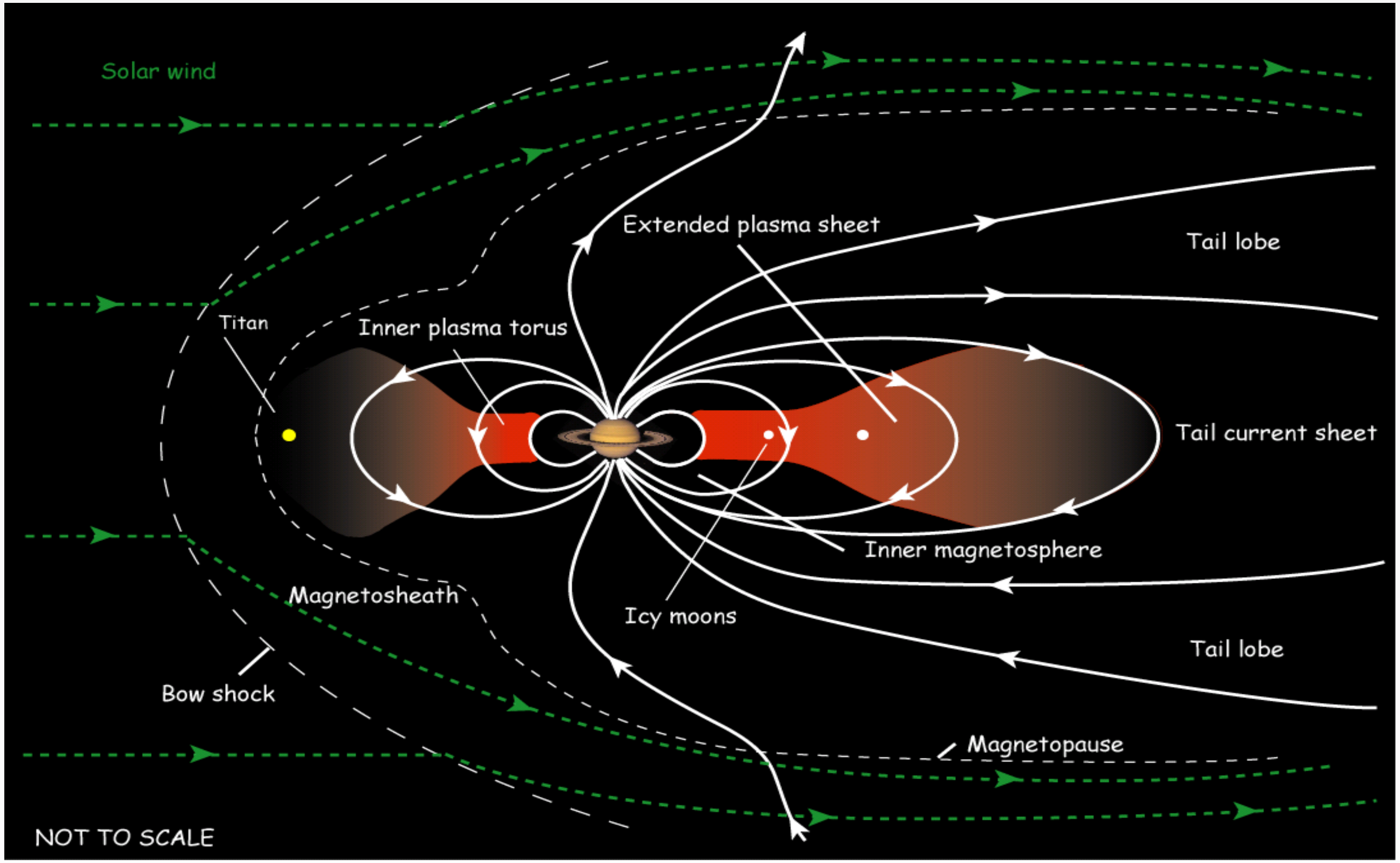
Seasonal Influence on Current Sheet Stucture at Saturn

Courtesy Emma Bunce (U. Leicester)

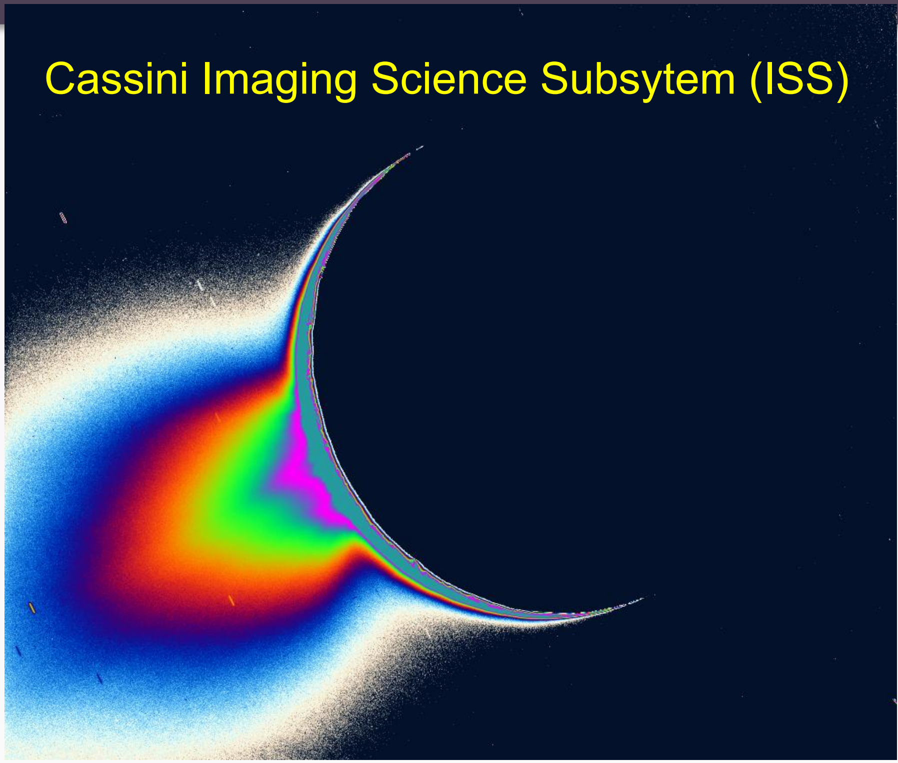


•**Magnetodiscs** are magnetised, rotating discs of plasma, 'fed' by sources such as Io (Jupiter) and Enceladus (Saturn).

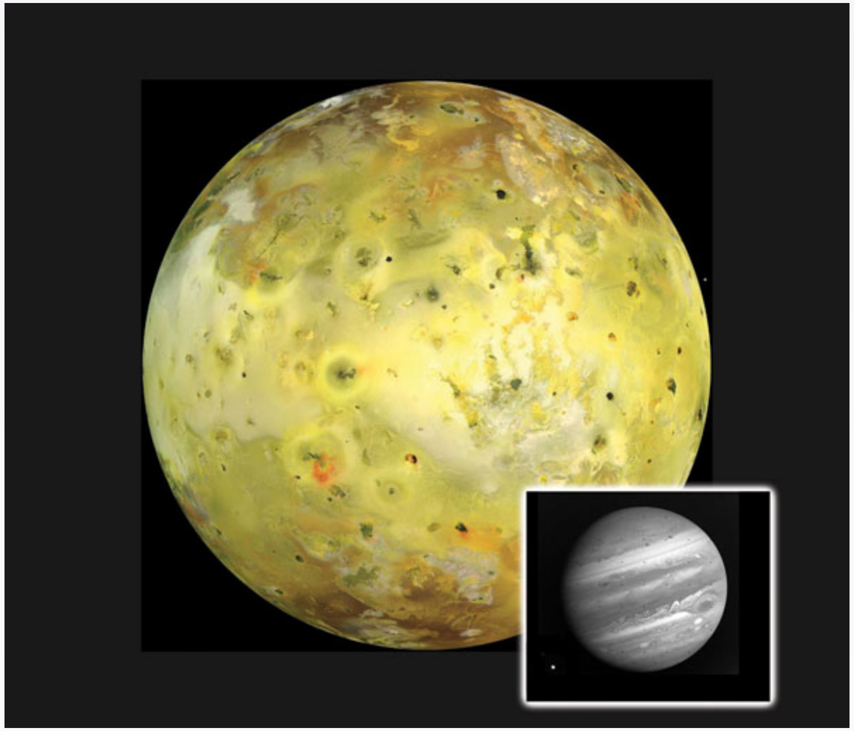
• For rapid rotation, centrifugal force confines plasma towards the equatorial plane.

