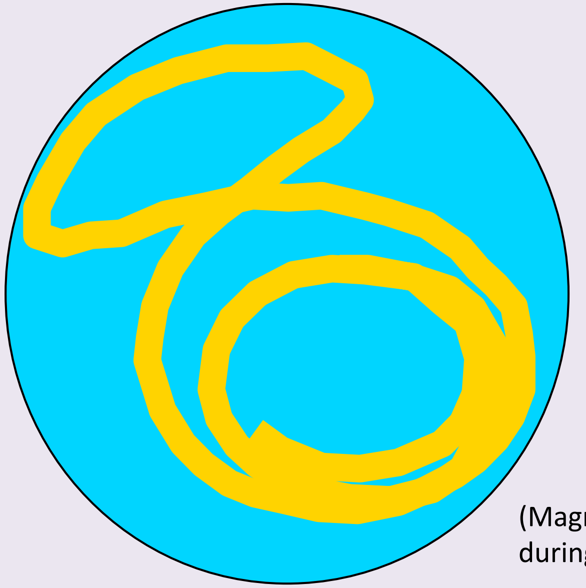


(Magnetic footprint of *Cassini* during Saturn Orbit Insertion)

Cassini Magnetometer Observations: *An Overview*

N. Achilleos / M. K. Dougherty

(Acknowledgement: Cassini MAG team and collaborators from MAPS community and elsewhere)

In interests of time, focus on three examples of ‘strands’ of work in which *Cassini* MAG measurements have played a prominent role:

- Internal magnetic field of Saturn.
- External ‘signals’ or ‘perturbations’ in the magnetic field.
- The Titan-Saturn interaction.

Examples of Internal Field Models

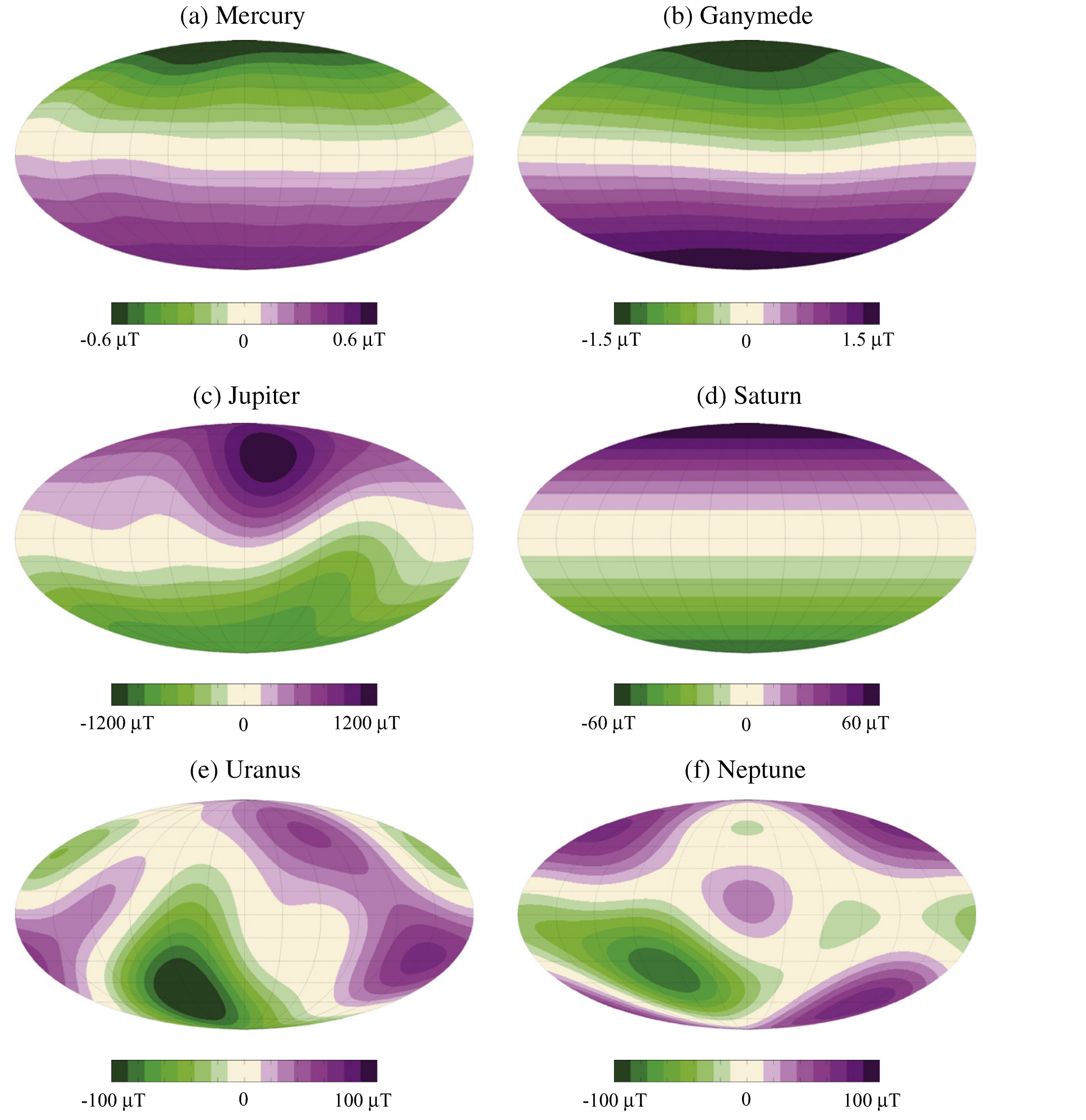
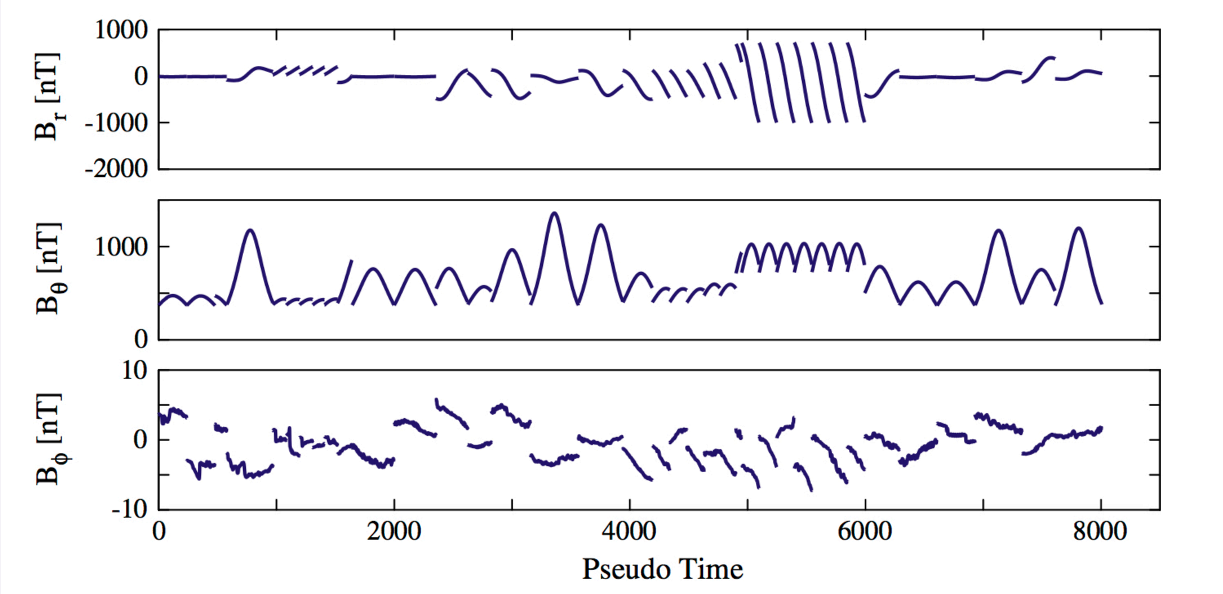


Fig. 2. Radial magnetic field at the surfaces of (a) Mercury, (b) Ganymede, (c) Jupiter, (d) Saturn, (e) Uranus, and (f) Neptune. Data taken from Uno et al. (2009) for Mercury (with spectral resolution $l, m \leqslant 3$), Kivelson et al. (2002) for Ganymede ($l, m \leqslant 2$), Yu et al. (2010) for Jupiter ($l, m \leqslant 3$), Burton et al. (2009) for Saturn ($l, m \leqslant 3$), and Holme and Bloxham (1996) for the ice giants ($l, m \leqslant 3$).

