University of Leicester

A review of studies of near-planetary period oscillations in Saturn's magnetosphere: *Results from Cassini concerning the periodicity, structure, and seasonality of these unique phenomena*

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S. W. H. Cowley, G. Provan, K. C. Clarke, J. D. Nichols, L. Lamy, P. Zarka, B. Cecconi, A. J. Coates, D. J. Southwood, M. K. Dougherty

Uppsala, November 2011

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Outline

0 - Introduction

1 - Equatorial field structure

2 - Unexpected north-south asymmetries

3 - Discovery of a rotating radio source

4 - “Magnetic equinox”, or not?

5 - Conclusions

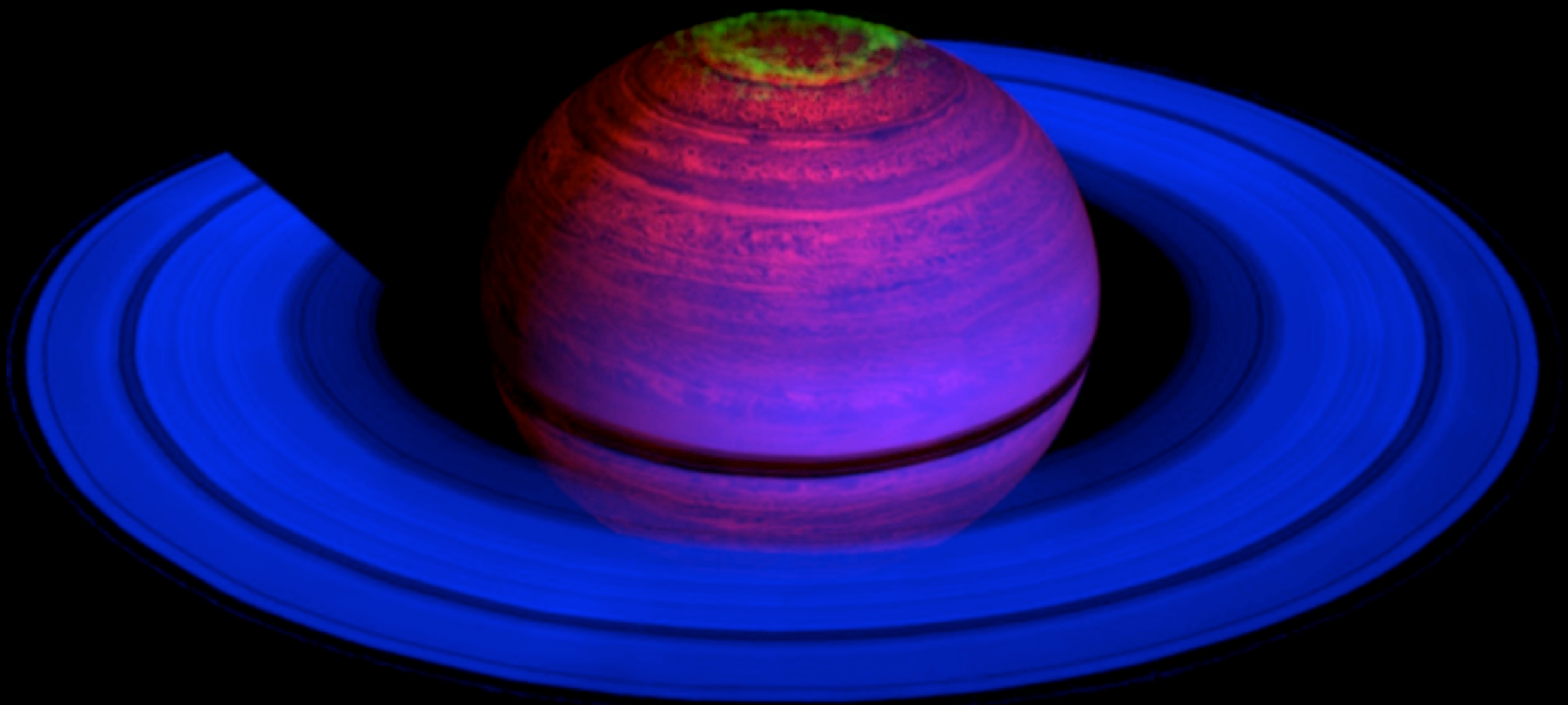
The messåge:

Field öskillåtiöns detekted åt Såturn with periöds klöse tö the ~10.5 h plånetäry rötåtiön periöd, ånd reläted phenömenå, åre ä “trending töpik” in plånetåry mågnetöspheres. Möre thån ä dekåde since their diskövery, we understånd much öf the dätå, but little öf the reål örigin öf these öskillätiöns.

[I learnt Swedish from Monty Python]

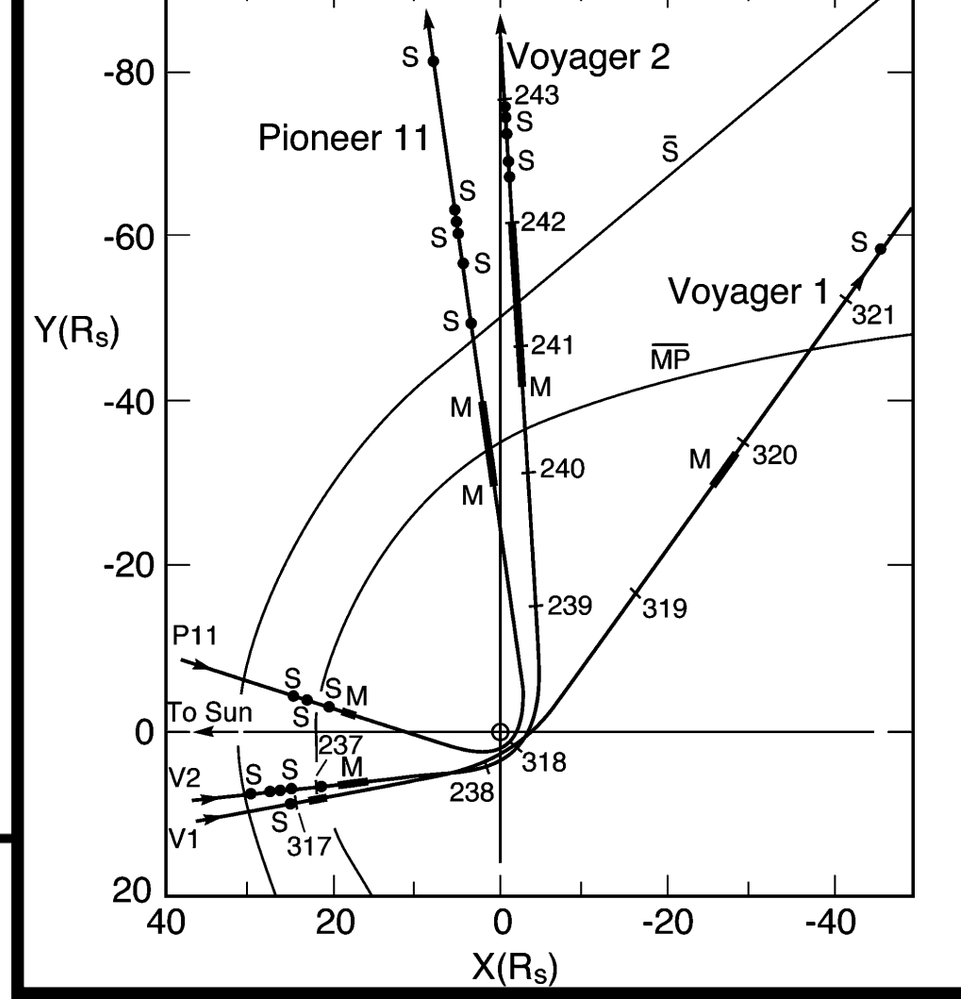
0
Introduction
(how little we know)

How long is a day on Saturn?



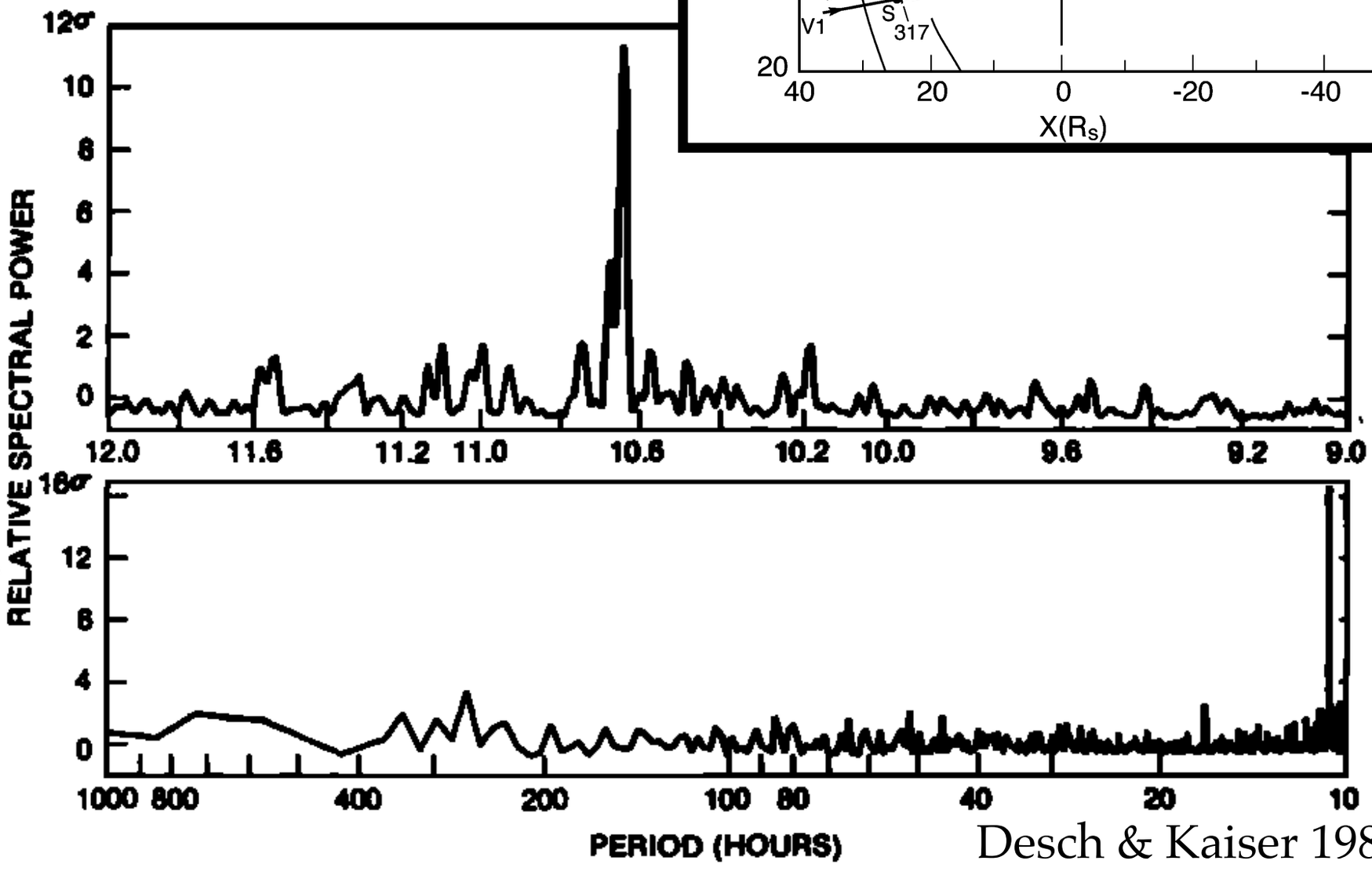
Voyager measurements of the SKR

- Saturn Kilometric Radiation is emitted from sources a few R_S over Saturn's auroral regions
  - *Cyclotron maser instability associated with upward field-aligned currents*
  - *Tens to hundreds of KHz.*
  - *Almost continuously observed*



Dougherty et al. 2004

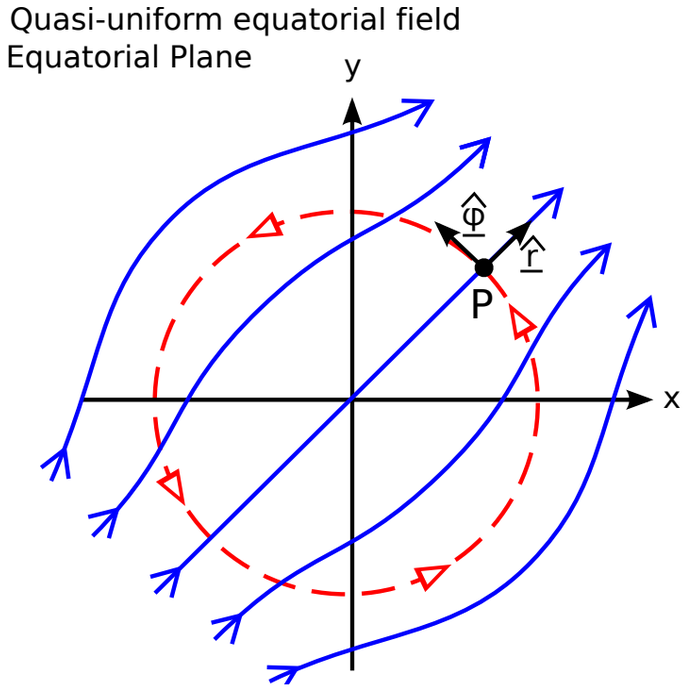
- Desch & Kaiser [1981] measurement of the periodicity of the SKR using Voyager Planetary Radio Astronomy instruments
  - *Principal ~10.5 h component*
  - *Analogous to rotation period modulations in similar Jovian emissions?*
  - *Used as definition of IAU Saturn coordinate system*



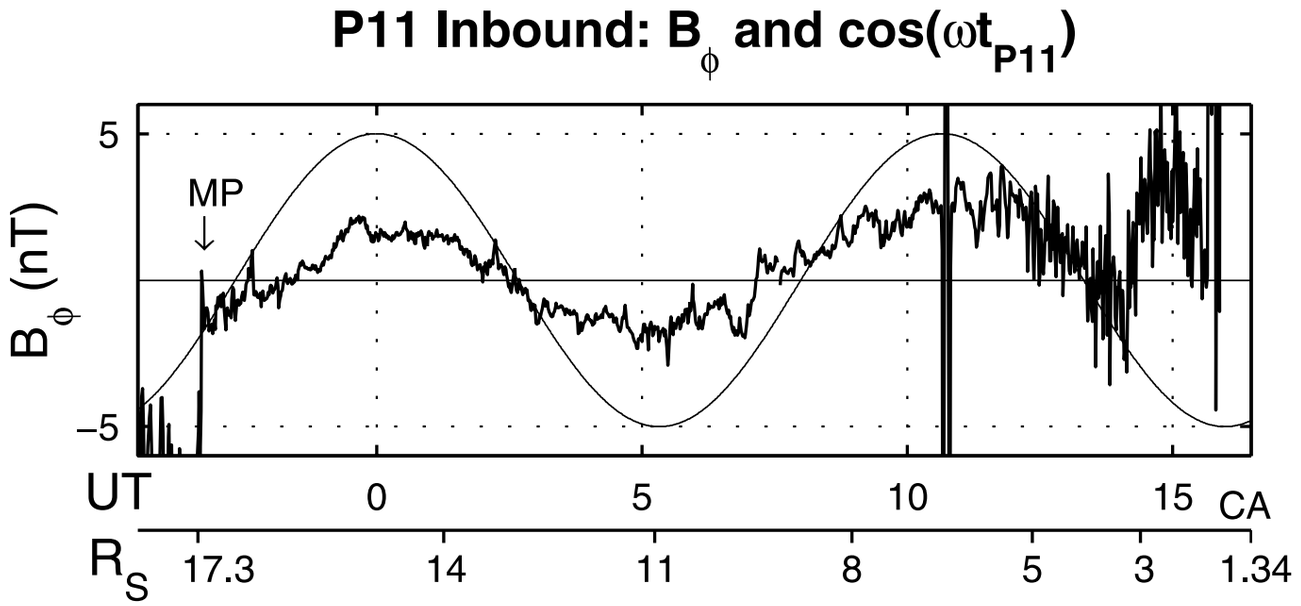
Desch & Kaiser 1981

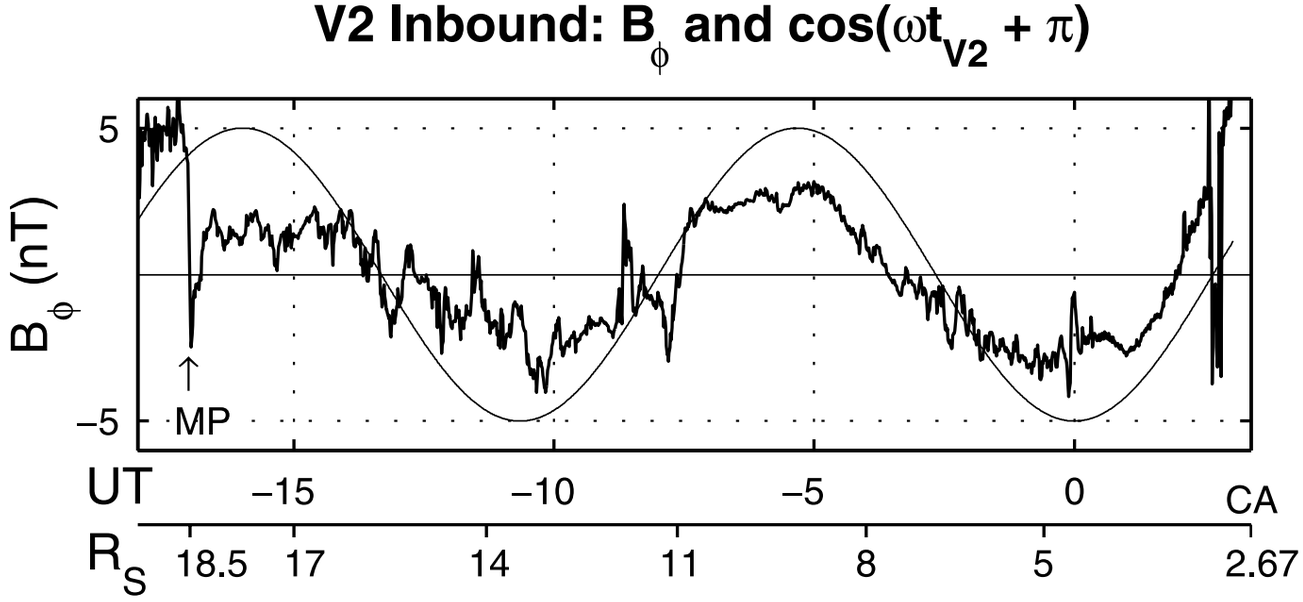
Espinosa et al. [2001, 03a, b]

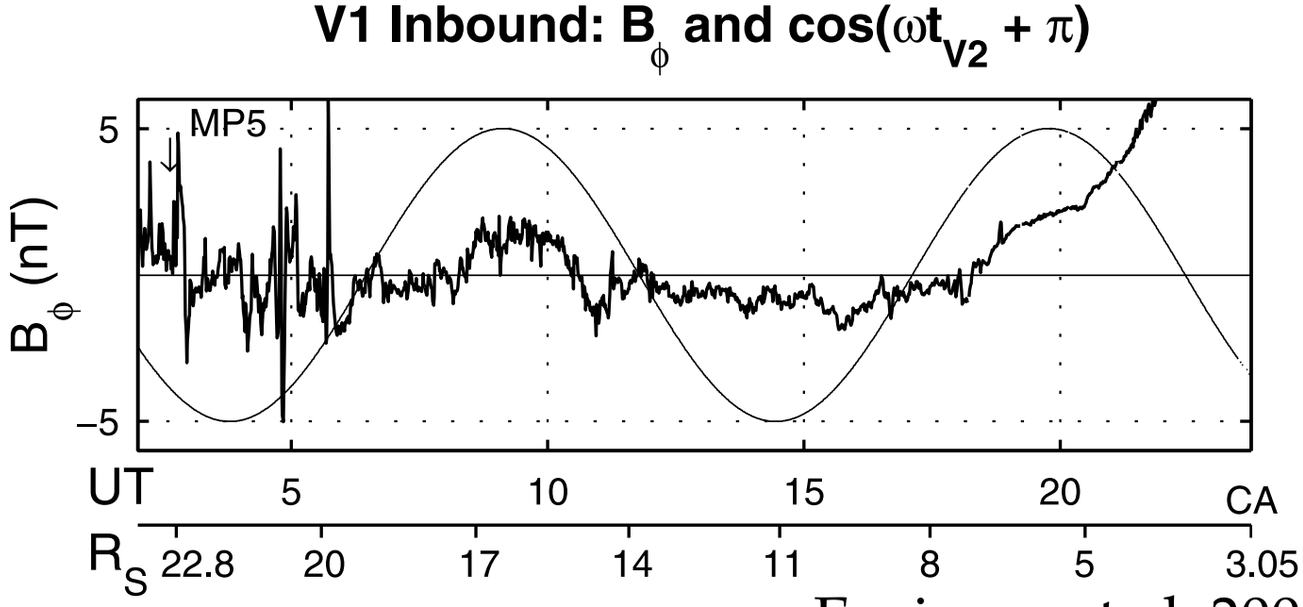
- First detection of periodic modulations in Saturn's field
  - *Observed throughout flybys, significant amplitudes out to the magnetopause*
  - *External origin*
  - *Boundary oscillations also hypothesised*
  - *Compressional MHD wave?*
- Specific polarisation of the field
  - *Azimuthal field in lagging quadrature*



