Solar dynamo theory – recent progress, questions and answers

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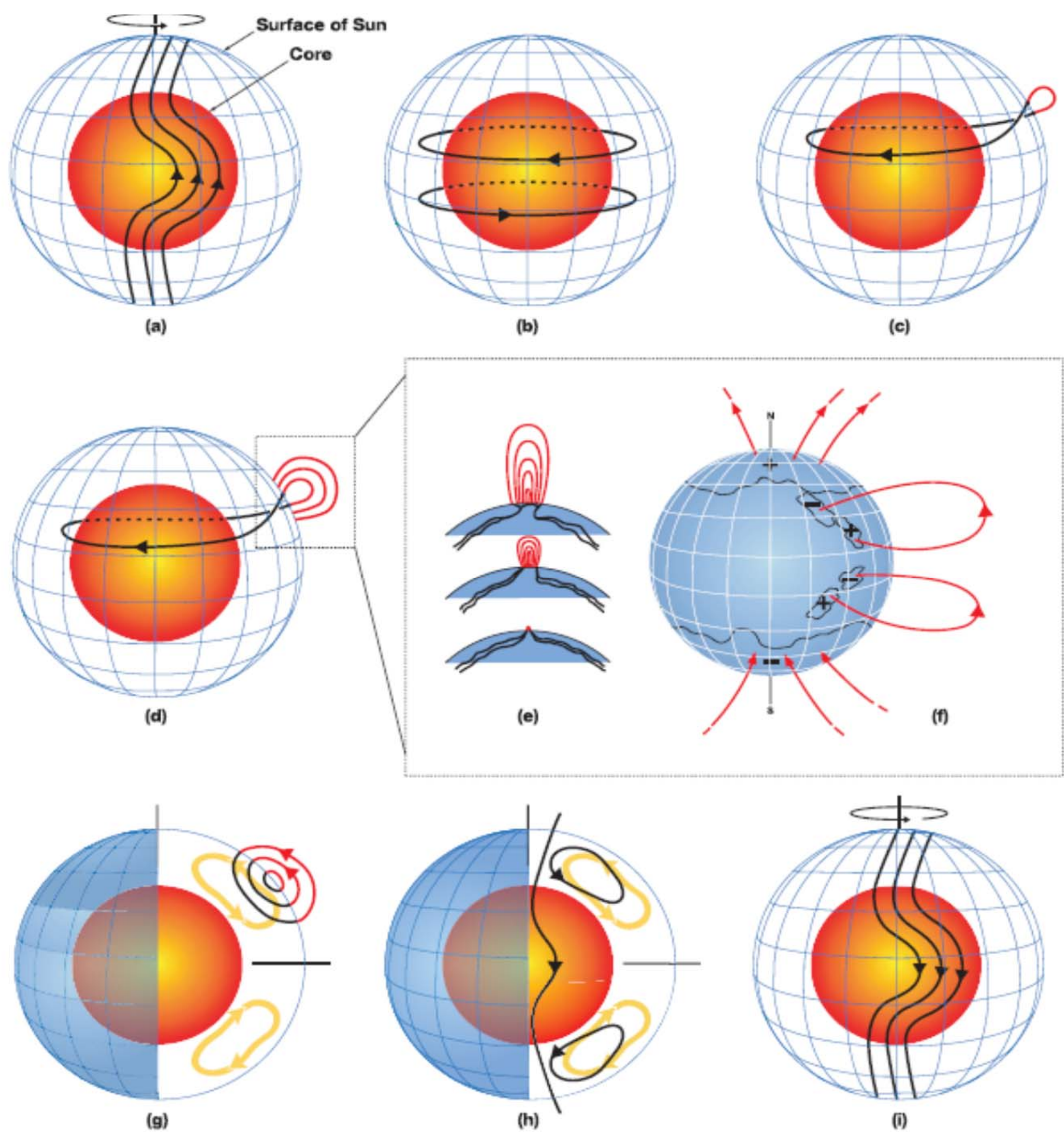
How the solar dynamo works



Dikpati and Gilman, 2006

Solar dynamo theory - questions

- Is it correct?
- Values and variations of the dynamo parameters (diffusivity, meridional flows)
- Regime of operation
- Grand minima

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Predictions of the theory

- The amplitude and period of the sunspot cycle are governed by the speed of the meridional circulation (Wang, Sheeley, Lean (2003), Hathaway (2003), Passos and Lopes, 2009, 2011), Karak (2019), Karak and Choudhuri (2011),…

- The value of the coefficient of turbulent diffusivity determines the regime of operation of the dynamo (Yeates, Nandy and Mackay, 2000; Hotta and Yokoyama, 2010; Choudhuri, 2010,…)

Solar dynamo theory - questions

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- **Values and variations of the dynamo parameters (diffusivity, meridional flows)**
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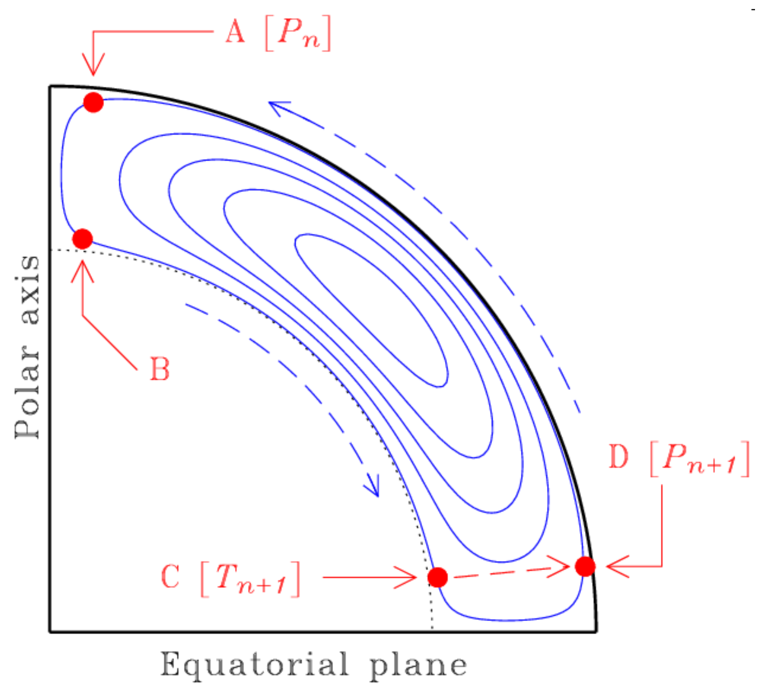
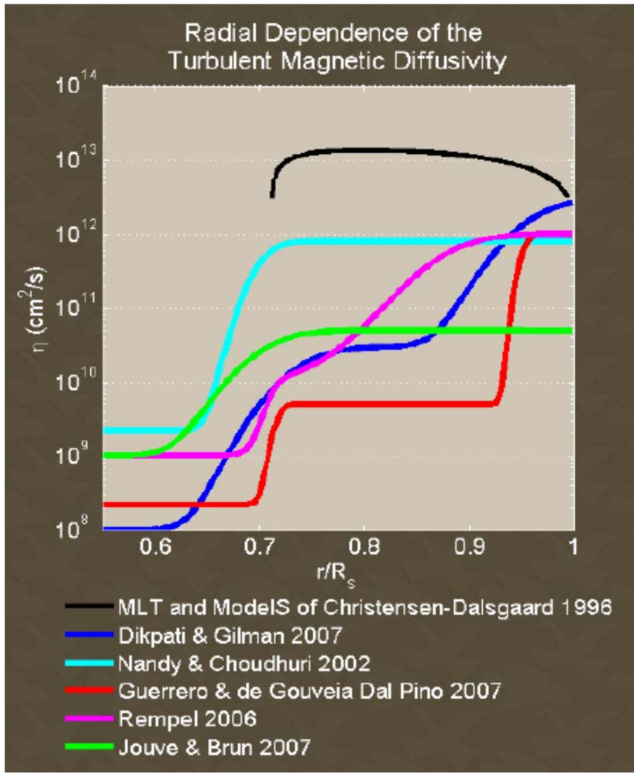
Values of the dynamo parameters



meridional circulation

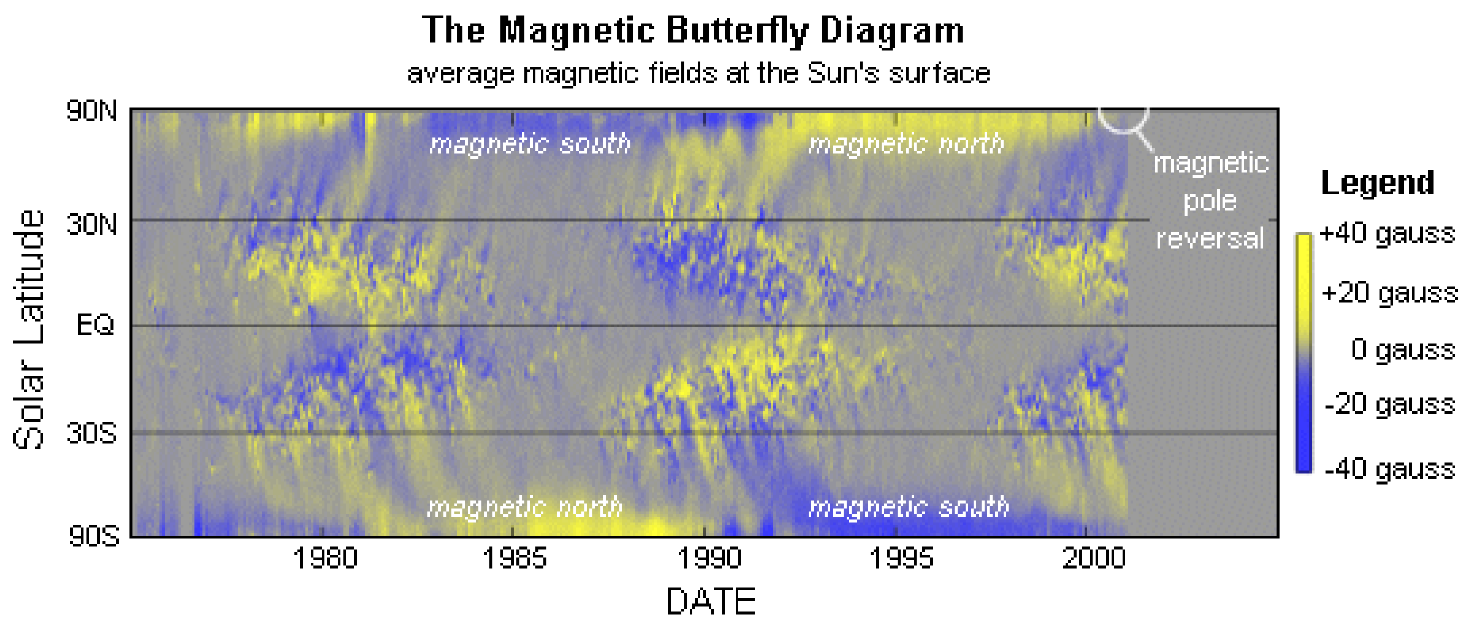


diffusion

Both largely unknown from observations, especially on long-term scale

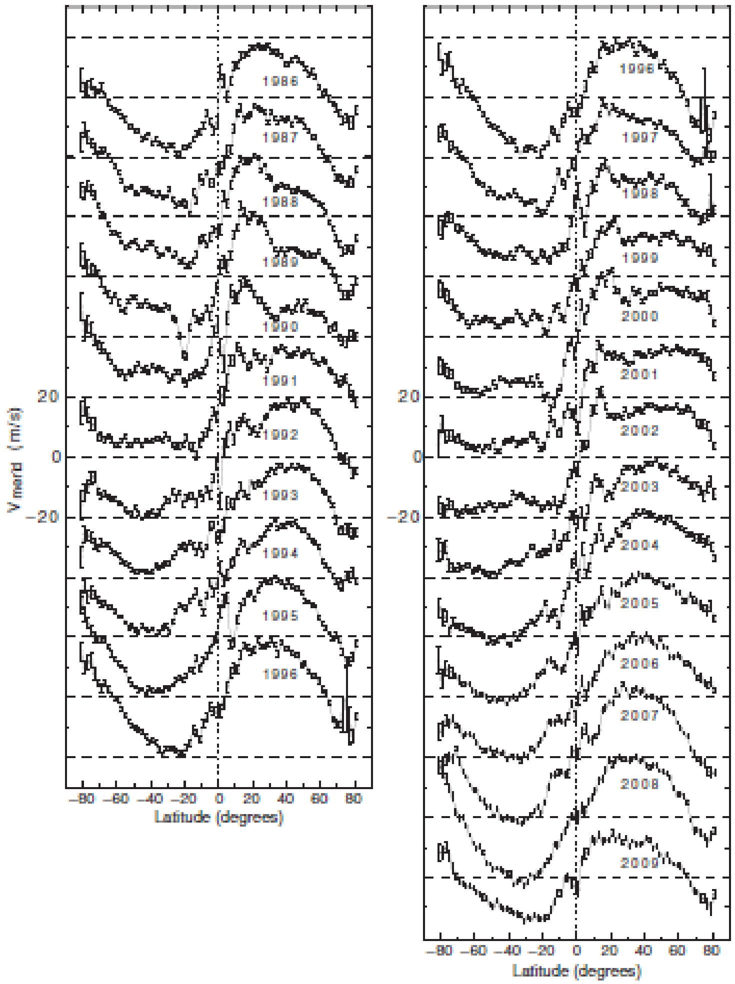
Surface poleward meridional circulation has been measured directly during the last 3 sunspot cycles:

- Doppler measurements (Duvall, 1976; Ulrich et al., 1988; Hathaway, 1996 …)
- Tracers (Komm et al., 1993; Javaraiah, 2006 …)
- Helioseismology (Giles et al., 1997; Fan and Braun, 1998…)

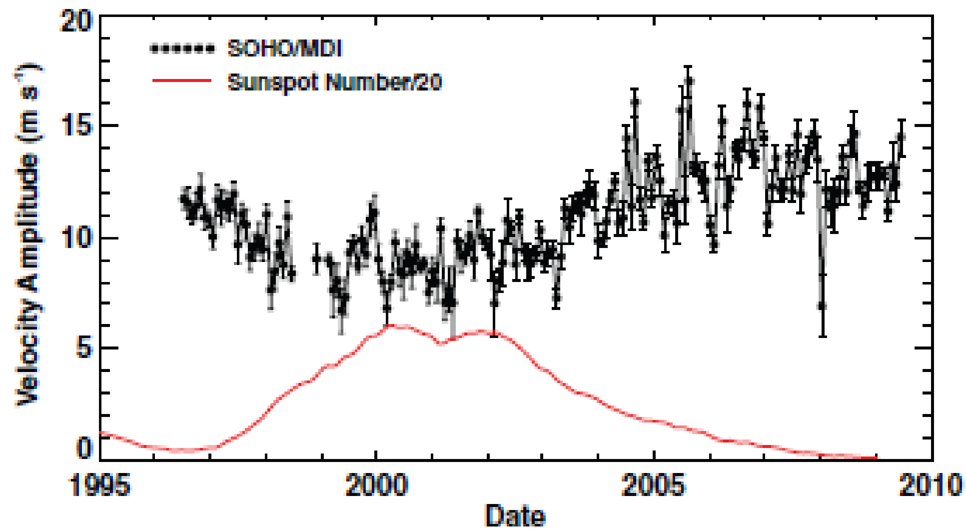


Estimated velocity: 10-25 m/s

Latitudinal and solar cycle variations of surface meridional circulation

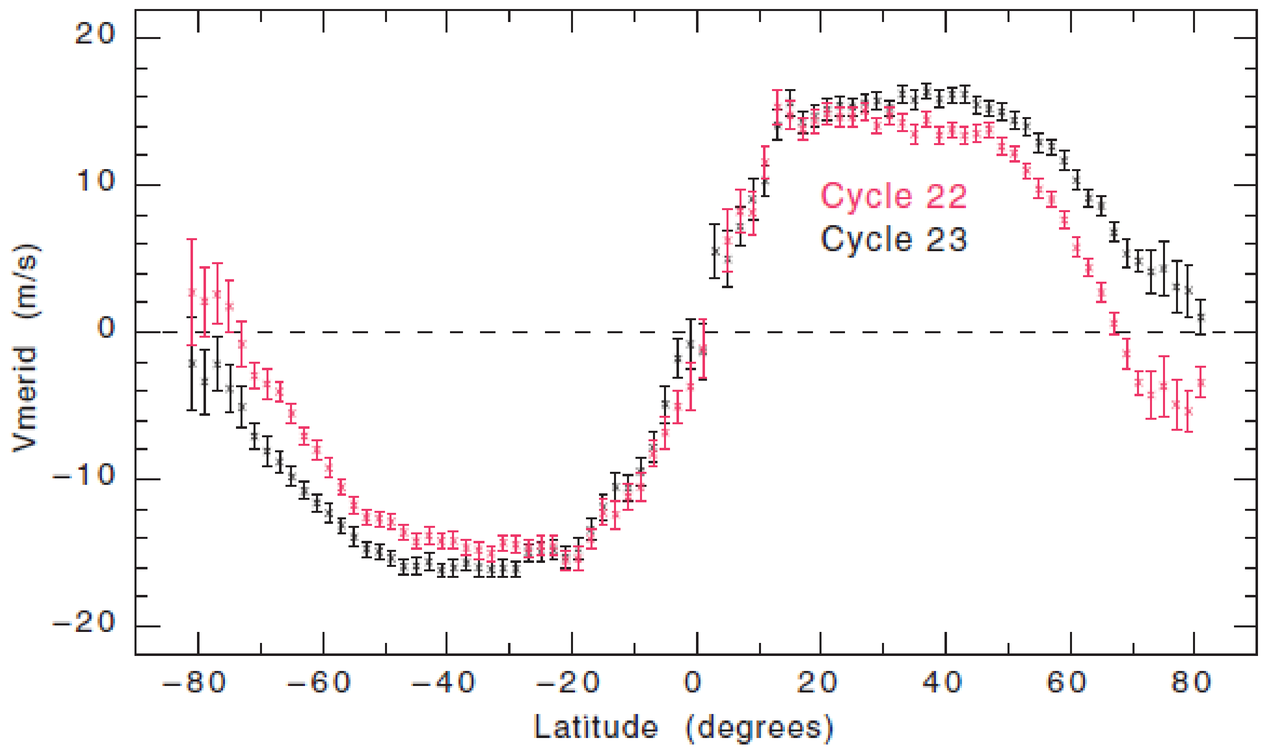


From Doppler shift of gas velocity
(Ulrich, 2010)



from magnetic features tracking
(Hathaway and Rightmire, 2010)