- From overview by *Schubert and Soderlund* (2011).
- Modelling tries to capture the external (curl-free) magnetic signature of the internal (dynamo) field.
- Models shown here use spherical harmonics with *l*, *m* <= 3. Saturn model from *Burton et al.* (2009) is zonal – don't know the accurate rotation period.
- Compare Jupiter and Saturn – different dipole tilt w.r.t. planet rotn axis.

Properties of the Internal Field



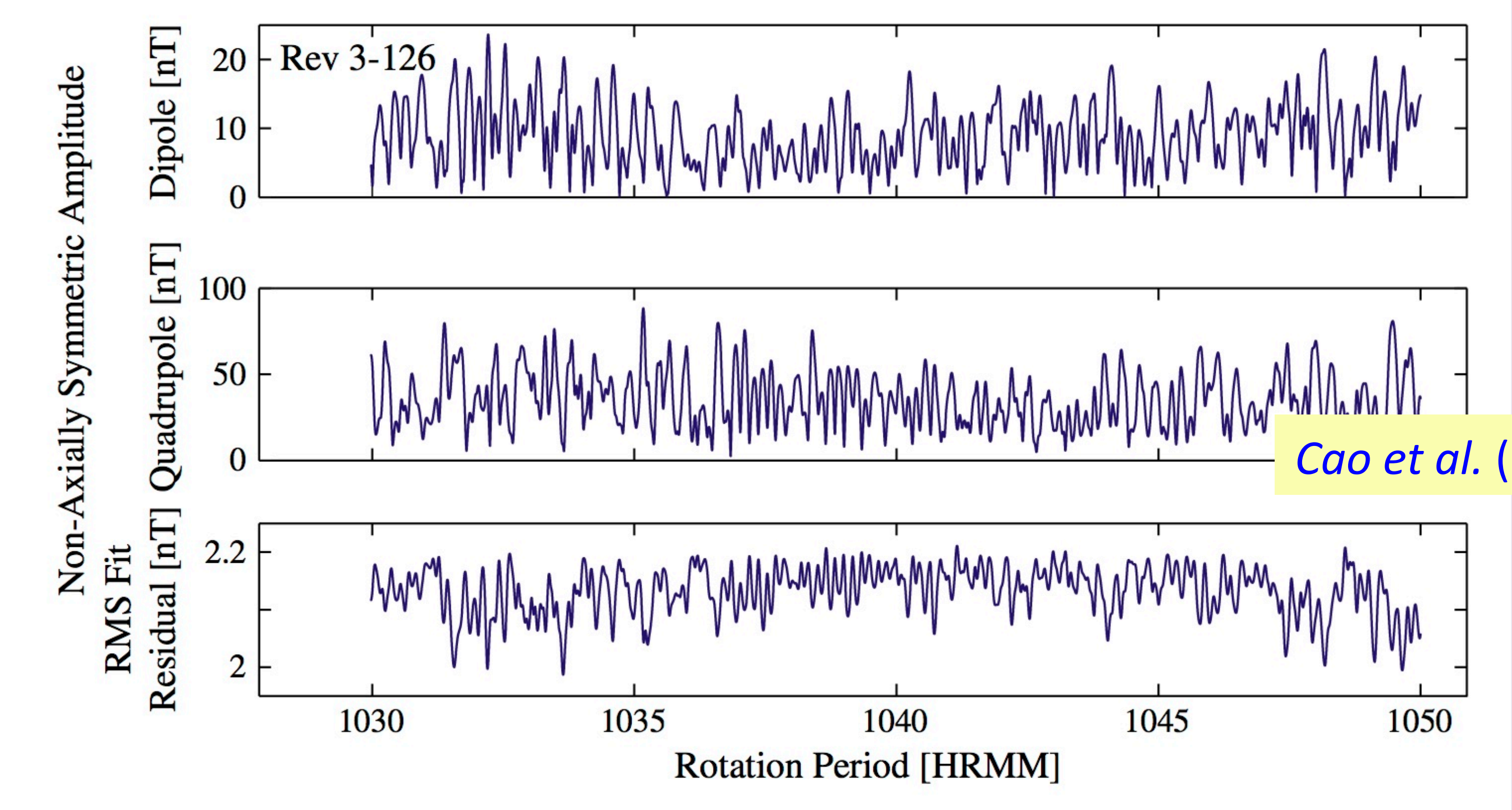
- From *Cao et al.* (2011): Field components from *Rev 3-126 (2005-10)* limited to *L < 3.8 RS* to avoid FACs.
- Bϕ << Br, Bθ

- Result of fitting a zonal model.
- *l*=4,5 terms not 'resolvable'
- Comparison with e.g. *SPV* model gives dipole varn of ~1.2+/-1.6 nT/yr – c.f. terrestrial 19.6 nT/yr for ~C20/21

Coefficients of axisymmetric models for Saturn based on Cassini observations inside L = 3.8 Rs from Rev 3 to Rev 126. The SPV model (Davis and Smith, 1990) based on Pioneer 11, Voyager 1 and 2 measurements and the Z3 model (Connerney and Acuna, 1982) based on Voyager 1 and 2 measurements are also presented here for comparison. All values are in units of nT (nanotesla). One Saturn radius is 60,268 km in all three models.

Coefficients	Cassini (Rev 3–126)	SPV	Z3
g_1^0	$21{,}191 \pm 24$	21,225	21,248
g_2^0	1586 ± 7	1566	1613
g_3^0	2374 ± 47	2332	2683
$(g_4^0)^*$	(-70 ± 243)		
$(g_5^0)^*$	(-148 ± 1070)		
G_1^0	-13 ± 1		
RMS	2.2		