- Aspects of magnetosphere-solar wind interaction.
- Current sheet shape.
- Response to solar wind *direction* with respect to planetary magnetic field.
- **Many of the concepts here will be expanded upon in 'Planetary Magnetospheres'**

Internal Mass Sources for the Disc: Moons



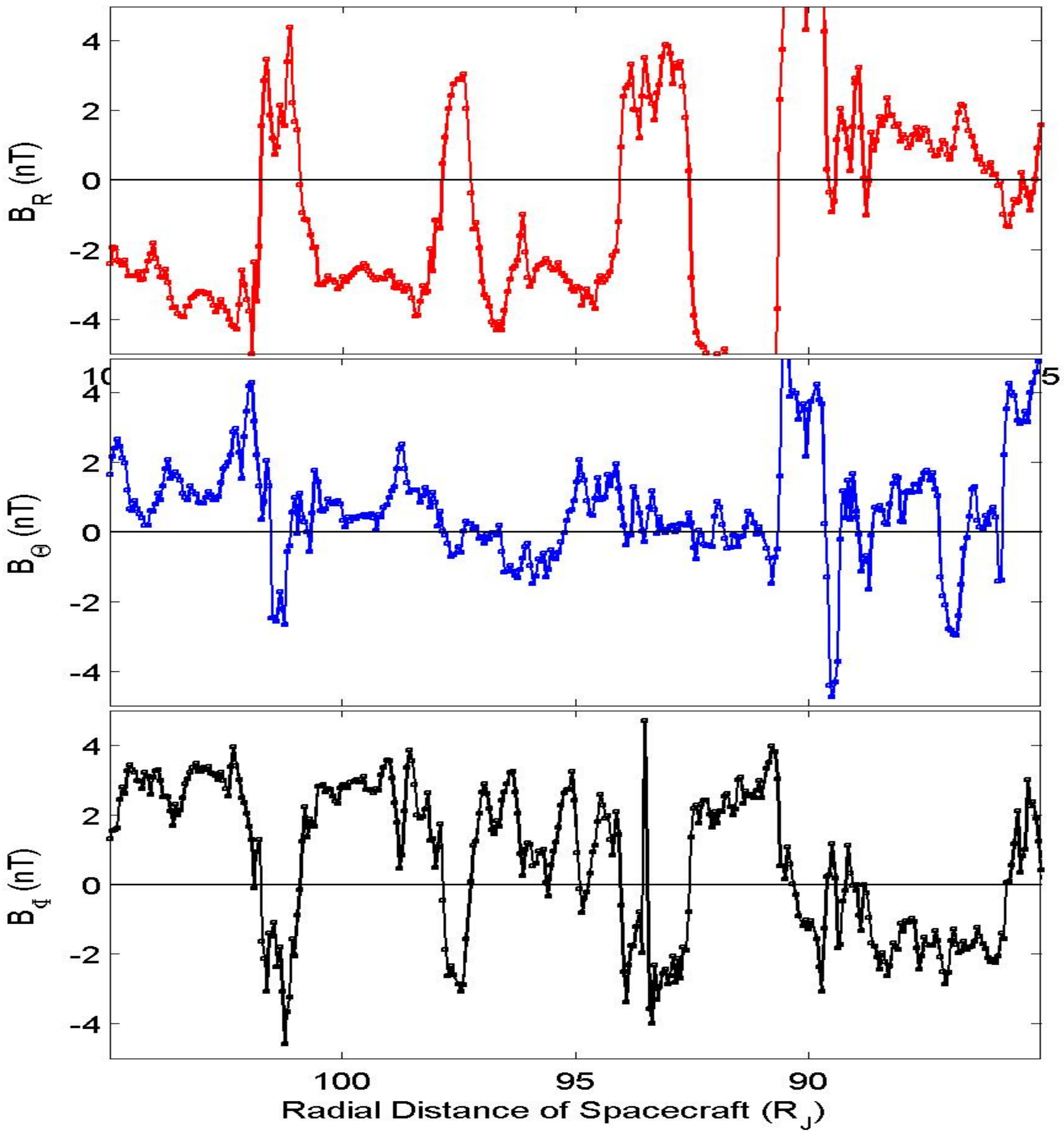
Enceladus (icy satellite): Mass source for Saturn's E ring, magnetosphere (~10-100 kg/s of plasma) **First discovered by MAG** *(Dougherty et al, Science, 2006)*



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:
Jupiter as example

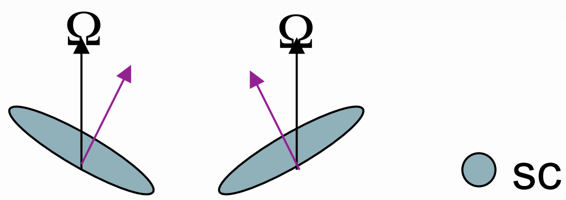


- **Galileo** insertion orbit at Jupiter - an equatorial pass

- Notable 'square waves' in radial and azimuthal field, in *antiphase*, with *sign* change, 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:
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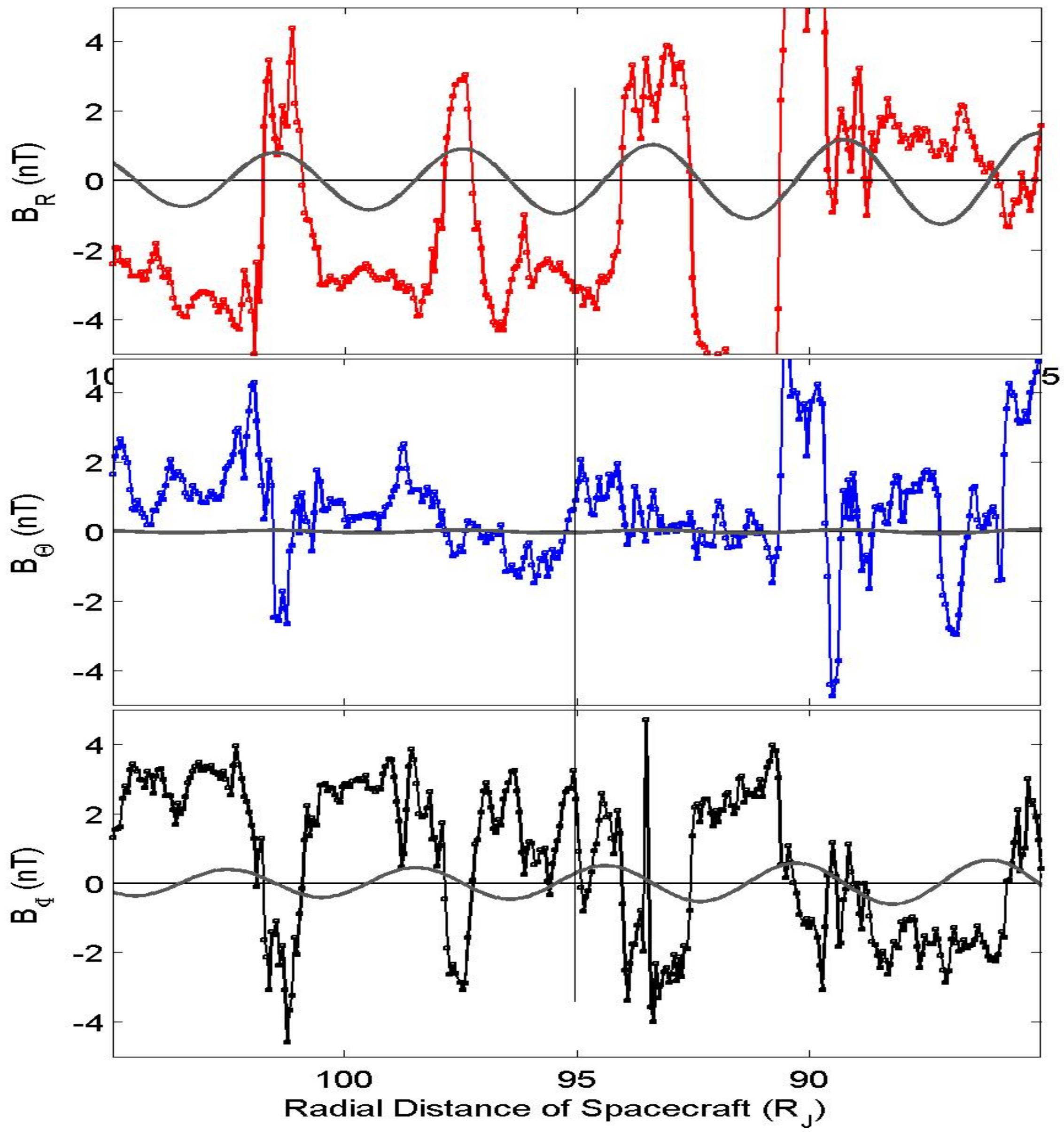


- **Here** we see the field predicted by only the rotating planetary dipole of Jupiter.