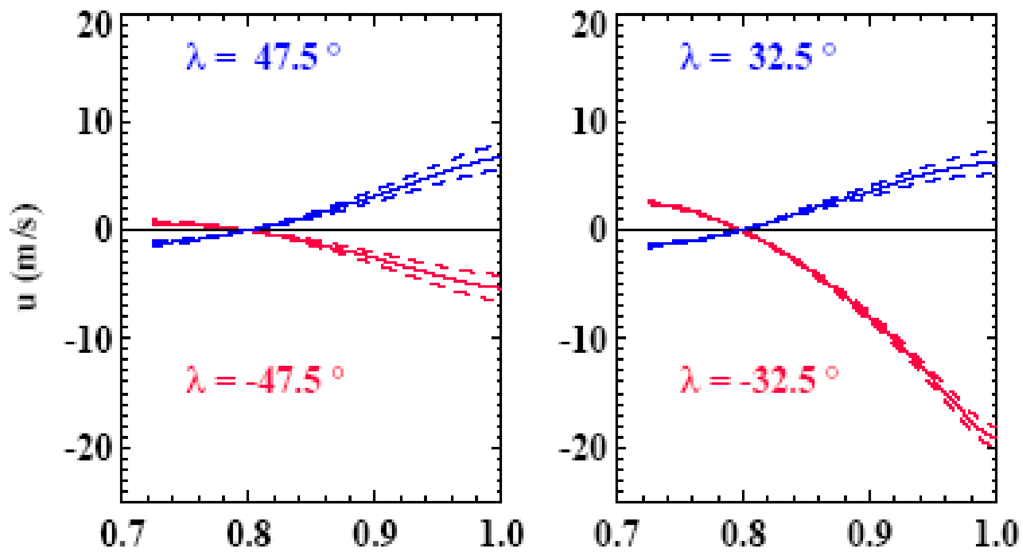
Cycle to cycle variations of surface meridional circulation



Faster surface circulation in cycle 23

Doppler shift measurements *(Ulrich, 2010)*

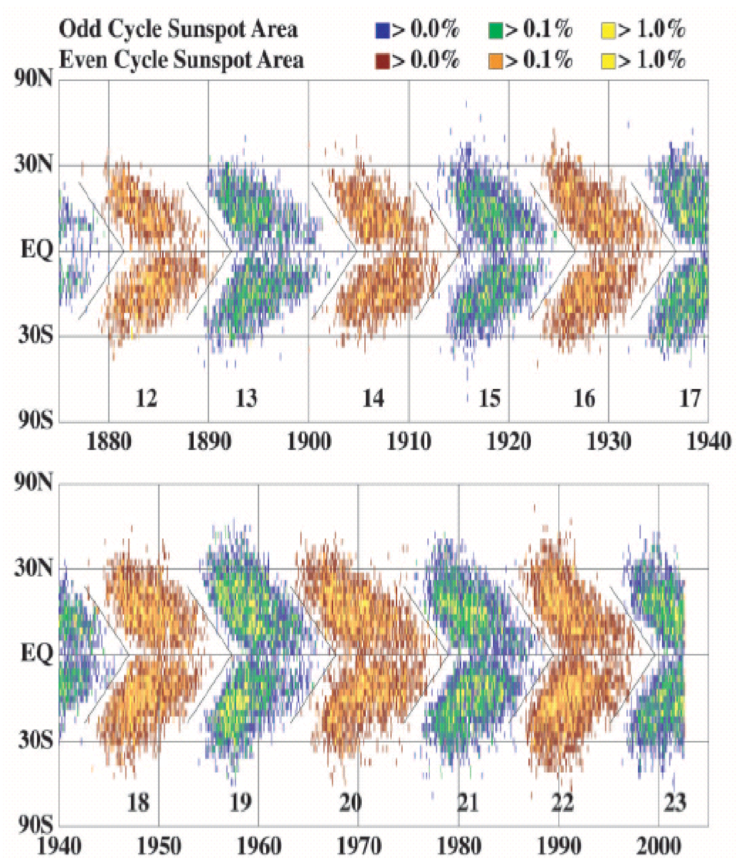
Limited data for the deep equatorward circulation

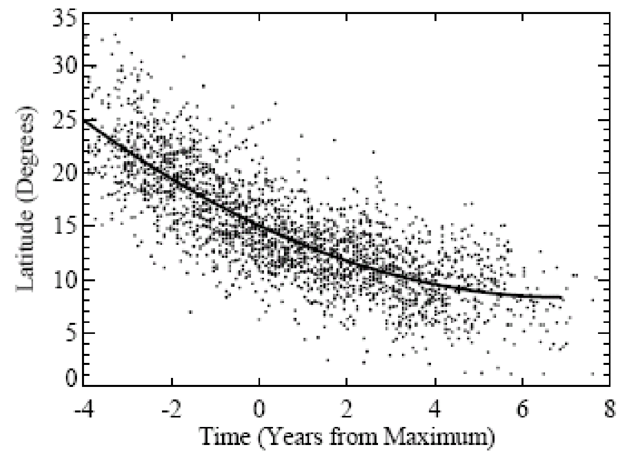


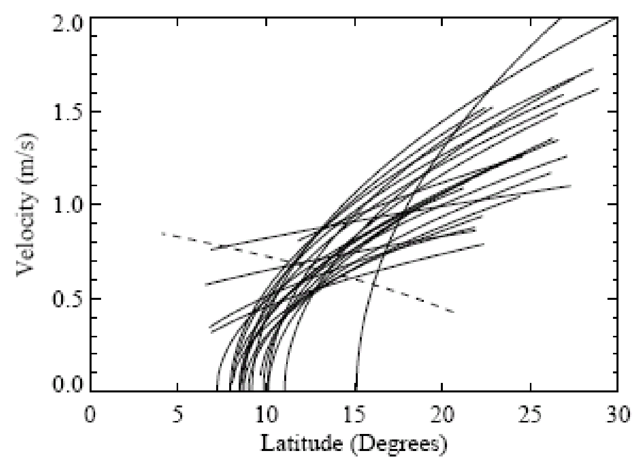
Giles (1998) from helioseismology:

Much slower than the surface circulation (2-10 m/s)
Latitudinal dependence;
Hemispheric asymmetry;
Reversal of the flow about 0.8 R

Hathaway et al. (2003) – deep equatorward circulation from the latitude drift of sunspot zones







Latitudinal and temporal dependence

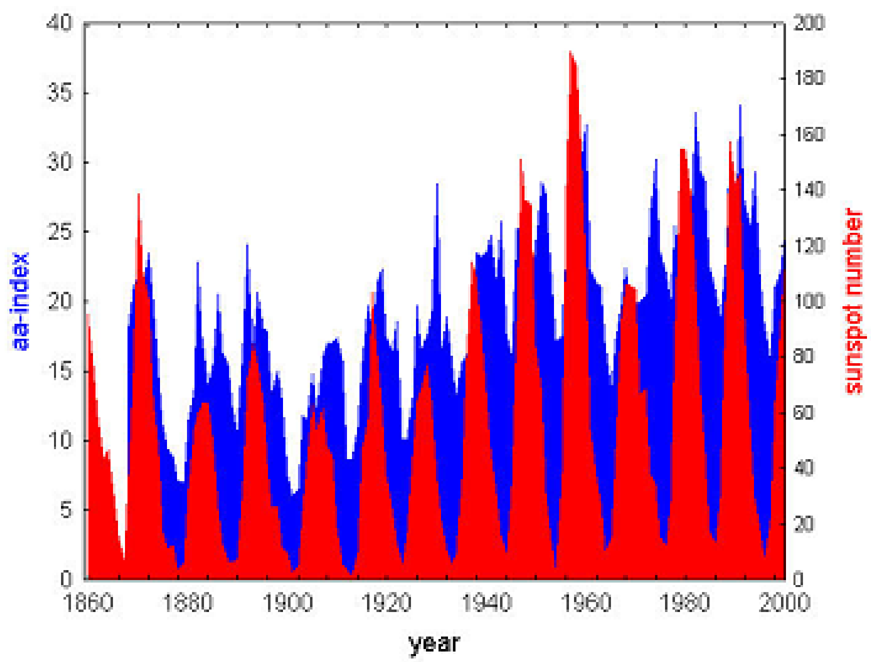
Estimated velocity at sunspot latitudes: **0 – 2 m/s** below 30^{o}

Georgieva and Kirov (2007) - estimation from geomagnetic data

Double-peaked cycle of geomagnetic activity:

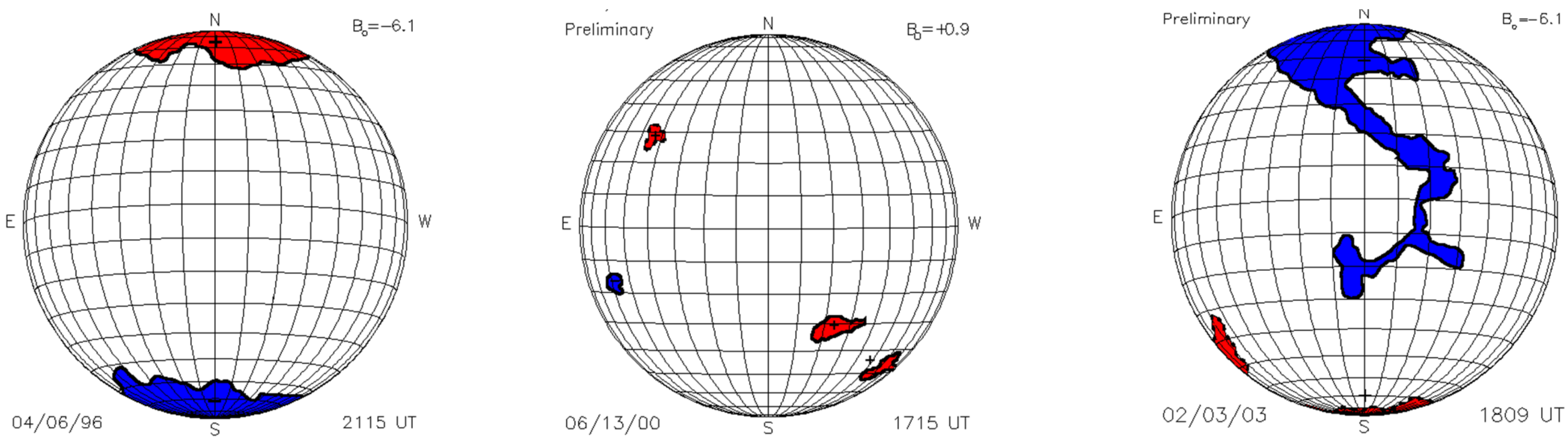
one peak in sunspot max,

the second one on the the sunspot decline phase



- Sunspot max peak – max in sporadic solar activity (coronal mass ejections)
- Sunspot decline phase peak – max in recurrent solar activity (high speed solar wind from coronal holes)

When is geomagnetic activity maximum on the sunspot decline phase?



Sunspot min:
large polar coronal holes; no coronal holes at low latitudes

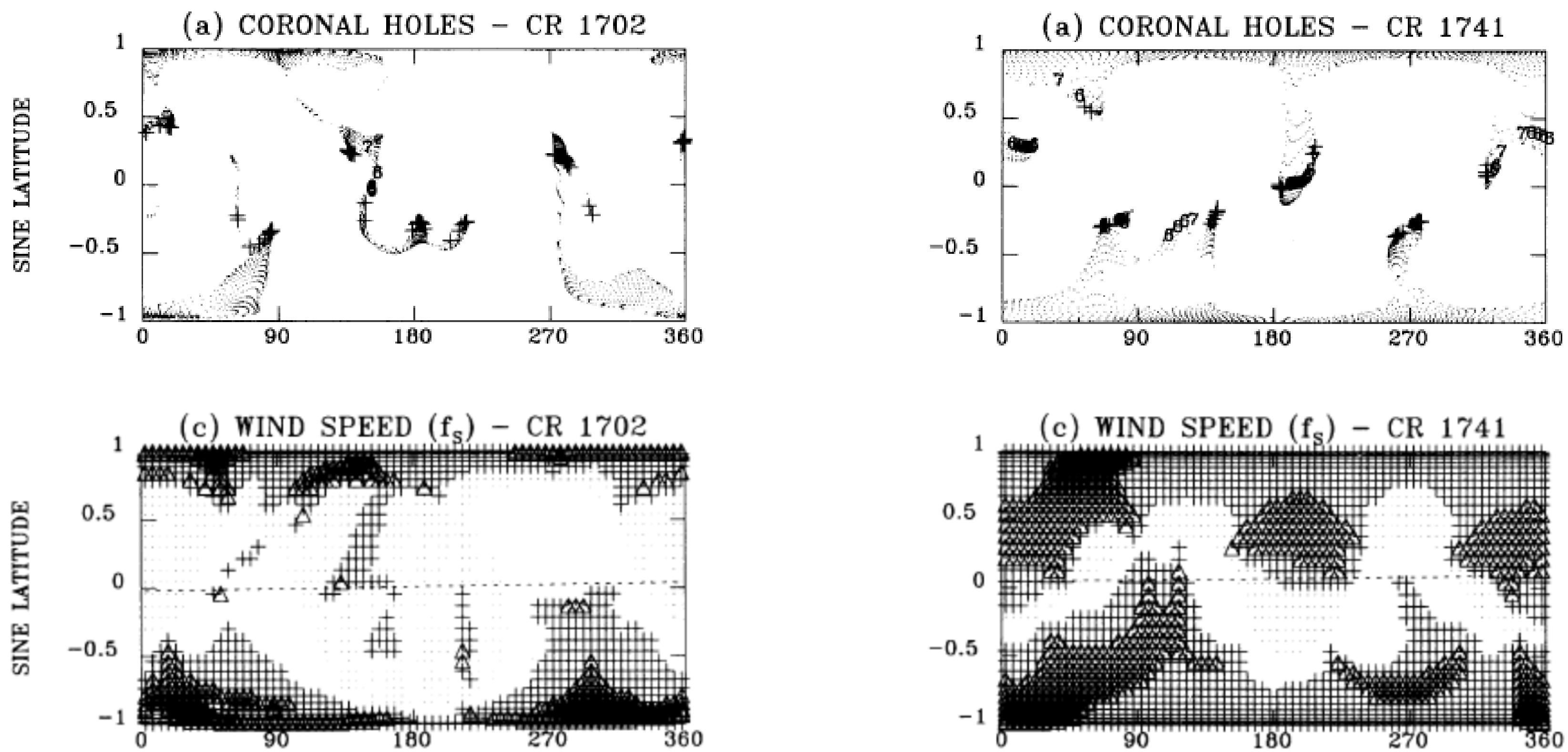
Sunspot max:
small scattered short-living coronal holes at all latitudes

When the trailing polarity flux reaches the poles, the low latitude holes begin attaching themselves to the polar holes and growing ⇒ long-lasting wide streams of fast solar wind

(Wang and Sheeley, 1990)

