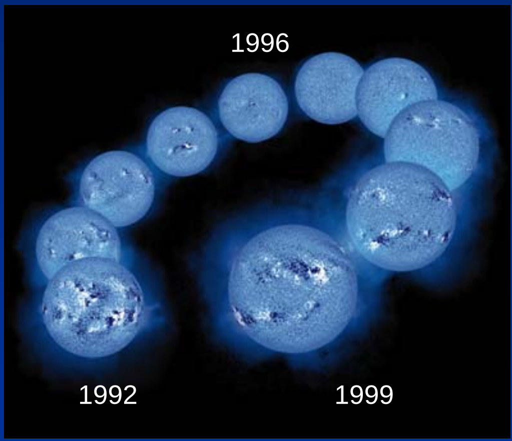
# Origin of solar magnetic variability

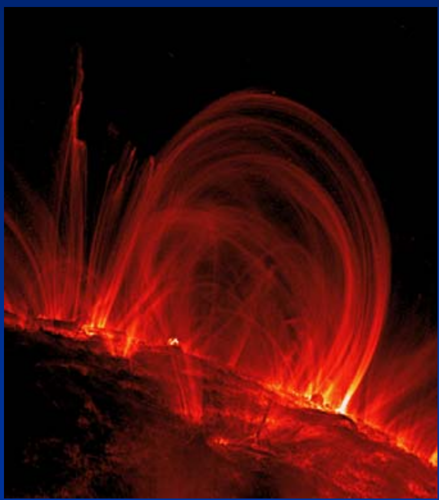
**Dieter Schmitt**

Max Planck Institute for
Solar System Research
Katlenburg-Lindau
Germany

Monte Porzio Catone
27 June – 1 July 2005



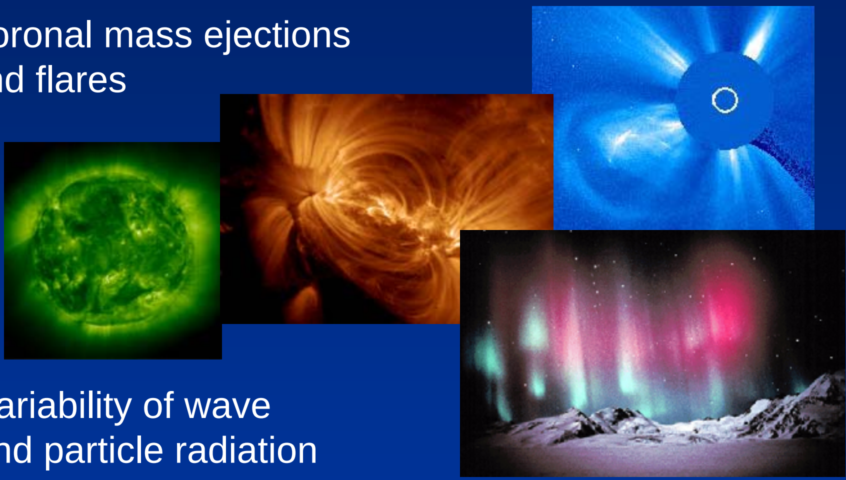

# The solar magnetic field ...



- is responsible for the various phenomena of ‘solar activity’
- is generated by a dynamo process driven by convection and rotation
- varies on many timescales
- is the driver and source of energy release in CMEs and flares

