Topology of large scale solar magnetic field

E l e n a G a v r y u s e v a

National Institute of Astrophysics , Florence, Italy

THE FIRST SUMMER SCHOOL
IN ASTRONOMY AND GEOPHYSICS
BELGRADE, SERBIA, 06.08. - 10.08. 2007

Abstract

Observations of the large scale magnetic field in the photosphere taken at the Wilcox Solar Observatory since 1976 up to 2007 have been analyzed to deduce its latitudinal and longitudinal structures and asymmetry, its differential rotation, and their variability in time.

New approach has been suggested to reveal the influence of the weak and strong magnetic fields on the organizing of global topology of the field and dynamic of solar variability over last three cycles N 21, 22 and 23.

The latitudinal topology of the photospheric magnetic field is composed of

1) a four zonal 20-22-year periodical structure and
2) polarity's waves running from the equator to the poles with periods of 2-3-years about.

The boundaries of the four zones are located at the equator and at ±25 degrees (where the solar activity has the highest amplitude). The polarities of the pre-equatorial zones coincide to the polarities of leading sunspots and have opposite signs in the Northern and Southern hemispheres. It is important to study whether the non-zero level of the magnetic field calculated as a mean around the Sun at different latitudes is a component of a basic background field or the result of the misbalance of the strong magnetic field mainly concentrated in active regions.

The polarity's waves have different periods in the Northern and Southern hemispheres, but they are synchronized by solar activity cycle. The study of the origin of these waves was performed in view of their relationship with the presence of the differential rotation and torsional waves in the magnetic field of the Sun. The velocity of the meridional flows of the magnetic field was calculated. North-South asymmetry of solar magnetic field and its short and long term variability in time have been studied.

Differential rotational rate of the magnetic field and its temporal dependence has been evidenced at different latitudes through activity cycles. The time of emergence was estimated roughly (???).

Extremely interesting quasi-stable over 30 years longitudinal structure has been found. Its relation to the latitudinal topology of the magnetic field was studied.

Experiments and materials

Experiments:	Materials:
WSO, Magnetic field	Cortesy of Prof. S.Solanki,
SOHO (MDI, GOLF)	J.Christensen-Dalsgaard,
GONG, BISON, IRIS	M.Tompson, S.Vorontsov,
Homestake, Gallex	A.Kosovichev, R.Howe,
GNO, Kamiokande	V.Gavryusev, R.Komm,
SuperKamiokande	P.Gilman, M.Dikpati
SAGE, SNO, Borexino	R.Ulrich, D.H Hataway

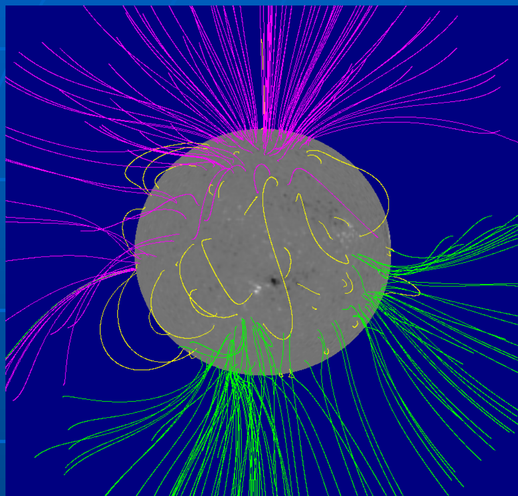
Subjects of the discussion

- Solar Activity
- Dynamo
-
- Latitudinal Structure S
- Longitudinal Structure M
- Rotation F
-
- of SOLAR MAGNETIC FIELD (SMF)

The Thinkers of Hamangia
(Neolitic Statiette, 6000-5000 years BC)

Slovaci u Srbiji,
(Summer School, Belgrade, Serbia, August 2007 years AC)

Magnetic Field: Structure & Origin



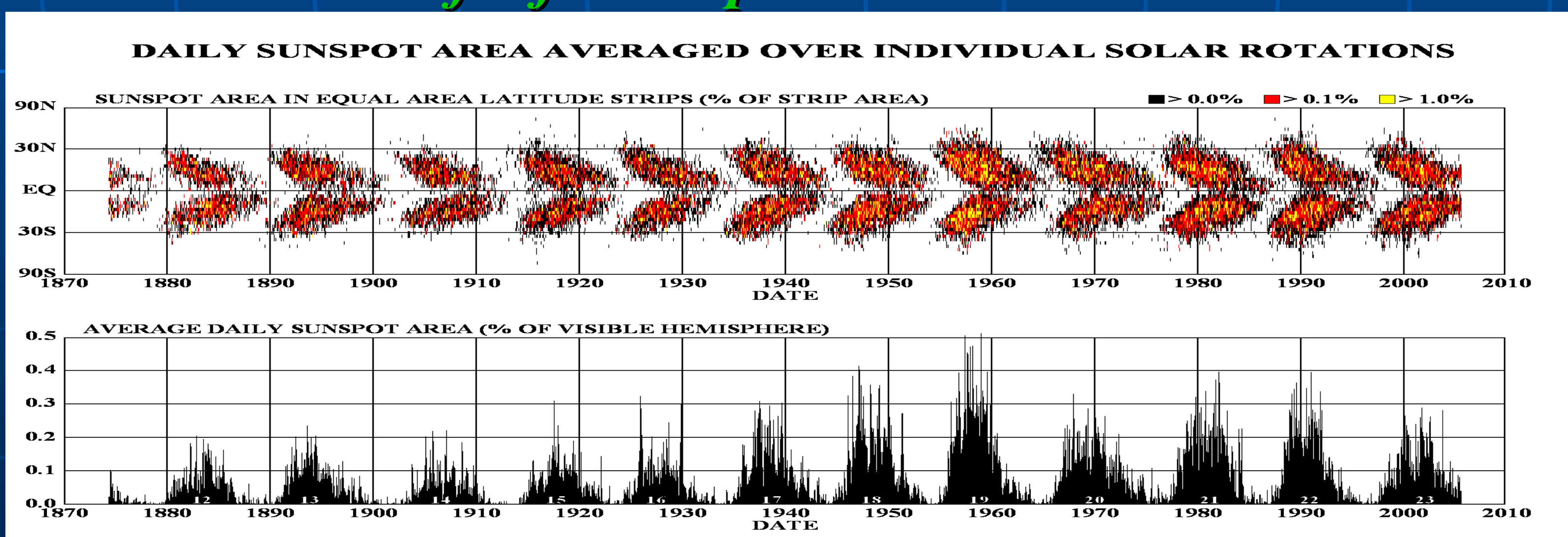
- **Solar Magnetic Field (SMF) can be measured in the Photosphere only.**

General questions:

- **Where the SMF is originated?**
- **What is the SMF structure?**
- **What are the SMF dynamics?**

Solar Activity Properties:

1. Latitudinal drift of Sun Spots

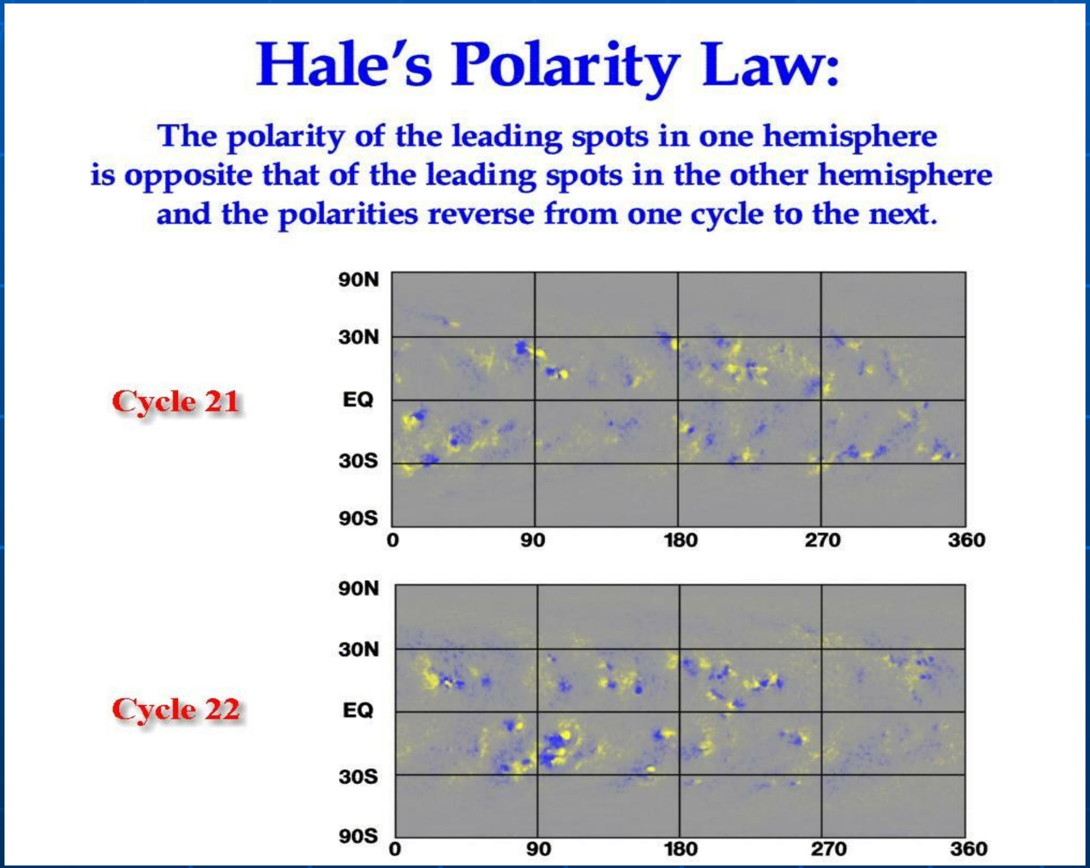


Butterfly Diagram

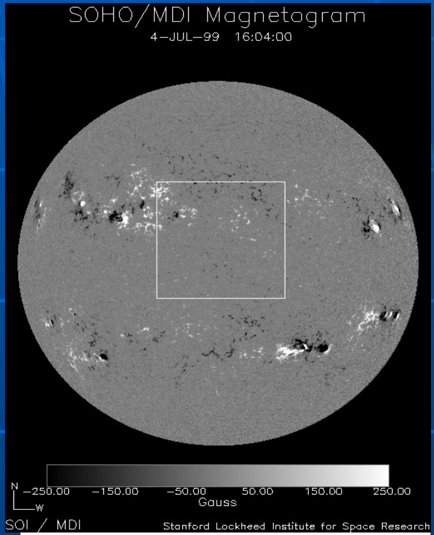
SSN Number

Solar activity properties:

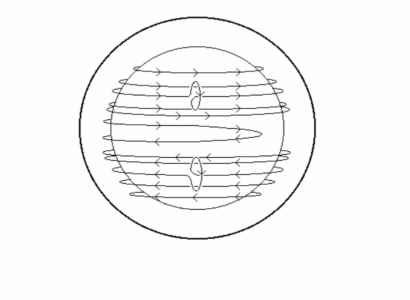
2. Dependence of Active Regions Polarity on the Cycle and on the Latitude



- Solar Surface
- Light is +
- Dark is --



- Dynamo:
- α– and
- β–effects

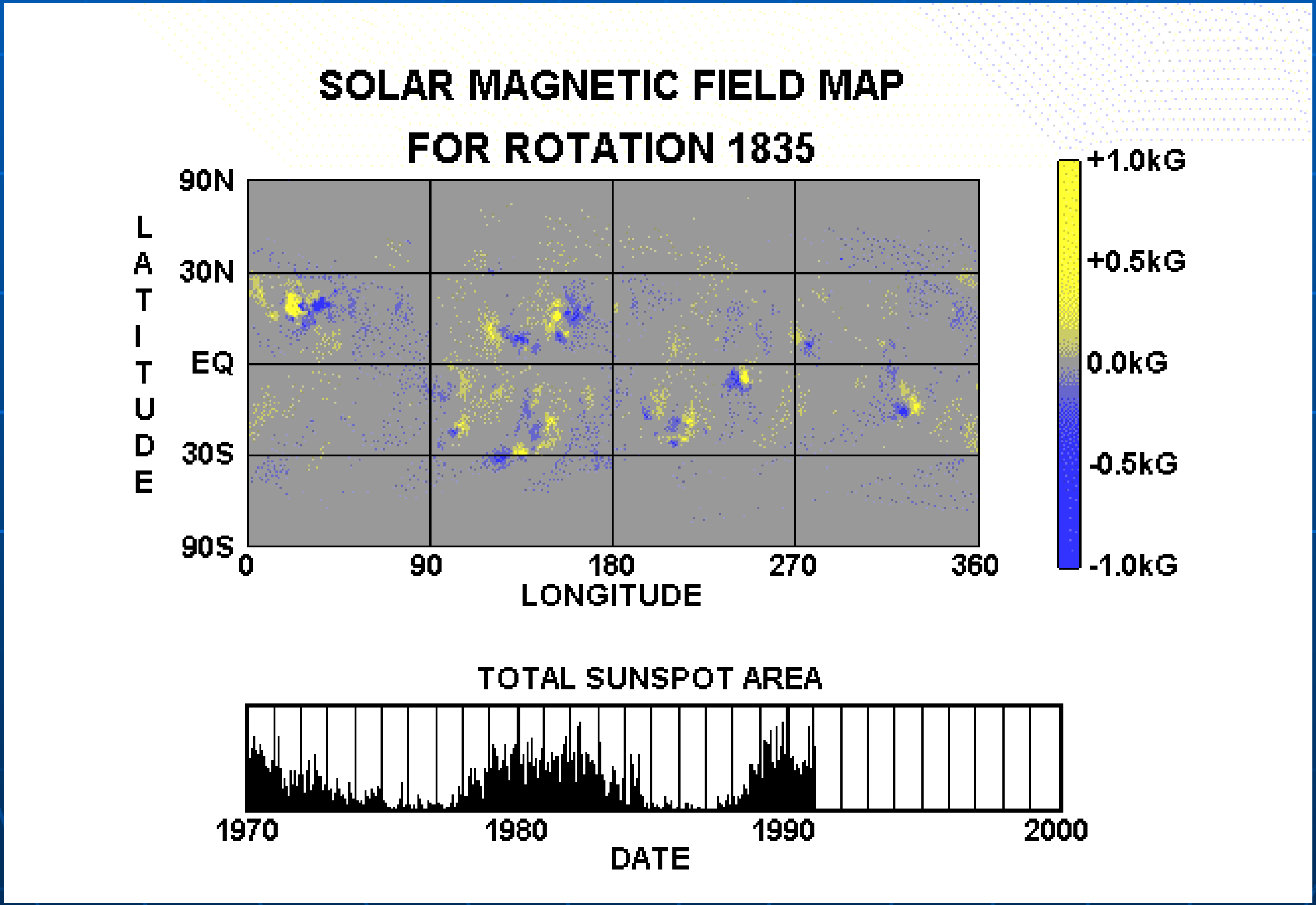


The α-effect

It is well known that there are two belts of the sunspots and two quiet polar casp of a certain polarity inverting each 11- years during maximum of solar activity.

Sun spots magnetic field and Area

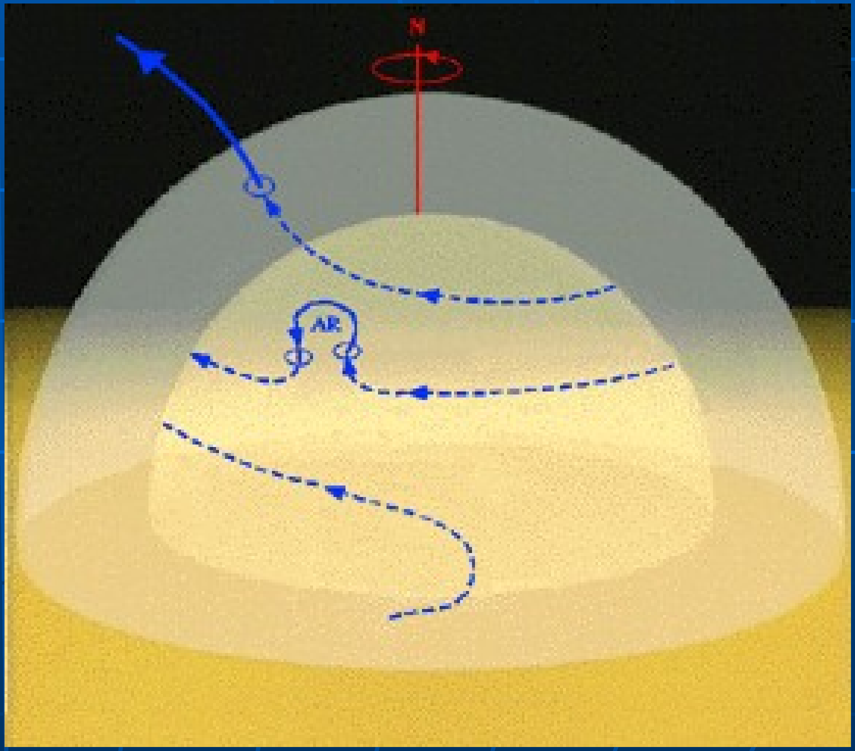
cortesy of D.H.Hathaway



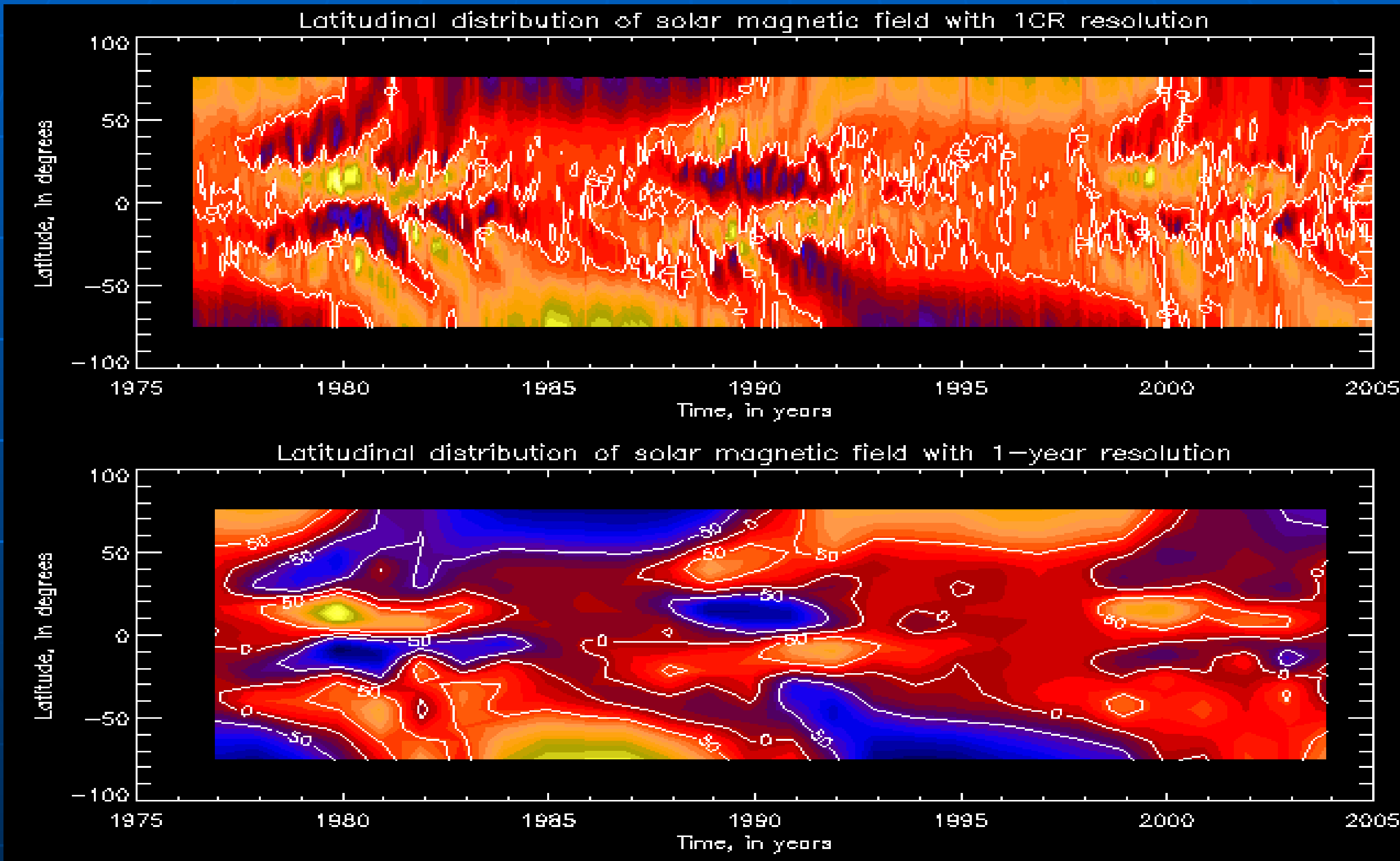
Solar Magnetic Fields

- Solar magnetic fields have long been believed to be generated by a solar dynamo, in which the turbulent inner motion generates the magnetic fields we see.
  - Longstanding problem to understand this dynamo in detail.

GONG

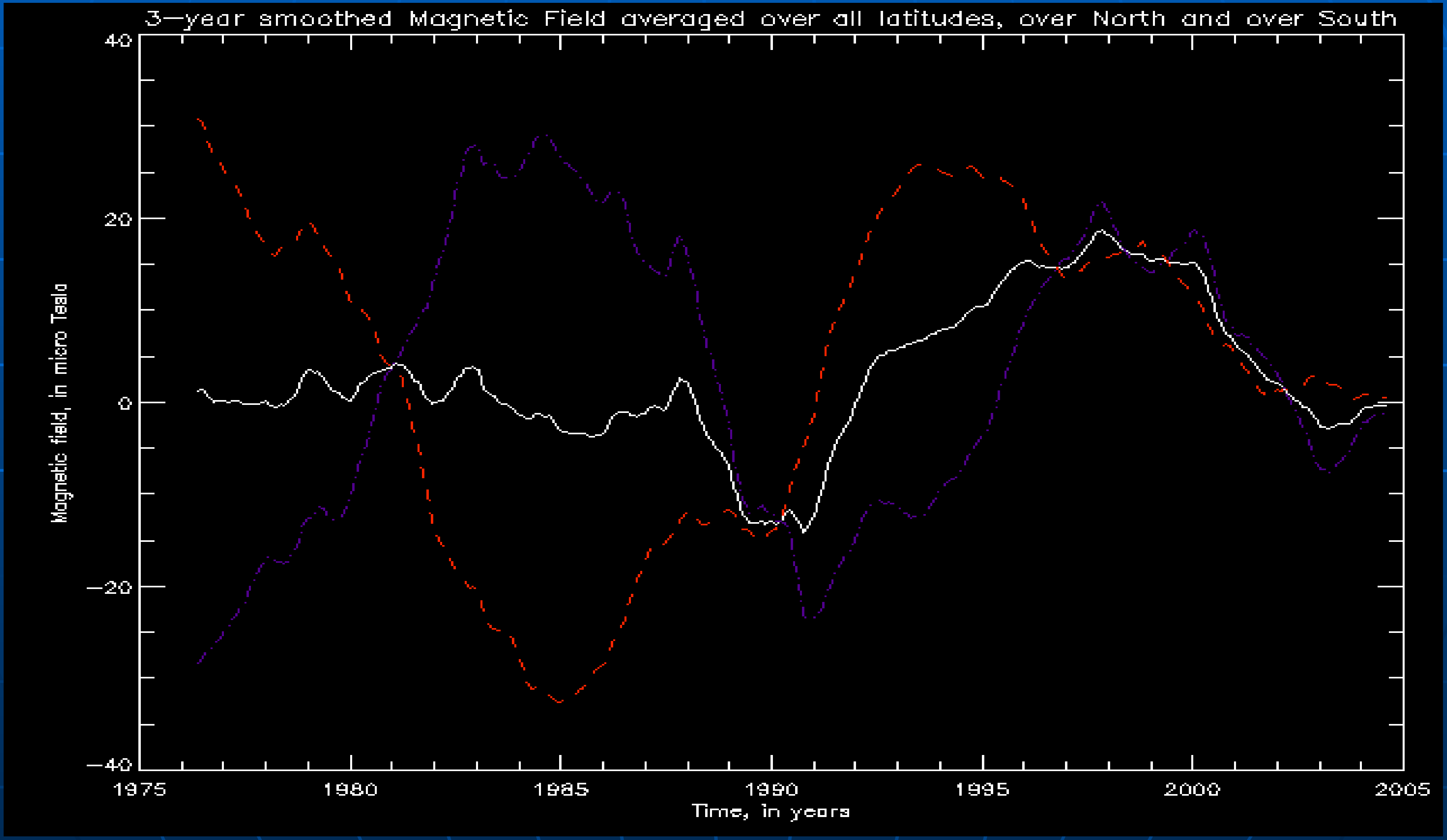


4-zonal latitudinal structure in Carrington system for 1 CR mean (top) and for 1-year mean (bottom)

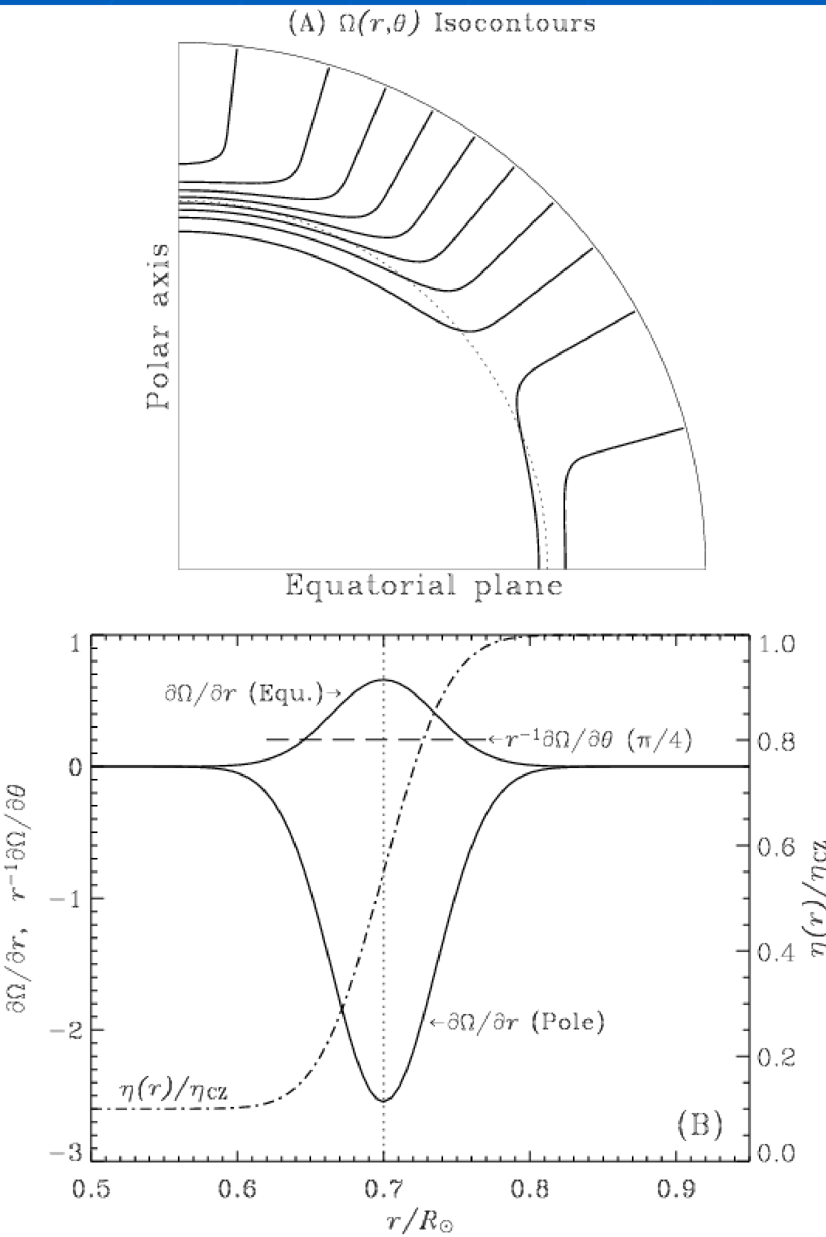


5.5 16.5 **Time** 27.5

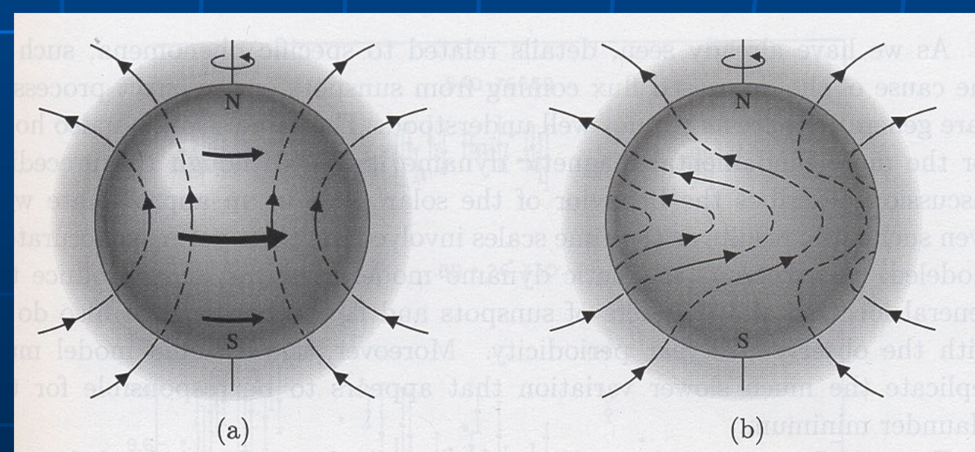
Magnetic Field mean over the Northern (red line) and Southern (blue line) hemispheres and over all latitudes (continous line) in Carrington system