B_φ in lagging quadrature with B_r

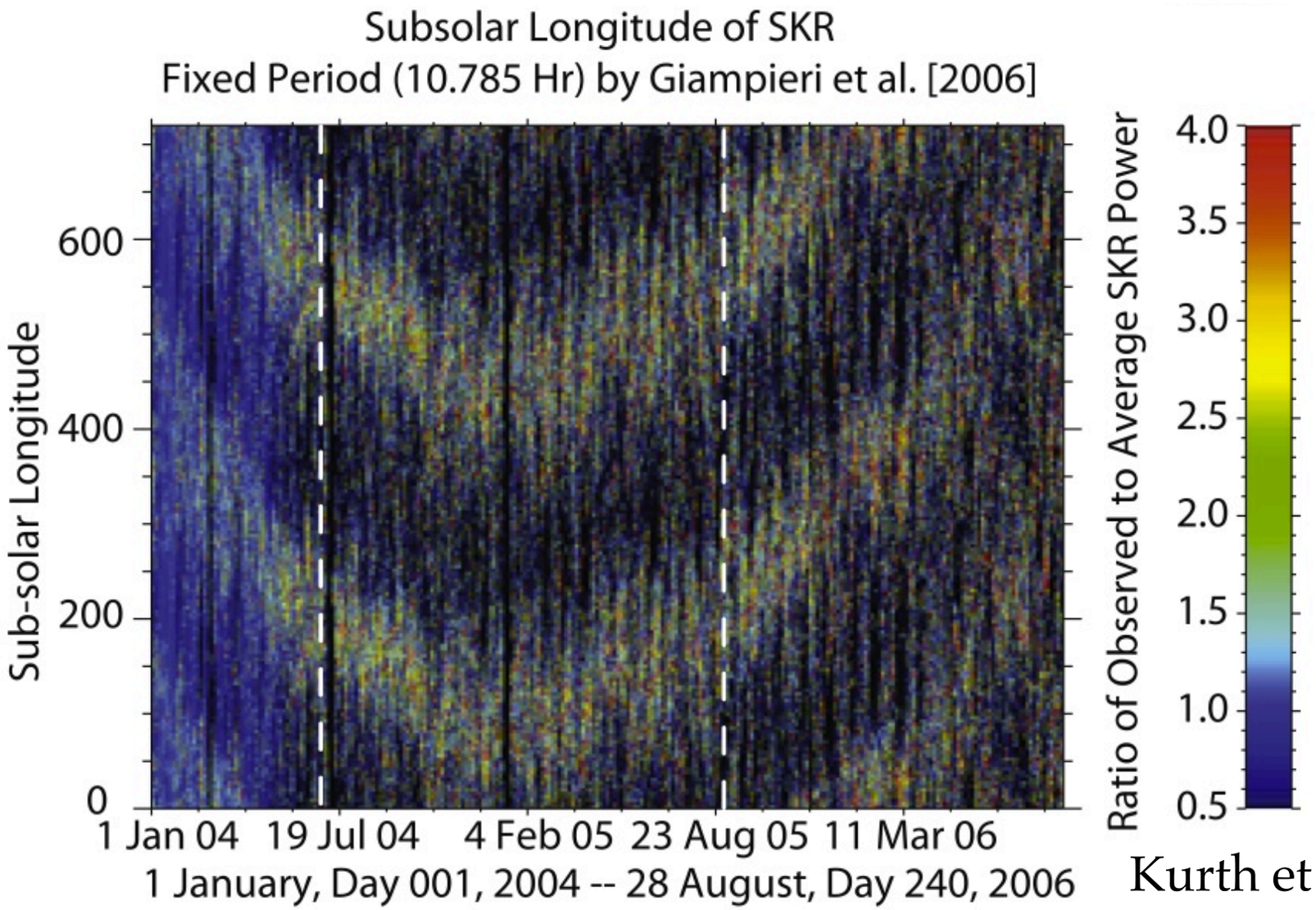






Espinosa et al. 2001

Time-variability of the SKR period



Kurth et al., 2007

- Discovery in Ulysses data of drifting SKR period [Galopeau & Lecacheux, 2000]
- Confirmed in Cassini RPWS data [Kurth et al., 2007]
  - *Phase determined relative to an arbitrary reference period*
  - *Modelled the time-variation using a 4th order polynomial*
- IAU reference frame is therefore without physical basis

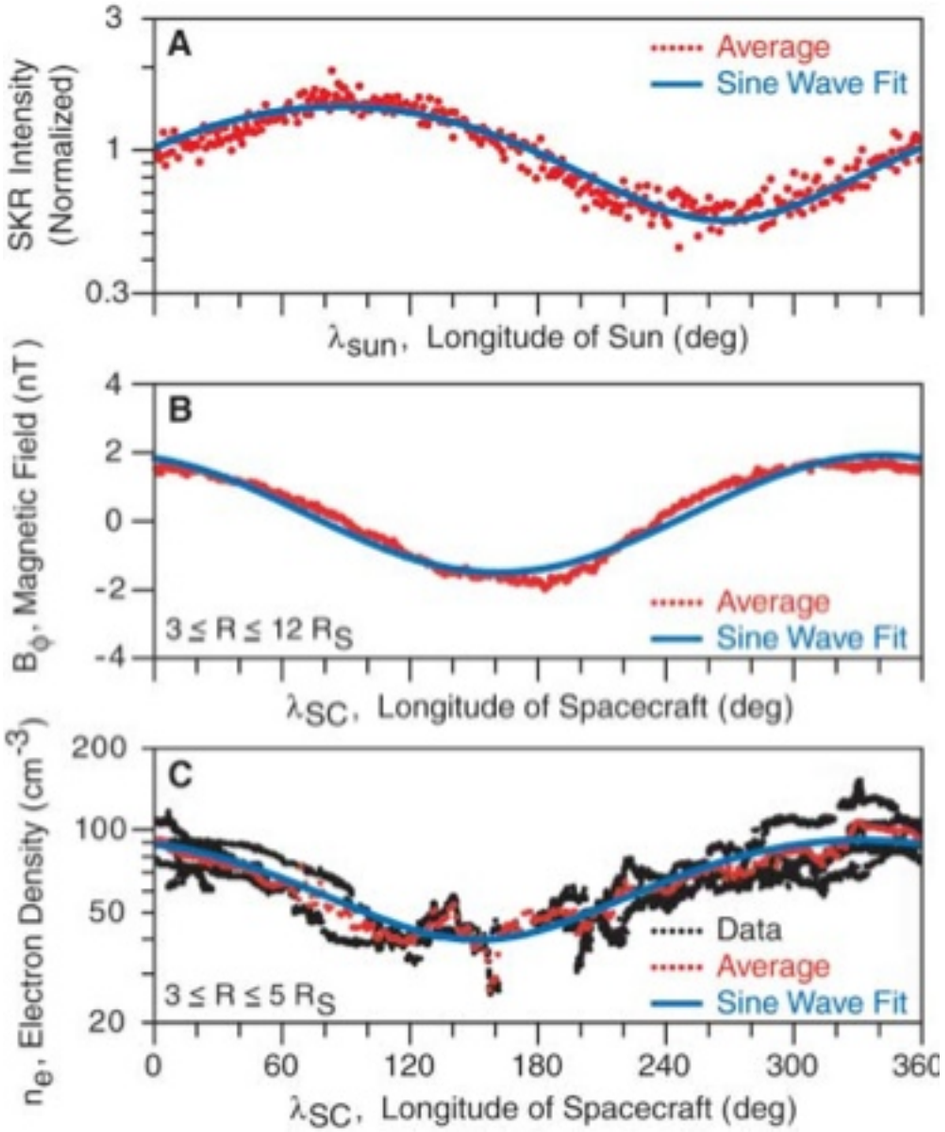
$$P_{SKR} \propto \cos\left(\Phi_{SKR}(t)\right)$$

$$\Phi_{SKR}(t) = 360^\circ \frac{t}{\tau_0} - \sum_{k=0}^{4} \alpha_k t^k$$

$$\tau_{SKR}(t) = \frac{360^\circ}{\frac{d\Phi_{SKR}(t)}{dt}}$$

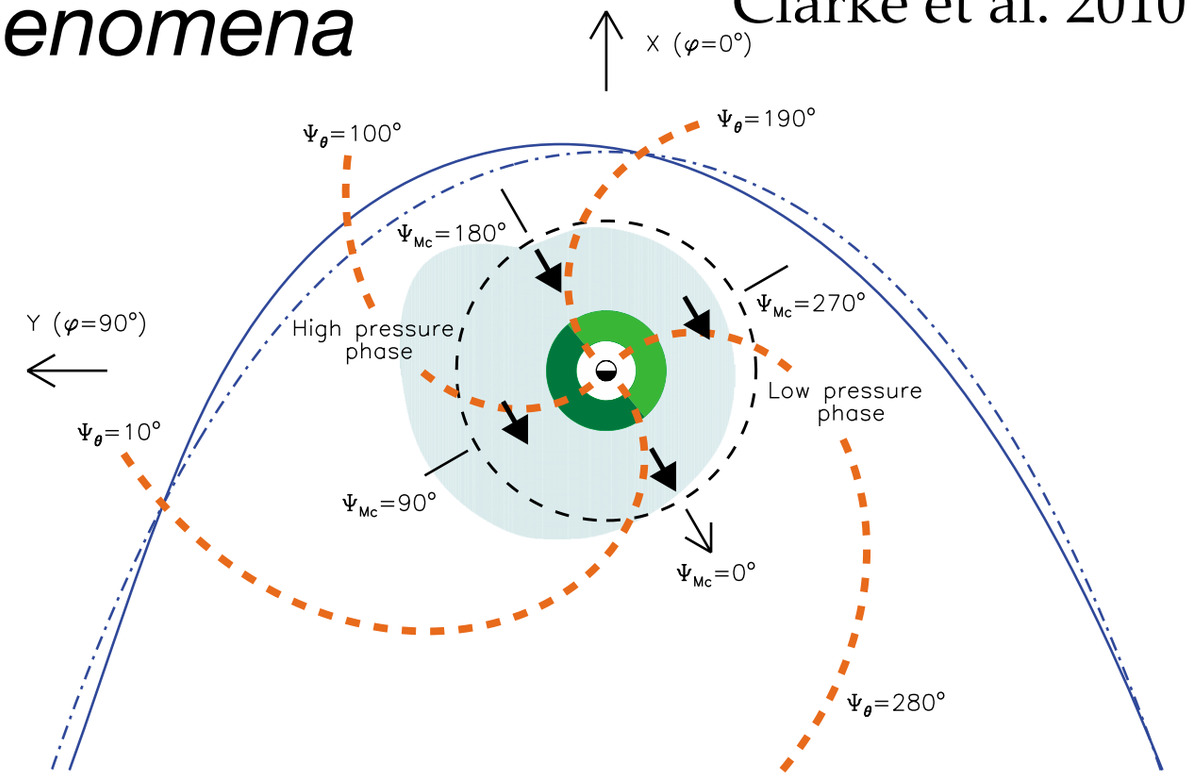
Cassini observations of periodic phenomena

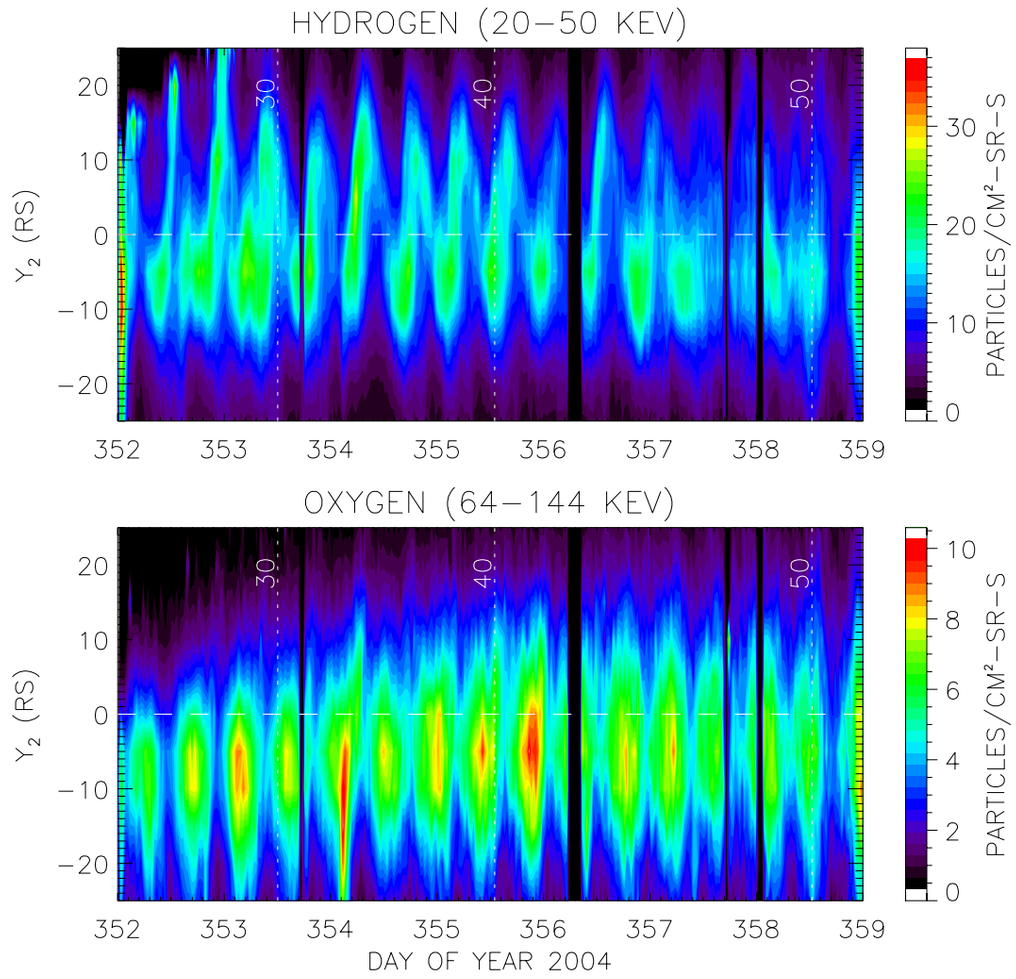
- m=1 variation in inner plasma density
- Outward propagation of phase fronts at ~100-400 km/s
- ~ 3 R_S Modulation in the standoff position of the bowshock and magnetopause
- Modulation in fluxes of ENA, high energy ring current plasmas