## Consequences of magnetic variability

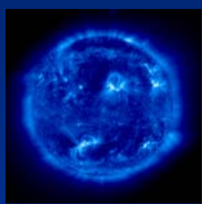
- Coronal mass ejections and flares



- Variability of wave and particle radiation

➡ Space weather and space climate

## Consequences of magnetic variability



- Irradiance variability
- UV, X-ray and particle radiation variability

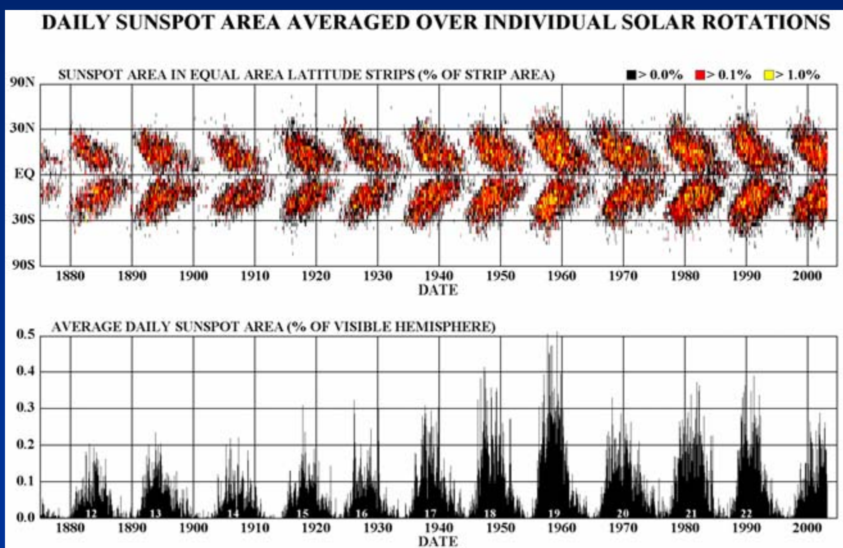
- Variability of galactic cosmic rays

➡ Effect on Earth's climate

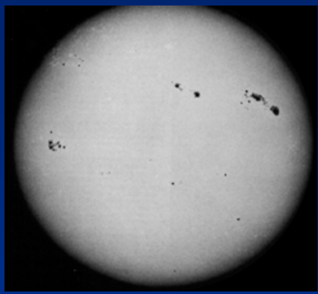
# Time scales of magnetic variability

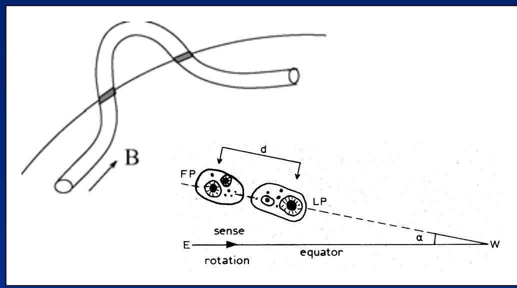
| Time scale | Phenomenon |
|---|---|
| • minutes ... days | • magneto-convection |
| • days ... months | • active region evolution |
| • months ... years | • global flux transport |
| • years ... decades | • 11-year solar cycle |
| • decades ... centuries | • modulation, grand minima |
| • ... and beyond | • ??? |