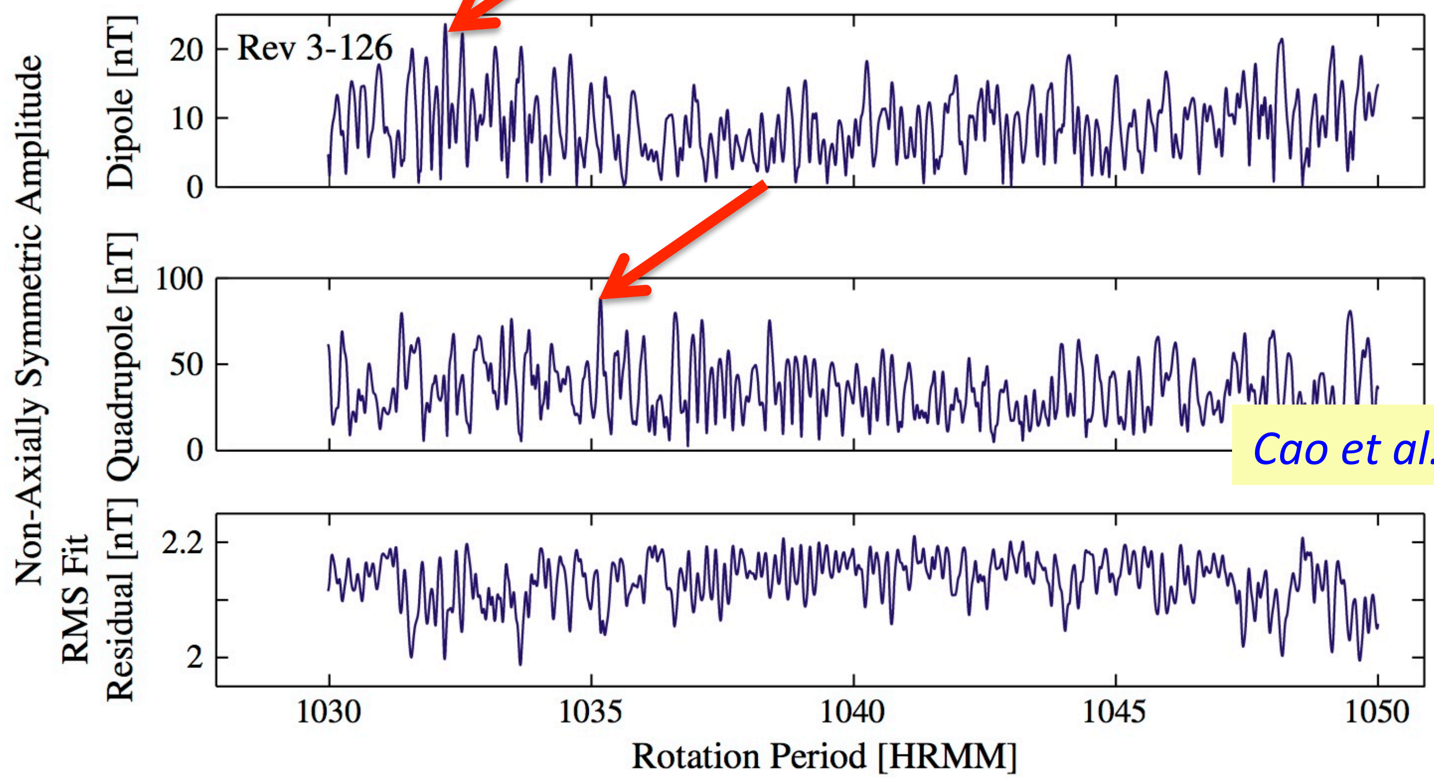
Non-Axisymmetric Components of the Field?



Cao et al. (2011):

- Treat rotation period as a free parameter in the model, constraining range based on atmospheric studies: 10h30m – 10h50m
- Check resulting non-axisymm dipole, quadrupole amplitude, and fit residuals.

Non-Axisymmetric Components of the Field?



Cao et al. (2011):

- Note that 'maxima' for dipole and quadrupole do *not* coincide at same P_{ROT}, and any improvement in fit is of order ~0.2 nT, similar to the 'noise' in the data for this field range.
- An estimated dipole tilt for the 'maximum dipole power' fit would be just ~0.06 degrees.
- *So why does the field show such a high degree of axial symmetry and such a weak secular variation?*

Imposing symmetry on the dynamo field

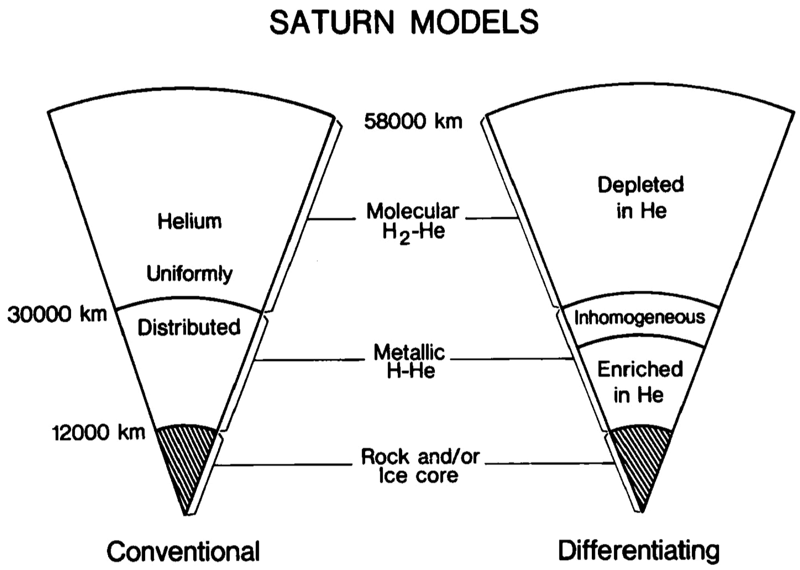


FIGURE 3 Schematic representation of Saturn models (dimensions only approximate). The "conventional" model on the left does not explain Saturn's heat output or magnetic field. The differentiating model has an intermediate, inhomogeneous layer in which helium raindrops form. Differential rotation in this layer tends to axisymmetrize the external field.

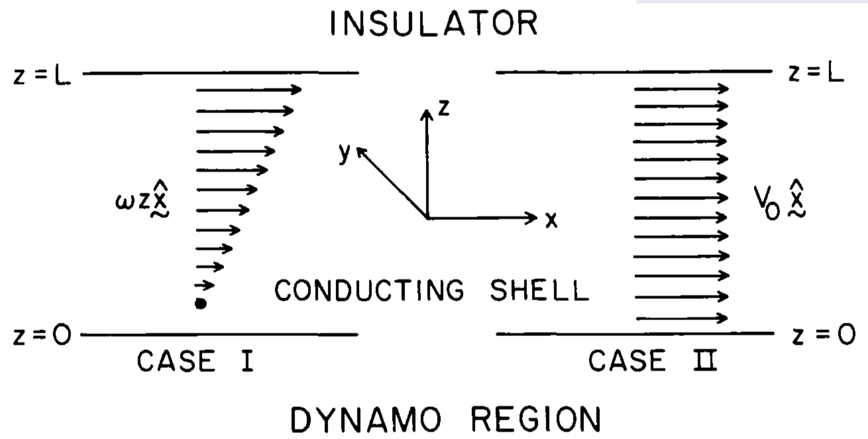


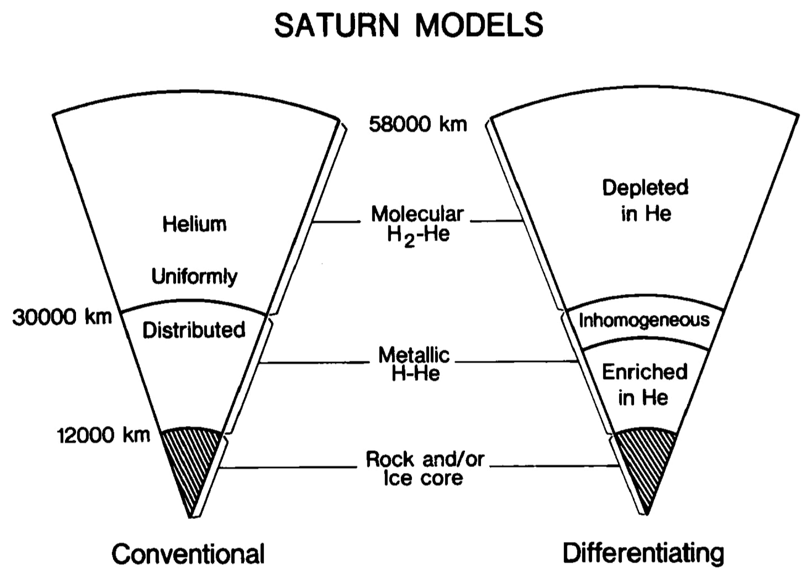
FIGURE 1 Schematic representation of geometry and flow fields of the two models. In each case, the flow fields are relative to the rotation state defined by the spin-axisymmetric components of the magnetic field. (The flow state of the insulating region above is irrelevant.)