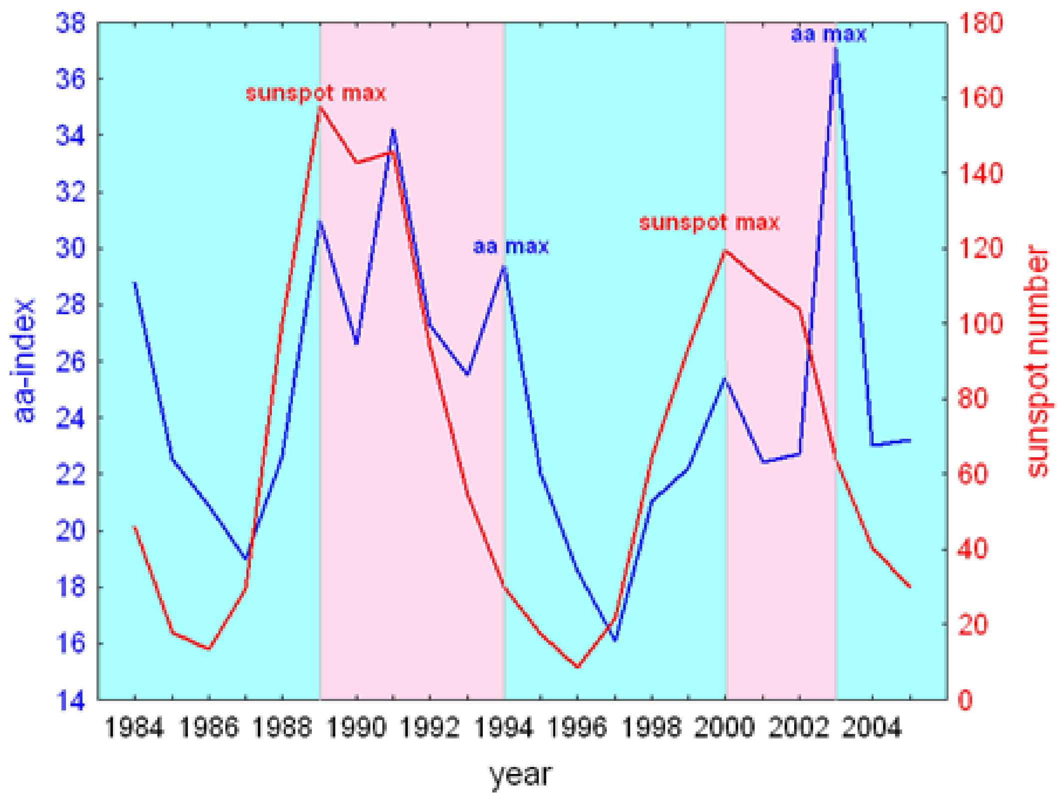
CH data compiled by K. Harvey and F. Recely using NSO KPVT observations under a grant from the NSF in the absence of polar coronal holes, small short-lived low latitude holes are formed with HSS at high heliolatitudes

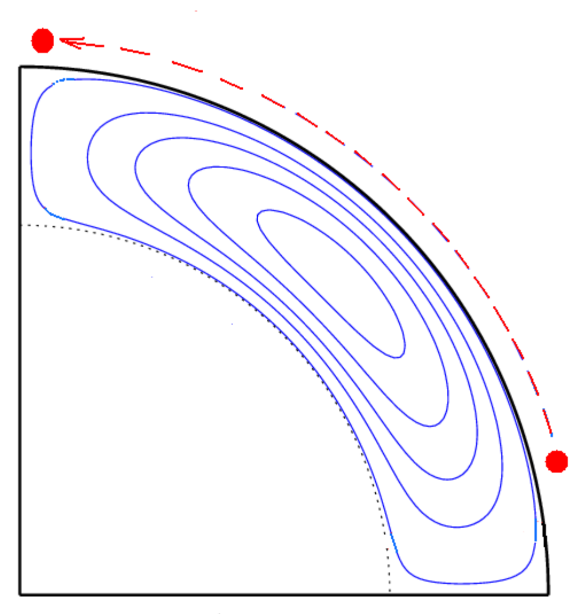
big long-lived low latitude coronal holes and HSS in the ecliptic plane are only formed in the presence of polar coronal holes



Wang and Sheeley, 1990

Time from sunspot maximum to geomagnetic activity maximum

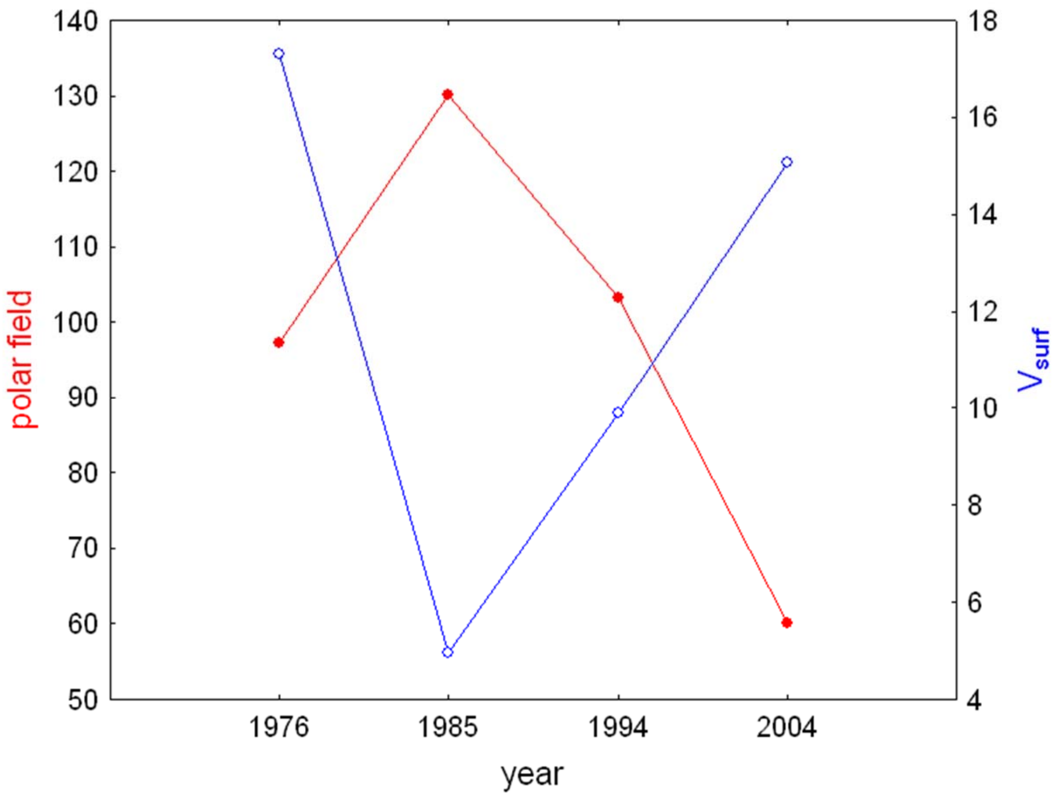




= the time for the flow to reach from sunspot max latitudes to the poles

From this time we can calculate the speed of the surface meridional circulation

Long-term variations in surface meridional circulation and the amplitude of the next sunspot maximum

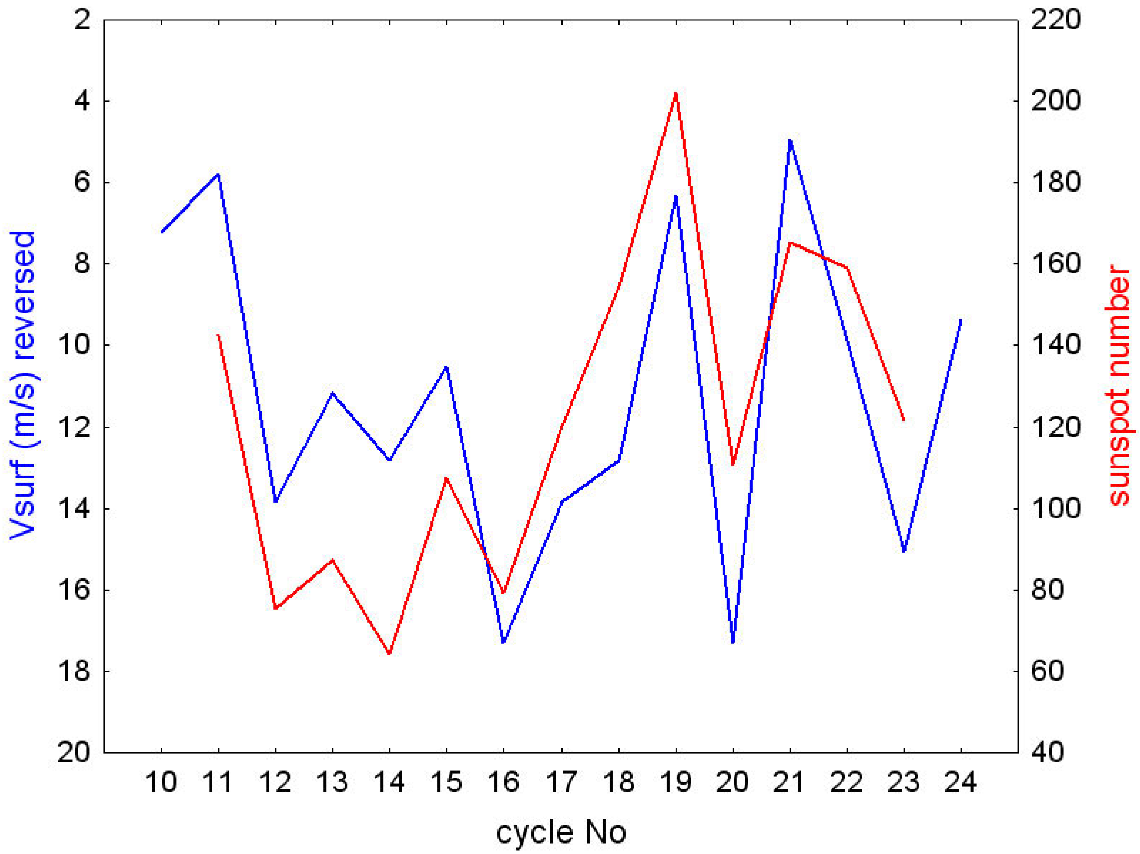


Strong dependence of the polar field and sunspot max on the preceding surface poleward circulation (r=-0.76)

Faster poleward circulation
⇒ weaker polar field

Verification of the theory!

Long-term variations in surface meridional circulation and the amplitude of the next sunspot maximum

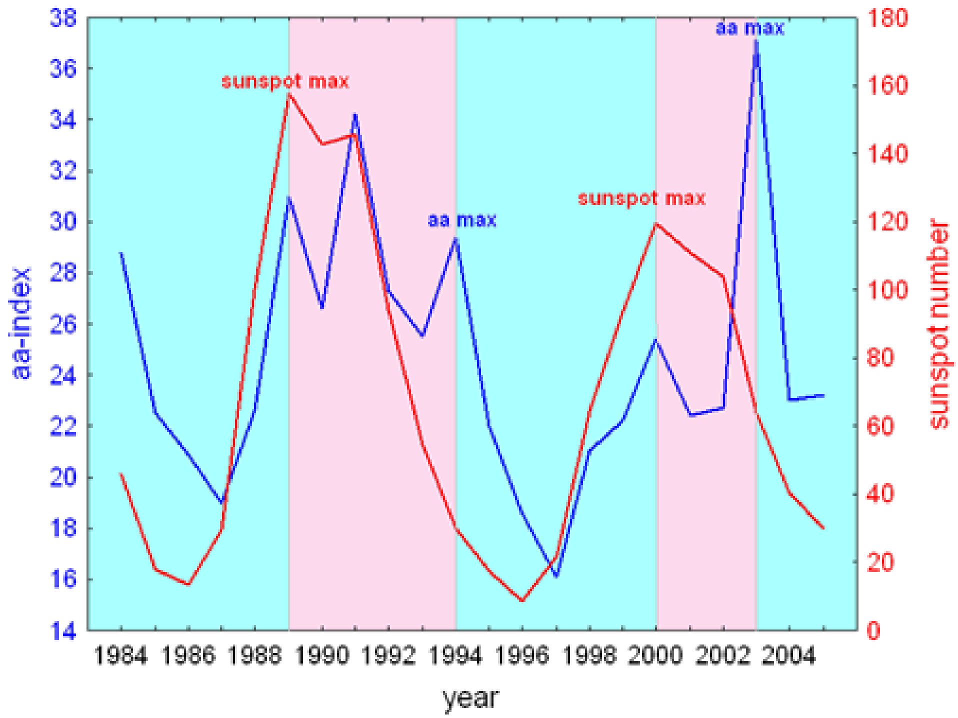


Strong dependence of the sunspot max on the preceding surface poleward circulation (r=-0.7, p=0.03)

Faster poleward circulation
⇒ lower sunspot max of the next cycle

Verification of the theory!

Time from geomagnetic activity maximum to next sunspot maximum?



Depends on diffusivity

3 regimes of operation

- **Fully advection-dominated**
  very low diffusivity
- **Intermediate**
  higher diffusivity
- **Strongly diffusion-dominated**
  still higher diffusivity

(Hotta and Yokoyama, 2010)

Time from geomagnetic activity maximum to next sunspot maximum?

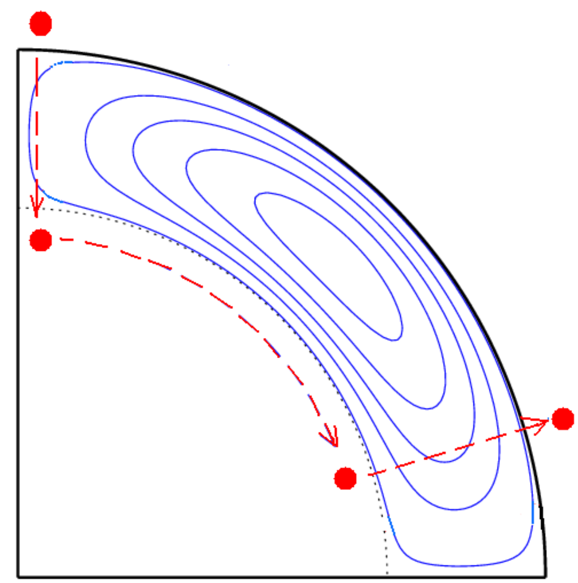
If the diffusivity is very low

all of the flux makes a full circle

Fully advection-dominated regime

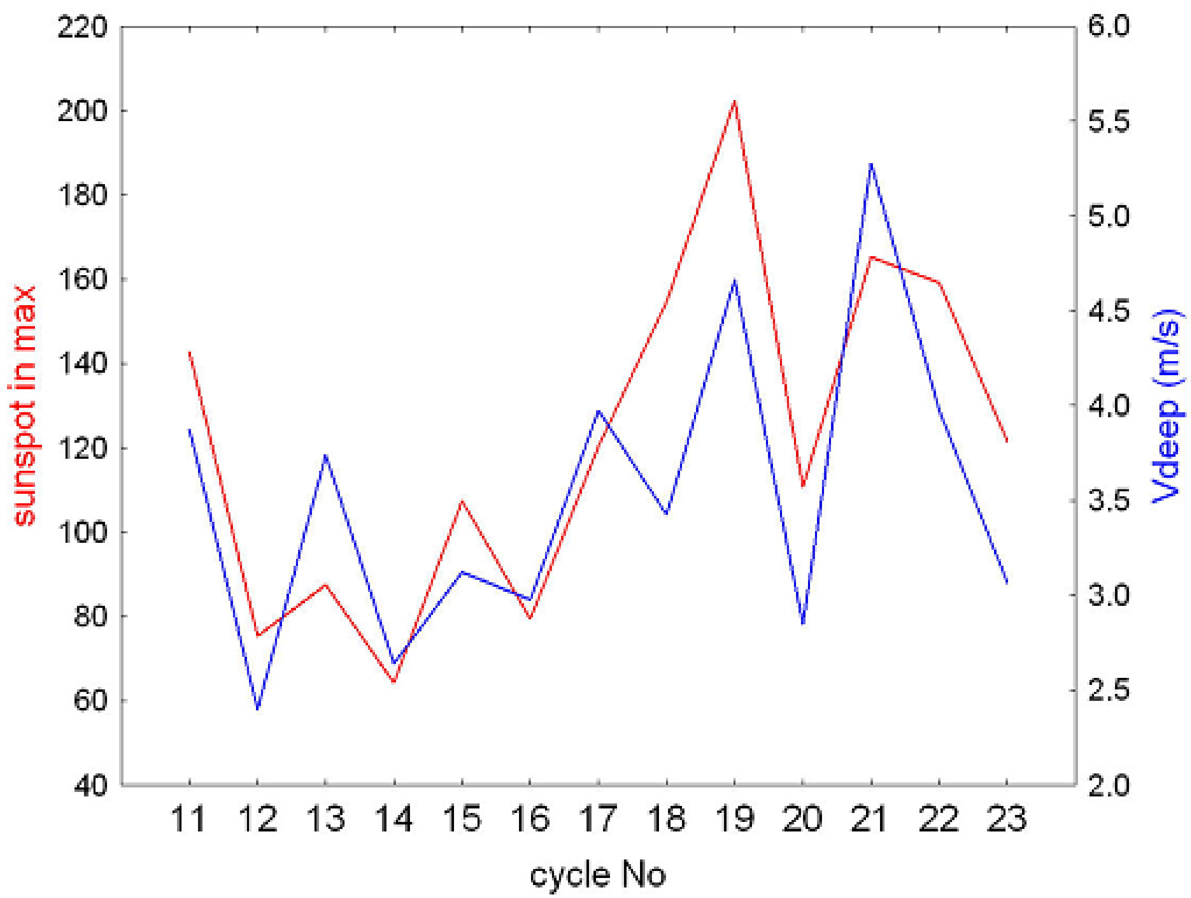
$\eta \sim 10^7\ m^2/s$

Jiang, Chatterjee, Choudhuri (2007)



