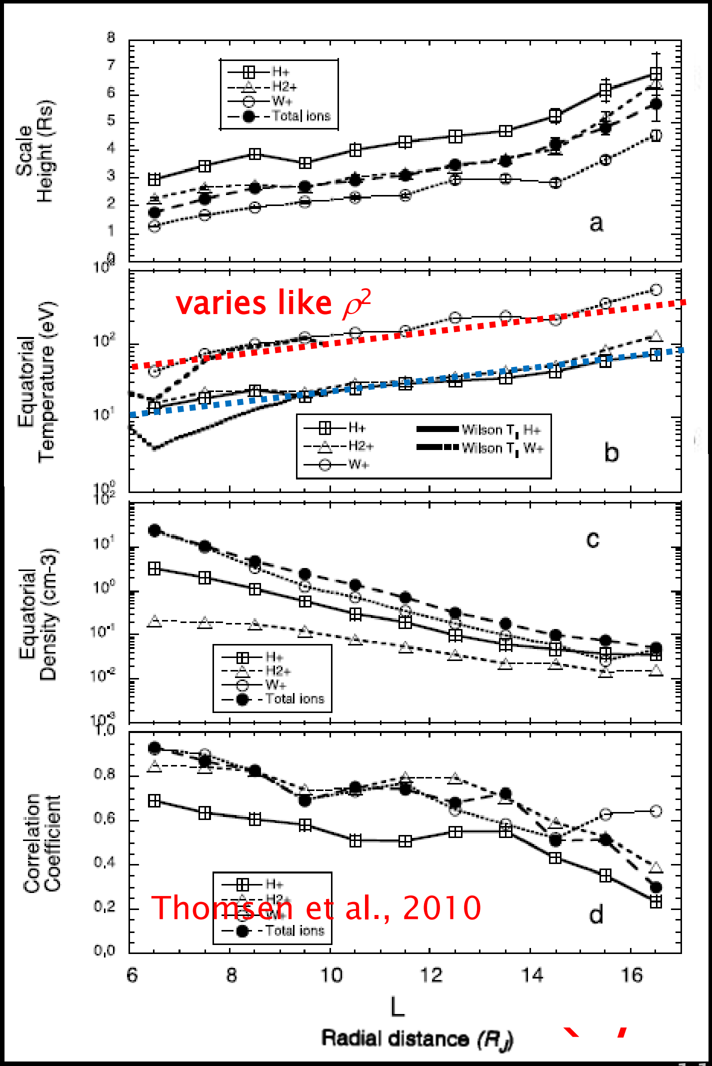


Figure 7. (a) Scale heights, (b) effective equatorial temperatures, (c) equatorial densities, and (d) correlation coefficients obtained from linear fitting of measured densities to $(1 - \cos^6\lambda)$ for the full range of available λ in various dipole L ranges. λ is the dipole magnetic latitude, and only data obtained when the corotation direction was within the CAPS FOV are used for the fits. In Figure 7b, the heavy lines without symbols show the values of $T_{\|H}$ and $T_{\|W}$ determined by *Wilson et al.* [2008].

Relevant to the issue of centrifugal accelrtn .

Outward transport of plasma in a static field occurs thru interchange:

- Interchange works without temporal change of field.
- Heavy ions move out from source in inner magnetosphere. If no $\partial B/\partial t$, they should conserve Northop/Birmingham's "*H*".
  - At Saturn, protons arise from dissociation of water and like heavy ions participate in outward (slow) interchange. *T* increases.
  - At Jupiter, protons probably come from solar wind. Maybe they move inward in narrow fingers too fast to conserve *H*. A puzzle.



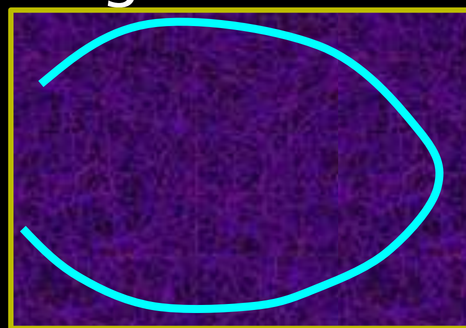
The temperature variation with distance is affected by multiple processes

- I have ignored significant contributions from:
  - pickup ions, charge exchange
    - Saur et al. (2004) argue that at Saturn, the effect of ion-neutral collisional drag may slow plasma as much as does charge exchange.
  - radiation
  - Coulomb interactions
  - Charged dust
- Centrifugal forces may be modifying the plasma in ways that have not been fully analyzed.

