Planetary influence on solar activity from the point of view of the flux transport dynamo

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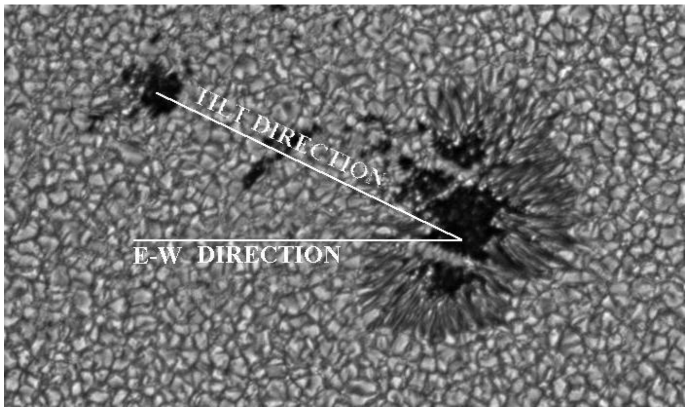
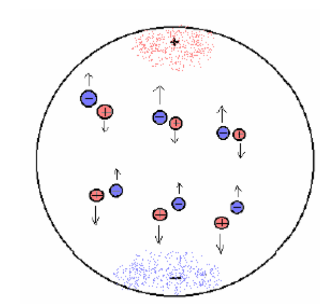
Our approach:

- How the solar dynamo operates
- What solar dynamo parameters determine the amplitude of the sunspot cycle
- What external factors can modulate these parameters
- Do observations confirm this
- Order of magnitude estimation of the reality of the relations

Babkock-Leighton mechanism – regeneration of poloidal field

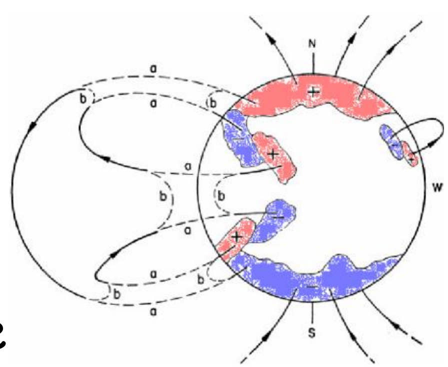


Due to the Coriolis force during the flux tube emergence, the sunspot pairs are tilted to the E-W direction



Late in the sunspot cycle:

leading spots diffuse across the equator cancel with the opposite polarity leading spots in the other hemisphere.

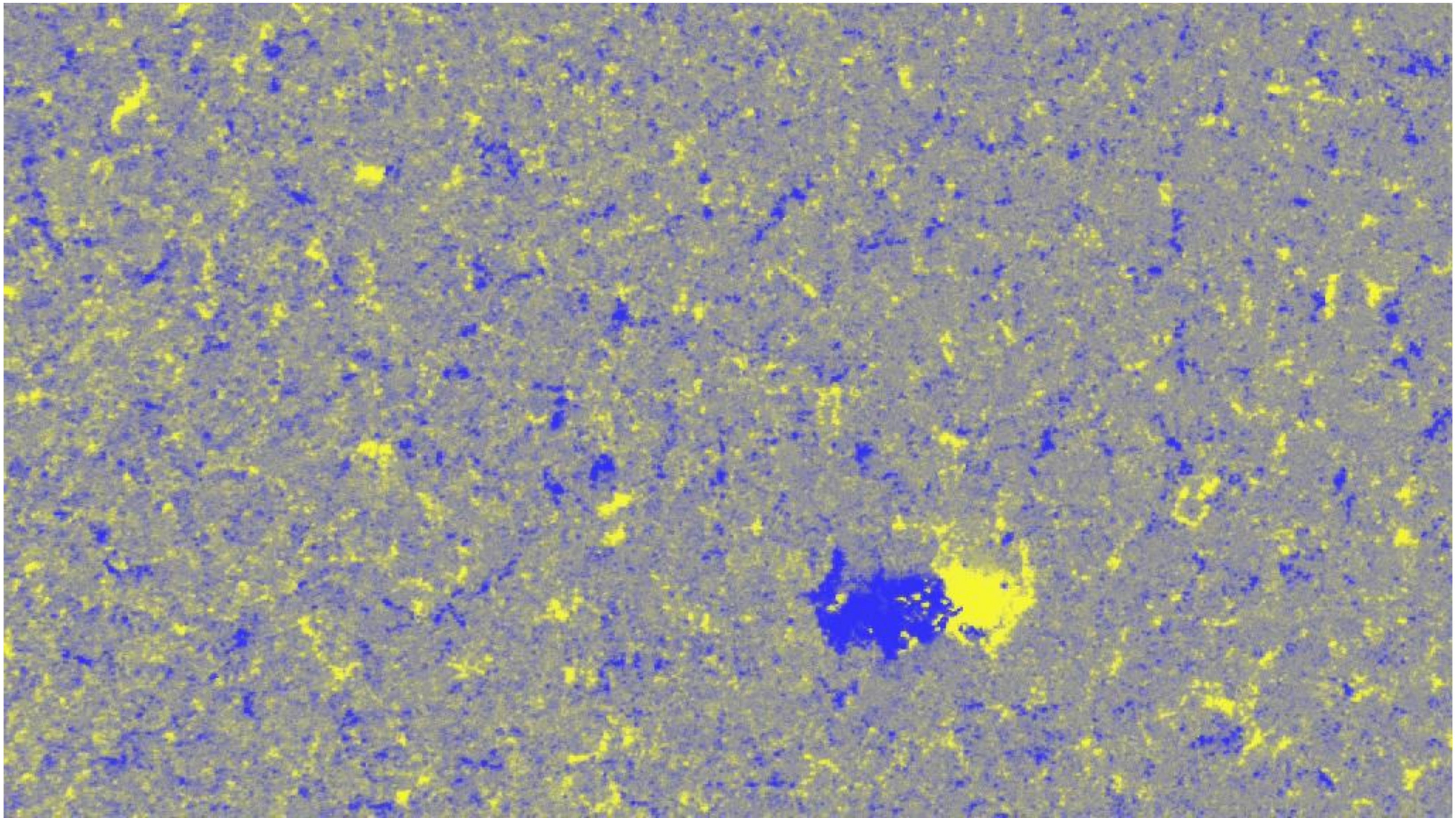


⇒ excess trailing spots flux carried to the poles

- cancels the flux of the previous cycle
- accumulates to form the poloidal field of the next solar cycle with the opposite polarity

The flux is carried to the poles by two processes:

1. random-walk diffusion process caused by super-granulation convection currents in the solar outer layers (according to the original Babkock-Leighton mechanism)



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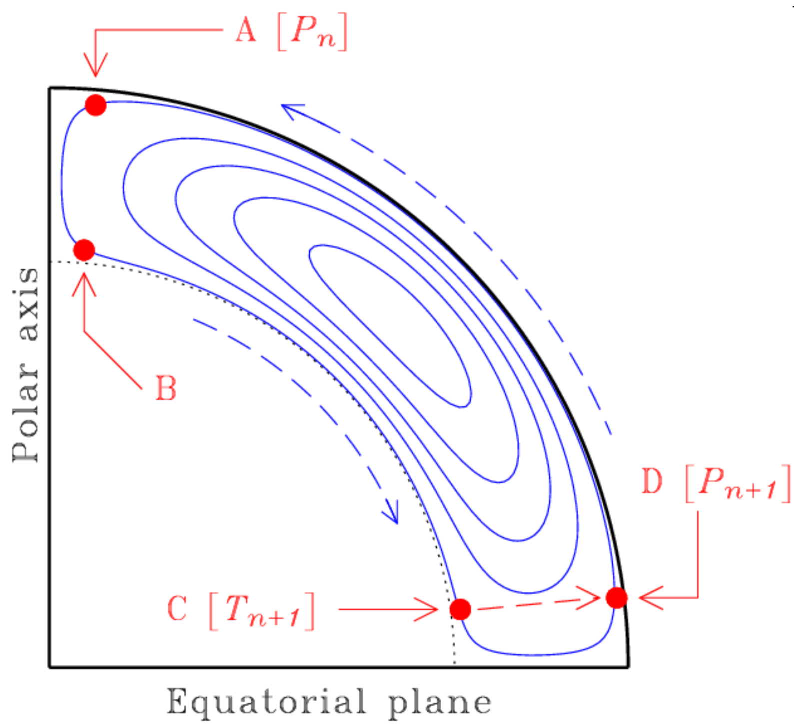


2. Large-scale meridional circulation

(Wang et al., 1991)

- carries the remnants of sunspot groups to the pole
- there the flux accumulates
- sinks to the base of the convection zone
- and is carried by the counterflow there back to sunspot latitudes to emerge as sunspots of the next cycle

Two time-scales

- advection time-scale $\tau_{adv\_surf} = L_{surf}/V_{surf}$
- diffusion time-scale $\tau_{dif\_surf} = L_{surf}^2/\eta_{surf}$

L_{surf} - distance from sunspot latitudes to the poles

η_{surf} - diffusivity in the upper part of the solar convection zone

V_{surf} - speed of the surface poleward circulation

Dependence of the poloidal field during the next sunspot minimum on the time for which the flux reaches the poles:

- If $\tau_{adv\_surf} < \tau_{dif\_surf}$

  the meridional circulation carries the flux to the poles before it can reach there by supergranular diffusion

  shorter time (= faster Vsurf) = less time for diffusion across the equator = more uncanceled flux = weaker polar field