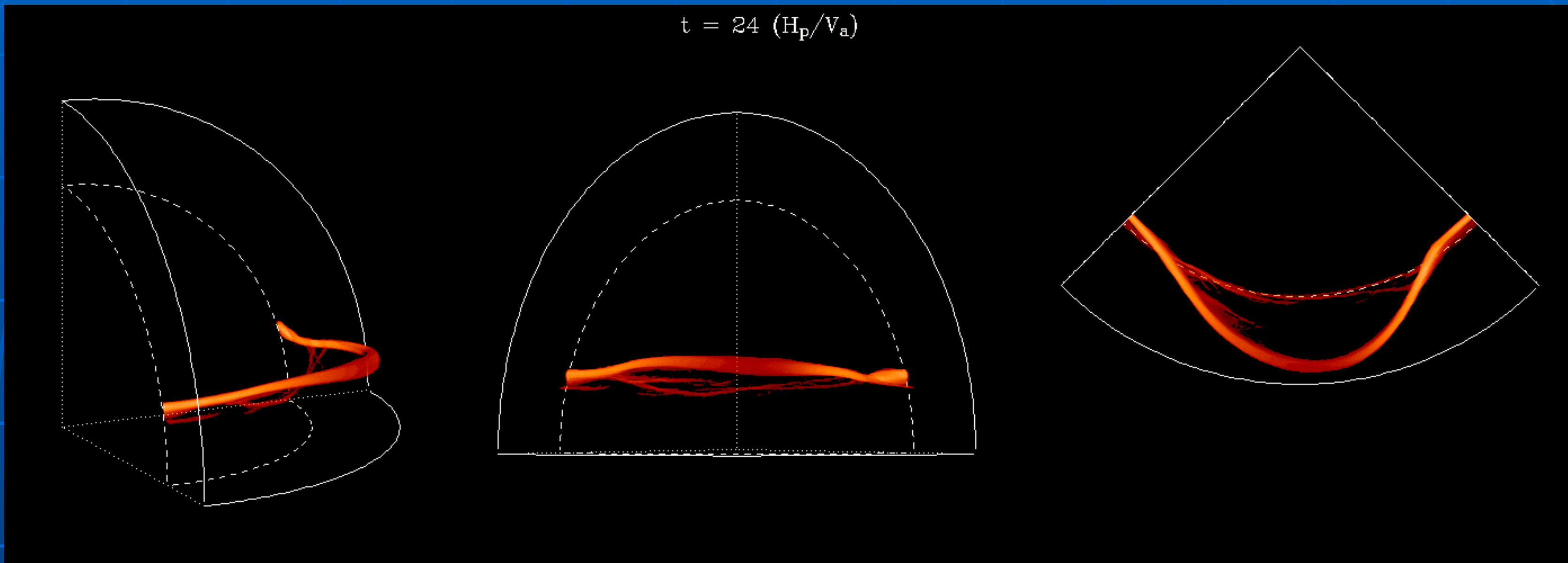
For the solar cycle, the driving velocity shear is believed to come from differential rotation

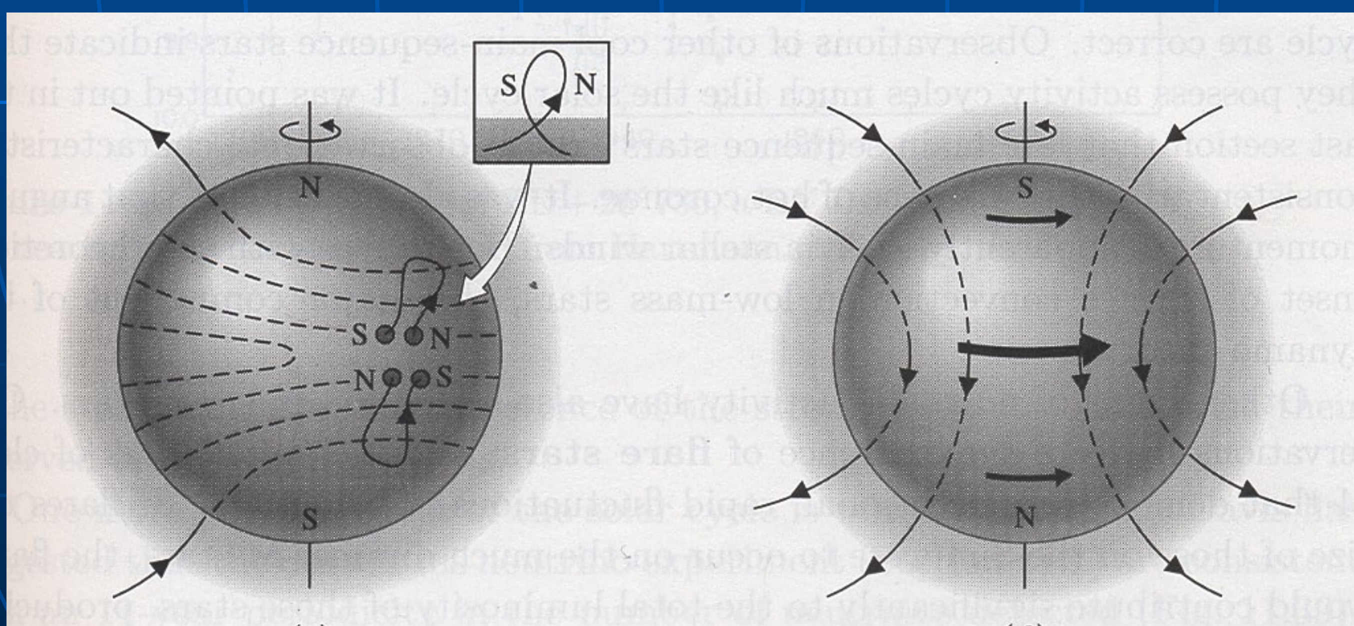


Differential rotation will act to stretch out an initially poloidal (N-S or radial) magnetic field into the azimuthal (toroidal) direction.



The toroidal field erupts, is twisted by the Coriolis force, and generates a new poloidal field of the opposite sign





Mathematical Formulation

Under MHD approximation (i.e. electromagnetic variations are nonrelativistic), Maxwell's equations + generalized Ohm's law lead to induction equation :

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B} \right) . \qquad (1)$$

Applying mean-field theory to (1), we obtain the dynamo equation as,

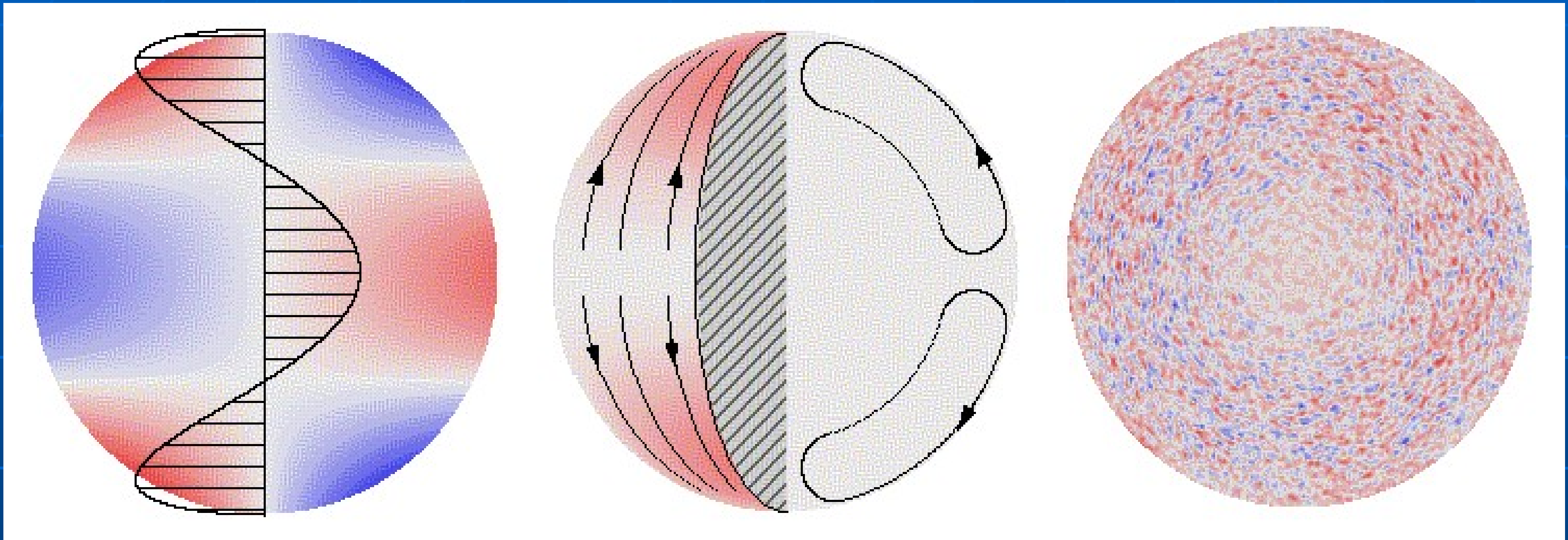
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\mathbf{U} \times \mathbf{B} + \alpha \mathbf{B} - \eta \nabla \times \mathbf{B} \right) , \qquad (2)$$

- $\mathbf{U}$: Differential rotation and meridional circulation from helioseismic data
- $\alpha \mathbf{B}$: Poloidal field source from active region decay
- η: Turbulent magnetic diffusivity

Assume axisymmetry, decompose into toroidal and poloidal components:

$$\mathbf{B} = \underbrace{B_\varphi(r,\theta,t)\,\hat{\mathbf{e}}_\varphi}_{\text{Toroidal field}} + \underbrace{\nabla \times \left(A(r,\theta,t)\,\hat{\mathbf{e}}_\varphi \right)}_{\text{Poloidal field}}, \quad \mathbf{U} = \underbrace{\mathbf{u}(r,\theta)}_{\text{Meridional circulation}} + r\sin\theta\,\underbrace{\Omega(r,\theta)\,\hat{\mathbf{e}}_\varphi}_{\text{Differential rotation}},$$

Flows in the Sun,
Stanford Group of SOI/MDI



Differential rotational rate of the magnetic field measured in the photosphere was calculated and its temporal dependence was studied using two independent methods.

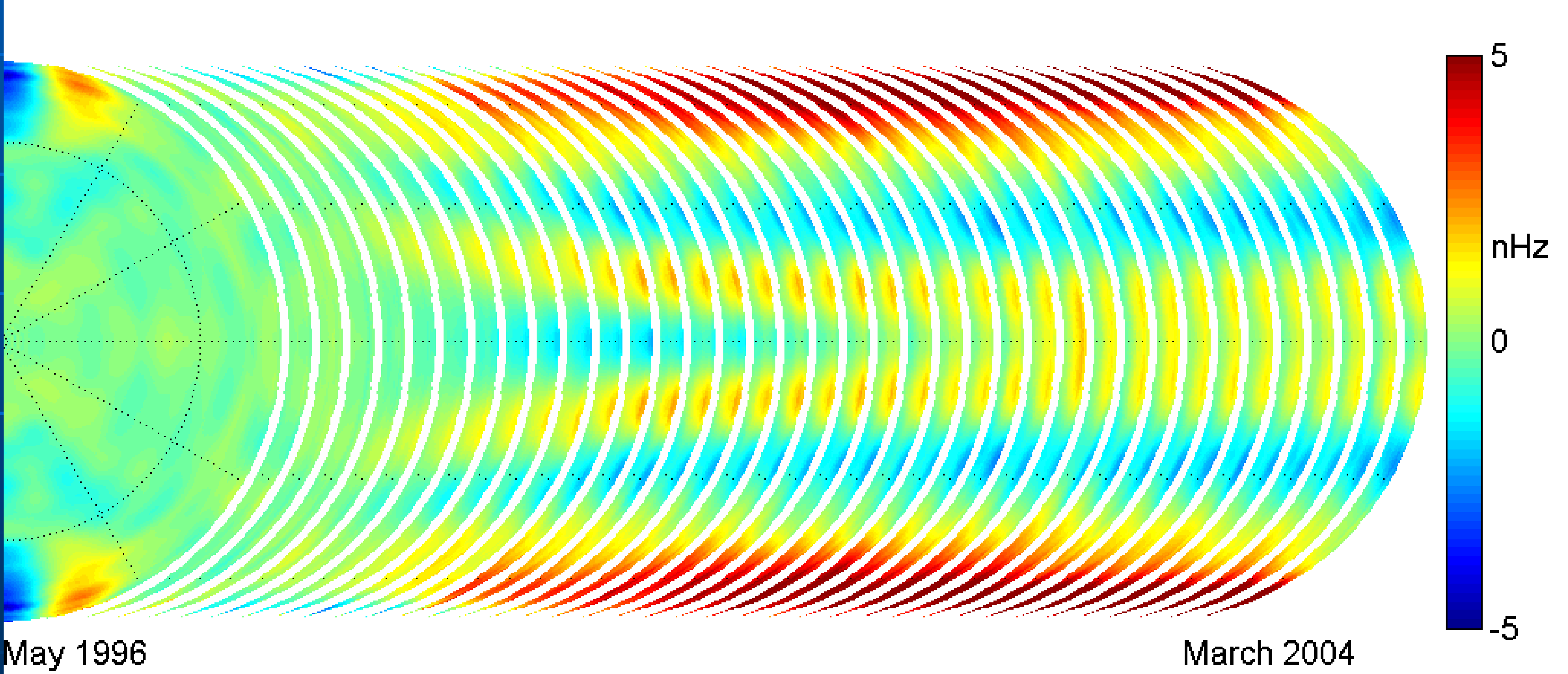
It was found that the rotational rate has a periodical character: at high latitudes it is closel related to the solar activity cycle.

The shorter periodicities of 5-6 years about has been revealed in the middle and low latitudes in addition to the torsional waves.

The variability of solar magnetic field rotation with periods of 1 and 1.25 and 11 years have been analyzed and the results are presented in comparison with the helioseismological findings and the rotational rate of solar corona from UVCS/SOHO data.

Zonal flows

Rotation rate - average value at solar minimum



Vorontsov et al. (2002; Science 296, 101)

Why should the Sun or any star generate magnetic fields?

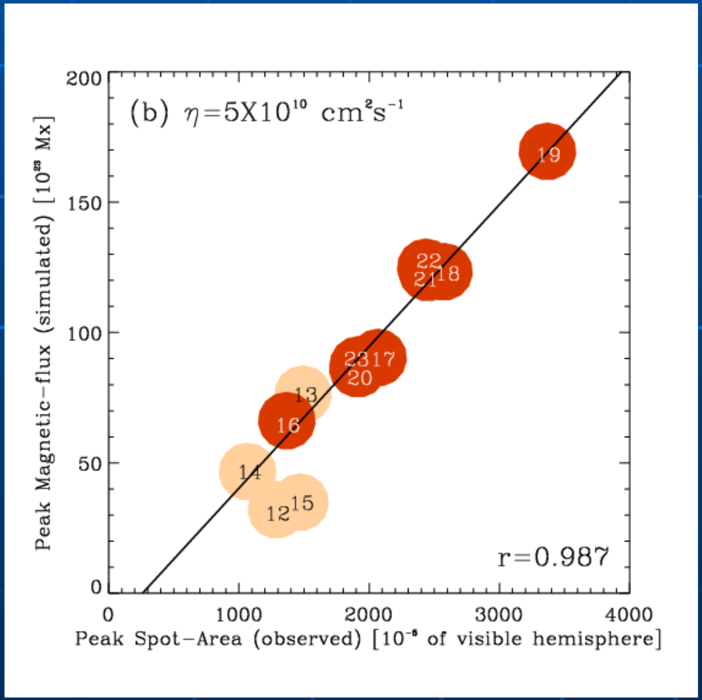
The first term in the expansion of the ideal MHD electric field represents the stretching of magnetic field by velocity shear – this is the driving term for dynamos in stars.

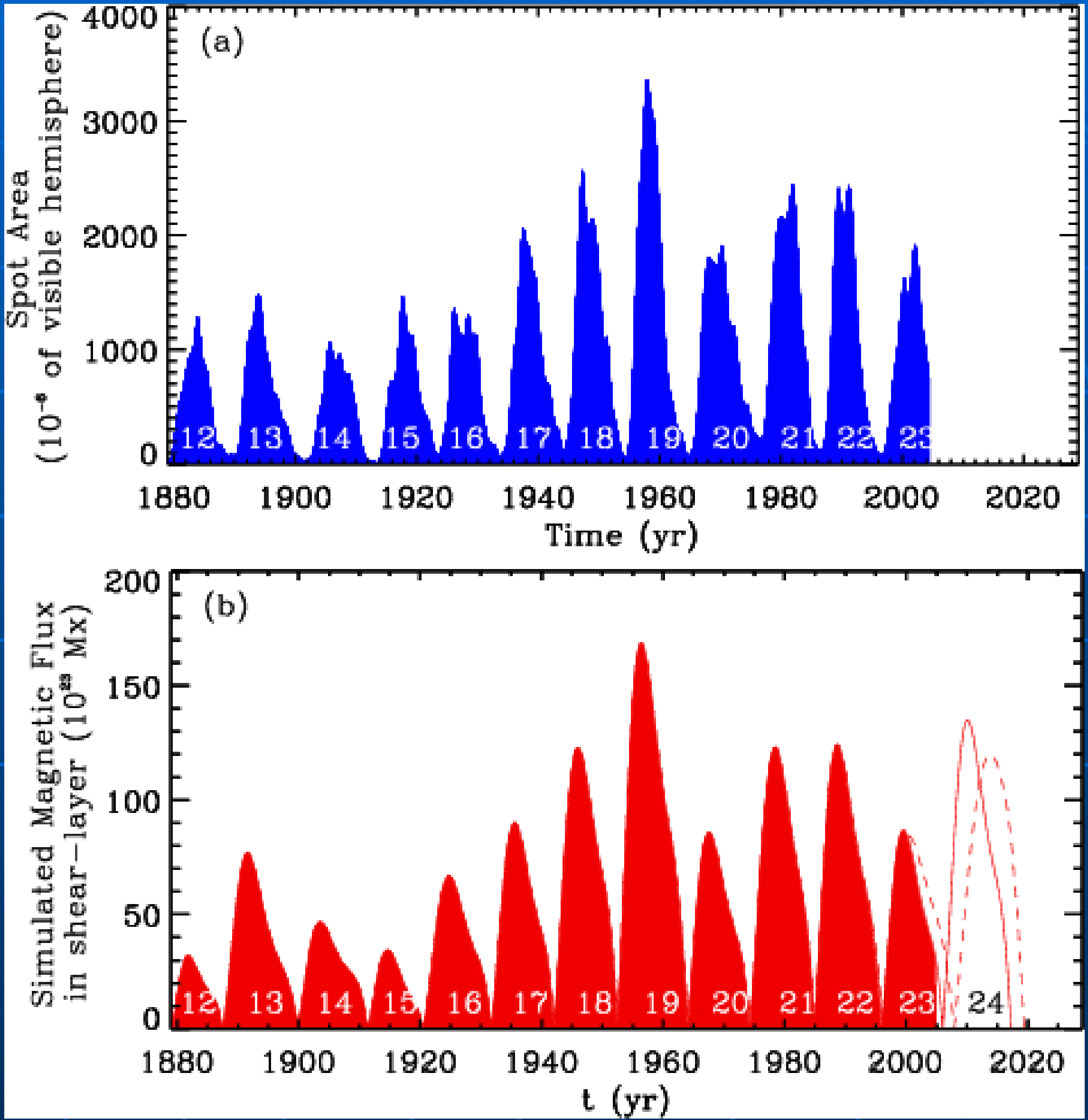
Magnetic fields will grow until they are dissipated resistively or until balanced by a back-reaction from the Lorentz force.

Review: simulations of relative peaks of cycle 12 through 24

- We reproduce the sequence of peaks of cycles 16 through 23

- We predict cycle 24 will be 30-50% bigger than cycle 23





(Dikpati, de Toma & Gilman, 2006, GRL)

Questions:

But WHAT can we say about the DISTRIBUTION of the POLARITY of the magnetic field in the photosphere ?

Simple questions…

- **1. Does it exist any GLOBAL STRUCTURE of the magnetic field distribution in the photosphere?**

If YES,

- **2. HOW MANY LATITUDINAL ZONES exist ?**
- **3. What are the relationships between the SMF polarity in zones in EACH HEMISPHERE ?**
- **4. What are the RELATIONSHIPS BETWEEN the corresponding zones in the NORTHERN and in the SOUTHERN hemispheres?**
- **5. HOW their relations are changing DURING solar CYCLE ?**
- **6. HOW their relations are changing FROM CYCLE to CYCLE ?**

Questions:

More complex problems related to the LONGITUDINAL STRUCTURE.

- **7. DOES the LONGITUDINAL structure EXIST?**

If YES,

- **8. WHAT is the LIFETIME of the longitudinal structure?**

To answer these questions we should take into account the differential rotation of the solar magnetic field, which is the next problem to be studied.

- **9. WHAT is the ROTATIONAL RATE of the solar magnetic field?**
- **10. HOW does it depend on the LATITUDE ?**
- **11. HOW does it depend on the TIME ?**
- **on the CYCLES ?**
- **on the HEMISPHERE ?**
- **12. WHAT would be the DISTRIBUTION of the magnetic field reconstructed in the coordinate system rotating like photosphere does?**

or

in the coordinate system rotating together with active longitudes?

WSO data

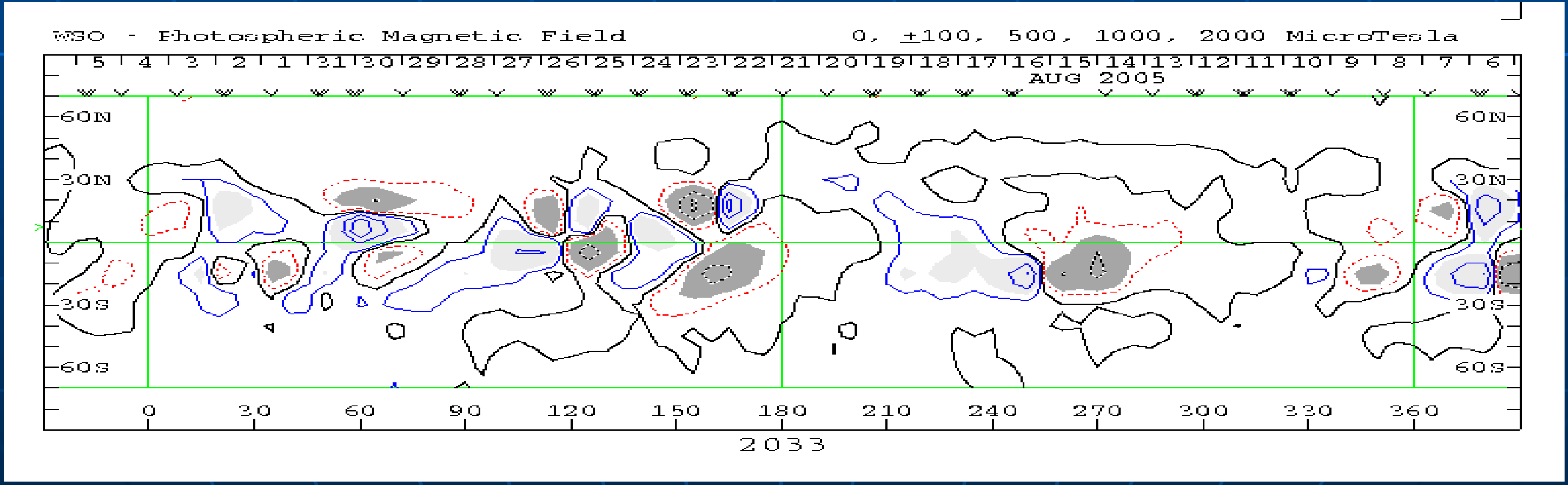
- The observations of the large scale magnetic field in the photosphere taken at the Wilcox Solar Observatory (WSO) since May 27, 1976 up to 2007 have been analyzed (http://wso.stanford.edu/synoptic.html).

- This interval of time covers the solar activity cycles No 21, 22 and 23 and corresponds to the Carrington Rotations (CR) since 1642 to 2050.

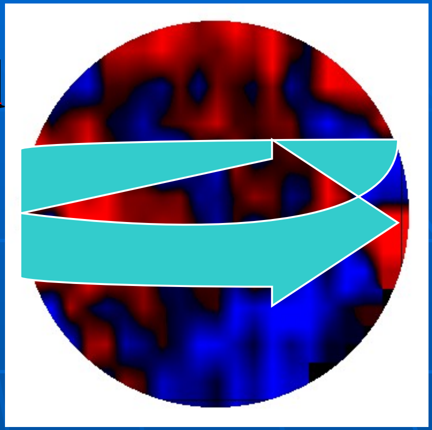
- The line-of-sight component of the photospheric magnetic field (SMF) is measured by the WSO's Babcock solar magnetograph using the Zeeman splitting of the 525.02 nm Fe I spectral line.

- The grid of the available data is made of 30 equal steps in latitude *sine* from 75.2 North to 75.2 South degrees and of 5 degrees steps in heliographic longitude.

- Each longitudinal value is a weighted average of the observations made in the longitudinal zone within 55 degrees around central meridian.



Latitudinal structure of Solar Magnetic Field

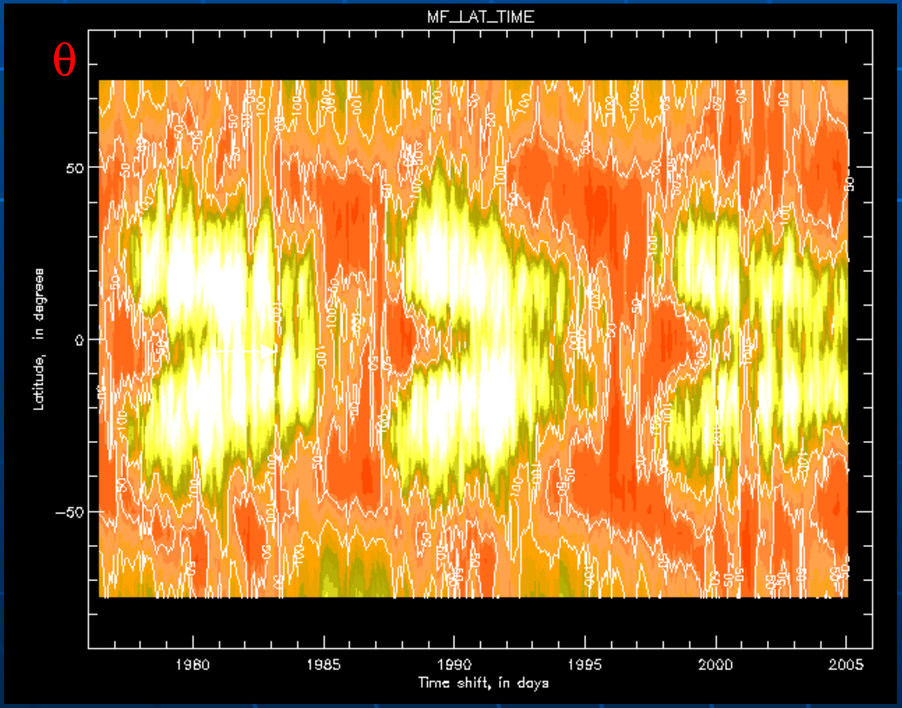


Mean Latitudinal Field over 1 or more solar rotations was calculated. **Let us call this field as a**