- Above remarks applied to a static field in the rotating frame.
- Not too bad an assumption out to some critical ρ, but . . . LT dependence of boundary location invalidates the assumption of a static field in the rotating frame at larger ρ. What then?

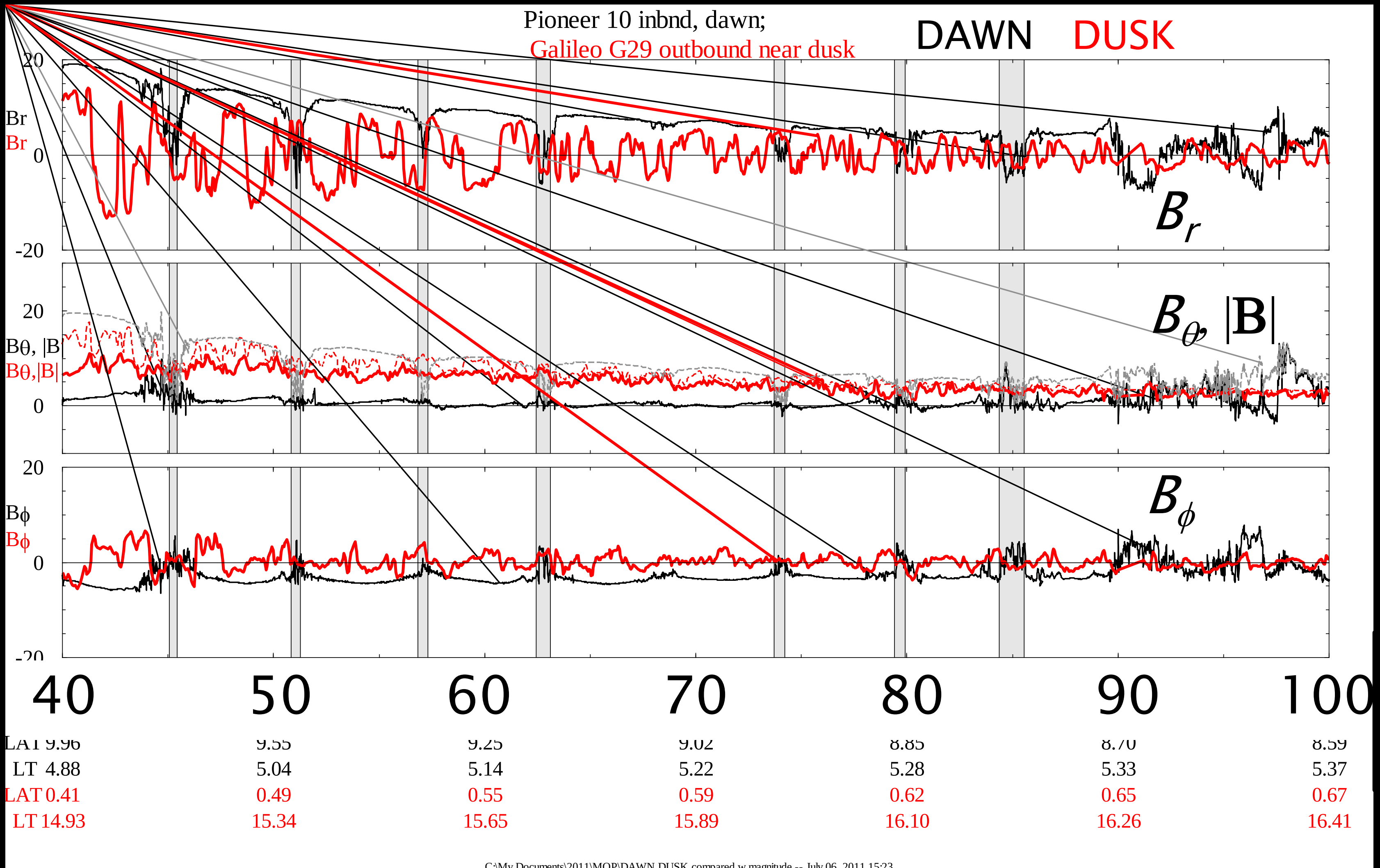
In the outer magnetosphere, the field in the rotating frame is NOT constant.