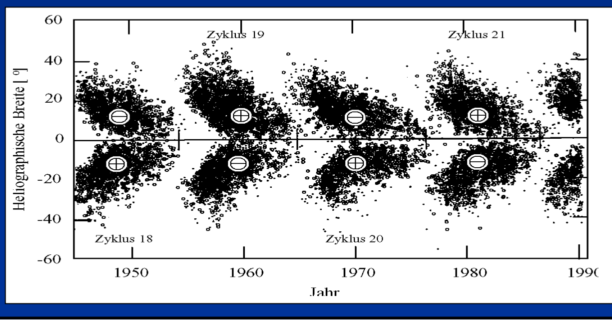
# Solar cycle



# Bipolar regions and polarity laws

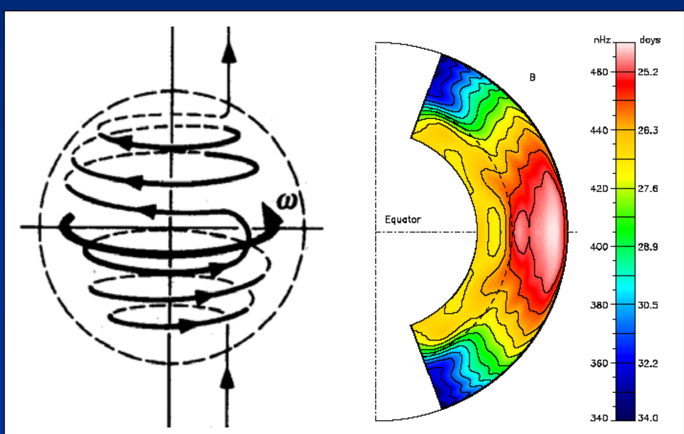




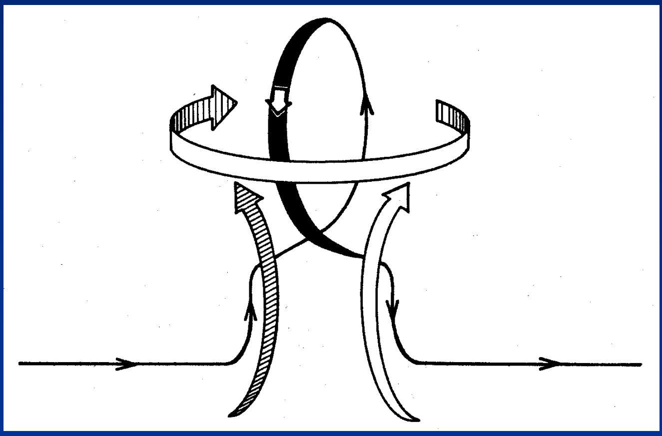

# Dynamo processes I

- Differential rotation

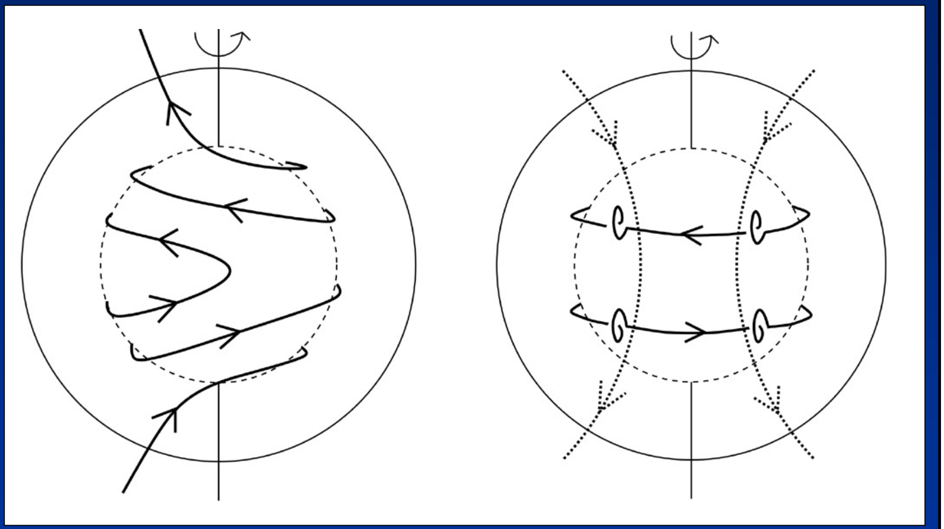


# Dynamo processes II

- Helical motion (convection, hydromagnetic instabilities)



# Solar dynamo

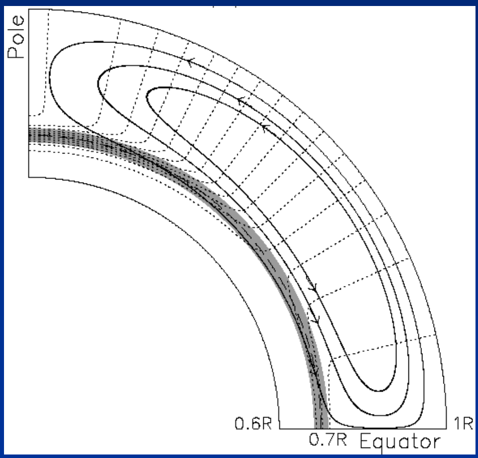


Differential rotation

Helical convection

# Dynamo processes III

- Meridional circulation



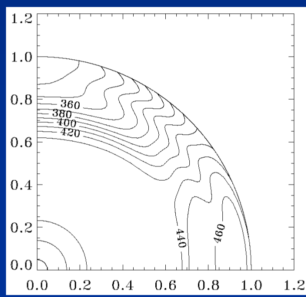

# Dynamo models

- Convection zone dynamos
- Overshoot layer dynamos
- Interface dynamos
- Flux transport dynamos

# Difficulties of convection zone dynamos

- Intermittency: B´ >> <B>
- Polarity rules: B ~ 10^5 G
- Magnetic buoyancy and storage problem:

  rise time << cycle length
- Rotation law:




# Overshoot layer dynamos

**Advantages:**

storage, reduced diffusivity, rotation, dynamic $\alpha$-effect due to hydromagnetic instabilities

**Disadvantages:**

many overlapping wings, parity selection,
$d\Omega/dr$ largest near poles:

- $\alpha$ concentrated near equator
- equatorward flux transport

(Schmitt 1993, Rüdiger and Brandenburg 1995, Dikpati and Gilman 2001)

# Interface dynamos

Parker (1993), Charbonneau and MacGregor (1997), Zhang et al. (2004)

