Magnetodiscs of Giant Planets

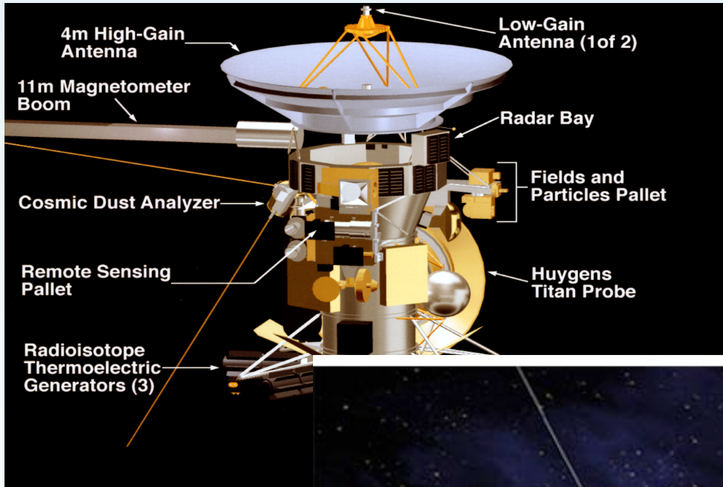
Nick Achilleos, Atmospheric Physics Laboratory / Centre for Planetary Sciences

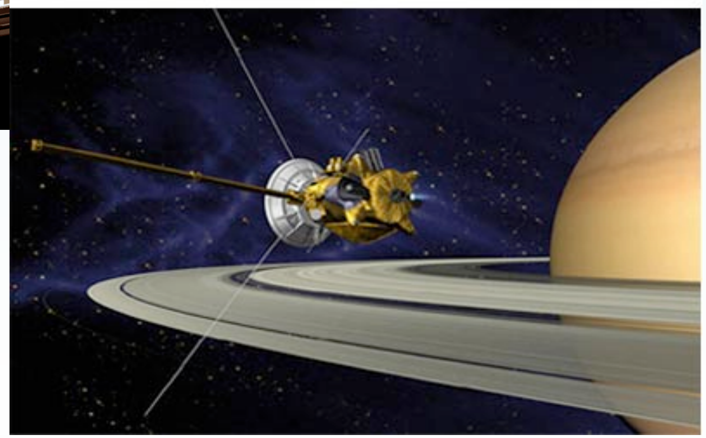
- Planetary magnetic fields: **There is more to a planet than meets the eye.**

- Magnetospheres as ‘plasma laboratories’

- The role of rotation and plasma discs at the giant planets: Saturn and Jupiter

- Investigations at Saturn with Cassini (magnetometer)



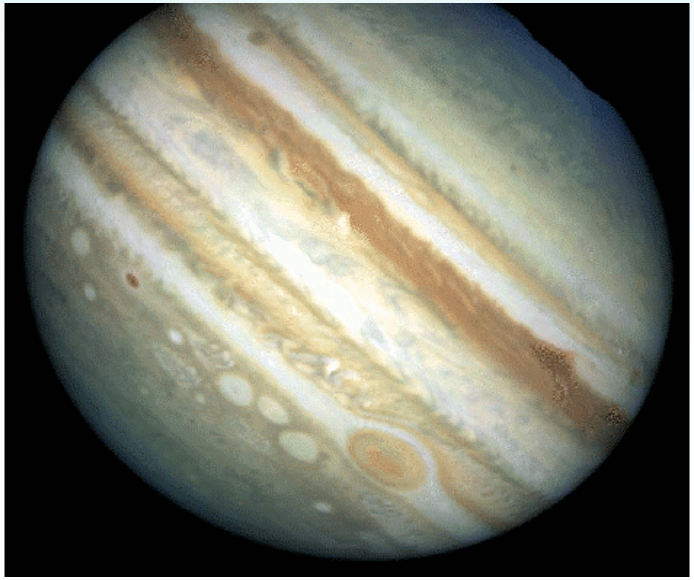


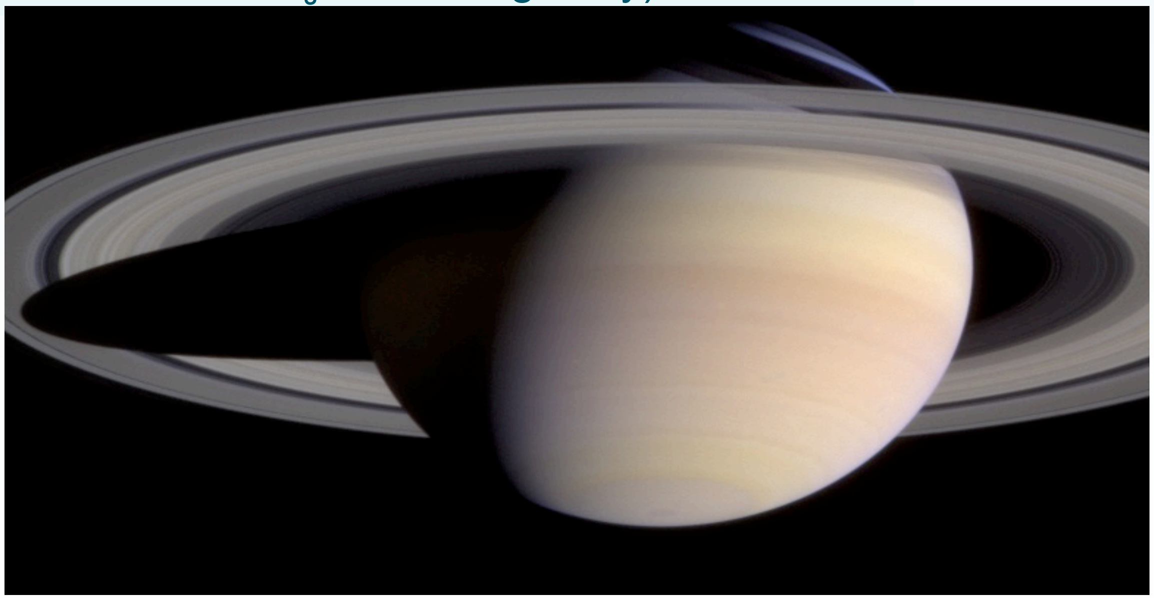
Planetary Magnetism and Rotation

Planet	Mass	Radius	Period of Rotation	Planetary Dipole: Moment ($B_{eq} R^3$)	Tilt
Earth	1	1 (6400km)	1 day	1 (B_{eq} = 32000nT)	10.6 deg
Jupiter	318	11	0.414	18000	9.4
Saturn	95	9.5	0.426	550	< 1

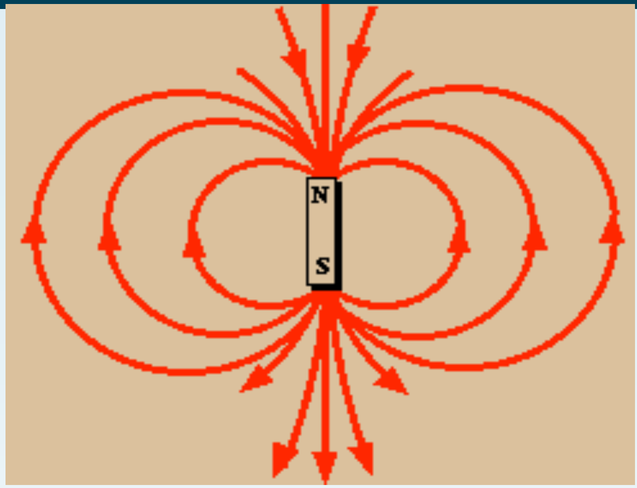
Giant planets are rapid rotators *for their size*:
Liquid metallic hydrogen above ‘rocky’ core → excellent conductor → strong magnetic field from dynamo action (planet rotation plus convection in interior)

Rapid rotation in giants produces strong effects on structure of B-field in outer magnetosphere (Jupiter: centrifugal acceleration at > 2 R_J exceeds gravity).

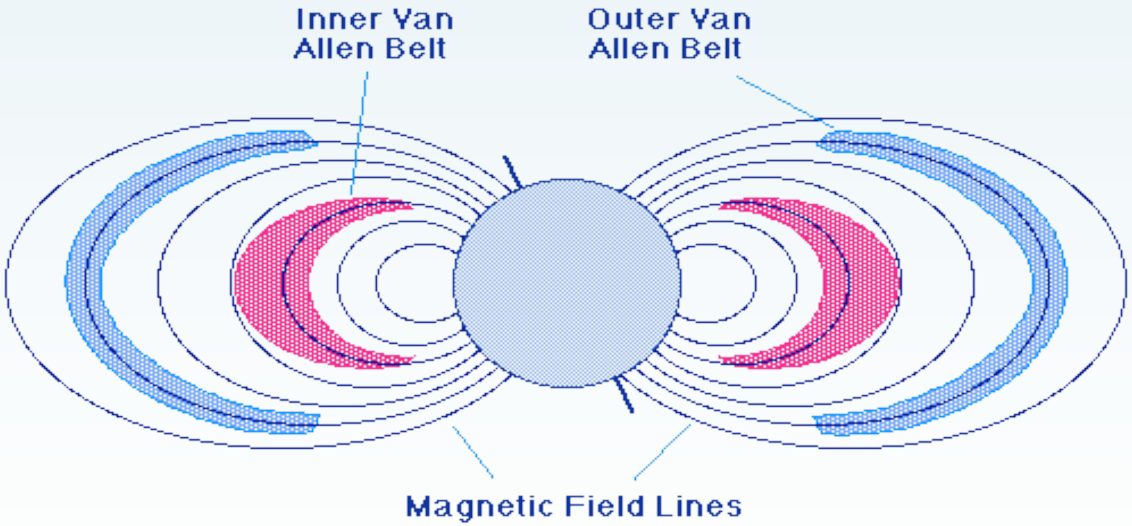




Magnetic 'Lines of Force'



Bar magnet – iron filings line up along 'lines of force'. Two poles, N and S.



Earth's magnetic field – also has two poles. Equatorial magnetic field is 32000 nano-Tesla units.