- Configuration and magnitude change with rotation phase.



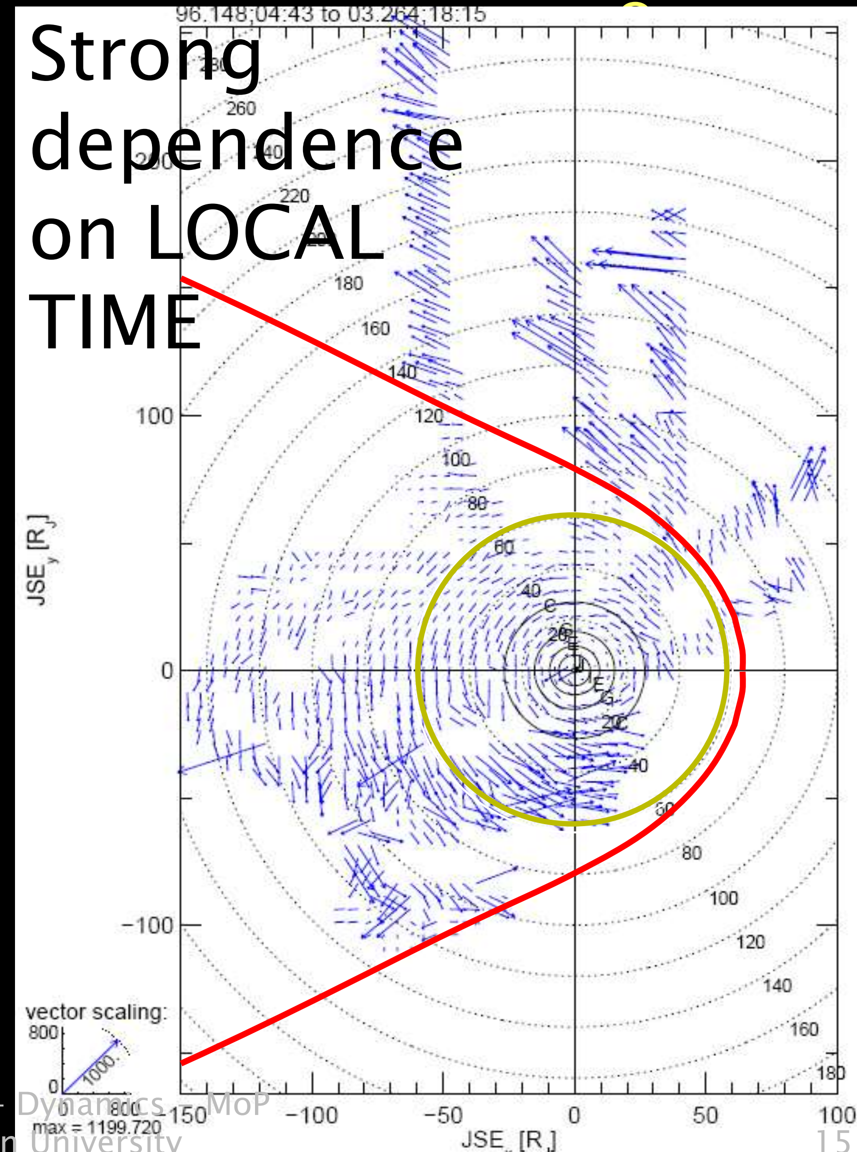
  - Flux tubes move inward from night to noon and outward from noon to dusk and beyond.
    - At fixed position in the rotating frame *dB/dt* ≠ 0.
- Bouncing particles are accelerated if rotating flux tubes stretch over a bounce period.
- It is likely that the centrifugal acceleration of plasma as it rotates from noon to dusk is responsible for changing the character of the plasma and of B.
- Local time variations of field and flow are considerable and we believe link to centrifugal acceleration.
- Marissa Vogt has a poster on this subject (#119). Please visit.