- 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

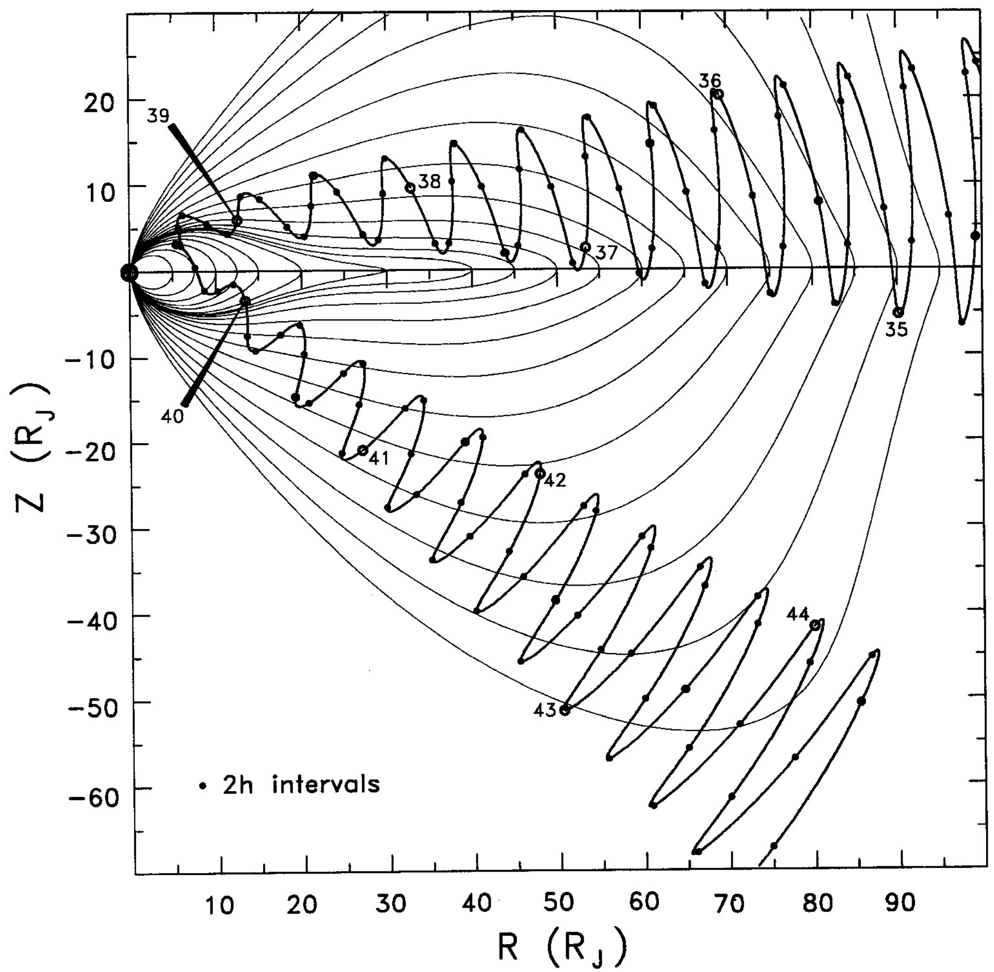
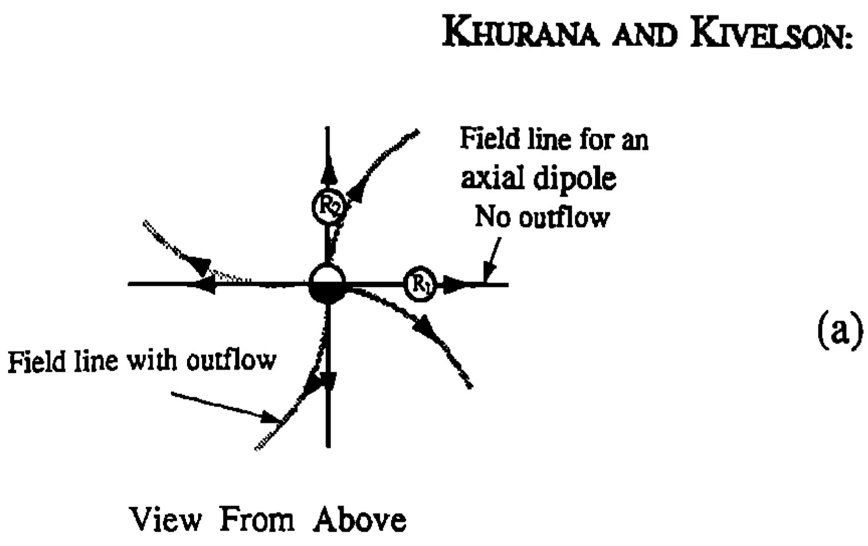


Figure 1. Trajectory of the Ulysses-Jupiter encounter in magnetic coordinates, superimposed on model magnetic field lines. The vertical (Z) axis is the distance (in R_J) along the magnetic dipole axis, while the horizontal (R) axis is the perpendicular distance from the dipole axis. The field model used 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.
- Current contribution from *differential particle drifts*.