latitudinal magnetic field

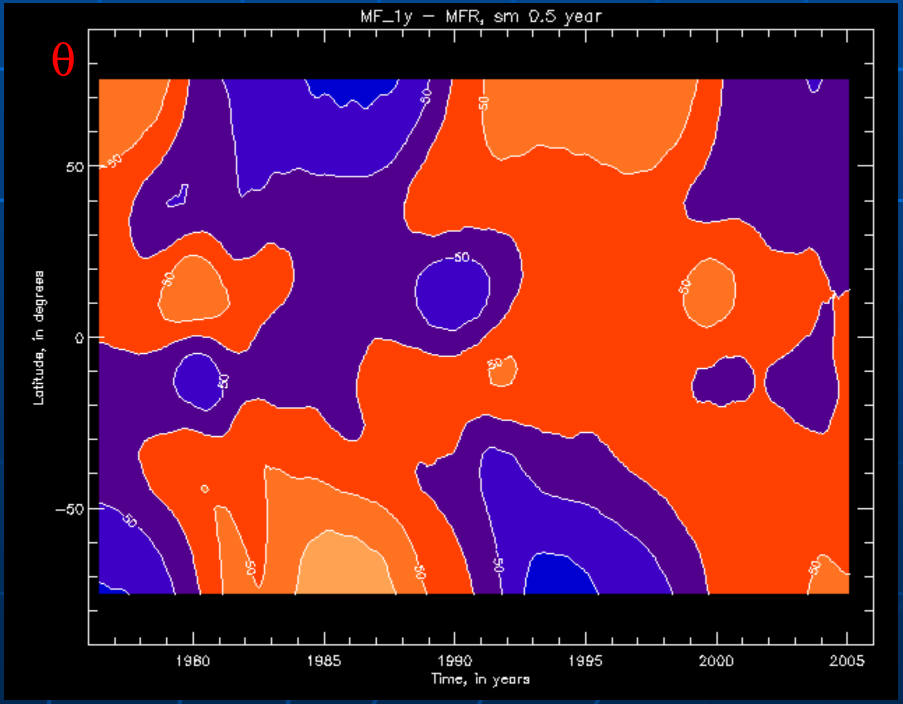
Magnetic Field Intensity

mean over 1 CR

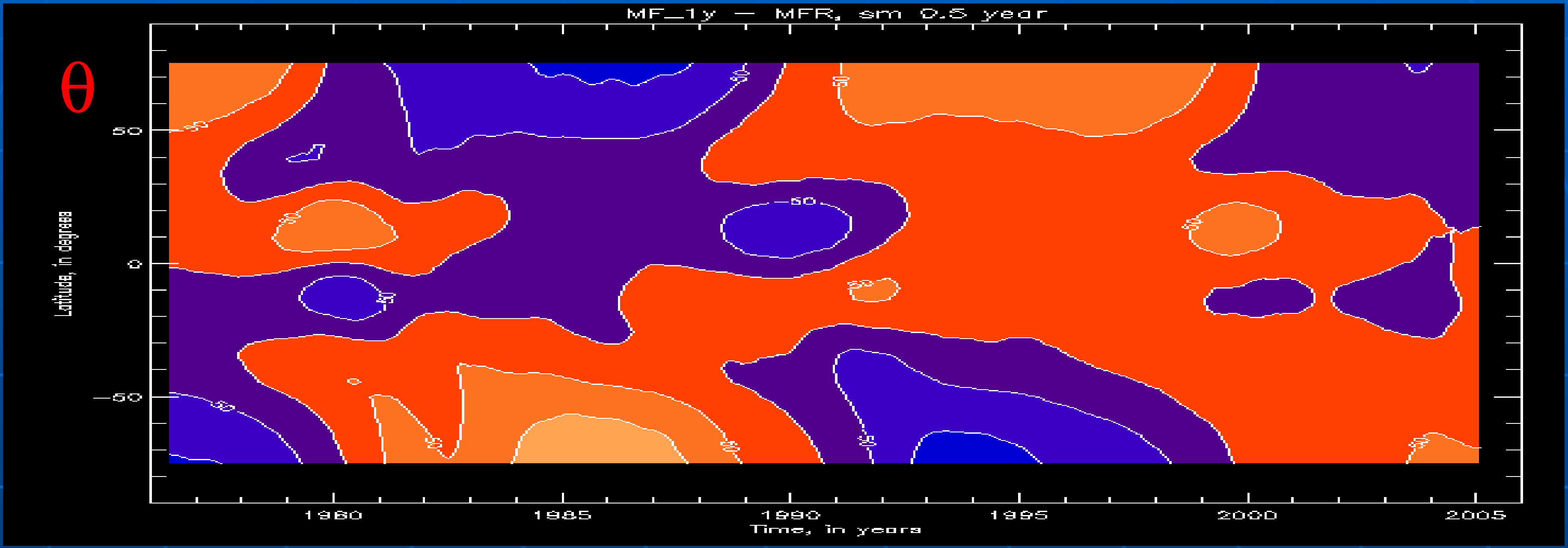


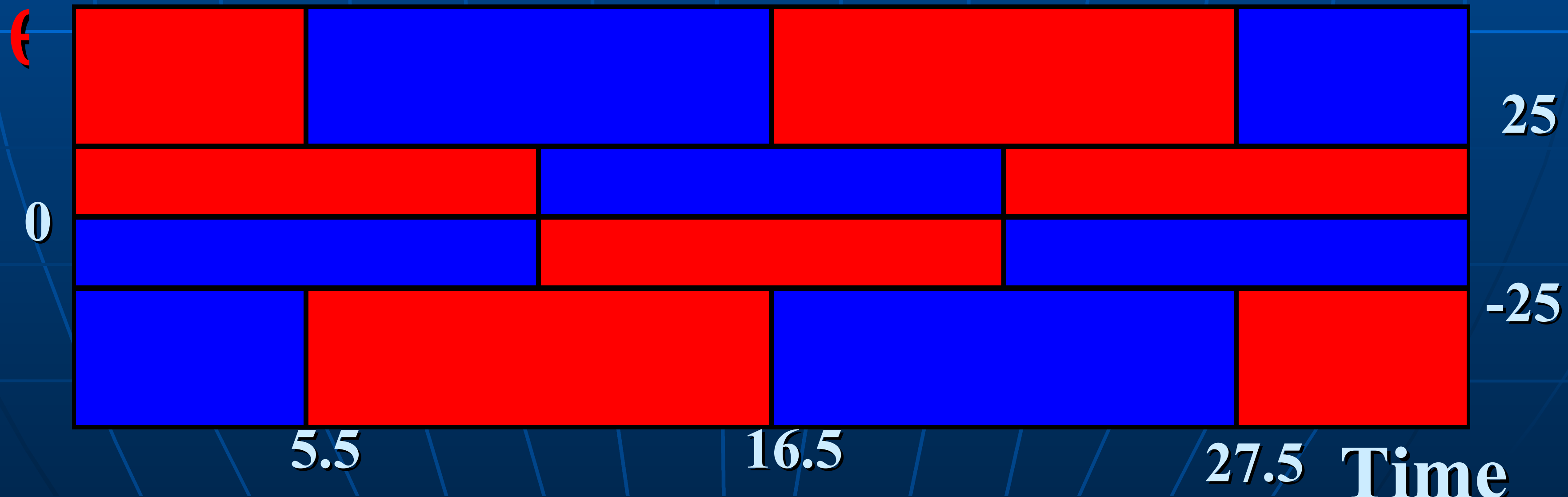
Magnetic Field

mean over 1 CR

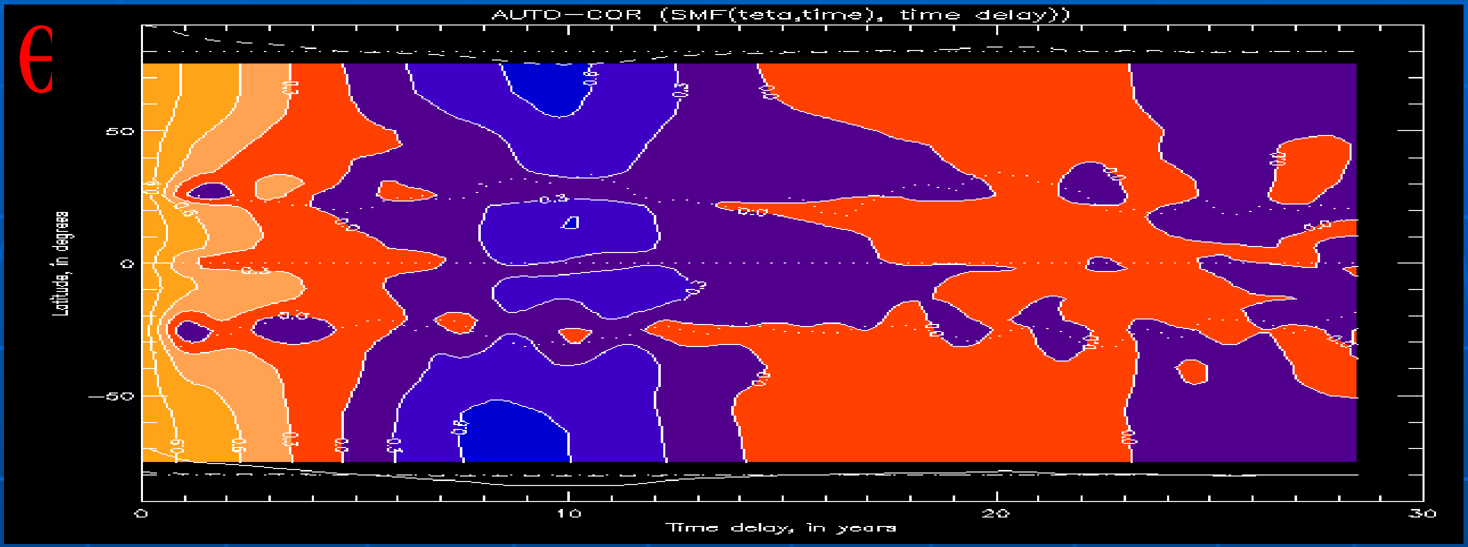


4-zonal latitudinal structure



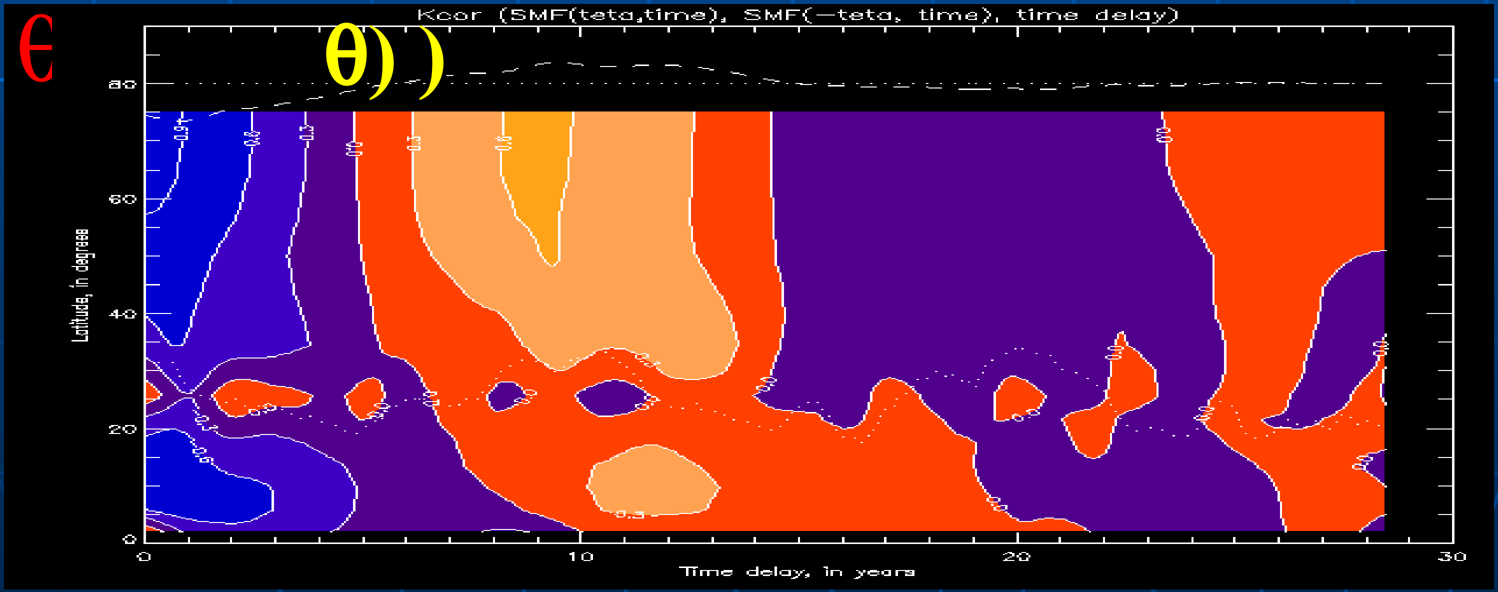


K auto-correlation SMF(θ)



18-22–year periodiciy
No correlation at +/-25degrees

K cor (SMF(θ), SMF(-θ))

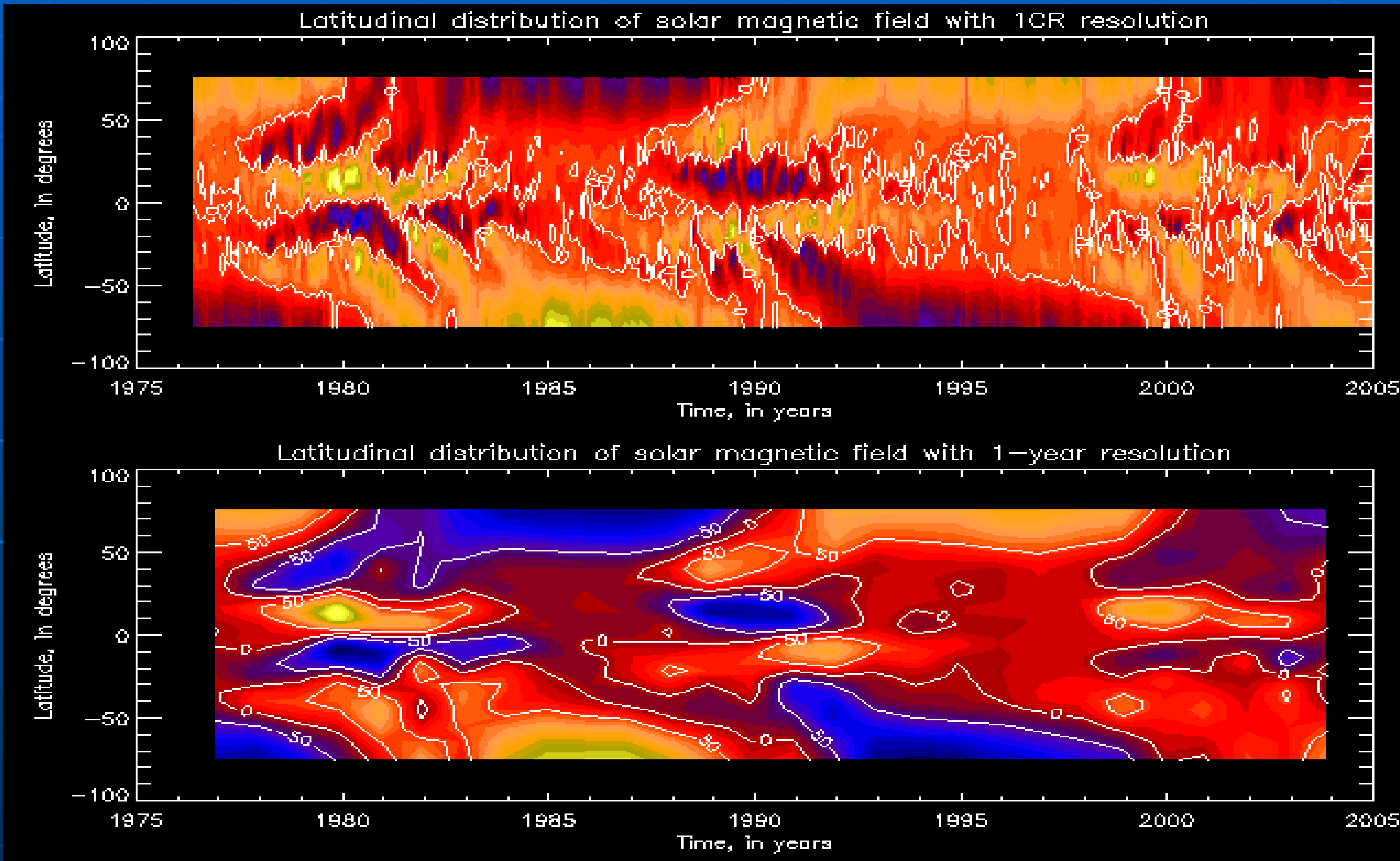


Anti-correlation at 0- shift

9-11 year periodicity

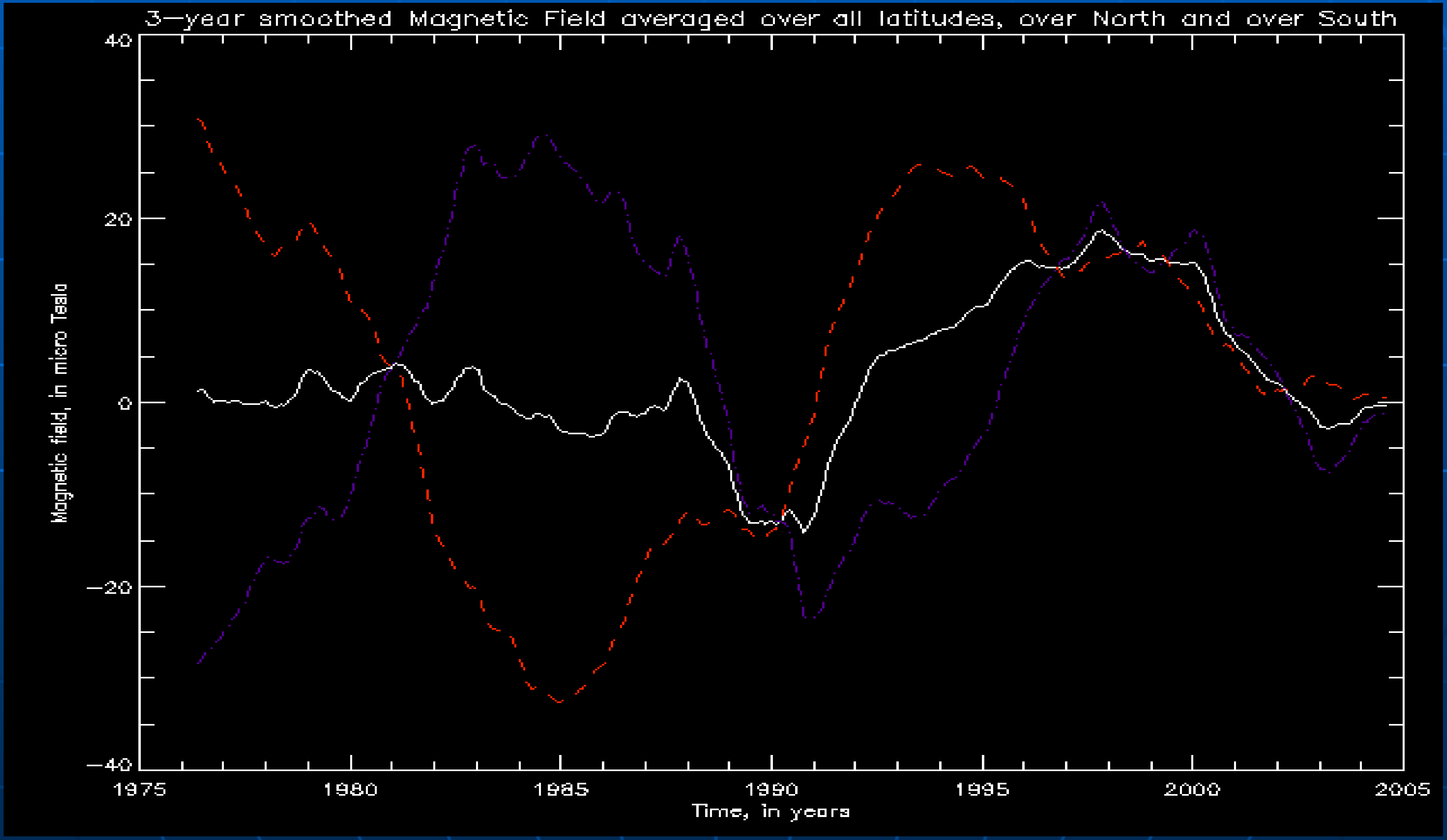
No correlation At +/-25 degrees

4-zonal latitudinal structure in Carrington system for 1 CR mean (top) and for 1-year mean (bottom)



5.5 16.5 **Time** 27.5

Magnetic Field mean over the Northern (red line) and Southern (blue line) hemispheres and over all latitudes (continous line) in Carrington system



MF_1y – MF_4zones = RMF

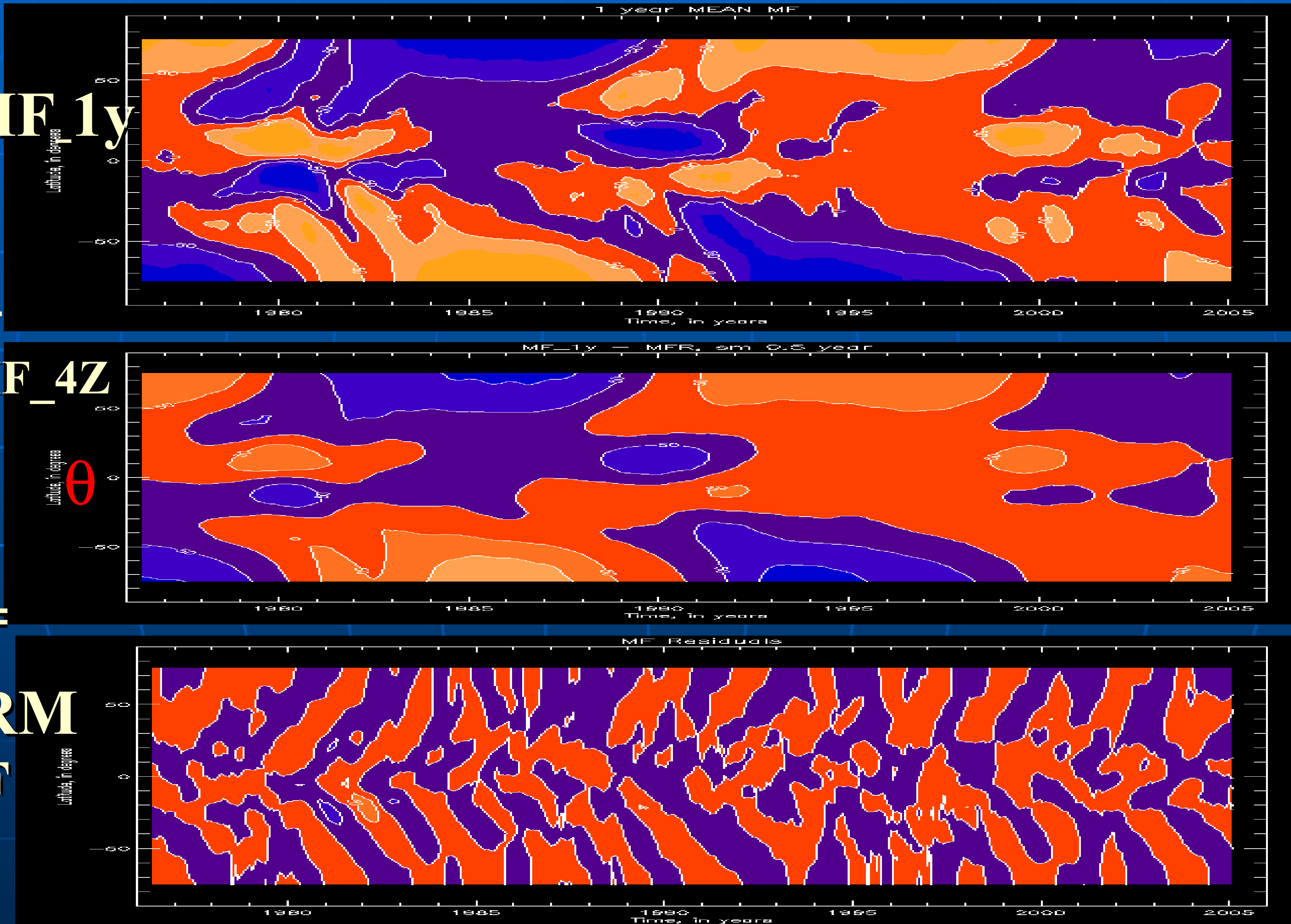
MF_1y

–

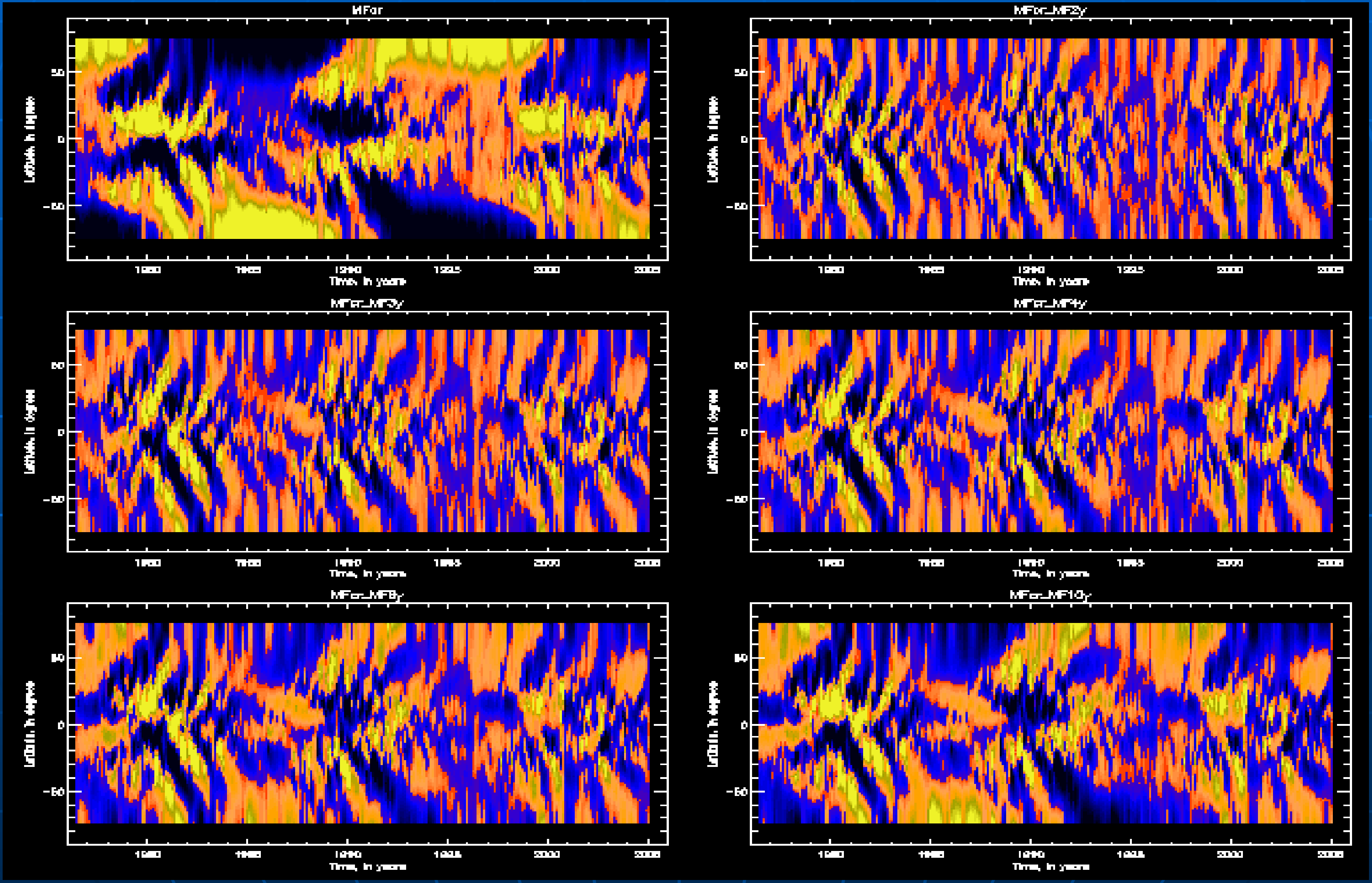
MF_4Z

=

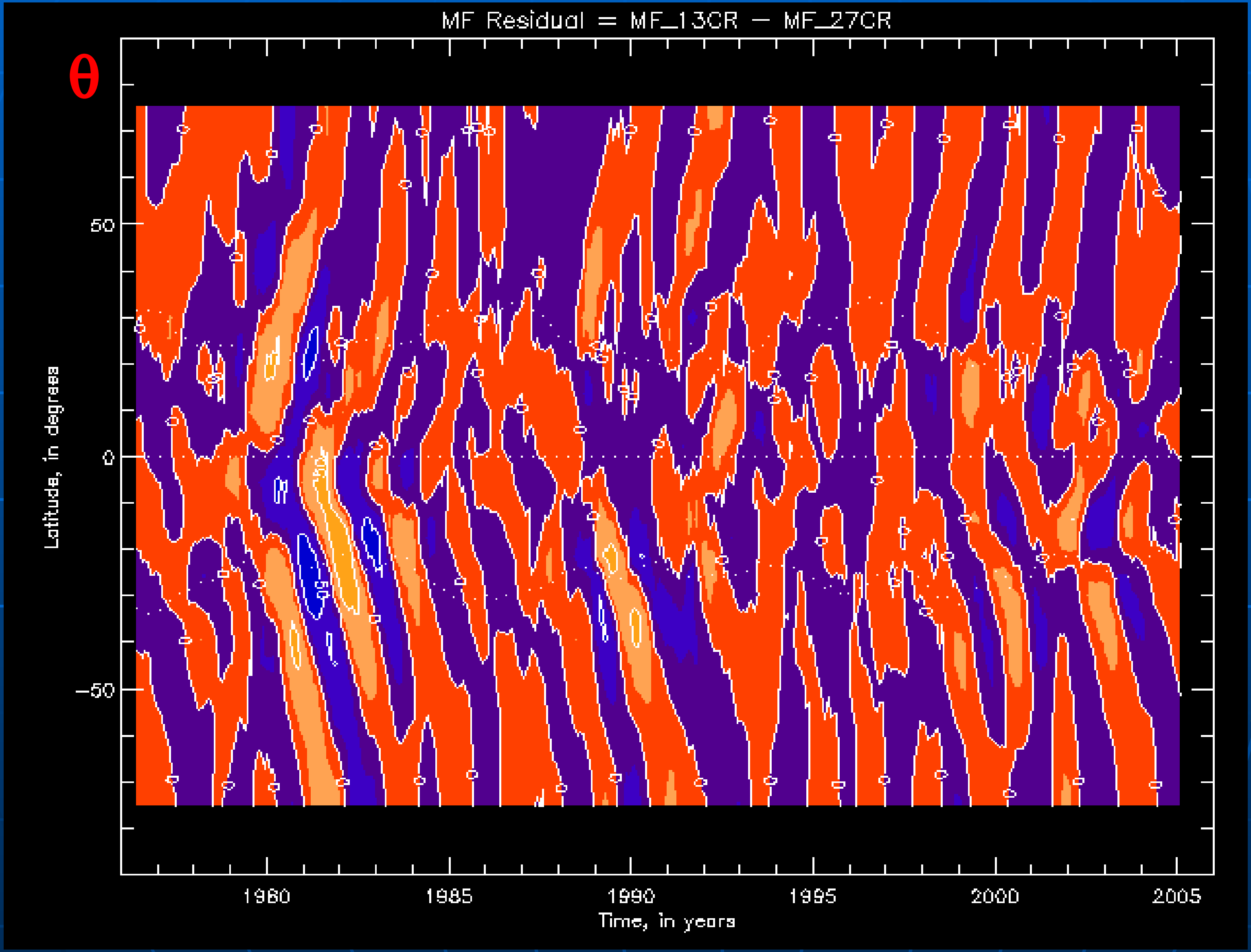
RMF



Waves of the magnetic field running from equator to the poles for different filters.