- If $\tau_{dif\_surf} < \tau_{adv\_surf}$

  a significant part of the poloidal field radially diffuses (or is pumped) down before it can converge at the pole under the action of the meridional circulation; only a small part of the trailing polarity flux reaches high latitudes before being diffused

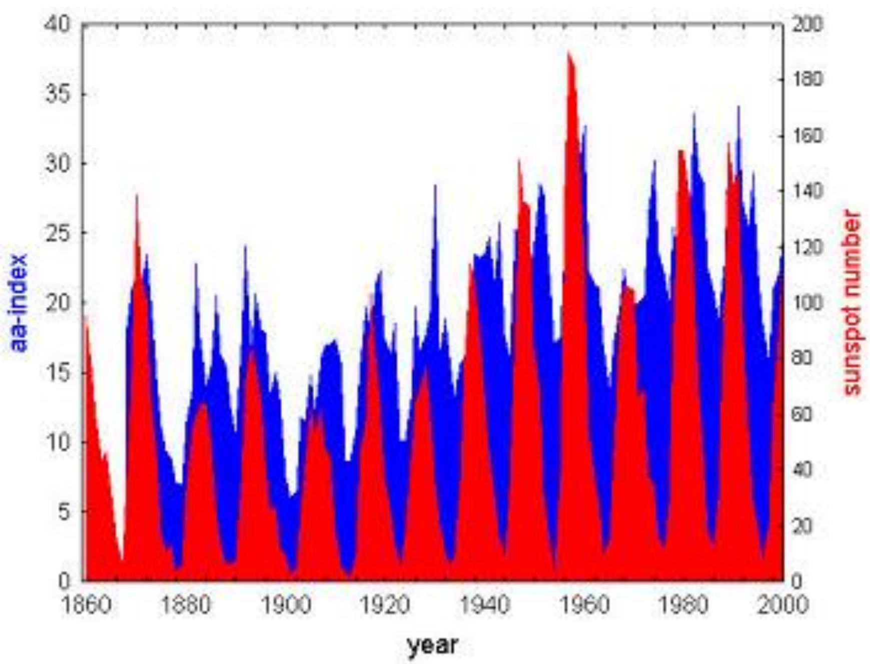
  shorter time = less time for diffusive decay = stronger polar field

What is the time for which the flux reaches the poles? Estimation from geomagnetic data

Double-peaked cycle of geomagnetic activity:

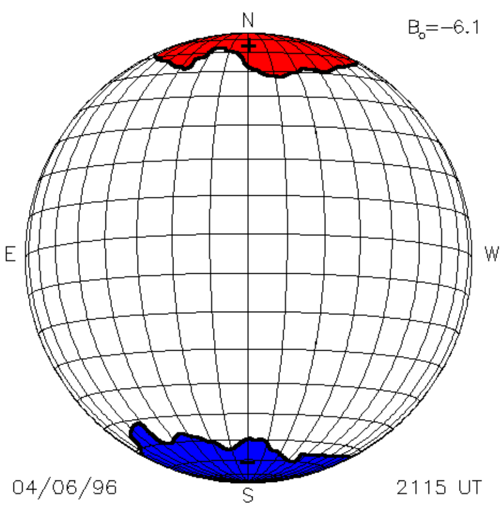
one peak in sunspot max,

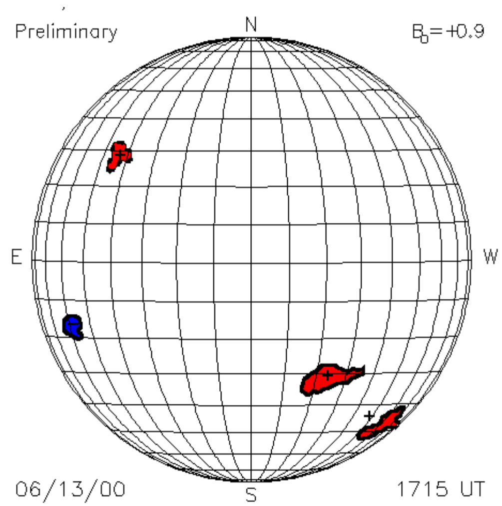
the second one on the sunspot decline phase

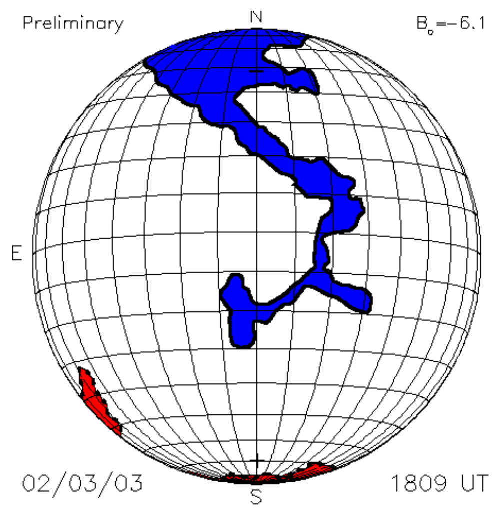


- Sunspot max peak – max in sporadic solar activity (coronal mass ejections)
- Sunspot decline phase peak – max in recurrent solar activity (high speed solar wind from coronal holes)

What causes the geomagnetic activity maximum on the sunspot decline phase?







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

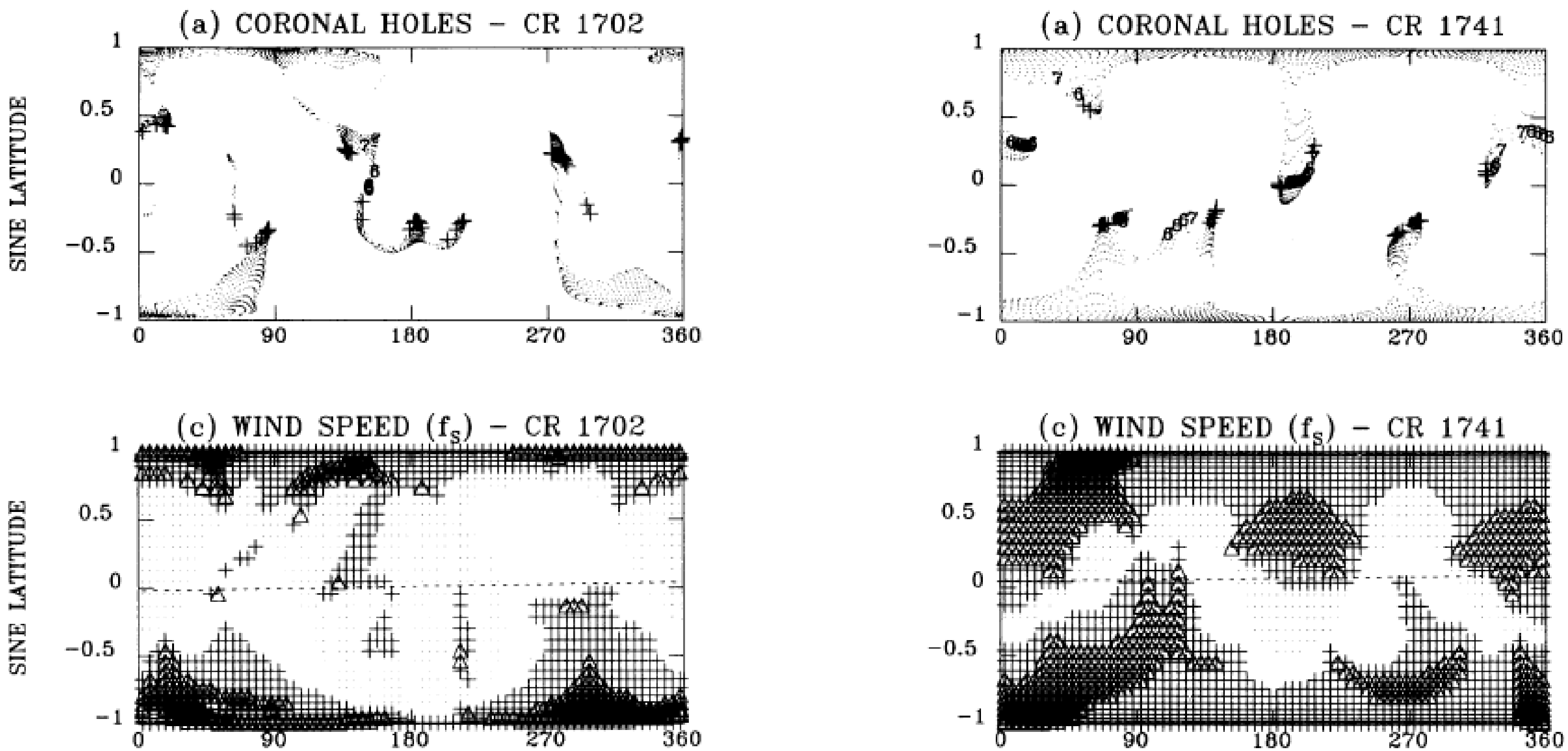
Sunspot max:
small scattered short-living coronal holes at all latitudes

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)