- ***Stevenson* (1982)**: attenuation of rotating, non-axisymmetric field components by a stable, stratified layer, related to 'helium rain'. Similar to the 'skin effect' from EM.

- Damping of the non-axisymm. field depends on a parameter which involves the *thickness* of the layer, and *ratio of timescales* of field 'diffusion' and differential rotation in the layer.

- Numerical dynamo calculations seem to confirm that this is plausible (e.g. *Stanley 2010*).

Imposing symmetry on the dynamo field



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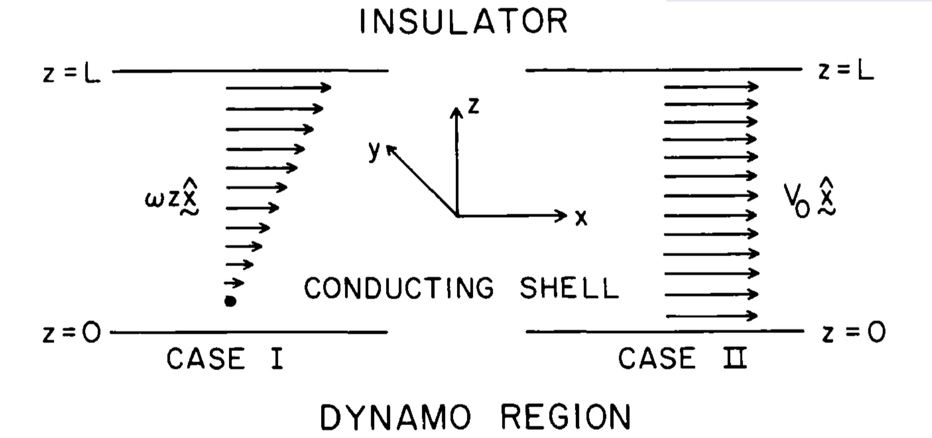
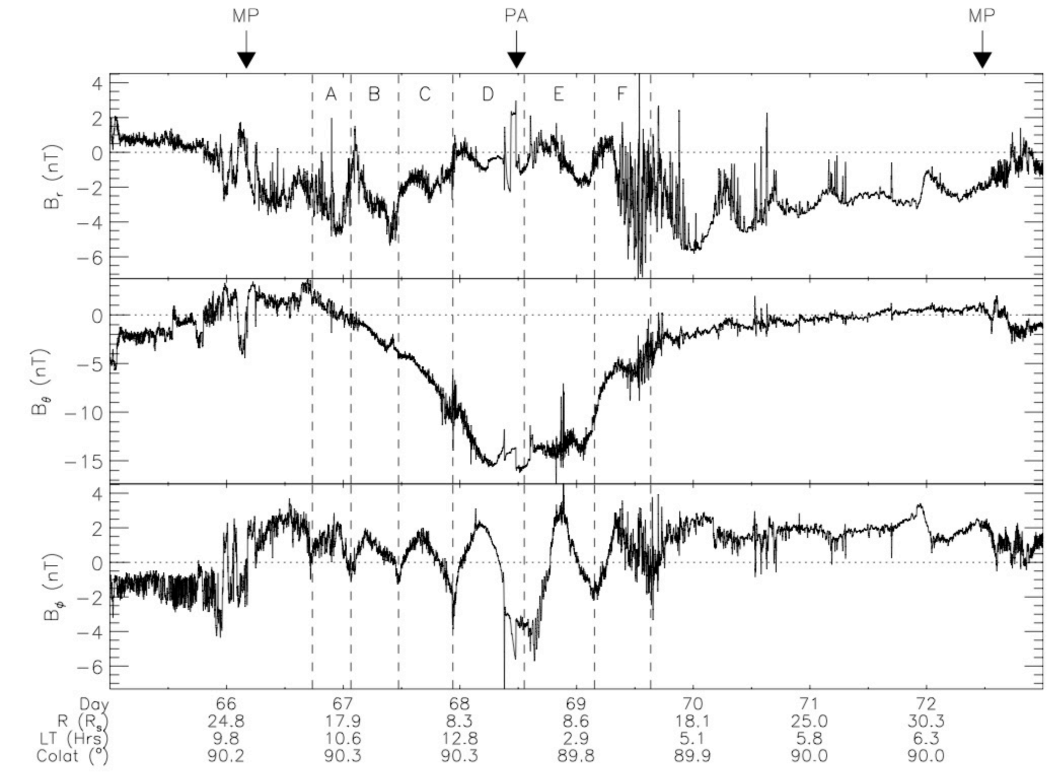


FIGURE 1 Schematic representation of geometry and flow fields of the two models. In each case, the flow fields are relative to the rotation state defined by the spin-axisymmetric components of the magnetic field. (The flow state of the insulating region above is irrelevant.)

- N.B. role of a 'spherical Couette' dynamo in generating an axisymmetric field with 'Saturn-like' interior flux concentrated near poles, as well as slow secular variation in field (*Cao et al. 2012)*

(Near-)PPOs: External quasi-periodic 'signals'



(Cowley et al. GRL 2006 – Cassini Rev 4, 2005)

- *Espinosa et al* (2003) analysed a periodic magnetic signal in *Voyager* data – 'camshaft' disturbance or wave whose phase fronts rotate with planet.
- Not a rotating tilted dipole (see also e.g. *Giampieri et al.* 2006 for *Cassini*)
- Data from *Cassini* confirmed this persistent field modulation at *non-fixed* period, very similar to SKR (e.g. *Cowley et al 2006*).

(Near-)PPOs: External quasi-periodic 'signals'