MFR = 1-year MF mean - 2-year MF mean



Velosity 40 km/h

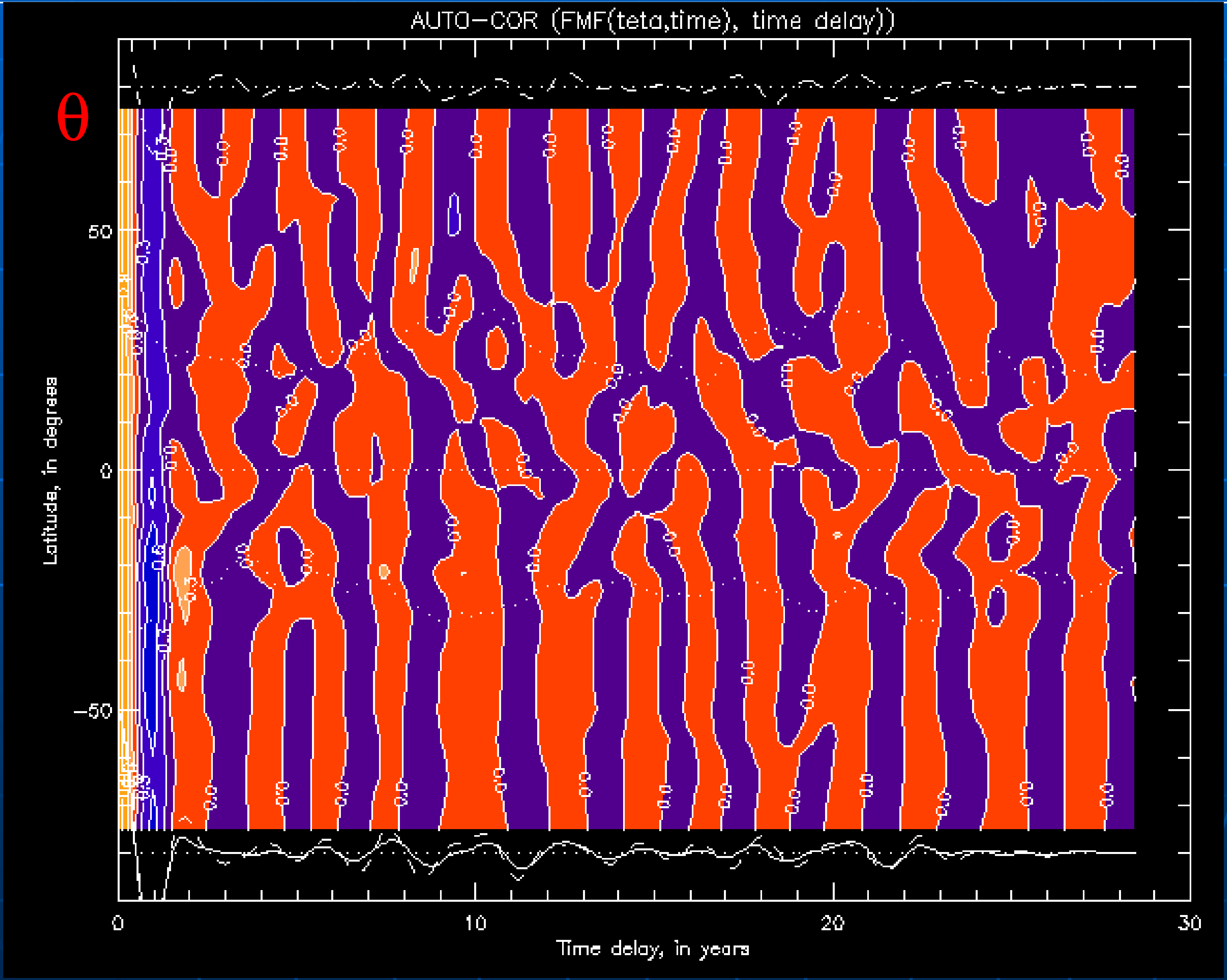
Interference of streams

Double Maxima

It takes 2-3 years to run from equator to pole

Time shift, in years

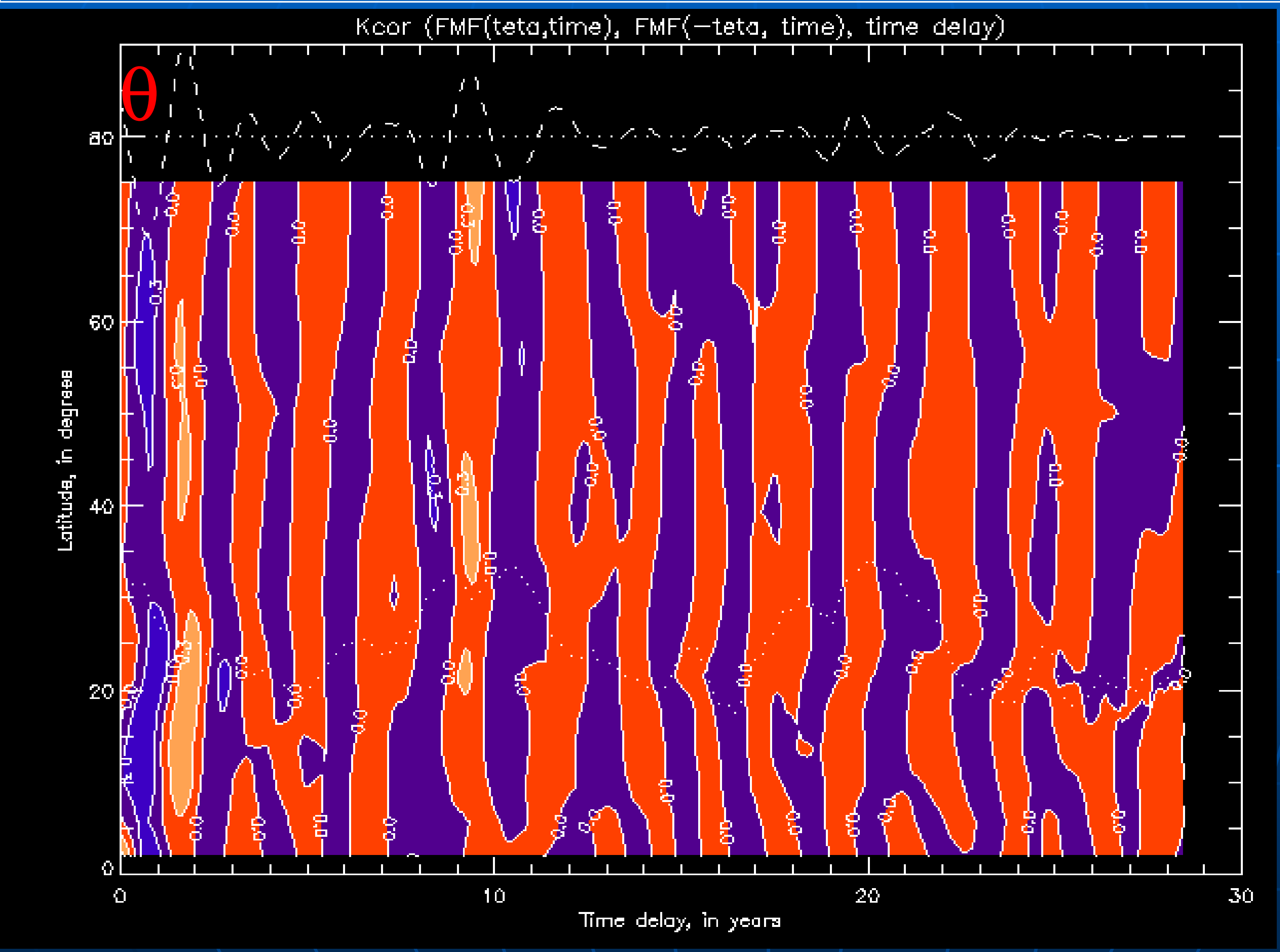
Auto-correlation of SMF Residuals



Quasi 2-3-year periodicity over all latitudes θ

Different in the Northern ans in the Southern Hemispheres

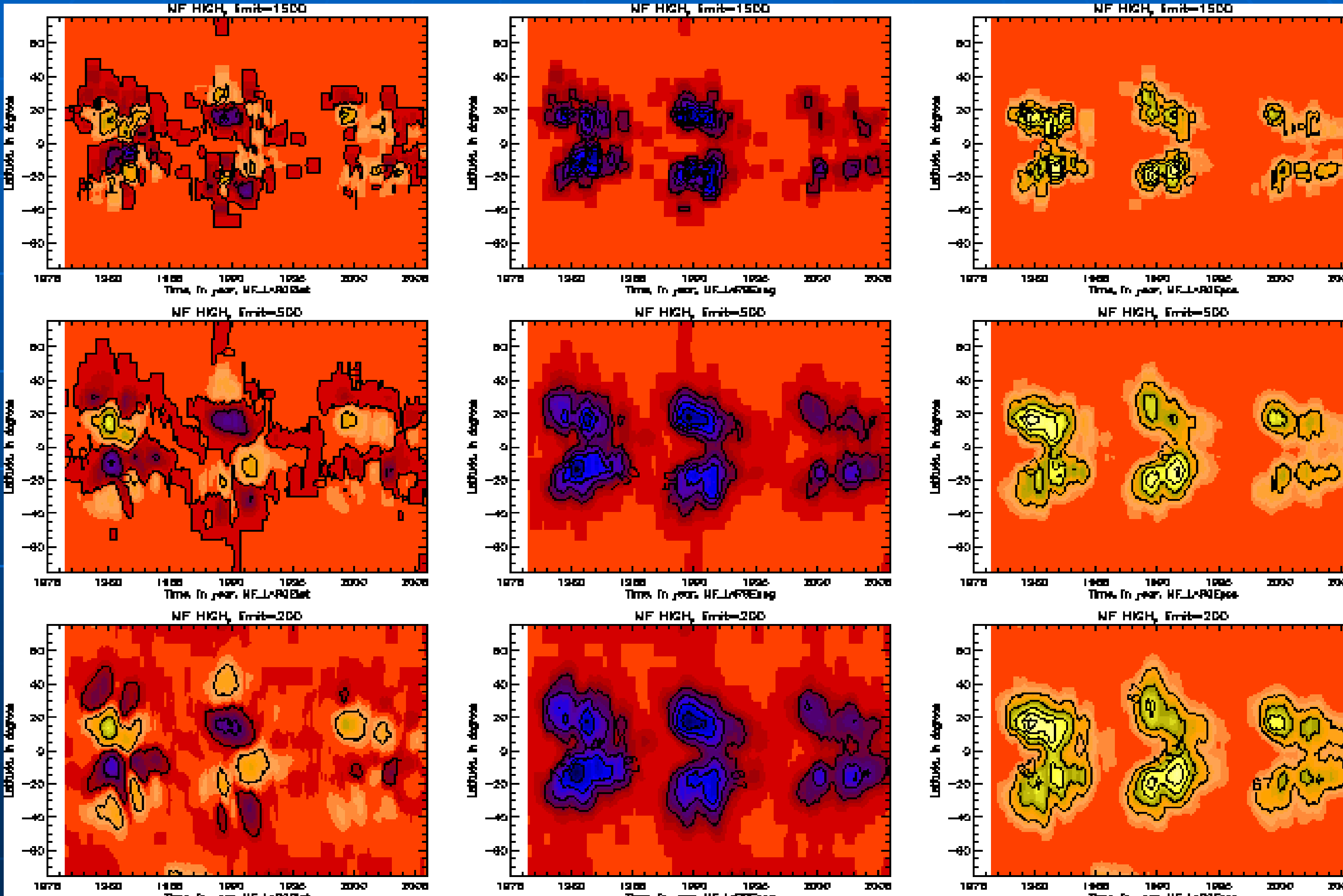
Cross-correlation of SMF Residuals *at* θ , –θ



2-year RMF periodicity over all latitudes θ

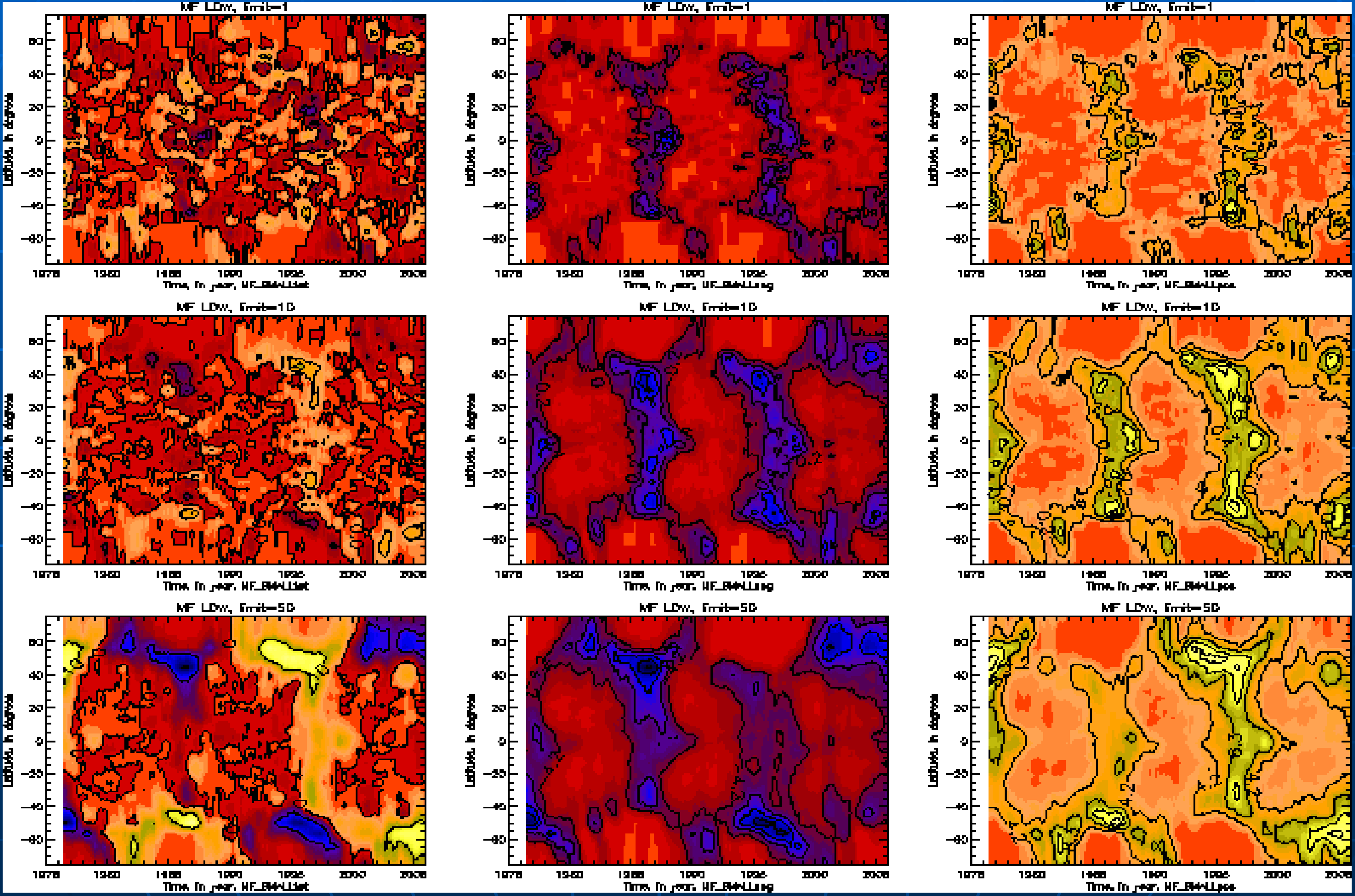
Phase reconstruction between N- S RMF each 9-11 years

HIGH MF

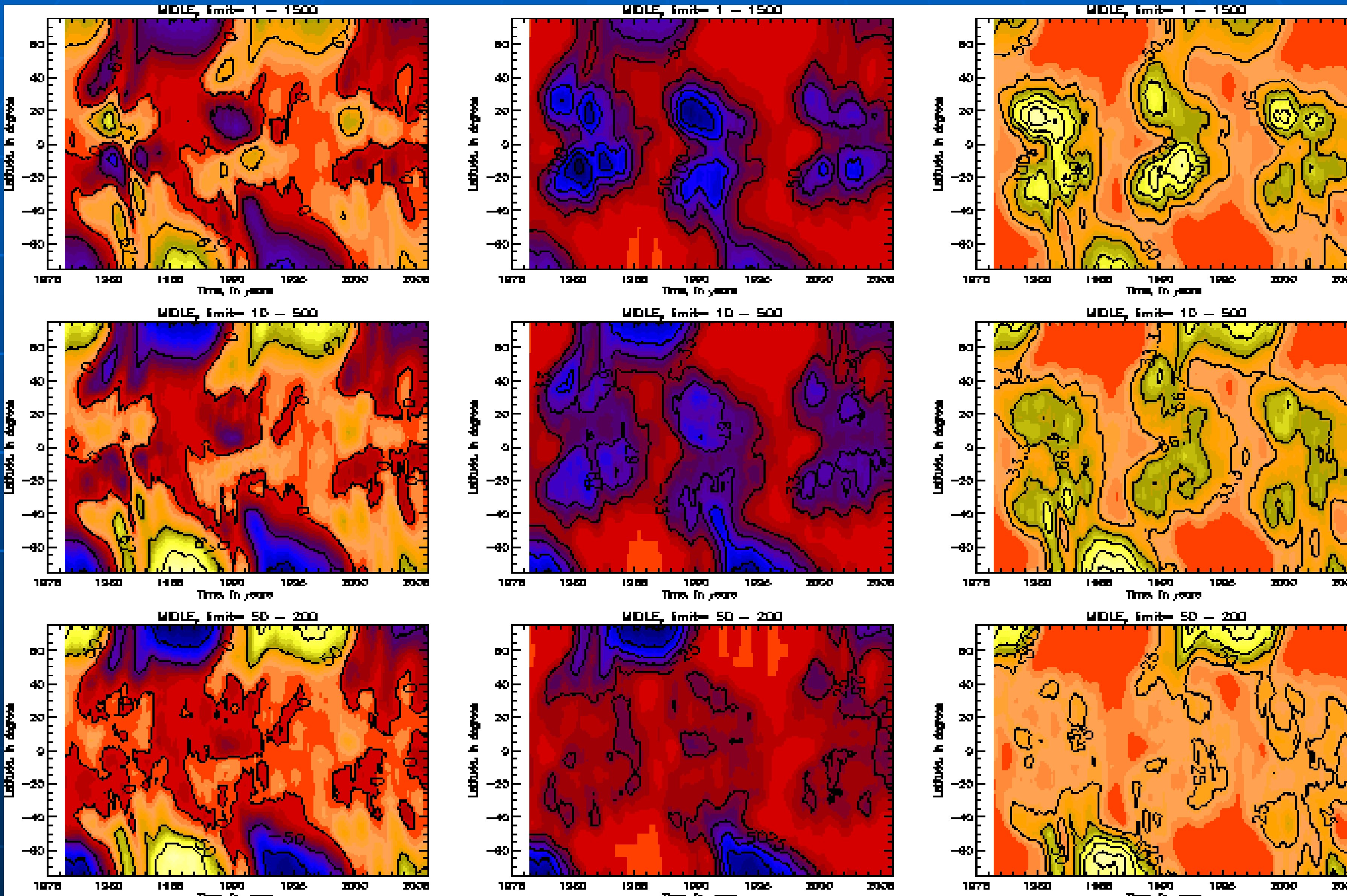


MF HIGH, limit=1500
MF HIGH, limit=500
MF HIGH, limit=200
MF HIGH, limit=1500
MF HIGH, limit=500
MF HIGH, limit=200

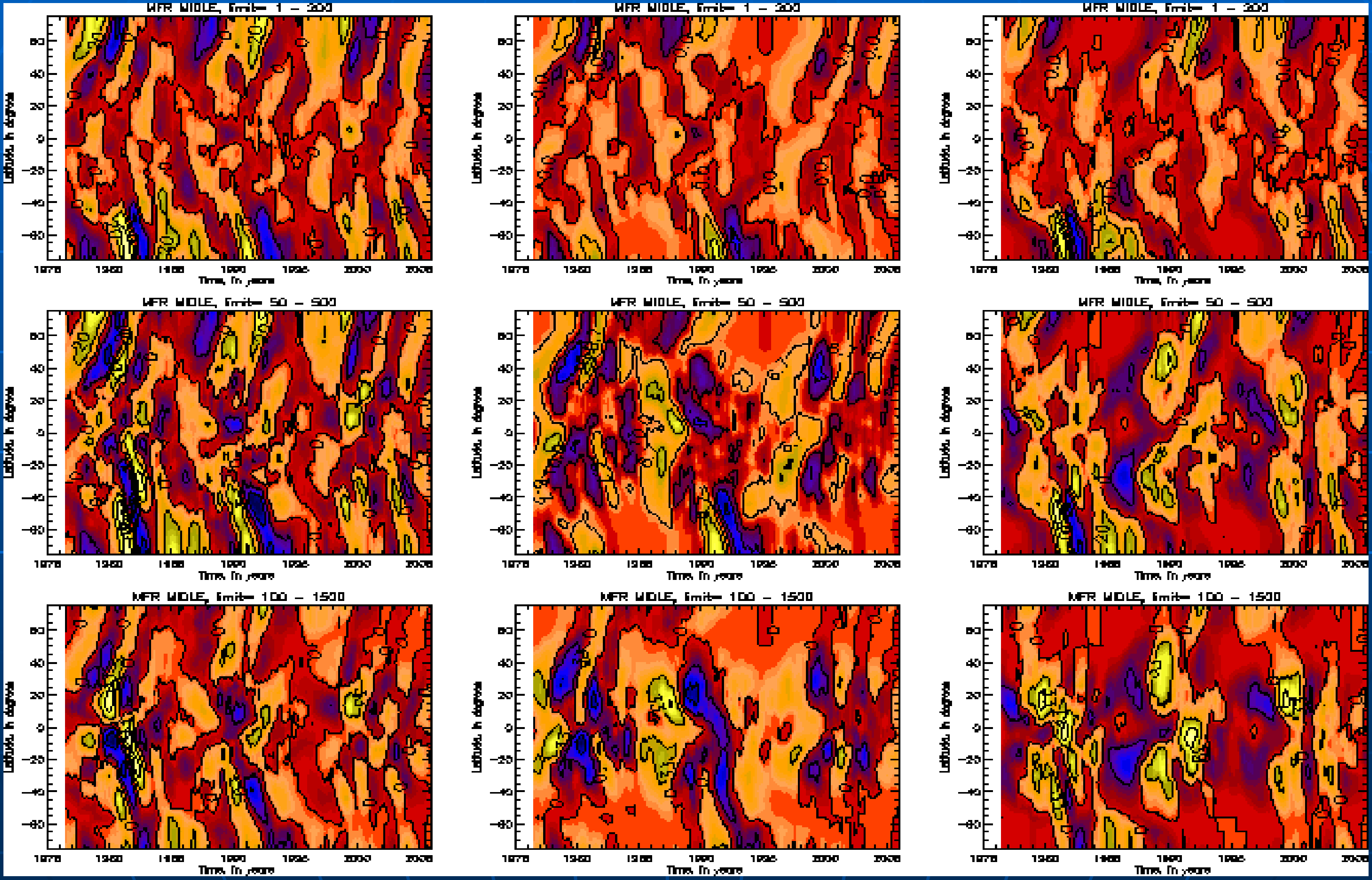
LOW MF



Middle MF

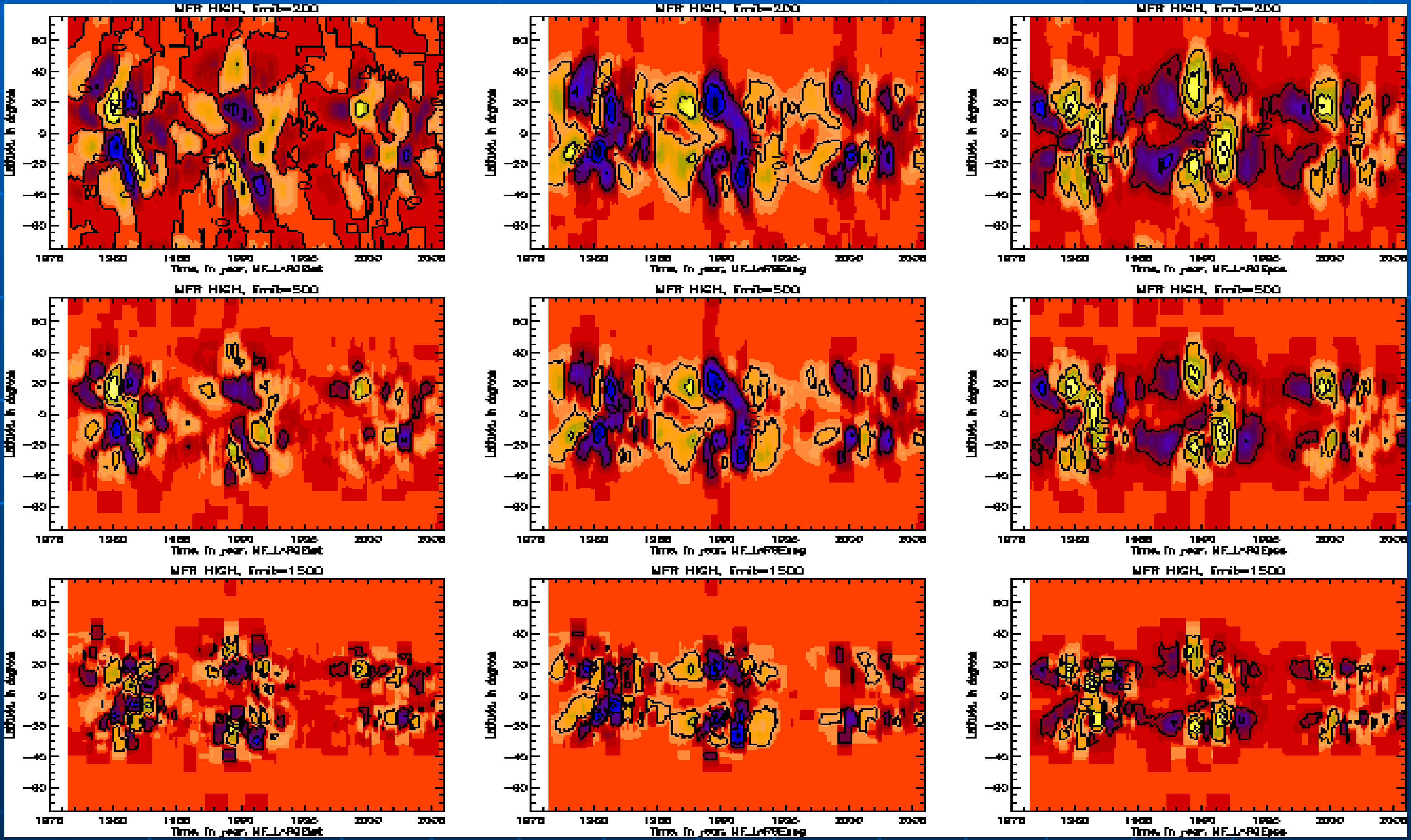

MIDLE, limit= 1 – 1500
MIDLE, limit= 10 – 500
MIDLE, limit= 50 – 200
Latitude, in degrees
Time, in years
1975 1980 1985 1990 1995 2000 2005
60 40 20 0 -20 -40 -60

Middle MF



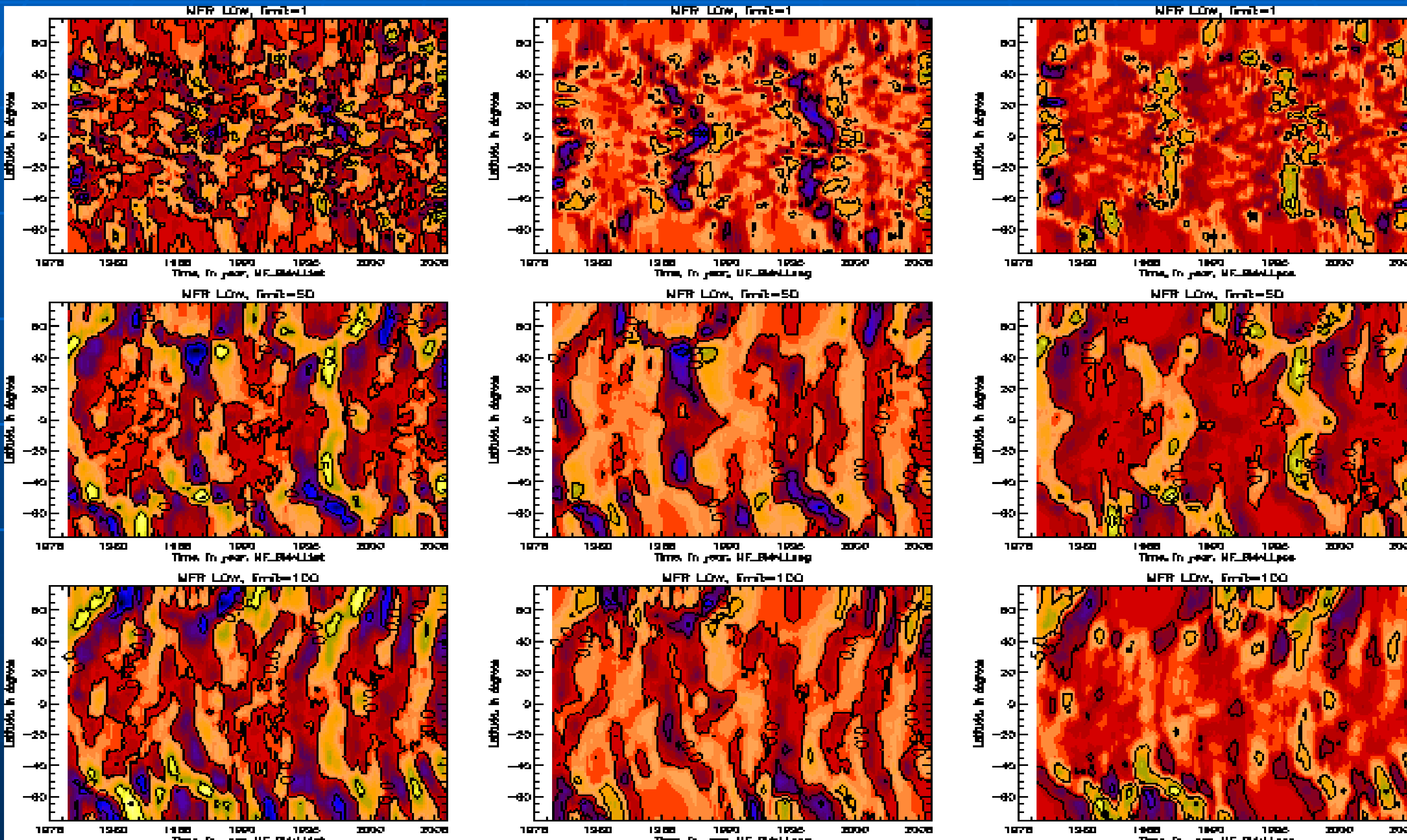
MFR MIDLE, limit= 1 – 200
MFR MIDLE, limit= 1 – 200
MFR MIDLE, limit= 1 – 200
MFR MIDLE, limit= 50 – 500
MFR MIDLE, limit= 50 – 500
MFR MIDLE, limit= 50 – 500
MFR MIDLE, limit= 100 – 1500
MFR MIDLE, limit= 100 – 1500
MFR MIDLE, limit= 100 – 1500
Latitude, in degrees
Time, in years