Gurnett et al. 2007

Clarke et al. 2010



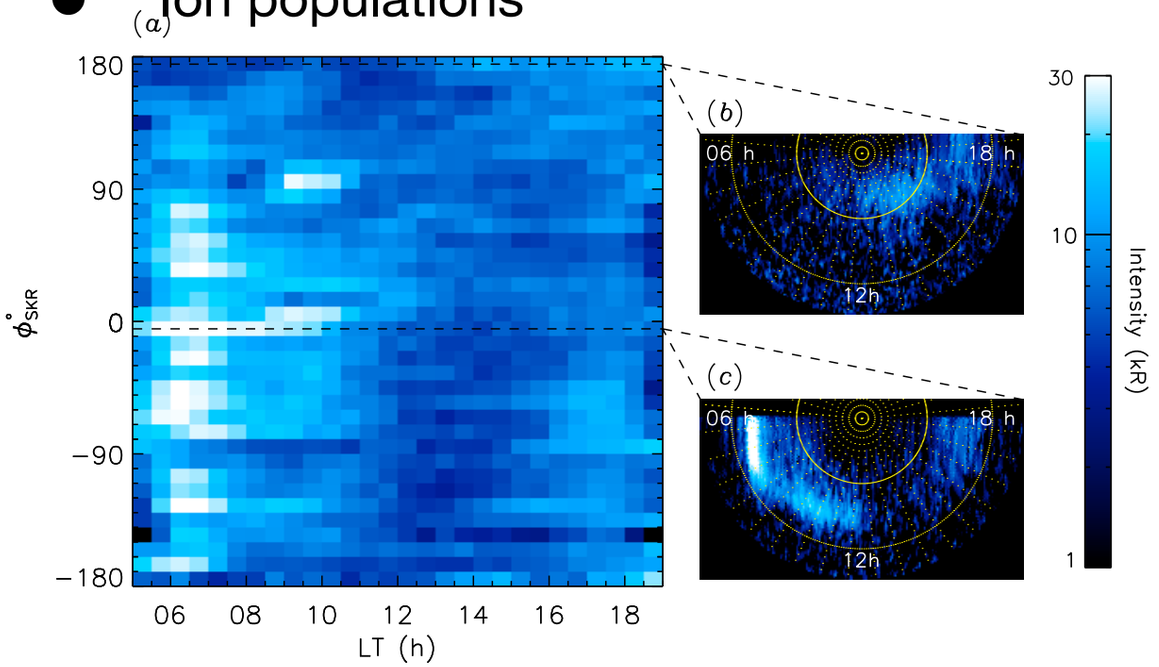


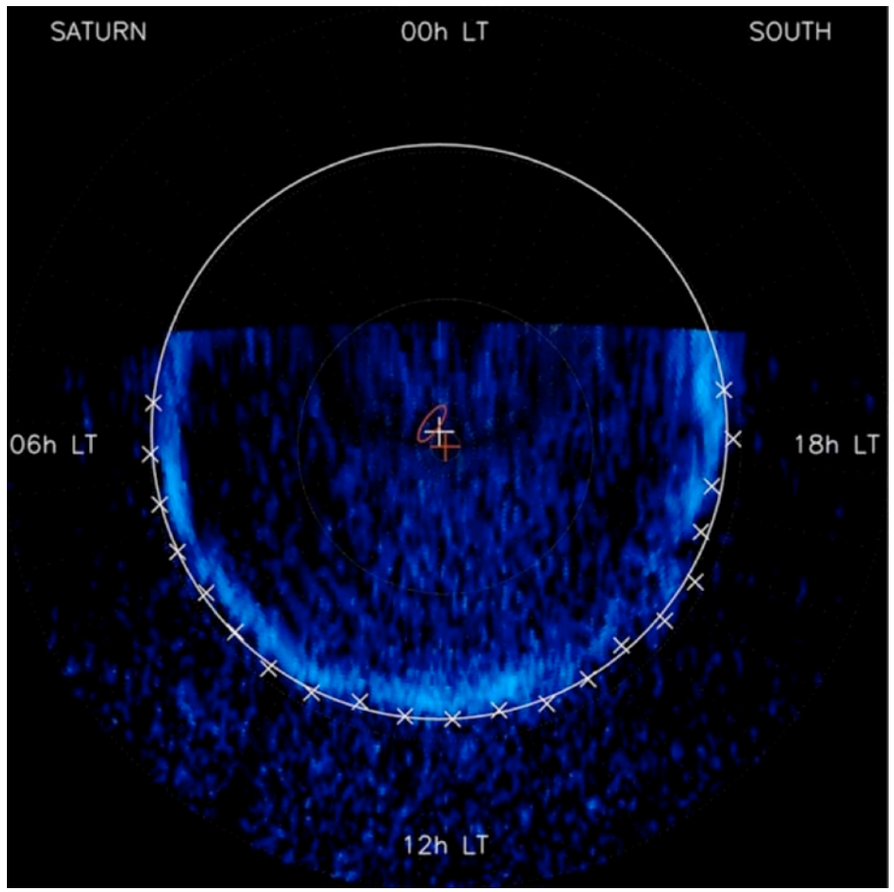
Carbary et al. 2008

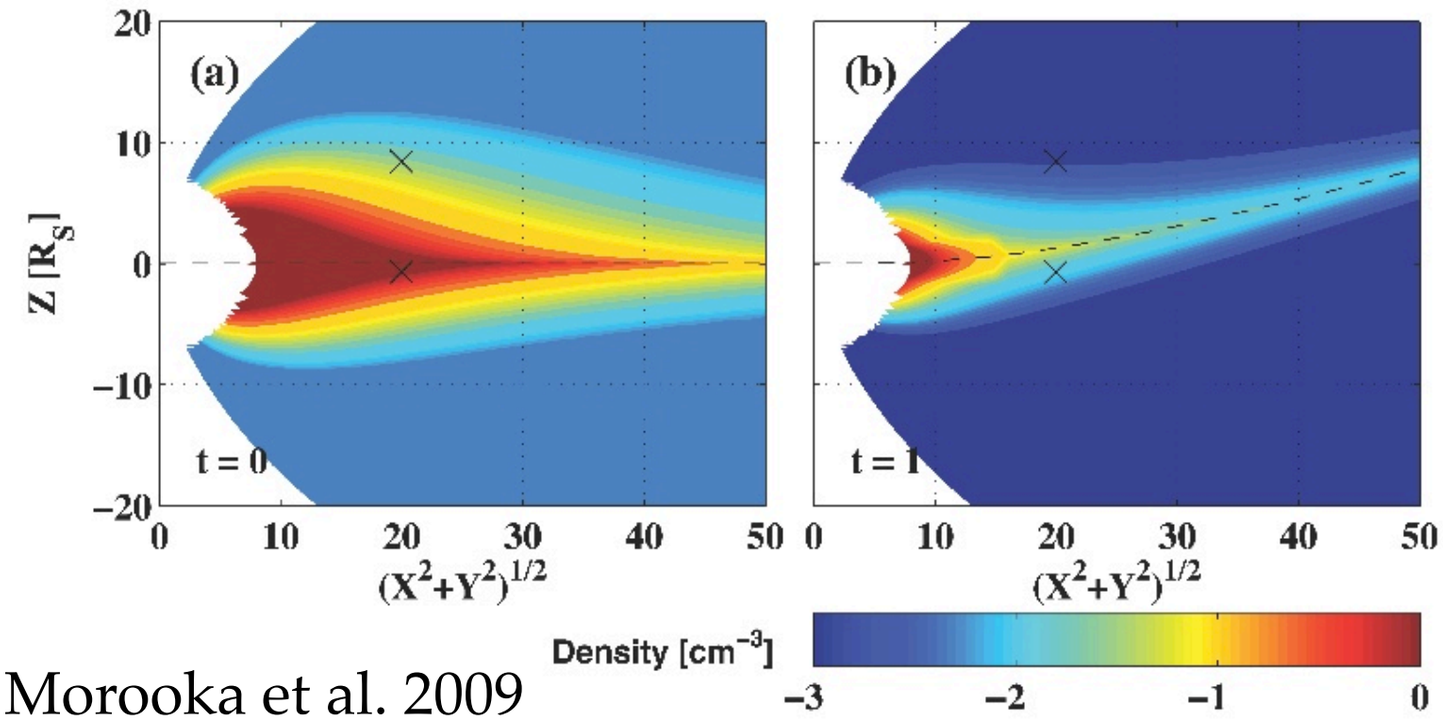
Cassini observations of periodic phenomena (2)

- Auroral oval intensity, position
- Plasma sheet motion
- Ion populations

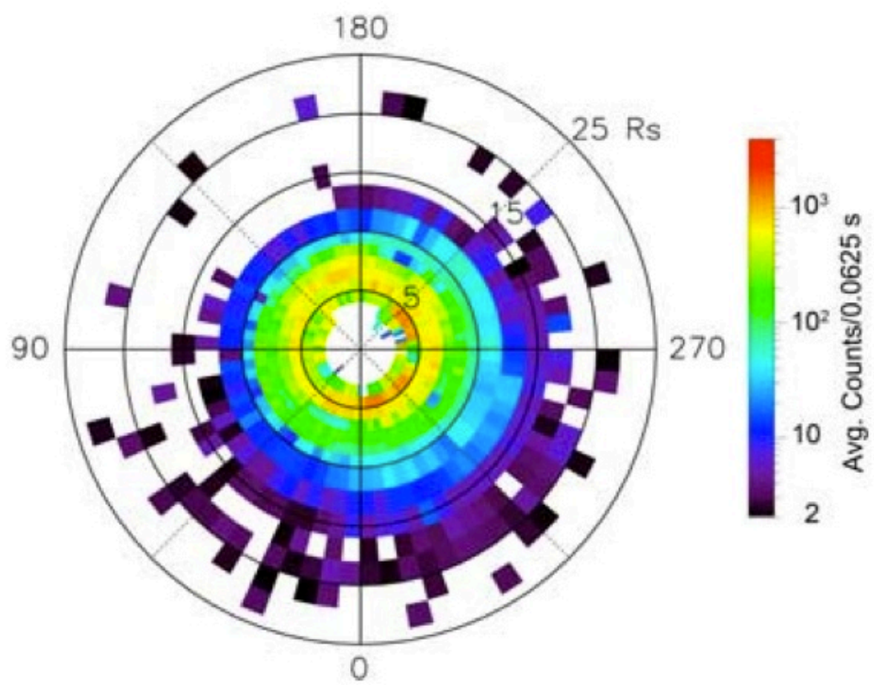
Nichols et al. 2008, 2010a







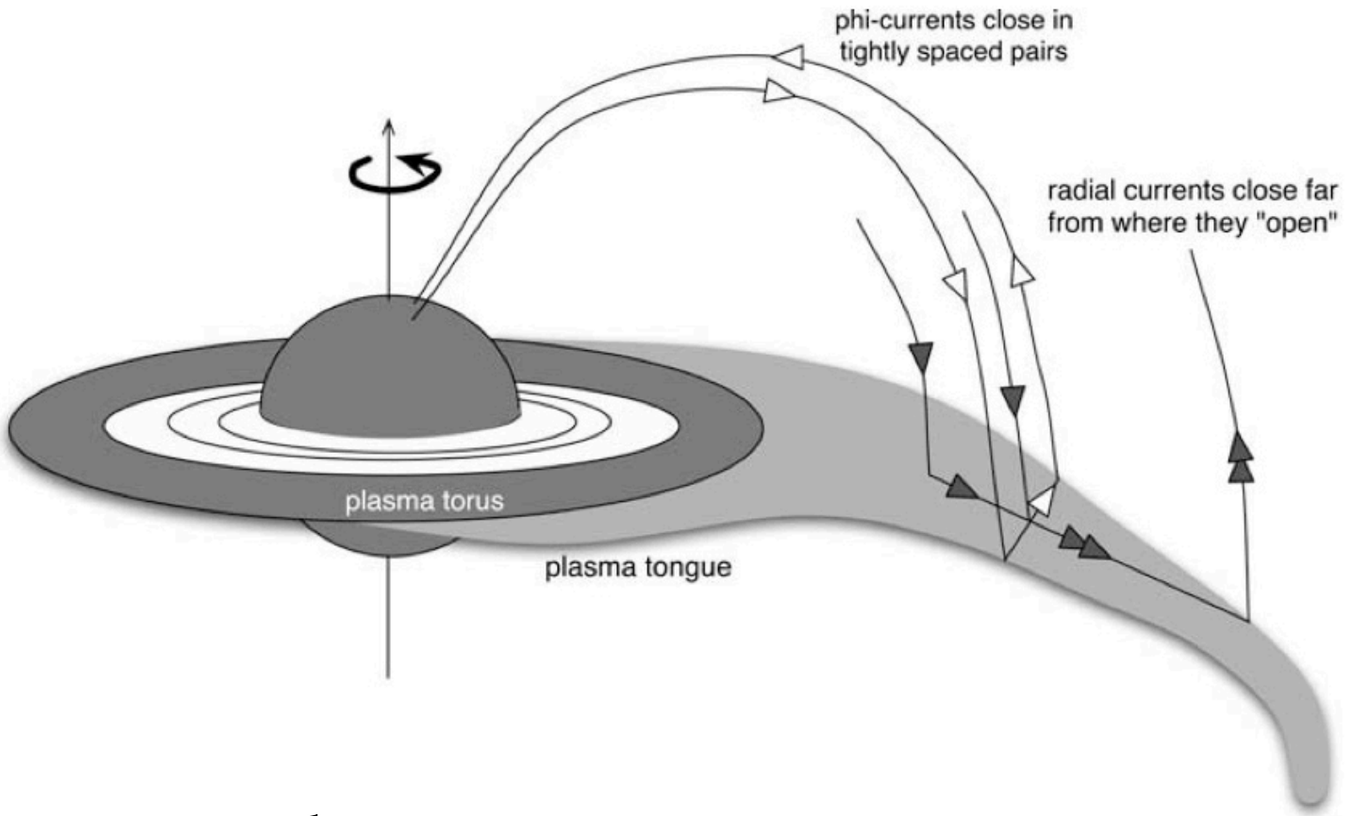
Morooka et al. 2009



Burch et al. 2009

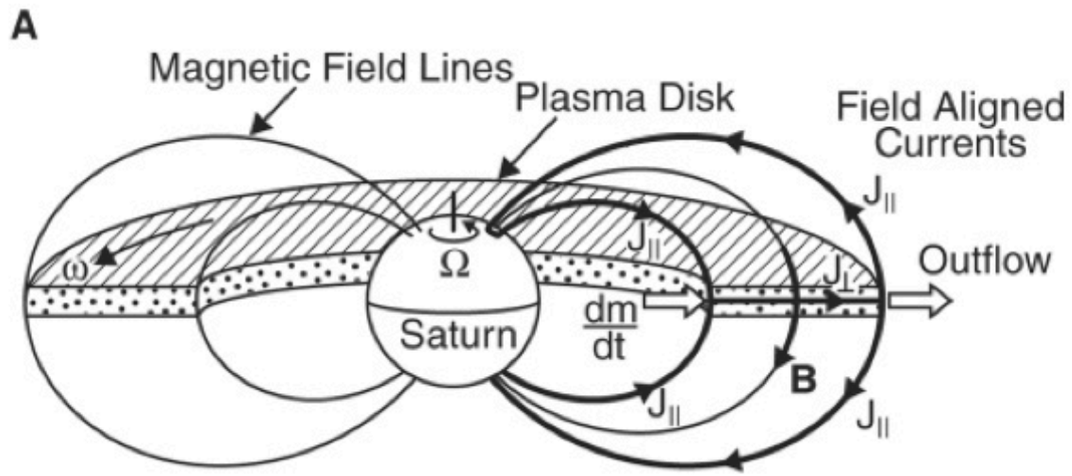
What is the source of these oscillations?

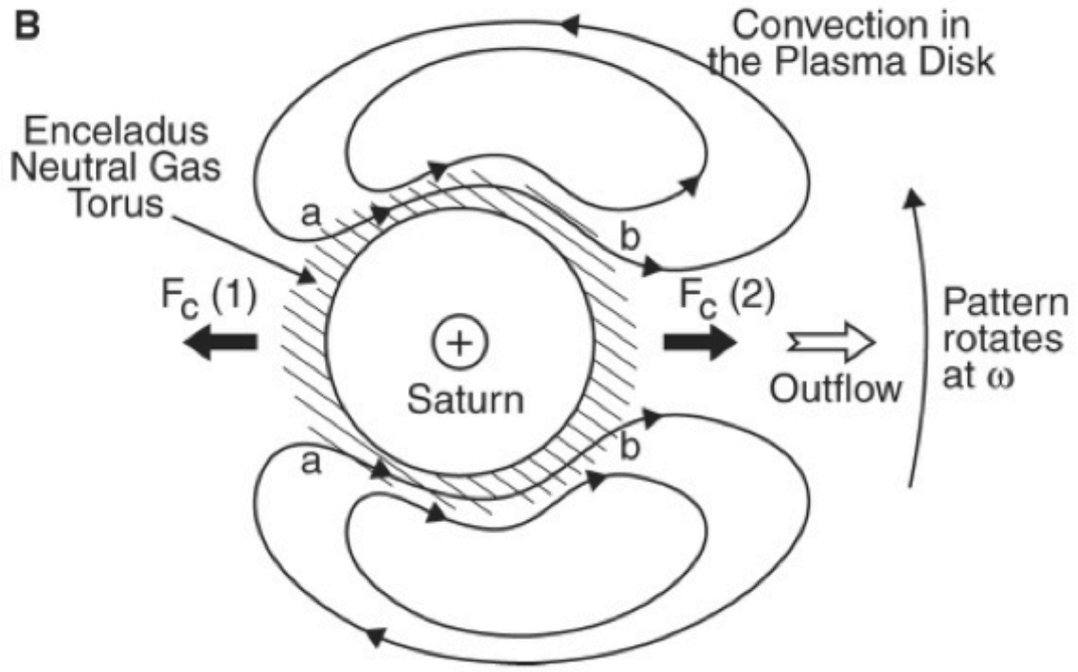
It depends on who you ask...



Goldreich & Farmer 2007

Gurnett et al. 2007





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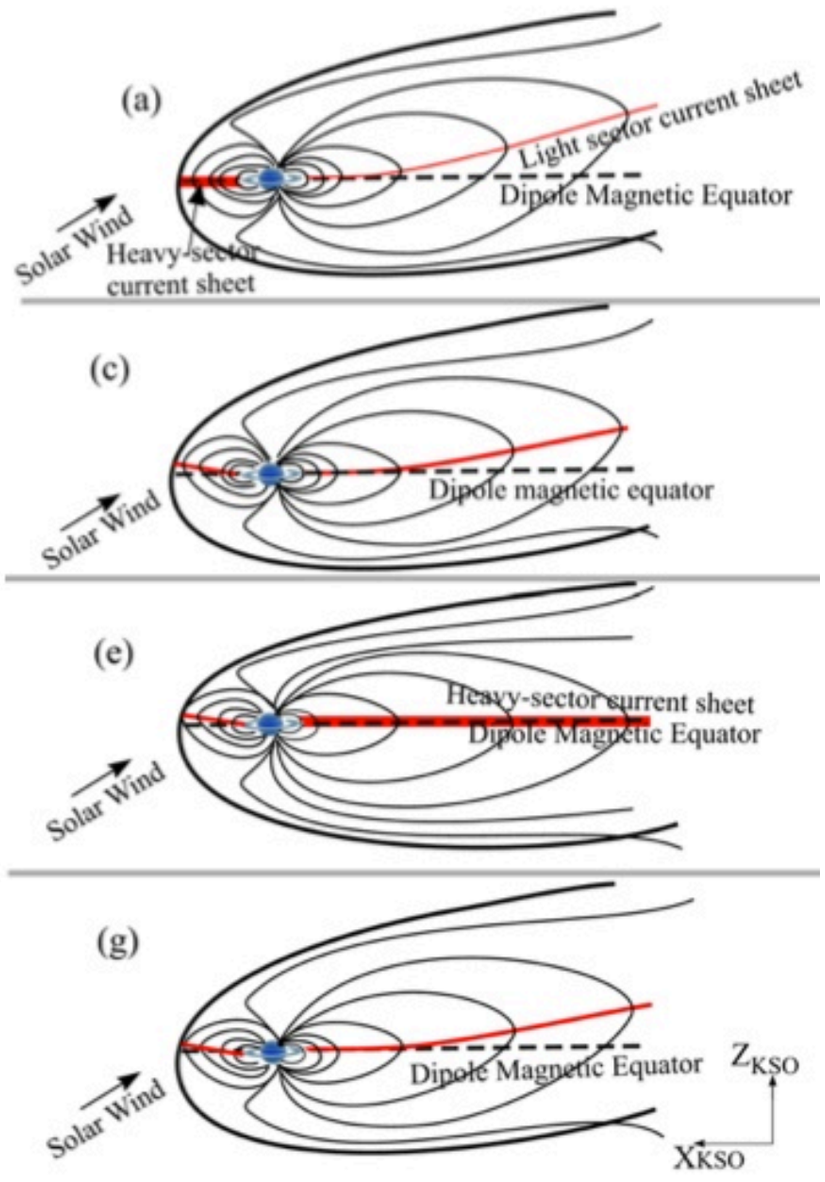
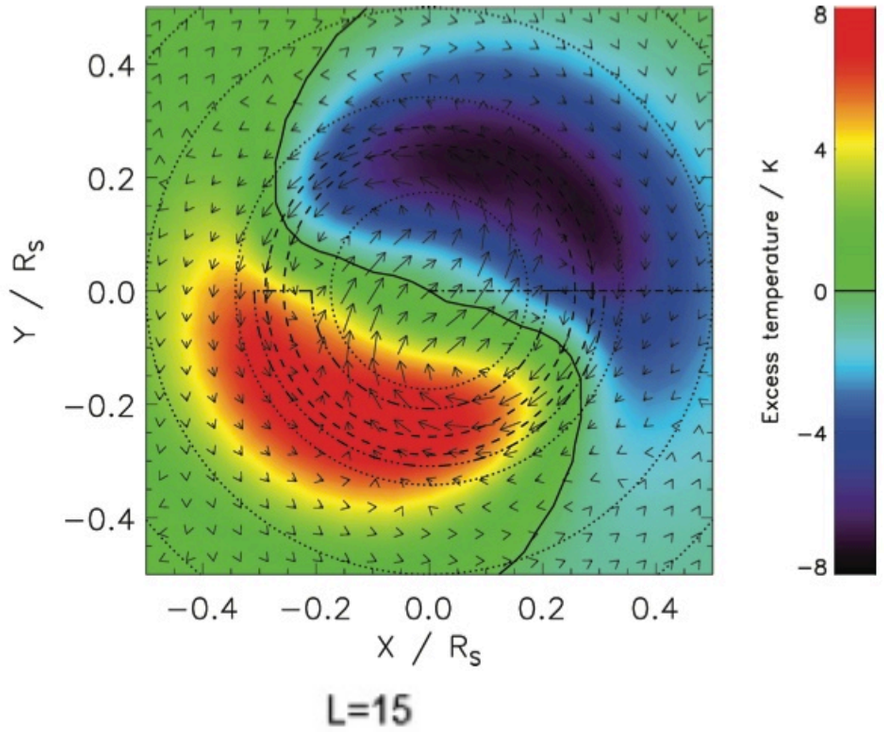
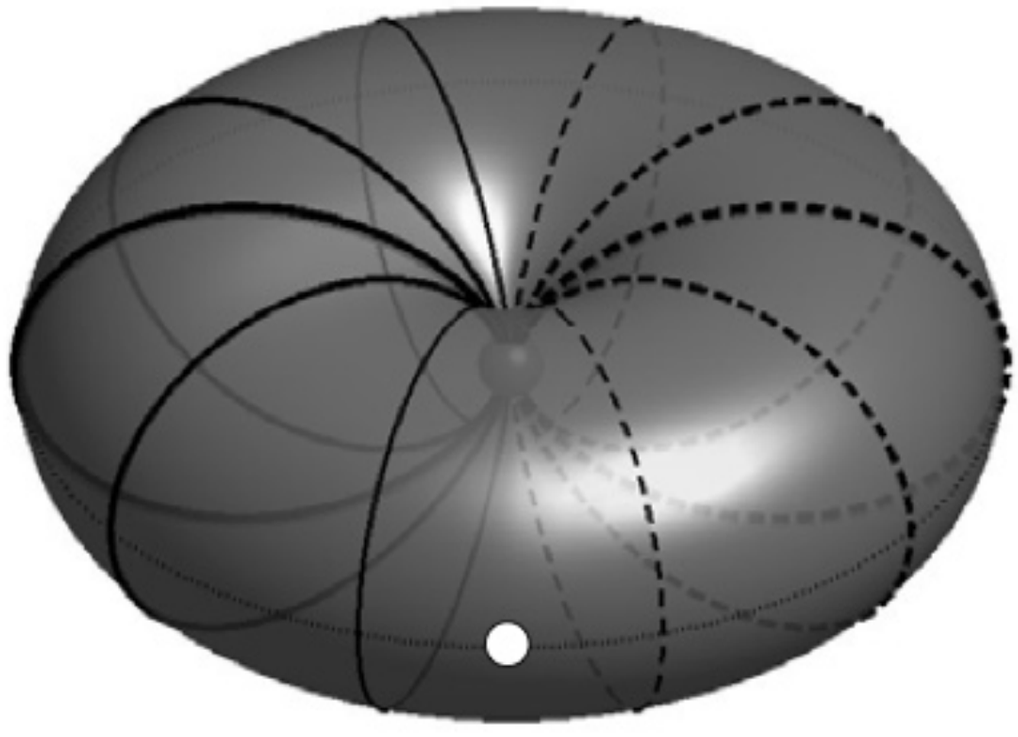


