Hemispheric Asymmetry of Solar Cycle Activities

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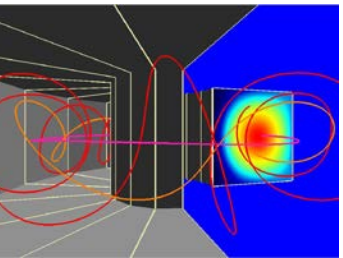
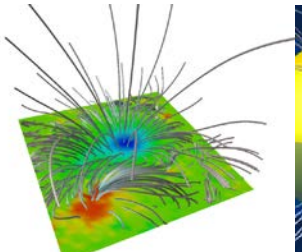
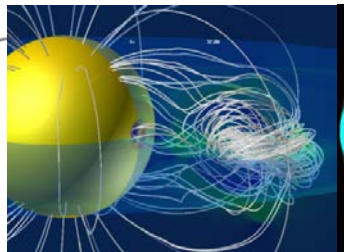
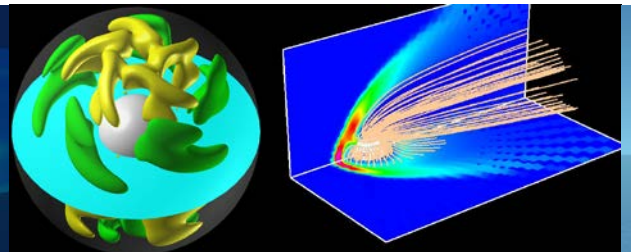
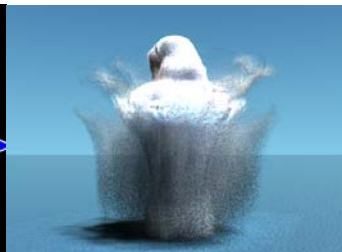
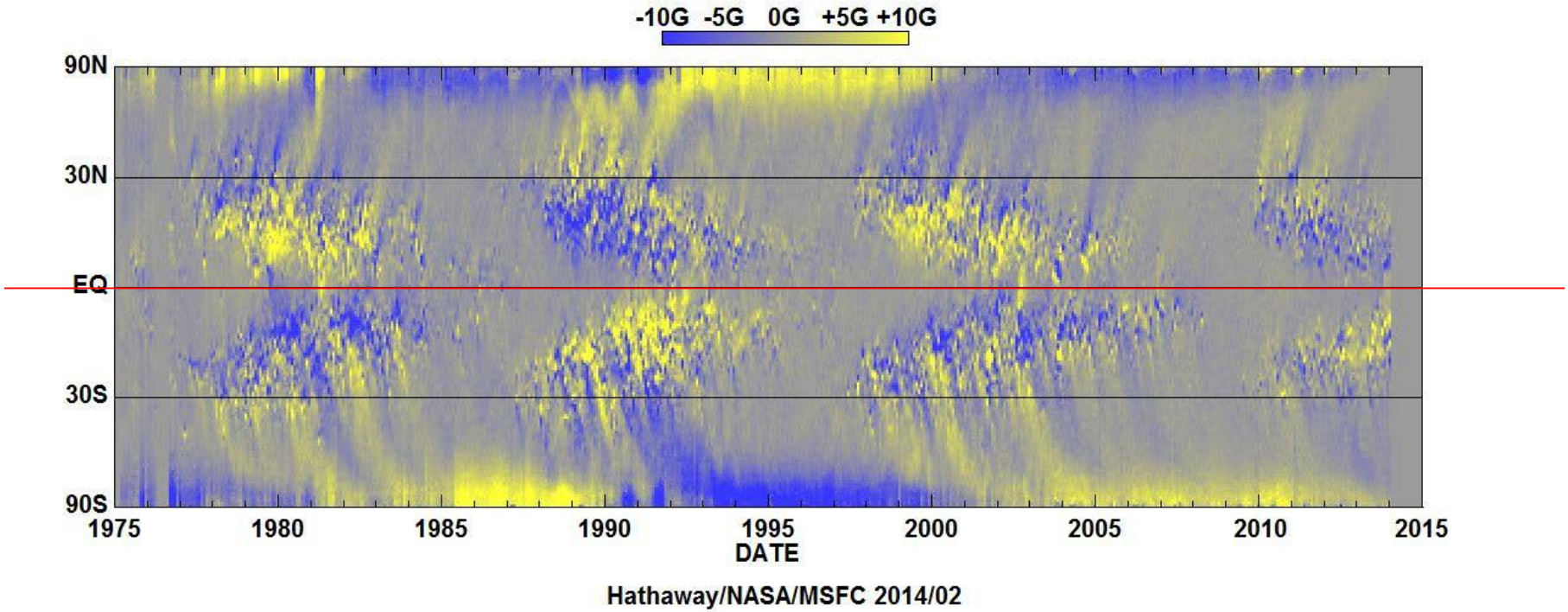