HIGH MF

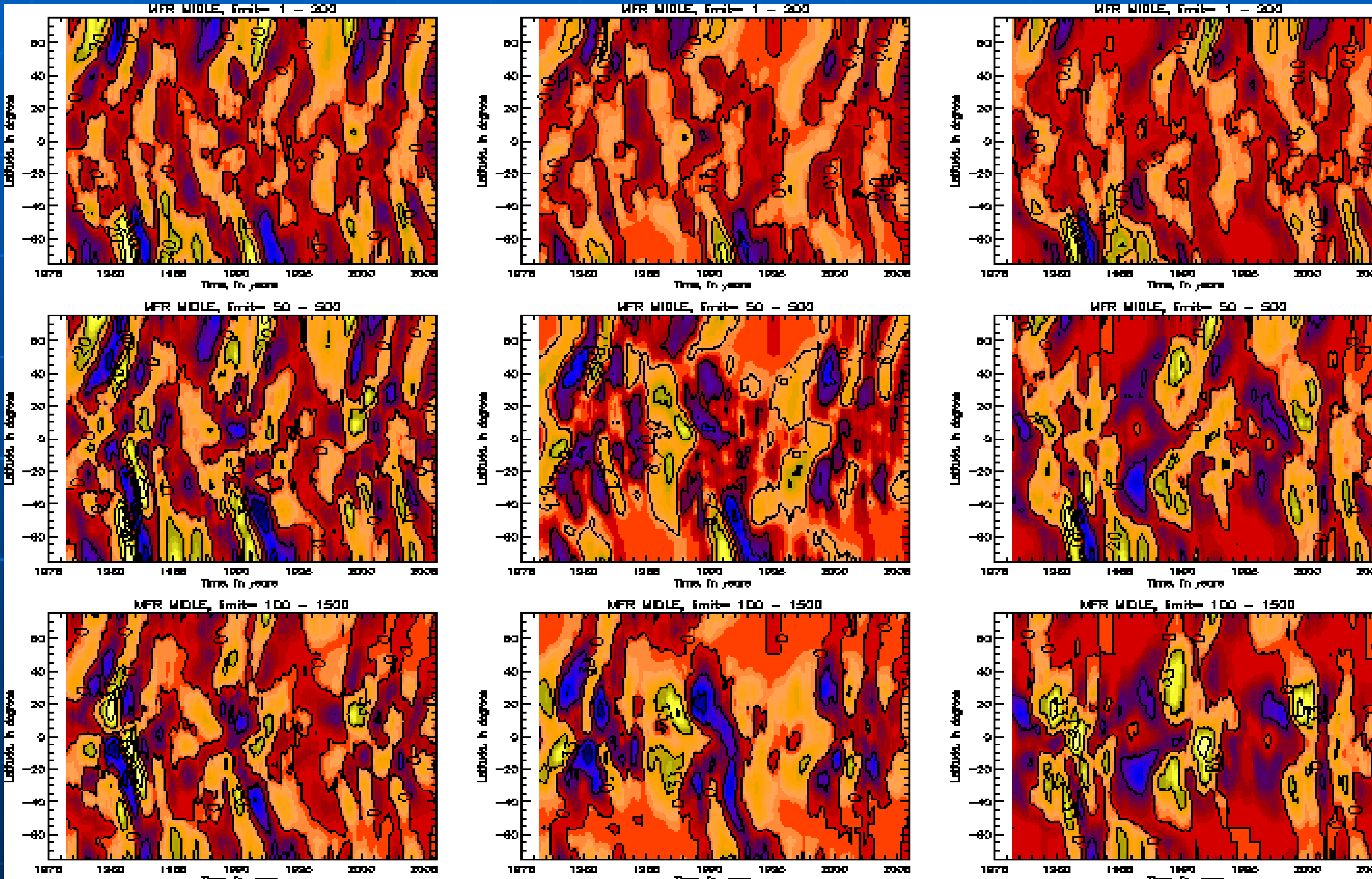


Latitude, in degrees
60
40
20
0
−20
−40
−60
1980
1985
1990
1995
2000

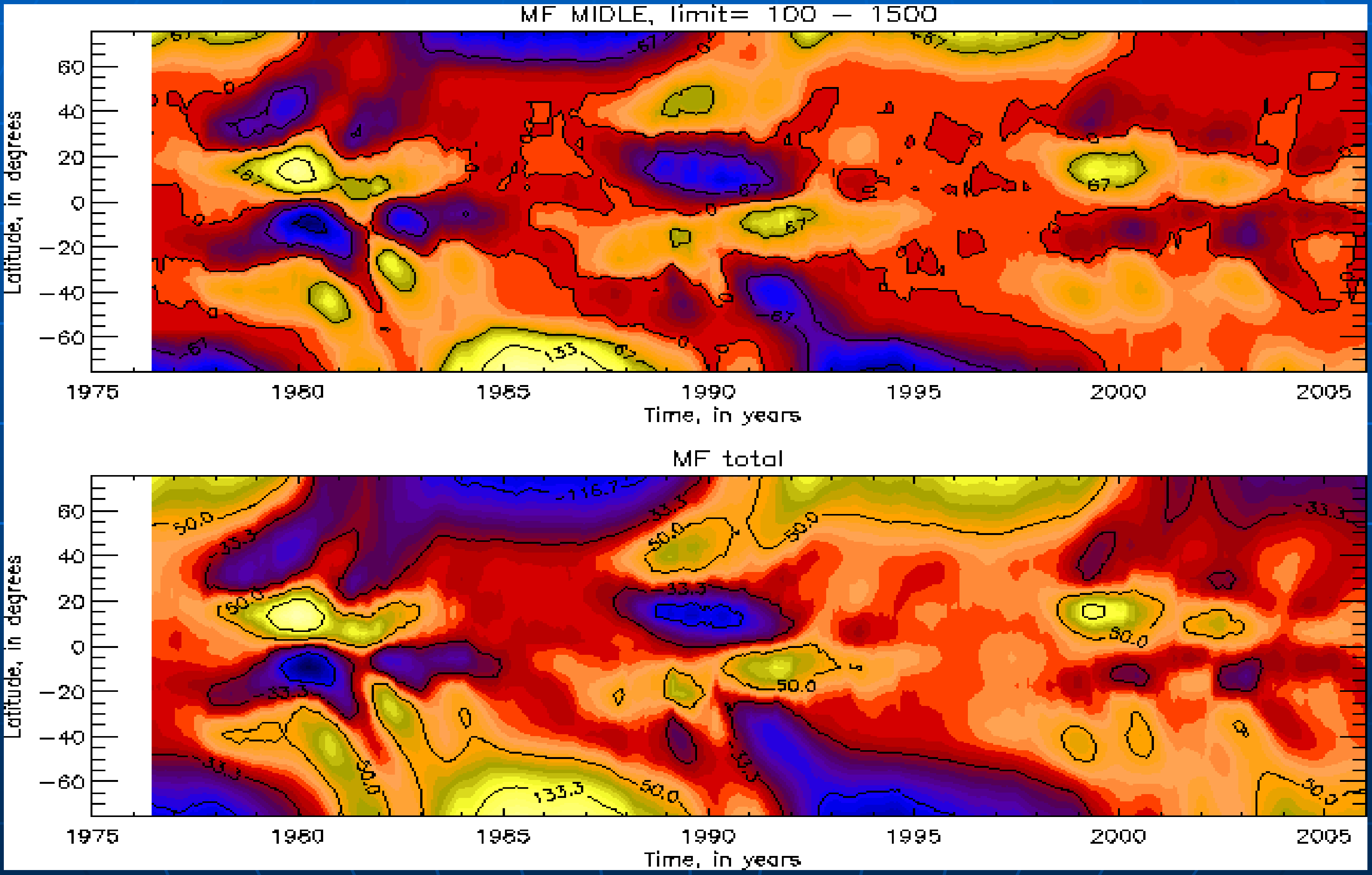
LOW MF



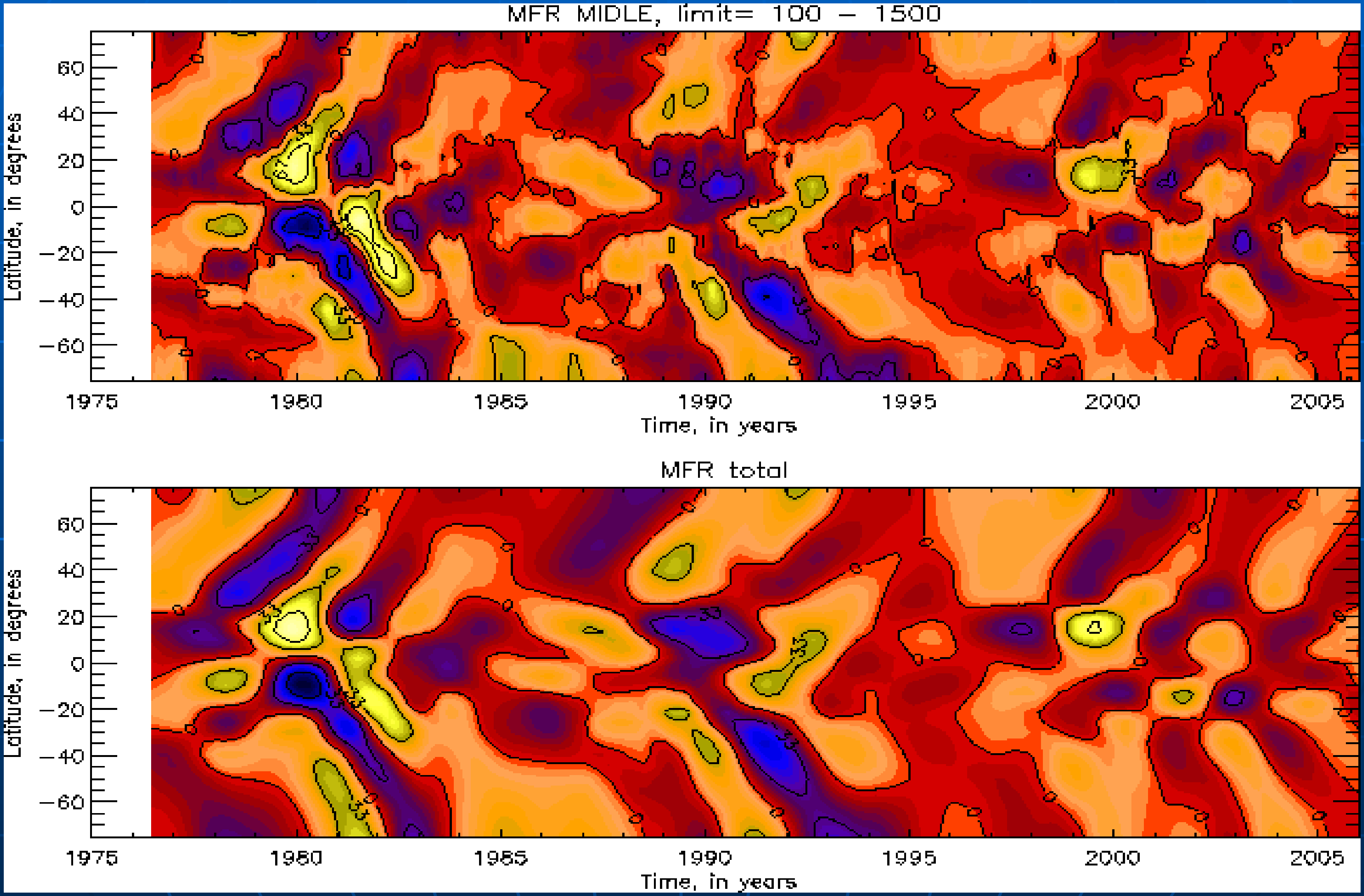
Middle MF


MFR MIDLE, limit= 1 – 200
MFR MIDLE, limit= 50 – 500
MFR MIDLE, limit= 100 – 1500
Latitude, in degrees
Time, in years

MF 1y mean , middle and total



MF, 1y-5y, middle and total



Solar rotation

Solar rotation

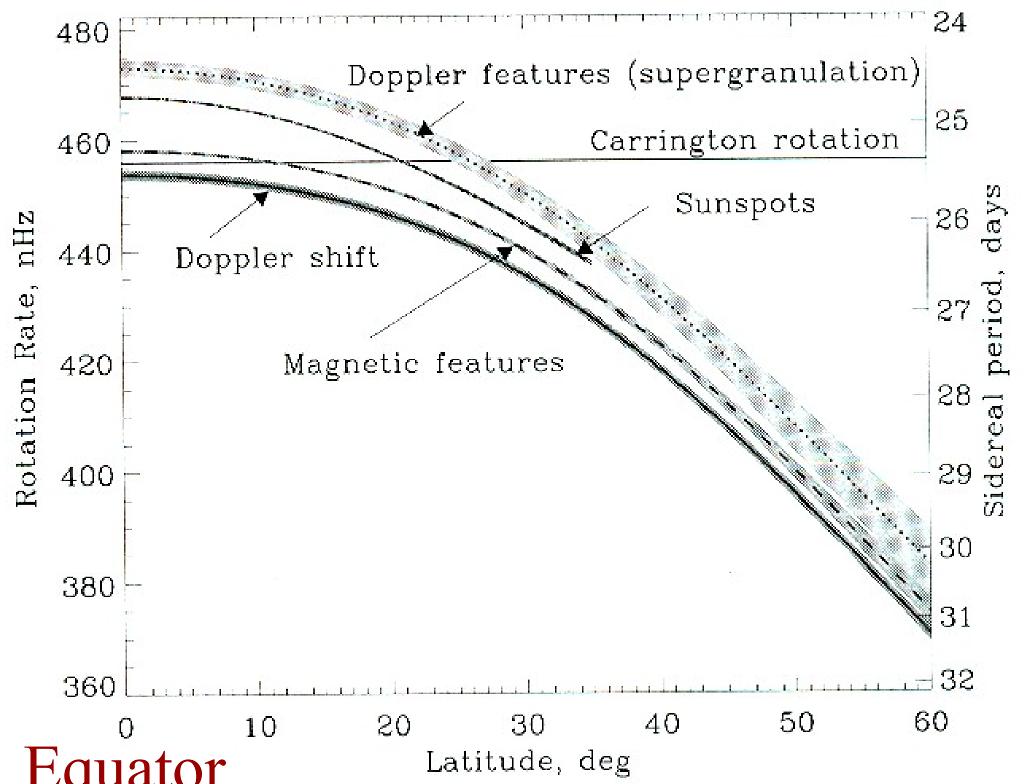
- The Sun rotates differentially, both in latitude (equator faster than poles) and in depth (more complex).
- Standard value of solar rotation: Carrington rotation period: 27.2753 days (the time taken for the solar coordinate system to rotate once).
- Sun's rotation axis is inclined by 7.1^{o} relative to the Earth's orbital axis (i.e. the Sun's equator is inclined by 7.1^{o} relative to the ecliptic).

Discovery of solar rotation

- Galileo Galilei and Christoph Scheiner noticed already that sunspots move across the solar disk in accordance with the rotation of a round body
- → Sun is a rotating sphere

Surface differential rotation

- Poles rotate more slowly than equator.
- Surface differential rotation from measurements of:
  - Tracers, such a sunspots or magnetic field elements (always indicators of the rotation rate of the magnetic field)
  - Doppler shifts of the gas
  - Coronal holes (not plotted) rotate rigidly



Equator

Figure 1. Rotation rate, $\Omega/2\pi$, and period of various tracers on the Sun's surface: recurrent (old) sunspots (dashed curve), magnetic features (dot–dash), and Doppler features (dots). The rotation rate and period determined spectroscopically through the Doppler shift are shown by the full curve. The shaded areas show the 1σ error estimates.

Surface differential rotation

- Description:

  $$\Omega = A + B \sin^2\psi + C \sin^4\psi$$

  where ψ is the latitude, $A = \Omega$ at the equator and $A+B+C = \Omega$ at the poles.

- Different tracers give different A, B, C values. E.g. spots rotate faster than the surface gas.

How come different rotation laws?

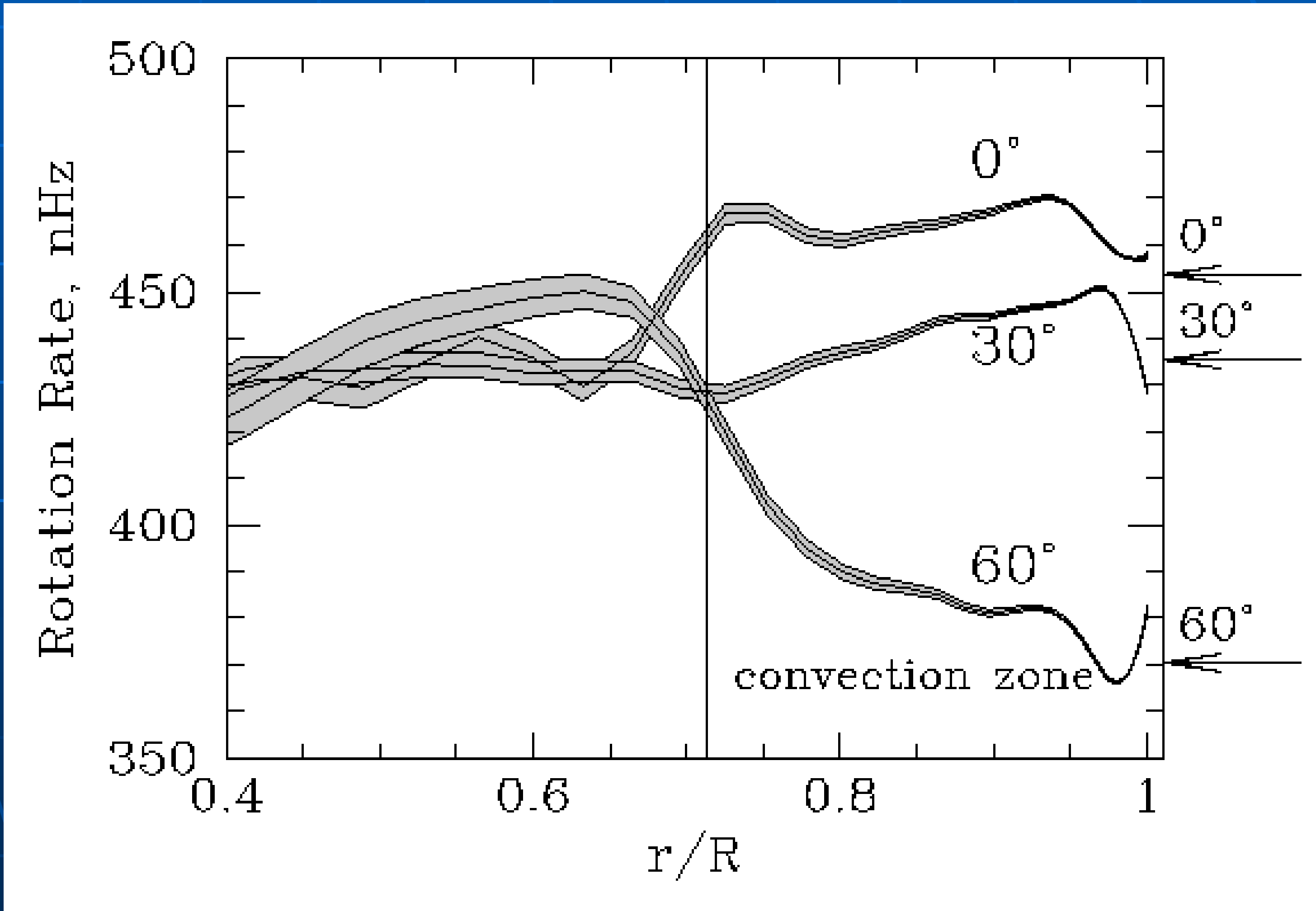
- Are different tracers anchored at different depths in the convection zone?
  - Evidence in support comes from sunspots: young spots rotate faster than older spots (→ older spots are slowed down by the surrounding gas)
- How come coronal holes rotate rigidly, while the underlying photospheric magnetic field rotates differentially?
  - ➔ Individual magnetic features must move in and out of coronal holes
  - ➔ Do they originated from the tachocline zone ?
  - ➔ Support: evidence for enhanced magnetic reconnection at the edges of coronal holes

Internal differential rotation

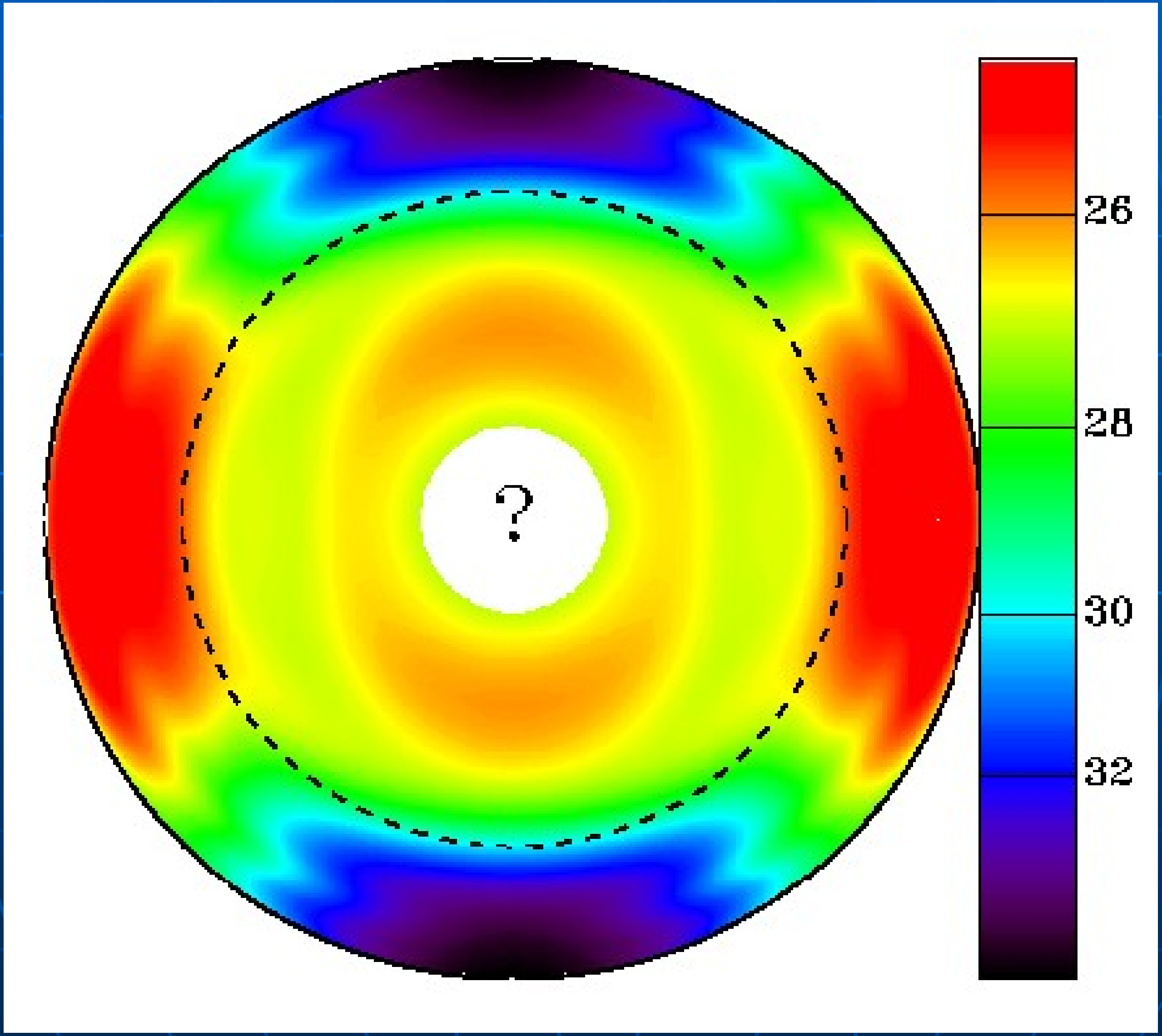
- Method: Helioseismic inversions
  - In a non-rotating star the individual modes of oscillation, described by "quantum numbers" n,l,m are degenerate in that their frequency depends only on n and l, but not on m.
  - Similar to Zeeman effect. Note that m distinguishes between the surface distribution of oscillation nodes. For a spherically symmetric star (no rotation) all these modes must have same frequency.
  - In a rotating Sun the degeneracy is removed and modes with different m have slightly different frequency.
  - Since modes with different l sample the solar latitudes in different ways, it is possible to determine not just vertical, but also latitudinal differential rotation by helioseismology.

Internal differential rotation III : tachocline

Large radial gradients in rotation rate at bottom of CZ (tachocline), but also just below solar surface (enigmatic). Note the slight missmatch of helio-seismic and Doppler measurements



What about rotation of solar core?



What about rotation of solar core?

- Rotation rate of solar core is not easy to determine, since p-modes are rather insensitive to the innermost part of the Sun.
- Different values in the literature for the core's rotation rate: $\Omega(r=0) = \Omega(r=R_{\odot}) \ldots 2\,\Omega(r=R_{\odot})$
- One way to set limits on $\Omega(r=0)$: quadrupole moment of Sun.
- Solar rotation leads to oblateness, i.e. diameter is larger at equator than between the poles.
- If core rotates more rapidly than surface, then oblateness will be larger than expected due to surface rotation rate.

Solar oblateness

- Oblateness = $\Delta R/R_\odot$
- Direct measurements: $\Delta R/R_\odot \approx 10^{-5}$
  - Very tricky, since oblateness 10^{-5} corresponds to $\Delta R = 14$ km (best spatial resolution achievable: 100 km).
  - Systematic errors due to concentration of magnetic activity to low latitudes → affects measurements of solar diameter, since shape of limb is distorted.
  - Initial measurements due to Dicke & Goldenberg (1967) gave $\Delta R/R_\odot \approx 5 \times 10^{-5}$ → required change of general relativity to explain motion of Mercury's perihelion (but was consistent with Brans-Dicke gravitation theory)
- Helioseismic measurements give for the acoustic radius of the Sun (which is not the same as the optical radius, but similar): $\Delta R/R_\odot \approx 10^{-5}$ (Redouane Mecheri)

Evolution of solar rotation

- Young stars are seen to rotate up to 100 times faster than the Sun.
- Did the Sun also rotate faster when it was young?
- Skumanich law: $\Omega \sim t^{-1/2}$, where t is the age of the star (deduced from observing stars in clusters of different ages).

➔ Sun also rotated faster as a young star.

- Question: where did all the angular momentum go?
- Answer part 1: Magnetic field ???
- Answer part 2: Solar wind ???

WSO data

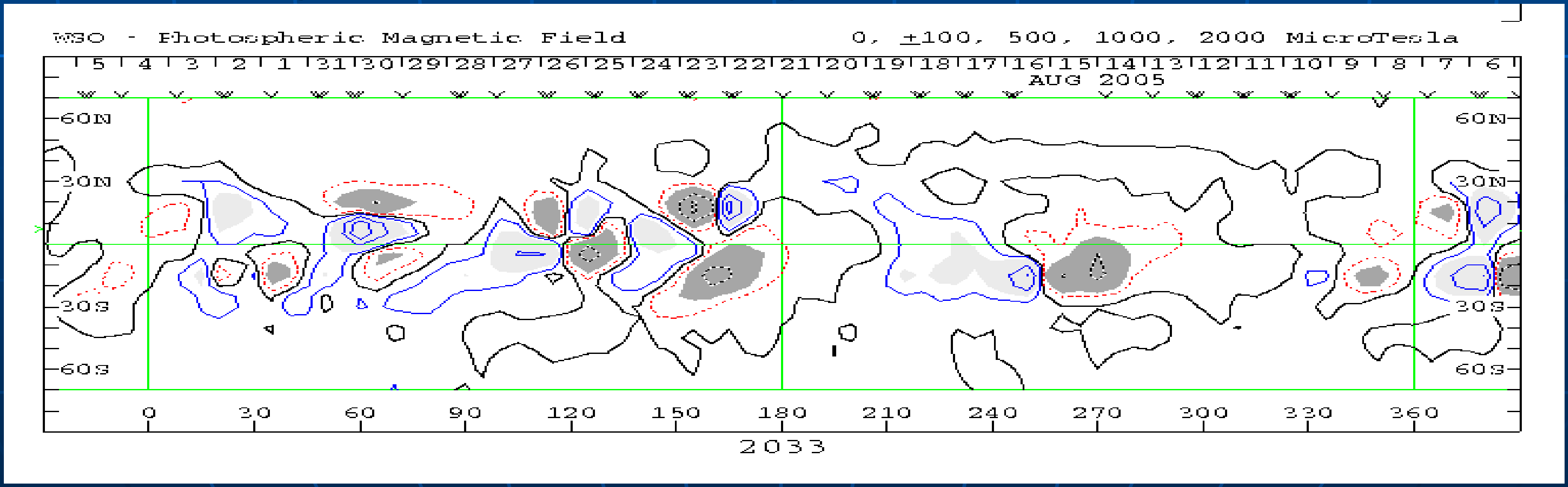
- The observations of the large scale magnetic field in the photosphere taken at the Wilcox Solar Observatory (WSO) since May 27, 1976 up to 2007 have been analyzed (http://wso.stanford.edu/synoptic.html).

- This interval of time covers the solar activity cycles No 21, 22 and 23 and corresponds to the Carrington Rotations (CR) since 1642 to 2050.

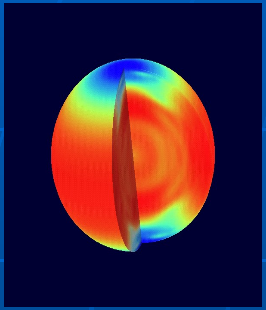
- The line-of-sight component of the photospheric magnetic field (SMF) is measured by the WSO's Babcock solar magnetograph using the Zeeman splitting of the 525.02 nm Fe I spectral line.