Khurana et al. 2009

Smith, 2011



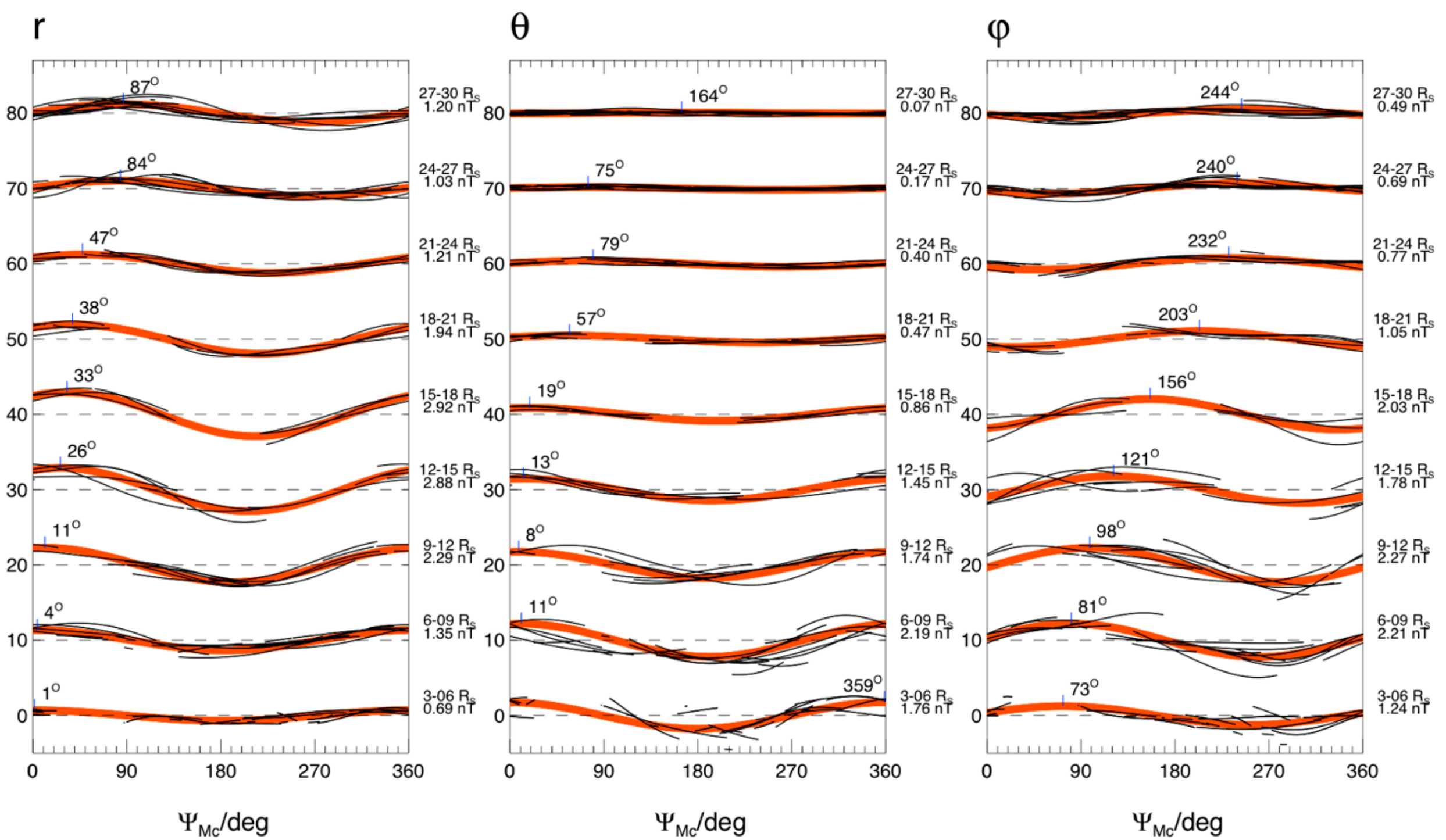


Southwood & Kivelson 2007

1
Equatorial field oscillations
(in which we apply Ampère's law)

Andrews, D. J., S. W. H. Cowley, M. K. Dougherty, and G. Provan (2010a), **Magnetic field oscillations near the planetary period in Saturn's equatorial magnetosphere: Variation of amplitude and phase with radial distance and local time**, *J. Geophys. Res.*, *115*, A04212, 10.1029/2007JA014729.

Amplitude and phase of field oscillations (near local midnight)

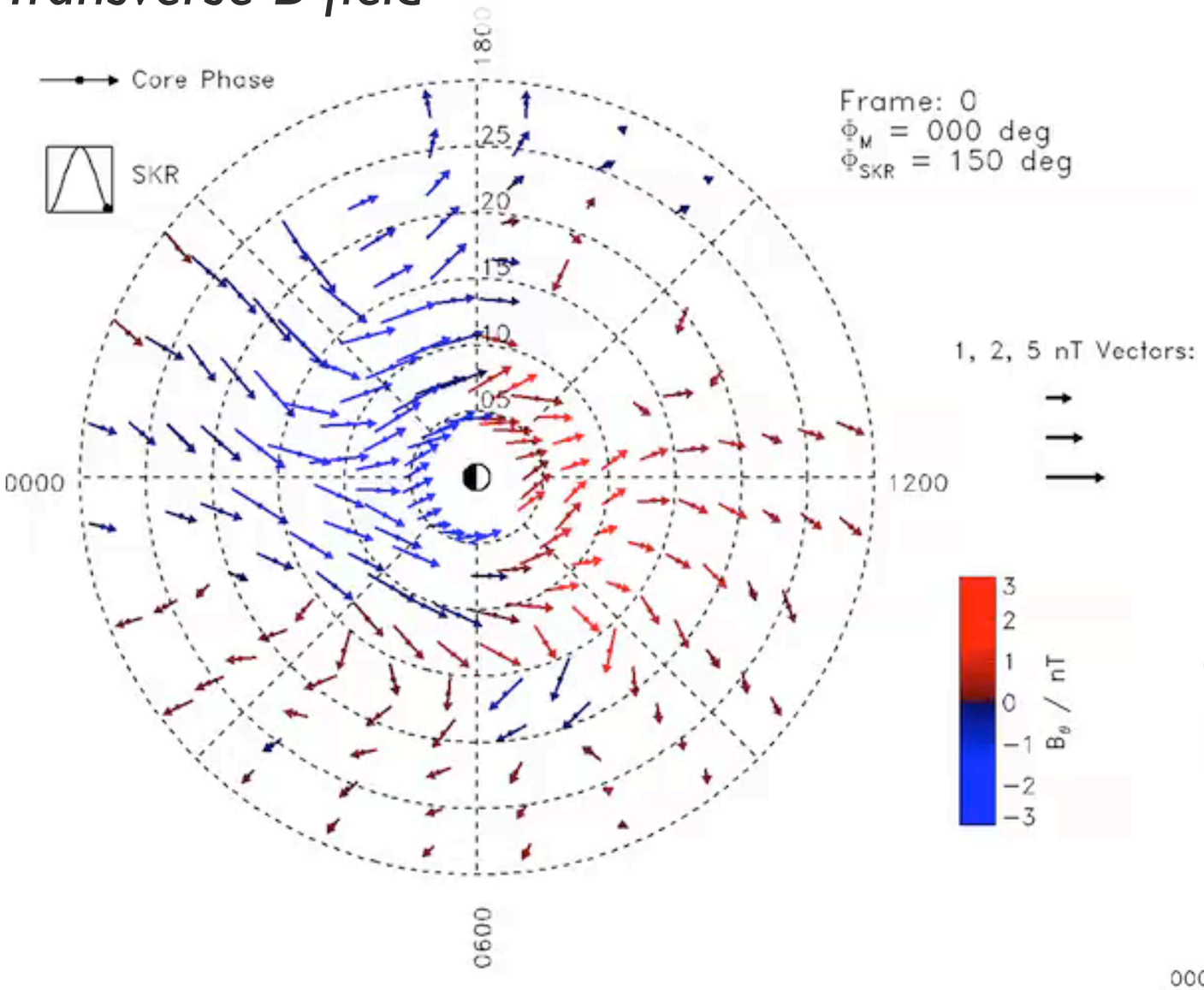


$$B_i(\varphi, t) = B_{i0}(r, \varphi) \cos\left[\Phi_{SKR}(t) - \varphi - \psi(r, \varphi)\right]$$

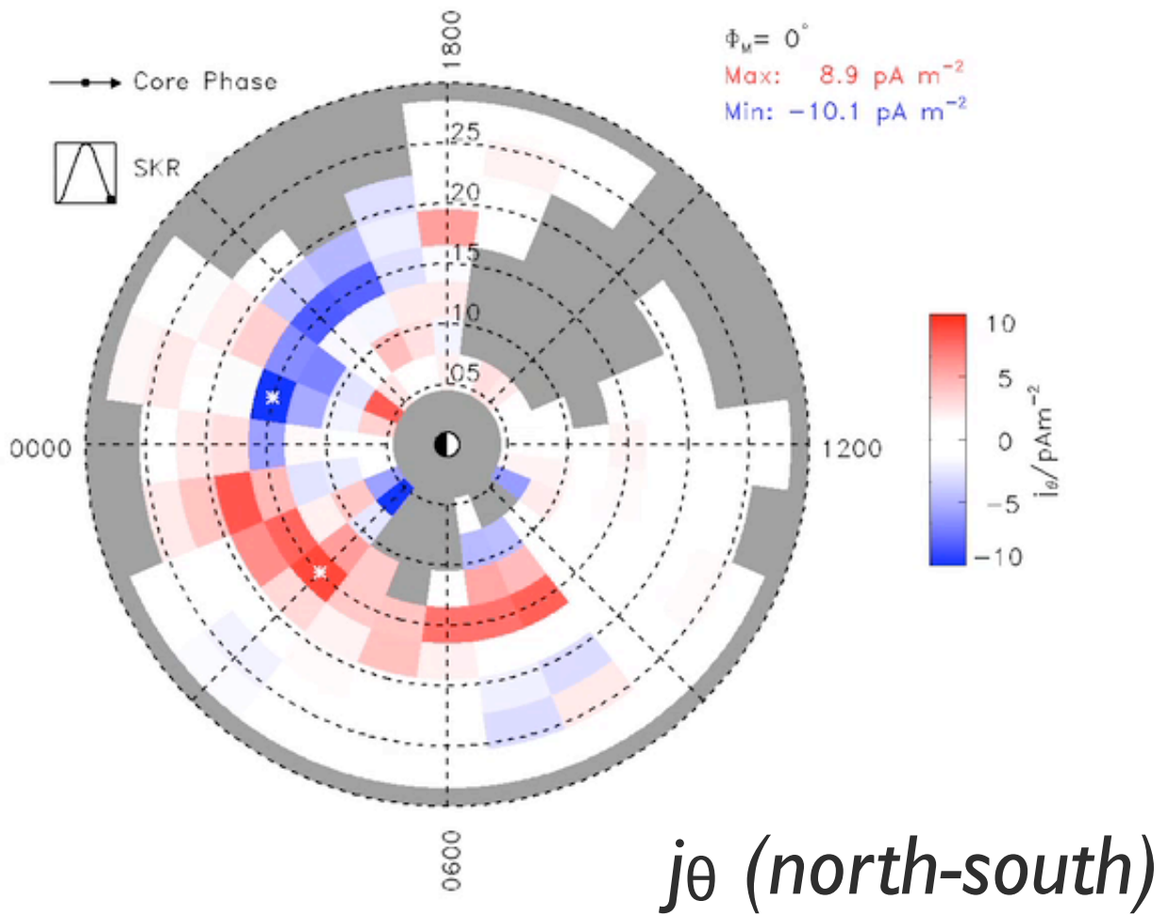
Equatorial field oscillations

- Previous work has determined the form of the rotating magnetic field in Saturn's equatorial magnetosphere
  - *Data from 2004-2008*
  - *Quasi-uniform 'core' region out to L~12-15*
  - *Currents flowing at the edge of this region, ~±5 MA (~30% of the ring current)*

Transverse B field



- Exclusion of the field in the inner region
  - *Within L~3-4 (near Enceladus torus / rings)*
  - *Currents here too, ~±2 MA*



Andrews et al., 2010a

j_θ (north-south)

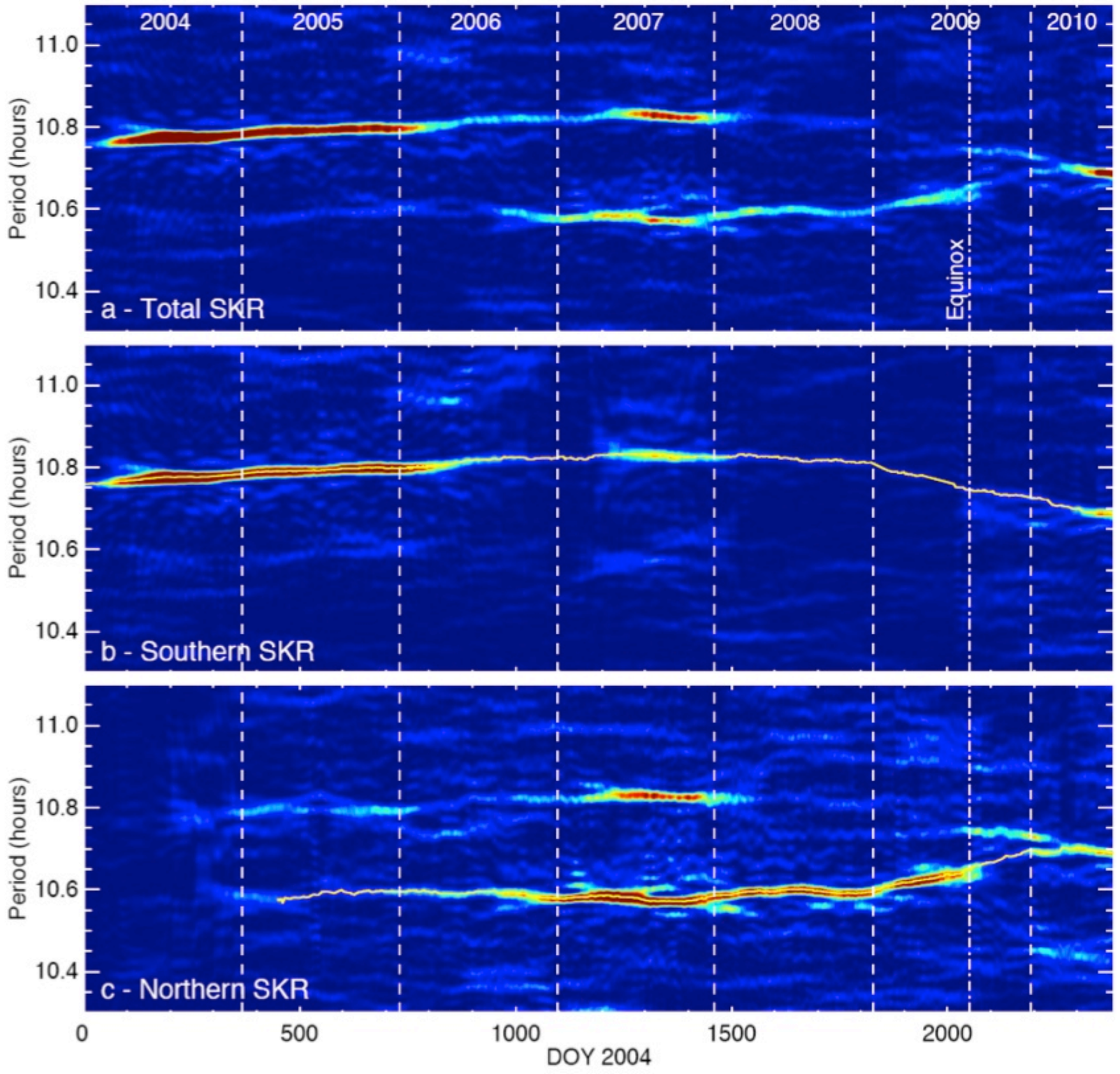
2
North-south asymmetries in periodicity
(the plot thickens)

Andrews, D. J., A. J. Coates, S. W. H. Cowley, M. K. Dougherty, L. Lamy, G. Provan, and P. Zarka (2010b), **Magnetospheric period oscillations at Saturn: Comparison of equatorial and high-latitude magnetic field periods with north and south SKR periods**, *J. Geophys. Res.*, *115*, A12252, 10.1029/2010JA015666.

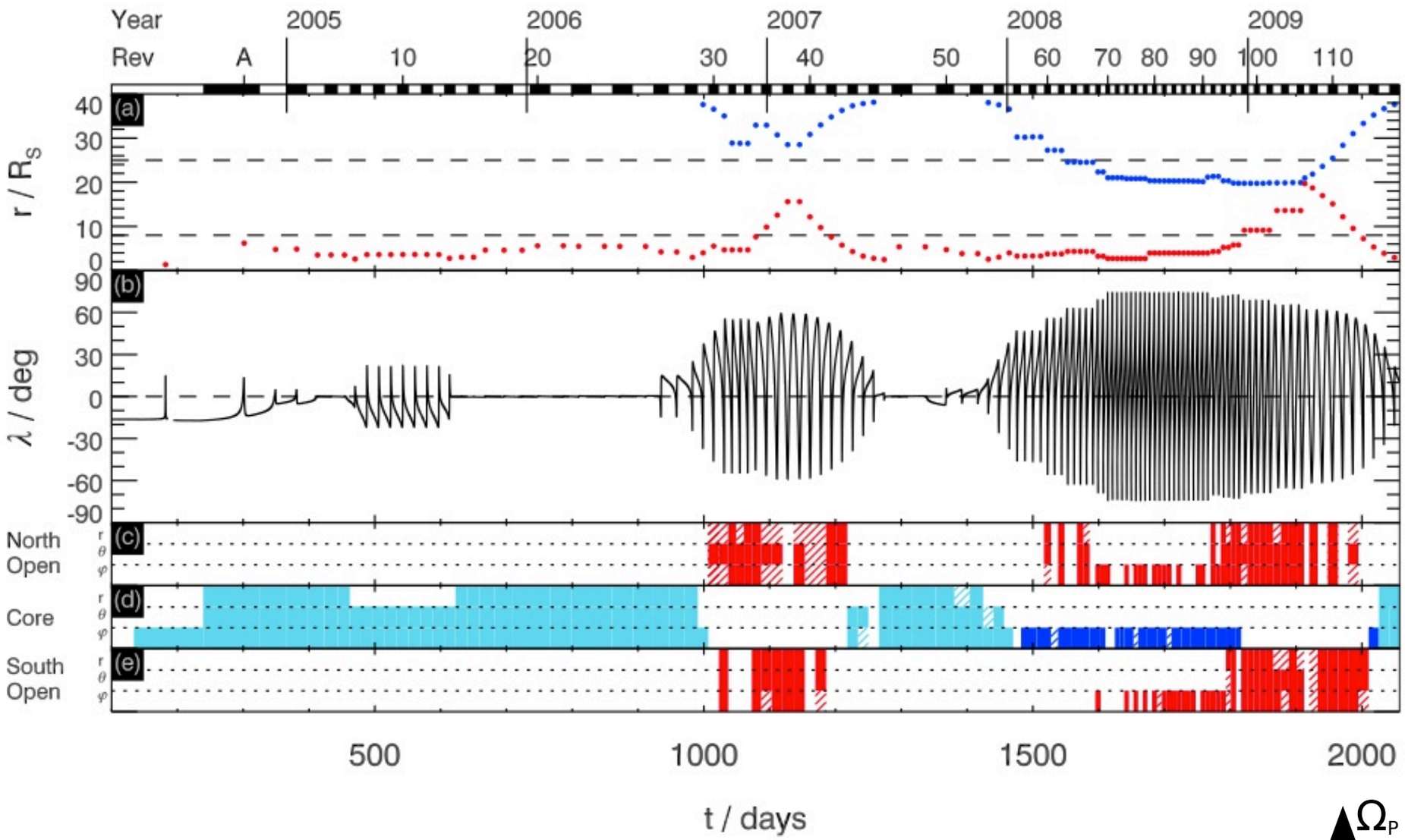
North-south asymmetry in the SKR modulation periods