At Jupiter's equator B_θ shows that flux per dr is much smaller at dawn than at dusk.



adapted from N. Krupp
Galileo/EPD flow measurements in the equatorial plane.
Look INSIDE MAGNETOPAUSE

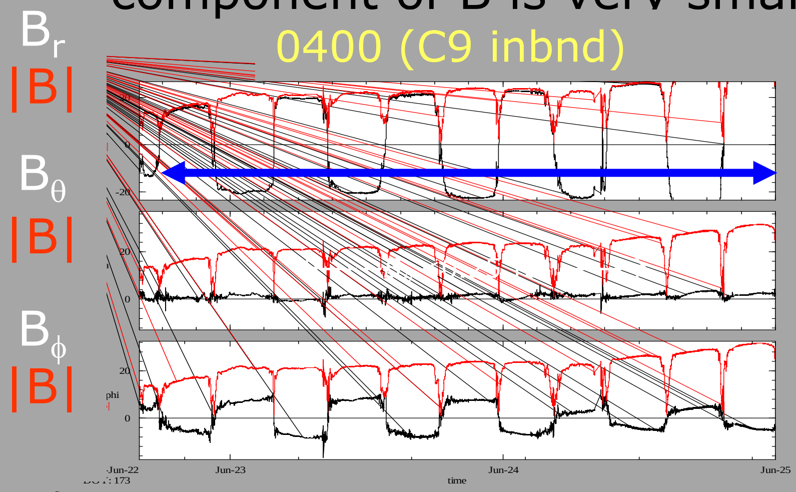
Flows also differ greatly between dawn and dusk. Slowed particle flow is found in Jupiter's afternoon-dusk sector, where equatorial B_θ increases. That is not fortuitous!



Magnetic signatures show near equatorial B becoming more dipolar and more variable as LT increases

Near dawn, the north-south component of B is very small.

In the afternoon, B_θ dominant and |B| variable.



$40 \leq 60\ R_J$

When B_θ~|B| at equator, the radius of curvature large and plasma sheet is thick even at large r. Requires hot plasma.

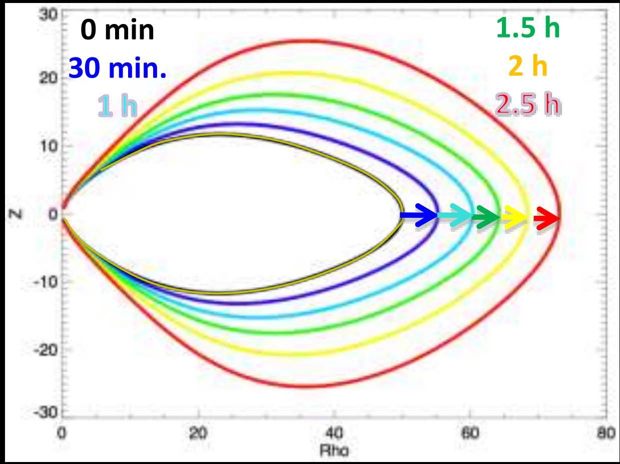
- Heating the plasma?
  - In rotating frame, include centrifugal force; take $\partial \mathbf{B}/\partial t \neq 0$

$$m\frac{d\vec{v}}{dt} = q\left(\vec{E} + \vec{v}\times\vec{B}\right) + m\omega^2 r$$

where $\mathbf{B} = \nabla\times\mathbf{A}; \quad \mathbf{E} = -\frac{\partial\mathbf{A}}{\partial t}$

  - The flux tube expands during rotation from noon to dusk because the magnetopause lies increasingly far from planet.

Time evolution of a model field line starting at 50 R_J and stretching radially outward over 2.5 hours.