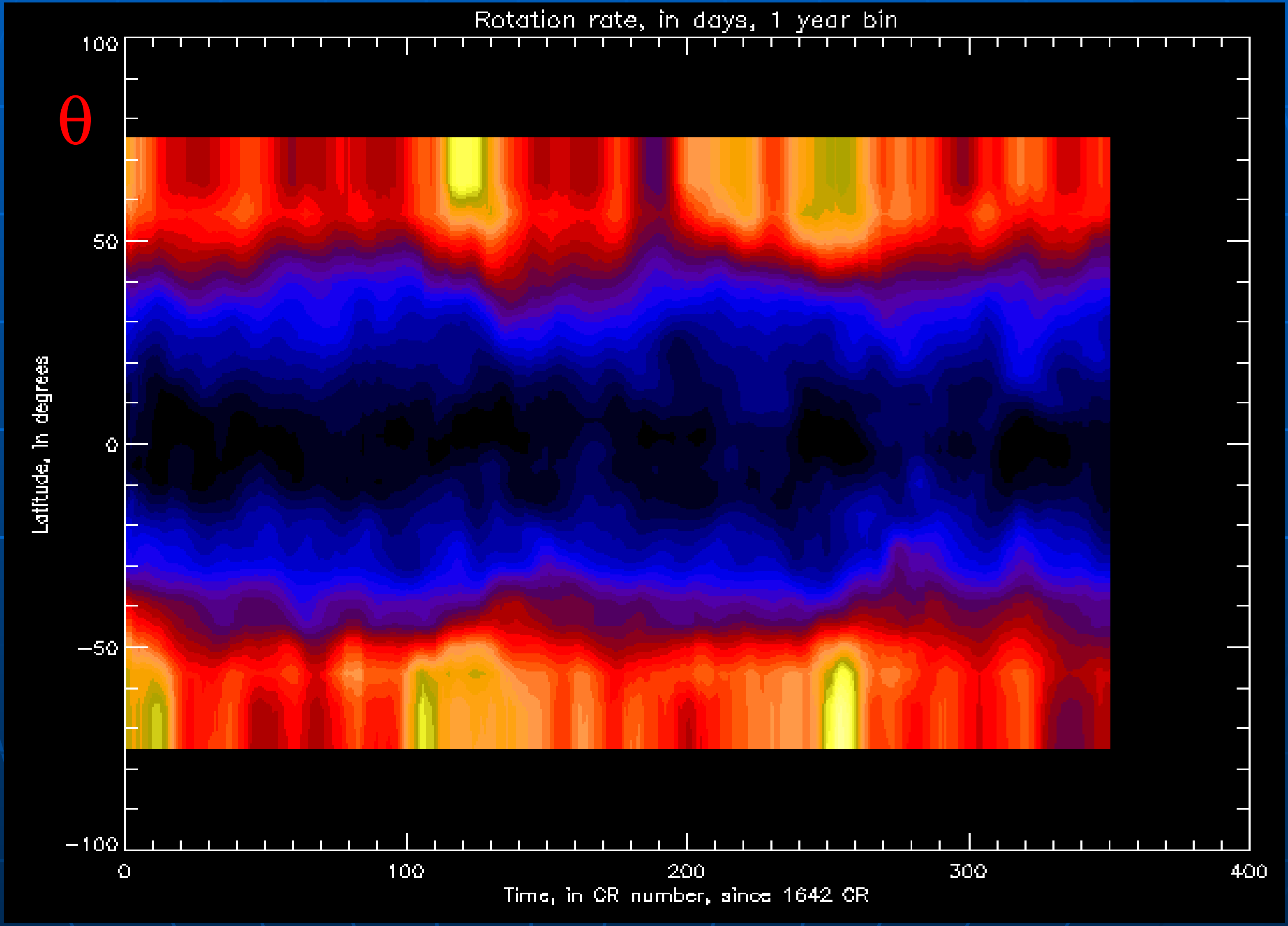
- The grid of the available data is made of 30 equal steps in latitude *sine* from 75.2 North to 75.2 South degrees and of 5 degrees steps in heliographic longitude.

- Each longitudinal value is a weighted average of the observations made in the longitudinal zone within 55 degrees around central meridian.

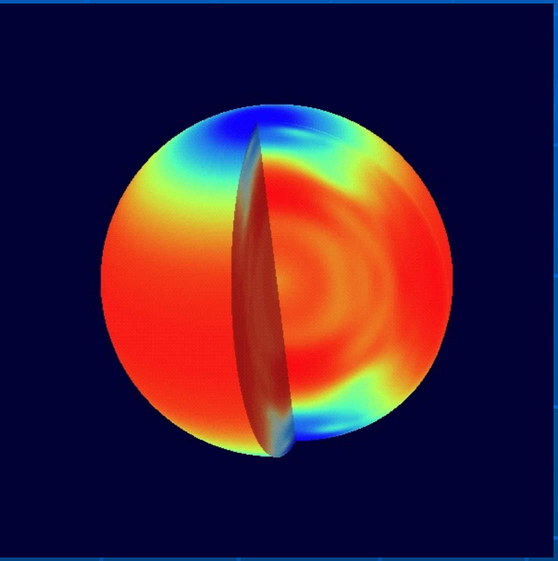


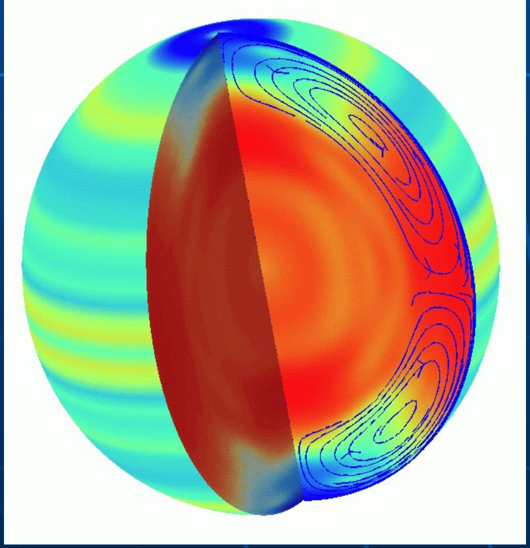
Differential Rotation of the SMF

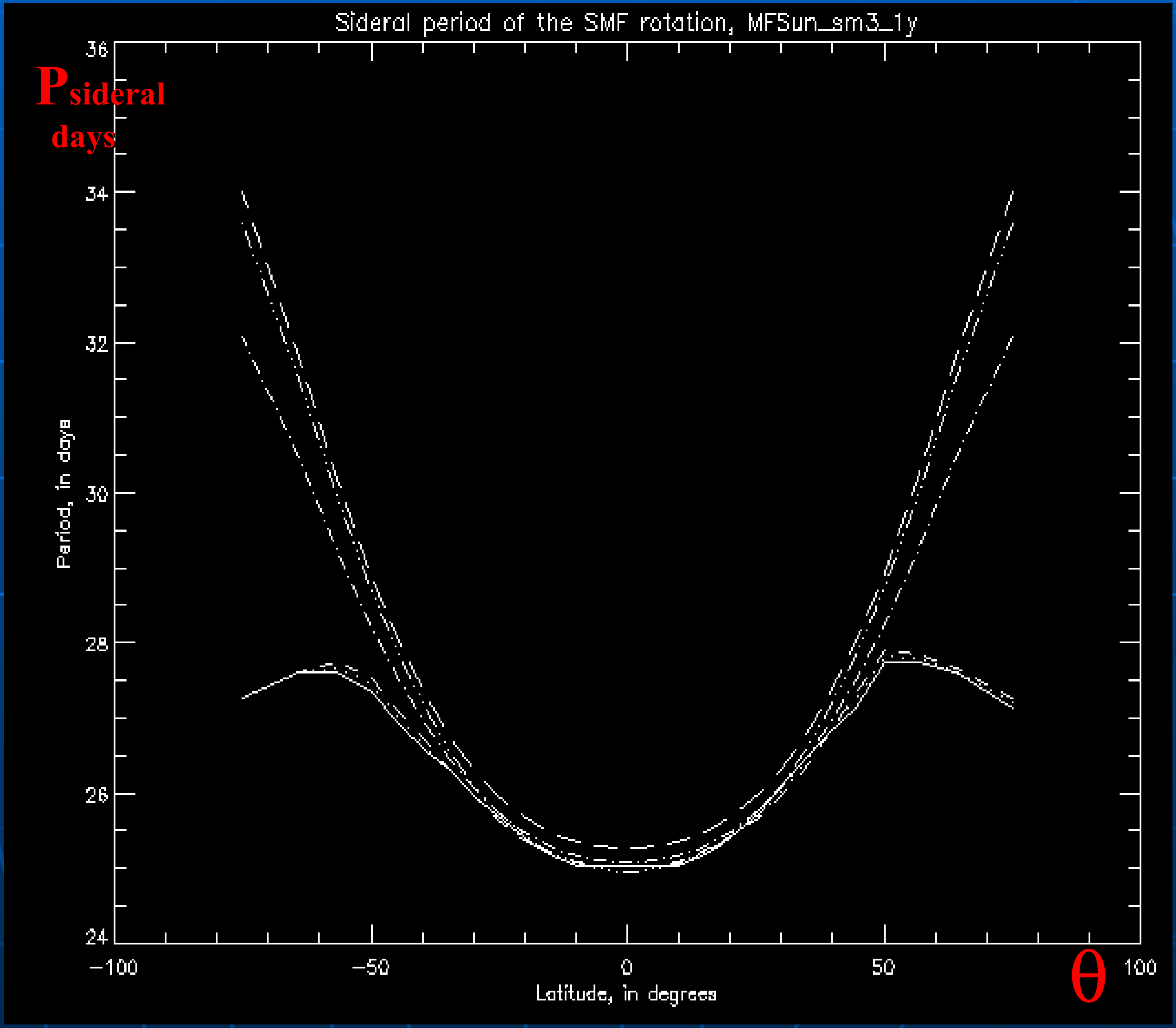




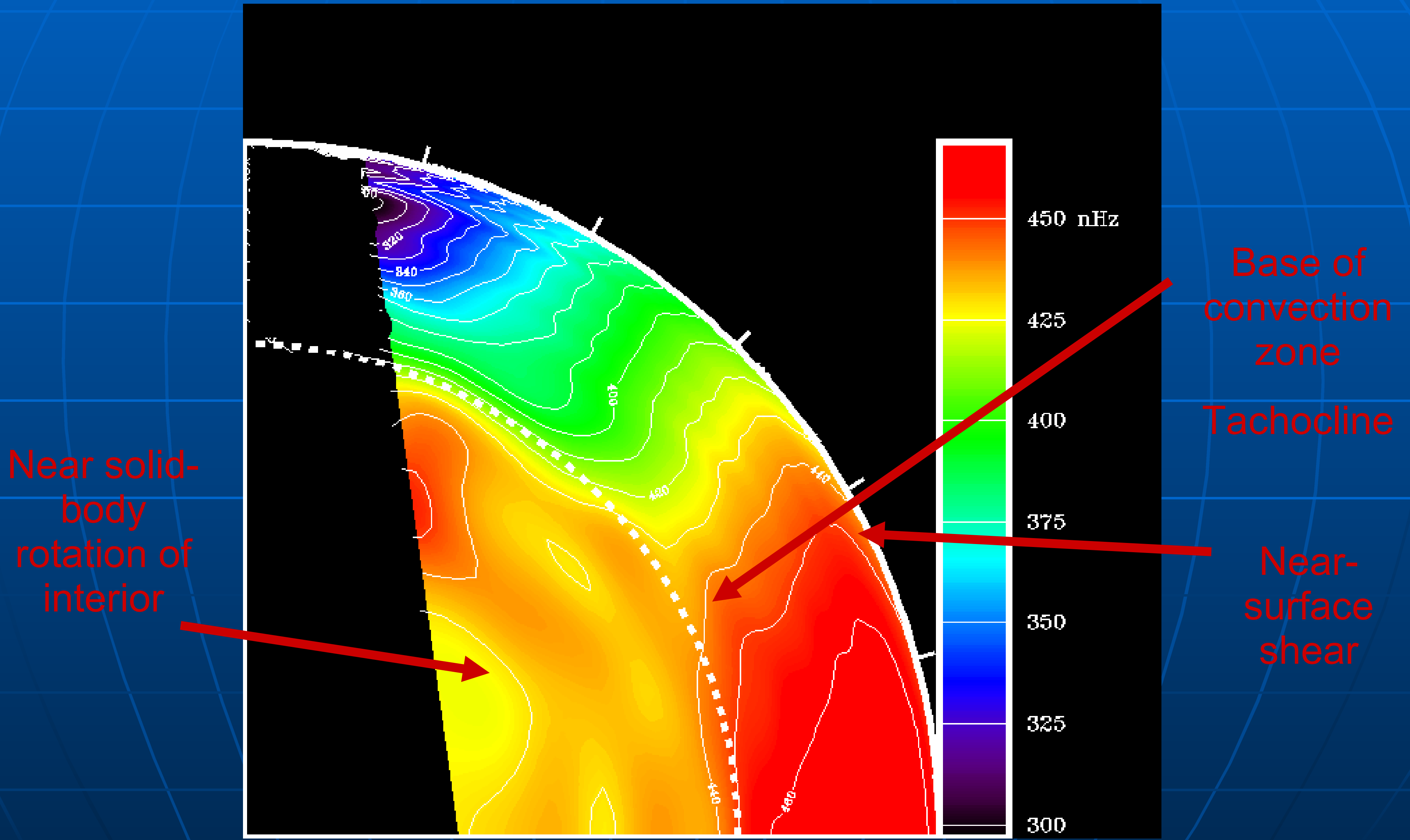
Differential Rotation of the SMF





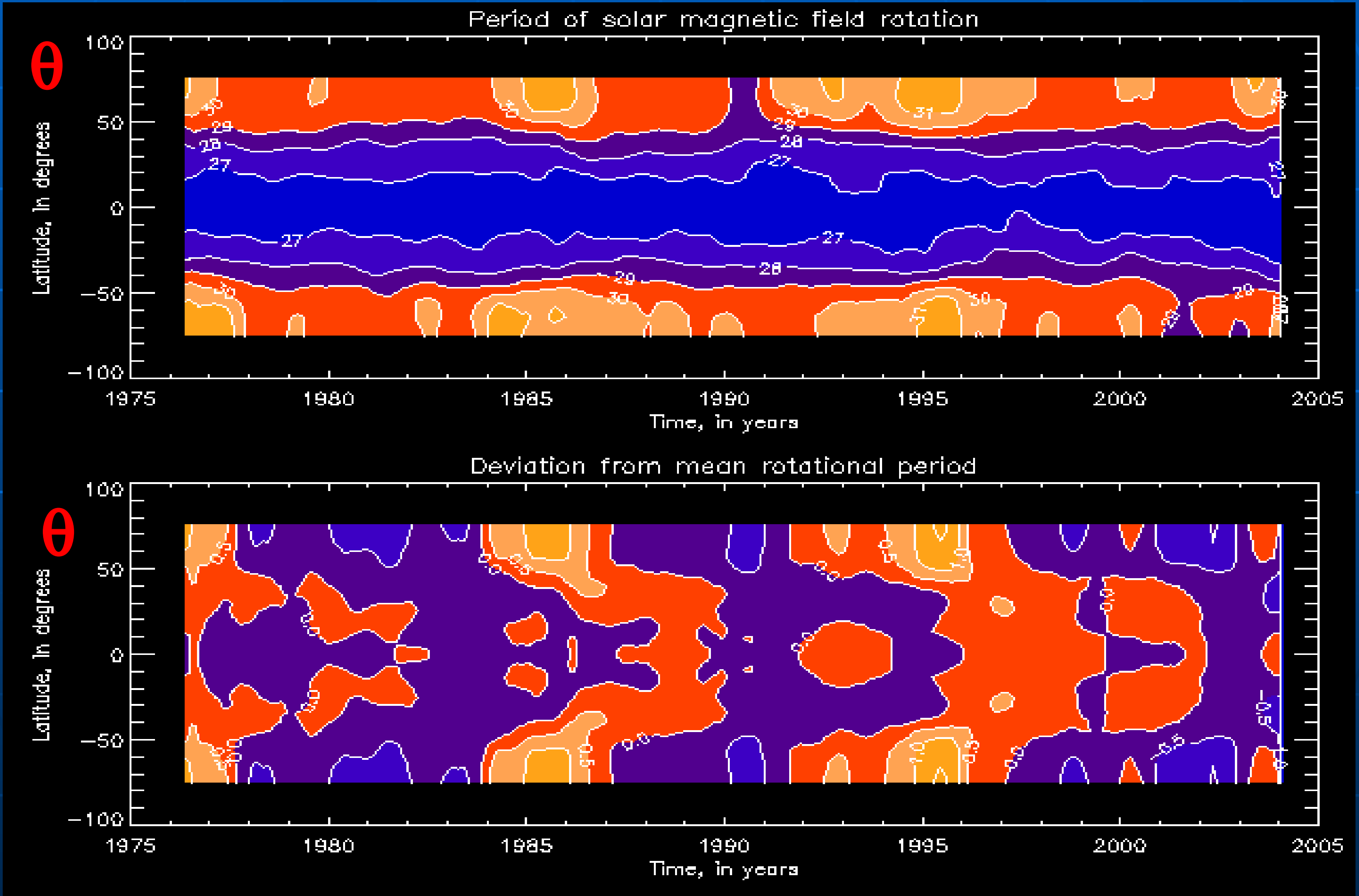


Inferred solar internal rotation



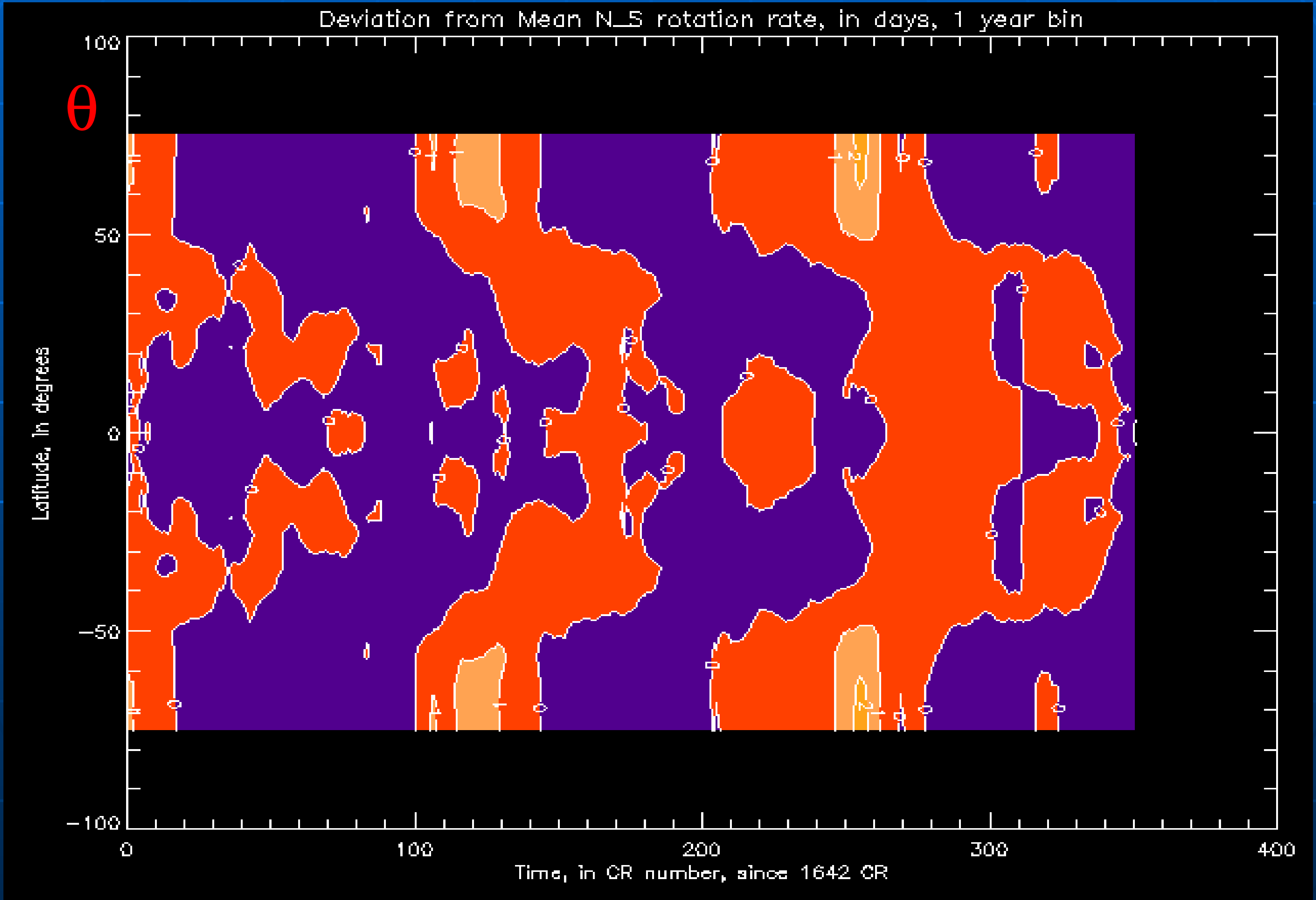
Differential Rotation of the SMF

Sideral Periods & Deviations from P mean, in days



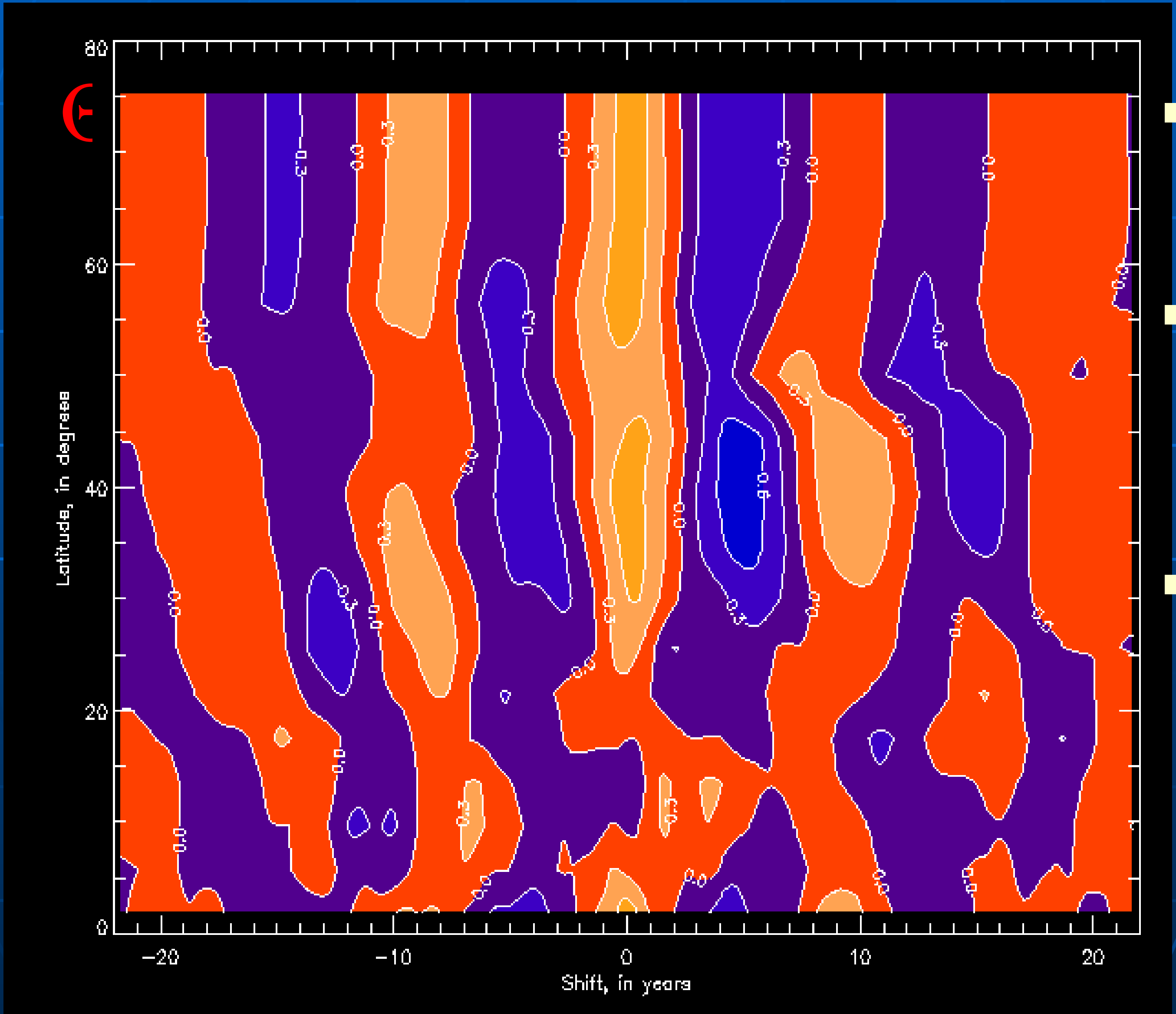
Deviations of SMF Periods from means over 2 cycles:

$$P(\theta, t) - P(\theta)$$



K cor (Ω(θ, t), Ω(-θ, t)),

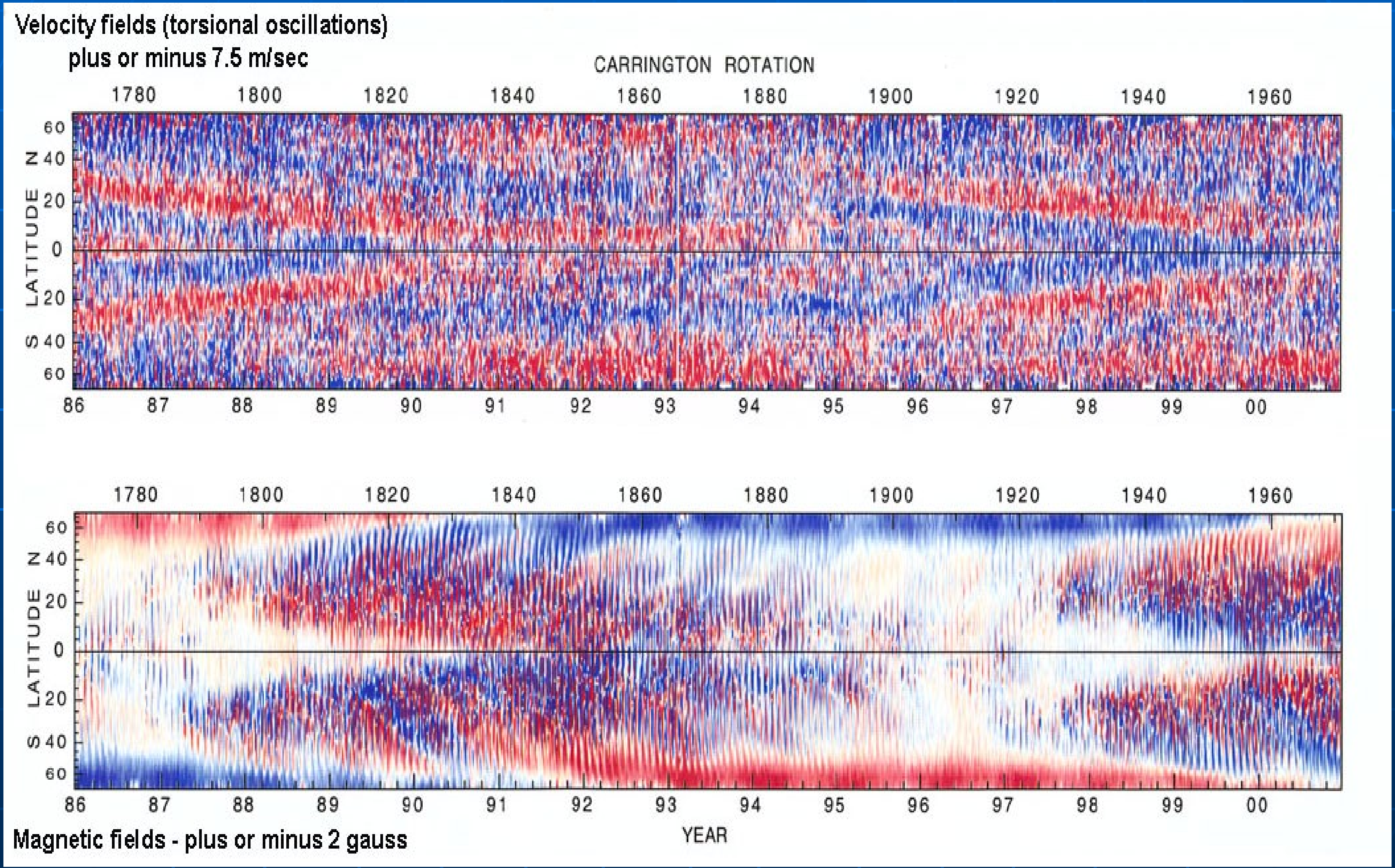
Ω(θ, t) = smooth(Ω(θ, t) over 1 year)



- **Correlation at 0- shift**
- **Quasi-10 year periodicity**
- **No correlation at +/-25 degrees**

Torsional waves

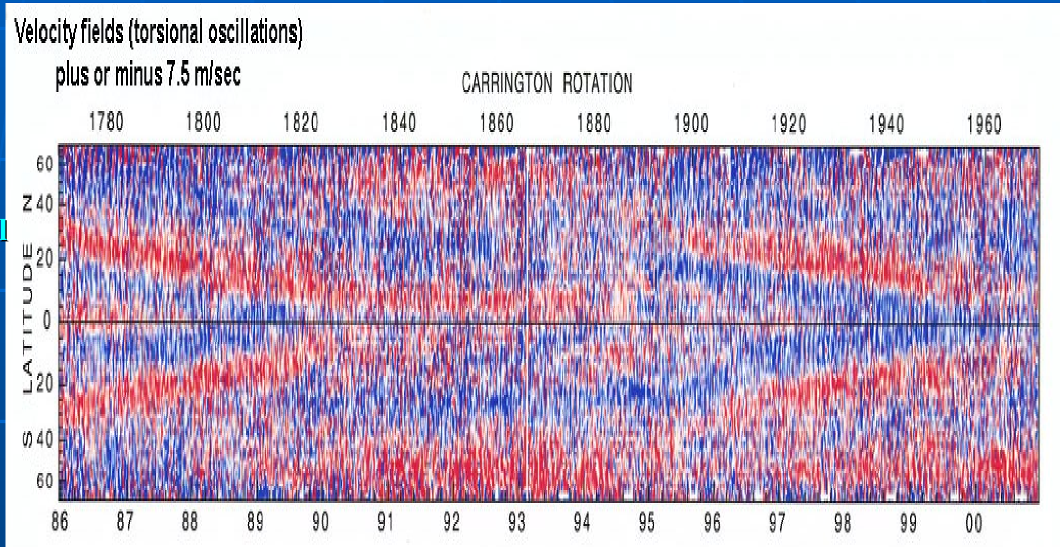
Howard R, LaBonte B.J., 1980



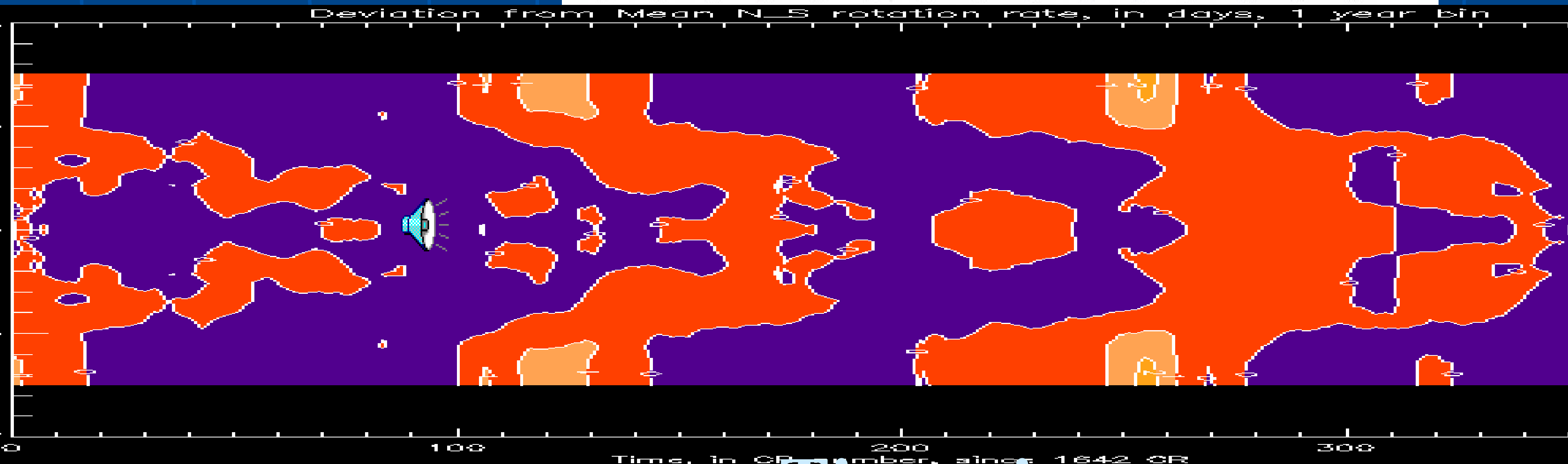
Torsional waves, P(θ, t) – P(θ)

The torsional waves firstly discovered by Howard and LaBonte in sunspot rotation are present in the magnetic field rotation rate as well (Snodgrass, 1985, 1987; Gilman and Howard, 1984; Makarov et al., 1997) up to high latitudes as it is seen on the bottom plot of Fig. 5. The 11-year variability of the deviations of the period from the mean one in the sub-polar zones correspond to the torsional waves. The rotational rate of the pre-equatorial zones varies in time with a periodicity of 55--60 CR about (4 -- 5 years).