From this time we can calculate the speed of the deep circulation

Long-term variations in deep circulation and solar cycle amplitude

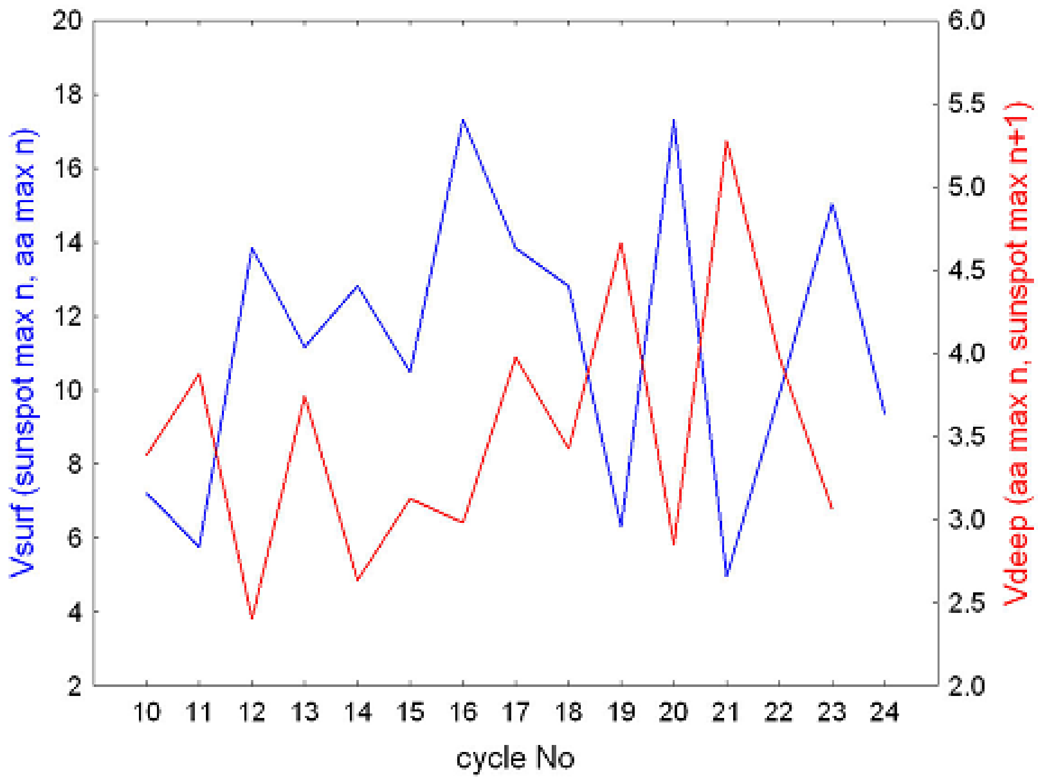


Strong dependence of the sunspot max on the preceding deep equatorward circulation ($r=0.81$, $p<0.01$)

Faster equatorward circulation
⇒ higher sunspot max

Verification of the theory!

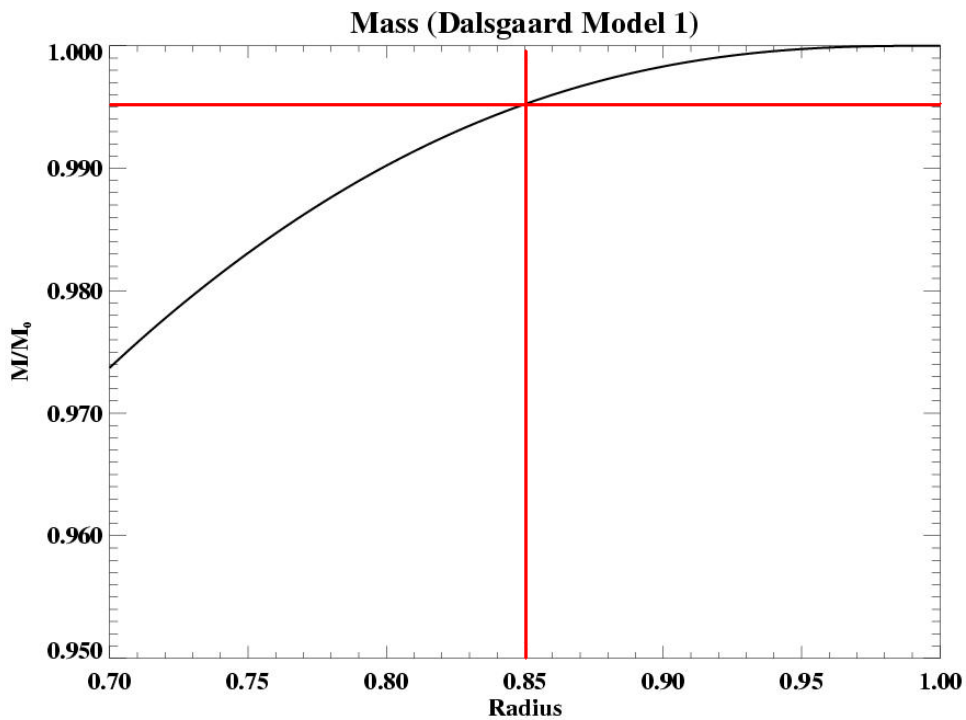
Most models assume positive correlation between Vsurf and Vdeep



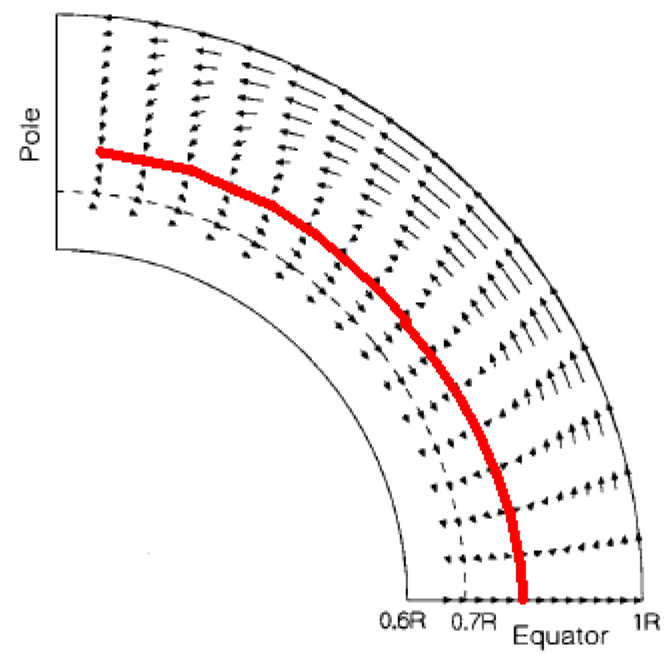
actually:

- Negative correlation (r=-0.75) between Vdeep and Vsurf preceding it
- No correlation between Vdeep and Vsurf following it

What is the physical meaning of the ratio Vsurf/Vdeep?



The surface poleward flow is much faster than the deep equatorward flow – mass conservation



The upper half of the convective zone contains 0.5% of the solar mass, and the lower part – 0.25%

Vsurf/Vdeep ~ reversal depth

Time from geomagnetic activity maximum to next sunspot maximum?

The other extreme:
If the diffusivity is very high

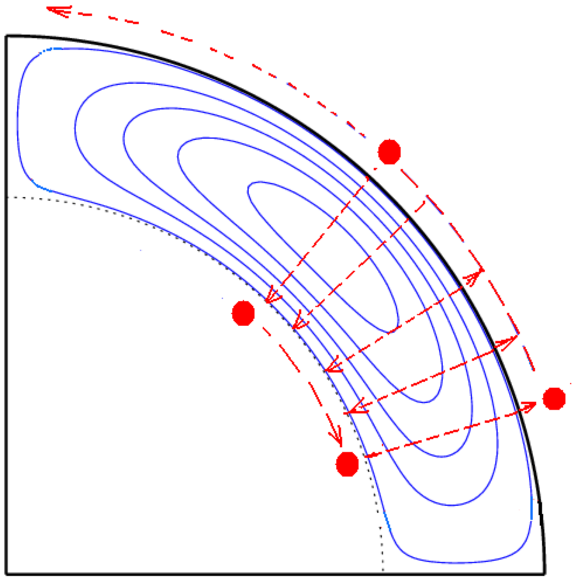
flux diffuses directly to the tachocline "shortcircuiting" meridional circulation

Strongly diffusion-dominated regime

$\eta \sim 2\text{-}9.10^{8}\ m^2/s$
$\eta/u_0 > 2.10^{7}\ m$

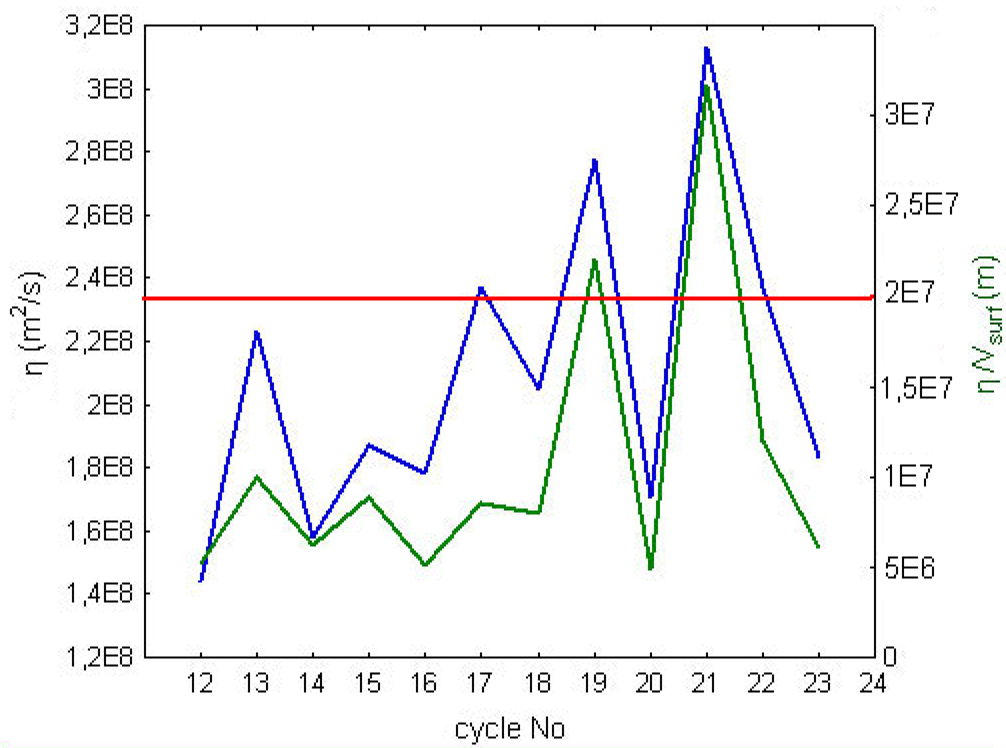
Hotta and Yokoyama (2010)

$T = L^2/\eta$



From this time we can calculate the diffusivity η and η/u_0

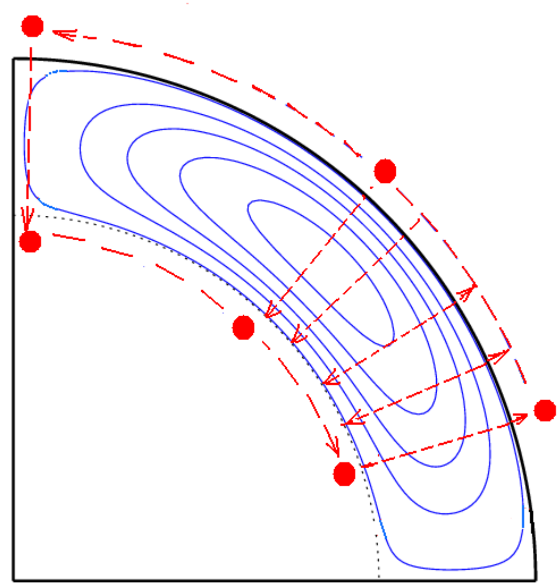
Long-term variations in the diffusivity and the ratio η/u_0



Both η (~ 1.4-3.10^8) and η/u_0 (~5.10^6-3.10^7) are not high enough for strongly diffusion-dominated regime and not low enough for fully advection-dominated regime

Time from geomagnetic activity maximum to the next sunspot maximum?

If the diffusivity is intermediate



a part of the flux short-circuits the meridional circulation, another part makes a full circle

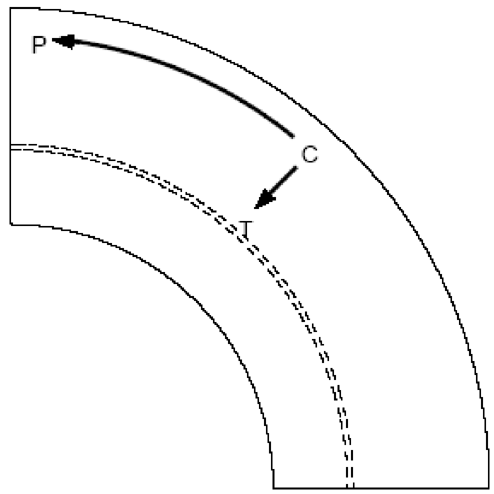
Intermediate regime

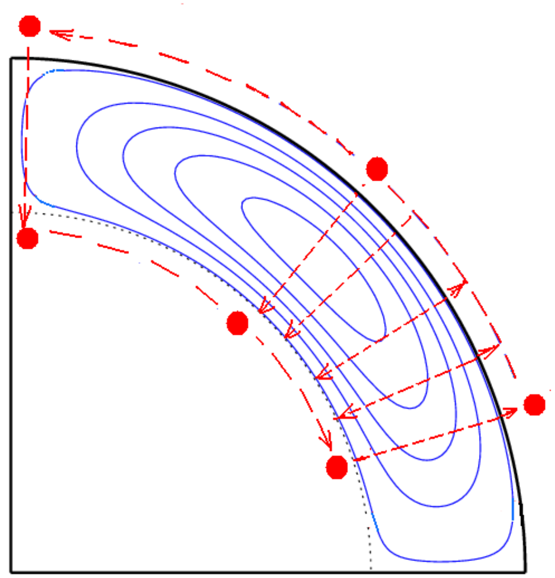
$\eta \sim 1\text{-}2.10^8\ m^2/s$

Jiang, Chatterjee, Choudhuri (2007)

Diffusivity consistent with our estimation

If the diffusivity is intermediate





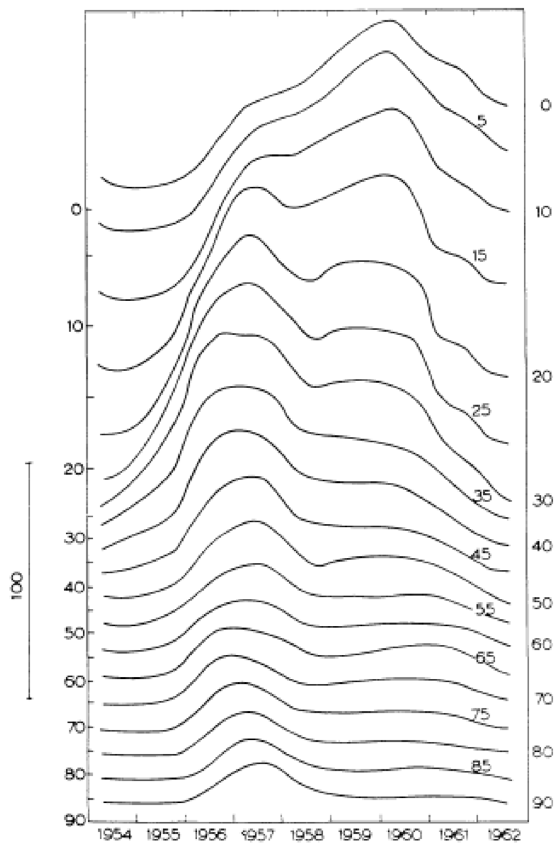
a part of the flux short-circuits the meridional circulation, another part makes a full circle