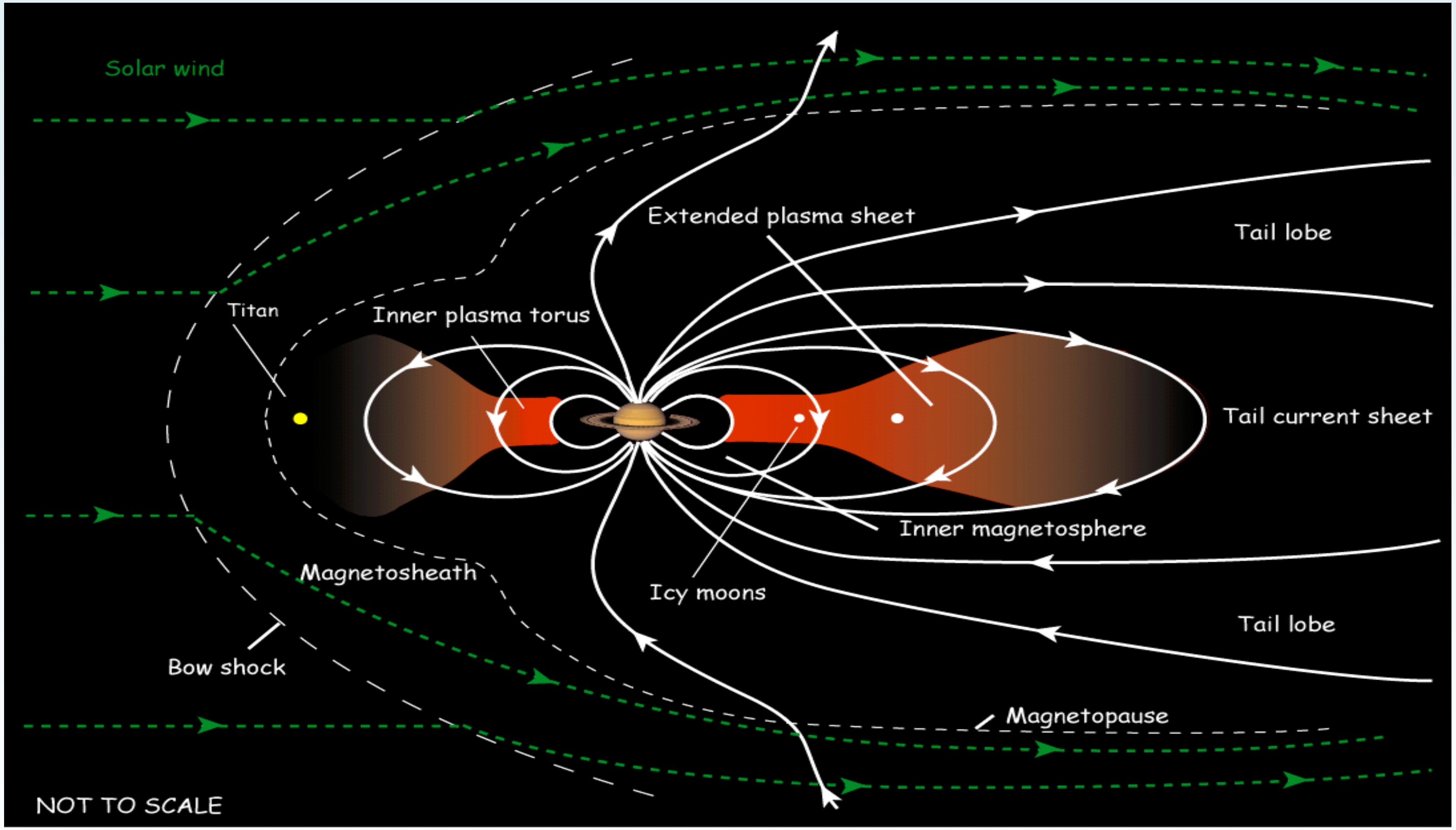
Compare with:

20000 nT (Saturn)

420000 nT (Jupiter)

The Solar Wind – Magnetosphere Interaction

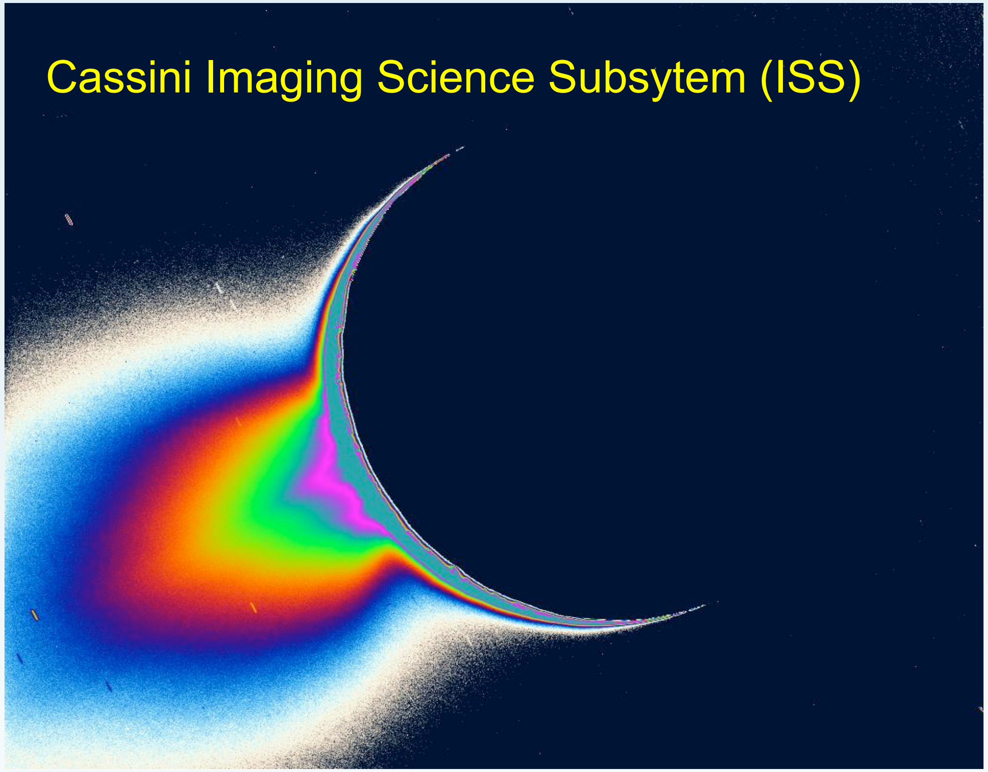
Courtesy Emma Bunce (U. Leicester)



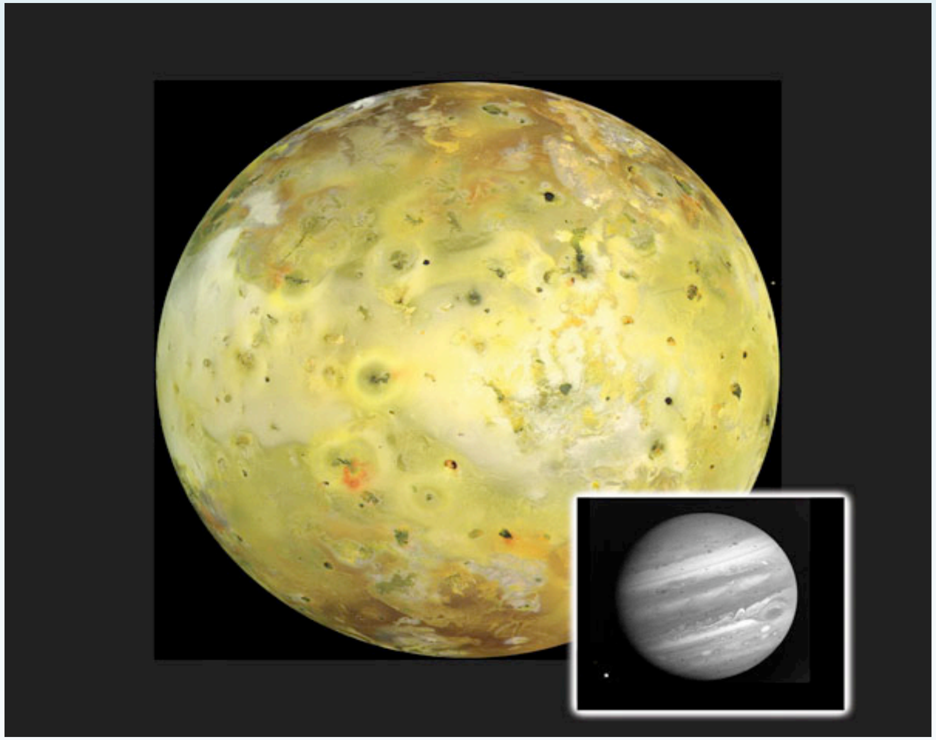
•**Magnetodiscs** are magnetised, rotating discs of plasma, ‘fed’ by sources such as Io (Jupiter) and Enceladus (Saturn).

• For rapid rotation, centrifugal force confines plasma towards the equatorial plane.

Internal Mass Sources for the Disc: Moons !



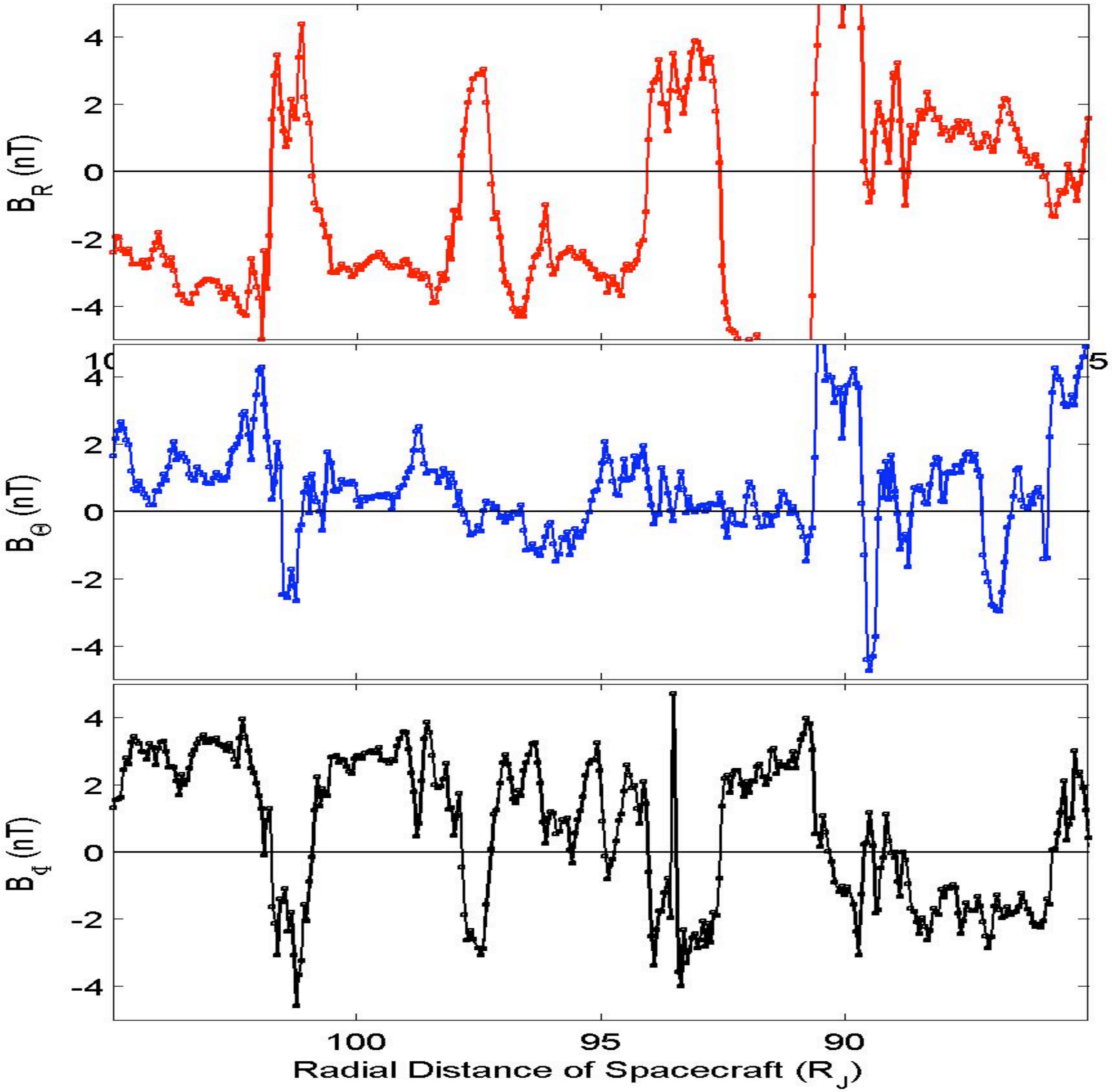
Enceladus (icy satellite): Mass source for Saturn's E ring, magnetosphere (~10-100 kg/s of plasma) **First discovered by MAG** *(Dougherty et al, Science, 2006)*