The azimuthal field - why nature is more complicated



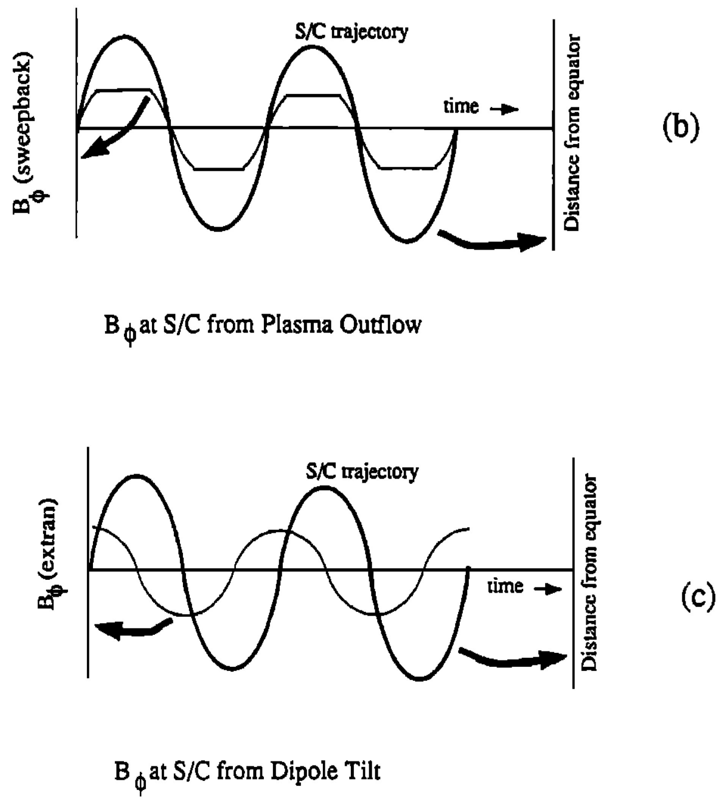
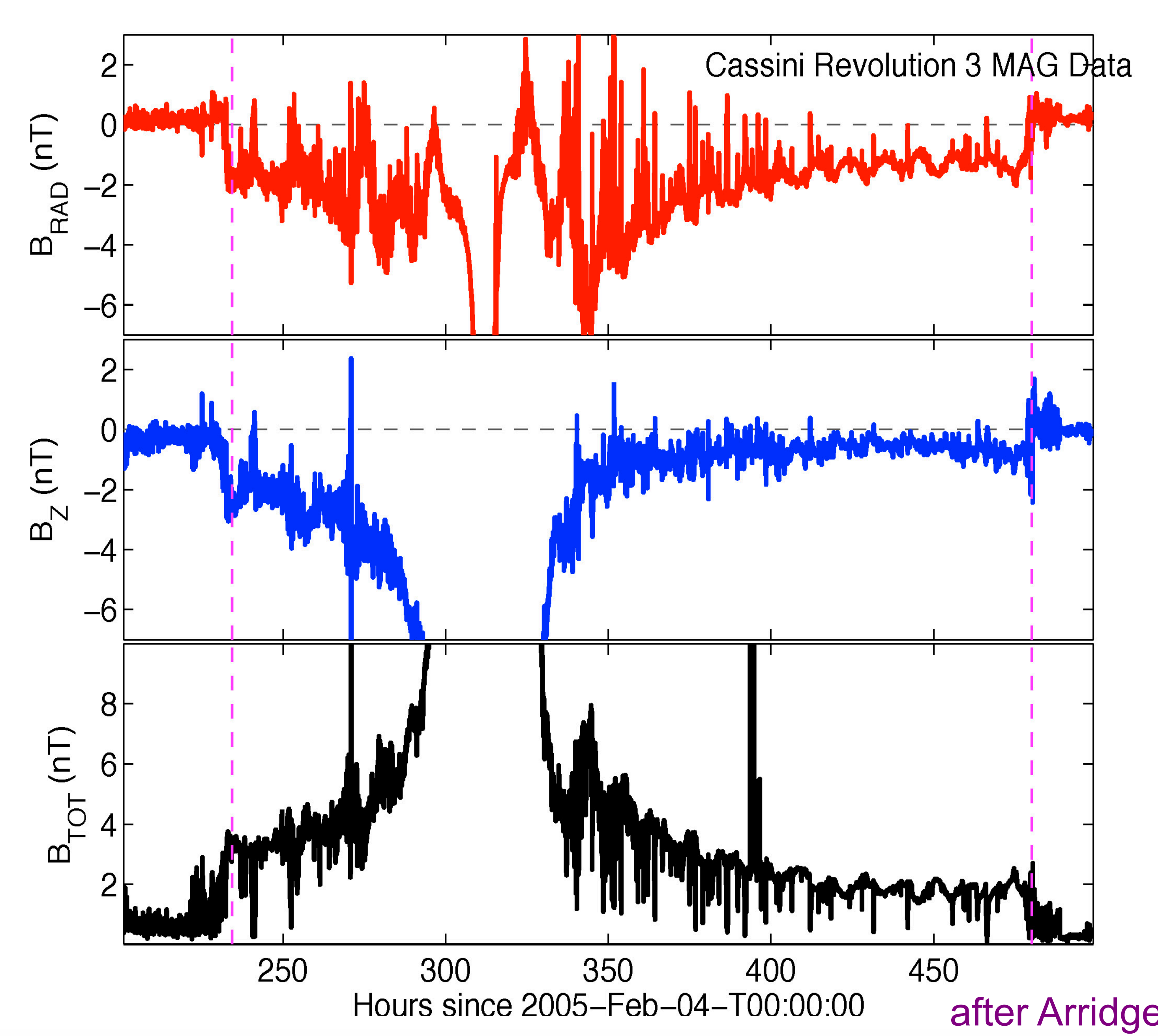


Fig. 2*a* Field lines of Jupiter in the absence of a plasma outflow (solid lines) and when a substantial plasma outflow is present (shaded lines). The view is from above the ecliptic plane. (*b*) The azimuthal component of the magnetic field generated at the S/C location by the radial currents induced by the outflowing plasma and the distance of an inertial S/C from the plasma sheet measured normal to it. (*c*) The azimuthal magnetic field resulting from the representation of the internal field of Jupiter and the field of its plasma sheet in the system III coordinates. Also plotted is the trajectory of the spacecraft with respect to the plasma sheet.

- **From Khurana and Kivelson (JGR, 1993)** the observed phase relations between Br and Bphi *require* the *true 'bendback'* of field lines out of a single plane, thought to be associated with plasma outflow from Io torus.

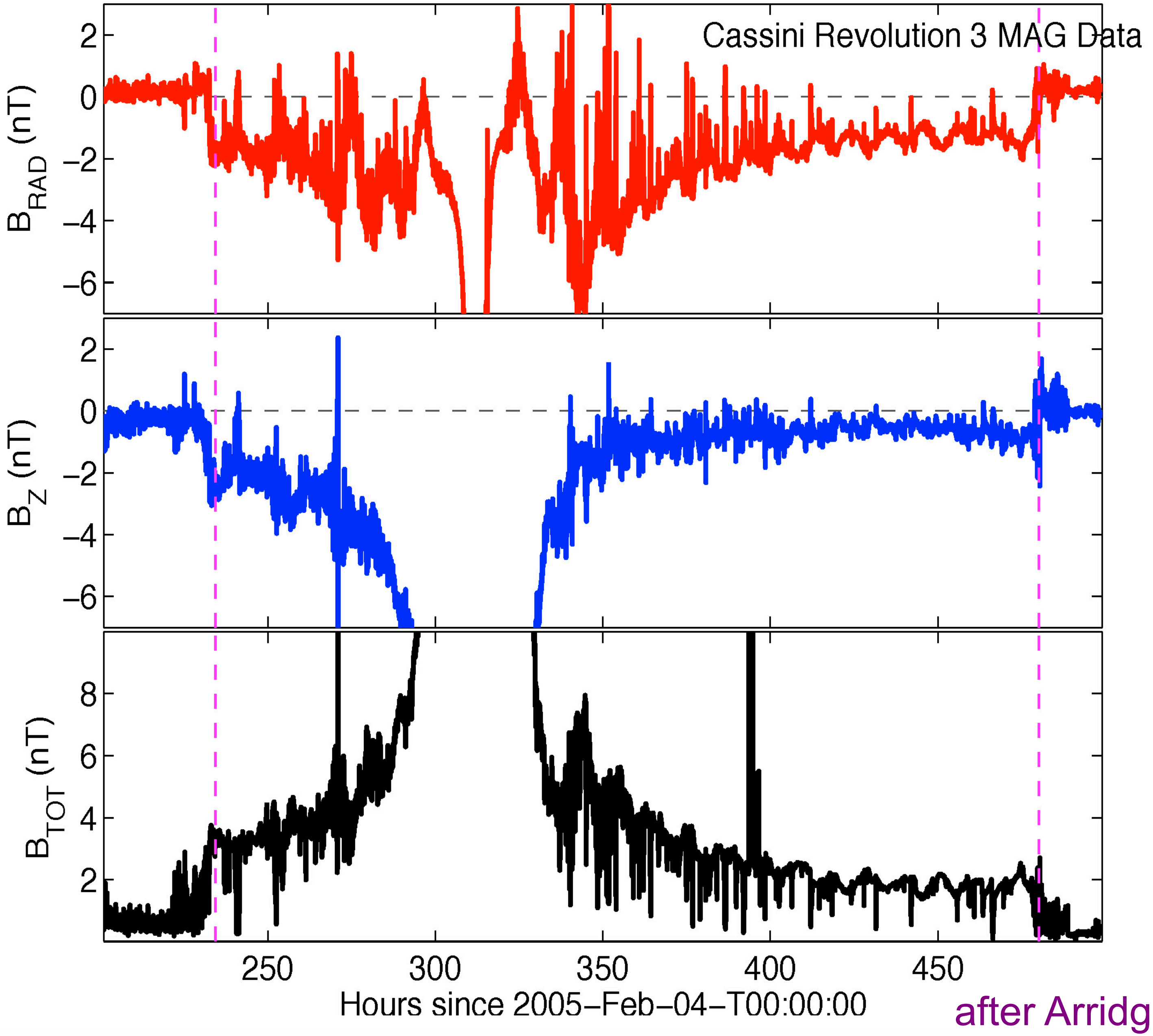
A Look at Saturn: Cassini Observation of 'Magnetodisc'



- Here we see field measurements from an early, *equatorial* Cassini orbit.
- The radial field is mostly non-zero, and in outer magnetosphere, *exceeds* the Z ('north-south') component.
- **Q: What does this imply about current sheet location ?**

after Arridge et al (GRL, 2007)