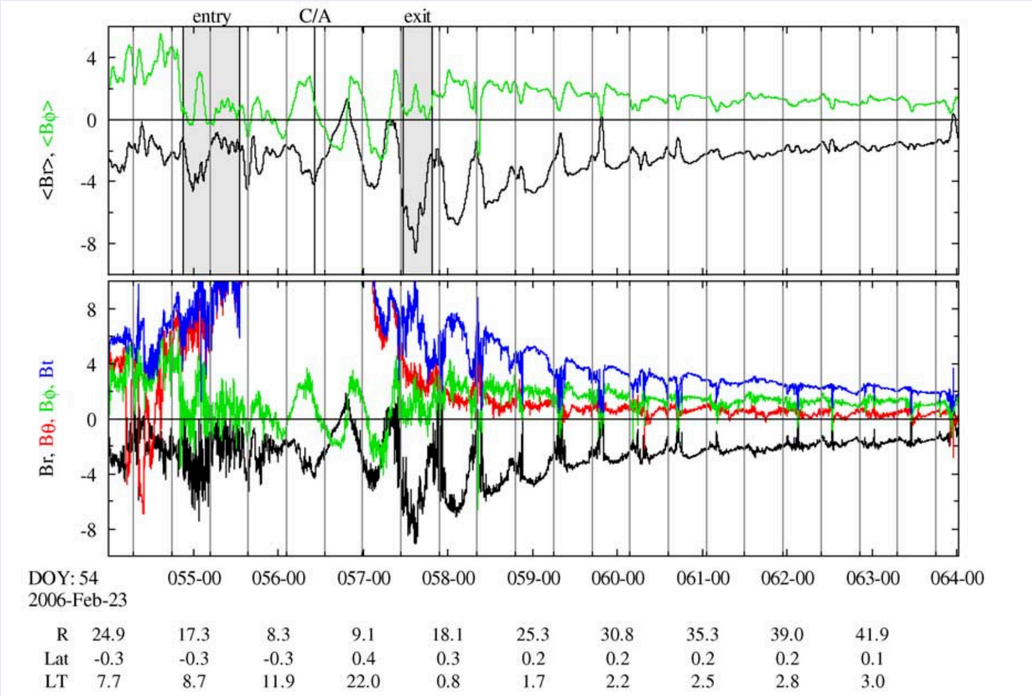


Figure 2a. Magnetometer data from a pass in February–March 2006 (periapsis 25 February) UT, showing (bottom) components of the field and the total field (color-coded) and (top) smoo (effectively a low pass filter) to the radial (black) and azimuthal (green) components. Radial distanc

- *Southwood and Kivelson* (2007) made use of *phase relations* to characterise the 'shell' of current responsible ('cam current')

(Southwood and Kivelson 2007)

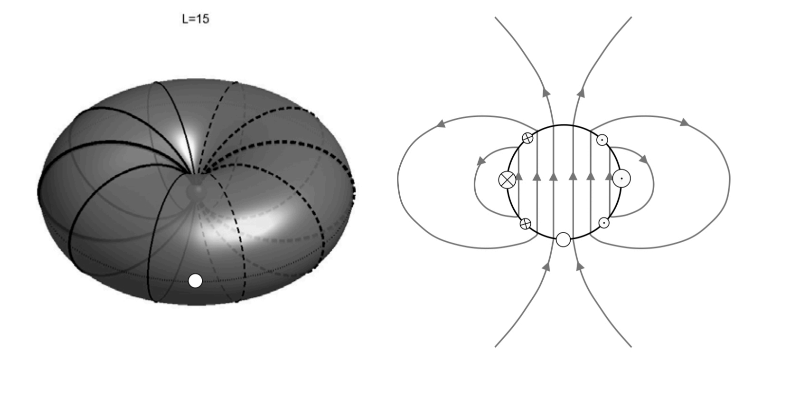
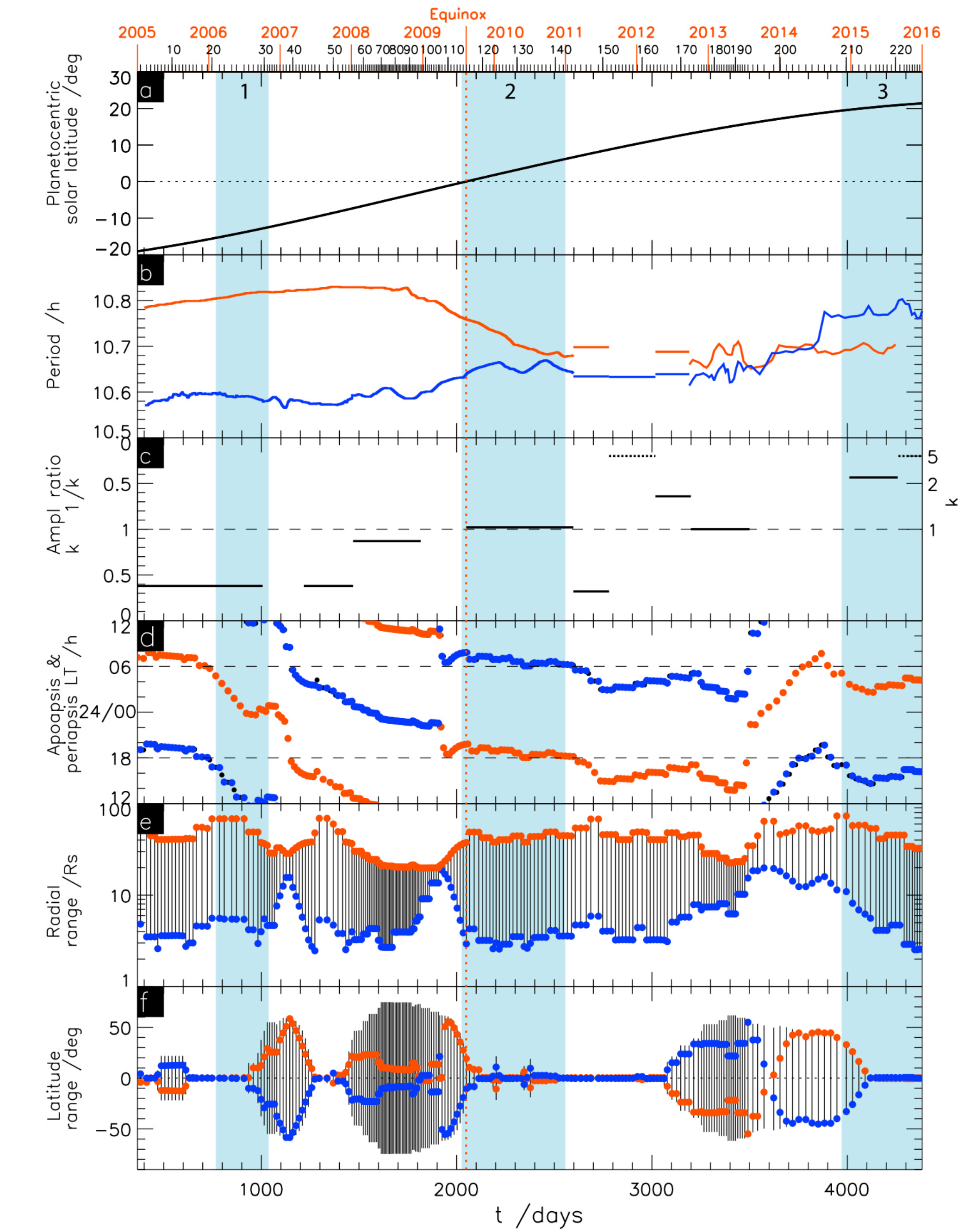


Figure 9. (left) Schematic shell of dipolar field lines at L ~15 R_S on which currents flow into and out of the northern ionosphere. If the current strength varied sinusoidally with longitude, as indicated by varying thickness of the lines representing the current, but flowed on a spherical surface, the perturbation field within the shell would be uniform. In order to produce the observed uniform field within a nonspherical surface, additional current loops must be present on the surface. (right) In a cut through the equatorial plane, field lines arising from the field-aligned currents at L = 15 shown in the left hand diagram. The field is uniform in the shaded area inside the shell at L = 15 (here shown on a different scale) and dipolar outside of that boundary. The white dots in the two images are at the same location on the boundary.