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

What about Earth ? No equivalent 'internal' source

Detecting a disc with magnetic field observations:

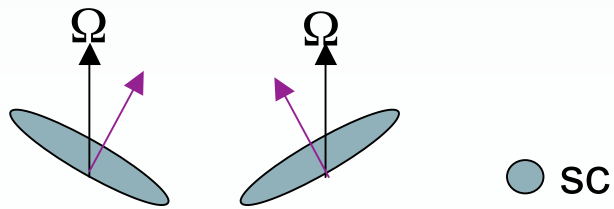


- **Galileo** insertion orbit at Jupiter - an equatorial pass

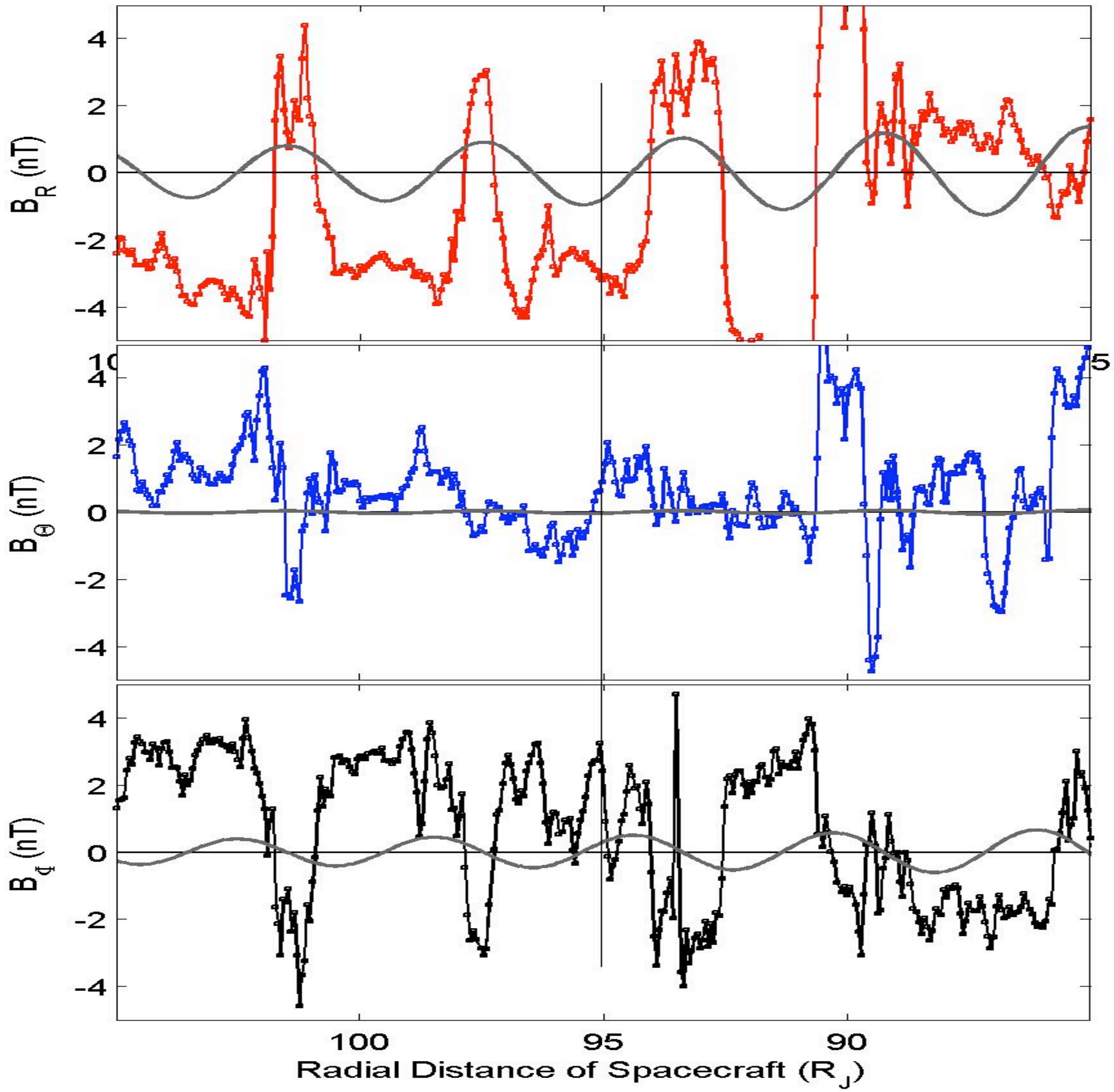
- Notable ‘square waves’ in radial and azimuthal field, in *antiphase*, and with period nearly equal that of planetary rotation.

- Is this the effect of a rotating tilted dipole field, placing the spacecraft alternately above and below magnetic equator ?

- ‘Wobbling plate’ picture.



Detecting a disc with magnetic field observations:



- **Here** we see the field predicted by only the rotating planetary dipole of Jupiter.
- The sine-like waveform is very different to what is seen by Galileo.
- The Br-Bphi *phase relations* are also very different to what is seen - why ?
- Another source of field is indicated.

An improved model - adding a 'disc-like' field

COWLEY ET AL.: PLASMA FLOW IN THE JOVIAN MAGNETOSPHERE

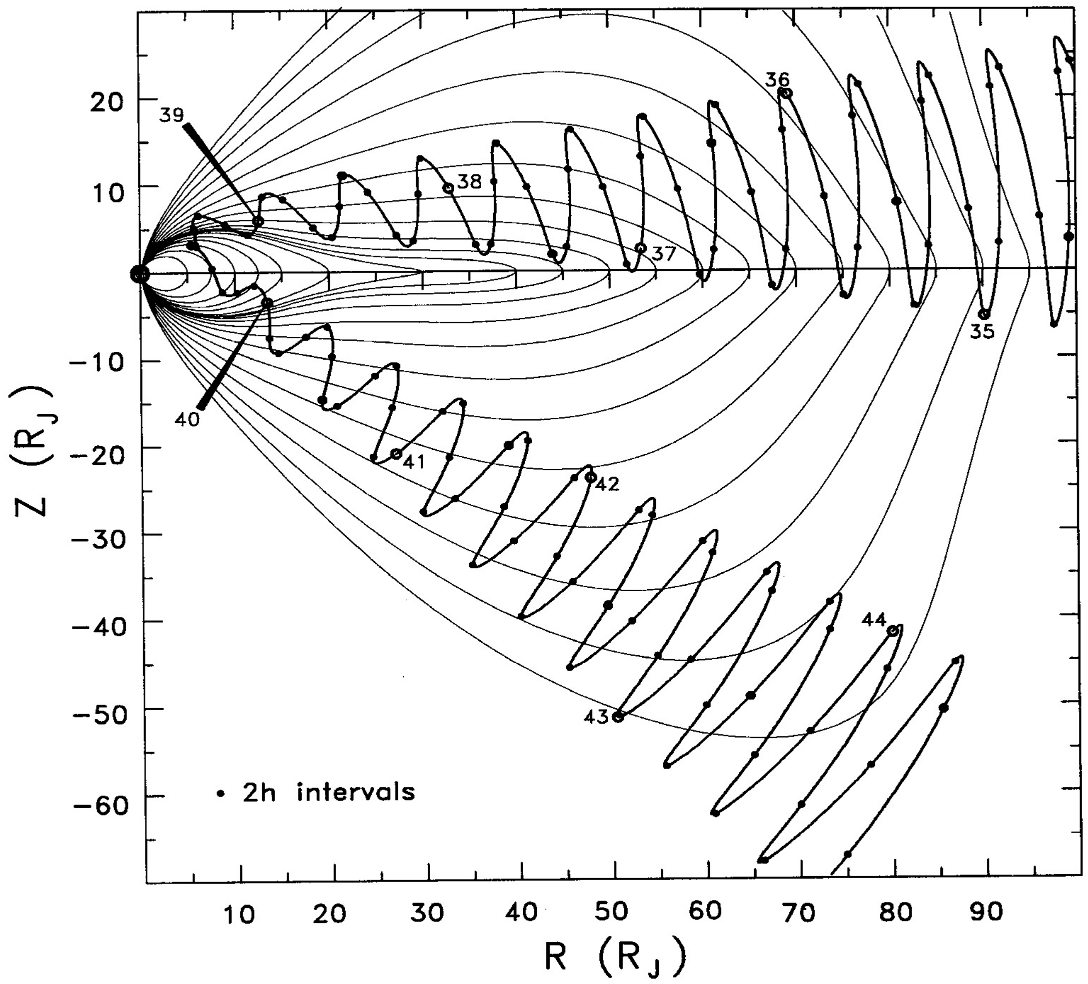


Figure 1. Trajectory of the Ulysses-Jupiter encounter in magnetic coordinates, superimposed on model magnetic field lines. The vertical (*Z*) axis is the distance (in R_J) along the magnetic dipole axis, while the horizontal (*R*) axis is the perpendicular distance from the dipole axis. The field model used to trace field lines is the Connerney model with a current sheet extended to 70 R_J to better represent the expanded magnetosphere encountered by Ulysses (at least inbound). Large numbered circles indicate the start of the day in question, other dots are spaced by 2 hours along the trajectory.

- **Fixing** coordinate frame to the magnetic equator transfers 'wobble' to Ulysses spacecraft trajectory.