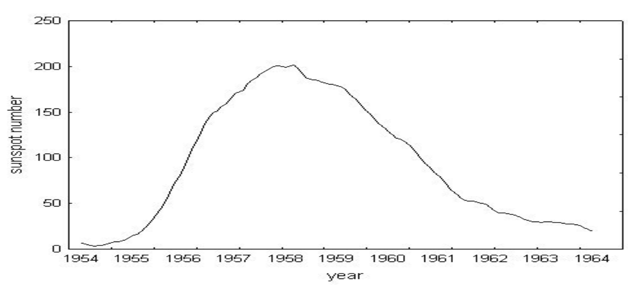
⇒ the sunspot cycle will be a superposition of the two surges of the toroidal field

⇒ double-peaked sunspot max

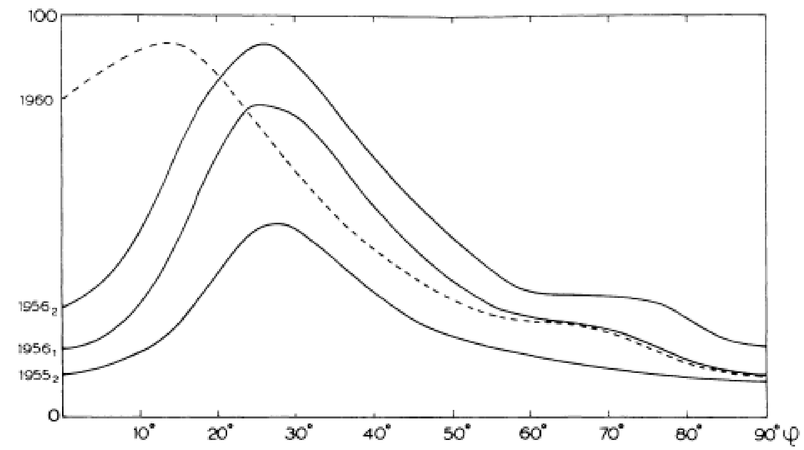
Gnevyshev (1963, 1965, 1967)

Sunspot cycle 19





The 11-year cycle does not contain one but two waves of activity with different physical properties

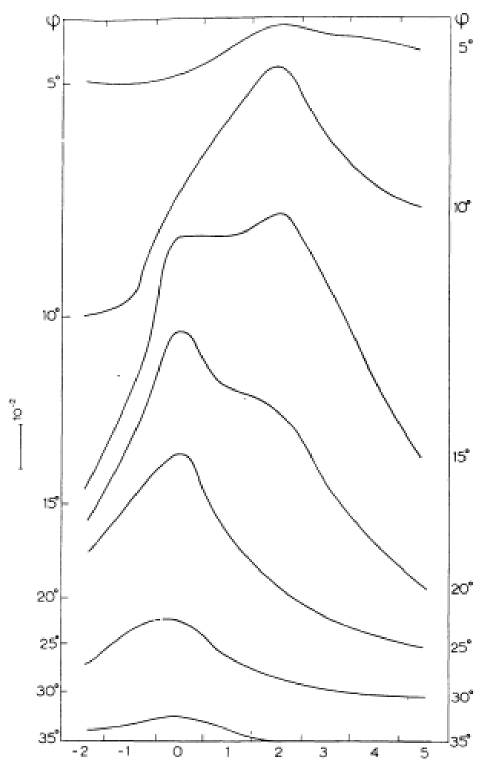


During the first maximum, activity increases and subsequently decreases at all latitudes.

The second maximum is only observed at low latitudes, but below 15° it is even bigger than the first one

Is this only true for cycle 19?

8 cycles superposed
(1874-1962)



Conclusions

2 maxima in all cycles resulting from different physical processes:

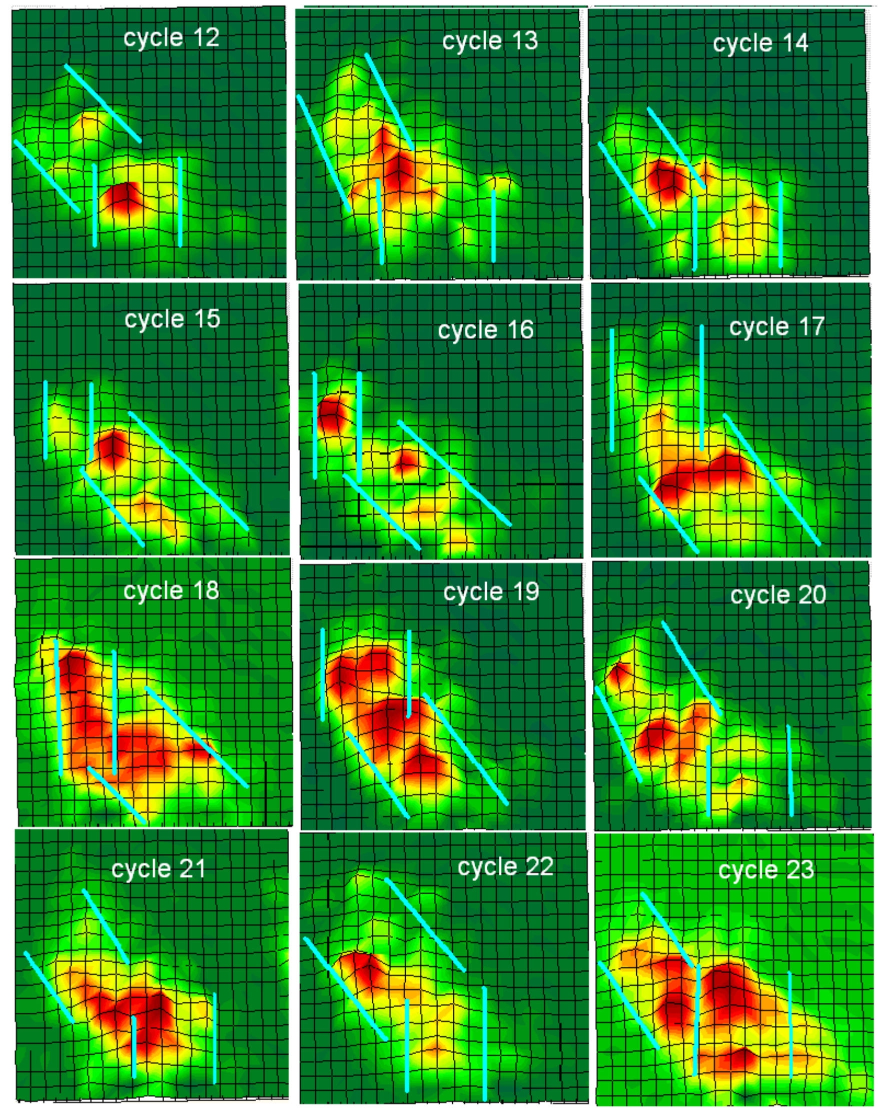
- earlier one at all latitudes
- later one at low latitude

Varying timing between them:

- if big enough $\Rightarrow$ 2 peaks seen
- if small $\Rightarrow$ 1 peak in lat averaged data

Georgieva (2011) – two maxima in all cycles from 12 to 23

- Diffusion generated: appears simultaneously in a wide latitudinal band
-
- Advection generated: moving equatorward with time



Verification of the theory!

Solar dynamo theory - questions

- Is it correct?
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- **Regime of operation**
- Grand minima

Regime of operation in the upper part of the solar convection zone

Intermediate - neither fully advection dominated, nor strongly diffusion generated

Relative importance of advection versus diffusion

magnetic Reynolds number

$$R_m = V_{surf} L / \eta_{surf}$$

V_{surf} - between 5 and 20 m/s

η_{surf} - between 1.5 and 4.5×10^8 m^2/s

$L \sim 10^9$ m

$\Rightarrow$ **R_m - between 10 and 60**

$\Rightarrow$ advection more important than diffusion

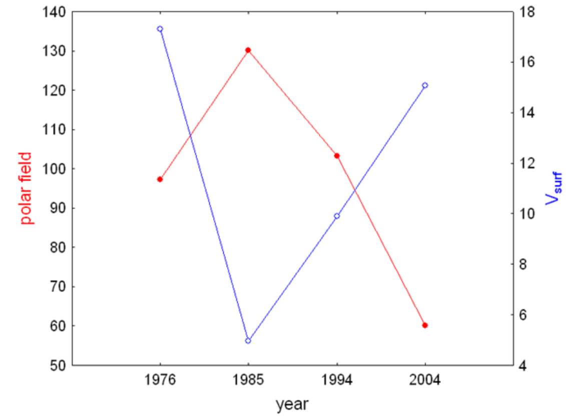
Explanation of the negative correlation of V_{surf} with sunspot max and polar field

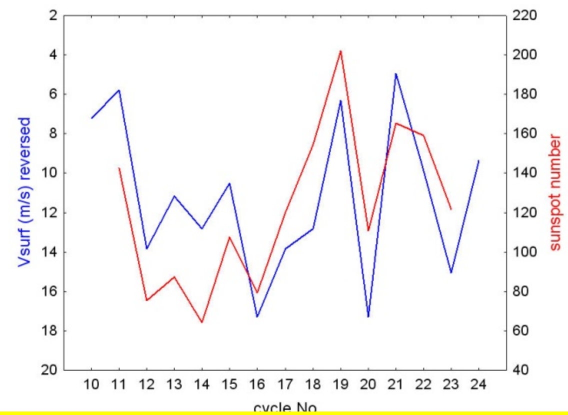
- **Advection more important than diffusion**

  Faster Vsurf = less time for the leading polarity flux to diffuse across the equator = less uncanceled flux reaching the pole = lower polar field = lower following sunspot max

- **Diffusion more important than advection**

  Faster Vsurf = less time for diffucive decay of the flux during its transport to the poles = higher sunspot max





negative correlation between the Vsurf and polar field, between Vsurf and next sunspot max

$\Rightarrow$ **advection-dominated regime**

Regime of operation in the lower part of the solar convection zone

Two possible regimes in the base of the convection zone:

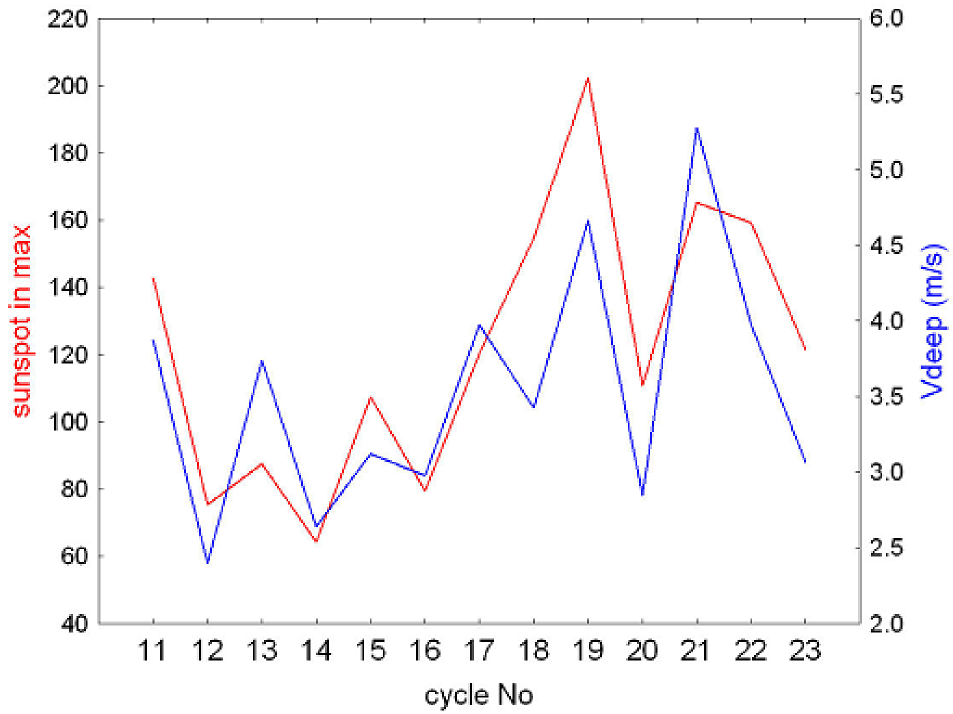
- Diffusion-dominated:

  Faster Vdeep = less time for diffusive decay of the field = higher sunspot max

- Advection-dominated:

  Faster Vdeep = less time for toroidal field generation = lower sunspot max

(Yeates, Nandy & Machay, 2008)



Positive correlation between the Vdeep and sunspot max

⇒ diffusion-dominated regime

Solar dynamo theory - questions

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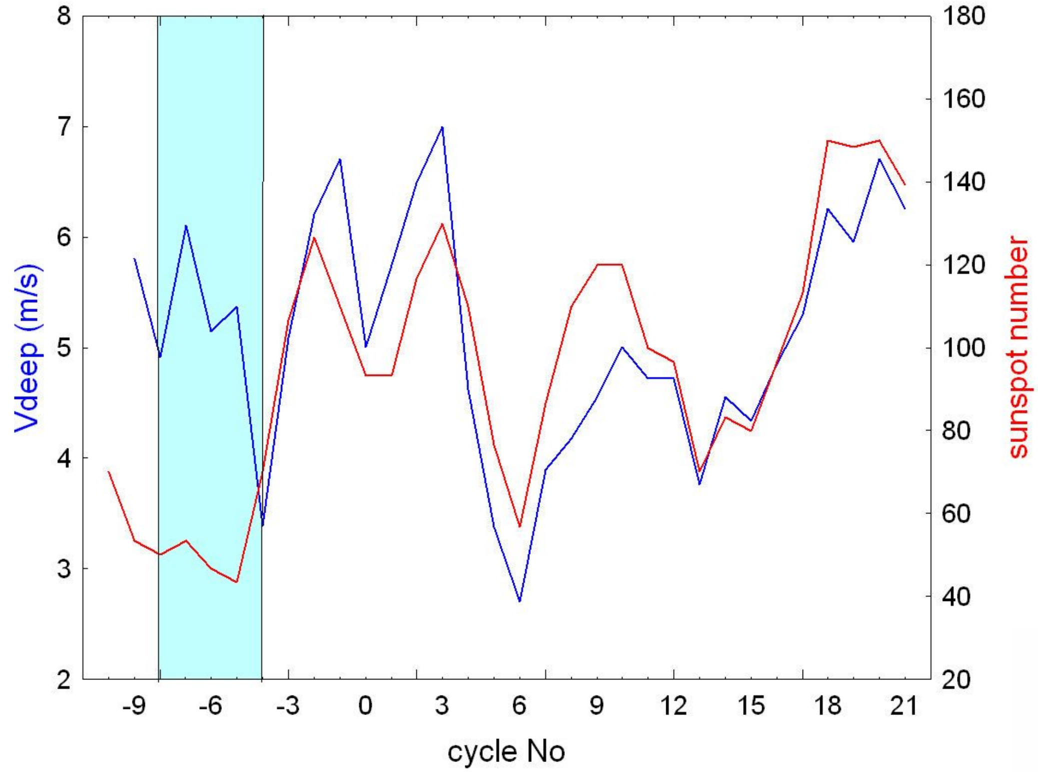
- Regime of operation
- **Grand minima**

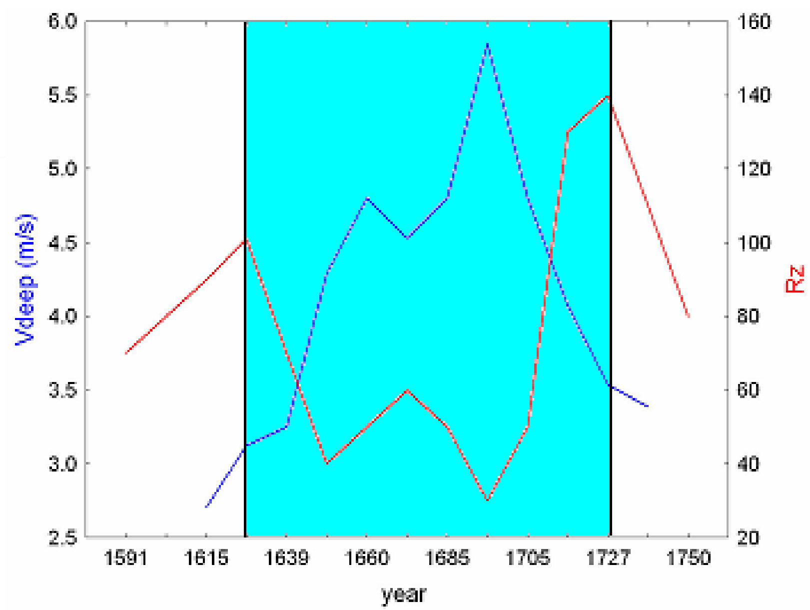
Long-term variations in Vdeep (ESAI database)