Outlook

- Introduction
  - What is the hemispheric asymmetry of solar cycle? Why should we study it?
  - Review of previous studies
    - Observations and Simulations
- 【Our study】A simple dynamo model of hemispheric asymmetry
  - Numerical Model
  - Results
- Discussion and summary

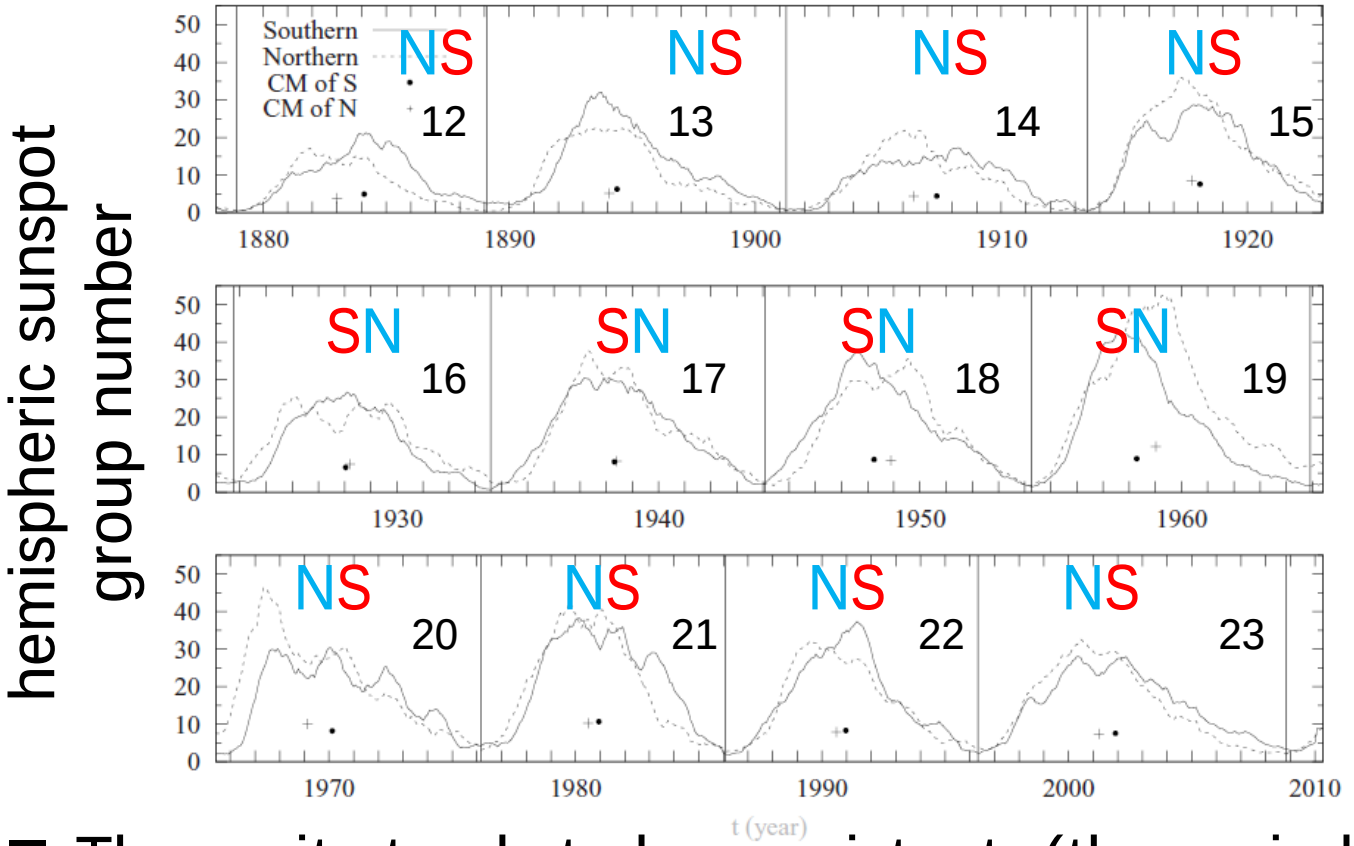
“Butterfly” is almost symmetric.