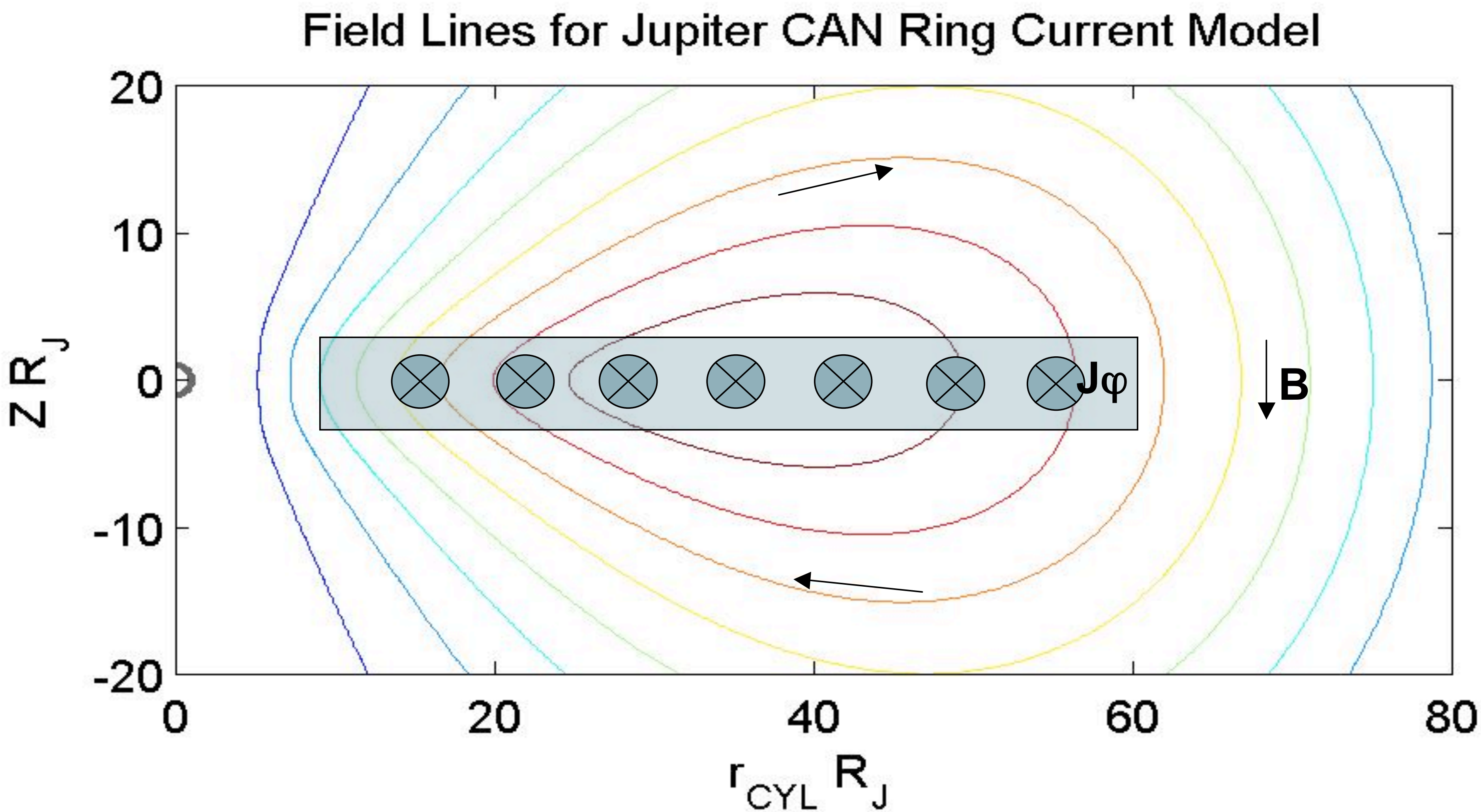
- The observations can be explained by periodic encounters with a 'disc-like' field component.

- Equatorial field is like radially 'stretched' dipole.

- Equatorial *current sheet* with current flow in the sense of planetary rotation.

- Currents from *differential particle drifts*.

First approach: Assume a current distribution *a priori*



CAN = Connerney, Acuna and Ness (JGR 1981)

- Proposed an 'annulus' with rectangular cross section for current disc.
- In this model, $J\varphi \sim 1 / r_{CYL}$
- Good for empirical modelling of the current region - no information about force balance in disc (source of current)

Caudal's Approach: Start with force balance, find field and current

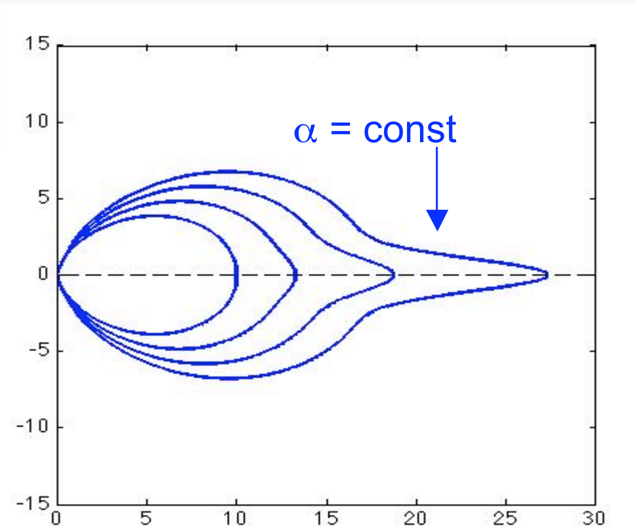
Background: **G. Caudal** (JGR, 1986) developed a magnetodisc field model for ***Jupiter*** based on the force balance in a *cylindrically symmetric system*:

General Force Balance: $\mathbf{J} \times \mathbf{B} = \nabla P - n\, m_i\, \omega^2\, r_{CYL}\, \mathbf{e_r}$

- **Represents balance between magnetic force, pressure gradient and centrifugal force on rotating plasma**

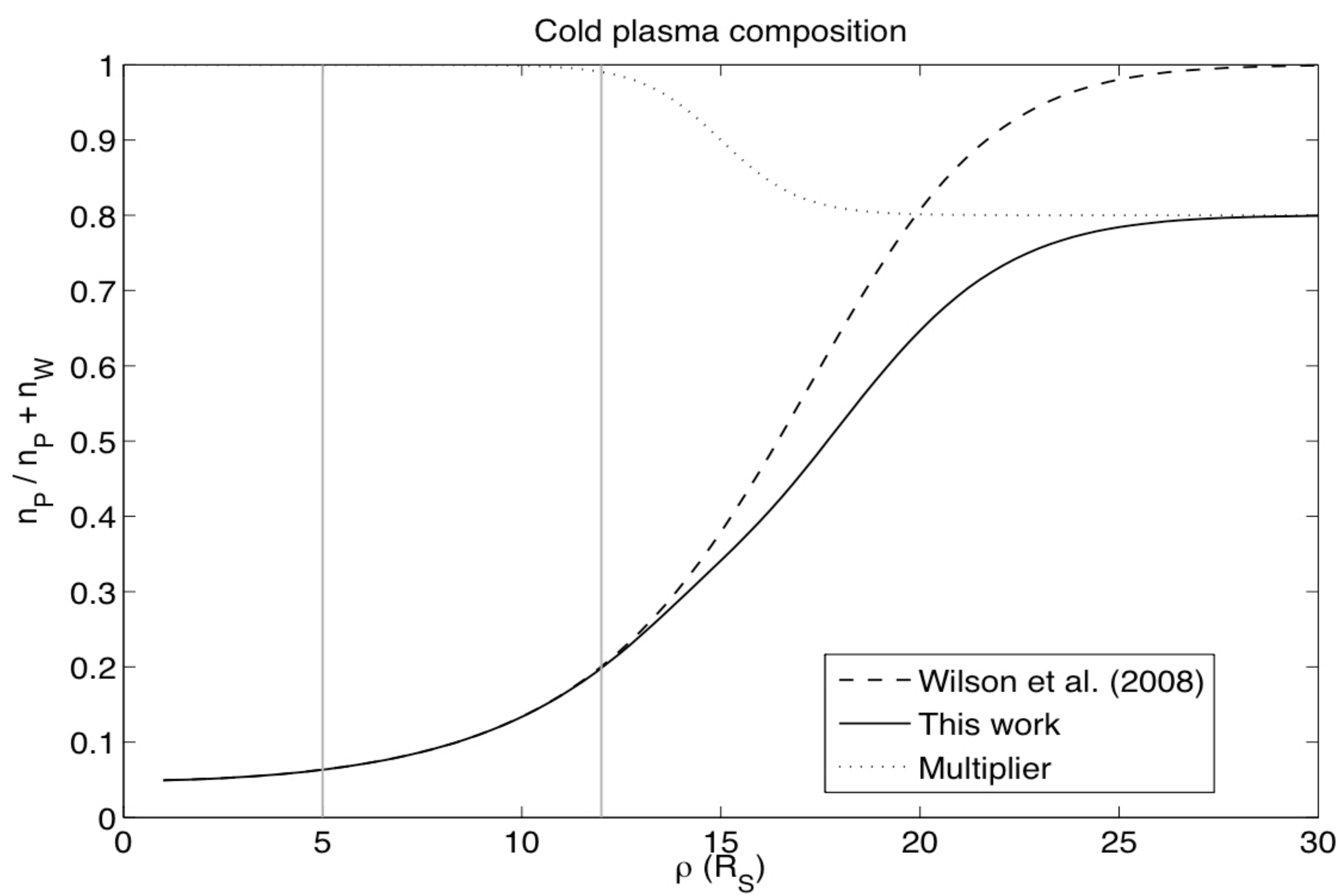
- **Symbols**: n, m_i are number density and mean mass of ions. ω is plasma angular velocity. r_{CYL} is cylindrical radial distance, $\mathbf{e}_\rho$ is unit vector.

- **Caudal** transformed force balance into a relation between **magnetic potential** α and equatorial plasma properties - one 'solves' for α which defines *field lines*:



Achilleos, Guio and Arridge (2009, MNRAS) -
Inputs needed for Saturn (equatorial):
- Cassini *equatorial* plasma data (density, T, composition, ω)
- Saturn's equatorial magnetic field (~20000 nT), radius (~60000 km)
- Magnetopause radius.