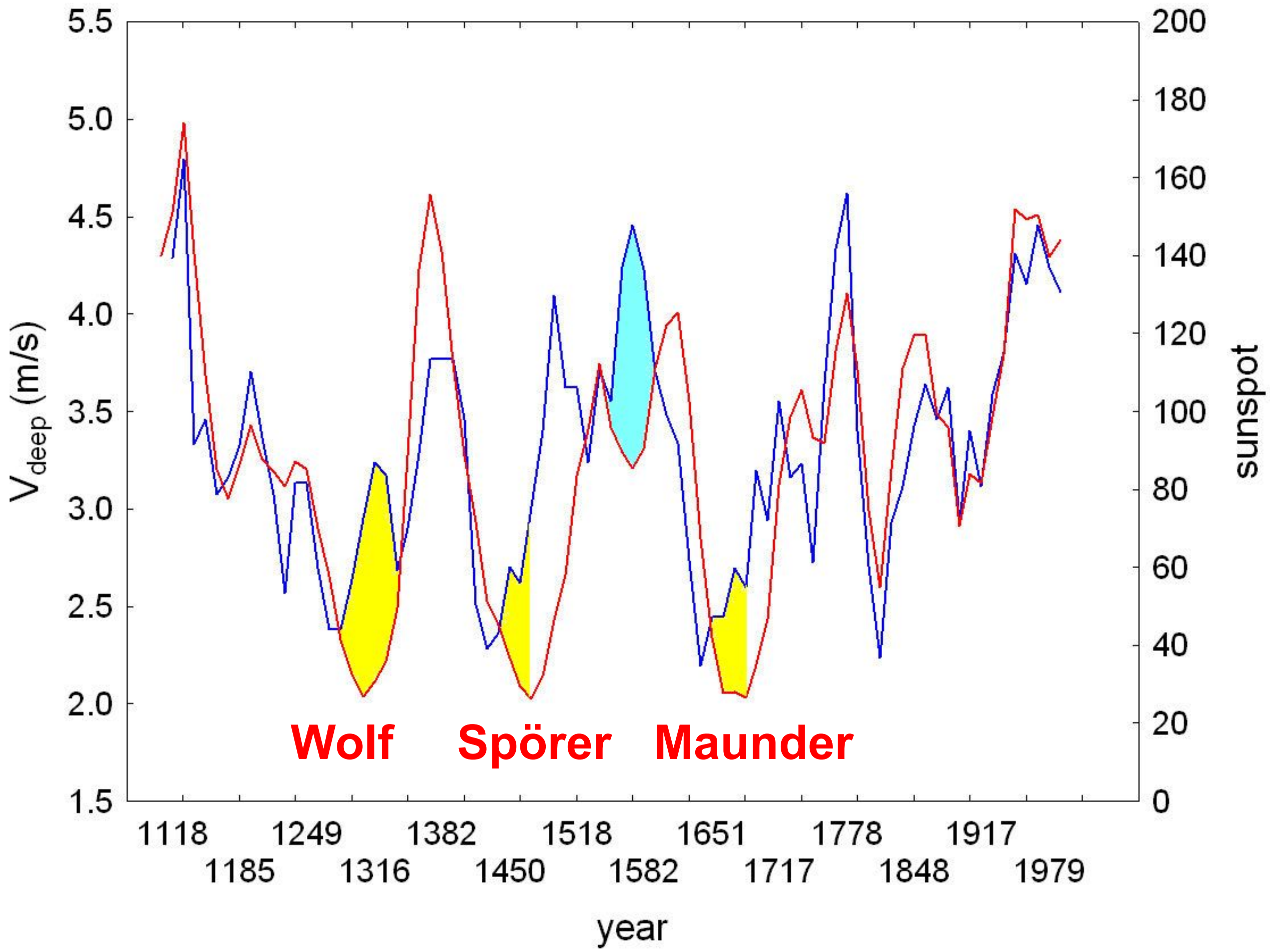
higher Vdeep = **lower** sunspot max
during the Maunder minimum

⇒ advection-dominated regime

Confirmed by 10Be data
(Beer et al., 1998)



Still longer reconstruction (ESAI)



higher Vdeep = lower sunspot max during all grand minima

= advection dominated regime during grand minima

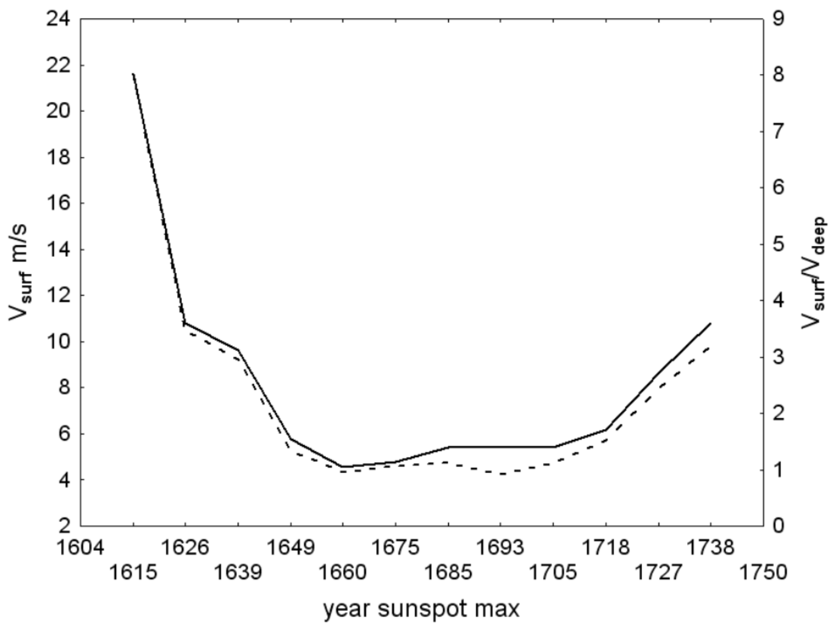
What is the difference between a "normal" period and a Grand minimum?

Vdeep, diffusivity – about the same

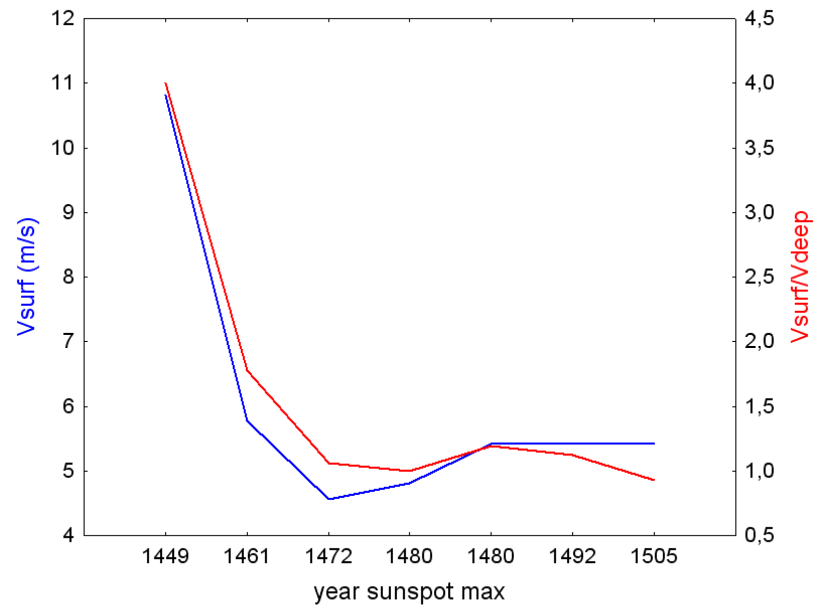
Vsurf drops to very low values

Ratio Vsurf/Vdeep ~ 1

Maunder minimum

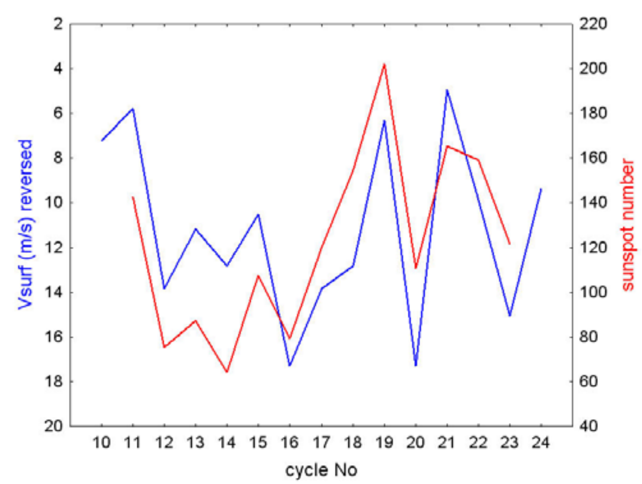


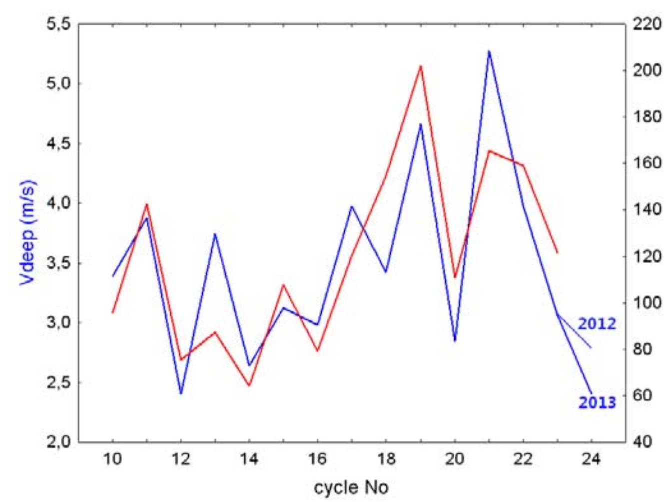
Sporer minimum



A we entering a new grand minimum?

- The answer is NO! – that is, NOT RIGHT NOW
- Because Vsurf is relatively high, Vdeep is very low -> Vsurf/Vdeep is high



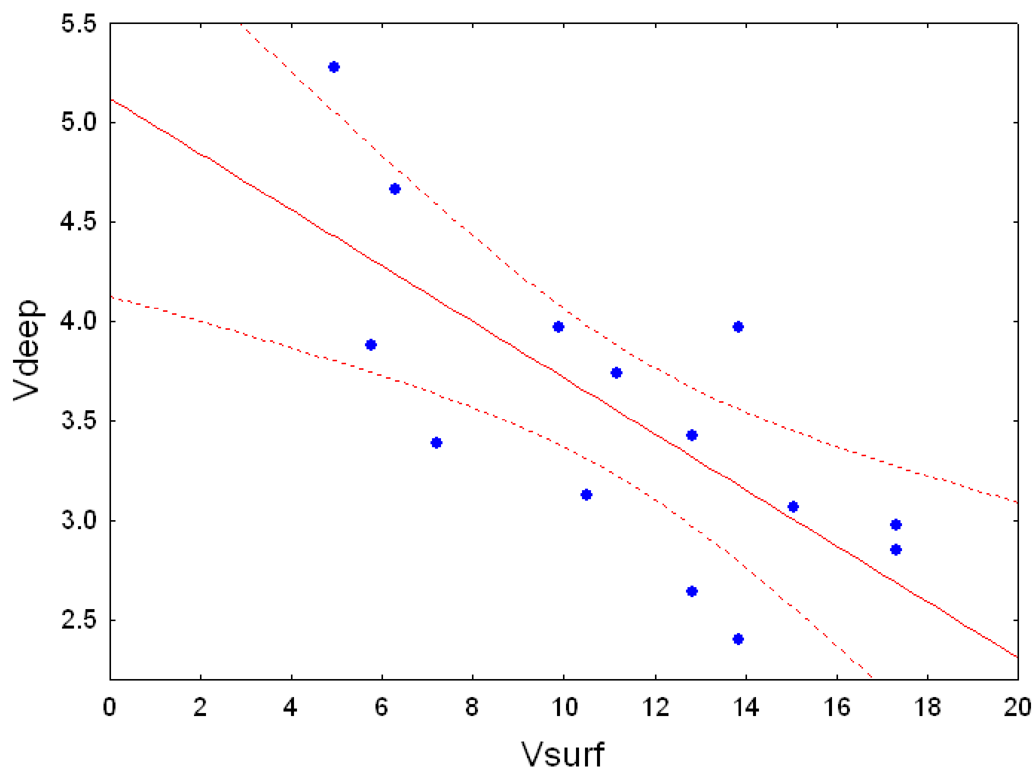


Thank you for your attention

Solar dynamo theory - questions

- Is it correct?
- Values of the dynamo parameters (diffusivity, meridional flows)
- Regime of operation
- Grand minima
- **Long-term variations and irregularities**
- Predictability

What is the reason for the long-term solar activity variability?



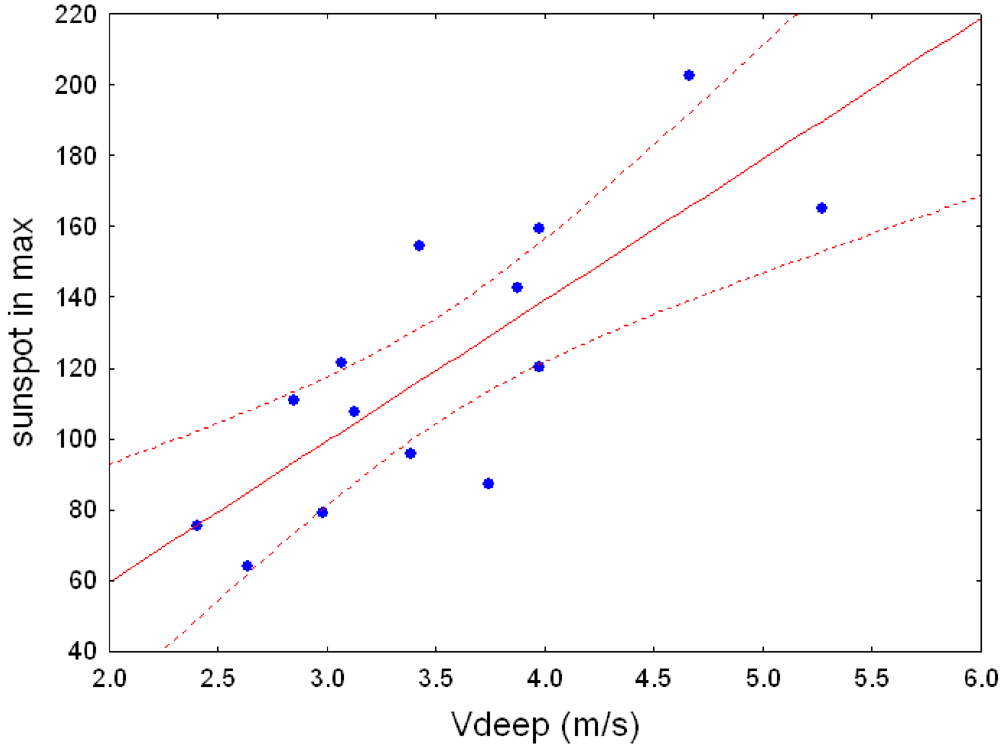
The sequence of relations

- Good negative correlation (r=-0.75) between Vsurf and the following Vdeep

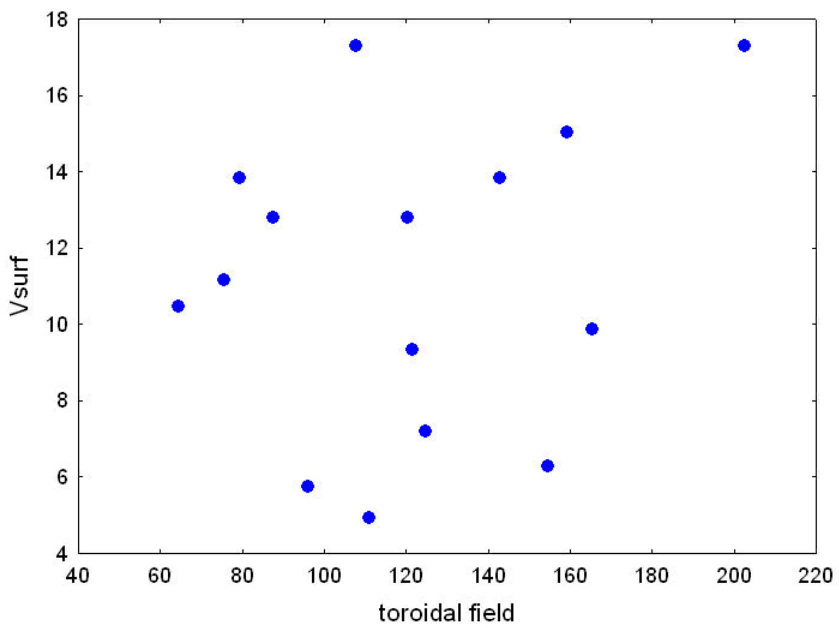
The sequence of relations

- Good correlation (r=0.81) between Vdeep and the following sunspot max (≡ toroidal field)