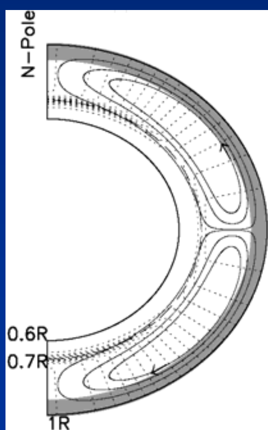
Dynamo on interface between

convection zone:
$\eta$ large, $\alpha$

overshoot layer:
$\eta$ small, $d\Omega/dr$, most flux

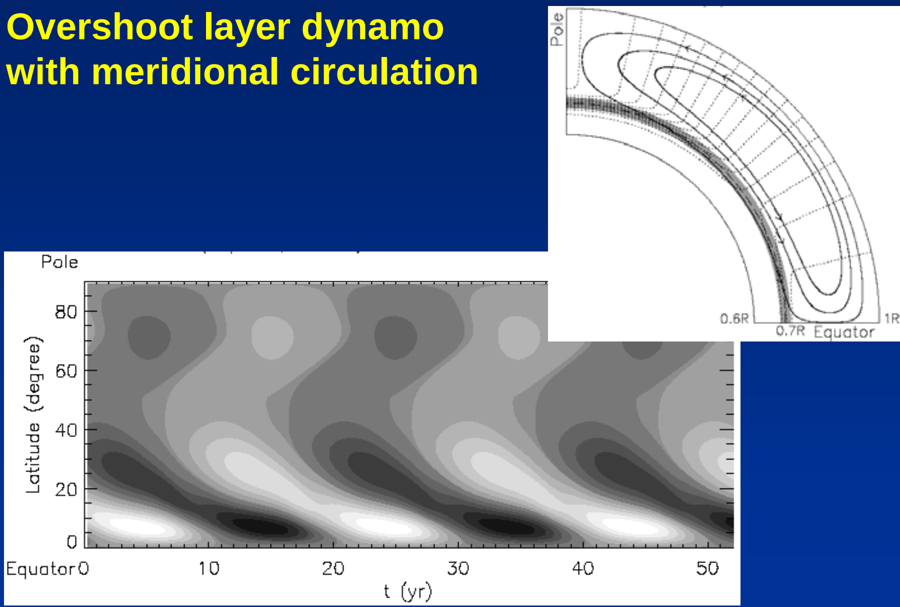
# Flux transport dynamos

- regeneration of poloidal field through tilt of decaying bipolar active regions
- rotational shear in tachocline
- transport of magnetic flux by meridional circulation




Durney (1995), Choudhuri et al. (1995),
Dikpati and Charbonneau (1999)

## Overshoot layer dynamo with meridional circulation

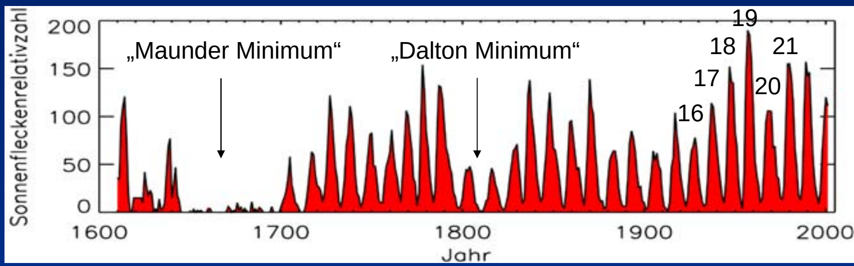


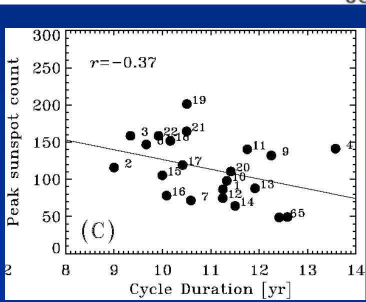

Dikpati and Gilman (2001)

# Long-term variations and grand minima

- Observations
- Modulation of differential rotation
- Stochastic fluctuations of the $\alpha$-effect
- Variation of meridional circulation
- On-off intermittency