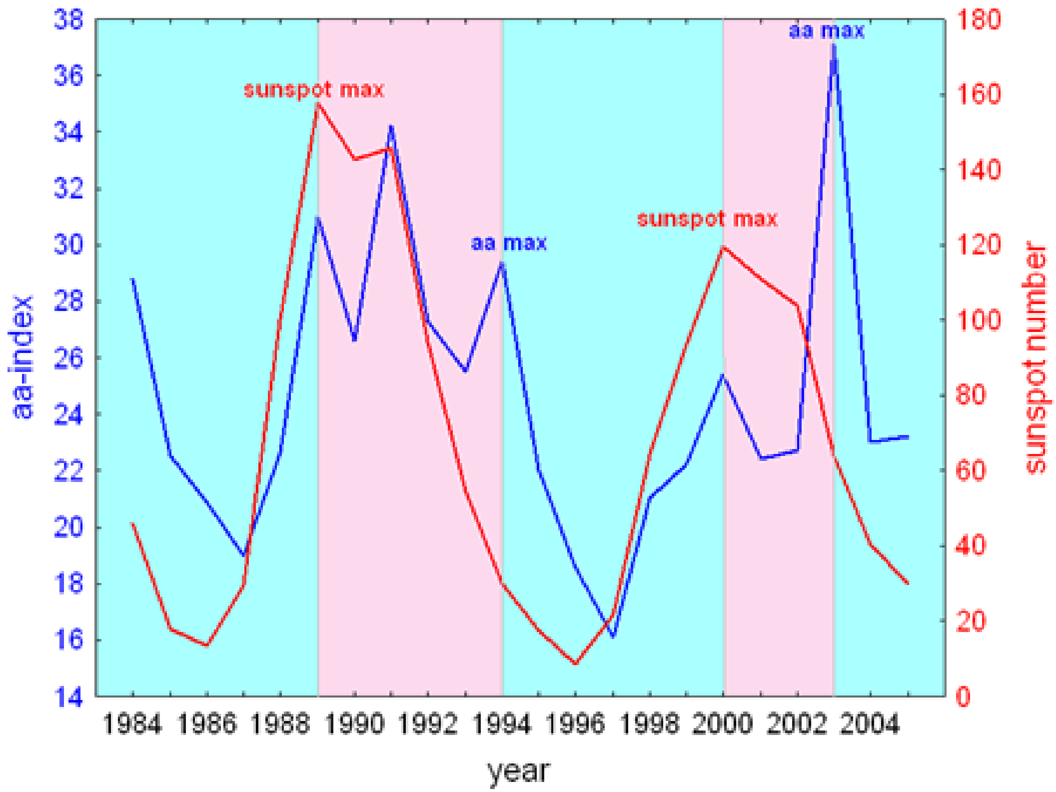
CH data compiled by K. Harvey and F. Recely using NSO KPVT observations under a grant from the NSF in the absence of polar coronal holes, small short-lived low latitude holes are formed with HSS at high heliolatitudes

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



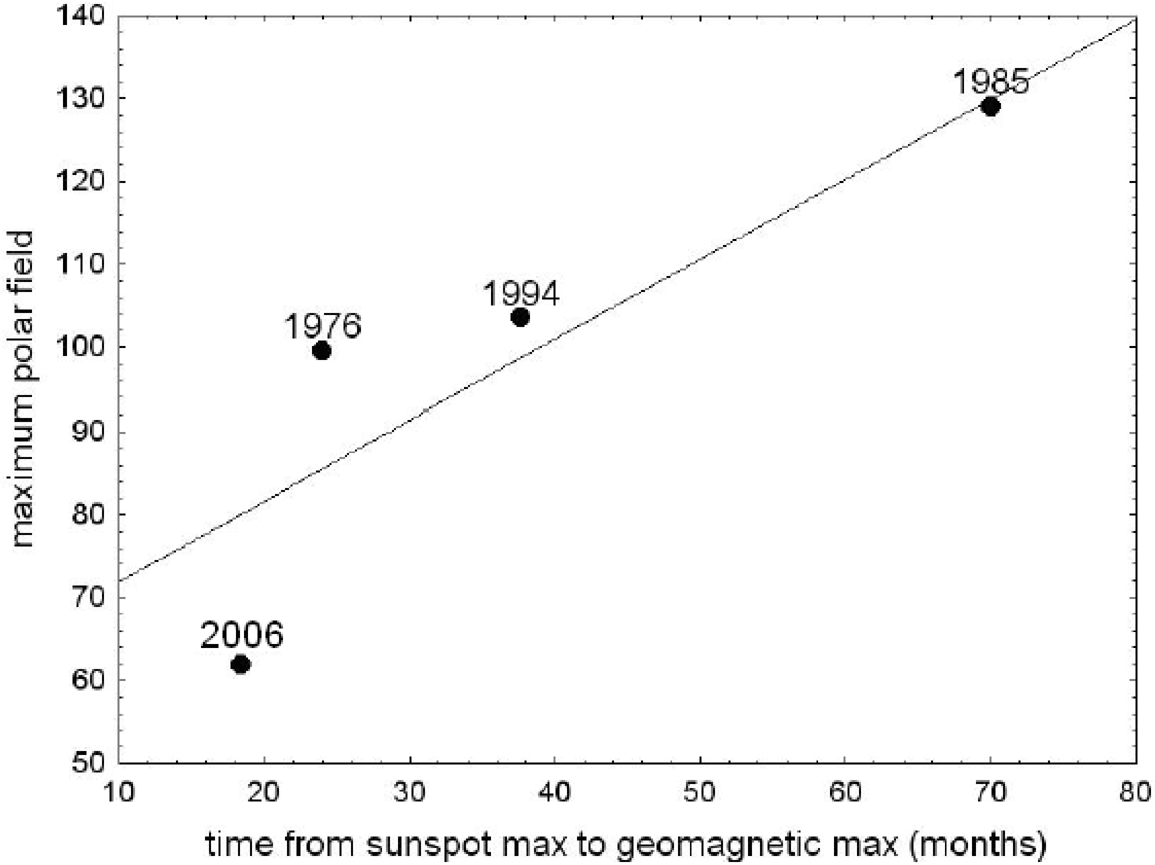
Wang and Sheeley, 1990

⇒ The time for the flow to reach from sunspot max latitudes to the poles



= the time from sunspot maximum to geomagnetic activity maximum

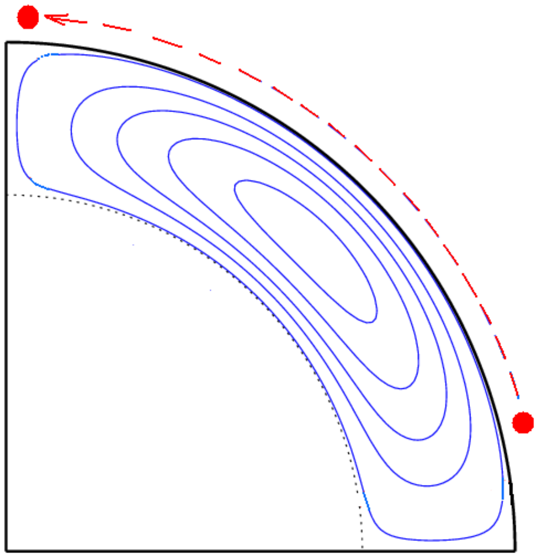
Shorter time for the flux to reach the pole = weaker polar field

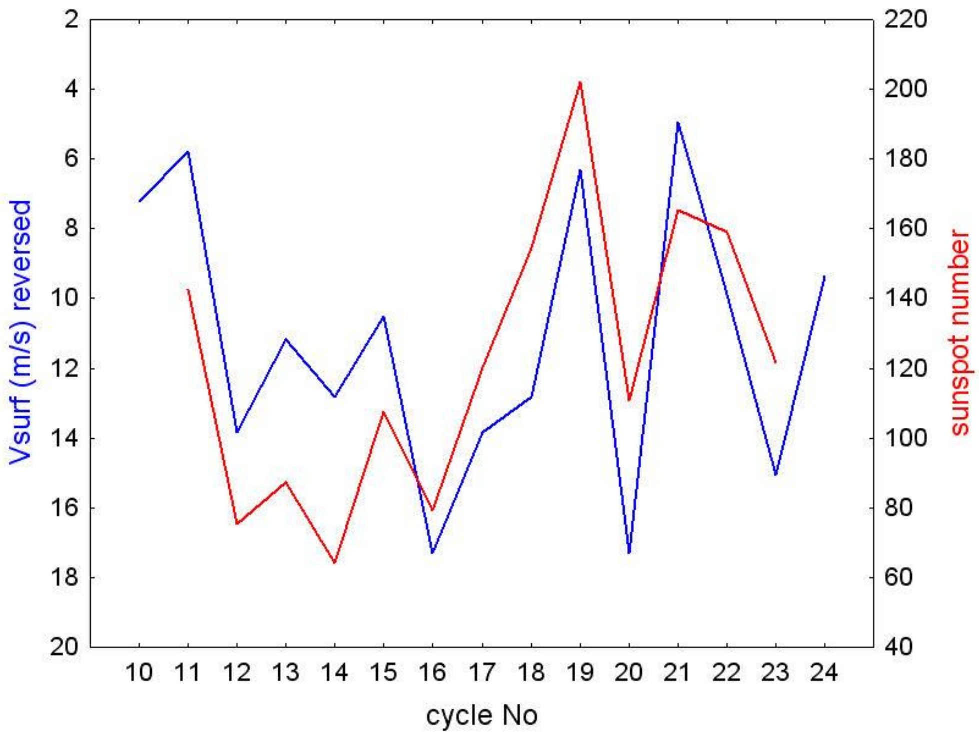


$\Rightarrow T_{adv\_surf} < T_{dif\_surf}$

The flux reaches the poles mainly carried by the poleward meridional circulation

From the time for the flux to reach the poles we can calculate the speed of the surface meridional circulation