  Indication that solar dynamo operates in diffusion dominated regime



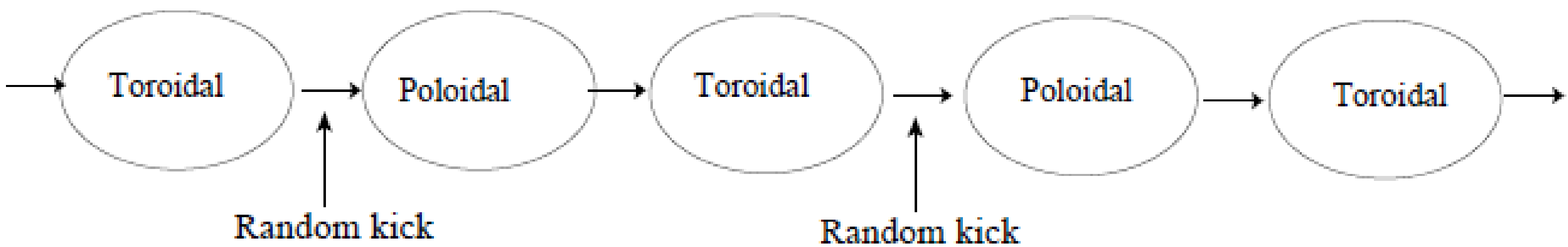
The sequence of relations



NO correlation between the sunspot max (≡ toroidal field) and the speed of the following surface poleward circulation Vdeep

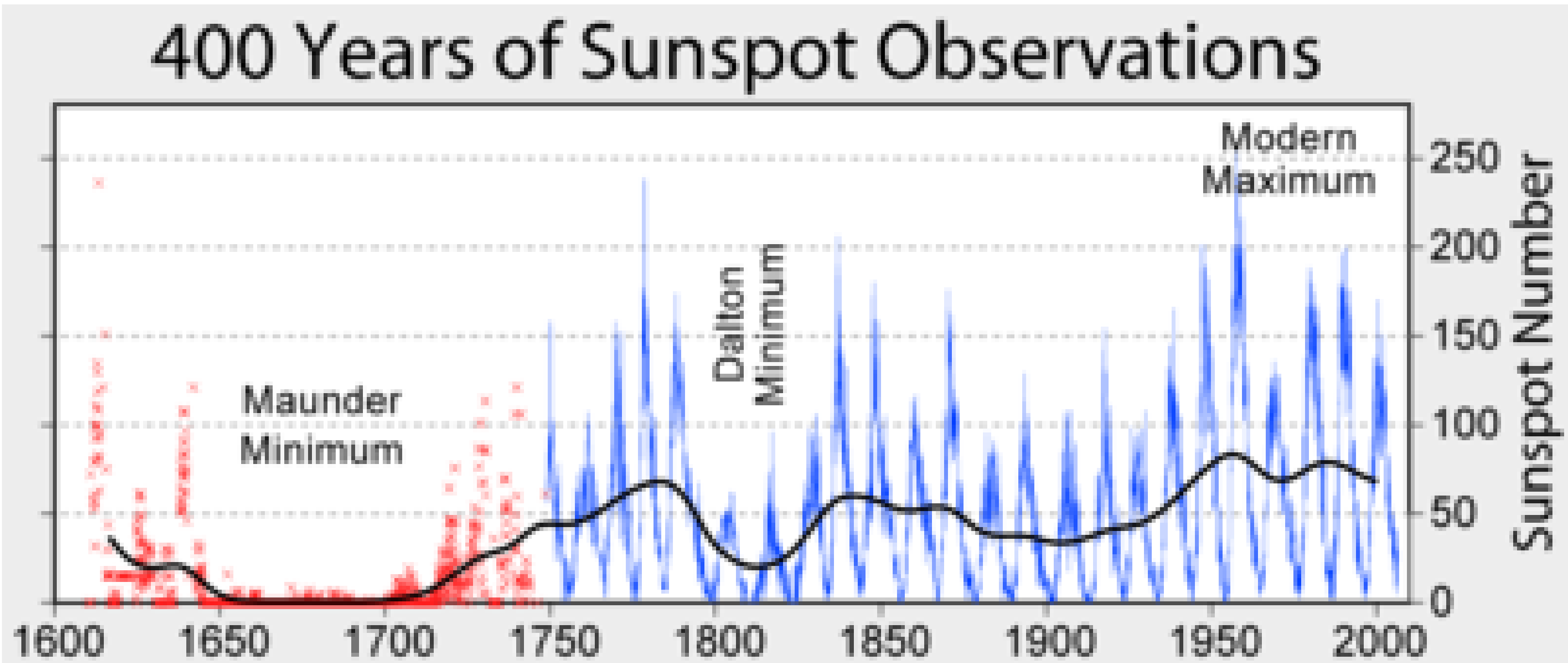
The sequence of relations

Vsurf ⇨ Bpol ⇨ Vdeep ⇨ Btor ~~⇨~~ Vsurf



The "kick" acts upon Vsurf

Is the “kick” random?

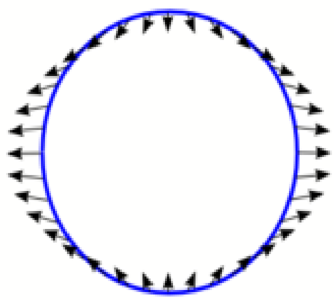


Not likely: systematic variations in the sunspot cycle magnitude (Gleissberg cycle)

This dynamo mechanism works for all stars with convective envelopes

What if the star has a planet?

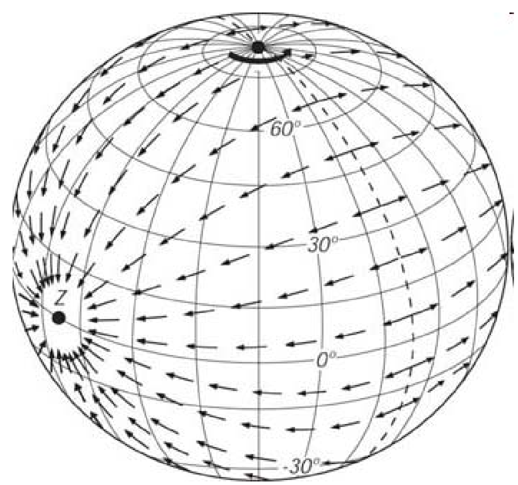
The simplest case: one planet on a circular orbit in the star's equatorial plane



In the case of the Sun, the elevation caused by all planets together is very small (~ 1 mm)

The elevation is due to the vertical component of the tidal force

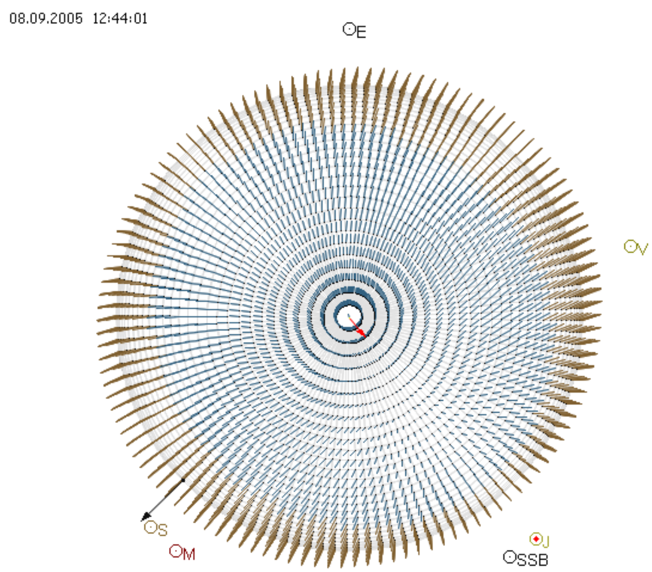
But we are interested in the horizontal, not in the vertical component of the tidal force

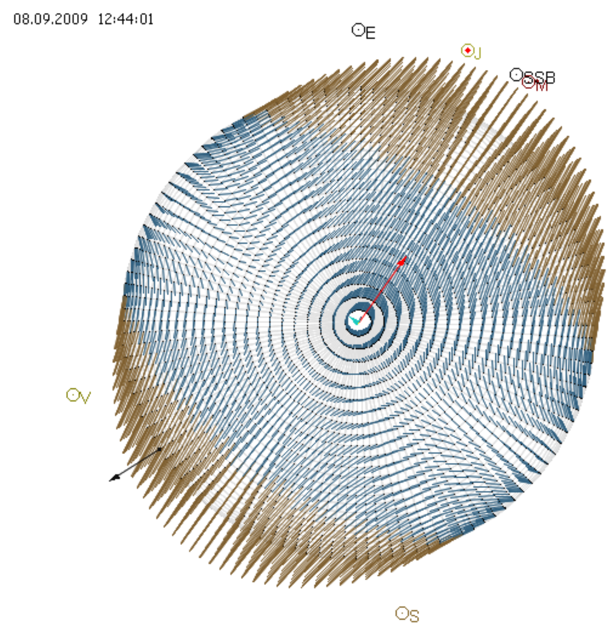


For one only planet, all vectors directed to the planet's subpoint

the case of the Sun with a number of planets

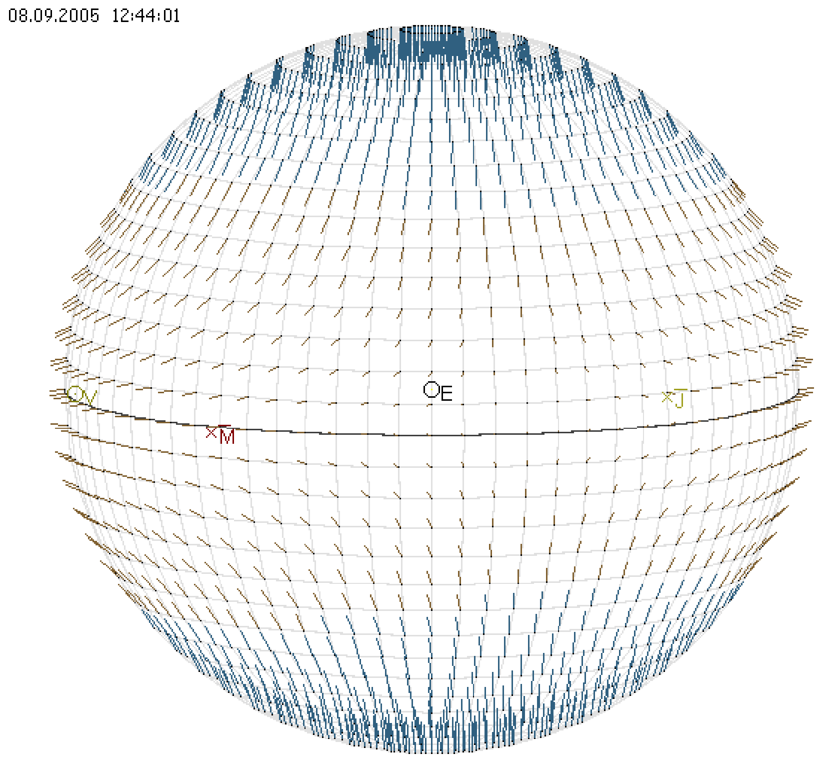
The tidal forces depend on the distance and relative positions of the major tide-creating planets (Jupiter, Earth, Venus, Mercury) which change with time

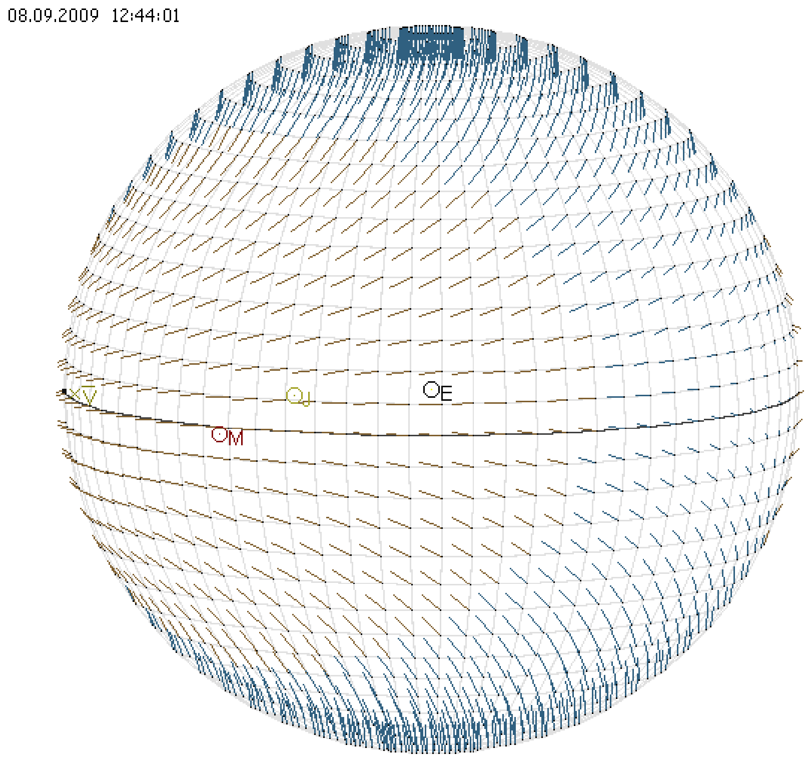




view from the pole (elevation)

Tidal acceleration in the horizontal plane





Meridional acceleration can change the meridional circulation
speed ~ 10 m/s

evaluation of the magnitude

- $a = F/\rho$
- $F \sim 10^{-10}$ N/kg
- $\rho \sim 10^{-5}$ gr/cm^3 = 10^{-2} kg/m^3