from Vogt et al. poster

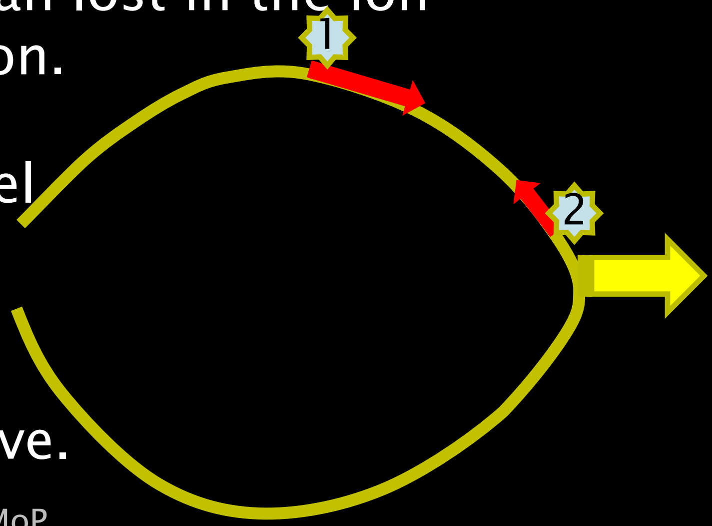
Bounce motion is not longer conservative.

Bounce times of 1 keV heavy ions are long compared with time for flux tube to rotate from noon to dusk → allows for plasma heating.

Bounce Times, 1 keV ion (20 m_p)		
Radial distance at equator (R_J)	Equatorial pitch angle (degrees)	Bounce Period (hours)
30	20	20.8
30	80	6.4
40	20	27.4
40	80	5.6
50	20	36.0
50	80	5.7
60	20	46.5
60	80	6.1

Vogt et al., poster

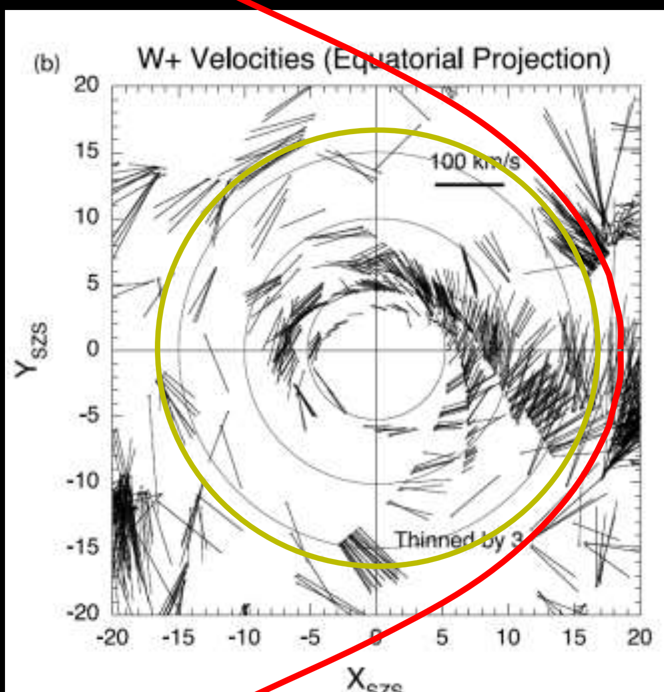
As ion 1 moves towards equator, the equatorial point of field line recedes; ion keeps gaining energy with increase of ρ. As ion 2 moves up the field line, it is also carried outward by the field stretching. More energy is gained than lost in the ion distribution.