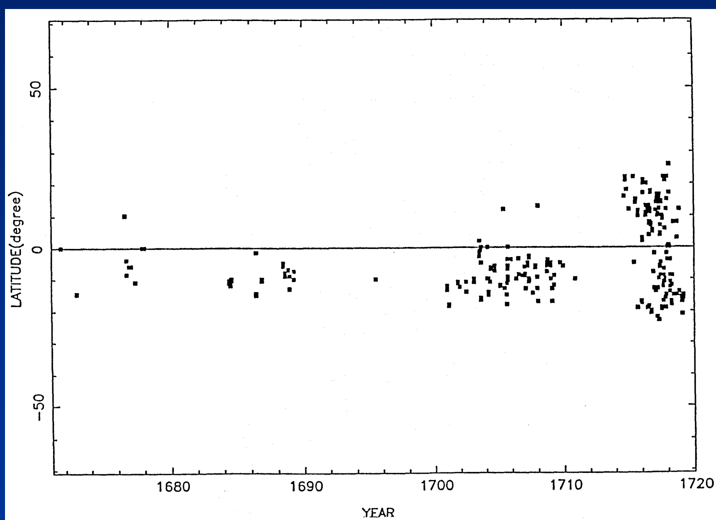
# Cycle length and strength




odd-even effect
(Gnevychev-Ohl)

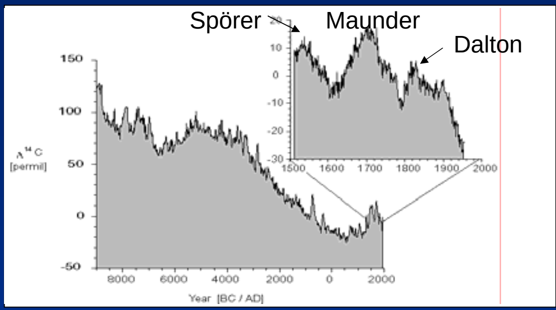
# Maunder Minimum



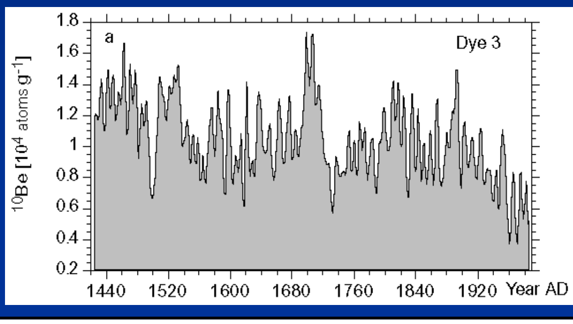

Oscillatory? Asymmetric?

Ribes and Nesme-Ribes (1993)

# Cosmogenic isotopes C14 and Be10

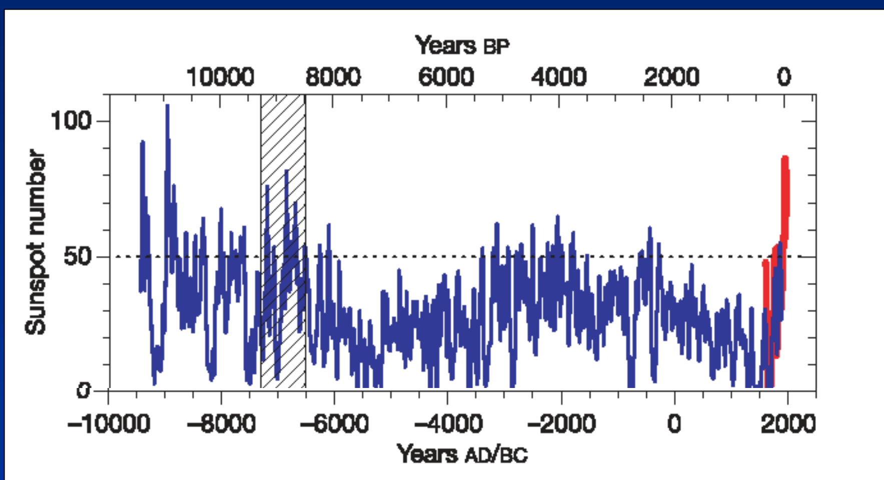



Stuiver et al. (1998)