Cassini Observations of Disc Plasma at Saturn: Composition



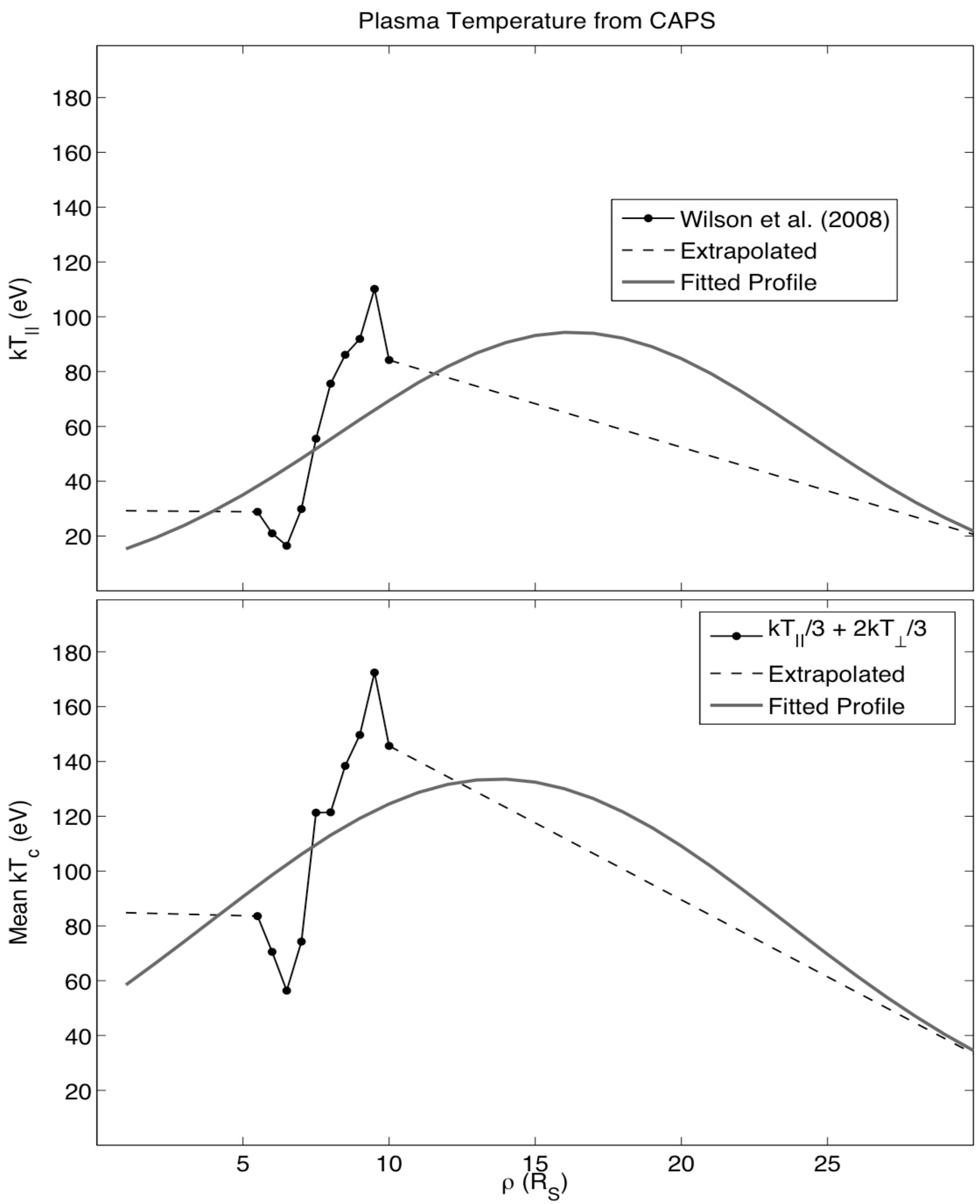
- Fits provided by Wison et al (JGR 2008) using data from CAPS ion beam instrument. Main species are protons (P) and water group ions (W).

- Valid for 5-12 R_S - beyond this we smoothly connect to a proton-rich plasma consistent with disc mass density (*Arridge et al, JGR, 2007*)

From Achilleos, Guio and Arridge (= AGA) (*MNRAS, 2009, online or arxiv*)

(UCL Centre for Planetary Sciences - P&A / MSSL)

Cassini Observations of Disc Plasma at Saturn: Temperature

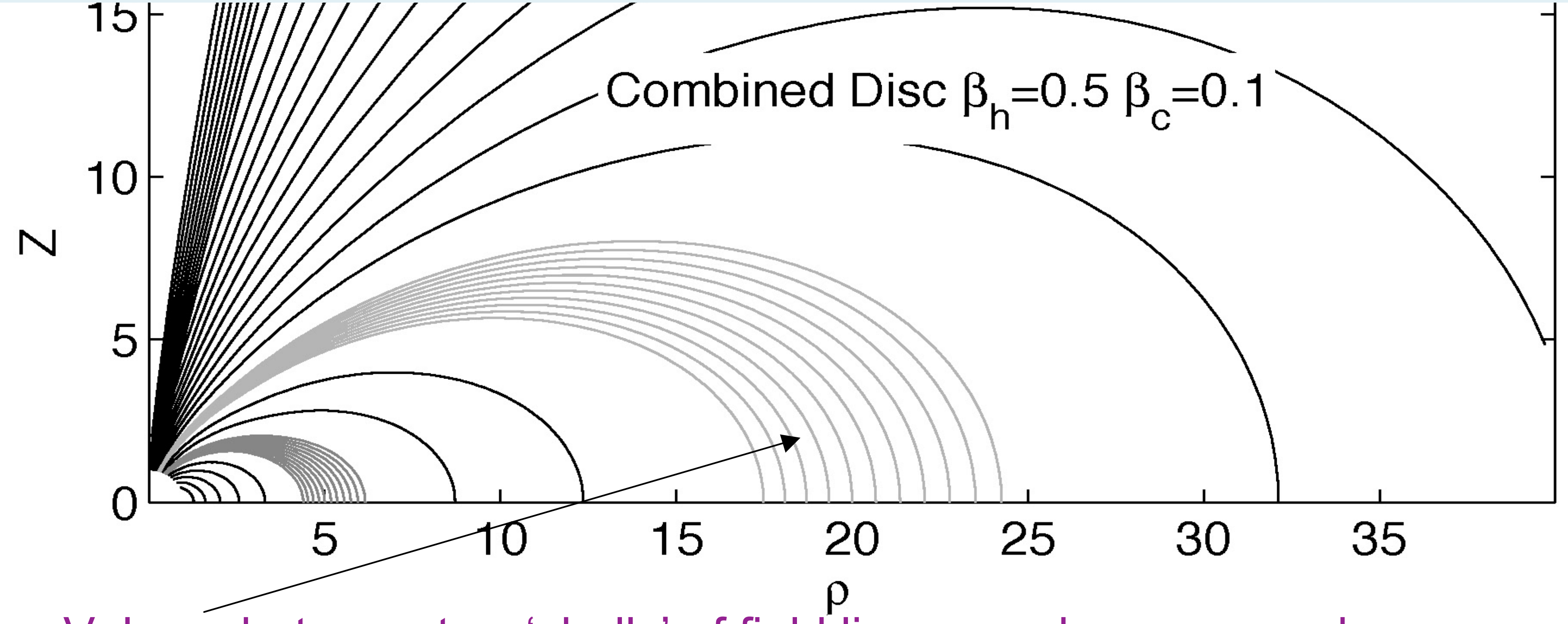


- *AGA* fitted CAPS temperatures tabulated by Wilson et al (2008) over 5-12 R_S
- P and W temps combined to give averages parallel and perp to **B**
- **Beyond** 12 R_S extrapolate assuming fixed temperatures for individual species.
- More recent work by McAndrews et al (*PSS, 2009*) shows outer MSP temps about 2-3 times as high.
- T_{par} determines how plasma *thermal* motions can compete with centrifugal potential. Scale length for pressure measured along field line is:

$$\mathbf{2\ k\ T_{par}\ /\ m_{ion}\ \omega^2}$$

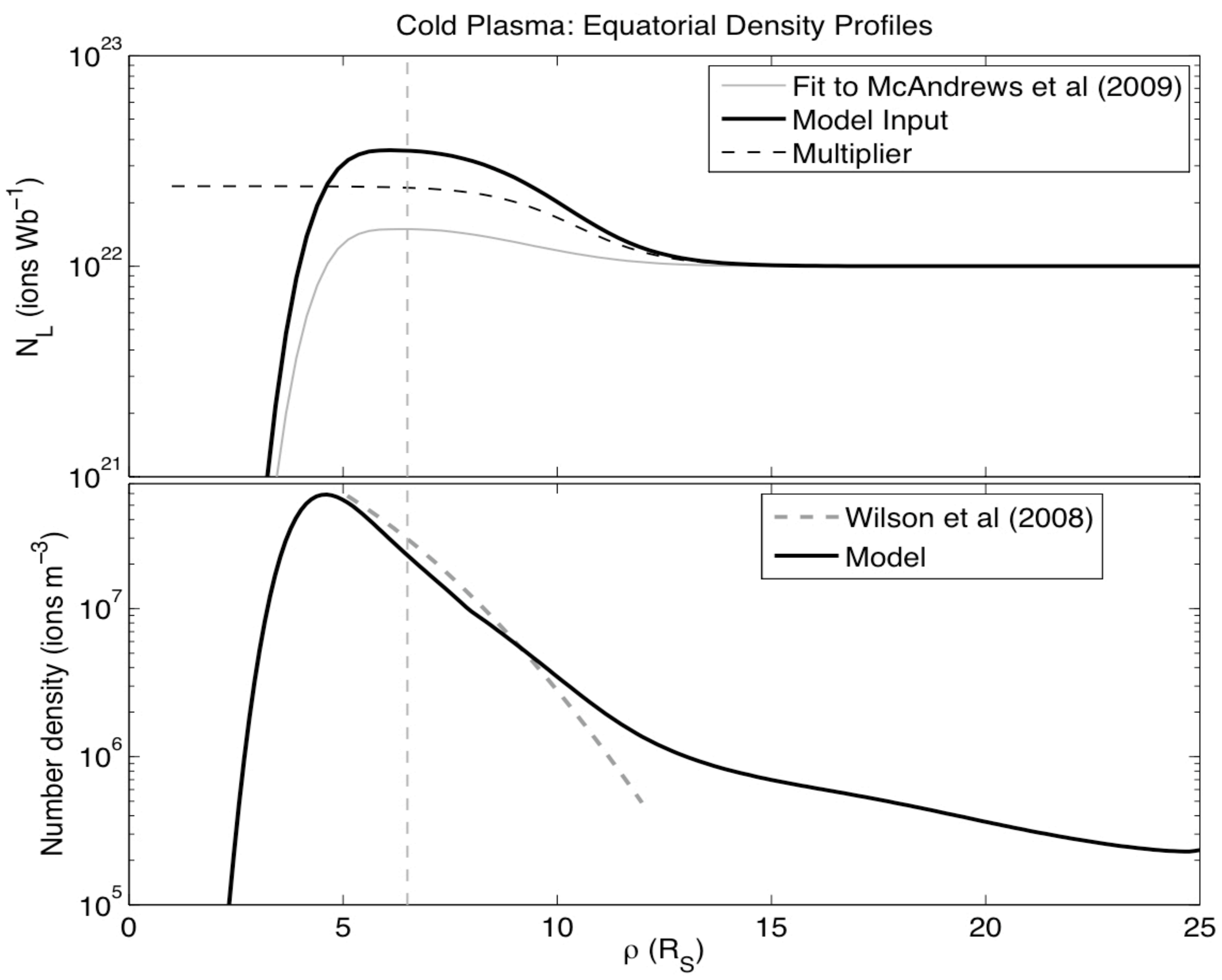
- **Same** for ions, e-s (a few R_S)