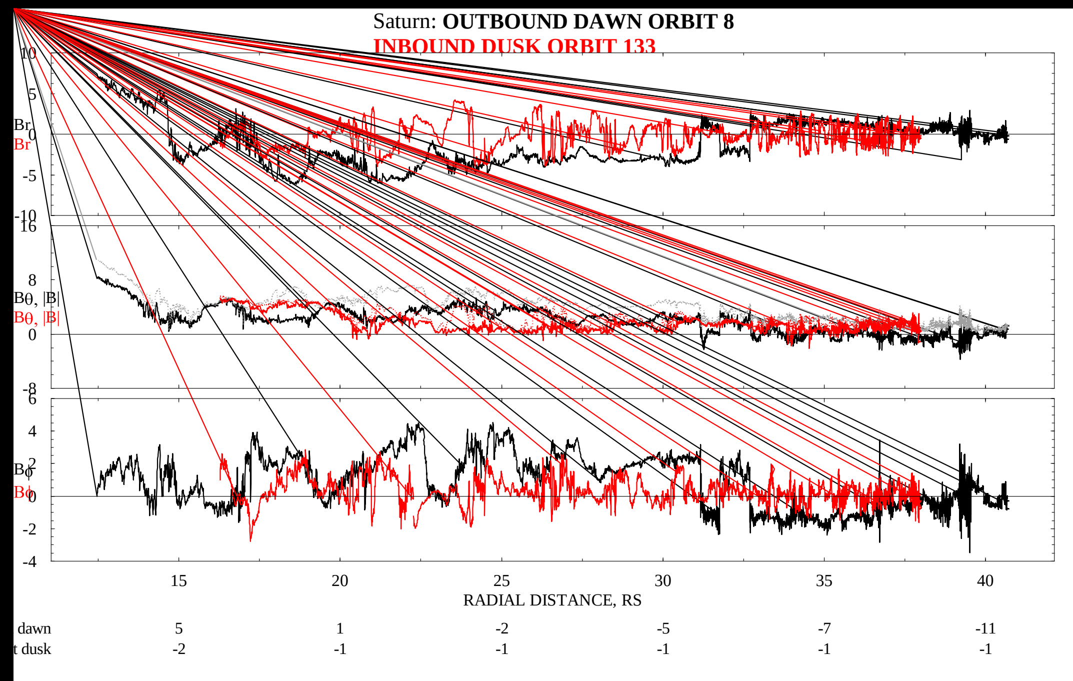


This model needs to be made quantitative.

The dawn-dusk asymmetry is absent in both field and plasma velocity at Saturn

- Maybe a hint in B_θ, but the magnetospheric scale is far too small for this process to be significant.