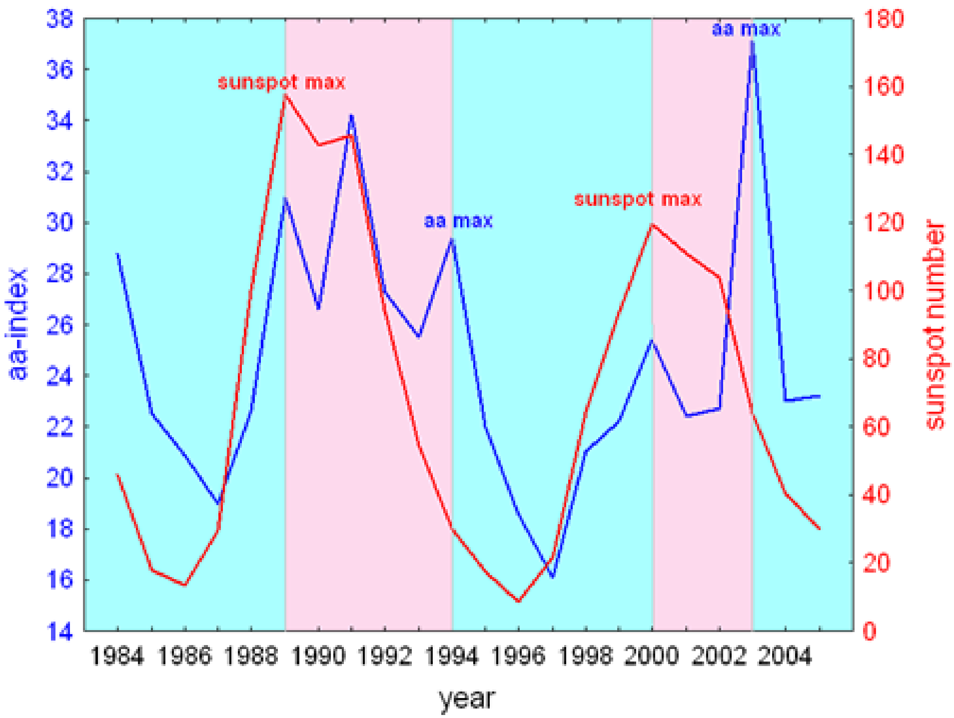




Strong dependence of the sunspot max on the preceding surface poleward circulation (r=-0.7, p=0.03)

Faster poleward circulation ⇒ weaker polar field ⇒ lower sunspot max of the next cycle

Time from the geomagnetic activity maximum to the 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)

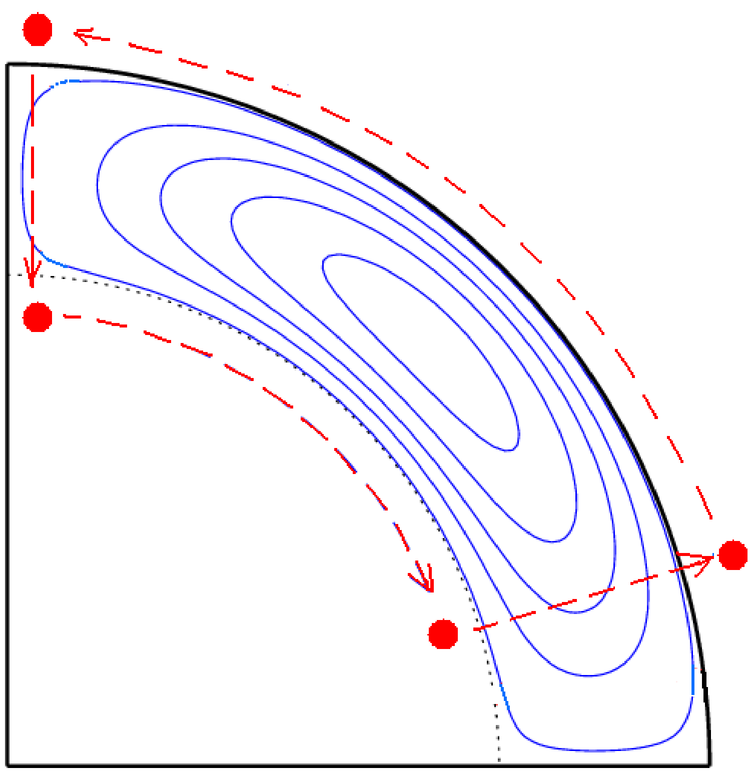
If the diffusivity is very low

all of the flux makes a full circle

Fully advection-dominated regime

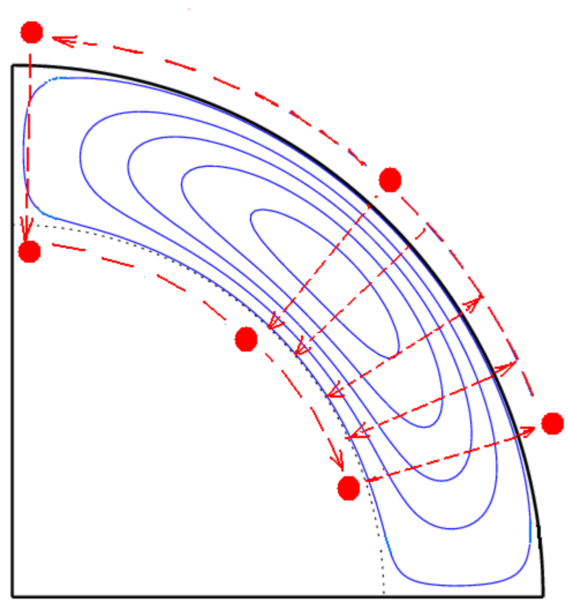
$\eta \sim 10^7\ m^2/s$

Jiang, Chatterjee, Choudhuri (2007)



If the diffusivity is intermediate

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



$\eta \sim 1\text{-}2.10^8$ m²/s

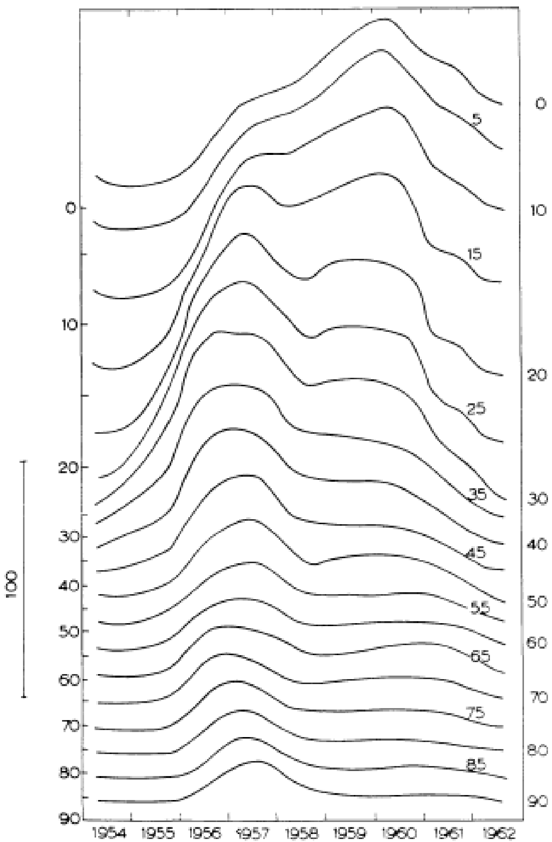
$\Rightarrow$the sunspot cycle will be a superposition of the two surges of the toroidal field

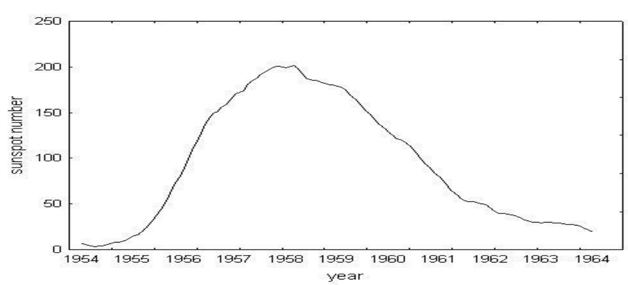
$\Rightarrow$double-peaked sunspot max

Jiang, Chatterjee, Choudhuri (2007)

Gnevyshev (1963, 1965, 1967)

Sunspot cycle 19





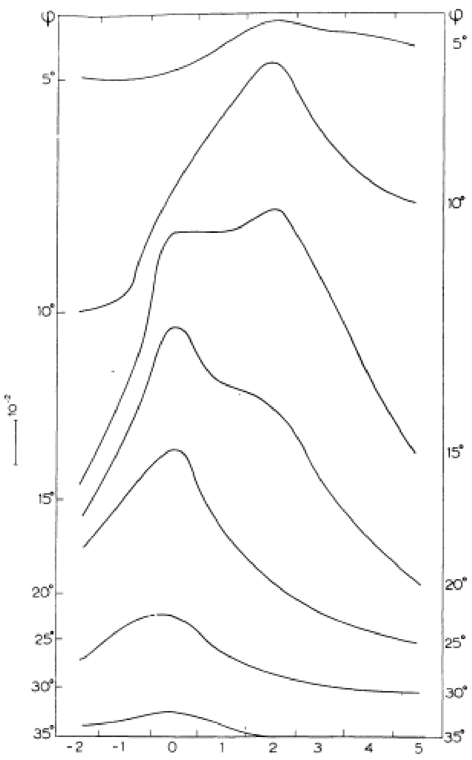
The 11-year cycle does not contain one but two waves of activity with different physical properties

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

The second maximum is only observed at low latitudes, but below 15º 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