Cassini Observations of Disc Plasma at Saturn: Density



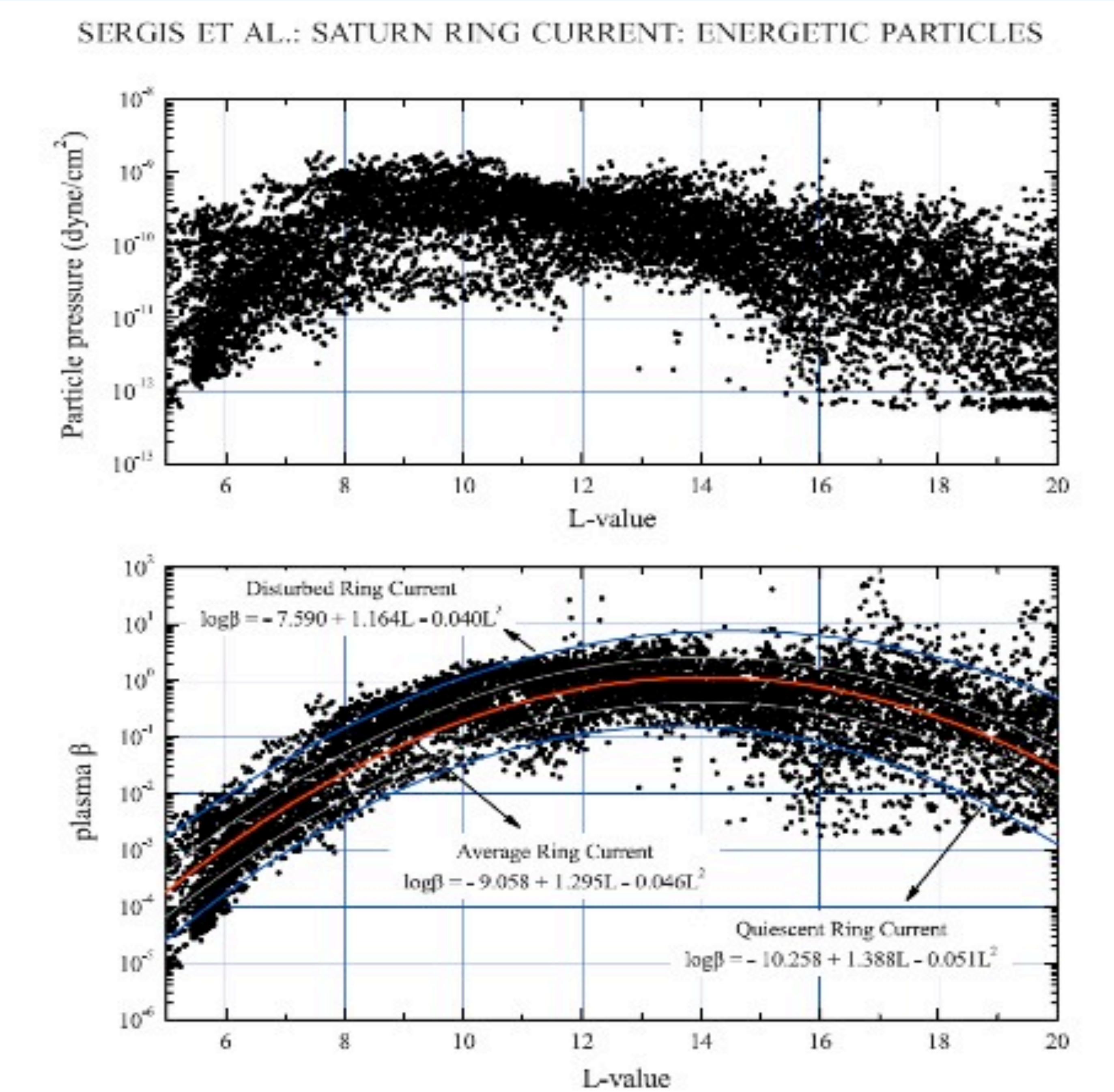
- Volume between two 'shells' of field lines may be expressed as $\mathbf{V}_\alpha \Delta\Phi$ where $\Delta\Phi$ is *magnetic flux* and V_α is known as *unit flux tube volume.*
- The number of ions in this shell is $\mathbf{N}_\alpha \Delta\Phi$ and $\mathbf{N}_\alpha$ the *unit flux tube content.*
- Using $\mathbf{N}_\alpha$ is convenient, because $\Delta\Phi$ and $\mathbf{N}_\alpha$ stay the same as magnetosphere expands / contracts

Cassini Observations of Disc Plasma at Saturn: Density



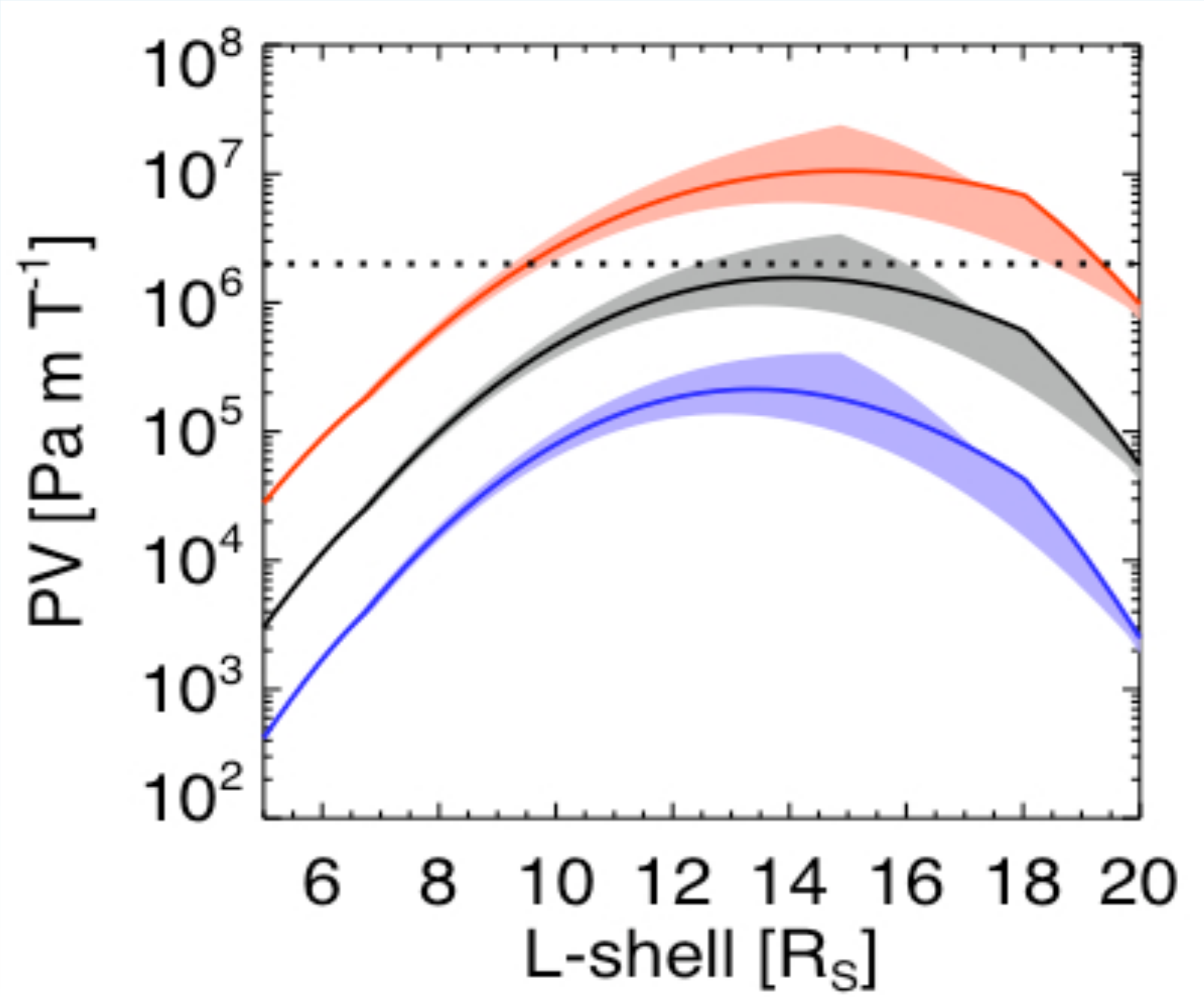
Largest density of cold plasma is near Enceladus - 4 R_S

Cassini Observations of Hot Plasma Pressure



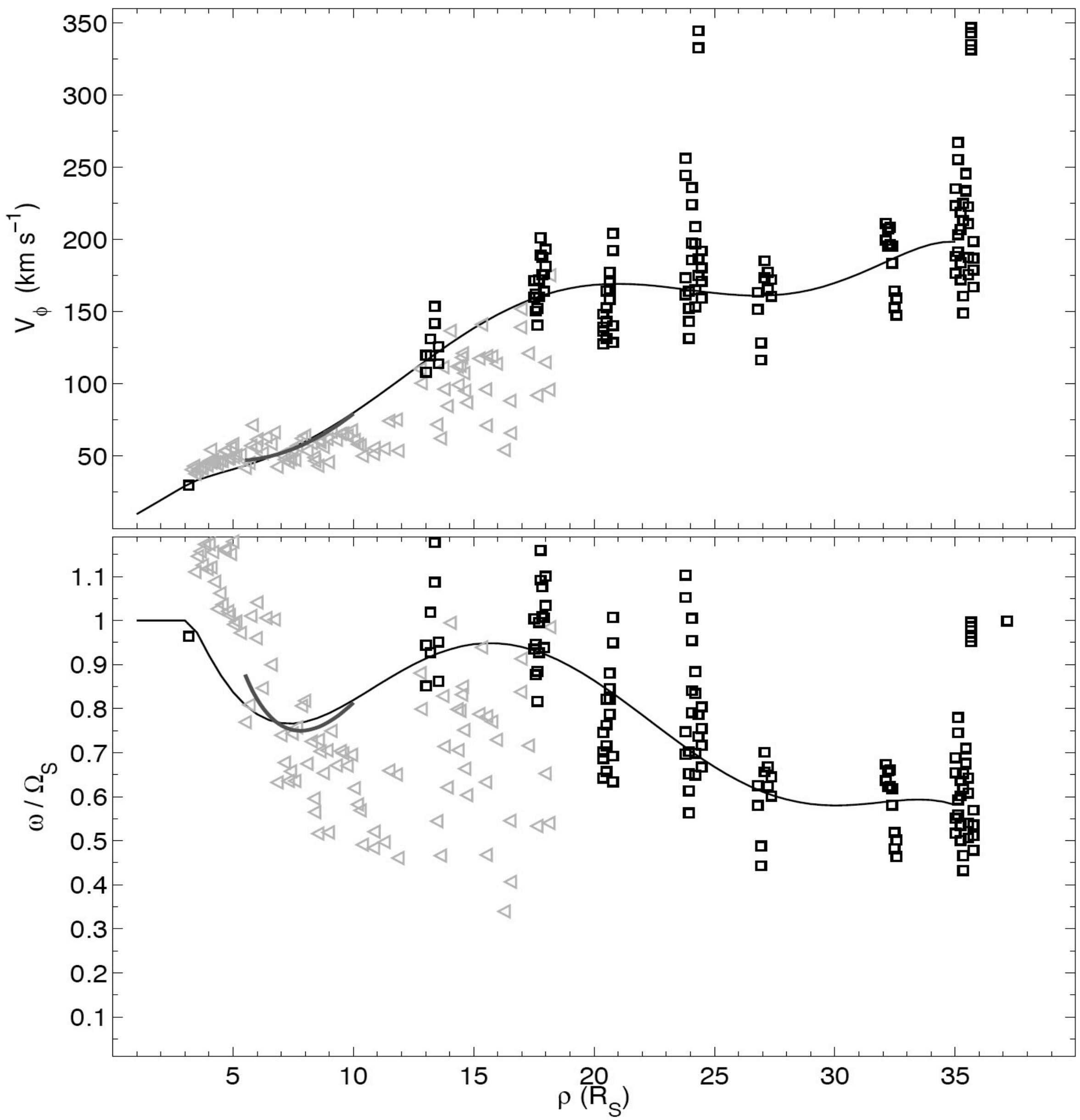
- Cassini Magnetospheric Imaging Instrument (MIMI) acquires energy distributions for hot plasma (> 3 keV).
- Sergis et al observations show strong variability.
- Plasma β = ratio of plasma pressure to magnetic presure.
- *Achilleos, Guio and Arridge (2009)* used the fits to hot plasma β provided by Sergis et al.