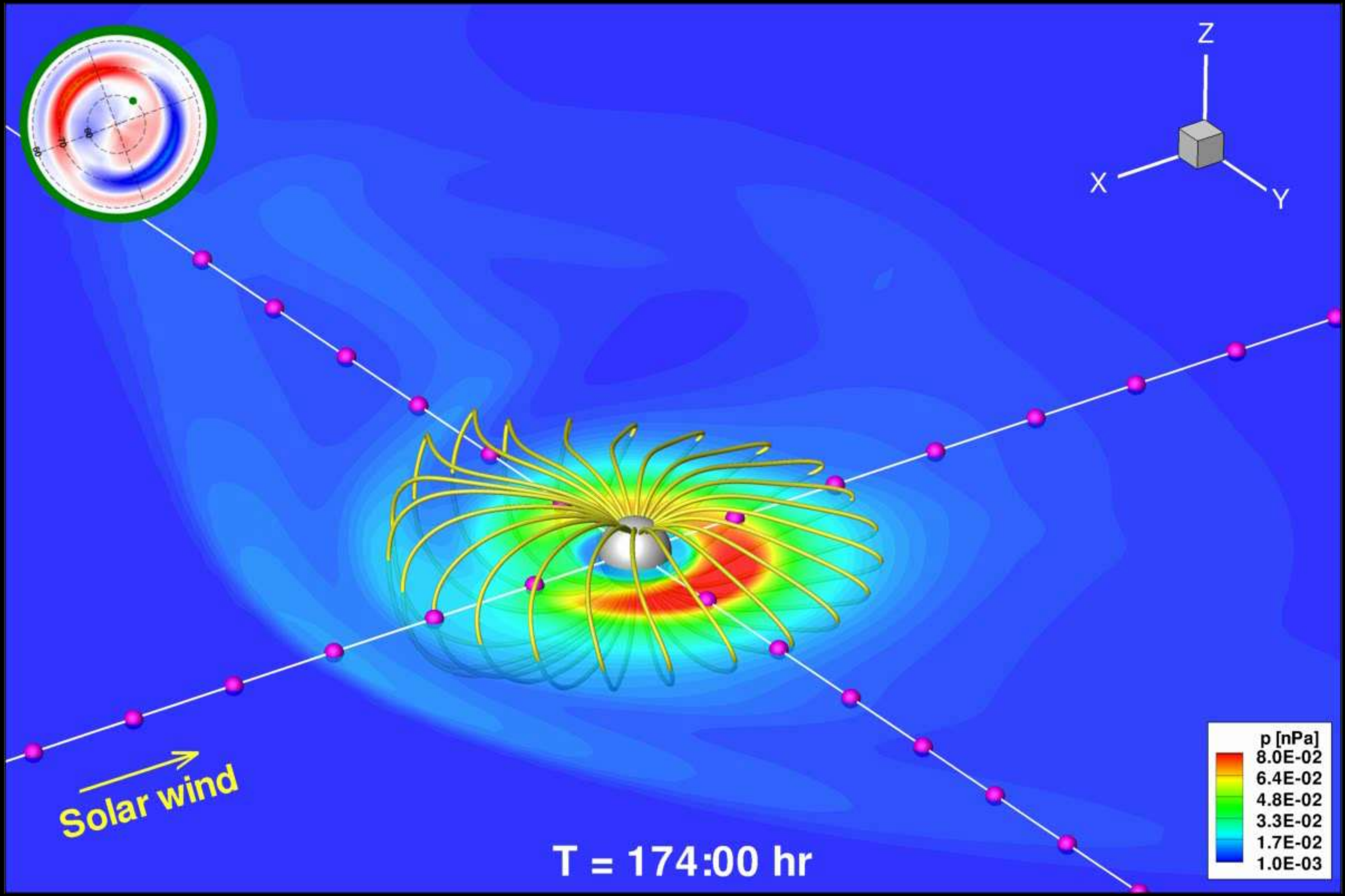


Velocities from Thomsen et al., 2010

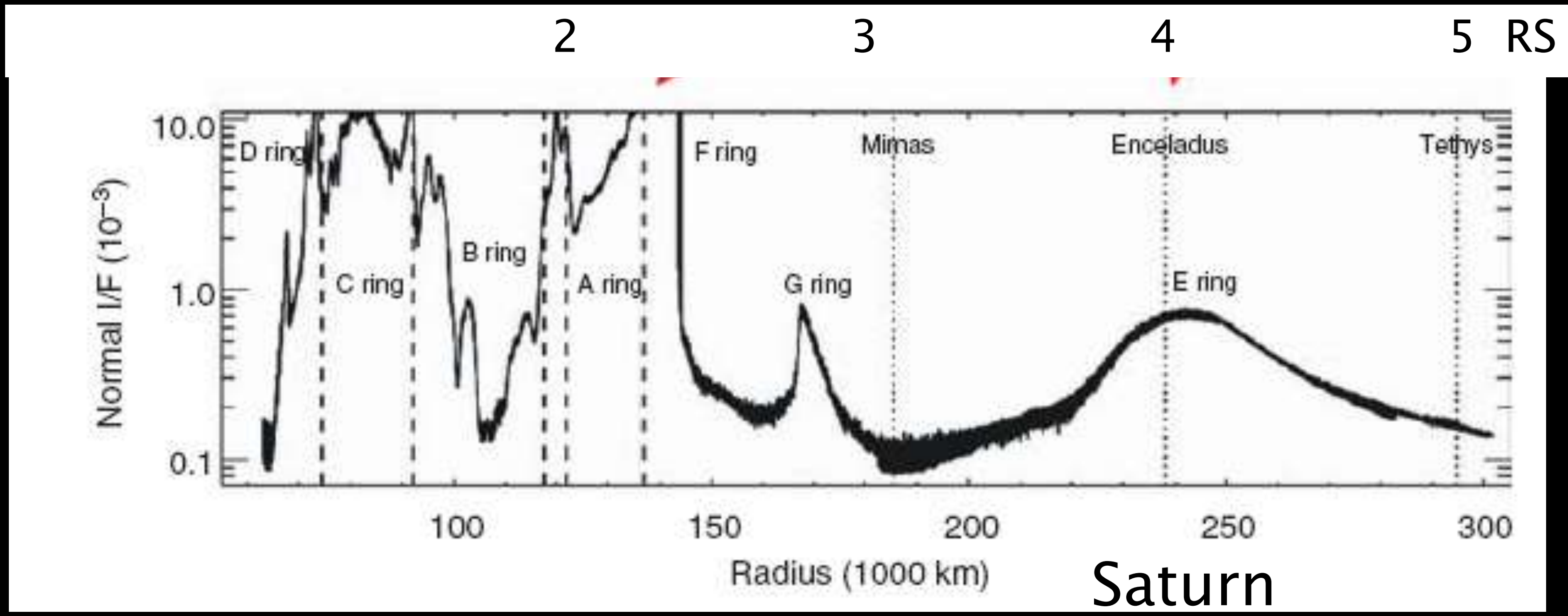
Periodicities

- Well established at Saturn.
  - seasonal effects
  - slow drift of period
  - different north and south
- Models have attributed periodicity to
  - convective instability in the magnetosphere,
  - to periodic disconnections,
  - to FACs driven by ionospheric flows.
- We will hear lots about this matter for Saturn during the meeting.
- For Jupiter
  - System IV (different from System III rotation period) periodicities have been reported from several types of observations.
- Is System IV (period 3% longer than System III) the Jovian equivalent of the SKR periodicity at Saturn?