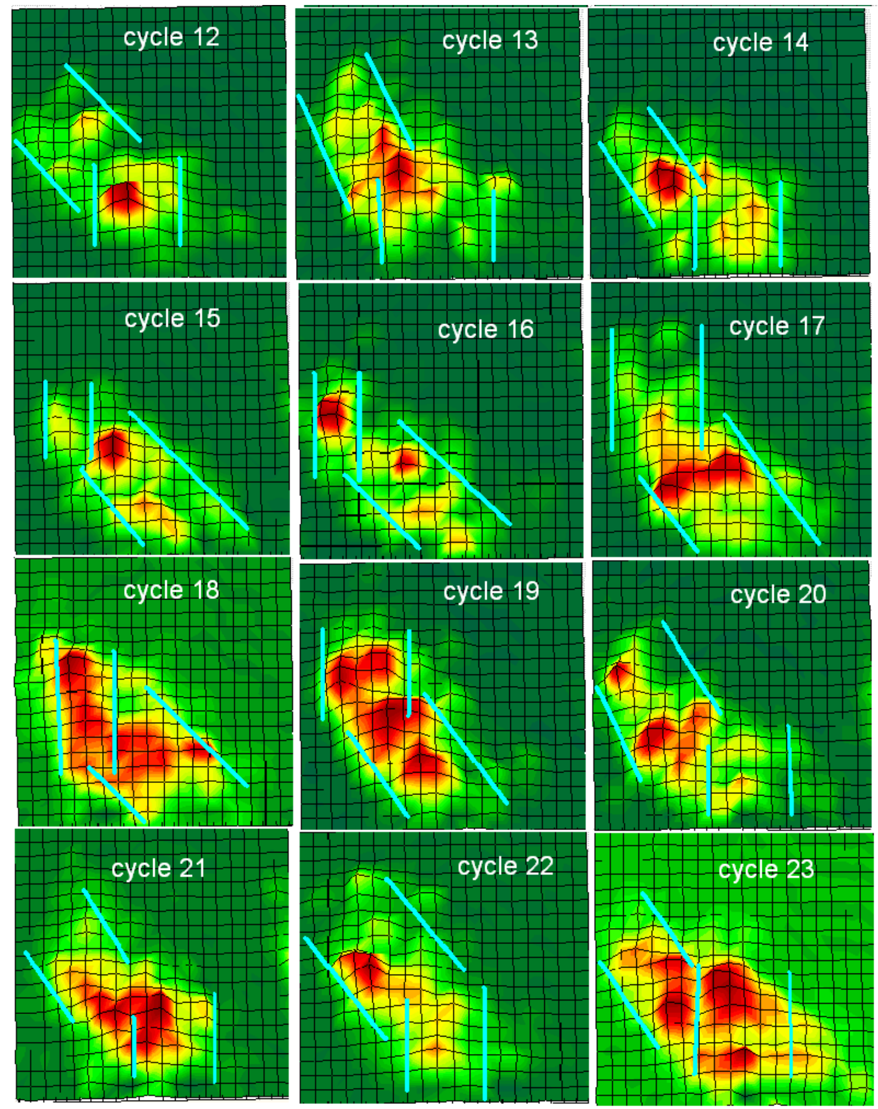
Varying timing between them:

- if big enough ⇒ 2 peaks seen
- if small ⇒ 1 peak in lat averaged data

two maxima in all cycles from 12 to 23

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

Georgieva (2011)



$\Rightarrow$ Intermediate diffusivity: a part of the flux short-circuits the meridional circulation, another part makes a full circle

- From the time between geomagnetic activity max and the advection-generated sunspot max we can calculate the speed of the deep circulation and the regime of operation of the dynamo in the lower part of the convection zone

- From the time between the geomagnetic activity max and the diffusion-generated peak we can estimate the diffusivity (~1-3.10^8 m^2/s)

Long-term variations in deep circulation and solar cycle amplitude

Two possible regimes in the base of the convection zone:

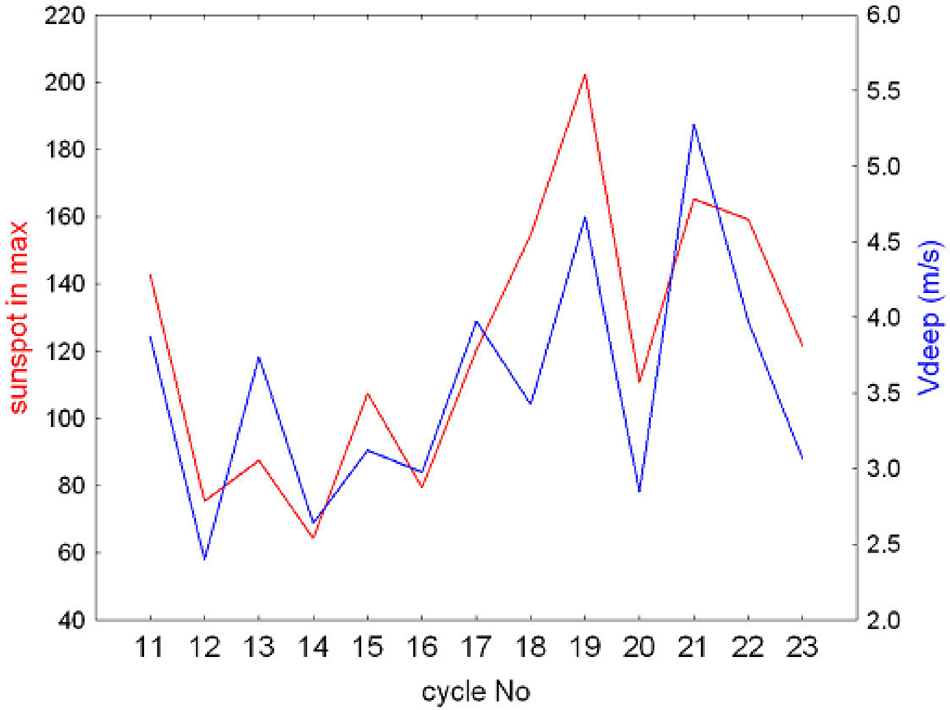
- Diffusion-dominated:

  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

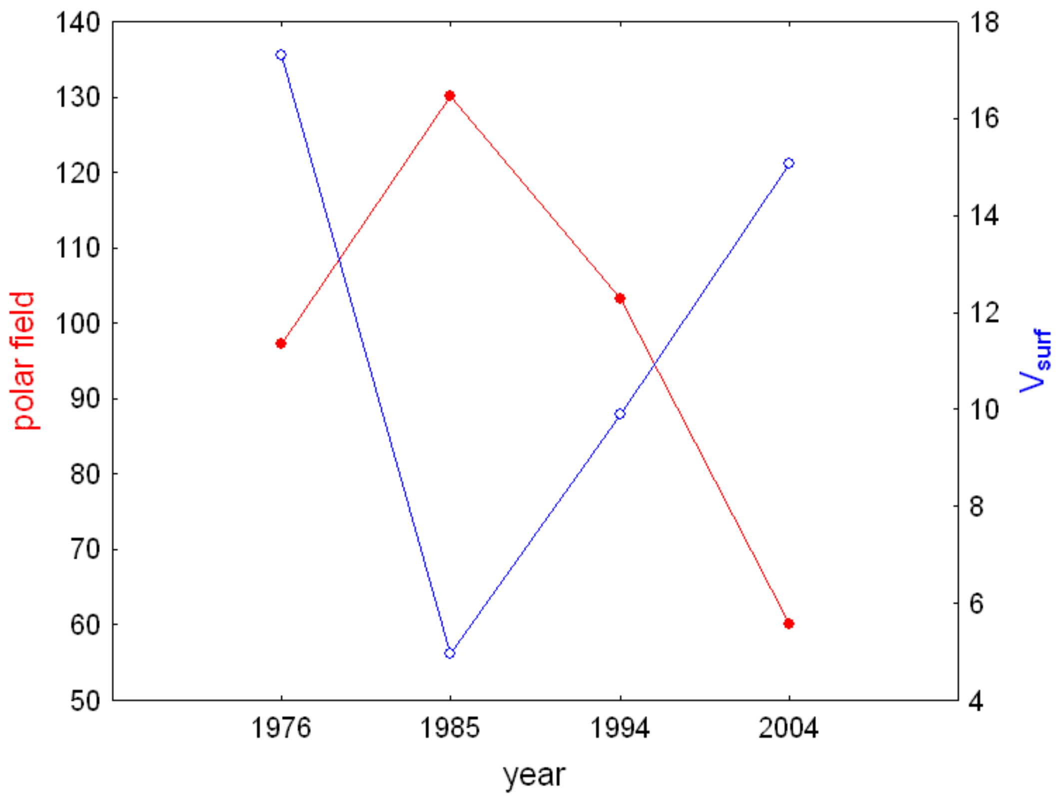
(Yeates, Nandy & Machay, 2008)