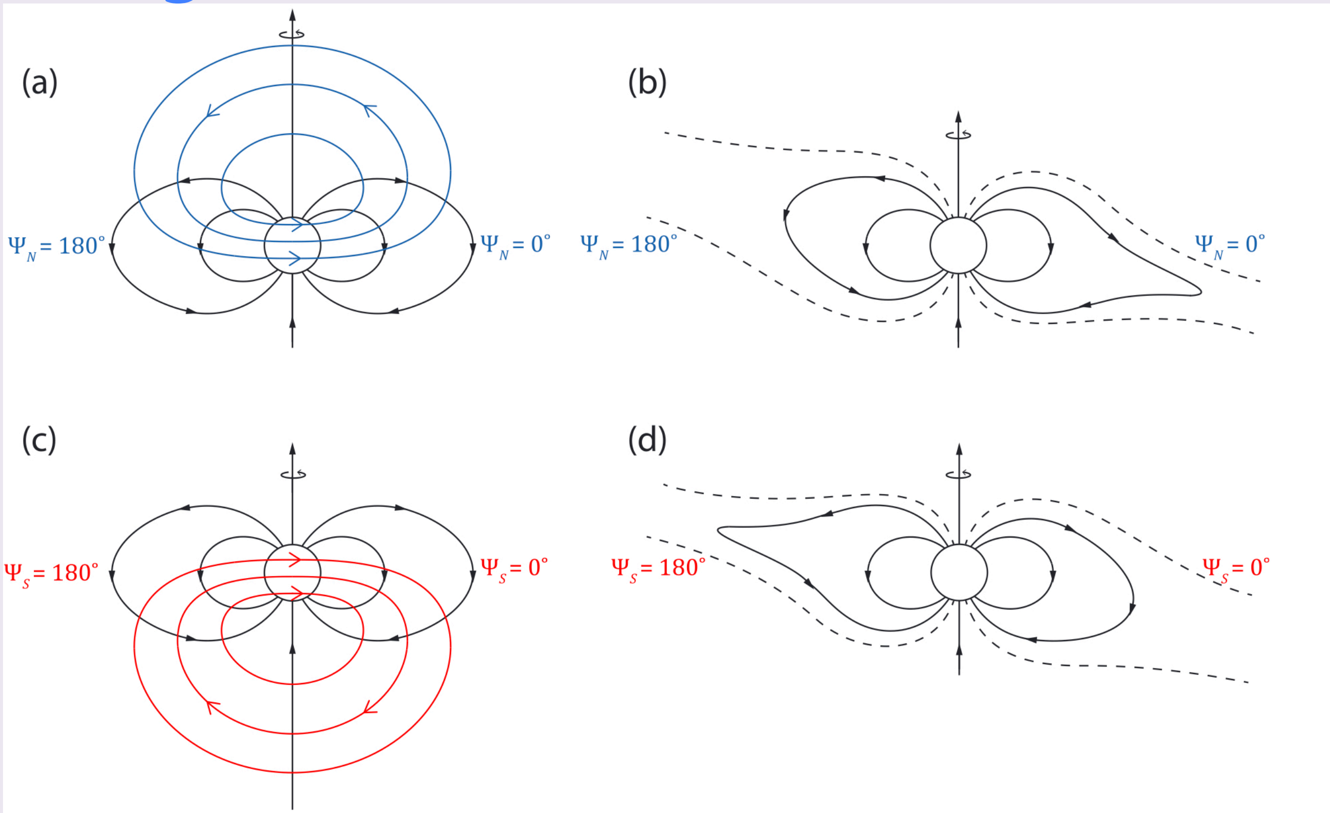
Two PPO signals – ‘northern’ and ‘southern’



- *From Cowley et al. (2017)* – summarises much analysis of ‘perturbation field’ data, pass-by-pass fitting of N and S signal periods and amplitudes in core (L<~12) region. (*Andrews+* 2012, *Provan+* 2013, 2014, 2016).
- Note behaviour of periods, and amplitude ratio, as a function of planetary season (subsolar latitude).
- Periods in general agreement with those of SKR (e.g. *Kurth+* 2008, *Gurnett+* 2009, *Lamy* 2011).

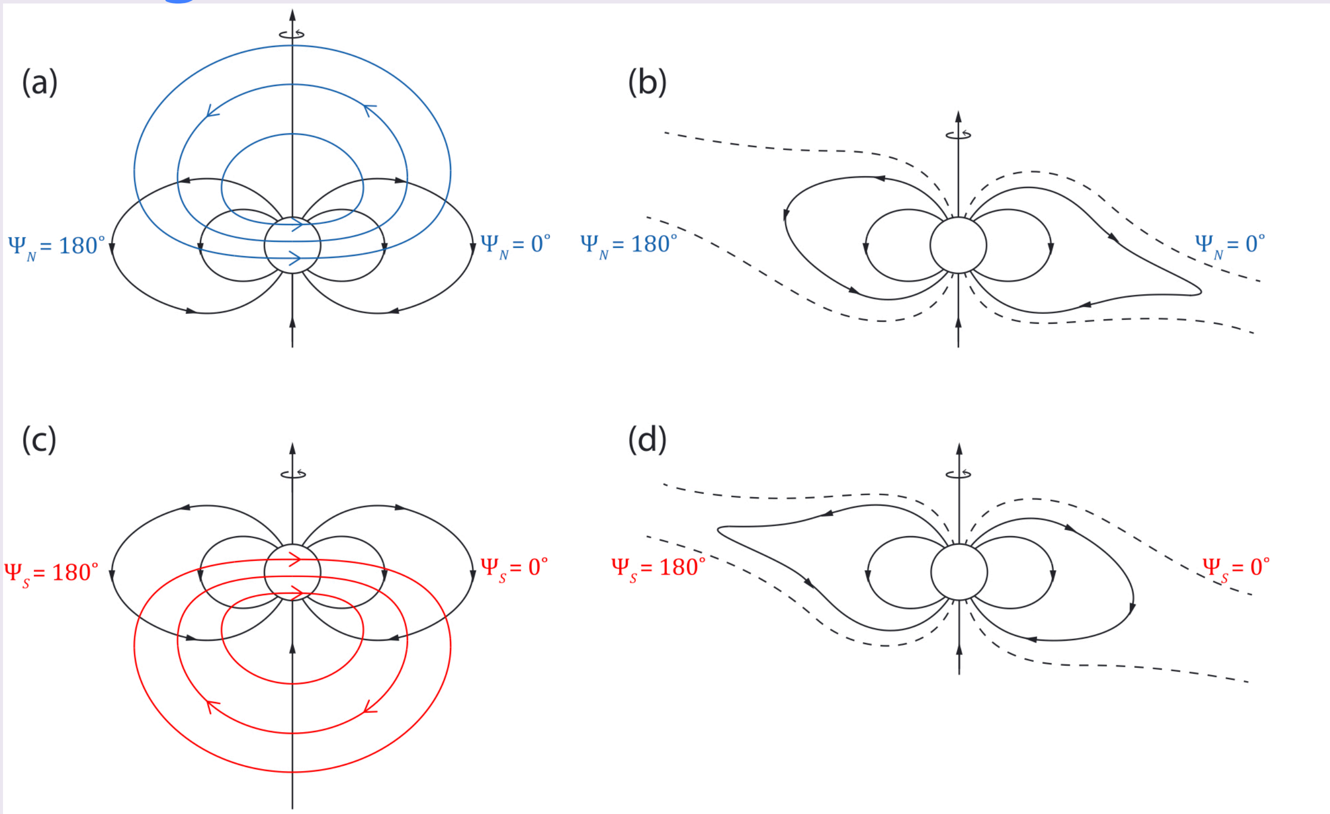
Two PPO signals – 'northern' and 'southern'

From Cowley et al. (2017)



- Two current systems and patterns of field rotating at different rates.
- 'Transverse dipole' field perturbation superposes with existing asymmetric field, leads to displacement of equatorial plasma sheet, as well as modulation of its thickness.
- Signals in phase: 'tilt' of sheet is dominant
- Signals in antiphase: thickening / thinning of sheet is dominant
- In between? (see e.g. *Cowley et al. 2017, Jia and Kivelson 2012*): Amplitude of variations in plasmasheet position and thickness depend on phase difference of the signals (beat cycle) and the relative amplitude of the N / S core field perturbation.