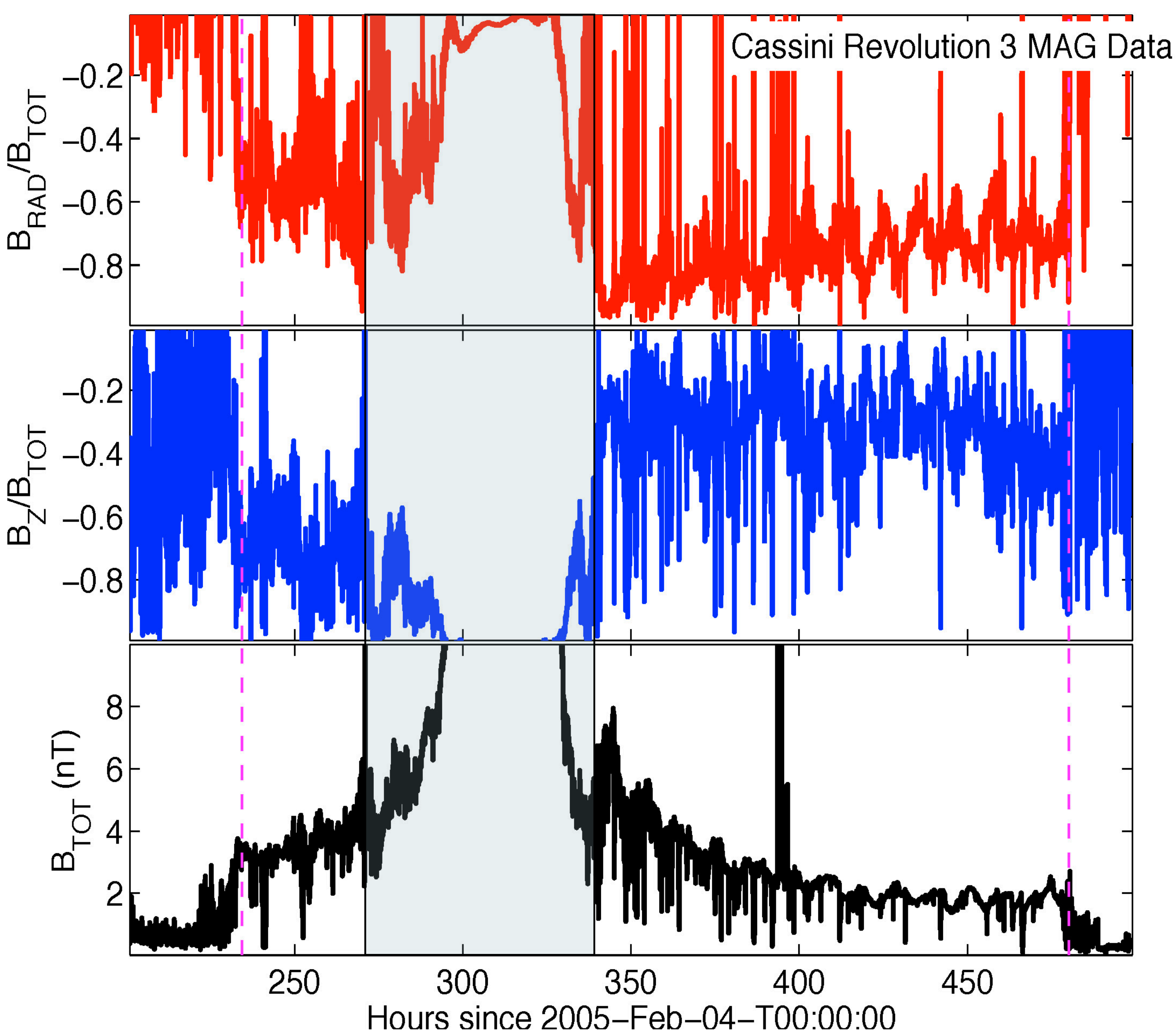
A Look at Saturn: Cassini Observation of 'Magnetodisc'



- Here we see field measurements from an early, *equatorial* Cassini orbit.
- The radial field is mostly non-zero, and in outer magnetosphere, *exceeds* the Z ('north-south') component.
- **Implies that the magneto-disc is *not* symmetric about equator.**

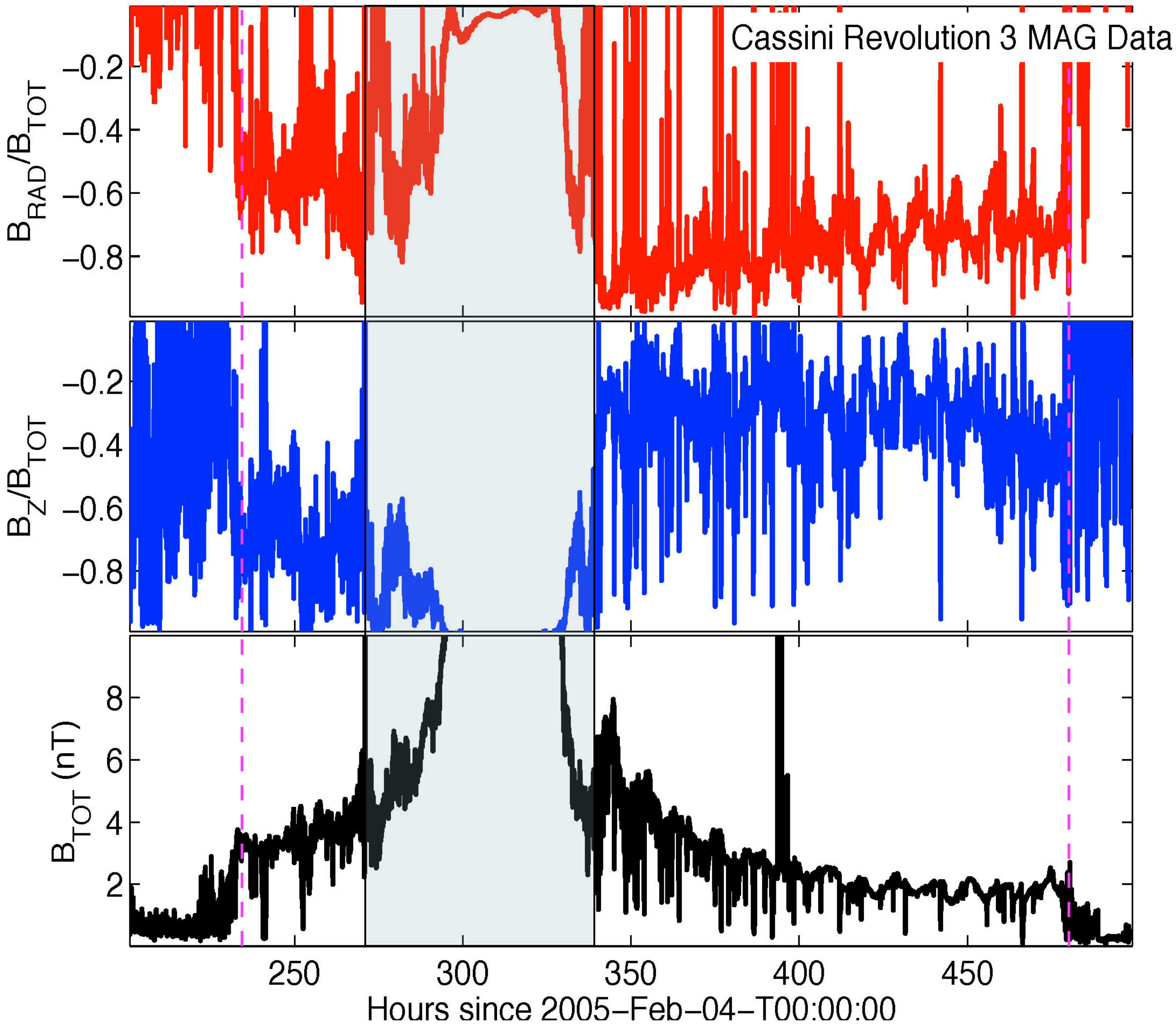
after Arridge et al (GRL, 2007)

Cassini Observation of Saturn ‘Magnetodisc’ Configuration



- Here we see field components expressed as fraction of the total field strength.
- We see a clear separation (around ~15 RS) between a ‘quasidipolar’ (shaded) and ‘current sheet’ region.
- We also see field ‘dropouts’ (‘flapping’) and a ~10.7-hour ‘oscillation’ (‘rotational anomaly’ / ‘camshaft’).