Positive correlation between the Vdeep and sunspot max

⇒ **diffusion-dominated regime**

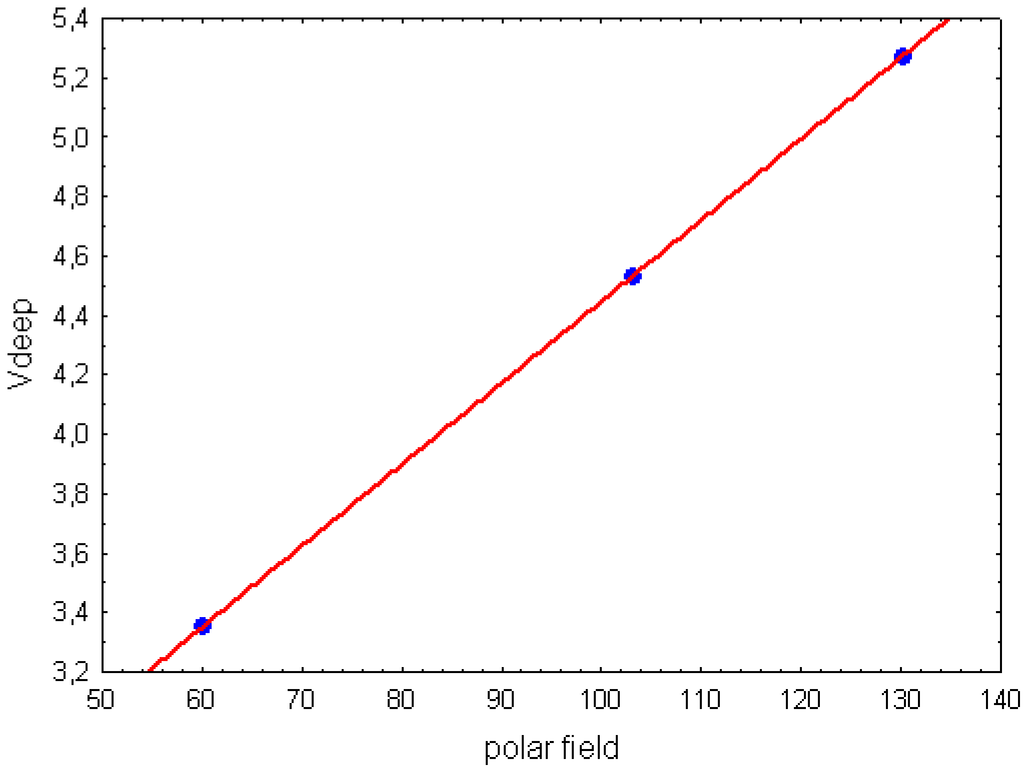
The sequence of relations



Good negative correlation of the polar field and the preceding surface poleward circulation (r=-0.76)

Faster poleward circulation
⇒ weaker polar field

The sequence of relations

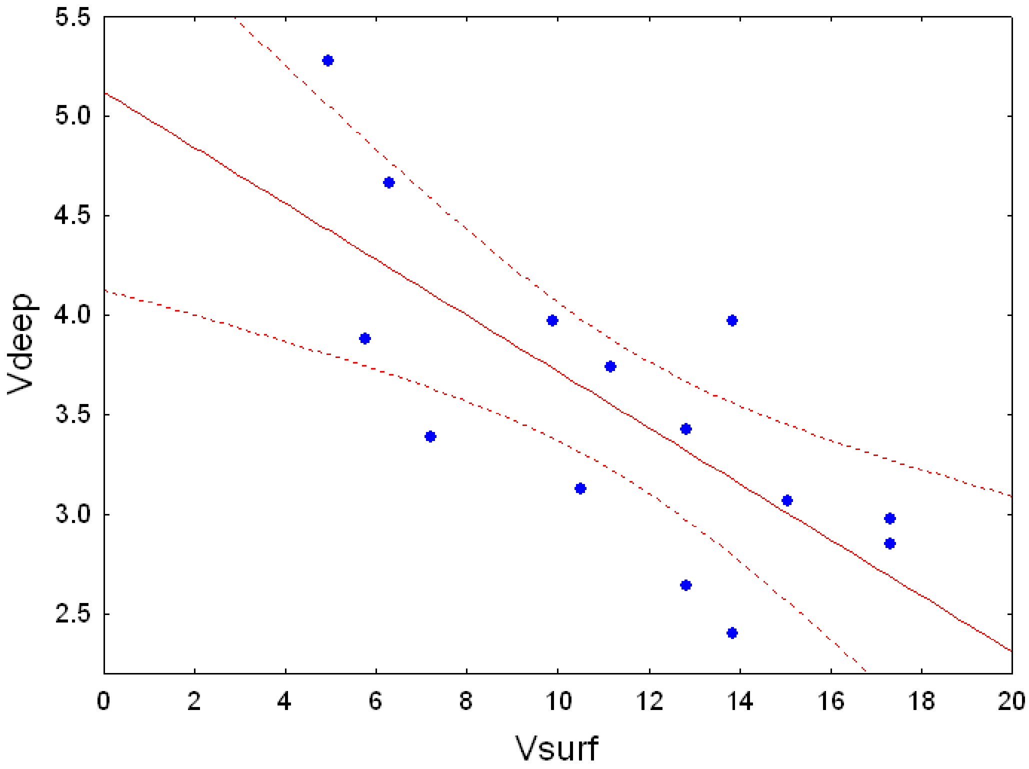


Good positive correlation of the speed of the deep equatorward circulation on the preceding polar field

Malkus and Proctor (1975) quenching of the flow by the Lonentz force produced by the magnetic field

Rempel et al. (2005) quenching of fields > 30 kG; weaker fields unaffected

The sequence of relations



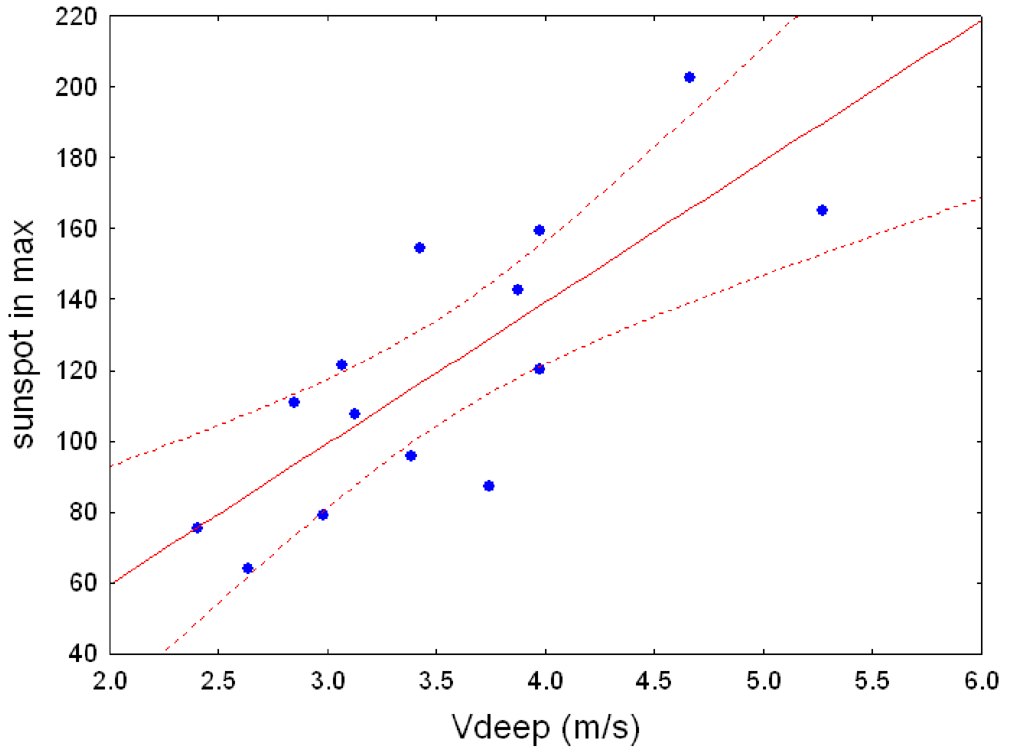
- Good negative correlation (r=-0.75) between Vsurf and the following Vdeep

Faster surface poleward circulation $\Rightarrow$ slower deep equatorward circulation