Lamy, 2011

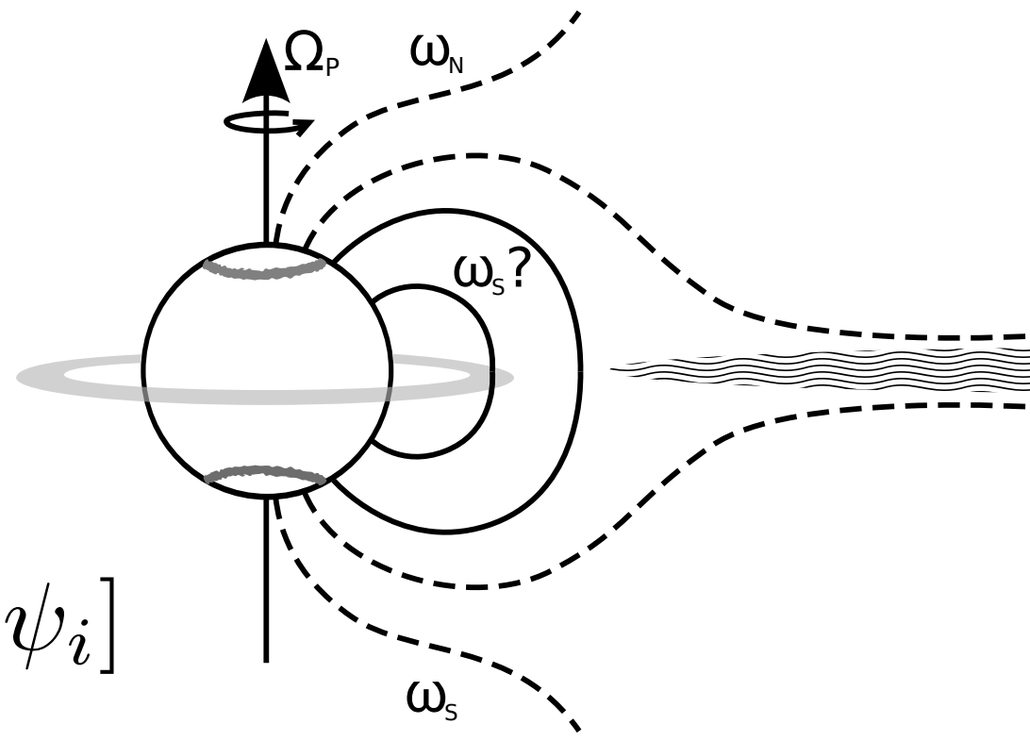
- Hints of important secondary periods present in the SKR data, even during Voyager era
  - *Gurnett et al. 2009 show that the weaker, shorter period emission originates from the north*
  - *Southern emission dominant, at least pre-equinox during the early Cassini mission*
  - *Both vary with time*
  - *Lamy, 2011 confirmed this, and produced independent phase models*



Is the same effect present in the magnetic data?



- Cassini's orbit extremely varied, covers a wide range of latitudes
- Polar orbits afford opportunity to study the open-field regions



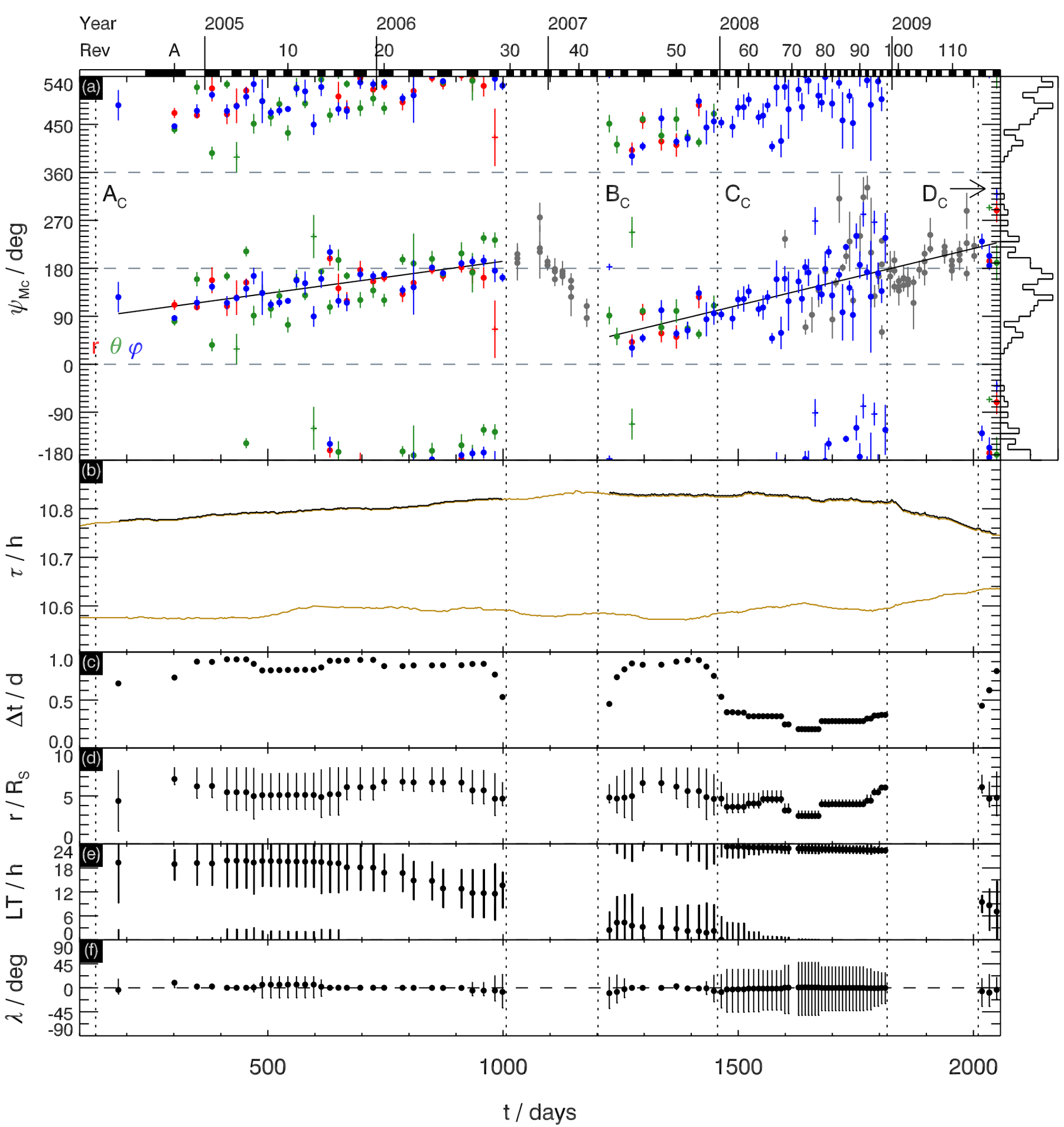
$$B_i(\varphi, t) = B_{i0} \cos\left[\Phi_{SKR}(t) - \varphi - \psi_i\right]$$

Core [L<8] results

(*With respect to **southern** SKR phase*)

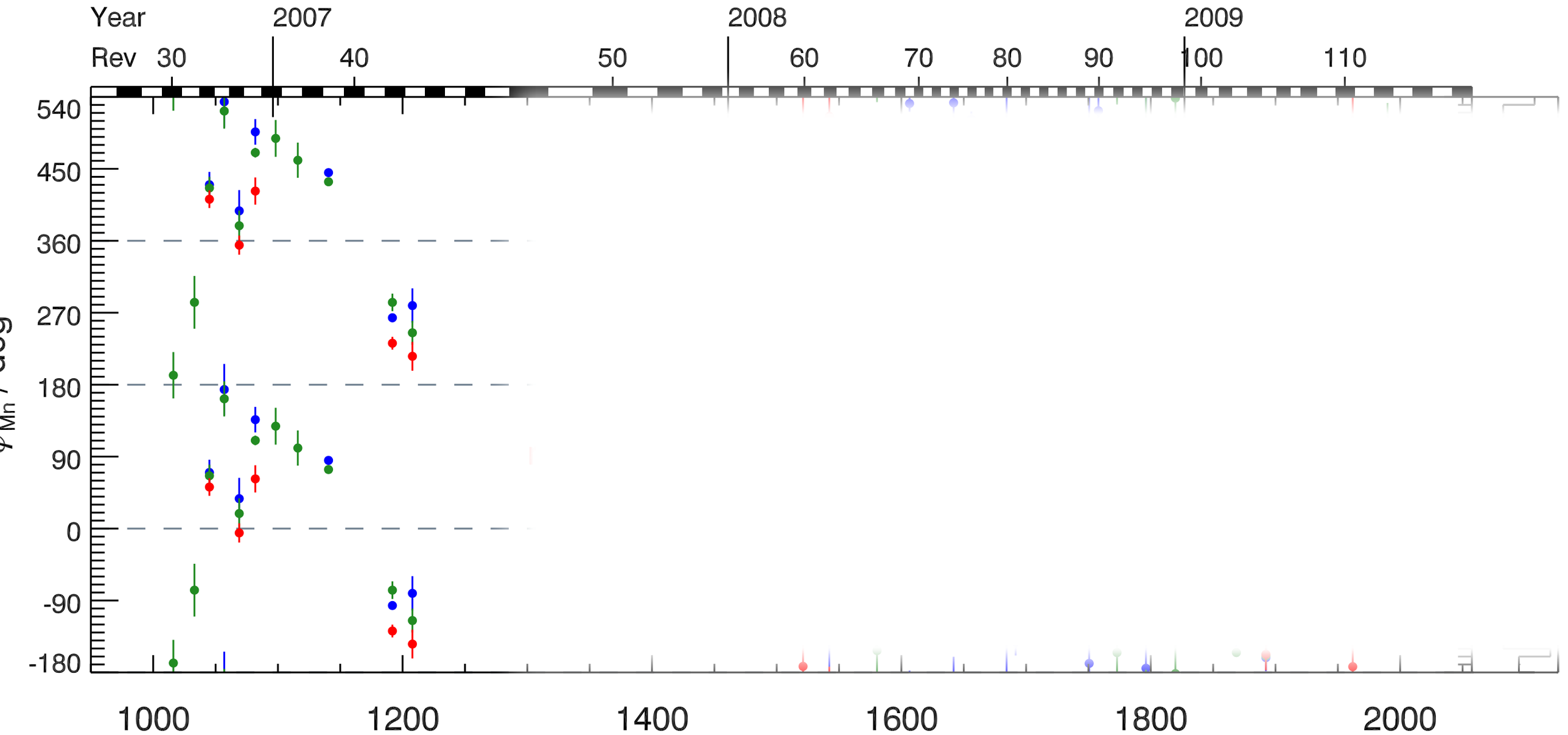
~10.8 h

- Clear banding of phase near ~**150º**
- Linear fits with small gradients imply period difference of ~**10 s**
  - *0.06% difference*
  - *Physical? Certainly consistent...*
- Polarisation implies **quasi-uniform rotating field** (90º subtracted from B_φ)
  - *Directed post-midnight at southern SKR maximum*



Northern hemisphere results

*(With respect to **southern** SKR phase)*



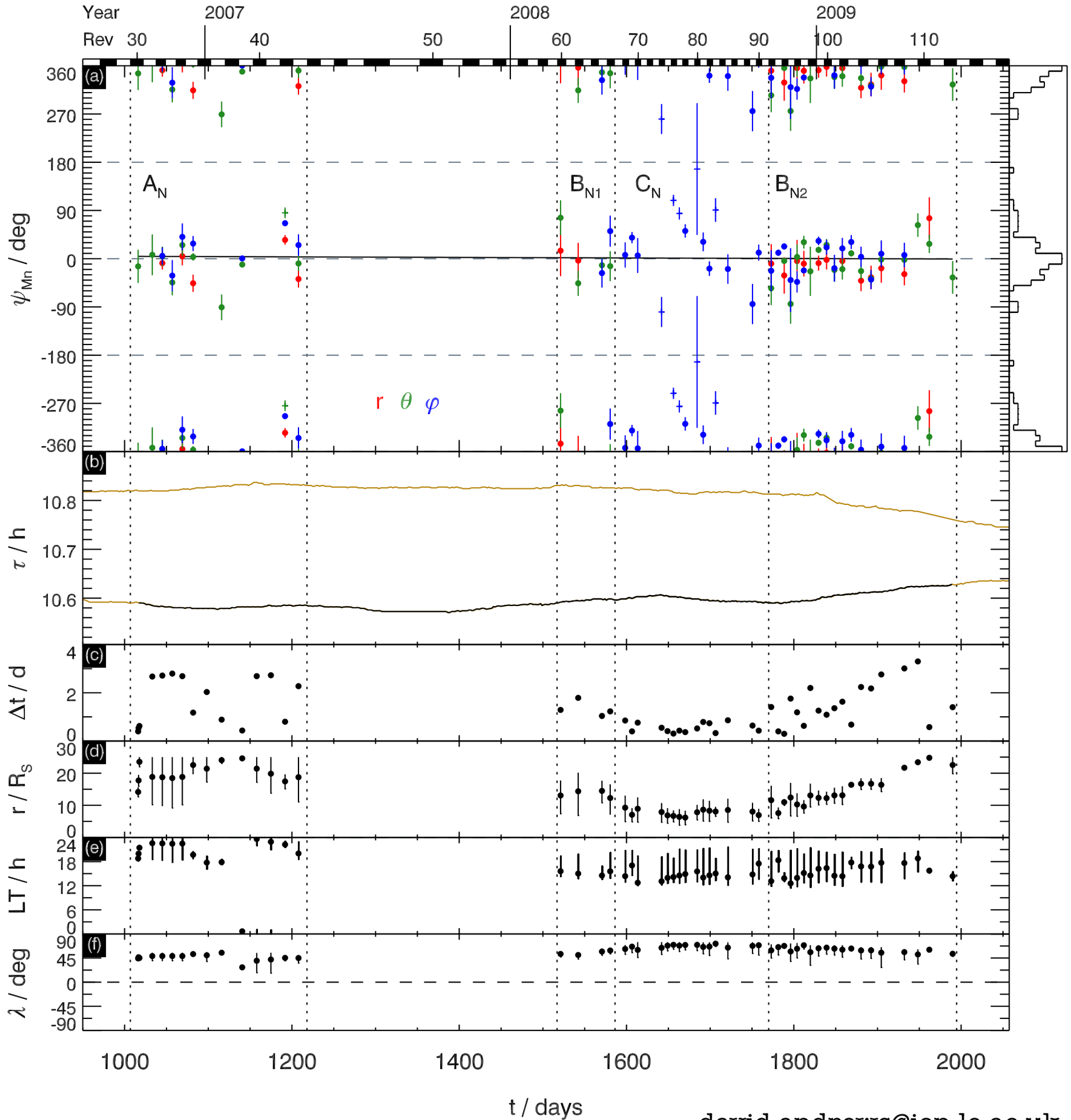
No phase organisation

Northern hemisphere results

(*With respect to **northern** SKR phase*)

~10.6 h

- Banding of phase near ~**0º** i.e. almost **180º** adrift from southern hemisphere result.
- No significant difference in periodicity
- Polarisation again implies a **rotating transverse dipole**
  - *Directed approximately sunward at northern SKR maximum*



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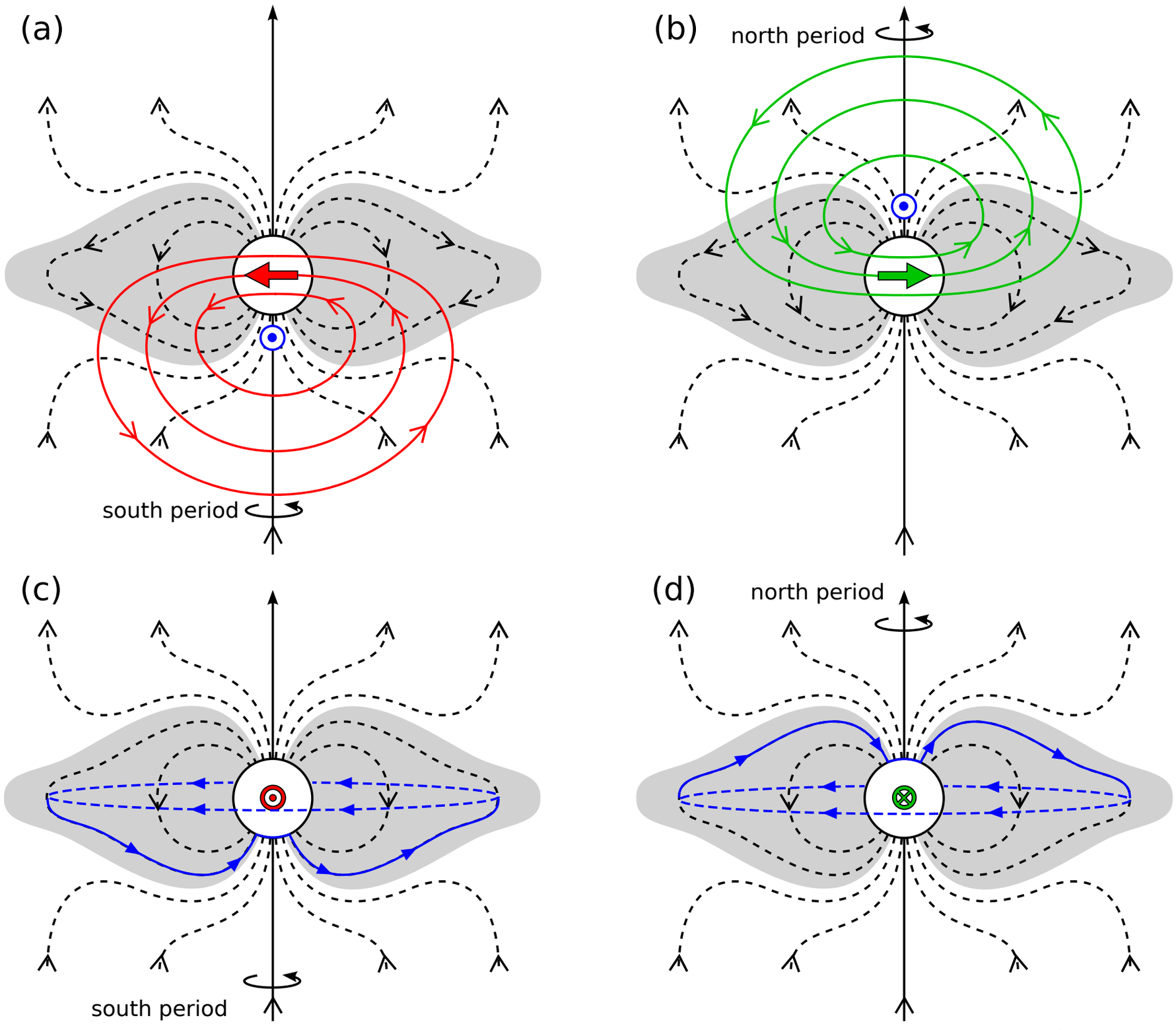
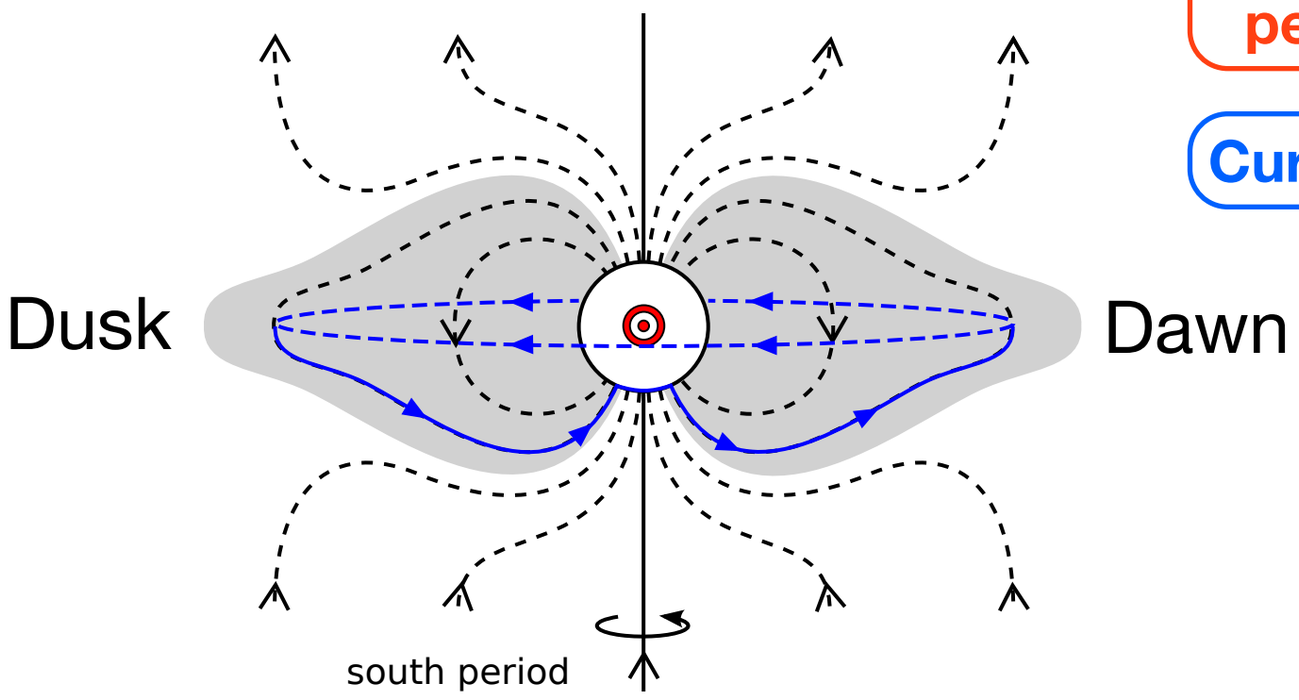

(a)
south period
(b)
north period
(c)
south period
(d)
north period

3
Rotational modulation of the SKR
(in which we are accused of "heresy")

Andrews, D. J., B. Cecconi, S. W. H. Cowley, M. K. Dougherty, L. Lamy, G. Provan, and P. Zarka (2011), **Planetary period oscillations at Saturn: Evidence in magnetic field phase data for rotational modulation of Saturn kilometric radiation emissions**, *J. Geophys. Res.*, 10.1029/2011JA016636.