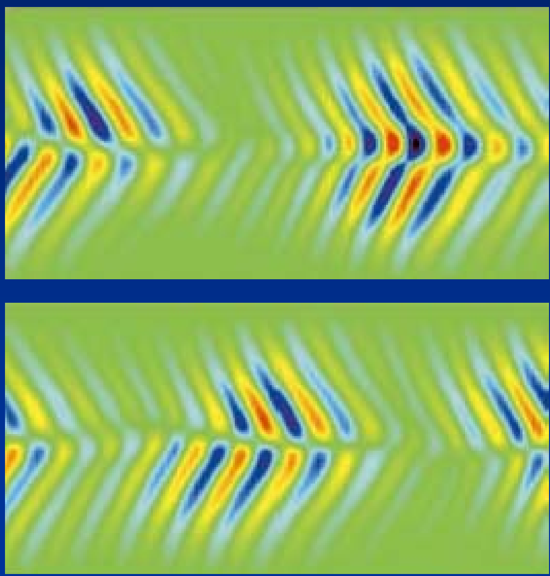

Beer et al. (1994)

# Solar activity in the last 11400 years



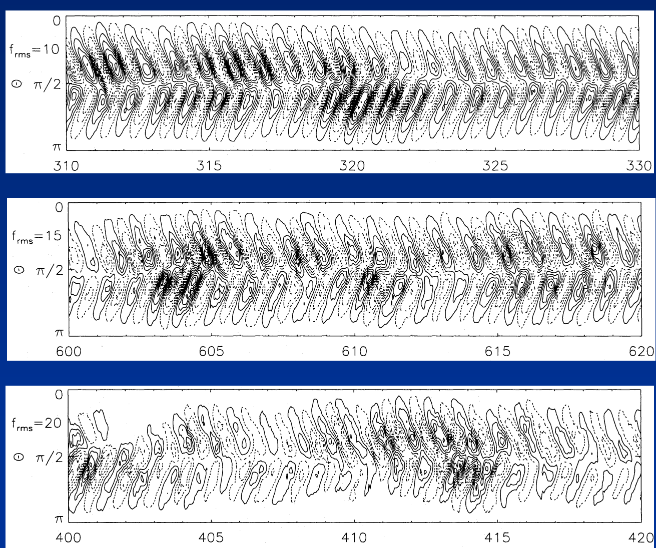

Solanki et al. (2004)

## Modulation of differential rotation



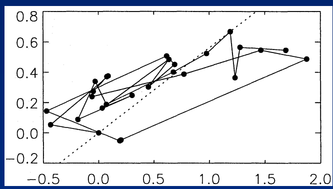
Weiss and Tobias (2000)

## Stochastic fluctuations of the $\alpha$-effect

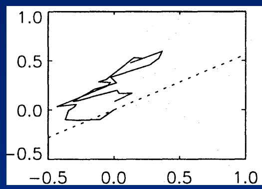



Ossendrijver, Hoyng, Schmitt (1996)