I can't resist some advance notice of a very current model of periodicity (Jia, Kivelson, Gombosi)



Dust is a significant element of the inner magnetospheres of Jupiter and Saturn



- Dust distribution. E ring is quite diffuse.
- Dust complicates the plasma

Dust particles are massive compared with ions

- Whereas ion motions are dominated by electromagnetic forces, more massive dust grains are controlled by gravitational forces → Keplerian orbits.
- Through most of Jupiter's and Saturn's magnetospheres, Keplerian speeds are slower than corotation.
- Anomalous rotation has been attributed to the effect of dust.

Dust affects plasma properties

- E.g. for Saturn, near the E-ring, there are multiple populations (Wahlund et al, 2009).
  - Hot ions ~corotate;
  - Dust grains move at ~Keplerian speed.
- Colder ions (T_i a few eV) and electrons can interact with the electrical potential cavities of the negatively charged (~Volt neg.) water-rich dust grains in the E-ring (Wahlund et al., 2009).

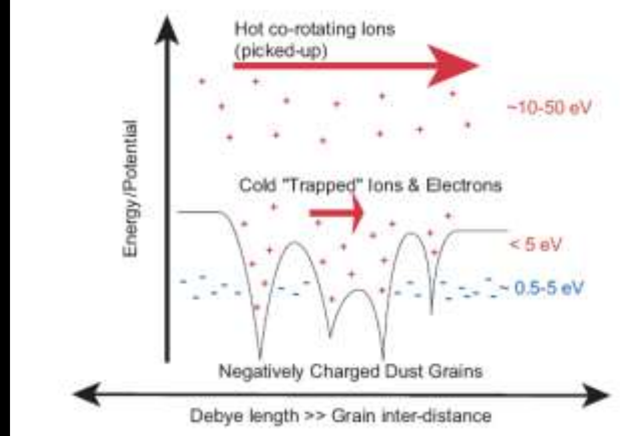


Fig. 13. Cartoon describing the physical picture as interpreted from the RPWS measurements. Ionized electron-ion pairs start with low energies, become trapped to a large degree by the steep potential gradients near the charged dust grains. Eventually, part of the ion population becomes accelerated by the co-rotation electric field around Saturn, and attain the larger co-rotation energies and can move more freely through the dusty plasma.

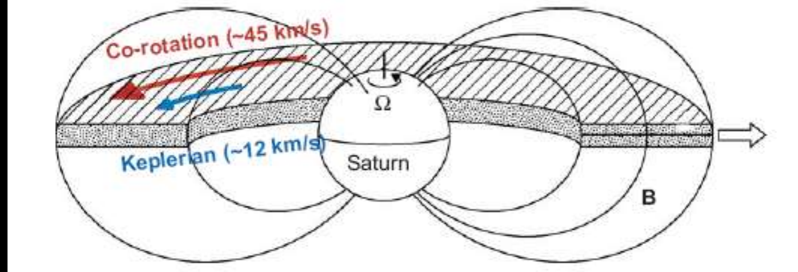


Fig. 14. Results presented here give observational evidence for that two ion populations with different drift speeds rotate around Saturn in the dusty plasma disk surrounding the E-ring. This may give rise to a current system that connects to Saturn's polar ionospheric regions, and possibly contribute to the release of plasma near the plasma disk edge near 8 R_S under the action of the centrifugal force.

Last words

- Touched on vary few matters.
- I hope I leave you with the sense that there is a good deal more to learn about the dynamics of the magnetospheres of Jupiter and Saturn.
- JUNO is coming.
- Cassini is continuing.
- MOP 2013 should be fun too.