Southern magnetic field oscillations and SKR modulation

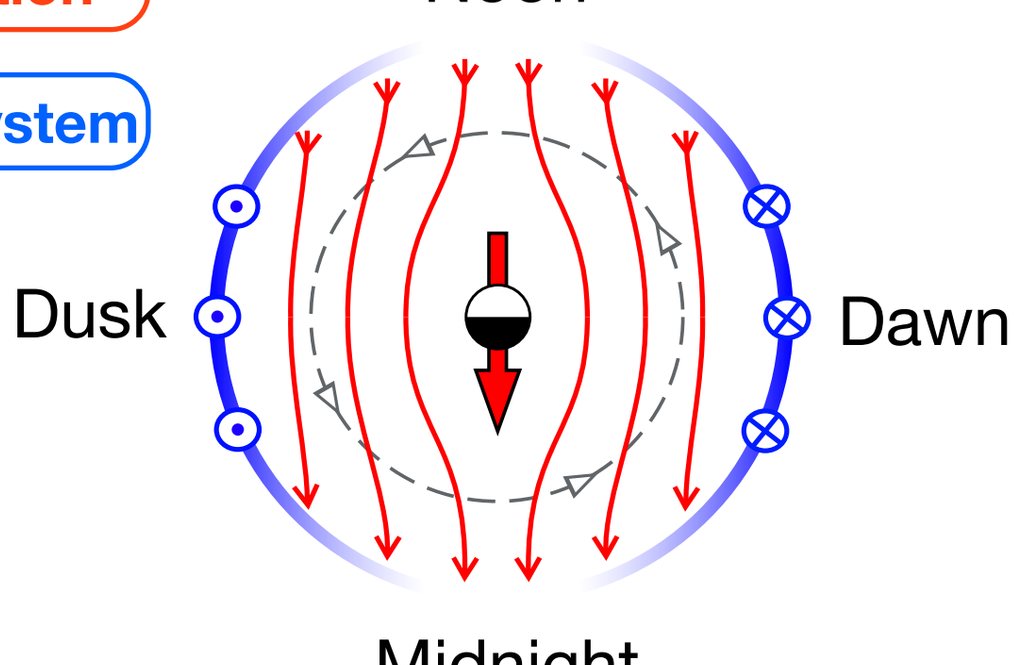
Meridional planes

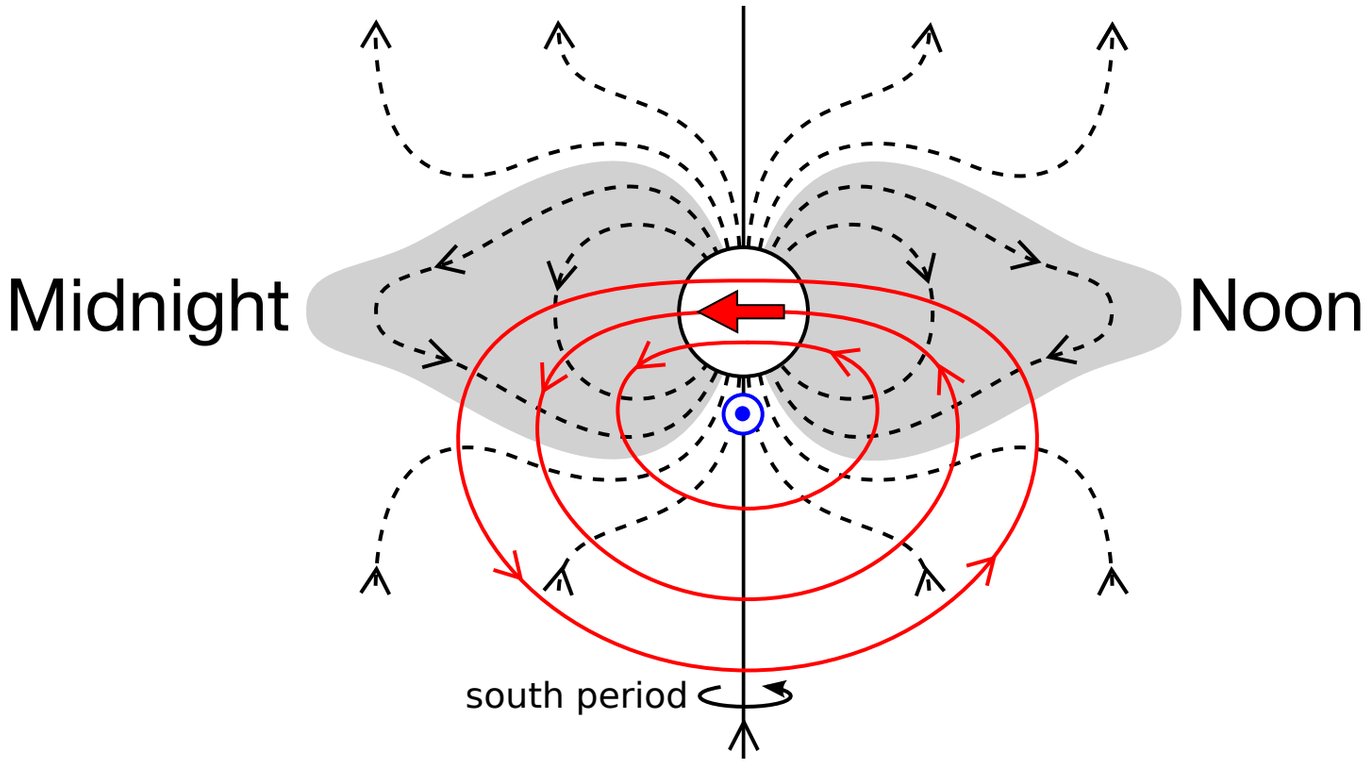


Magnetic field perturbation

Current system

Equatorial plane



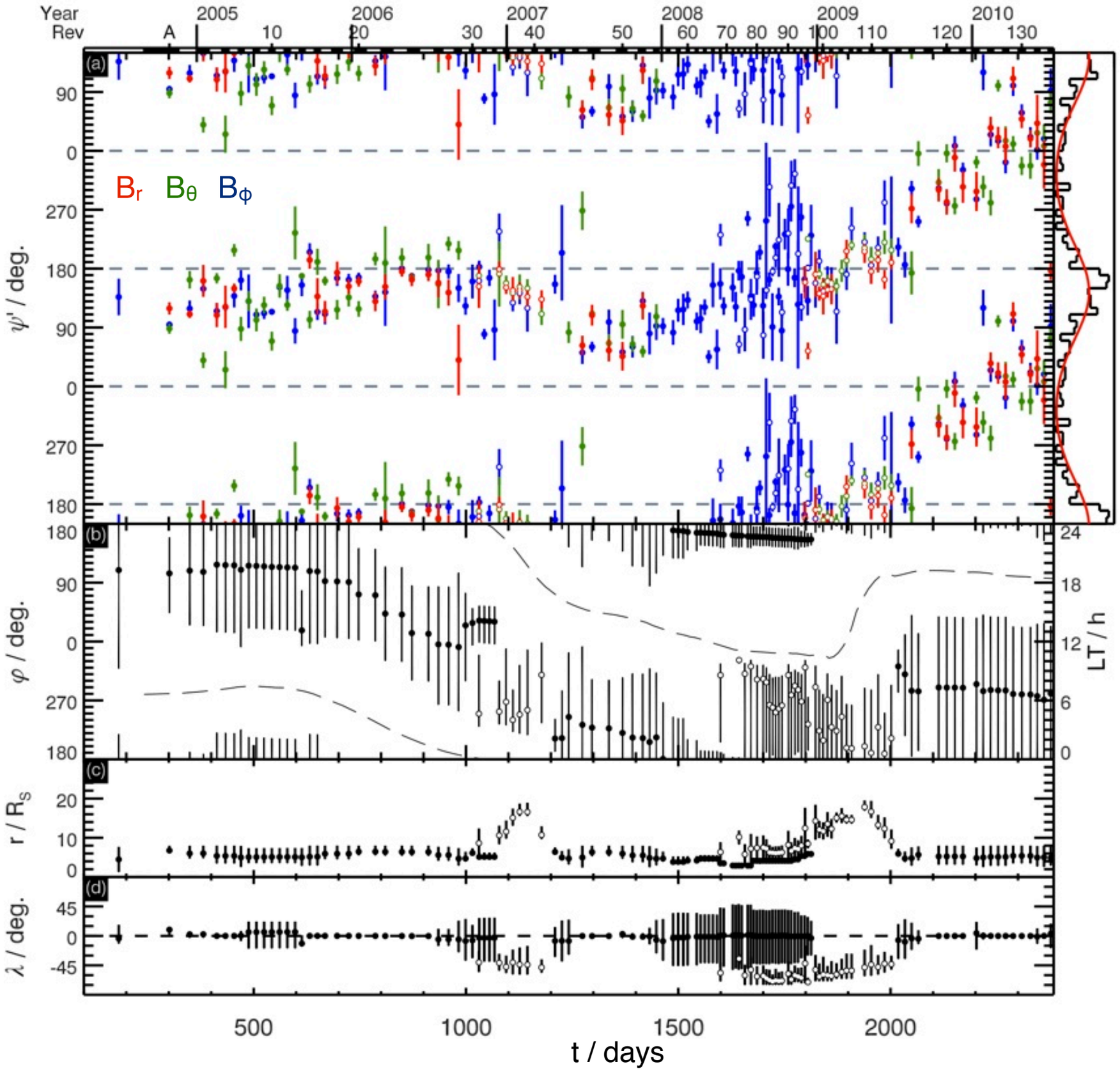


- Rotating current system producing magnetic perturbation field
- Current density has a ~cos(φ) dependence
  - *Produces observed rotating 'quasi-uniform' equatorial field*
  - *'Quasi-dipolar' field at high-latitudes*
- Equivalent northern system also exists
  - *Andrews et al. [2008,2010], Provan et al. [2009]*

Rotating magnetic field phase

$$B_i(\varphi, t) = B_{i0} \cos\left(\Phi_{SKR,s}(t) - \varphi - \psi_i\right)$$

- **Rotating** magnetic field phase determined in
  - *'core' magnetosphere (dipole L < 8)*
  - *open southern field lines*
- Determined relative to observed southern (dominant) SKR modulation phase
- Central value of ~150° implies core field points down-tail & post-midnight at southern SKR maximum (towards ~02 h LT)
- **Marked ~180° departure in most recent data**
- Persistent small gradients imply differences in period
  - *Typically ± few seconds*
  - ***Suggestion of variation with orbit geometry?***
  - ***Does the SKR observed modulation phase depend on position?***



A simple model of rotating SKR & its detection by Cassini

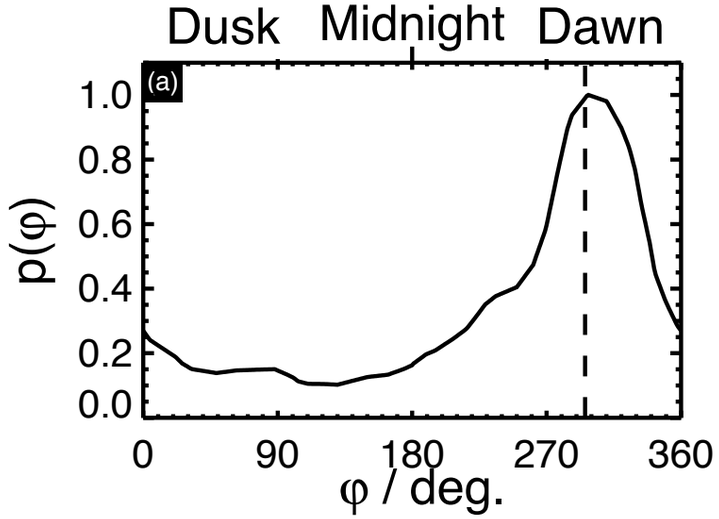
- Since detection in Voyager data, SKR believed to be strobe-like
  - *Modulation phase independent of observer position*

- **What if the SKR were a rotating phenomena?**
  - *Phase would then vary with observer azimuth*
  - ***Can this explain the changes seen in magnetic phase relative to SKR?***

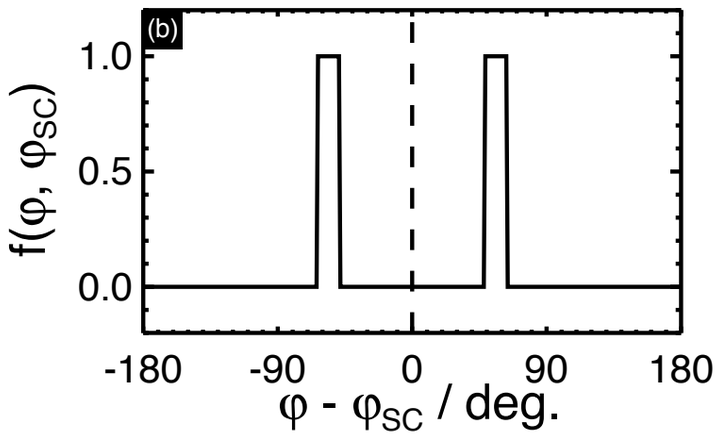
- SKR 'amplitude' strongly dependent on azimuth / LT

- Emitted at local gyrofrequency on high-latitude field lines:
  - *Visibility of SKR sources generally restricted to narrow bands either side of the spacecraft meridian*
  - *'Seeing function' based on results of Lamy et al. [2008] modeling study*

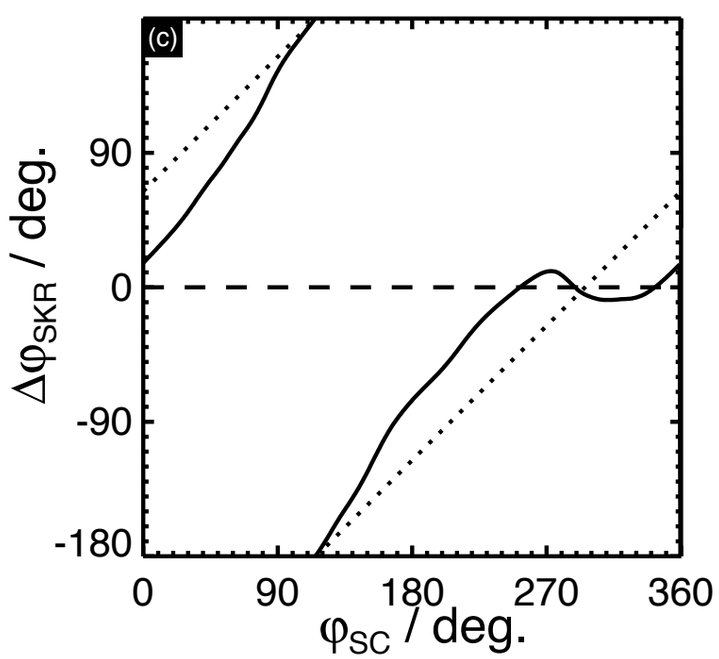
- Constructed a simple theoretical model including these effects
  - *Phase difference between the 'observed' modulation and that of the total emission is then*



Lamy et al., [2005]

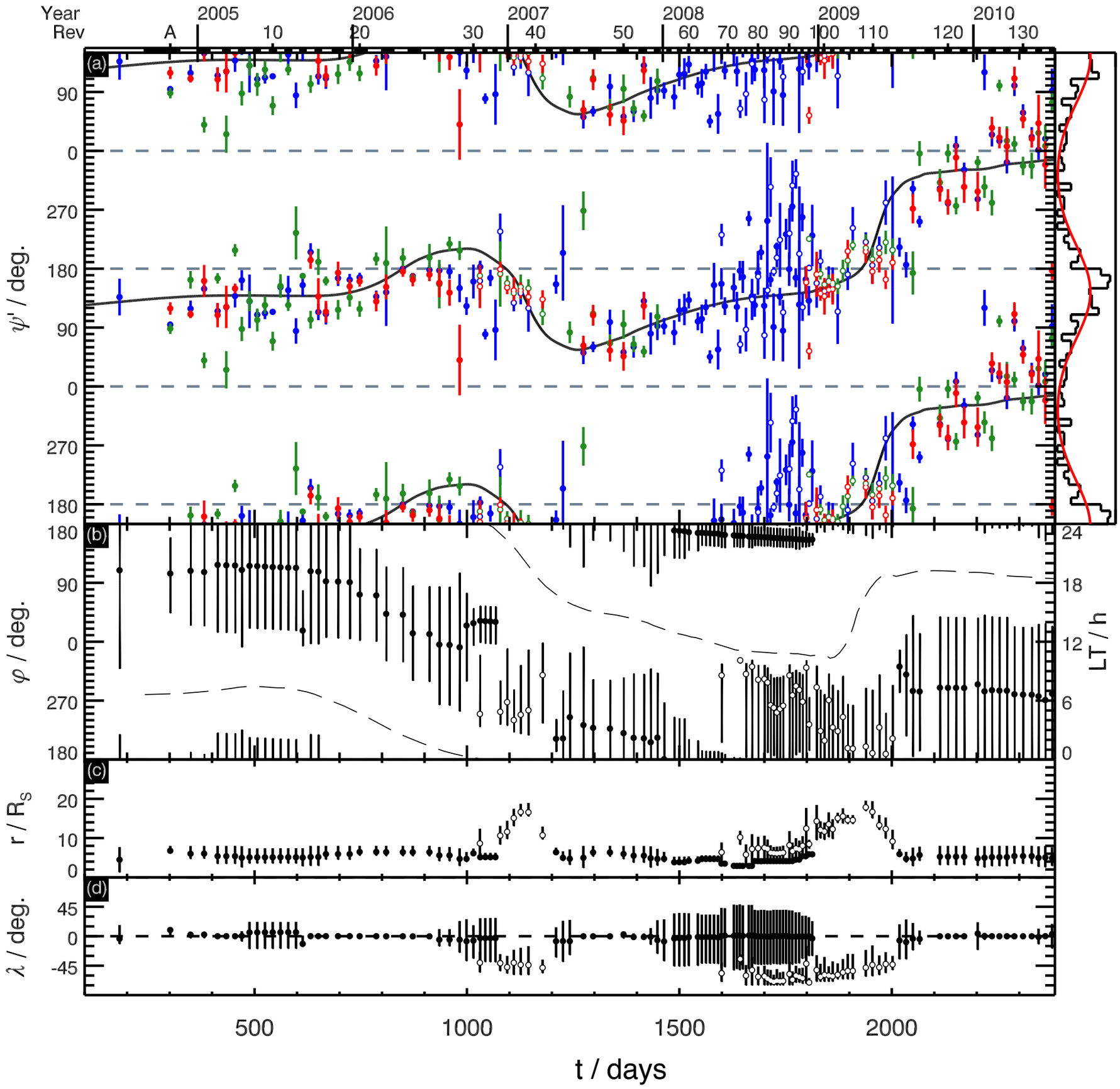


Lamy et al., [2008]