Dopler velocity, Howard R, LaBonte B.J., 1980



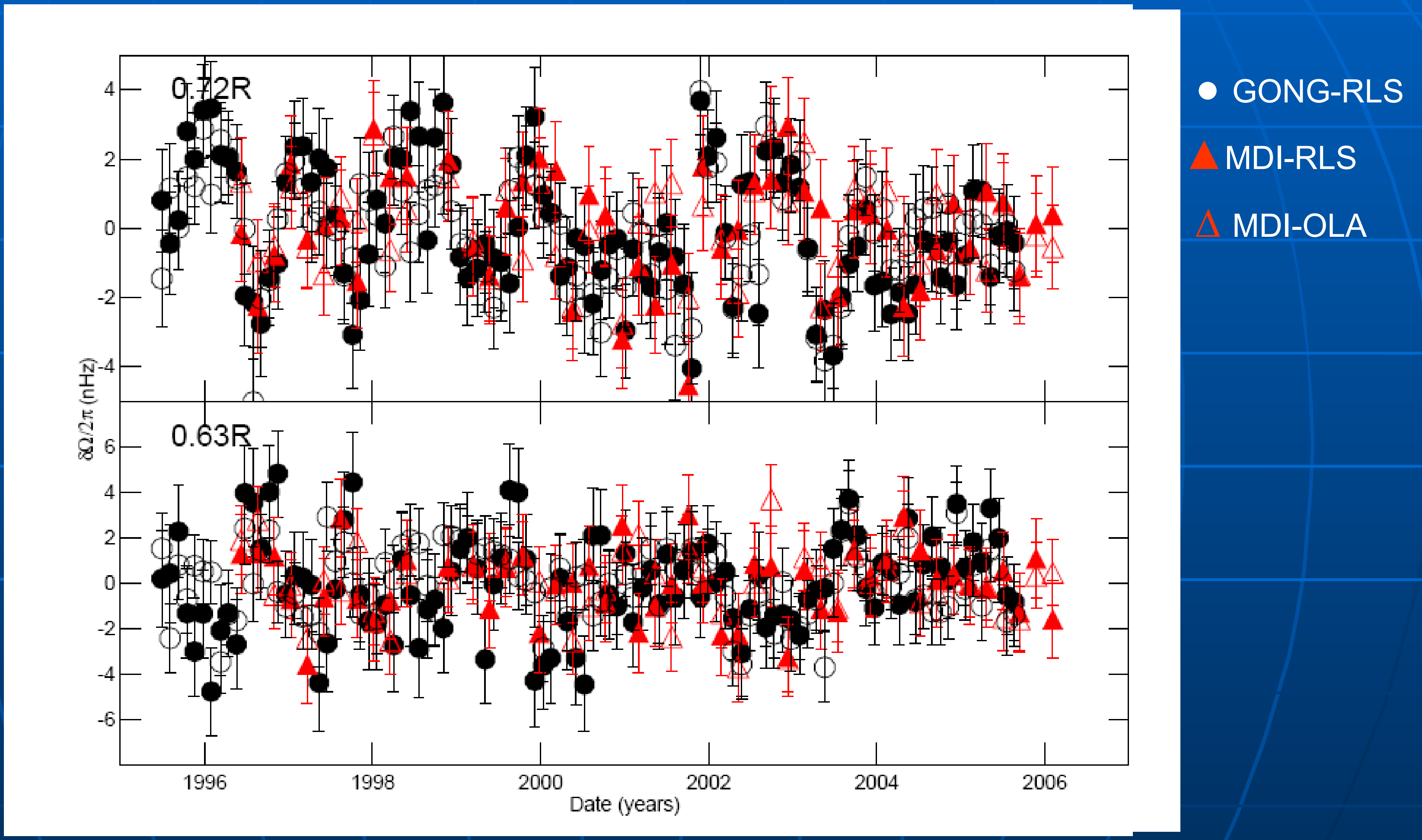
WSO MF Sun
Gavryuseva, 2006



Time, in years

Variation of the solar rotation velocity with period of 1.3 years

Tachocline oscillations?



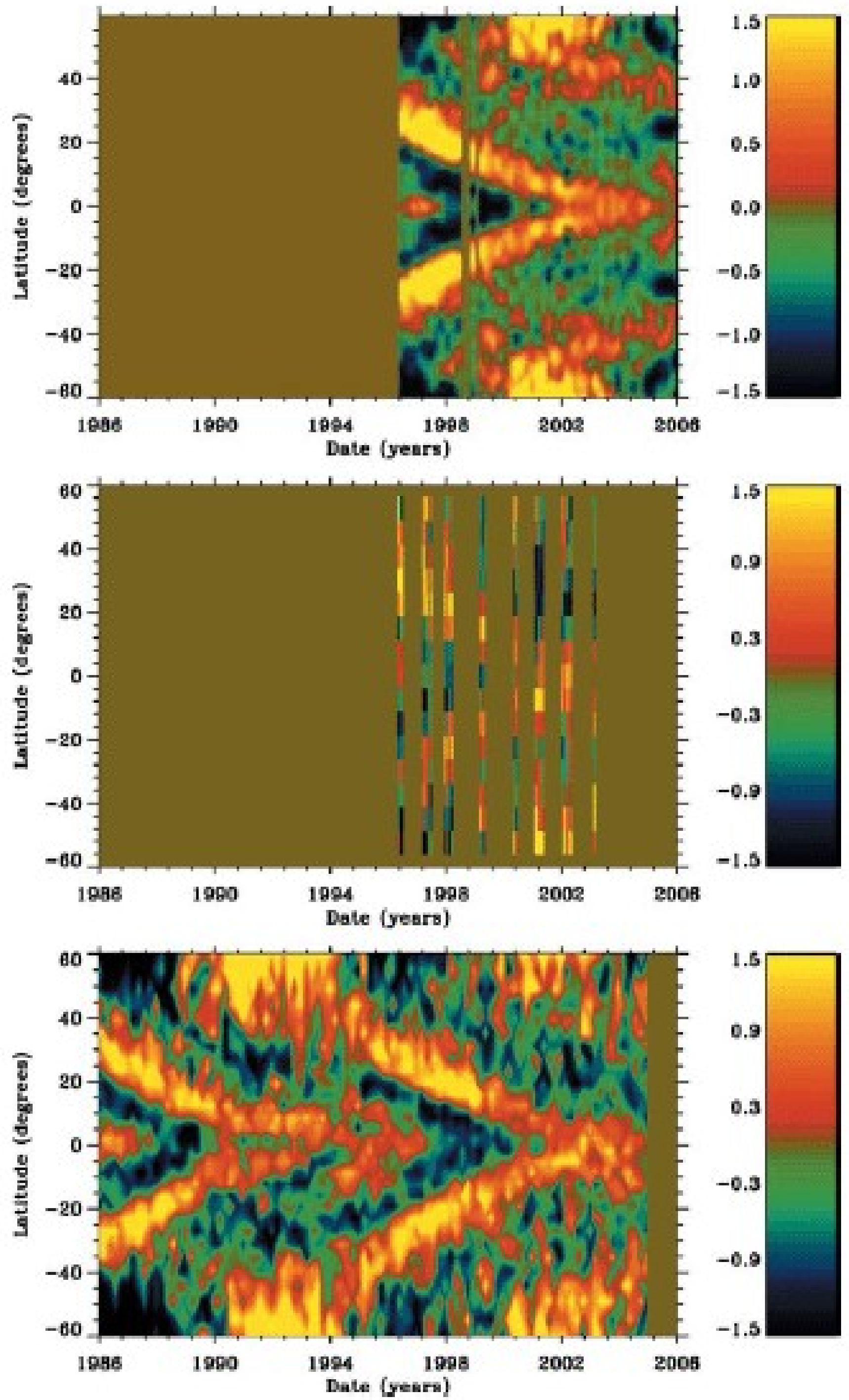
Howe, SOGO meeting, Sheffield, 2006

Global helioseismology, 0.99 R–

Local helioseismology, 0.99 R–

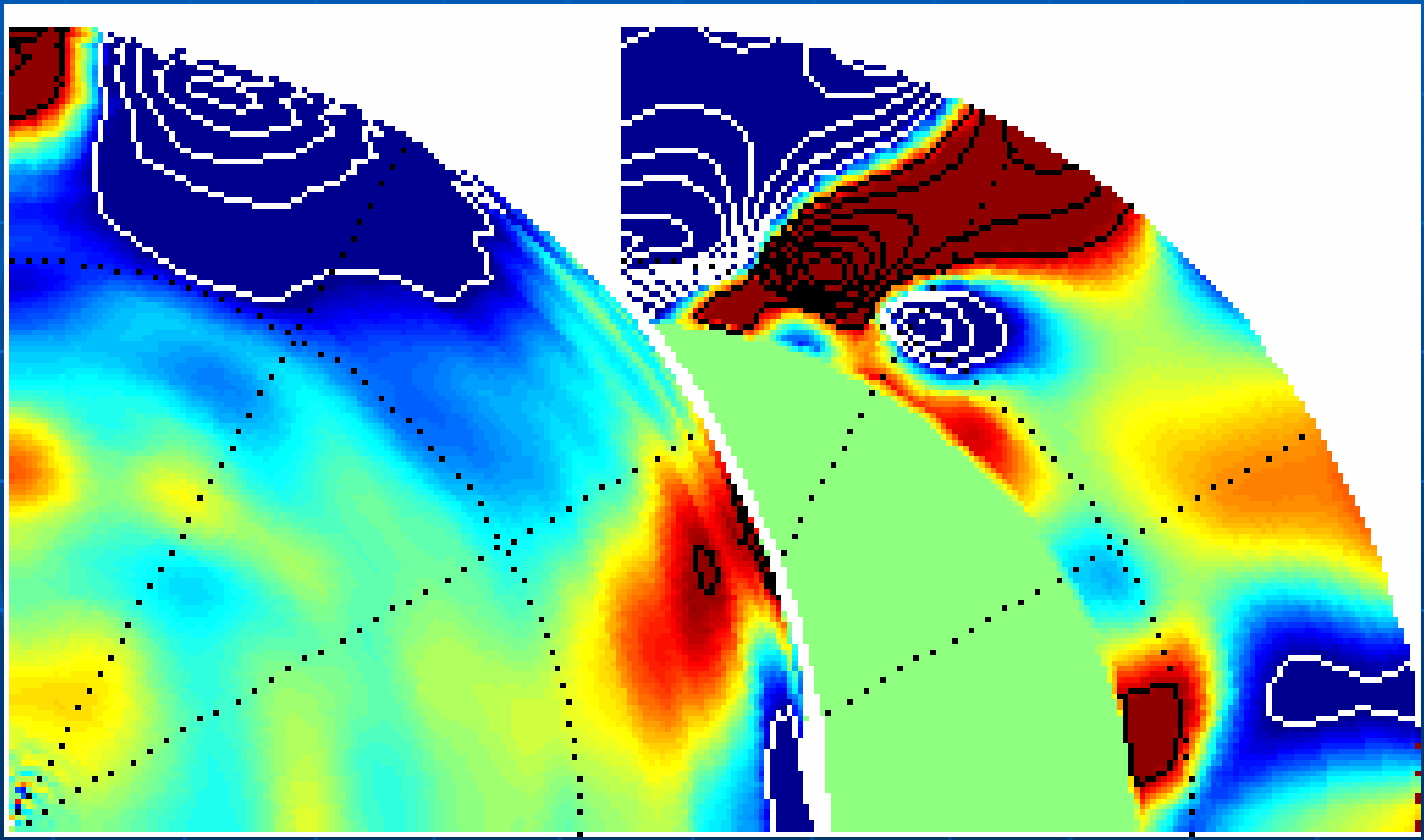
(note asymmetry)

Surface flow (Mt Wilson)



Howe et al. (2006; Solar Phys 235, 1)

Observed and modeled dynamics



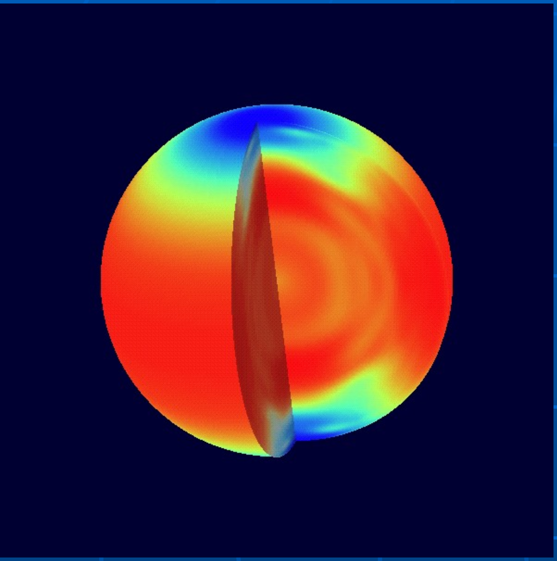
6 1/2 year MDI inversion, enforcing 11-yr periodicity

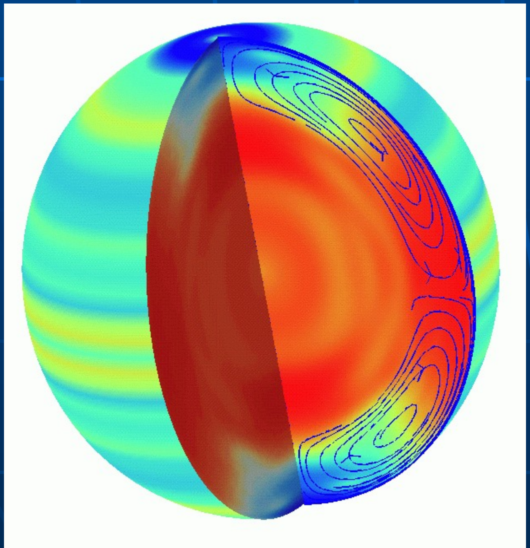
Vorontsov et al.

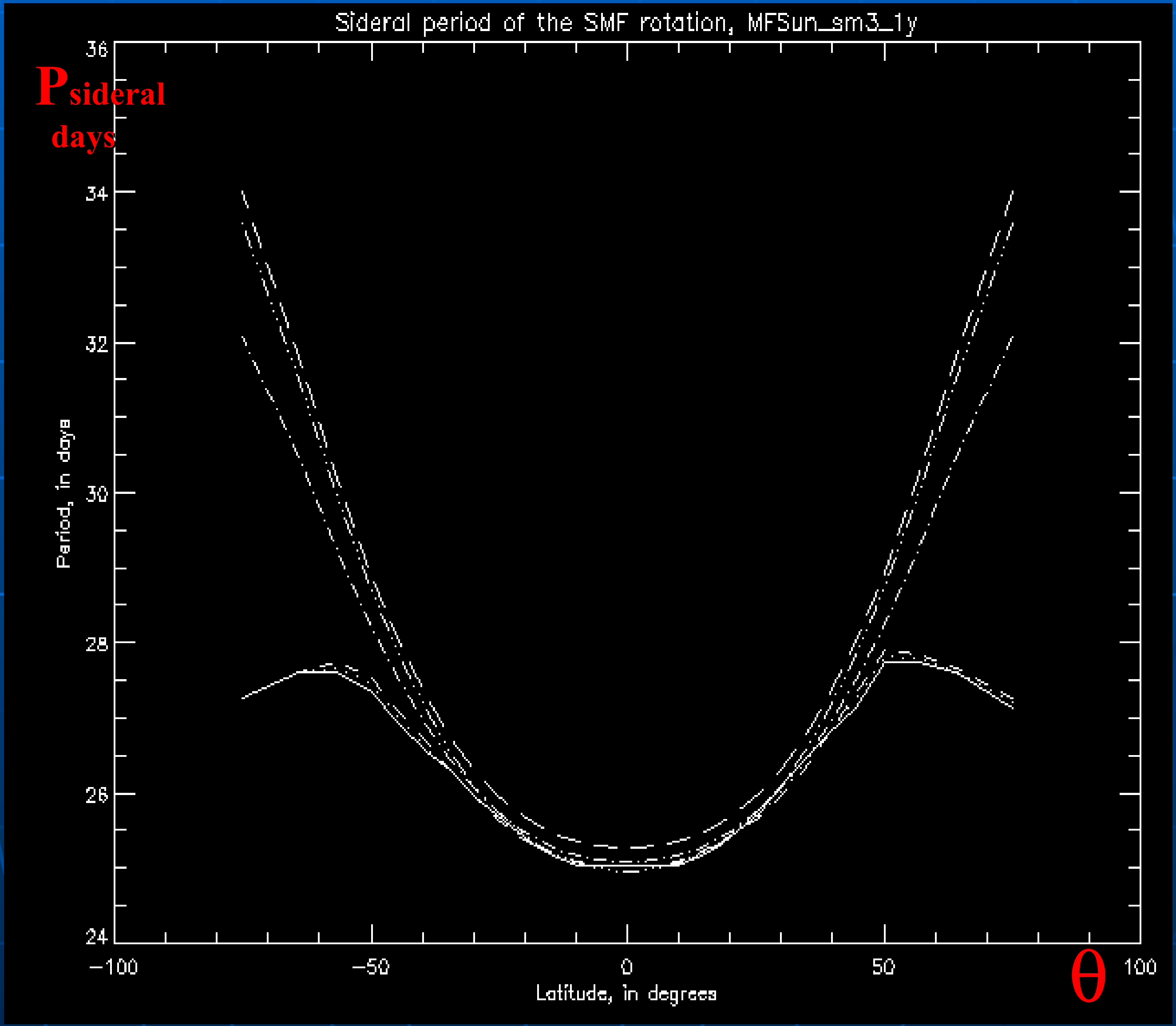
Non-linear mean-field solar dynamo models

Covas, Tavakol and Moss

Differential Rotation of the SMF



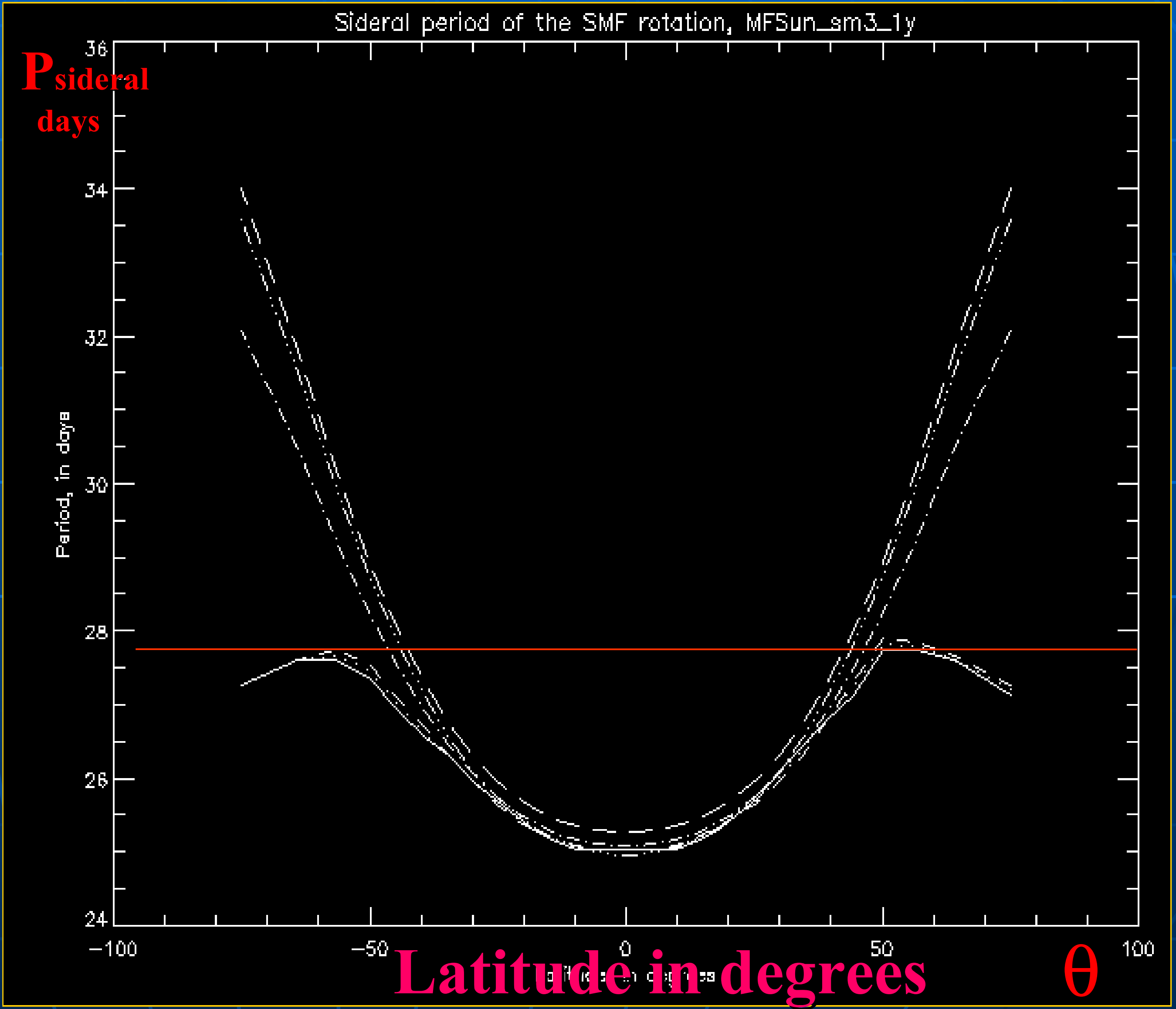




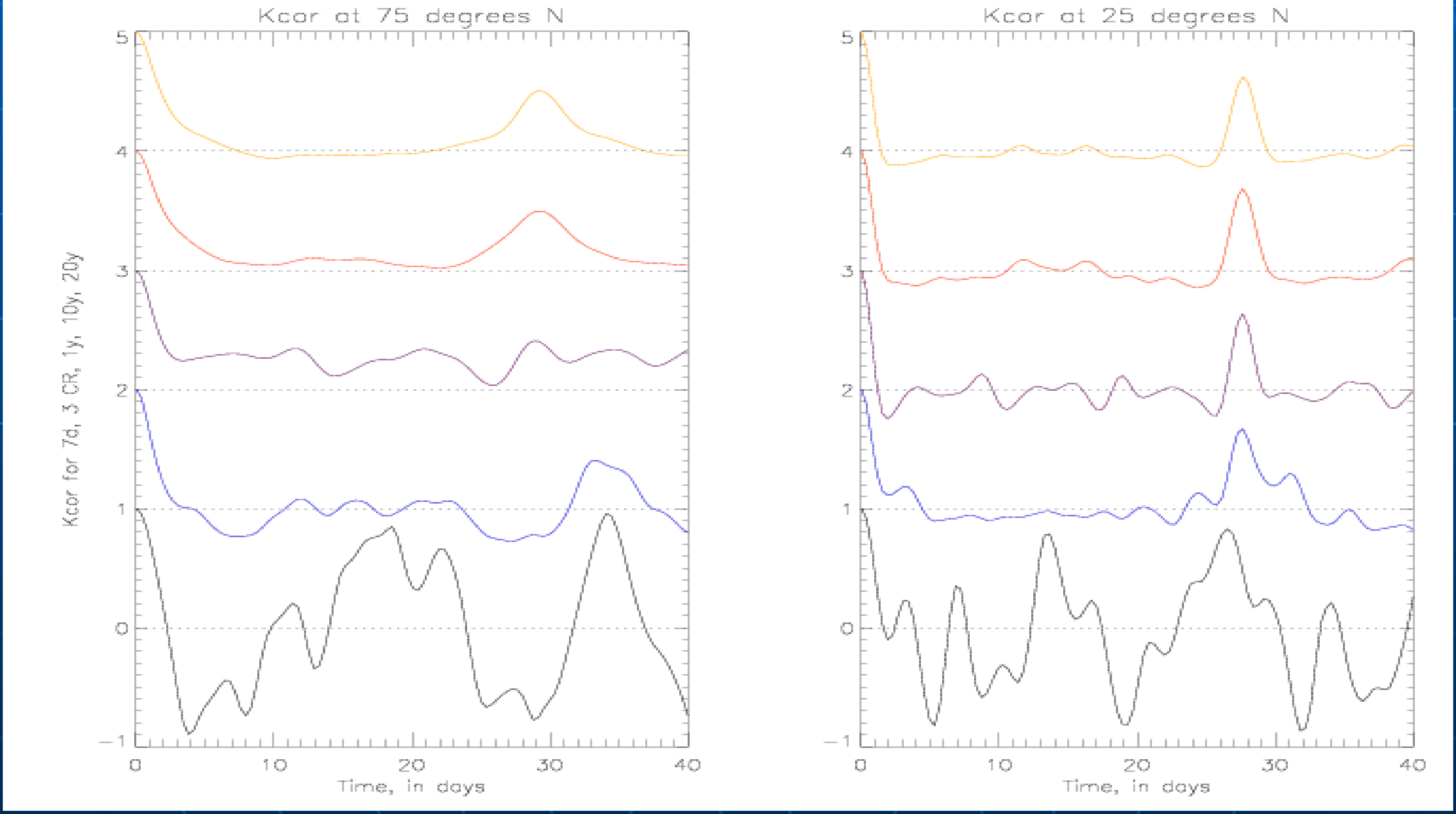
Period of Differential Rotation of the SMF

Continuos line is a sideral period of the SMF by auto-correlation method.
Dashed line is periods of plasma rotation by different methods.

Red line corresponds to Sideral Rotational Period of the longitudinal structure of the SMF
(P synodic = 30.3 day, or
T sideral = 27.8 day, or
ν sideral = 424.326 nHz).