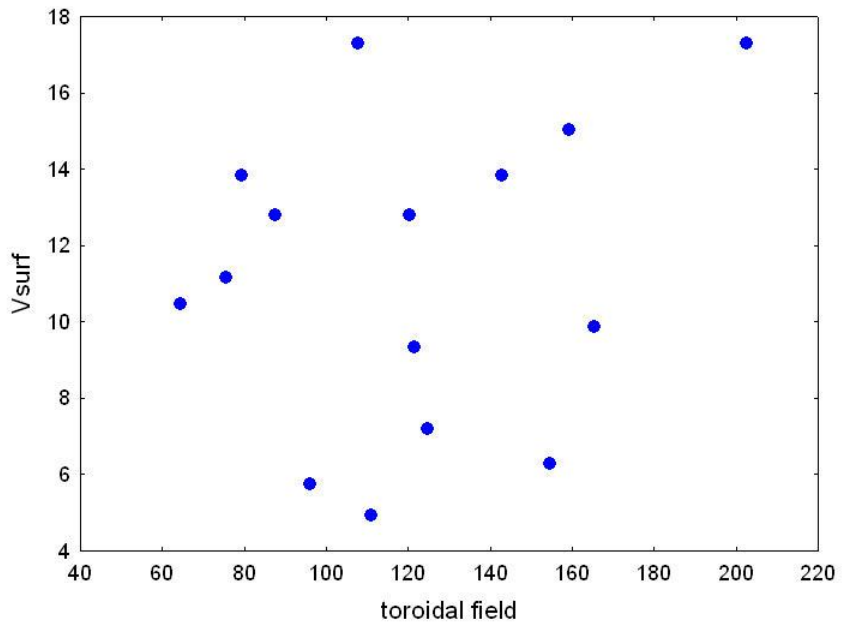
The sequence of relations

- Good positive correlation (r=0.81) between Vdeep and the following sunspot max

  Indication that solar dynamo operates in diffusion dominated regime



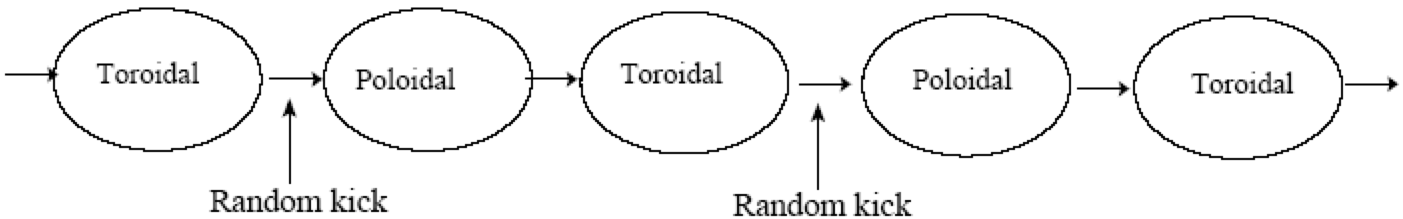
The sequence of relations



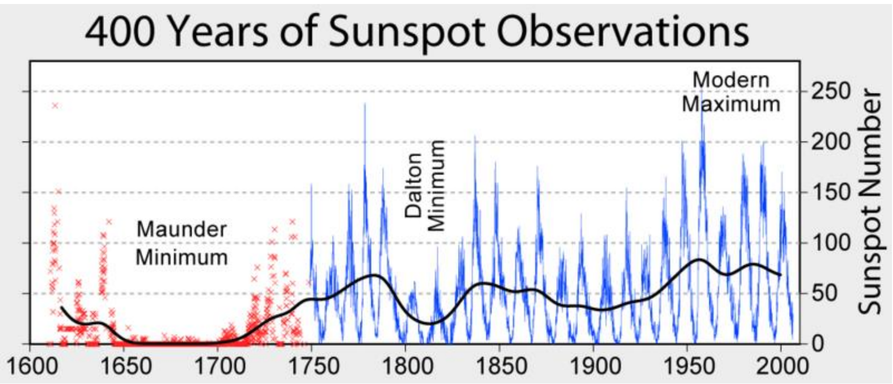
NO correlation between the sunspot max and the speed of the *following* surface poleward circulation Vdeep

The sequence of relations

- Vsurf ⇨ Bpol ⇨ Vdeep ⇨ Btor… and the chain breaks



Choudhuri (2011)



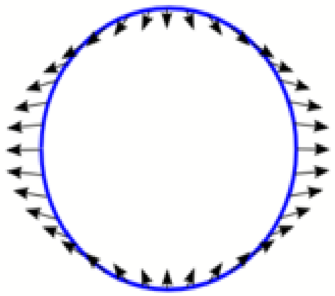
⇒ Vsurf is the factor which rules the amplitude of the sunspot cycle and through its influence on Vdeep, also the period of the sunspot cycle

What factor modulates Vsurf?

This dynamo mechanism works without any planets

What if the star has a planet?

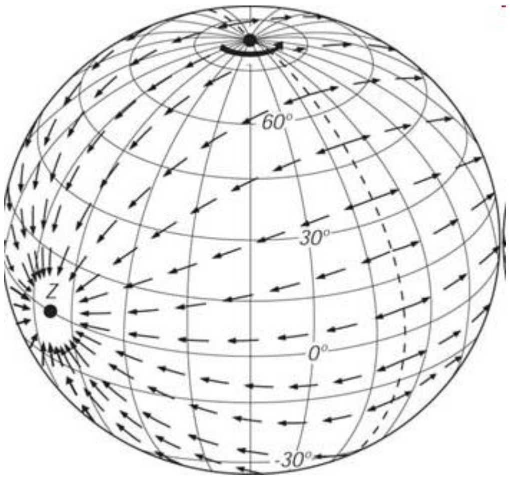
The simplest case: one planet on a circular orbit in the star's equatorial plane



In the case of the Sun, the elevation caused by all planets together is very small

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

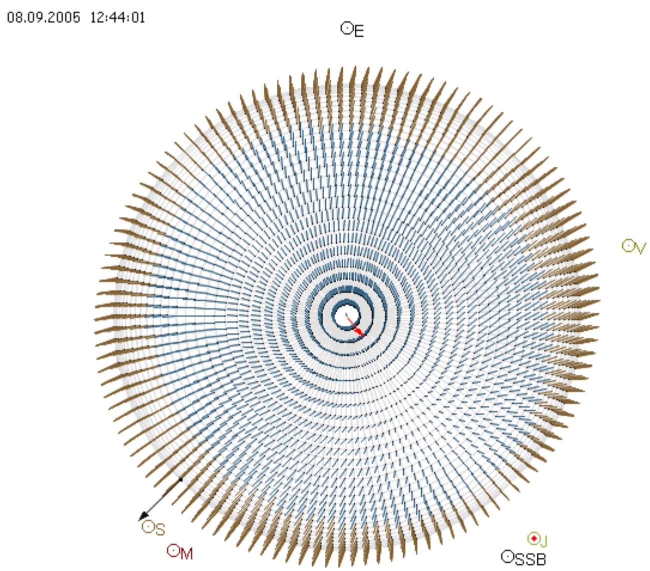
But we are interested in the horizontal, not in the vertical component of the tidal force

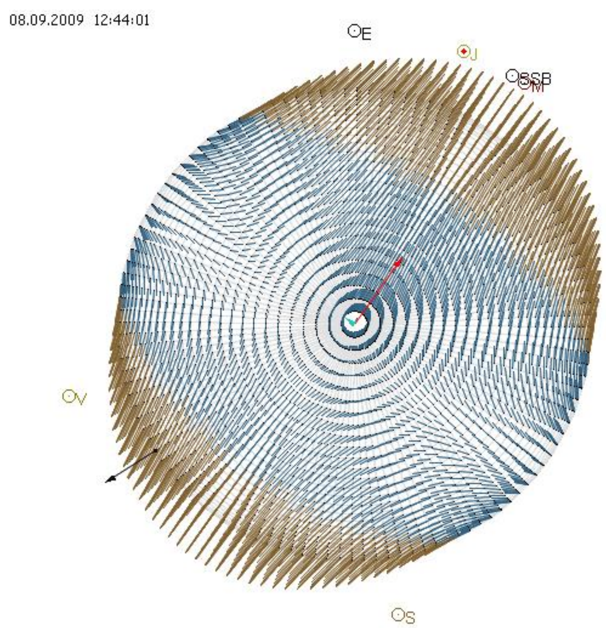


For one only planet, all vectors directed to the planet's subpoint

the case of the Sun with a number of planets

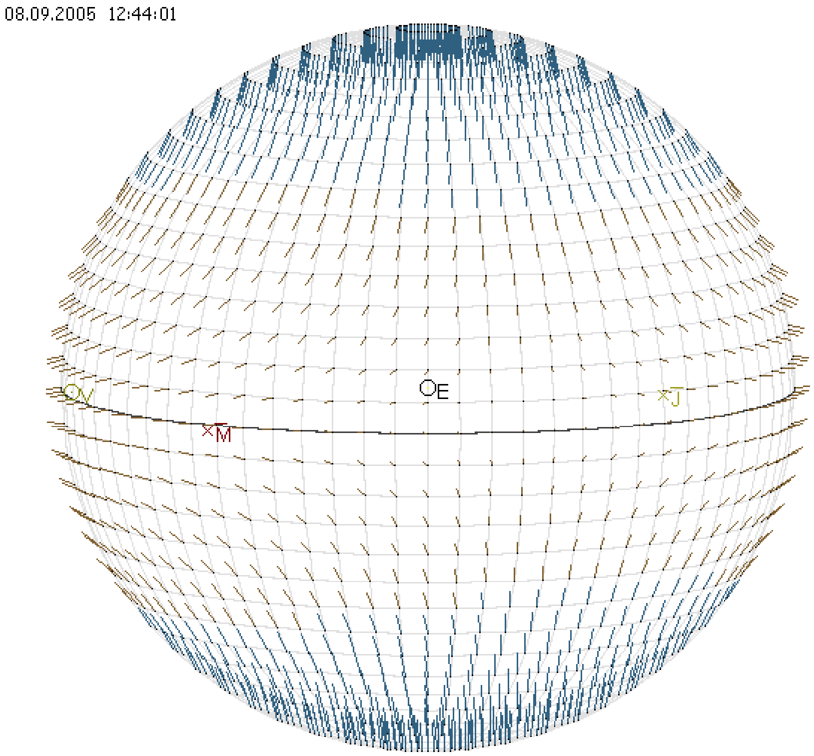
The tidal forces depend on the distance and relative positions of the major tide-creating planets (Jupiter, Earth, Venus, Mercury) which change with time

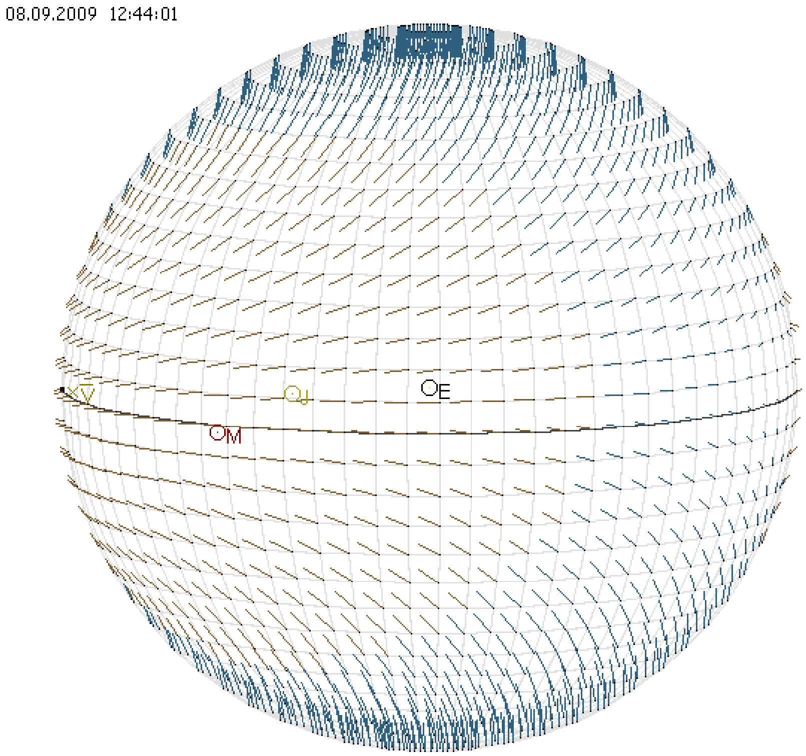




view from the pole (elevation)