Cassini Observations of Hot Plasma Pressure



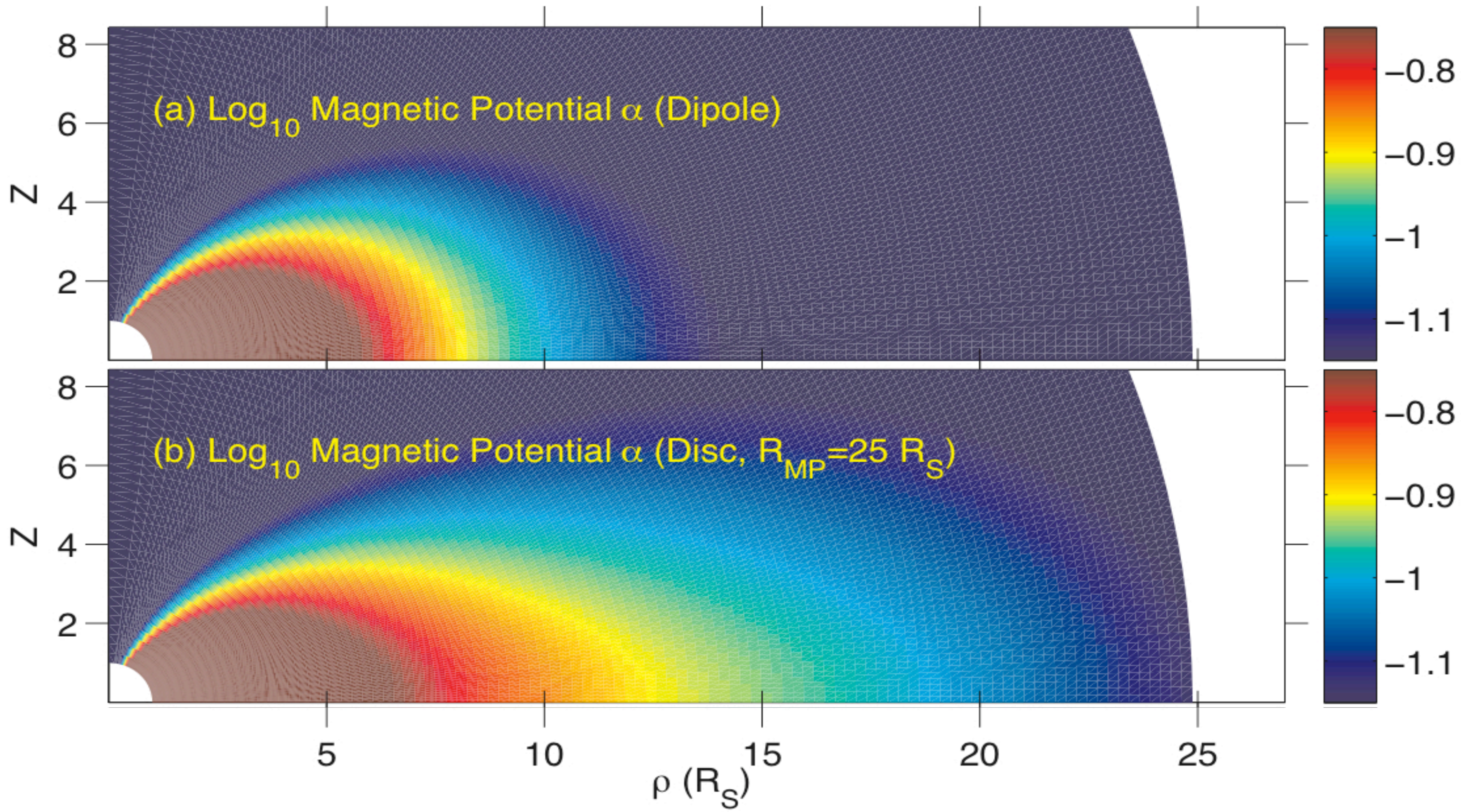
- Here we see the product of hot pressure and unit flux tube volume.
- This was used to parametrise the 'level of activity' of the ring current.
- We set PV = constant = K_h beyond 8 R_S
- K_h is a 'hot plasma index', typically 2×10^6 Pa m / T for 'average' RC conditions.

Cassini Observations of Plasma Angular Velocity

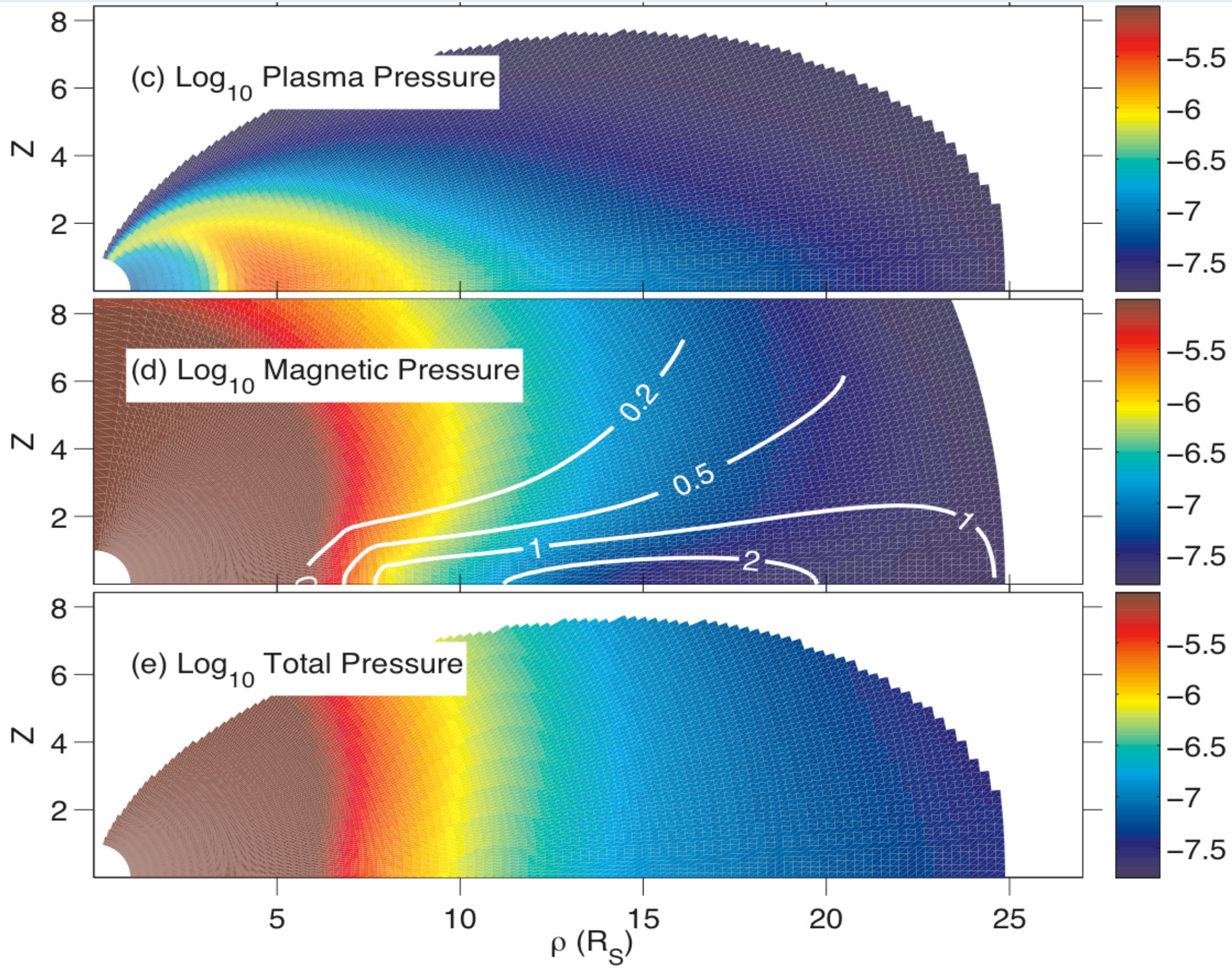


- Squares: MIMI observations by *Kane et al (GRL, 2007).*
- Small grey 'arc': fits by *Wilson et al (2008)* to CAPS ion data.
- Triangles: *Voyager* measurements by *Richardson (1998).*
- *Curve:* Fit used in our model, obtained from the *Cassini* points.

Magnetic Field Model for Saturn (Dipole plus Disc)

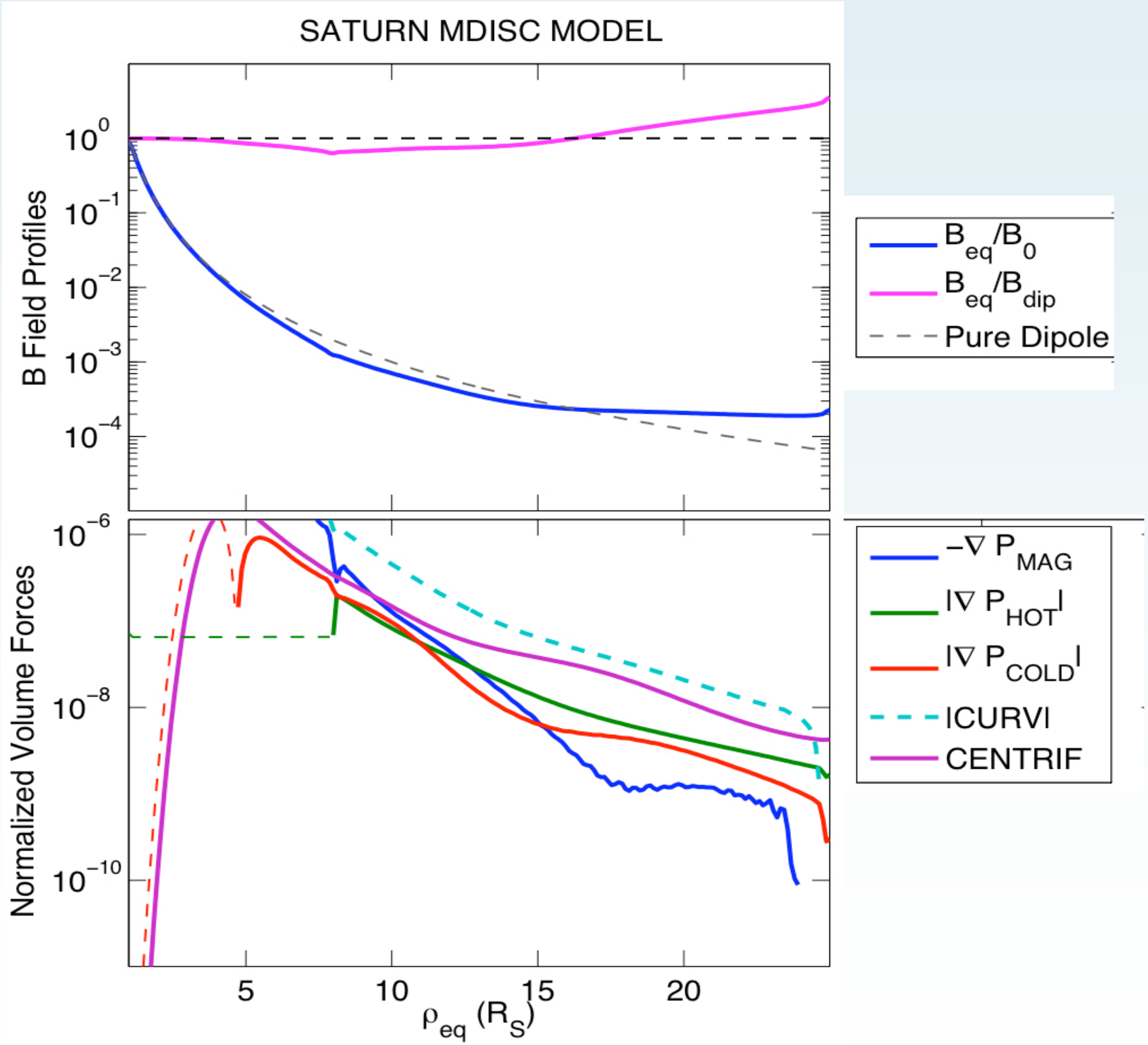


Magnetic and Plasma Pressure Models



- For balance in the Z direction, just outside equator where field lines are 'stretched out': **JxB** force is the gradient of a *magnetic pressure* ~ B^2