Two PPO signals – 'northern' and 'southern'



From Cowley et al. (2017)

- This picture is consistent with a variety of observed oscillatory behaviours in plasmasheet parameters (e,g. *Carbary+* 2008, *Morooka+* 2009, *Khurana+* 2009, *Arridge+* 2011, *Szego+* 2013, *Thomsen+* 2017) .

- But what is the origin of the required current systems?

An atmospheric source?

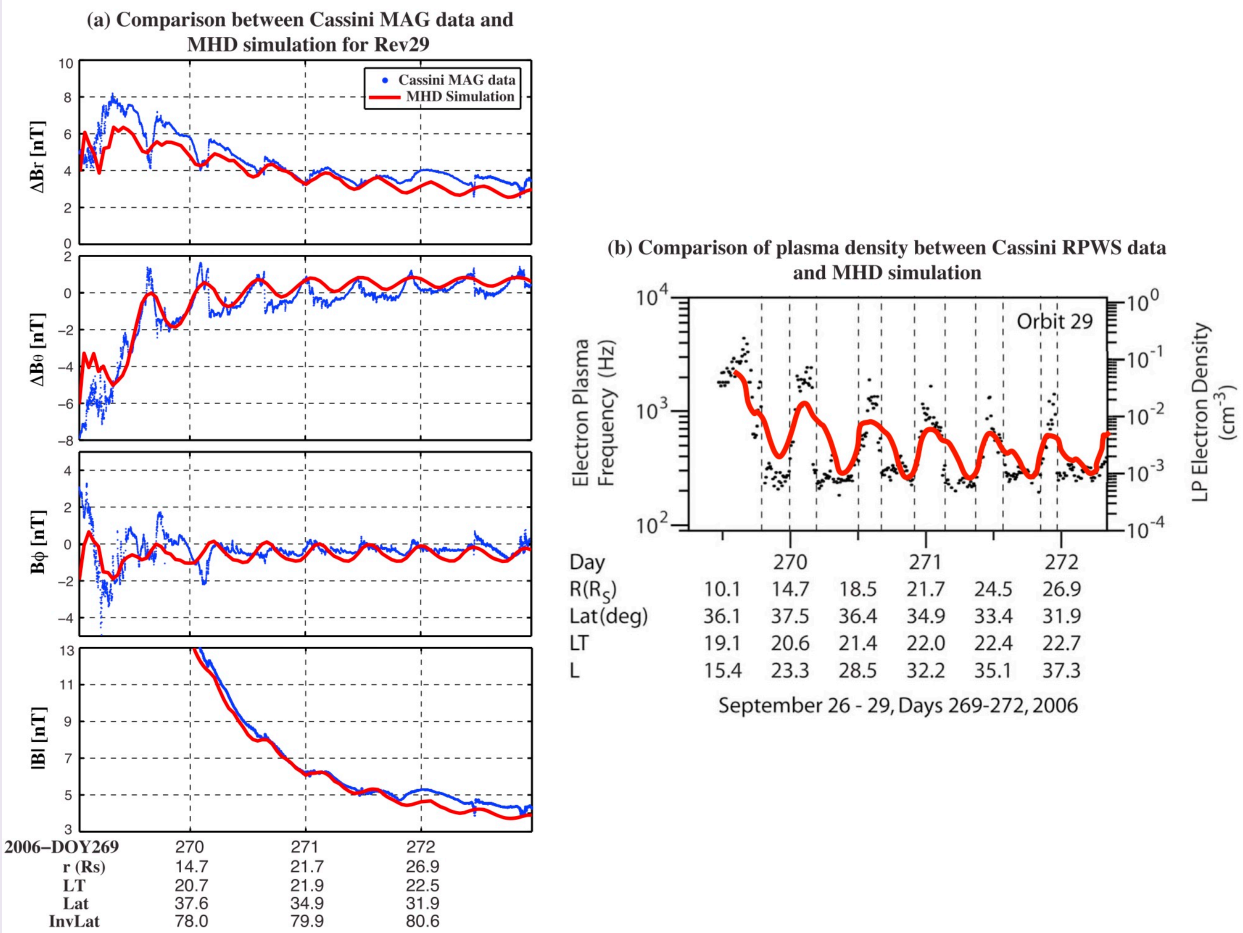


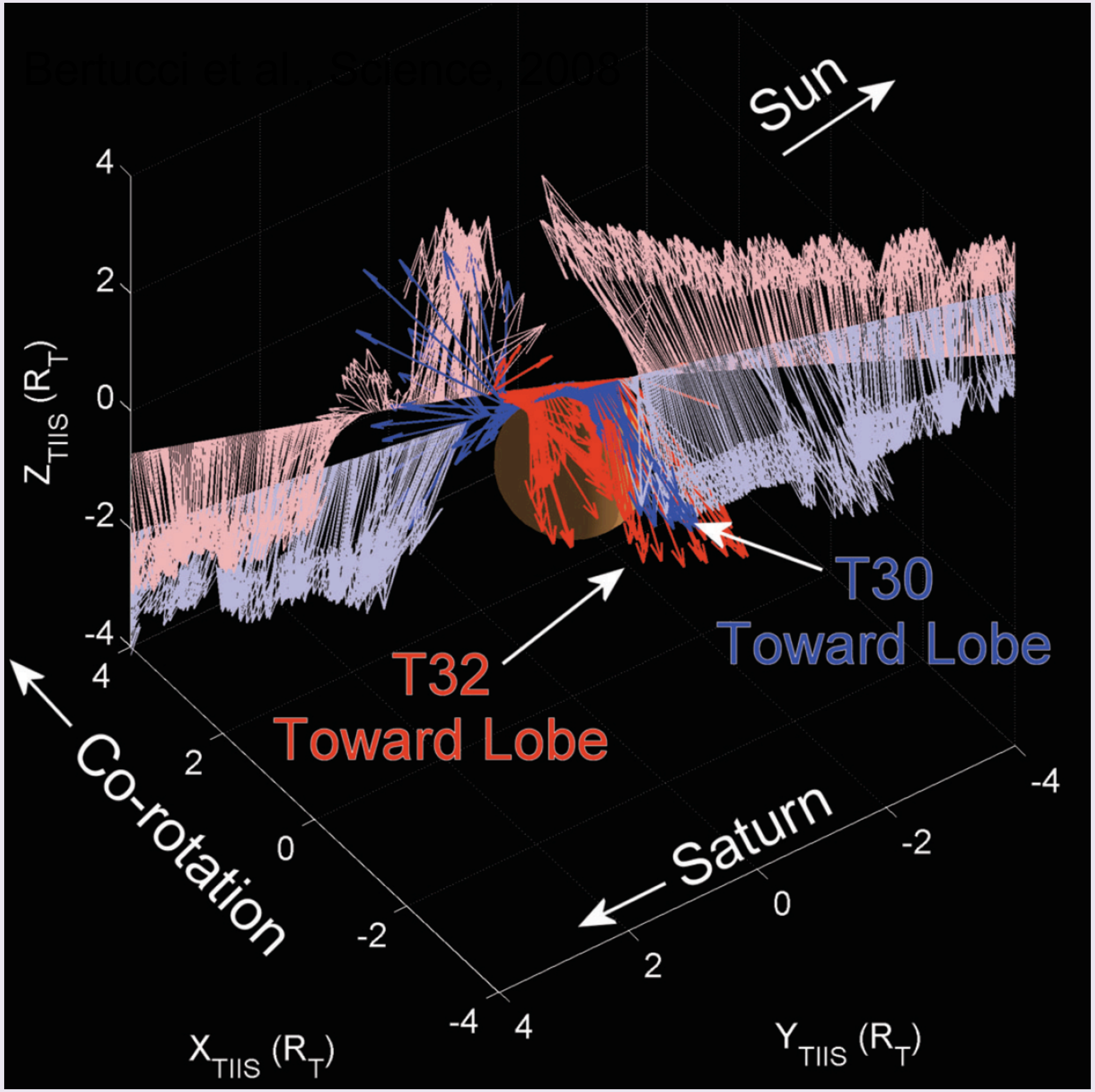
Figure 13. For Cassini orbit 29, (a) the magnetic field components and magnitude (B_r, B_θ, B_ϕ, |B| from top down): blue trace, from measurements of the Cassini Magnetometer [*Dougherty et al.*, 2004]; red trace, extracted from the simulation. (b) Ion density extracted from the simulation (red trace) along orbit 29, superimposed on the measured electron plasma density trace [*Gurnett et al.*, 2011] from Figure 12.