## log Amplitude vs Phase shift

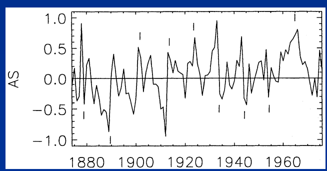



Sun

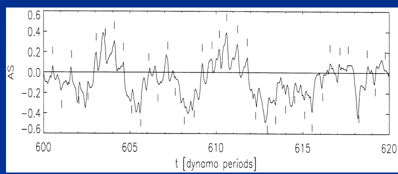



Model

## Asymmetry

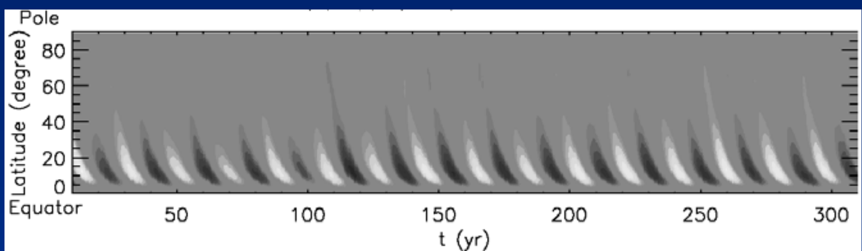


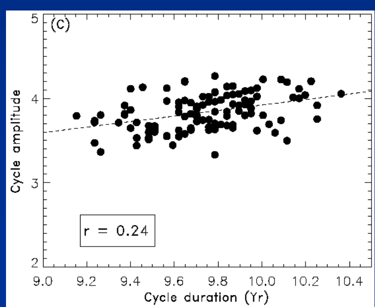

Sun




Model

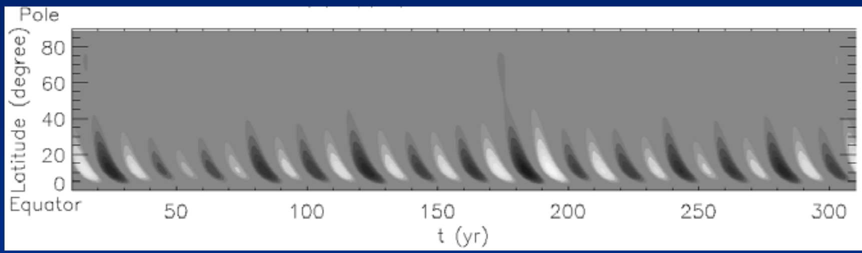
# Variation of meridional circulation

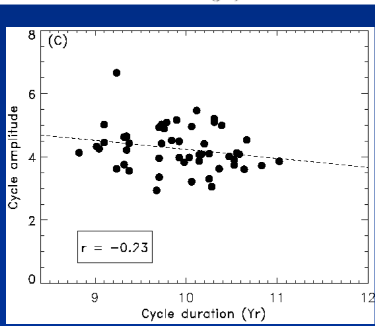



Charbonneau and Dikpati (2000)

# Variation of $\alpha$-effect

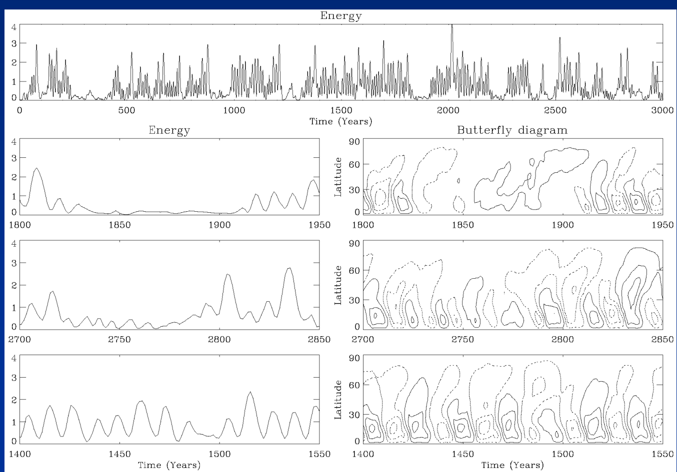



Charbonneau and Dikpati (2000)

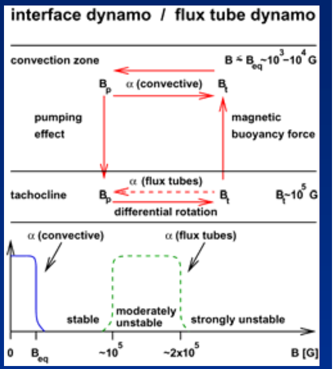
# On-off intermittency

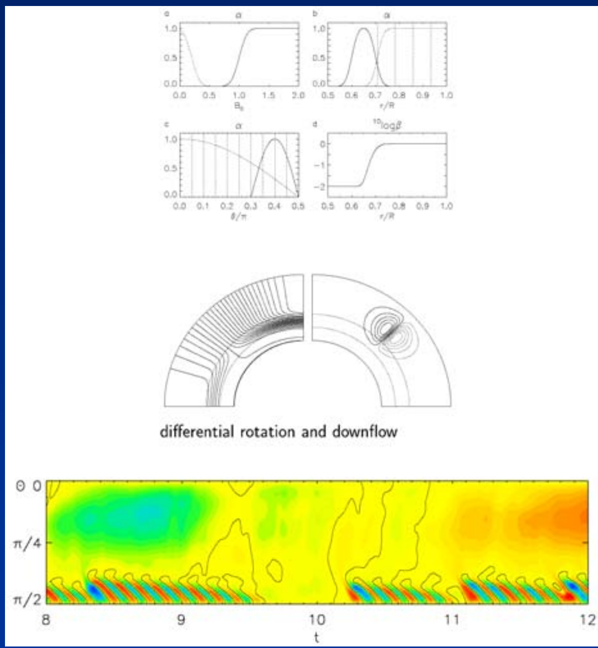
- overshoot layer dynamo driven by flux tube instability
- lower threshold in field strength for dynamo action
- random fluctuations due to magnetic fields in convection zone




Schmitt et al. (1996)

## 2D model




Ossendrijver (2000)

# Summary

- The solar magnetic field varies on a large range of time and spatial scales
- Consequences for space weather and terrestrial climate
- Variation of magnetic field due to variations of dynamo processes
- ... but no accepted solar dynamo model
- Helioseismic observations and numerical modeling required