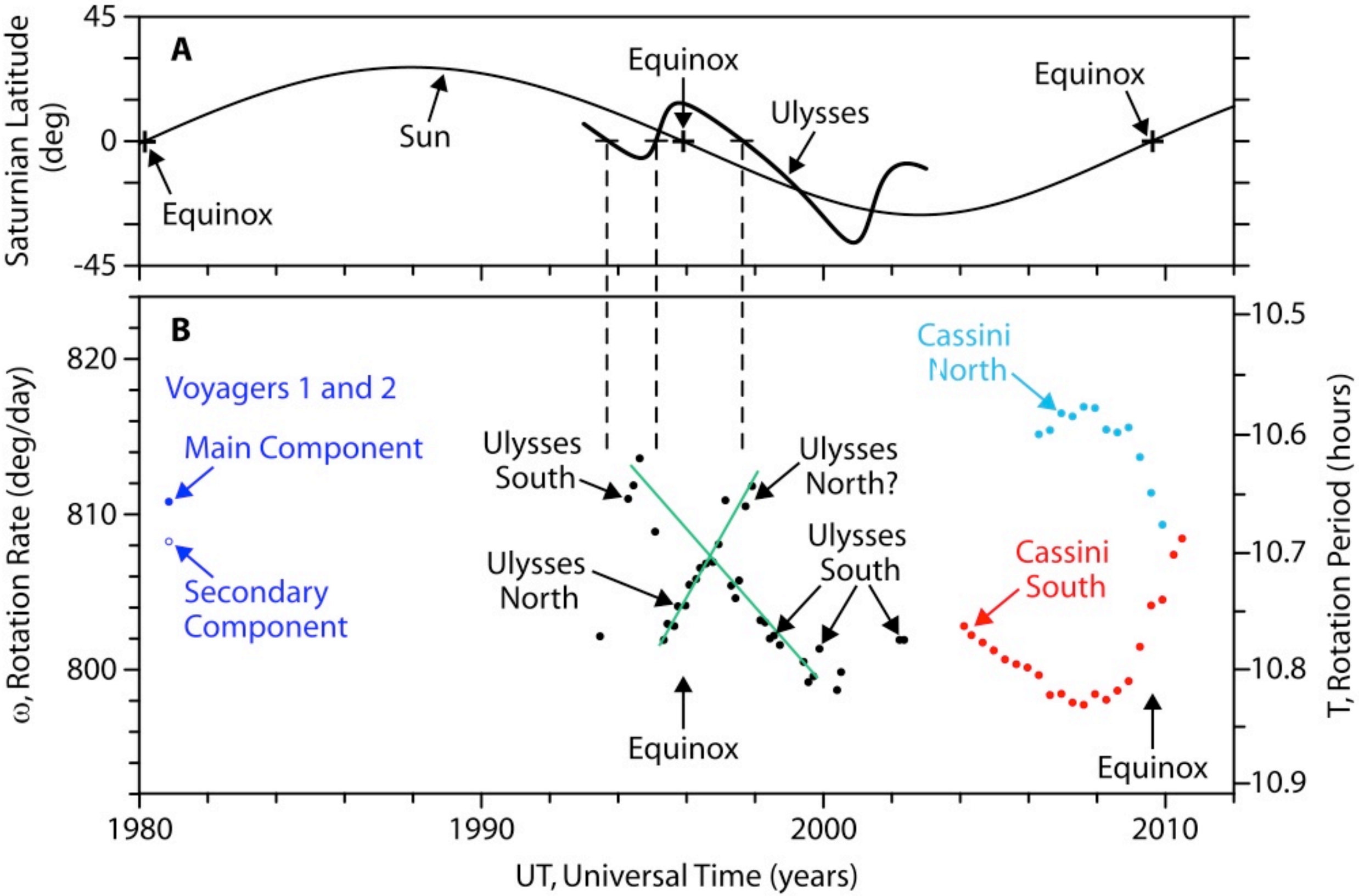
Differences in magnetic and SKR periodicity

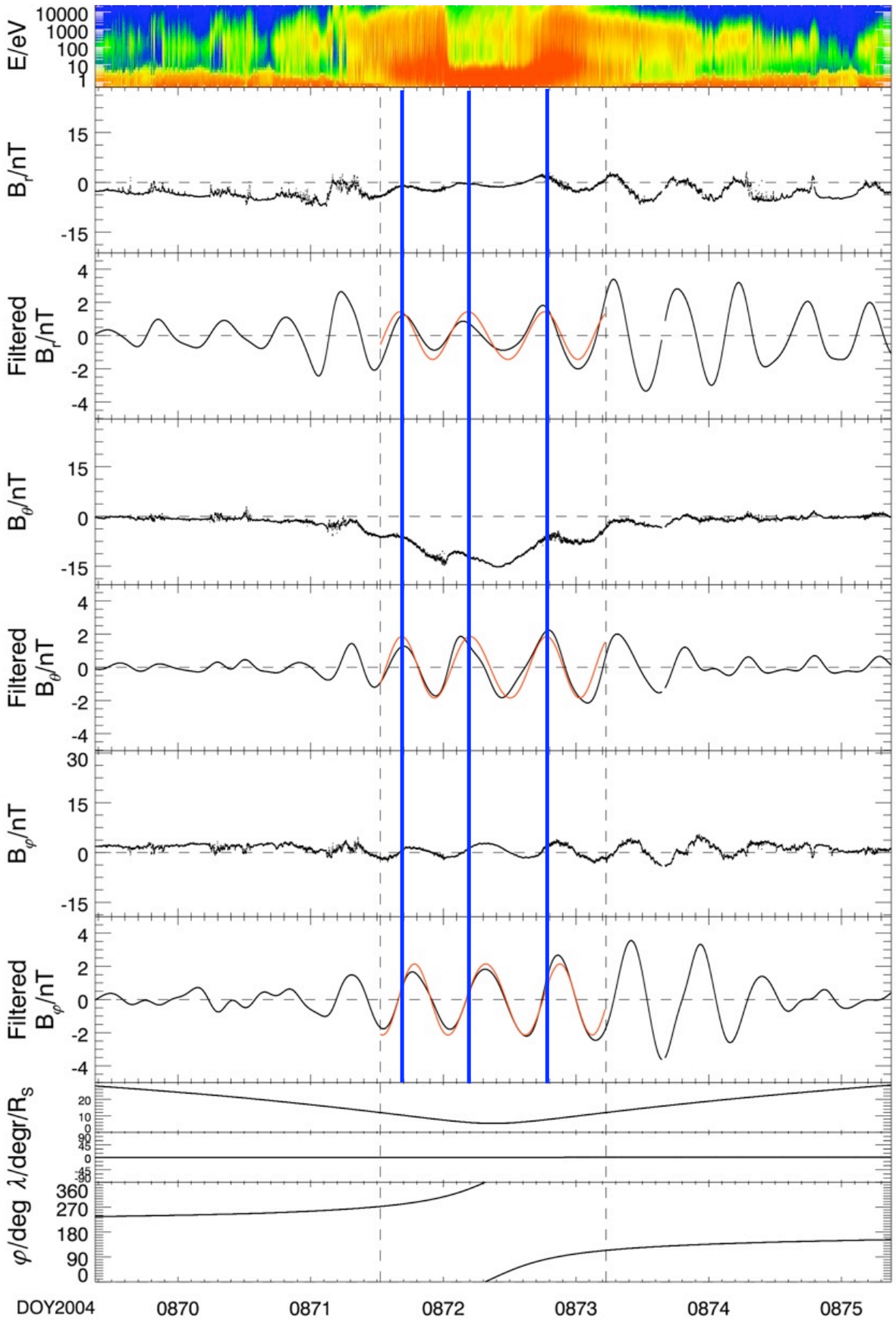
- Evaluate phase difference along spacecraft trajectory
  - *By (**directionally**) averaging phase difference over each orbit*
  - *Additional (**directional**) smoothing to allow comparison with ~200 day SKR modulation phases used*
- Modeled phase deviation is in excellent agreement with magnetic phase data
  - ***Subtracting this effect leads to significant ~30% reduction in the RMS variation***
  - *Matches the 180° shift in most recent data*
- **Magnetic phase therefore constant with respect to the 'true' rotating SKR modulation**



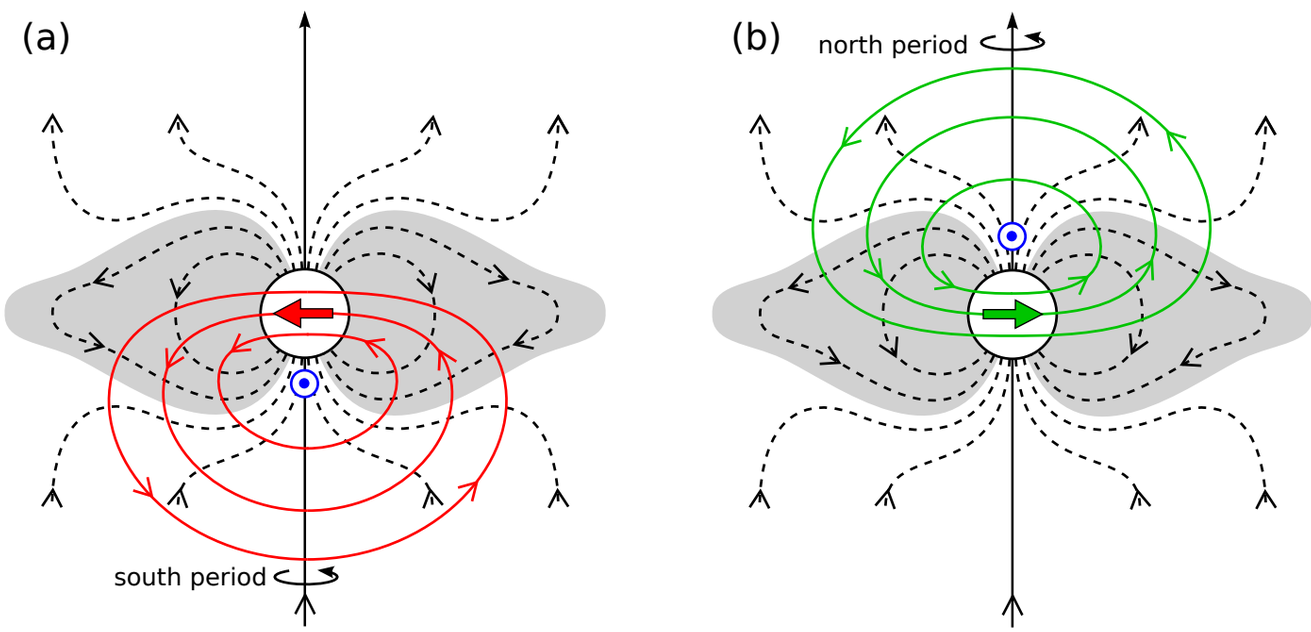
4
Magnetic equinox?
(*approaching submission, maybe?*)

Gurnett et al., 2010





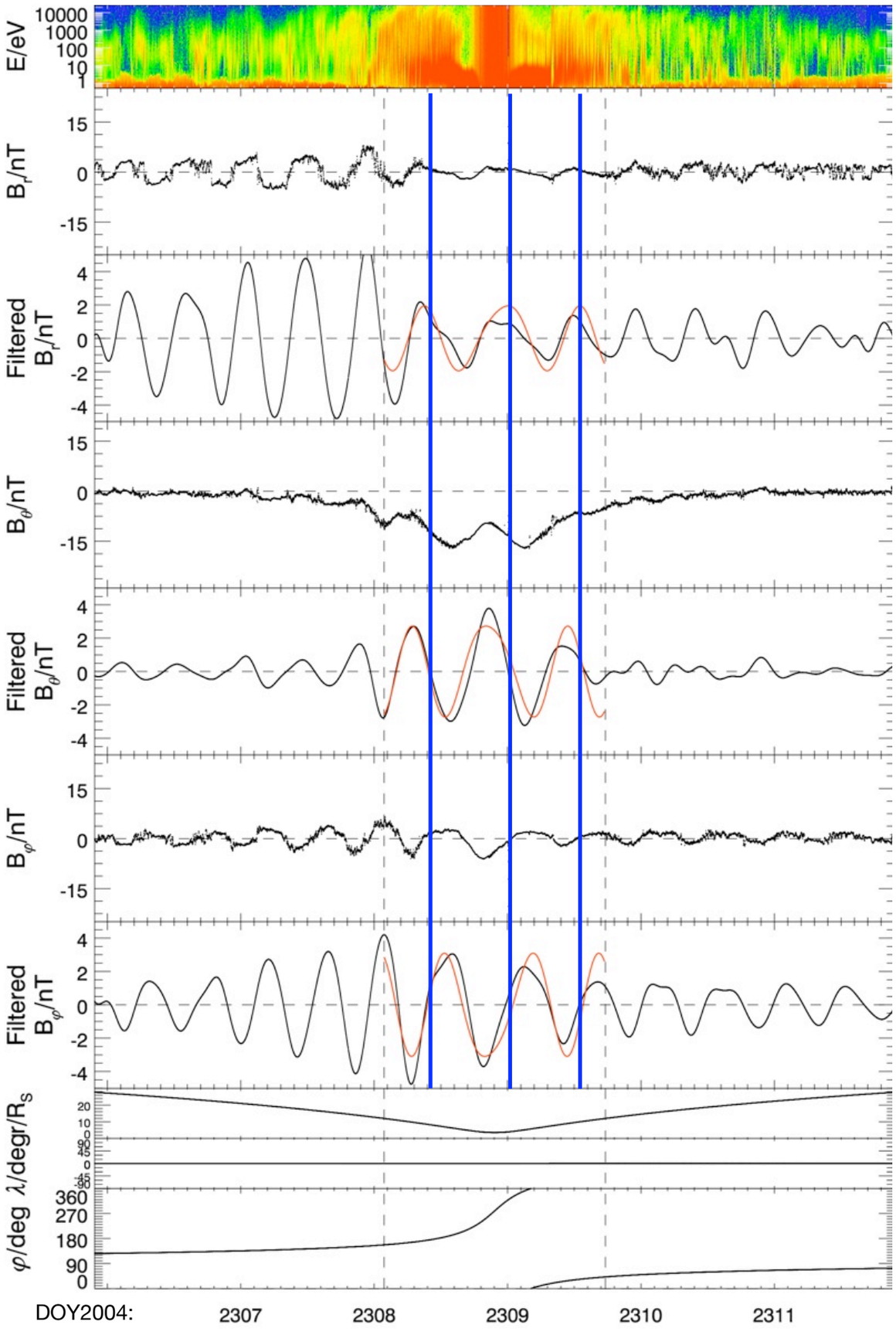
- Oscillations near the ~10.5 h planetary rotation period are ubiquitous throughout Saturn's magnetosphere
  - *Detected in Saturn kilometric radiation (SKR), magnetic field, auroral oval & power, magnetopause & bow shock, ...*
- Period changes by ~1% per year *[Galopeau & Lecacheux, 2000]*
- Recent discovery of a weaker, shorter period signal from the north in magnetic & SKR data
  - *Pre-equinox (August 2009), the southern 'system' was dominant*
  - *Seasonal convergence of both periods to a common value*
    [Gurnett et al., 2010; Lamy, 2011]



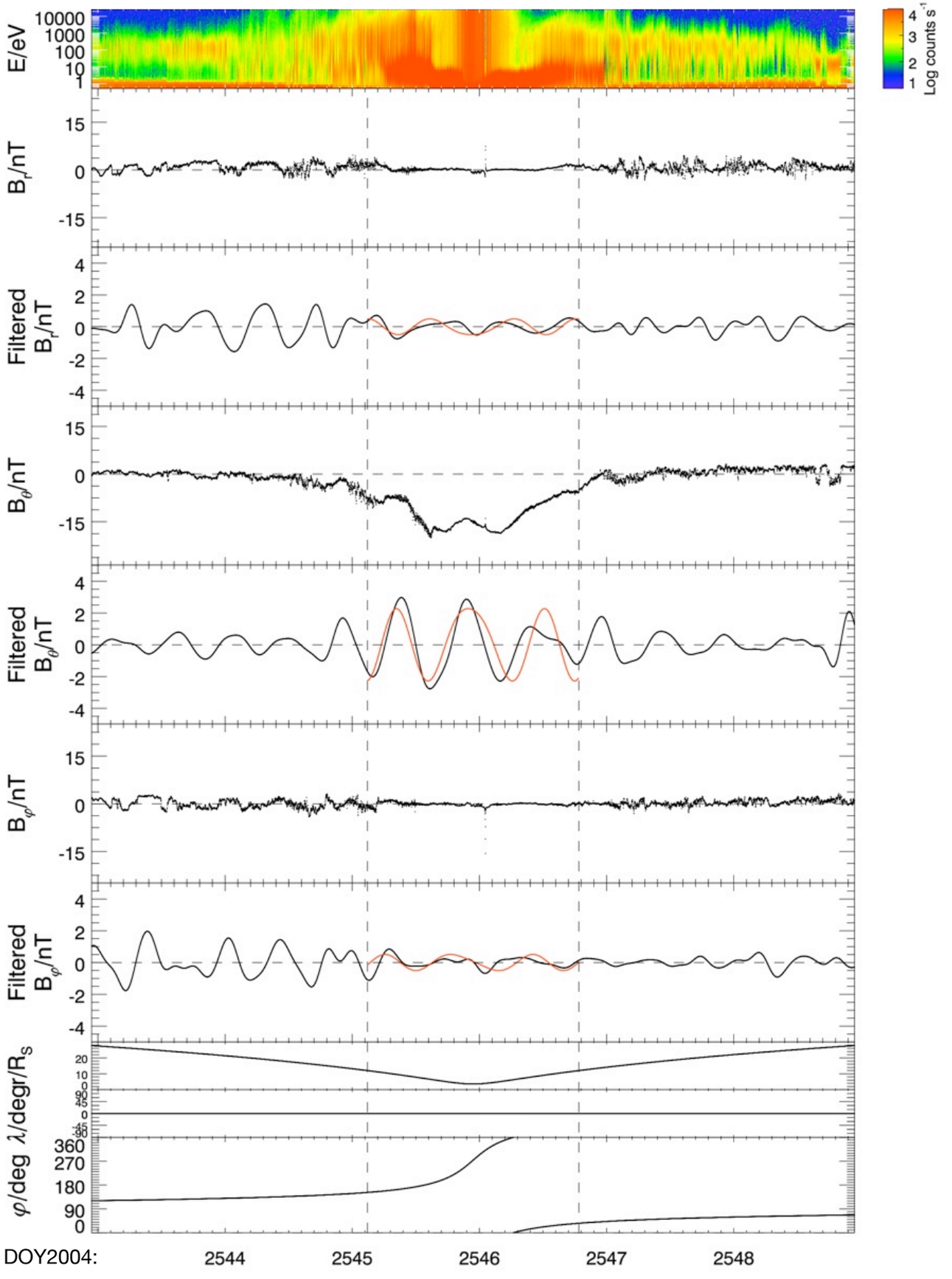
Andrews et al., [2010]