- *Jia and Kivelson (2012)* extended previous MHD model to now include *two* ionospheric vortical flow patterns.
- Flows produce FACs, FACs produce field and plasma perturbations.
- Quantitative comparisons with data very favourable – as in this example.
- We don't know how such flows arise from a 'first principles' point of view.

Titan's 'Magnetic Memory'

(T32 – 13 Jun 2007, near-noon, 975 km at CA)

Courtesy C. Bertucci (Cassini *MAG* team)



- The fields above Titan's collisional ionosphere during T32 are incompatible with draped IMF lines
- They coincide with Kronian draped fields at similar flybys within the magnetosphere (T28,T29, T30).
- Saturn's magnetic field lines are 'fossilized' in the near Titan non-collisional plasma as a result of the mass loading by cold exospheric ions.

Bertucci+ (2008)

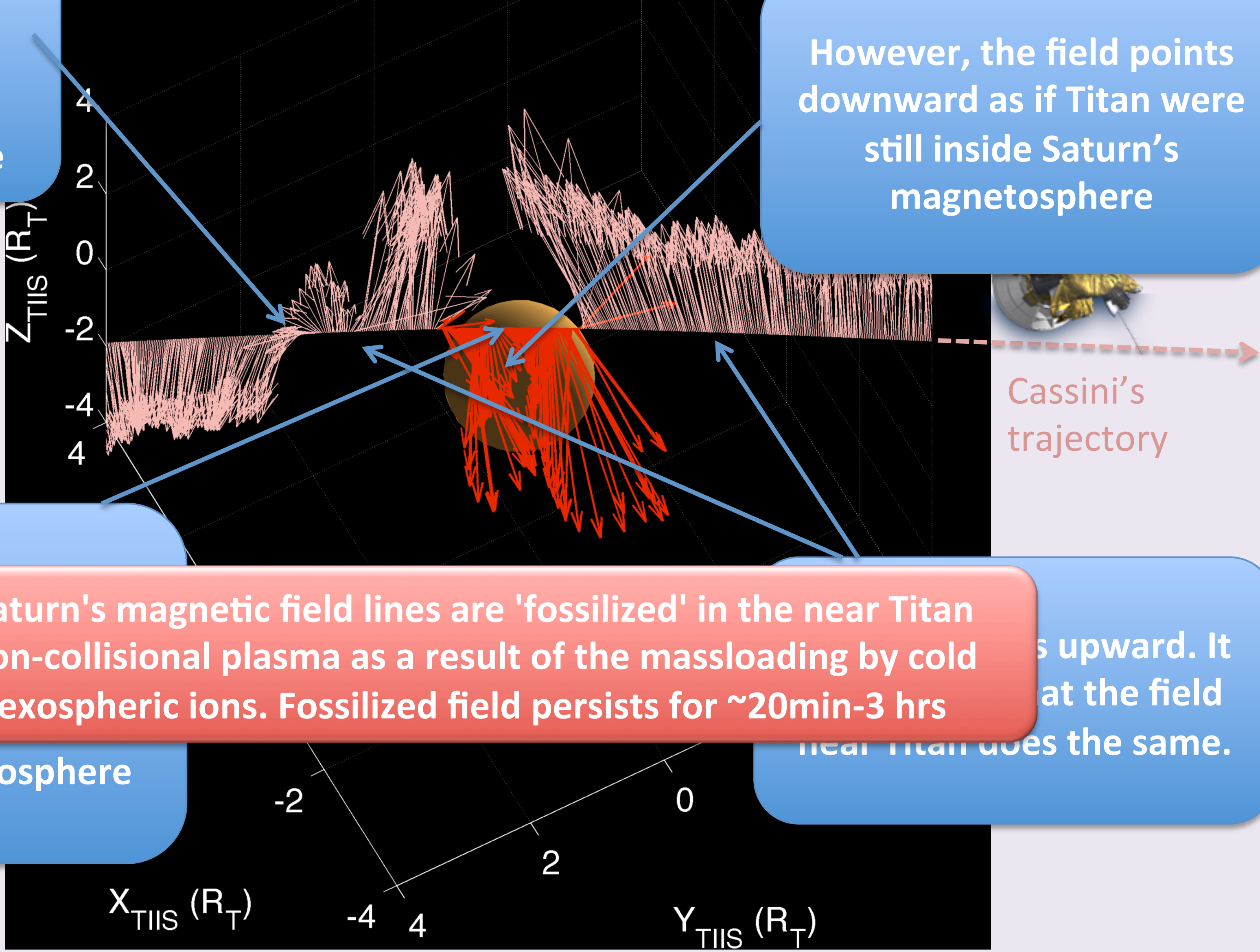
Cassini MAG observations during the Titan T32 flyby *(Bertucci et al., Science, 2008)*

(T32 – 13 Jun 2007, near-noon, 975 km at CA)

1
Cassini exits Saturn´s magnetosphere

However, the field points downward as if Titan were still inside Saturn's magnetosphere

Courtesy C. Bertucci (Cassini *MAG* team)



20 minutes
encounters
Saturn's magnetosphere

Saturn's magnetic field lines are 'fossilized' in the near Titan non-collisional plasma as a result of the massloading by cold exospheric ions. Fossilized field persists for ~20min-3 hrs

s upward. It
at the field
does the same.

SUMMARY

- Analysis of *Cassini* MAG observations has revealed a special type of interior structure and / or magnetic dynamo generating a steady, axisymmetric internal field at Saturn. Proximal orbit results – ‘watch this space’.

- Analysis of the perturbation field has revealed rotating external systems of current. These field perturbations modulate magnetospheric structure and dynamics and are likely a manifestation of an atmospheric phenomenon ‘propagating’ its influence into the magnetosphere.

- Observations at Titan reveal an interesting ‘magnetic archaeology’ where the slower layers of plasma closer to the ionosphere retain an ‘imprint’ of field environment further in the past.