Cassini Observation of Saturn 'Magnetodisc' Configuration

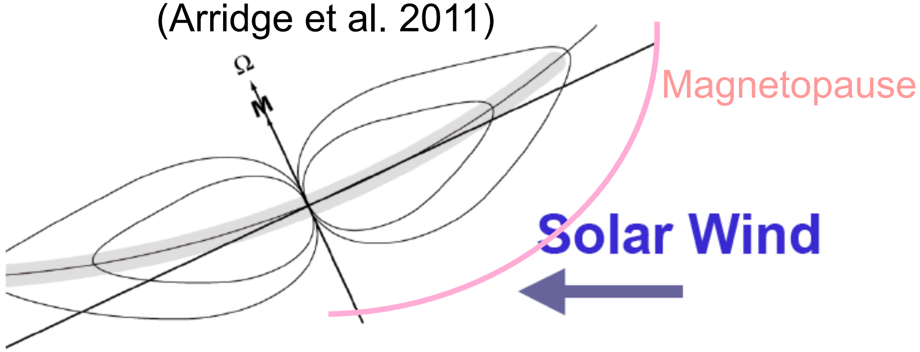


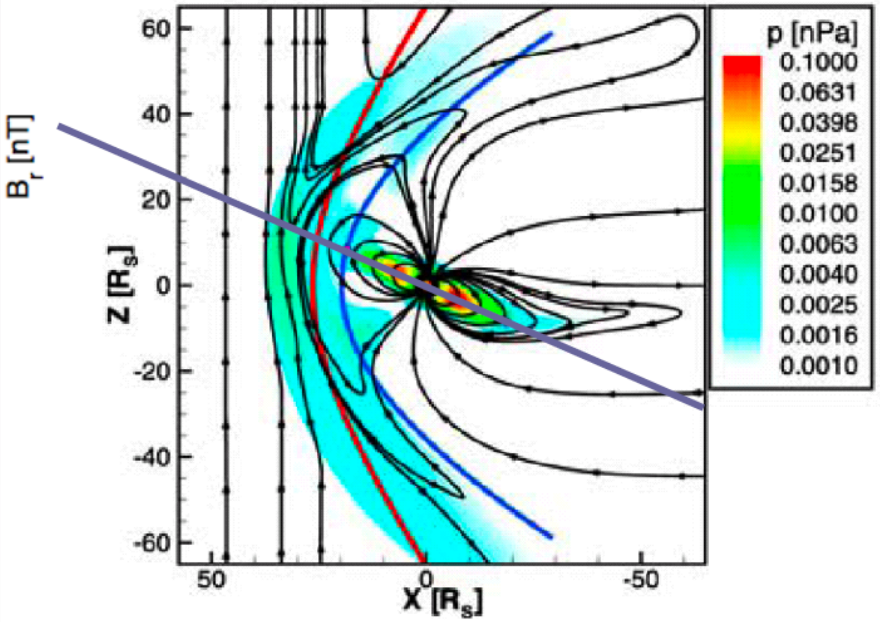
- **Note that the 'periodic' excursions towards and away from the sheet at Saturn are unusual.**

- The planet's internal dipole axis has an angle <~ 1 deg from rotation axis.

- 'Period' is subject of much research - is actually *two drifting* periods, each dominant in different hemispheres, due to rotating *current systems*.

A Bowl-Shaped 'Magnetodisc' Configuration

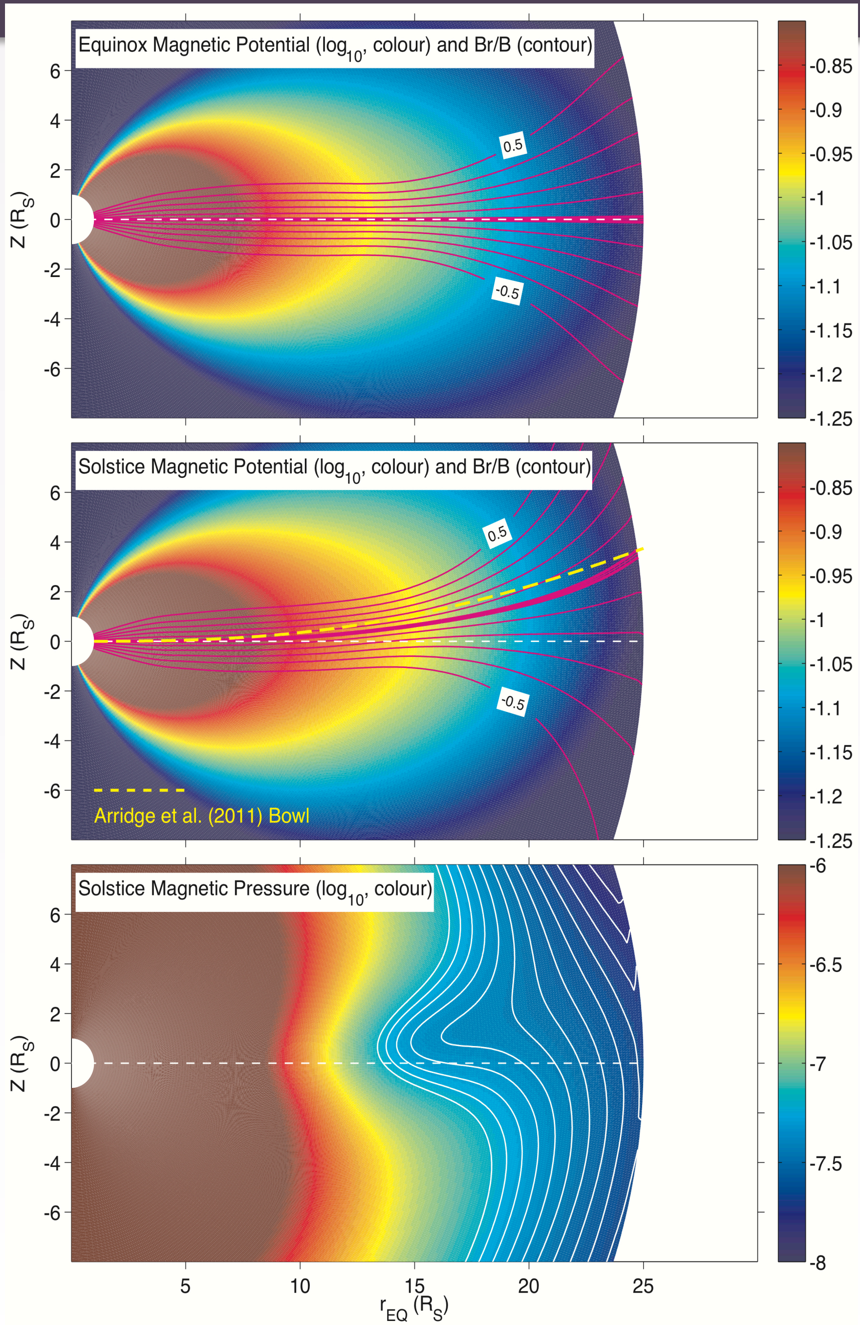




[Hansen et al. 2005]

- **Why are we 'under' the sheet at locations so close to the equator ?** Saturn's N mag. pole at the time was oriented at an angle ~70 degrees from upstream SW direction.
- Equivalent angle for Jupiter varies ~symmetrically according to *rotation* period - for Saturn variation is significant over *orbital* period.
- Saturn – leads to a 'transmitted' asymmetry in magnetic pressure on the top and bottom of the sheet.
- Saturn sheet adopts a 'bowl' shape to maintain *force balance*.

‘Magnetodisc’ Models based on Force Balance



- Achilleos et al (A10: MNRAS, 2010) adapted a model for the Jovian system by Caudal (1986) in order to model Saturn’s magnetic field and plasma distribution.