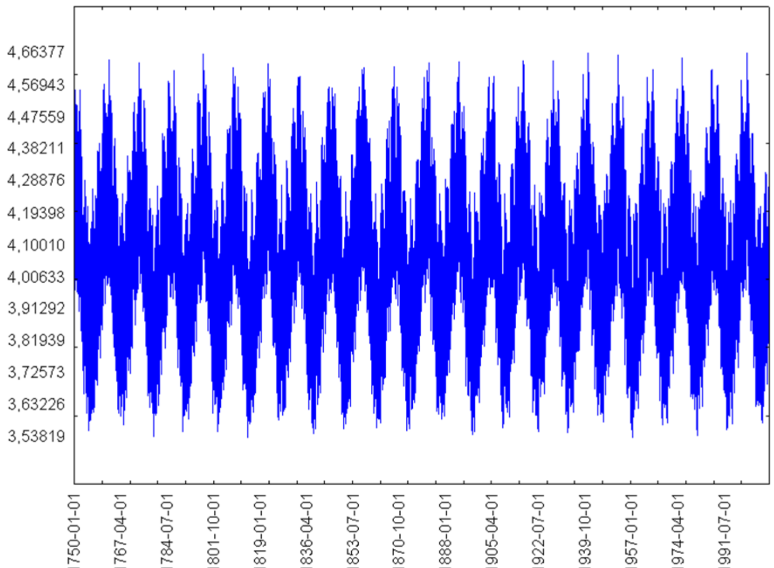
$\Rightarrow a \sim 10^{-8}$ m/s^2

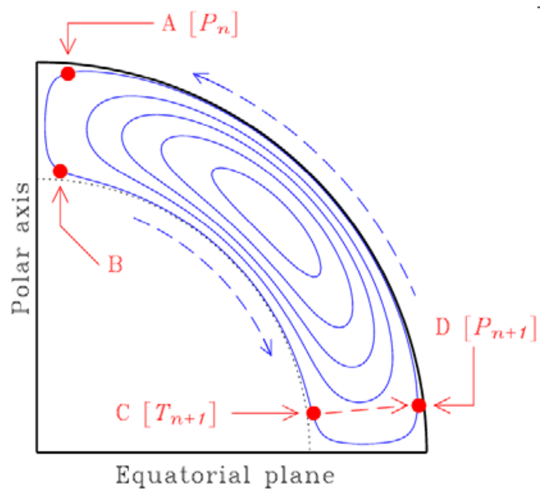
- $t \sim 10^8$ s

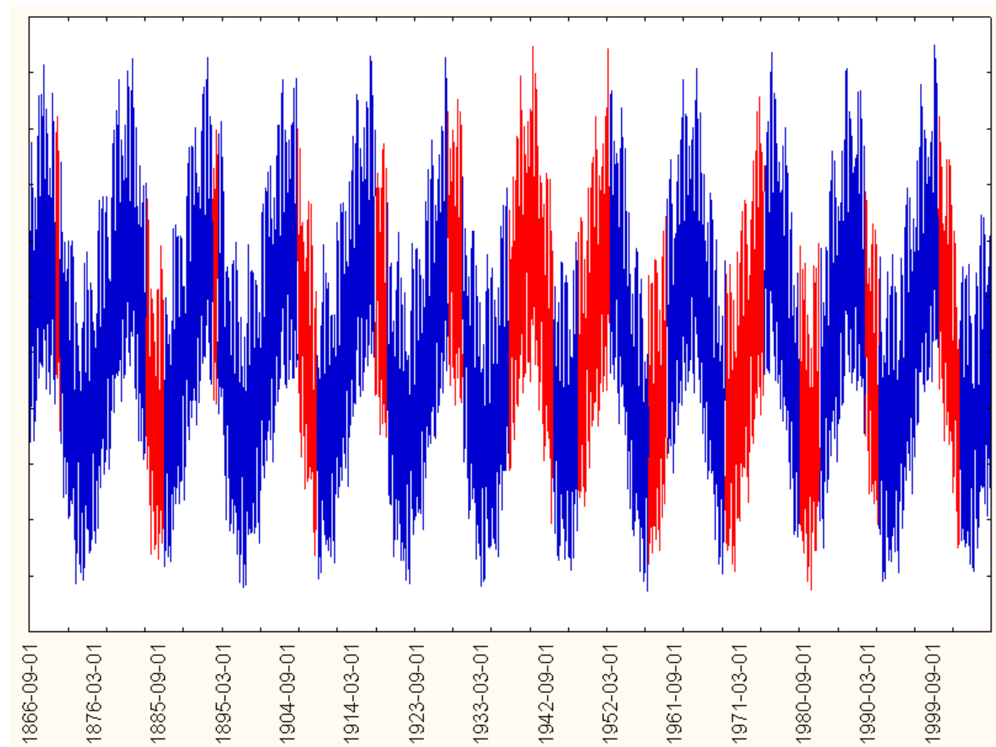
$\Rightarrow$ dVsurf ~ m/s

Corresponds to the observed variation of Vsurf

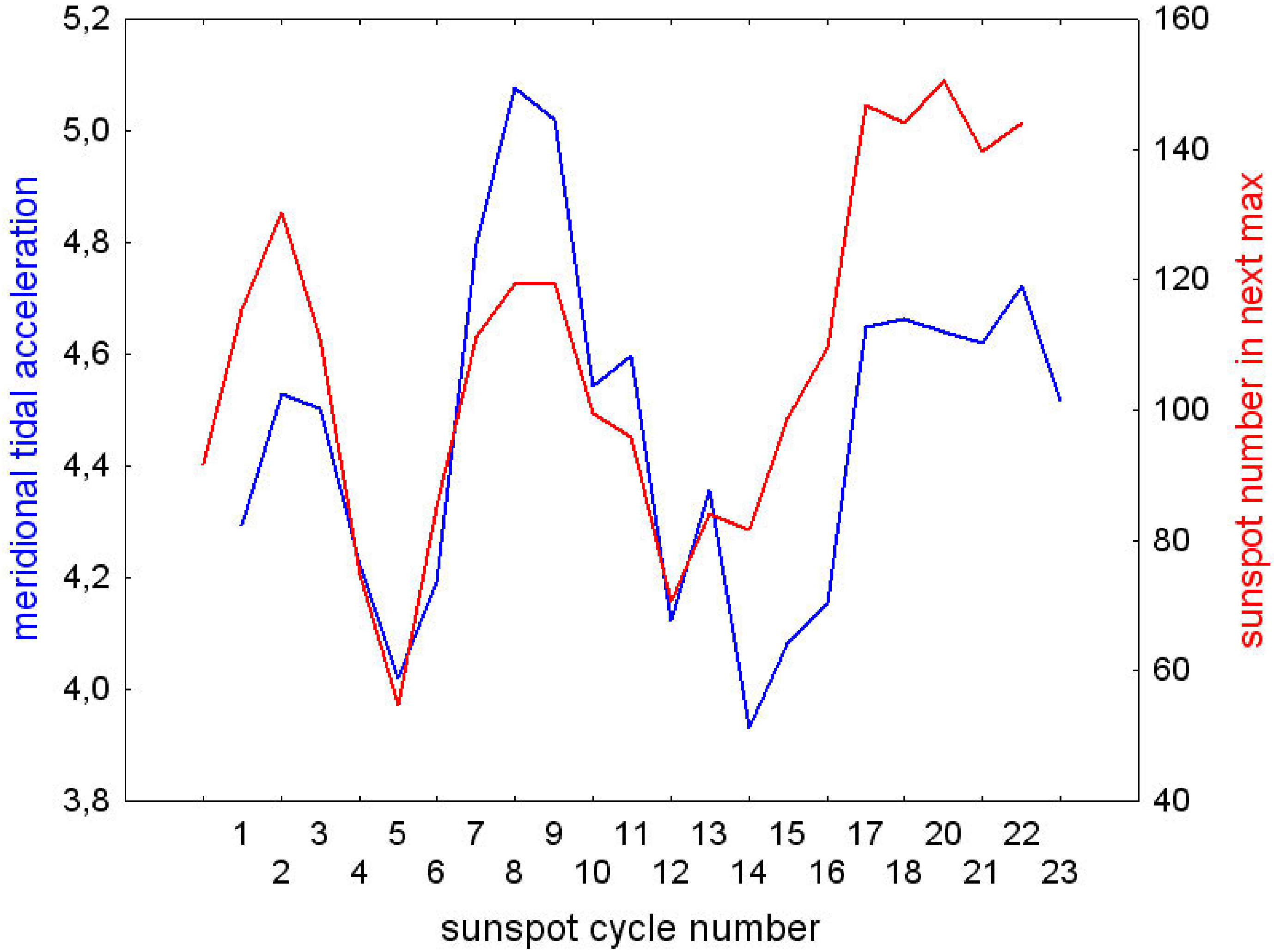
The average tidal force is important in the period when the surface meridional circulation carries the flux to the poles







bigger meridional tidal force
= slower poleward surface circulation
= higher sunspot number of the next cycle



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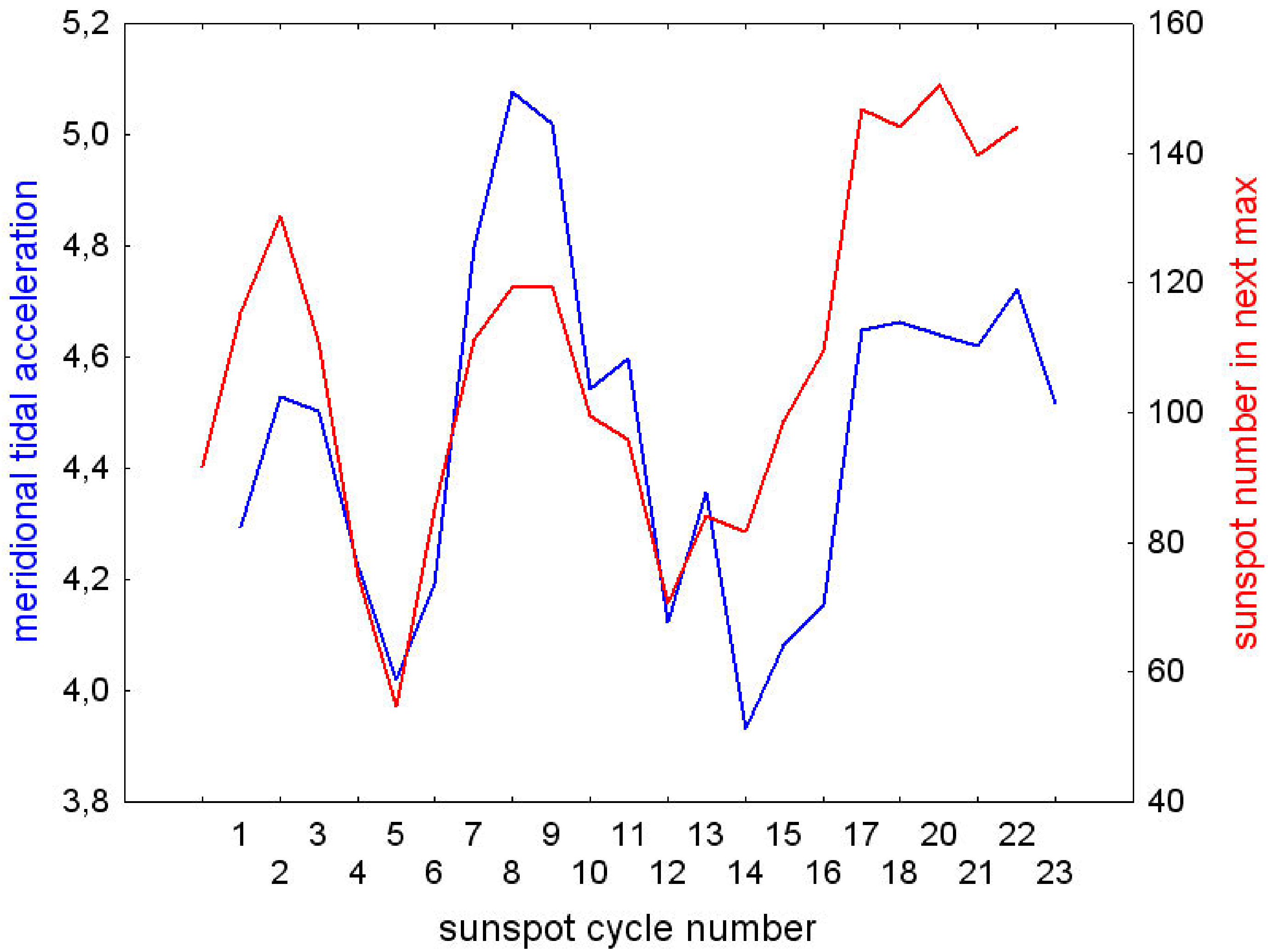


Solar dynamo theory - questions

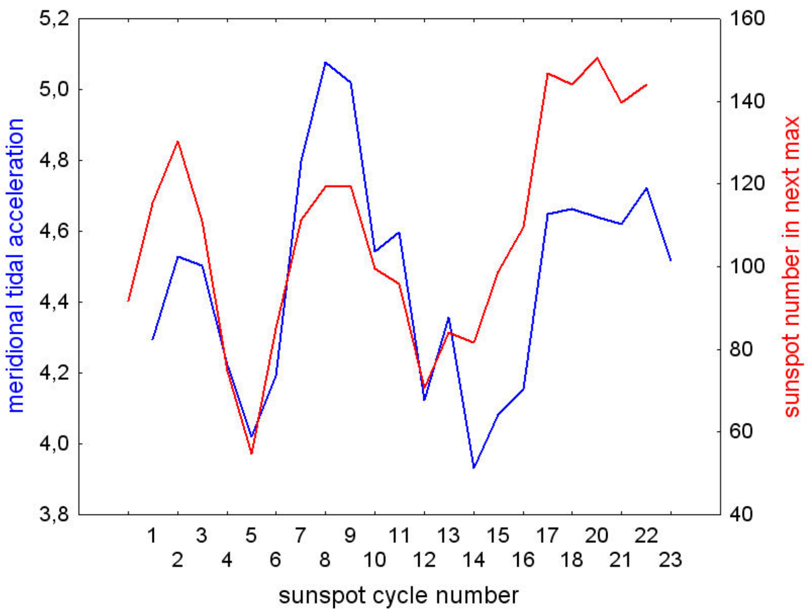
- Is it correct?
- Values and variations of the dynamo parameters (diffusivity, meridional flows)
- Regime of operation
- Grand minima
- Long-term variations and irregularities
- **Predictability**

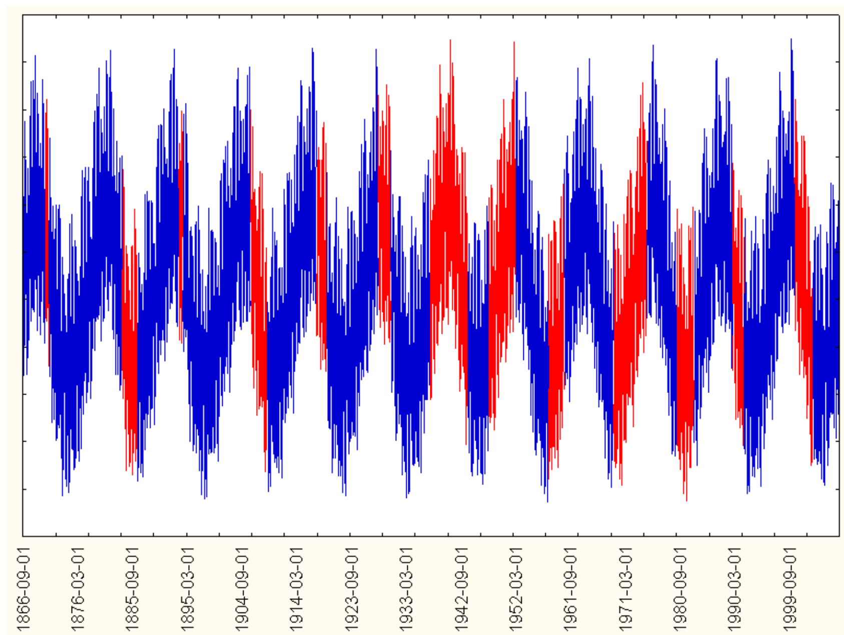
How far ahead can we predict?

Vsurf ⇨ Bpol ⇨ Vdeep ⇨ Btor ~~⇨~~ Vsurf

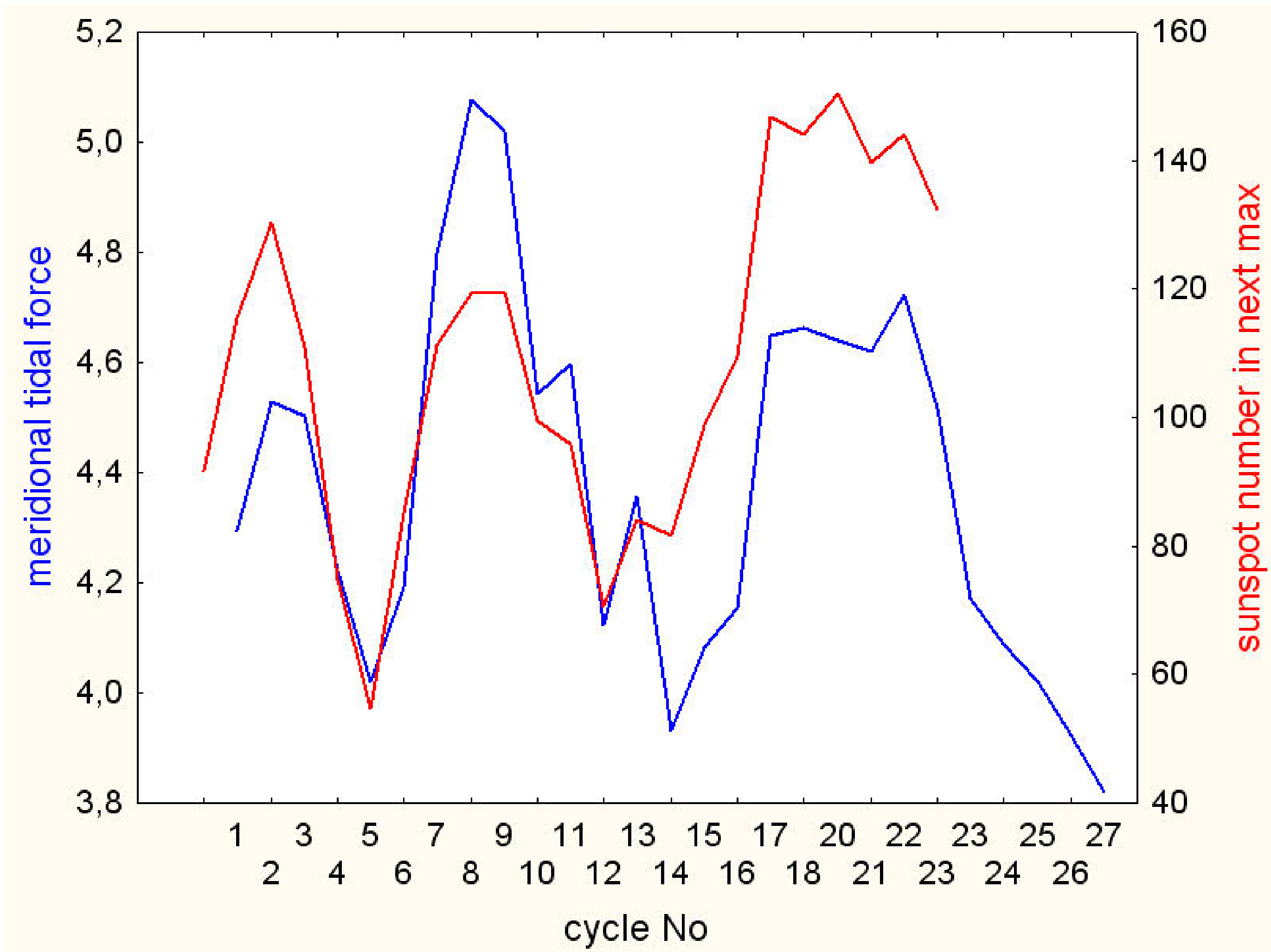
⇒ No more than 1 cycle memory

Can we predict from planetary influences?





Forecast???


meridional tidal force
sunspot number in next max
cycle No
5,2
5,0
4,8
4,6
4,4
4,2
4,0
3,8
160
140
120
100
80
60
40
1 3 5 7 9 11 13 15 17 20 22 23 25 27
2 4 6 8 10 12 14 16 18 21 23 24 26

Thanks for your attention