Force Balance in the Radial Direction: Saturn



- Here we see the forces in the equatorial plane of the model disc.

- The small radii of curvature of distant field lines as they cross equator: **$J \times B \sim B^2 / R_C$** 'magnetic curvature force' acting *inwards*

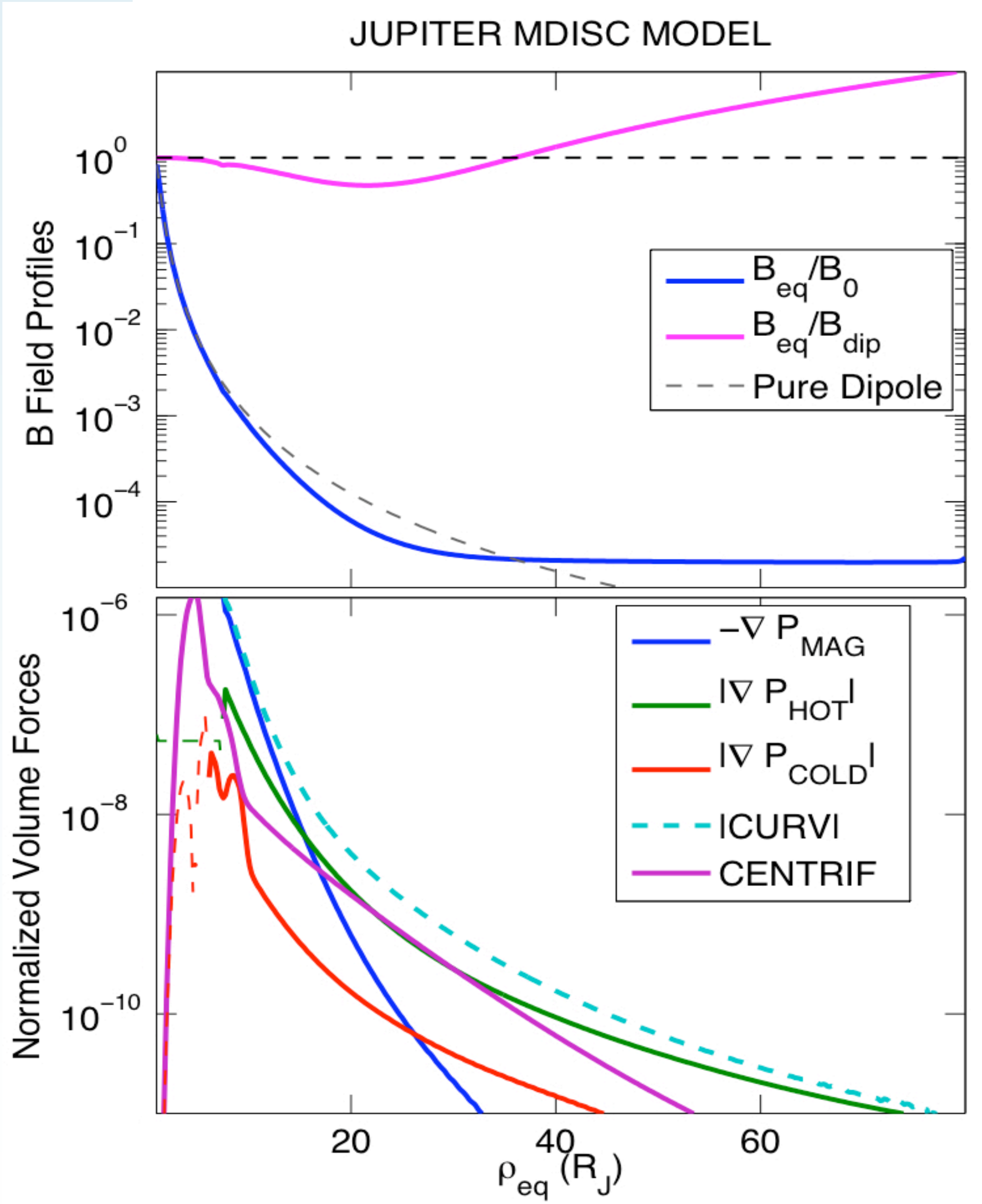
- Outer magnetosphere is mainly **curvature vs. centrifugal**.

Force Balance in the Radial Direction: Jupiter

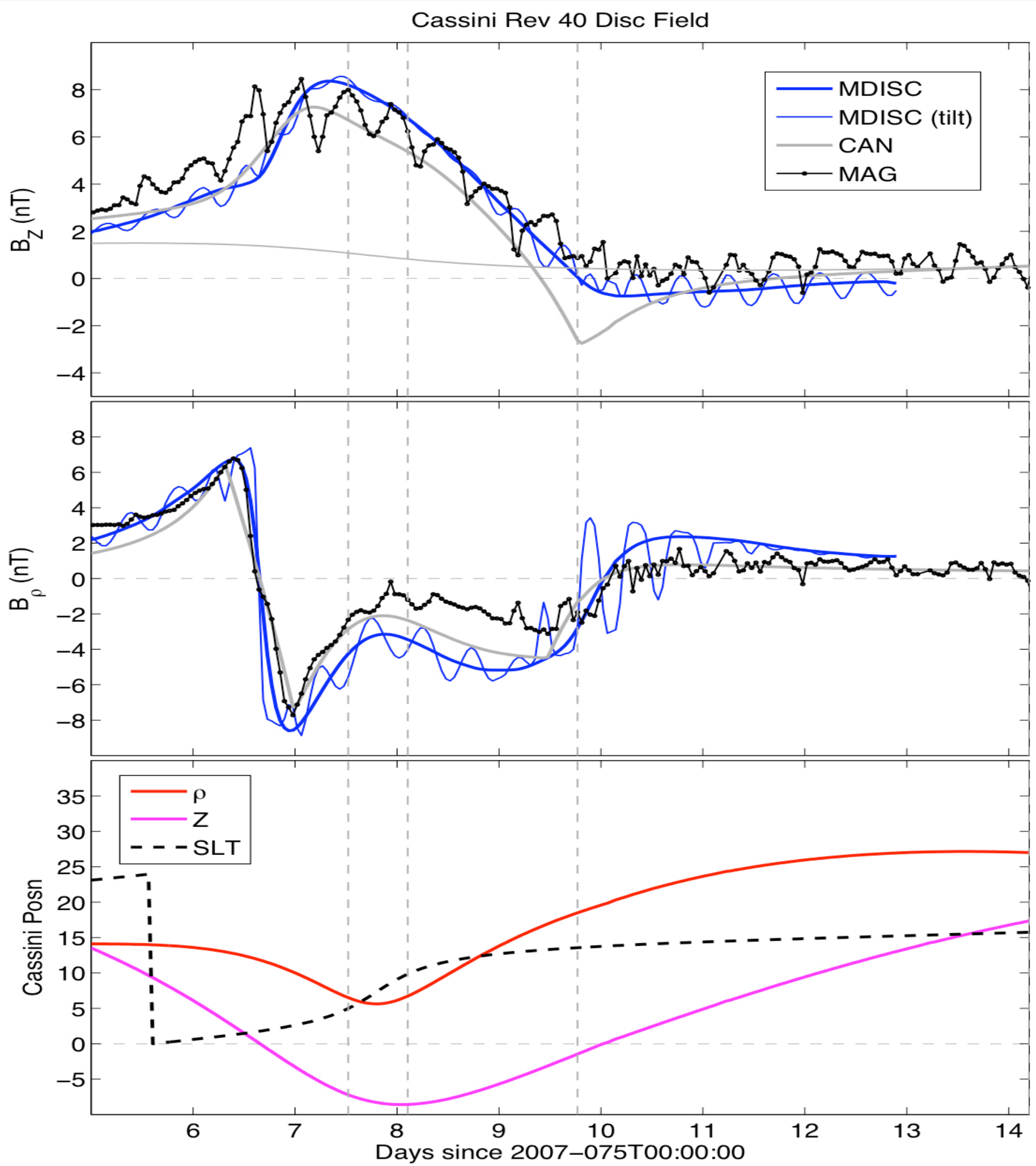
- Here *AGA* reproduce Caudal's original calculation for Jupiter and use it to explore force balance.

- For Jupiter, outer magnetosphere is mainly **curvature vs. hot plasma pressure.**

- The enormous Jovian system cannot sustain a large centrif force (plasma ω, density $\downarrow$ with distance)



Comparison with magnetometer data:



- *AGA* compared the field components predicted by the Saturn disc model with modified data from Cassini orbits (subtracted internal field of Saturn).
- For this orbit, two crossings of current disc.
- Both CAN and Caudal discs okay for 'large scale' features. Note edge effects.
- The quasi-periodic pulsations are *not* due to rotating tilted disc - 'camshaft signal'

Important Points

- Caudalian disc model gives us more insight into disc structure - it produces a self-consistent magnetic fields, currents and forces.

- The Cassini dataset continues to map Saturn's plasma environment, thus the model presented here will also evolve.

- Saturn outer disc structure is determined by a balance between curvature and centrifugal force - *but* the inner region where hot plasma is important may grow or diminish according to the hot plasma index (RC activity level).

- Jupiter outer disc structure is from curvature vs. *hot plasma pressure*.

- CAN and Caudal discs can be used to model the disc field. However for Saturn, the 'camshaft field' appears to require some sort of azimuthal asymmetry to be added - future work. *(e.g. Khurana et al, JGR, 2009).*

- Other future work includes investigating influence of hot plasma variability at Saturn (A. Koliopoulos) and coupling magnetodisc dynamics to UCL models of giant planet atmospheres (Japheth Yates).