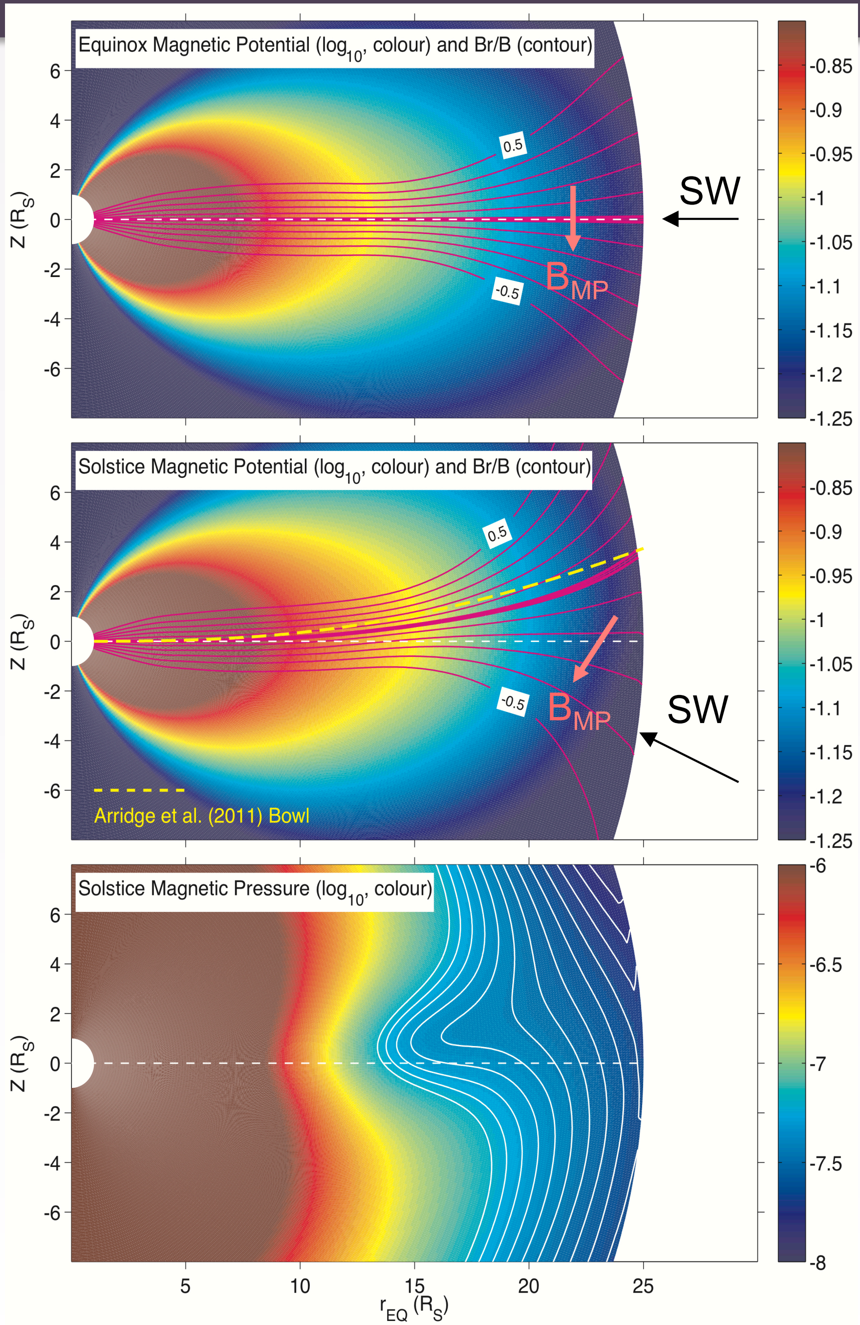
- Assumes a balance between plasma pressure gradient, magnetic (‘JxB’) force, and centrifugal force.

- Top panel: A north-south symmetric disc model, of the type considered by A10 - for equinox conditions. The ‘perturbation field’ from magnetopause is assumed uniform and points southward.

- Middle panel: ‘Solstice’ disc for solar wind direction 25 deg. South latitude (Cassini prime mission). Now a uniform, tilted perturbation field represents the magneto-pause.

- Bottom panel: Contours of constant magnetic pressure. The current sheet centre follows local minima.

‘Magnetodisc’ Models based on Force Balance



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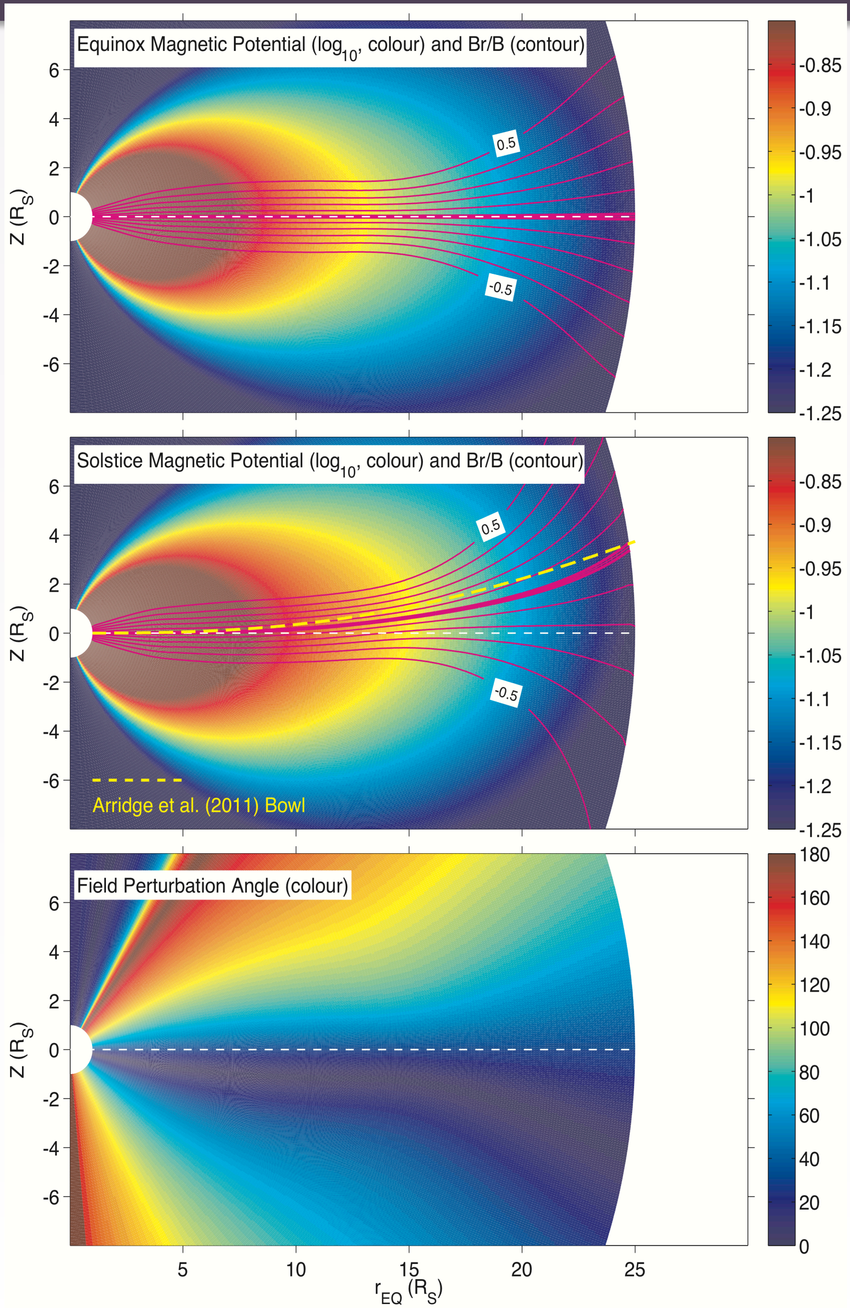
- Top panel: A north-south symmetric disc model, of the type considered by A10 - for equinox conditions. The ‘perturbation field’ from magnetopause is assumed uniform and points southward. Magnetic ‘JxB’ force on MP current layer ‘holds off’ solar wind flow.

- Middle panel: ‘Solstice’ disc for solar wind direction 25 deg. South latitude (Cassini prime mission). Now a uniform, tilted perturbation field represents the magnetopause.