Post-equinox field signatures

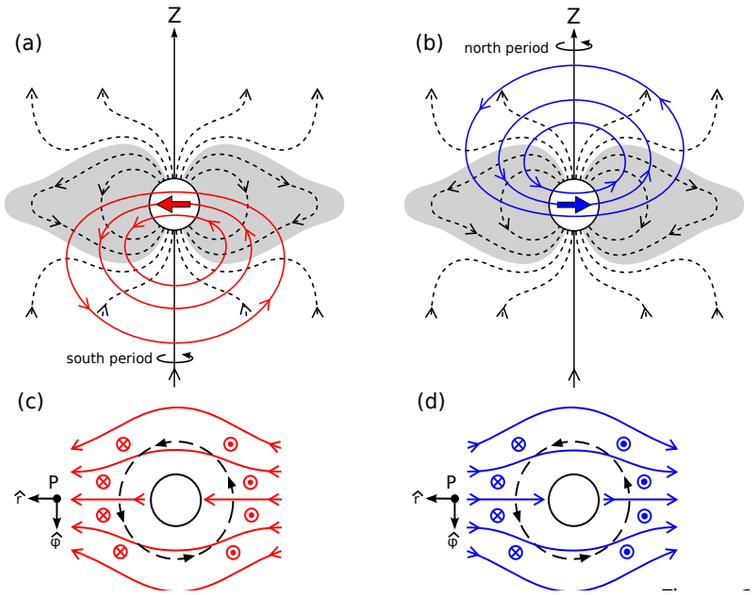
Rev 130: 2010/114-121



Rev 142: 2010/351-358

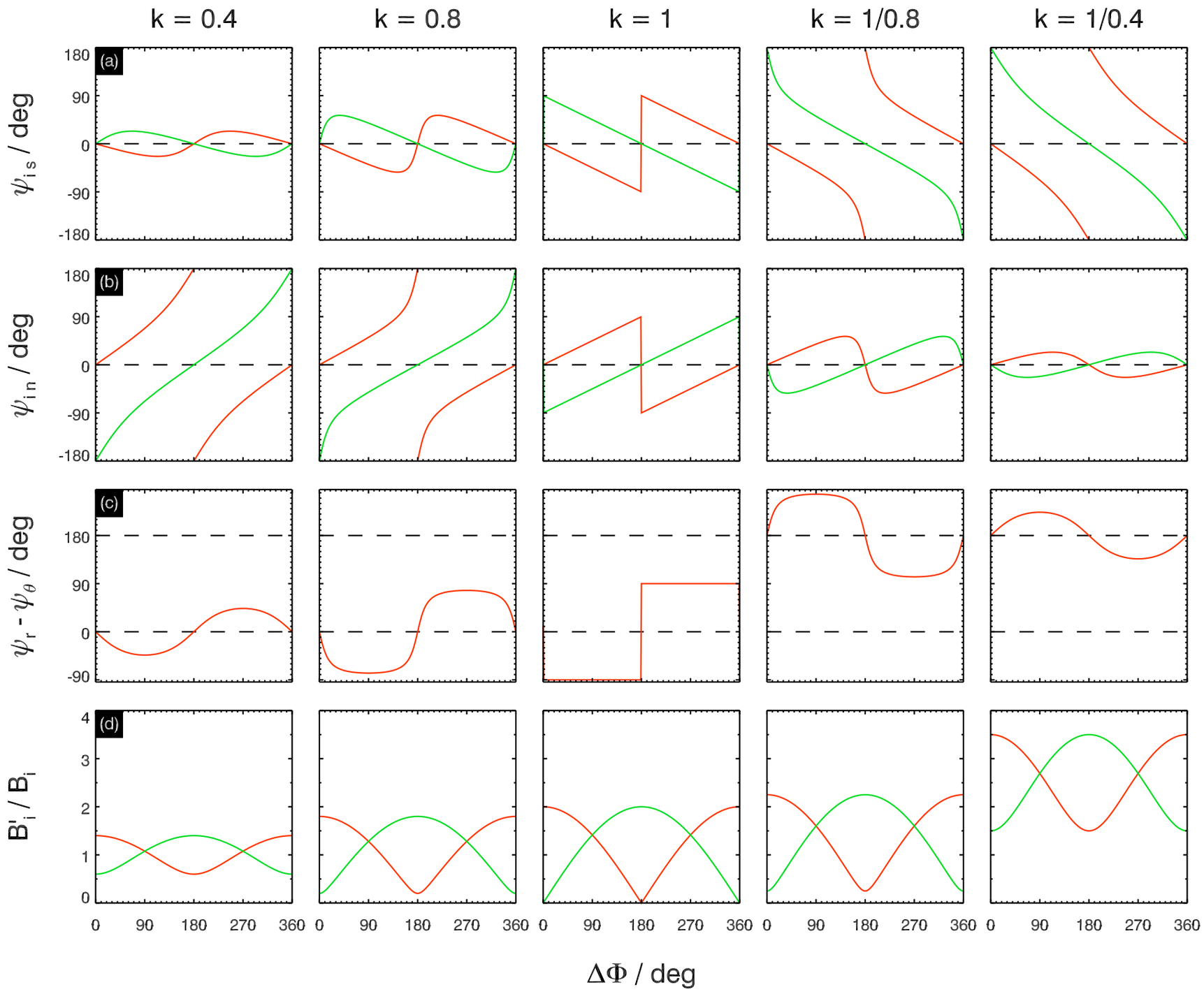


Effects of superposition of the two field perturbations



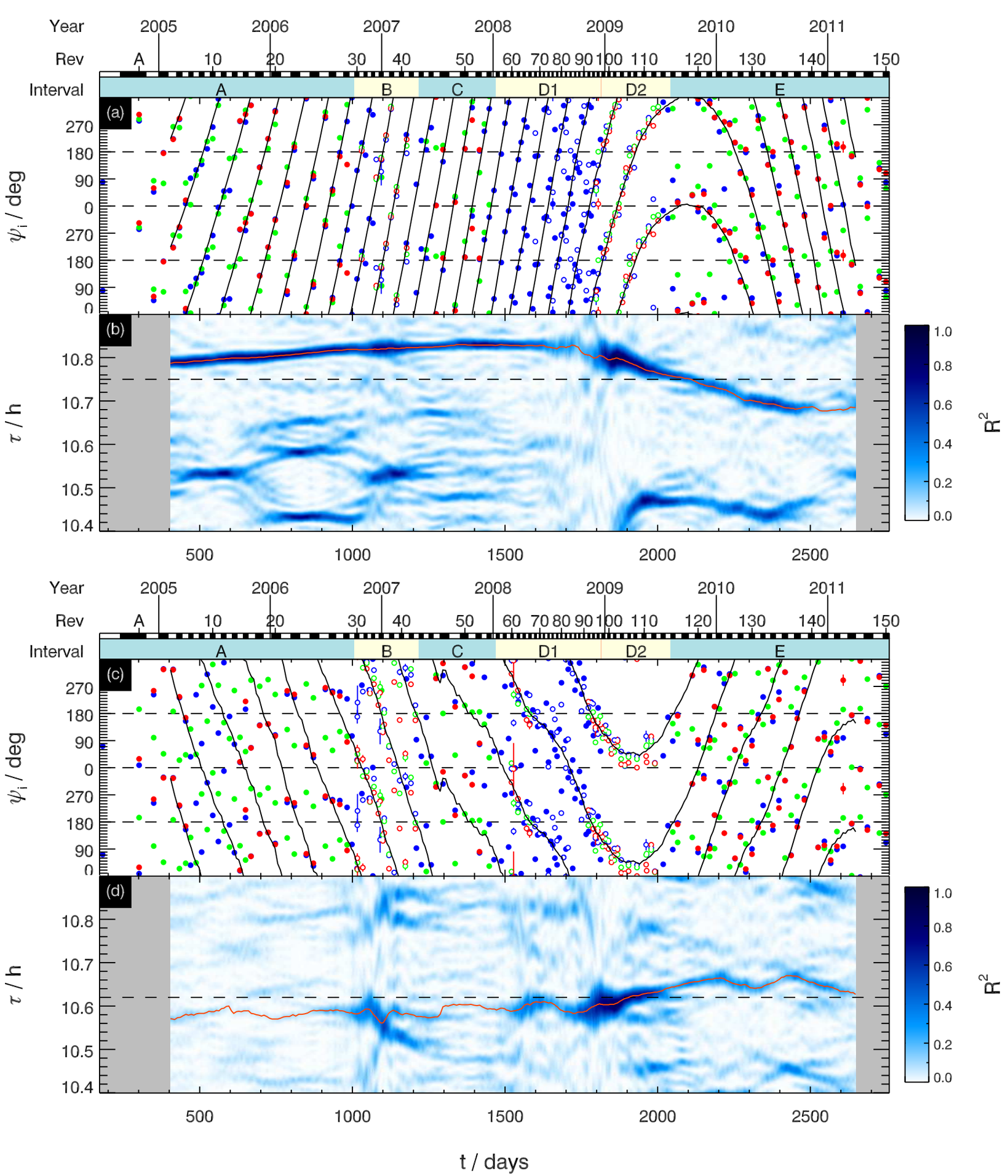
- Phase jitter varies on the ‘beat period’ ~ 23+ days
- Sense of the phase jitter can be used to determine the ratio of the two field strengths
- Same effect, but cycle is shifted for the θ component as compared to the transverse (r, φ)

- Both systems of field oscillations are superposed on closed field lines
  - *Causes coherent phase ‘jitter’ studied by Provan et al. 2011*

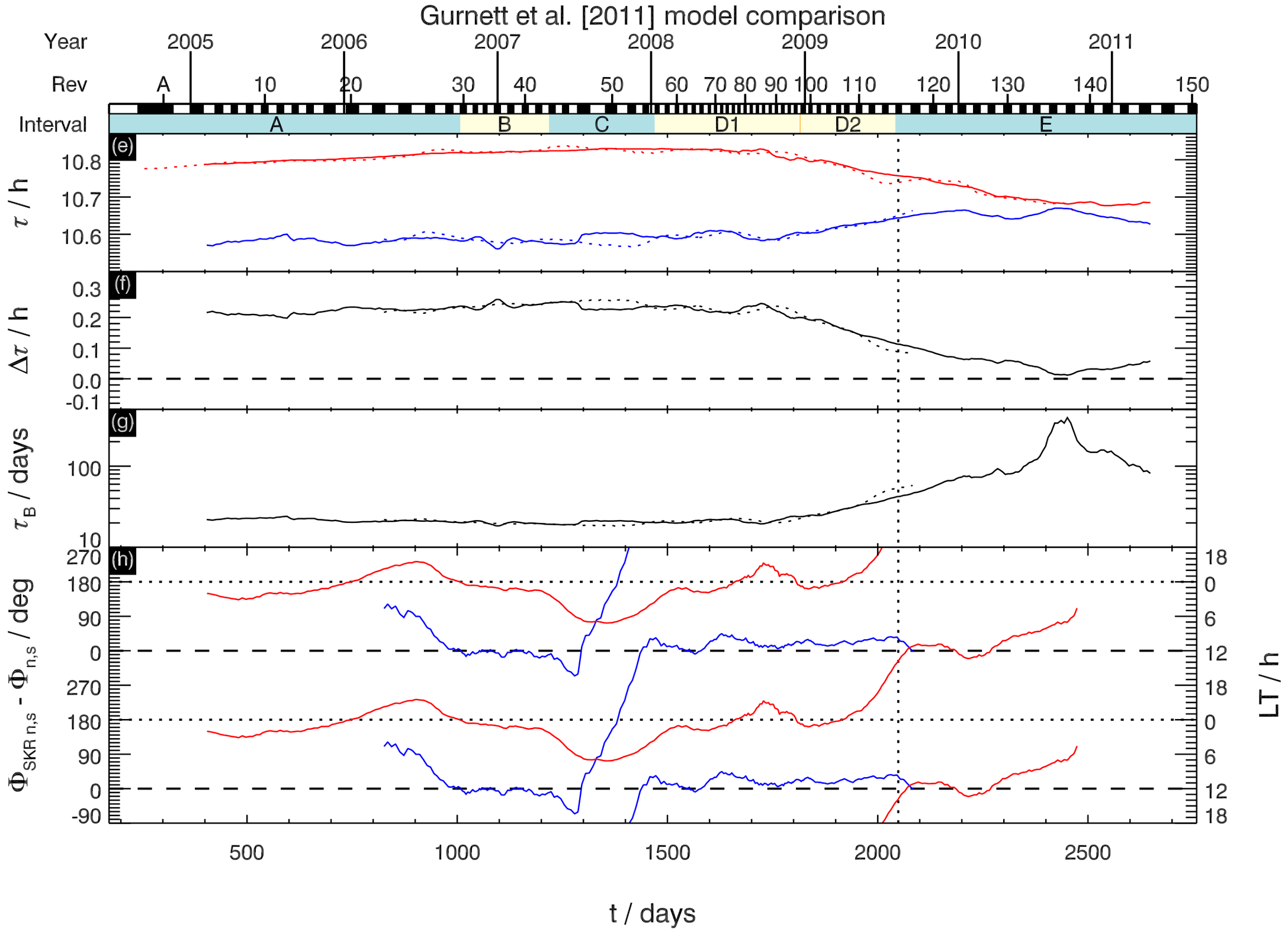


Determination of magnetic period

- "Directional statistics" used to determine period
  - *Determine phase relative to some arbitrary 'guide' period*
  - *Adjust the guide period to reduce variance in the phase about a linear trend*
- Both northern and southern, separately, by 'tuning' to the appropriate polarisation signature
- Generally reliable, but lots of aliasing with the orbital period



No “magnetic equinox” (at least, not in the ‘periodicity’ sense)



Summary

- Near-planetary rotation period oscillations are a “hot topic” among the planetary magnetospheric physics community
- Work at Leicester has pulled apart the spatial and temporal dependence of the magnetic field oscillations. We now well understand the structure of the field, and its relationship to other modulated phenomena.
- We are able to track the phase of these oscillations to high-accuracy over the duration of the Cassini mission. No other known magnetospheric process is so reliable (as far as we know)
- Observations of separate field rotation periods are puzzling - strong evidence for an ‘atmospheric driver’ of these phenomena?
- The discovery of a rotational modulation of the SKR is crucial in linking the periodic radio emissions to the rotating field perturbations, and overturns 30 years of ‘established’ interpretation held since the Voyager-era observations
- The problem is far from solved

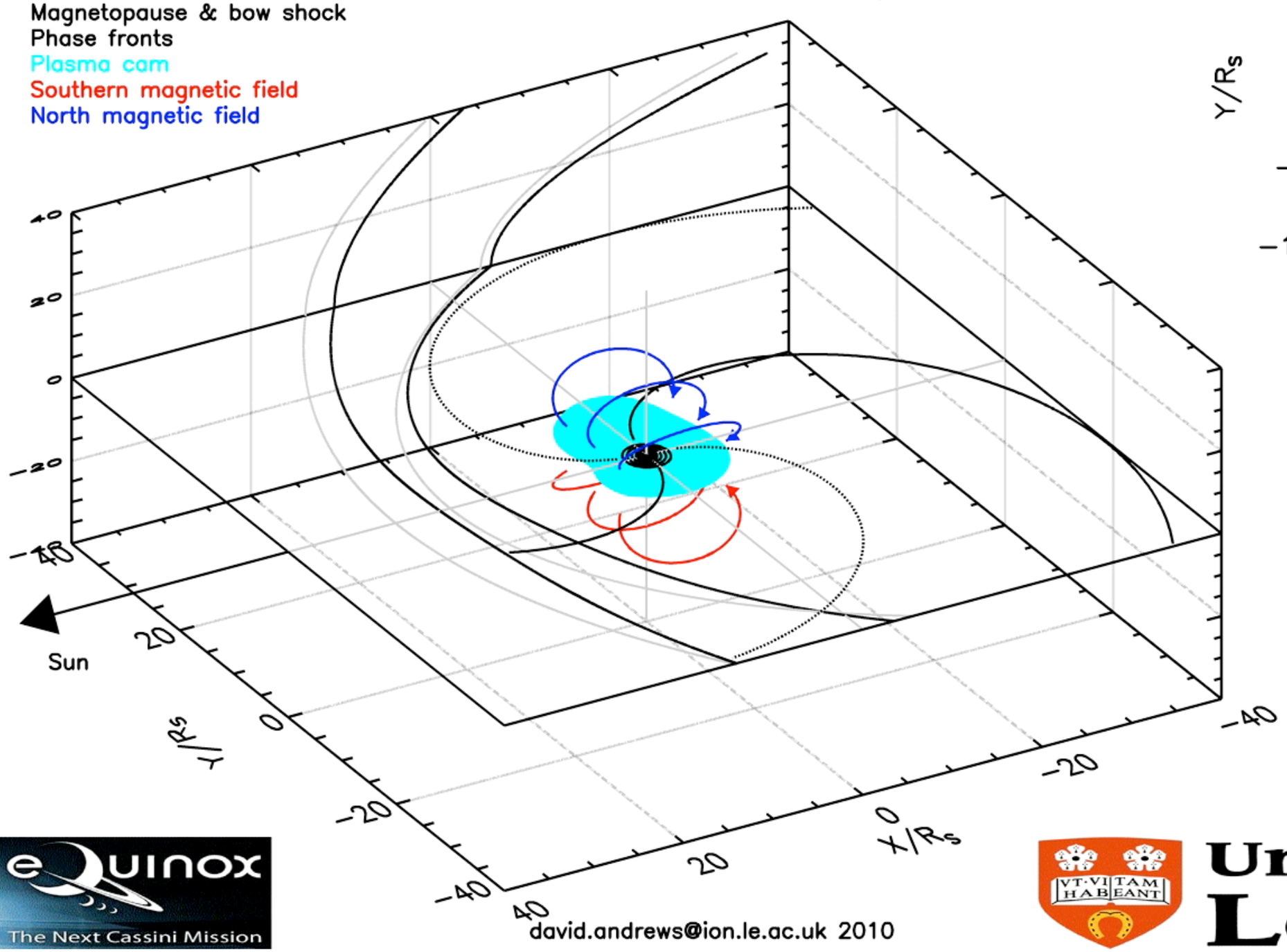
Oscillations in Saturn's magnetosphere – New Cassini Results

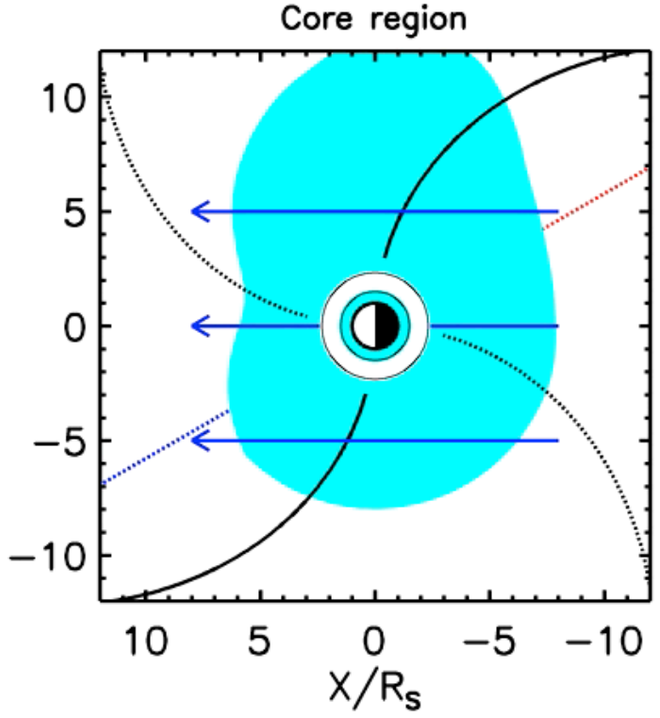
t = 0.0 h
Ψ_{MS} = 000°
Ψ_{MN} = 000°
Cycle = 0.00

North rotation period, τ_N = 8.1 h (exaggerated, actually ~ 10.6 h)

South rotation period, τ_S = 10.8 h

Magnetopause & bow shock
Phase fronts
Plasma cam
Southern magnetic field
North magnetic field





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equinox
The Next Cassini Mission

University of Leicester

Superposition of two oscillations

- Southern and northern oscillations simultaneously present on closed field lines
- *Provan et al. [2011]* have studied this effect, shown that it produces phase **"jitter"**, having amplitude of ~20-30°
  - *Corresponds to a northern signal ~0.4x weaker than the southern*
- Change of B_θ phase between north and south produces interesting effects:
  - *Shift in polarisation [difference between phases of (r, φ) and θ components] is **always identically ±90°** when k = 1*
  - *B_θ amplitude **falling** when $B_{r,\varphi}$ **rising***
- These effects predicted by *Provan et al. [2011]*

In a frame rotating with the southern oscillation, the northern rotates at the 'beat period" (~23 days)