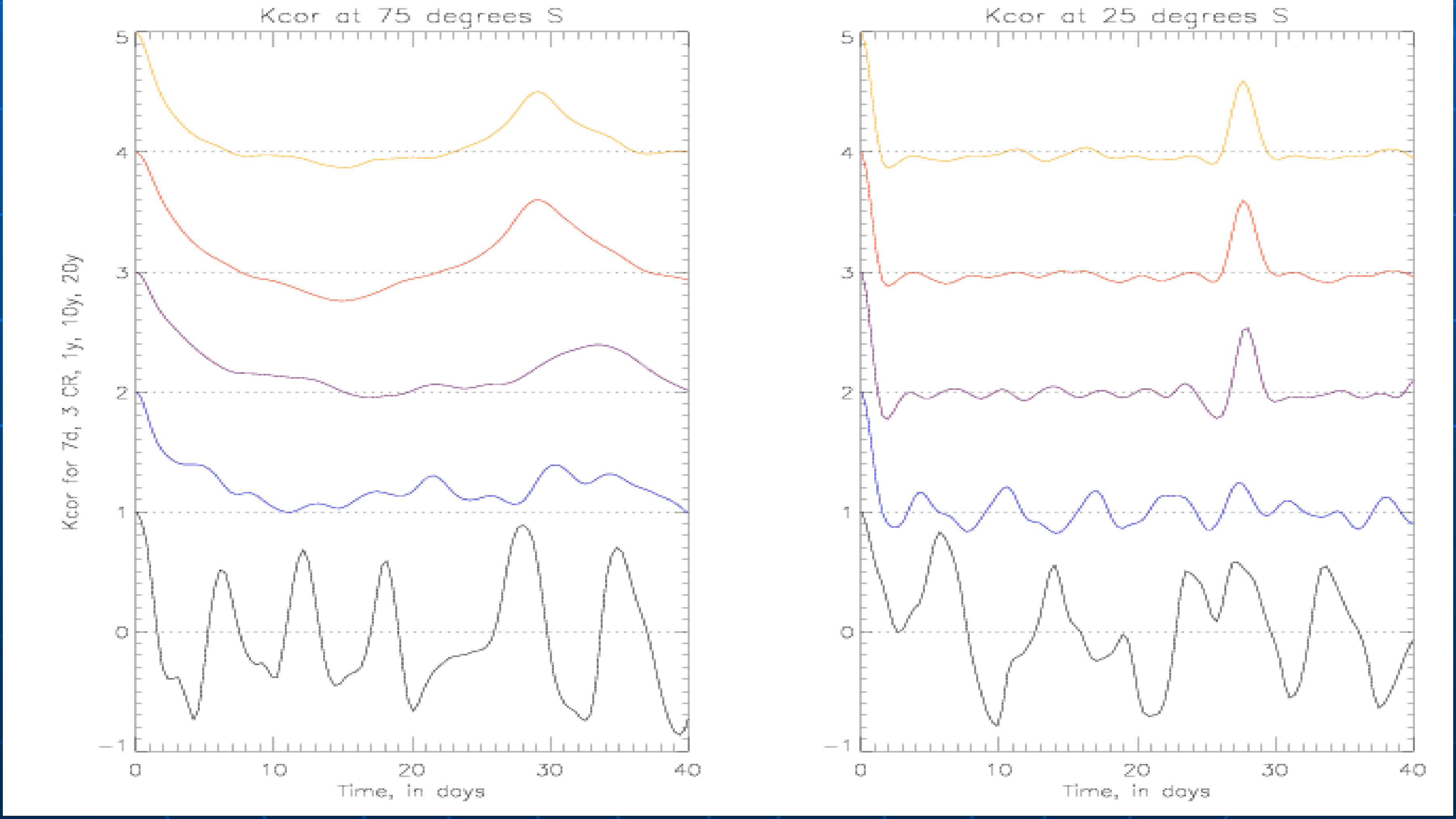


Northerm hemisphere,
K correlation at 75 & 25 degrees
for data set as long as 7 days, 3 CR, 1 year, 10 years, 20 years (from bottom to the top)



Southerm hemisphere, K correlation at 75 & 25 degrees

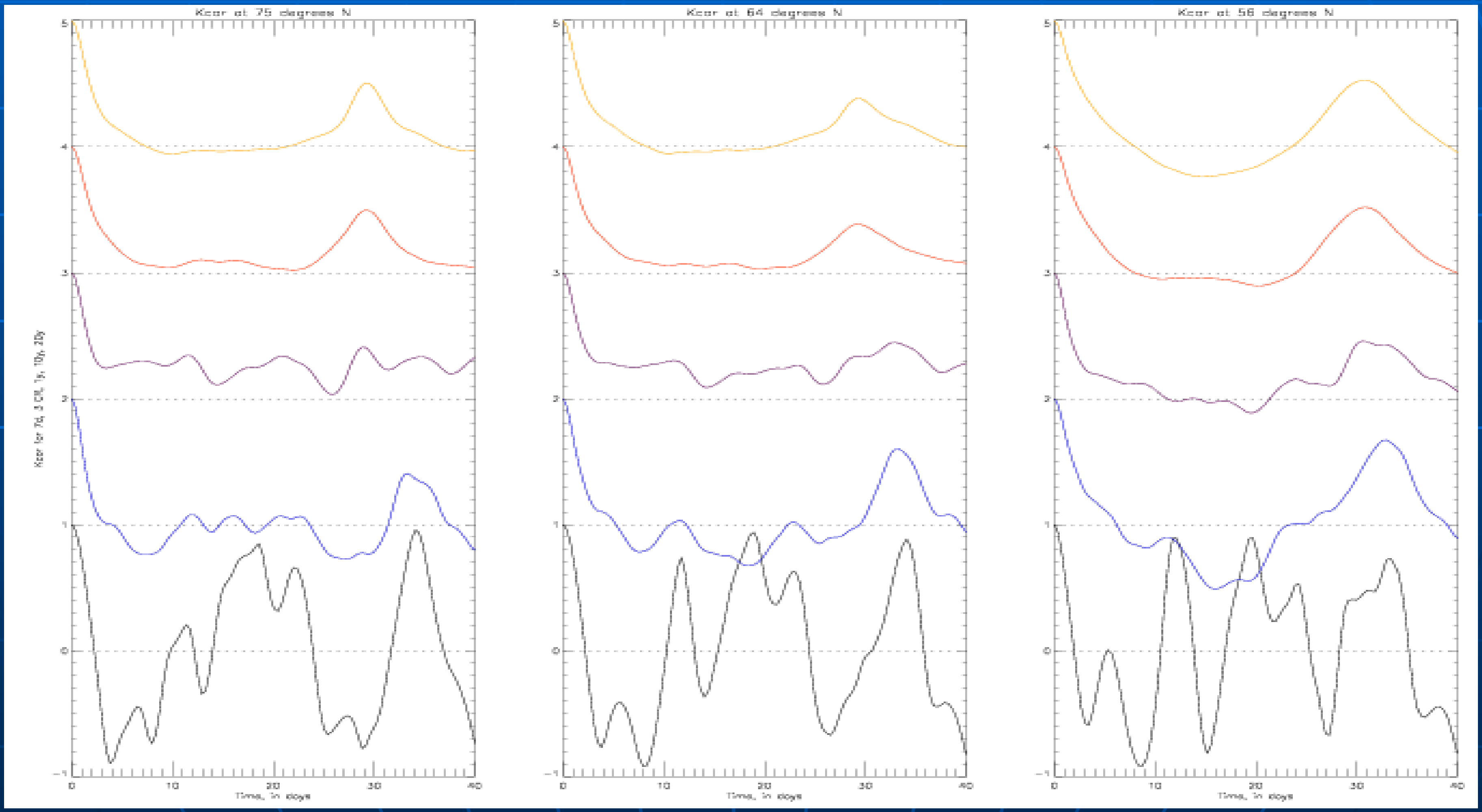
for data set as long as 7 days, 3 CR, 1 year, 10 years, 20 years (from bottom to the top)



Northerm hemisphere,

K correlation at 75, 65 & 56 degrees

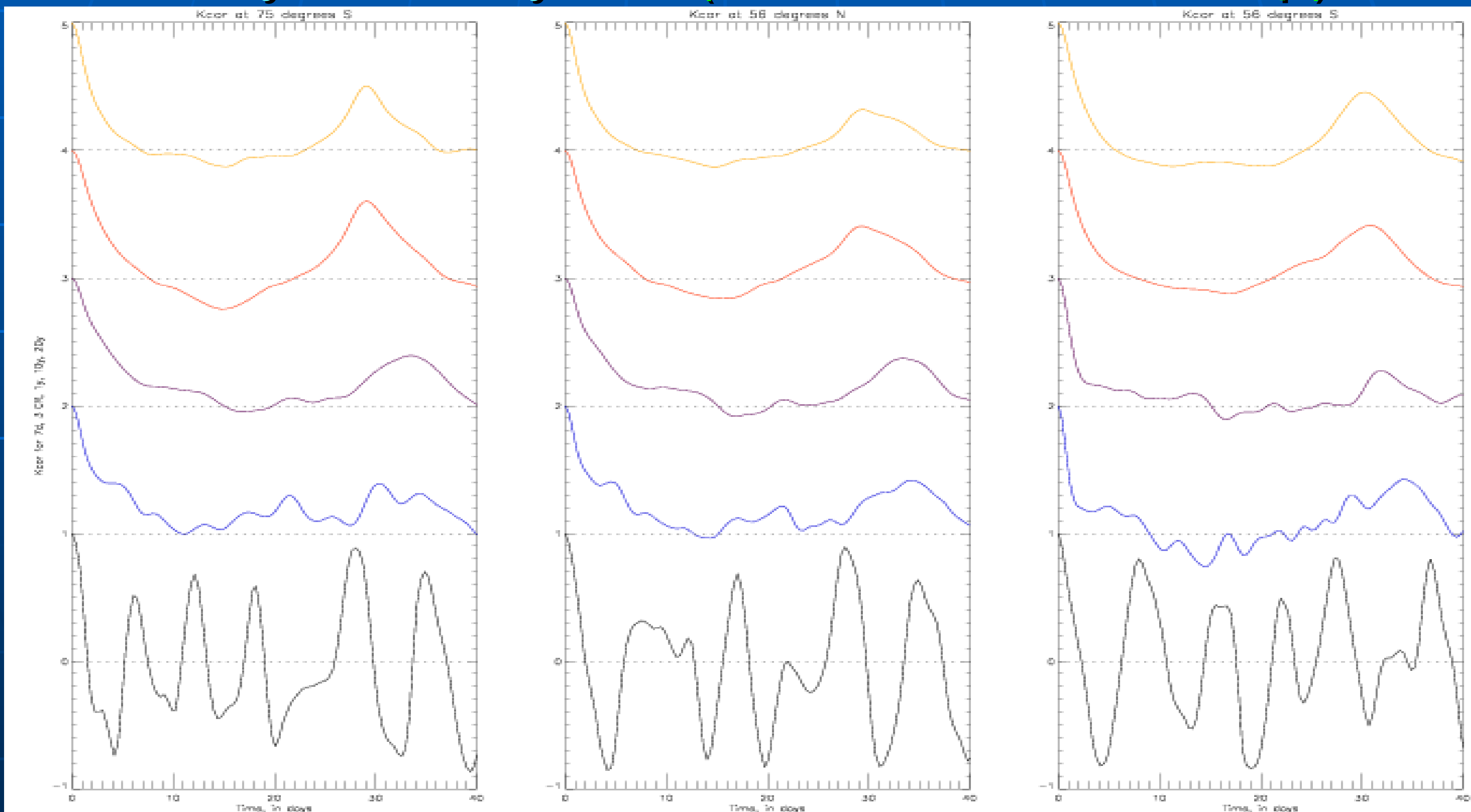
for data set as long as 7 days, 3 CR, 1 year, 10 years, 20 years (from bottom to the top)



Southerm hemosphere,

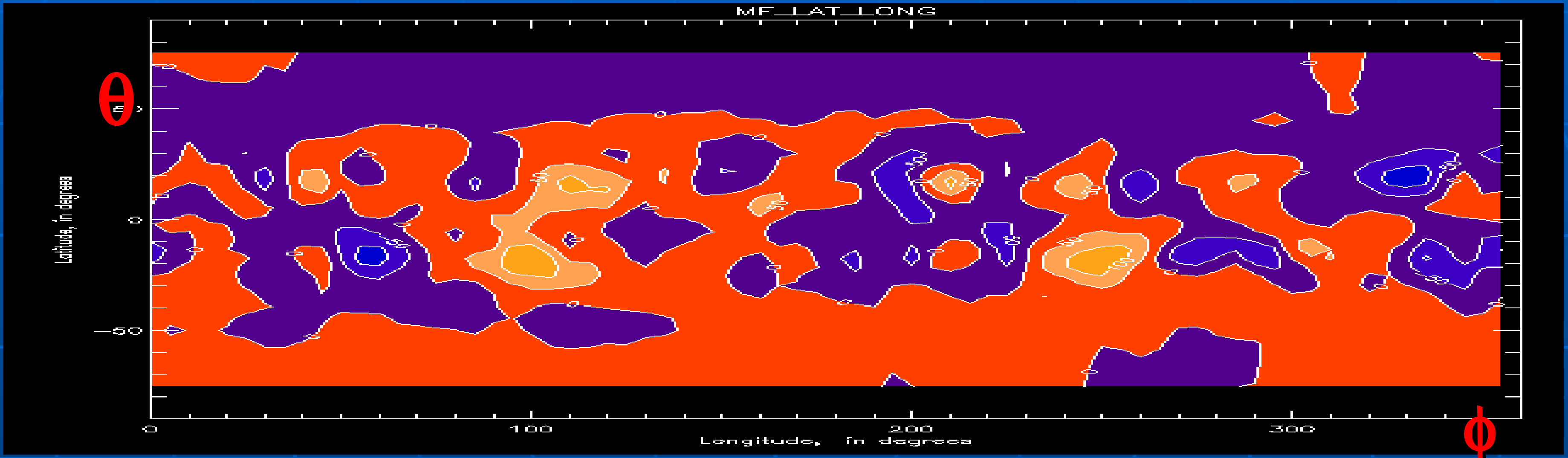
K correlation at 75, 65 & 25 degrees

for data set as long as 7 days, 3 CR, 1 year, 10 years, 20 years (from bottom to the top)

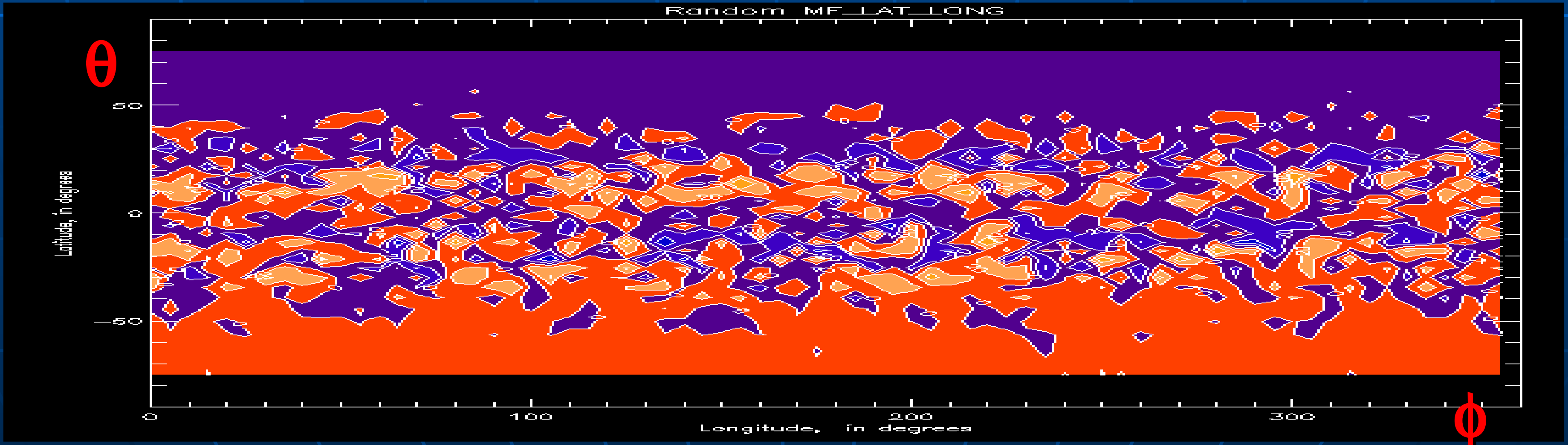


Longitudinal structure

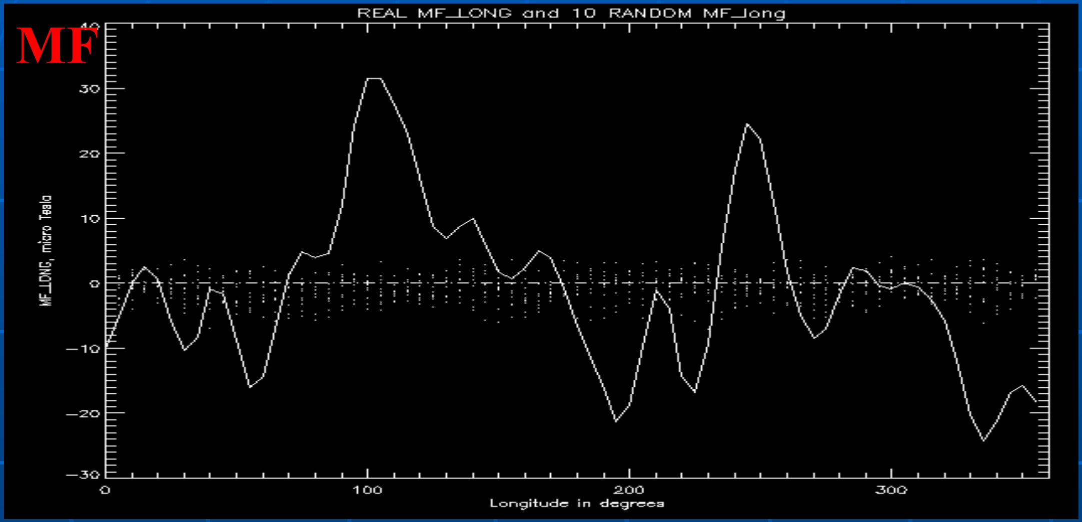
of Real SMF in Carrington System



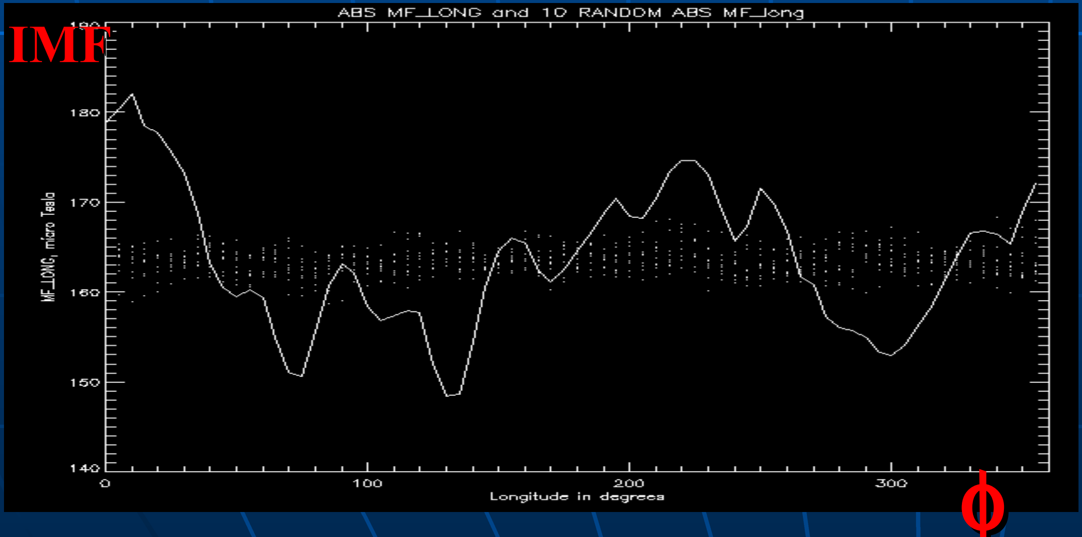
of Random SMF in Carrington System



Longitudinal structure
in Carrington System

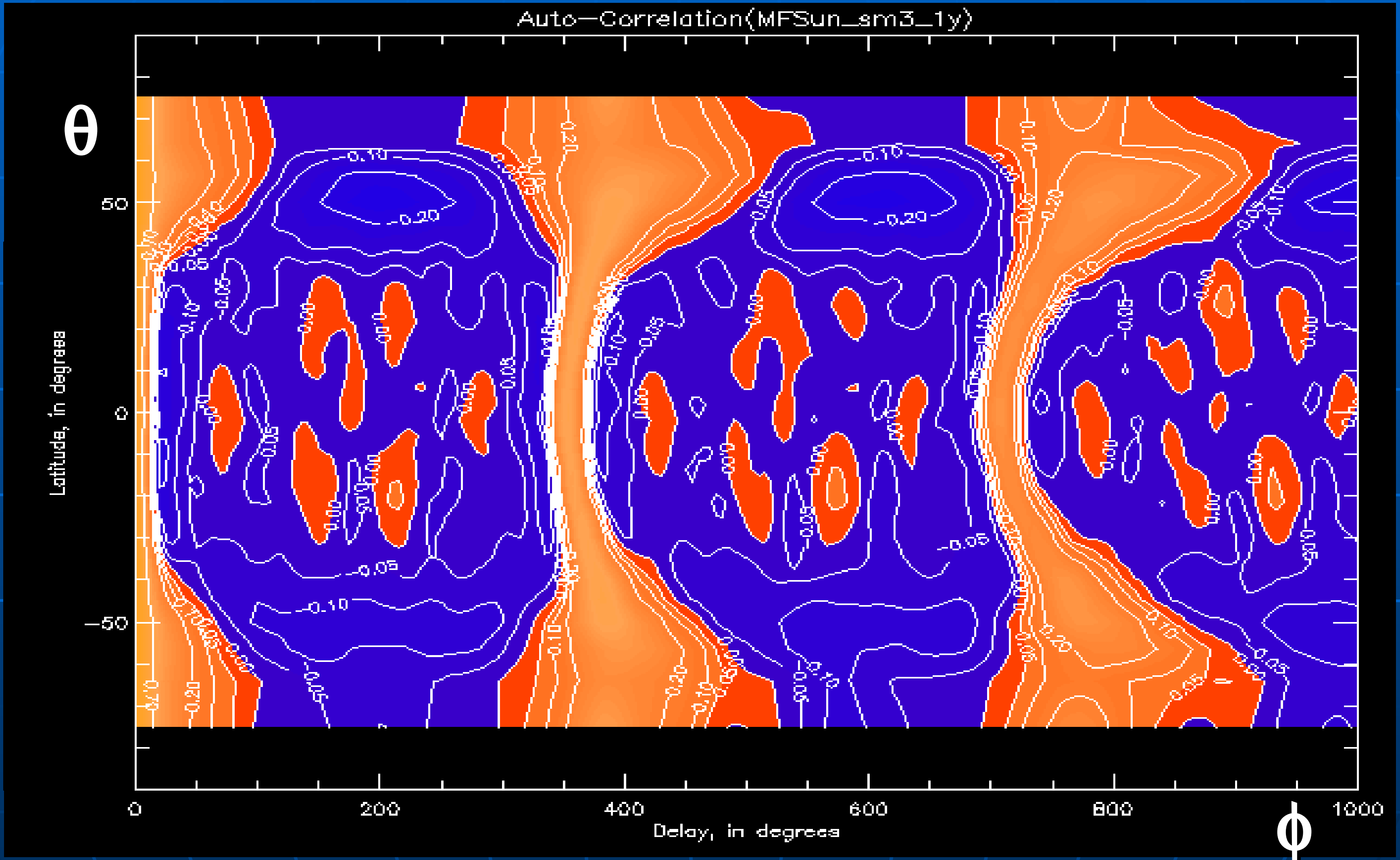


Longitudinal structures for Real and 10 Random Distributions



Longitudinal structures for SMF Intensity and 10 Random SMFI Distributions

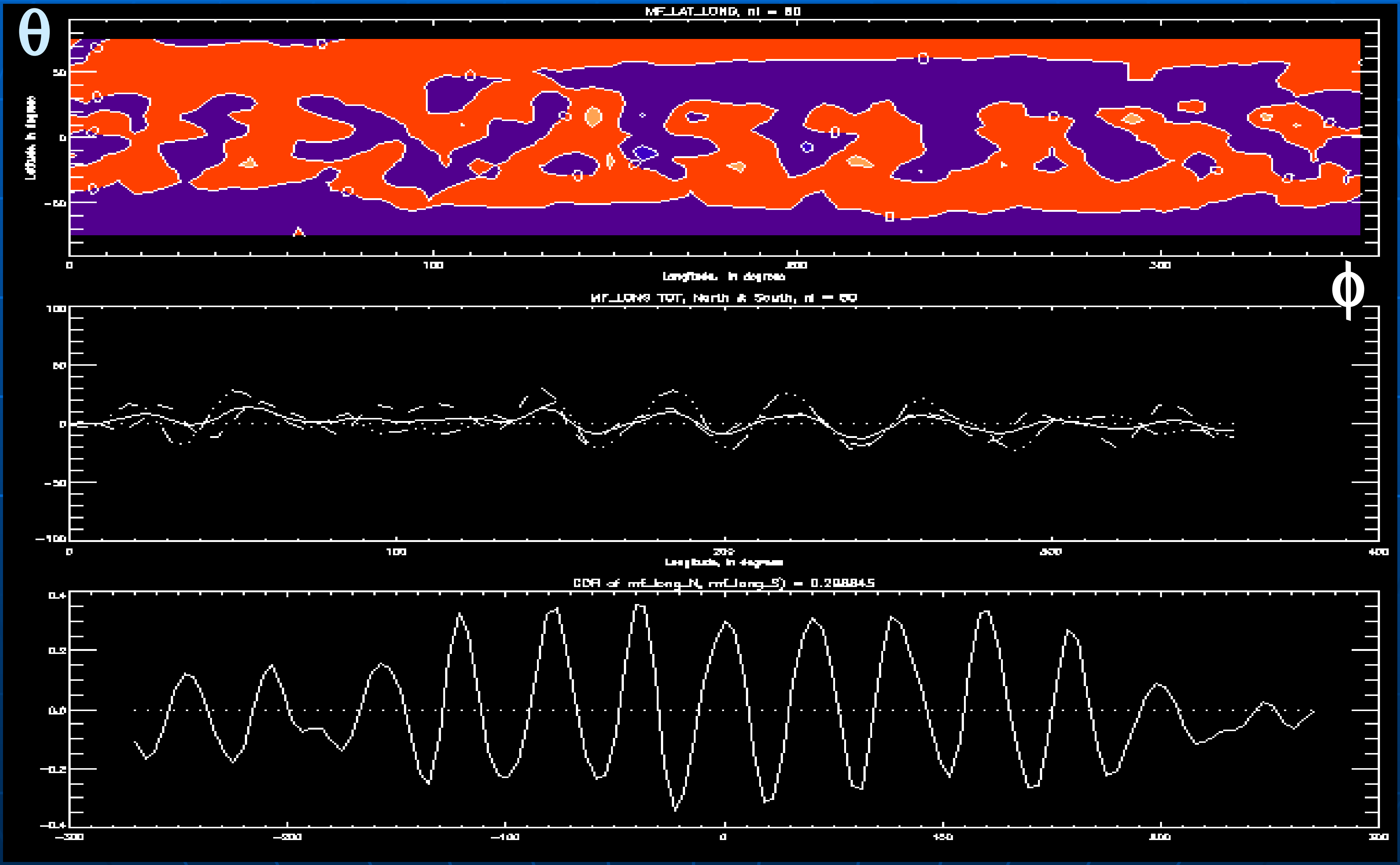
Auto-correlation of SMF (θ, φ)



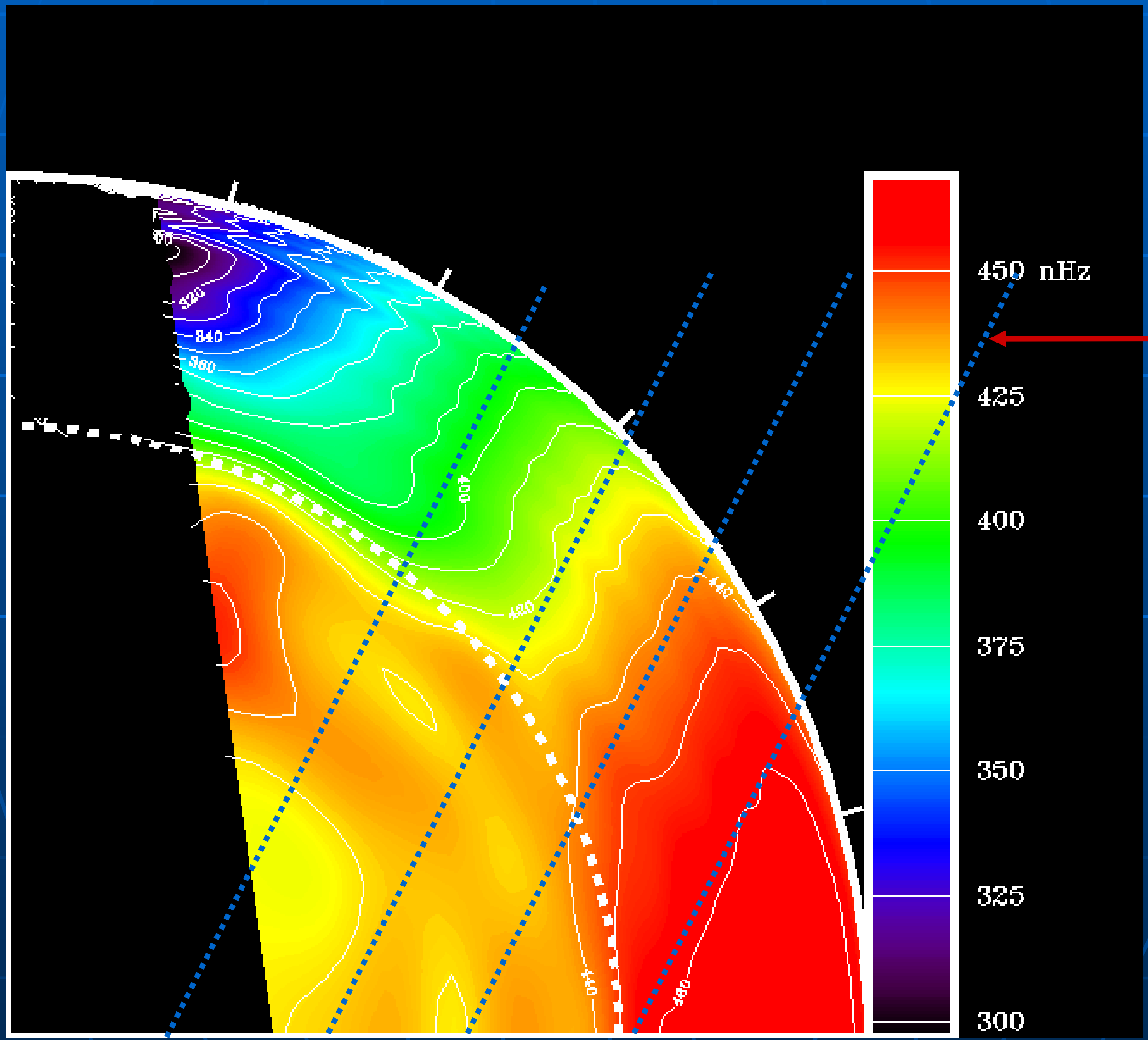
Eq: 1/5, 4/5 , ½; Act. lat : 2/5, 3/5 of Rotation

Longitude structure of Solar Magnetic Field

T synodic = 30.31 d



Inferred solar internal rotation



Inclined 27° to rotation axis

(see Gilman & Howe 2003; ESA-SP 517, 283)

Summary

The main results are the following:

- The latitudinal structure in Carrington system of the solar magnetic field has a period of polarity change of 22 years and consists of four zones: two sub polar and two pre-equatorial with boundaries around +25, 0 and -25 deg.
- The presence of the polarity waves running from the equator to the poles with quasi 2-3-year period has been clearly demonstrated
- North-South asymmetry of solar magnetic field and its short and long term variability in time have been studied.
- Differential rotational rate of the magnetic field and its temporal dependence has been evidenced at different latitudes through activity cycles.
- Highly organized quasi-stable over 30 years longitudinal structure was found for the magnetic field at different latitudes.
- Longitudinal structure in different coordinate systems rotating differentially like the photosphere does and with different constant rates were reconstructed.
- Latitudinal structure in Carrington system was compared with one Rotating lake longitudinal structure.
- Latitudinal structure as a function of number of rotations was revealed.

These results are fundamental for the understanding of the magnetic origin of the solar activity, dynamics, the heliospheric structure and for the prediction of the solar wind and magnetospheric perturbations.

Our Sun is an Object perfectly organized
in space and time with his own

basic Topology and Dynamics originated in solar Deeps, seen in the Photosphere and influencing the life on the Earth.

Gavryuseva Elena