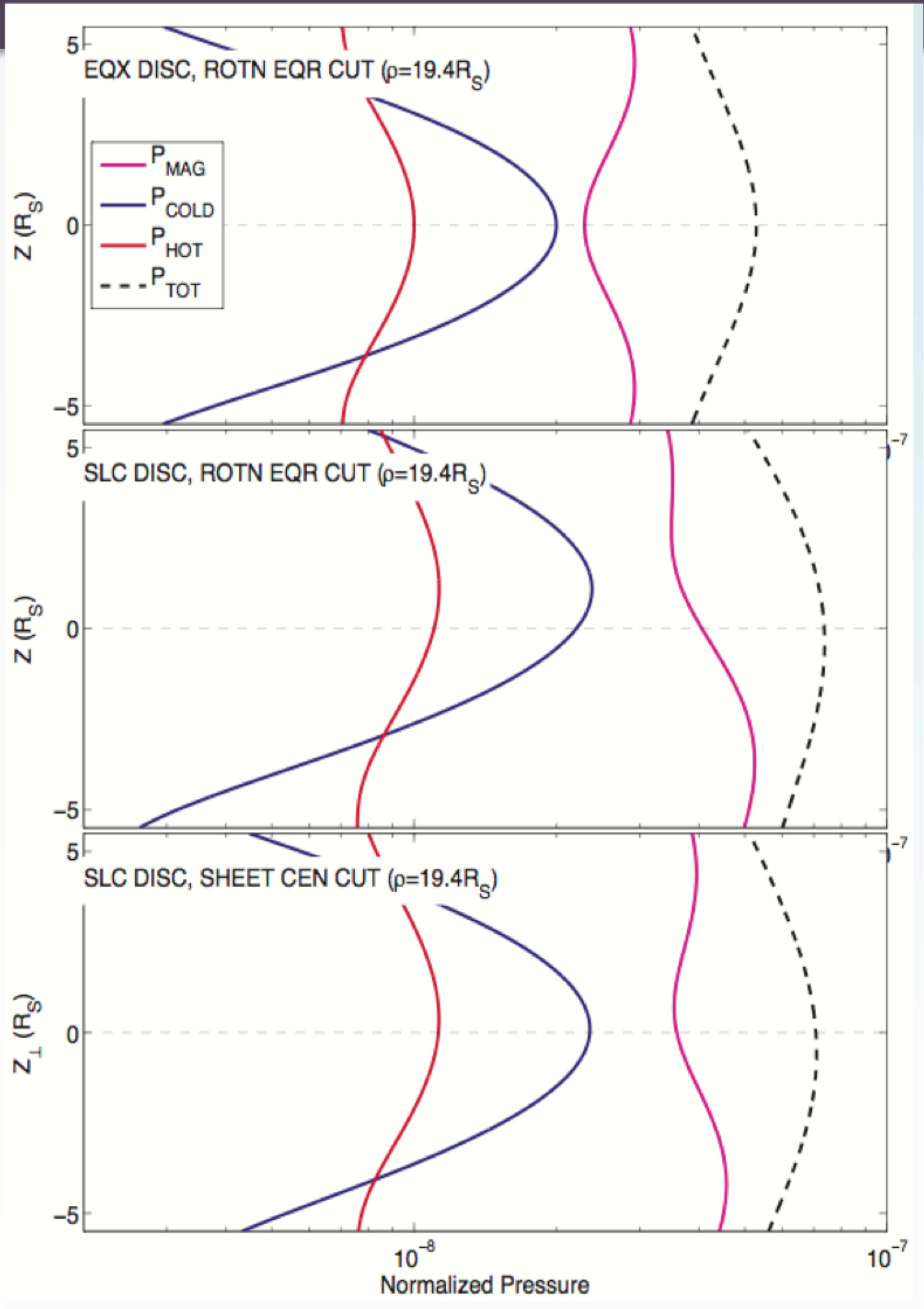
- Bottom panel: Contours of constant magnetic pressure. The current sheet centre follows local minima.

‘Magnetodisc’ Models based on Force Balance



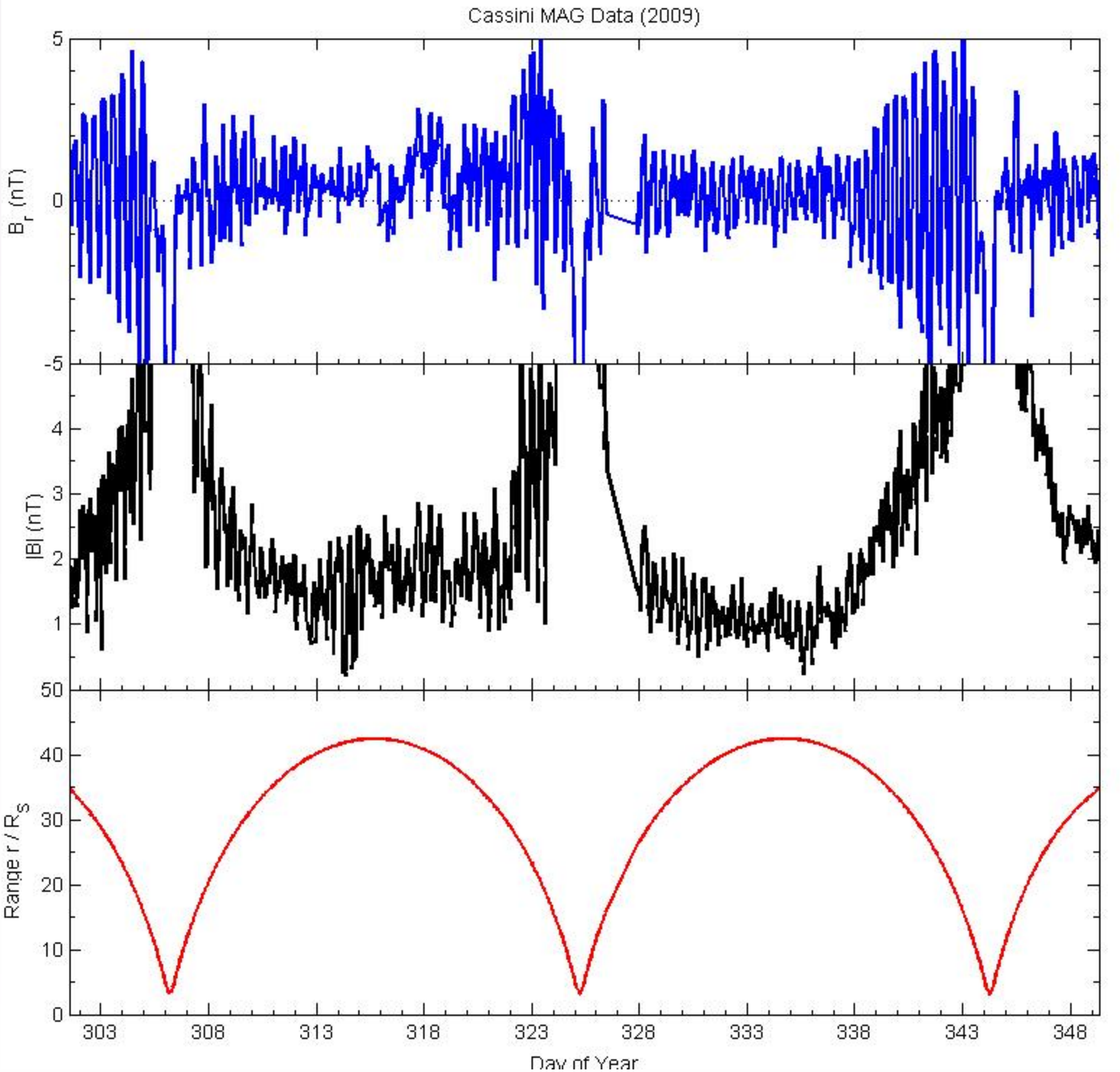
- Bottom panel now shows a ‘perturbation angle’ between the MP field associated with solstice solar wind, and the ‘equinox’ magnetodisc field.
- In the south, this angle is small: magnetic field and magnetic pressure are enhanced.
- In the north, at similar latitudes, the angle is near 90 deg, and the field perturbation is more ‘rotation’ than ‘compression’.
- Thus an equinox disc in the presence of a solstice solar wind is not in force balance, and must ‘bend’ away from the rotation equator to equalize pressures above and below the current sheet.

Profiles for Pressure



- Top: Vertical profiles of pressure at a fixed cylindrical radial distance - equinox disc.
- Middle: Profiles in Z for the solstice ‘disc’ - as expected, the symmetry is lost.
- Bottom: Profiles defined by the direction locally orthogonal to the central current sheet. Appropriate choice of coordinates ‘retrieves’ the symmetry in the profiles.

Equinox at Saturn: *Cassini* MAG Data



- During late Oct – early Dec, *Cassini* was close to rotational equator.
- 2009 was ‘equinox year’ – this period had dipole-SW angle <2 deg from orthogonal.
- Note the very different appearance of the radial field component – oscillations with change in sign are clearly seen, indicating regular crossings of the current sheet.

Summary

- The **current sheet** is an important magnetospheric region – it is a structure which plays a central role in plasma transport and loss.

- Current sheet structure is influenced by the balance of *forces* in a rapidly rotating magnetosphere. Centrifugal force imposes near-equatorial confinement of 'cold' plasma.

- Sheet structure is also affected by the nature of the *external* forces represented by the dynamic pressure of the *solar wind*.

- Information about solar wind 'attack angle' is 'transmitted' into the magnetosphere by the 'fringing field' associated with *magnetopause currents*.

- At Saturn, the magnetodisc has distinct configurations as a function of planetary season – 'bowl' for solstice, 'planar disc' for equinox.

- Similar effect at Earth described by *Tsyganenko (Ann. Geo. 2015)*