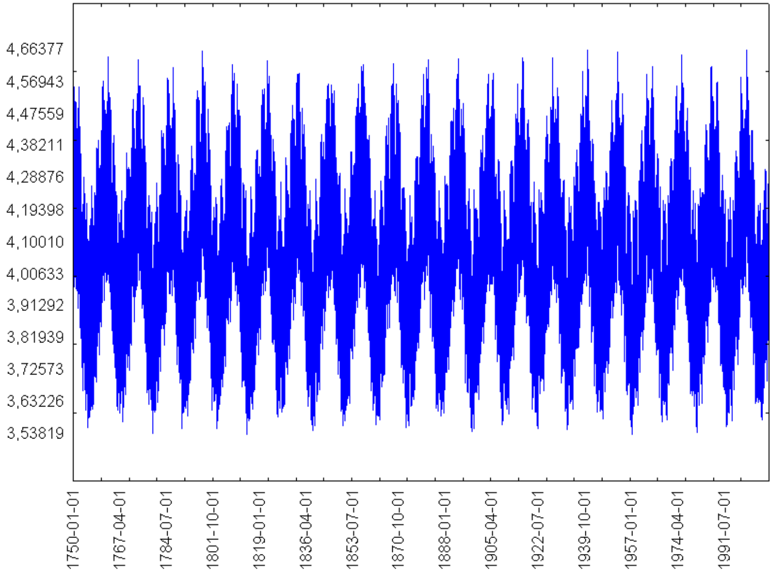
Tidal acceleration in the horizontal plane

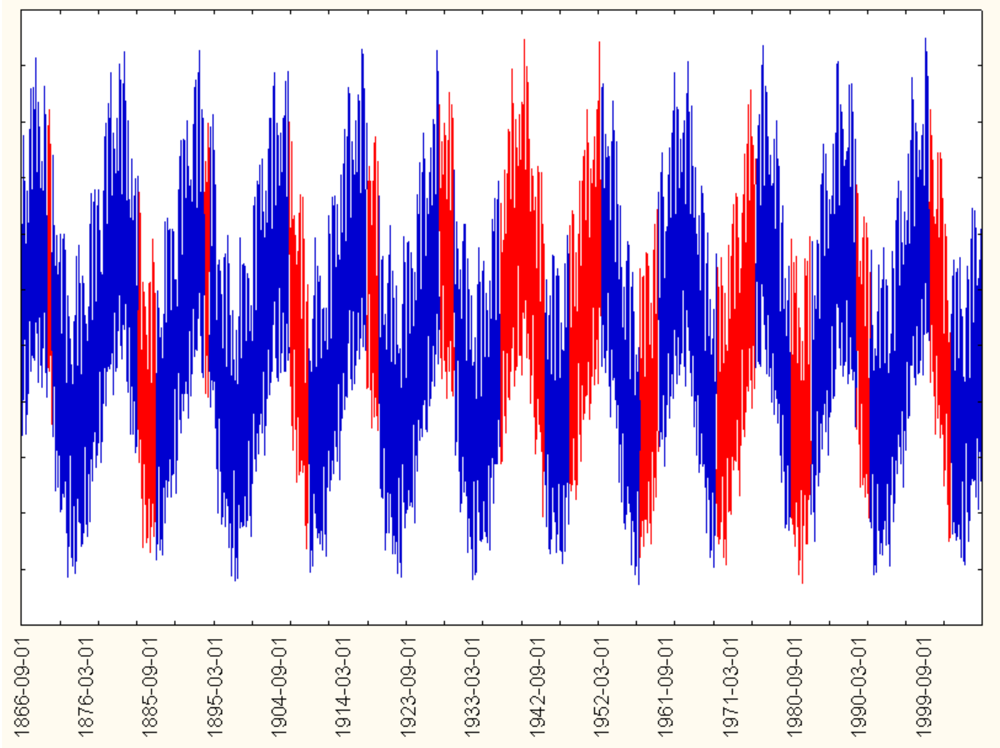


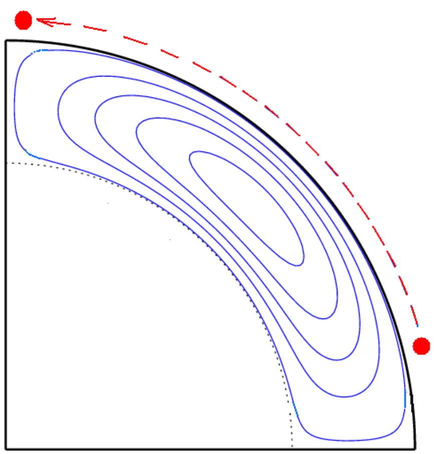


Meridional acceleration can change the meridional circulation
speed ~ 10 m/s

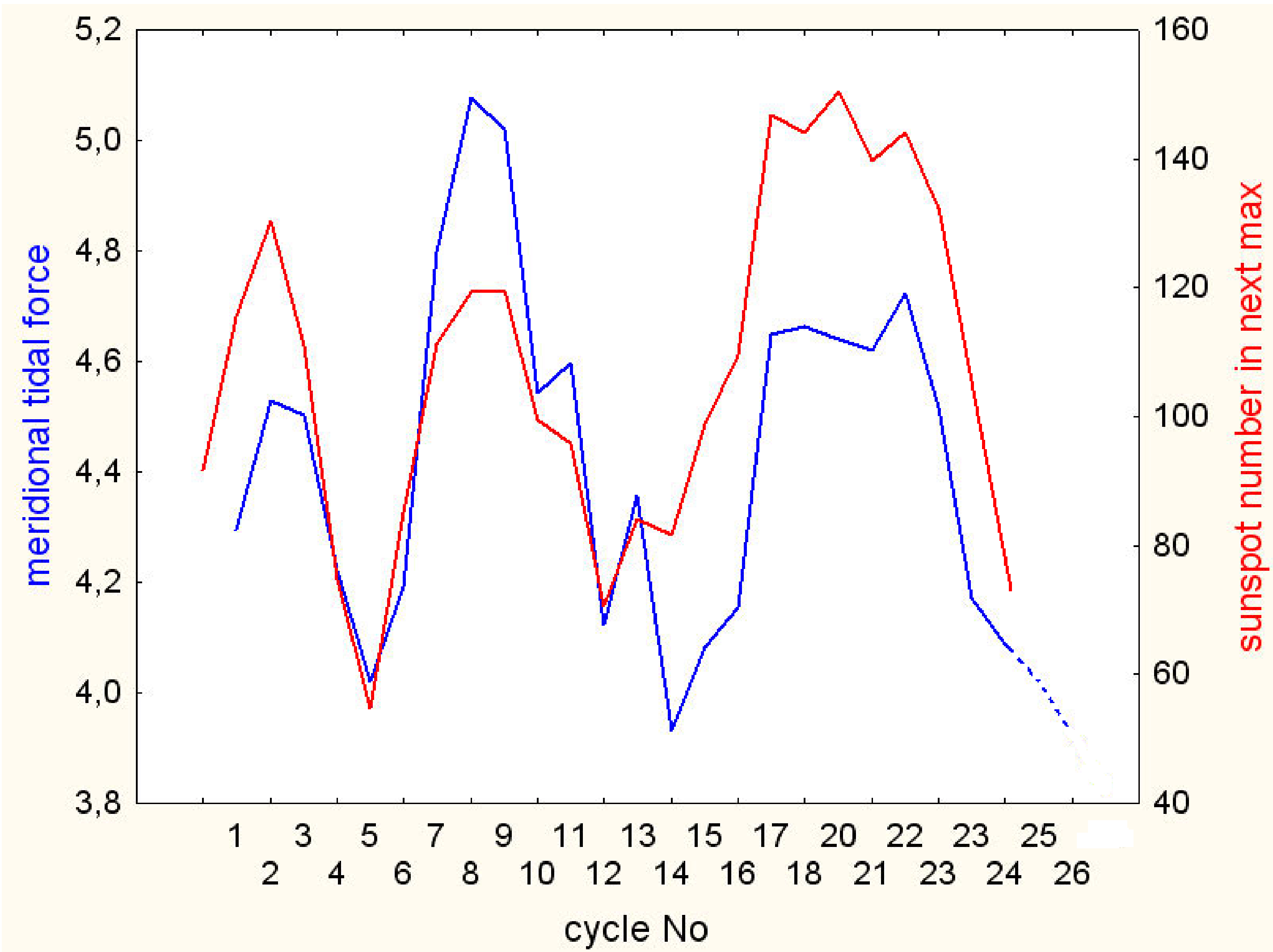
The average tidal force is important in the period when the surface meridional circulation carries the flux to the poles







Long-term variations



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