- Magnetic field on the solar surface



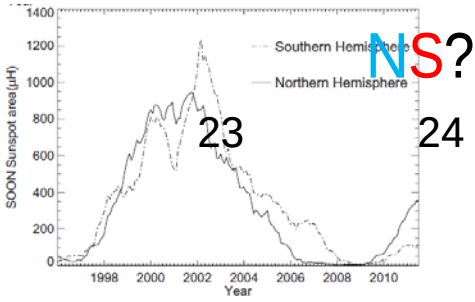
Hemispheric Asymmetry

- Phase of solar (sunspot) cycles



Muraközy & Ludmány 2012

Ravindra & Javaraiah 2015

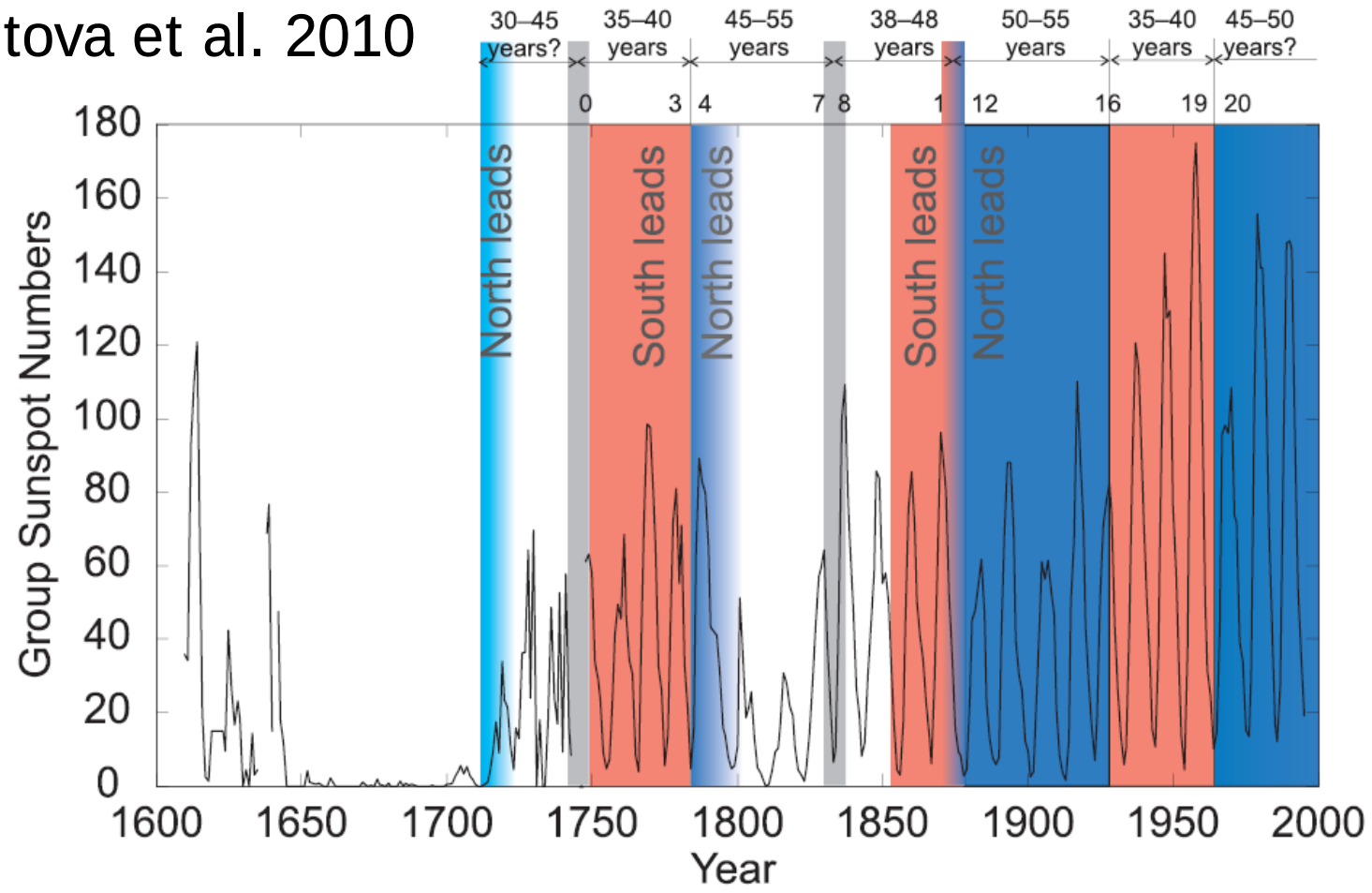


- The parity tends to be persistent. (the period of 4+4 cycle?)

Long-term evolution of N-S symmetry

The north-south asymmetry exhibits a long-term persistence, and it should not be regarded as a stochastic phenomenon.

Zolotova et al. 2010



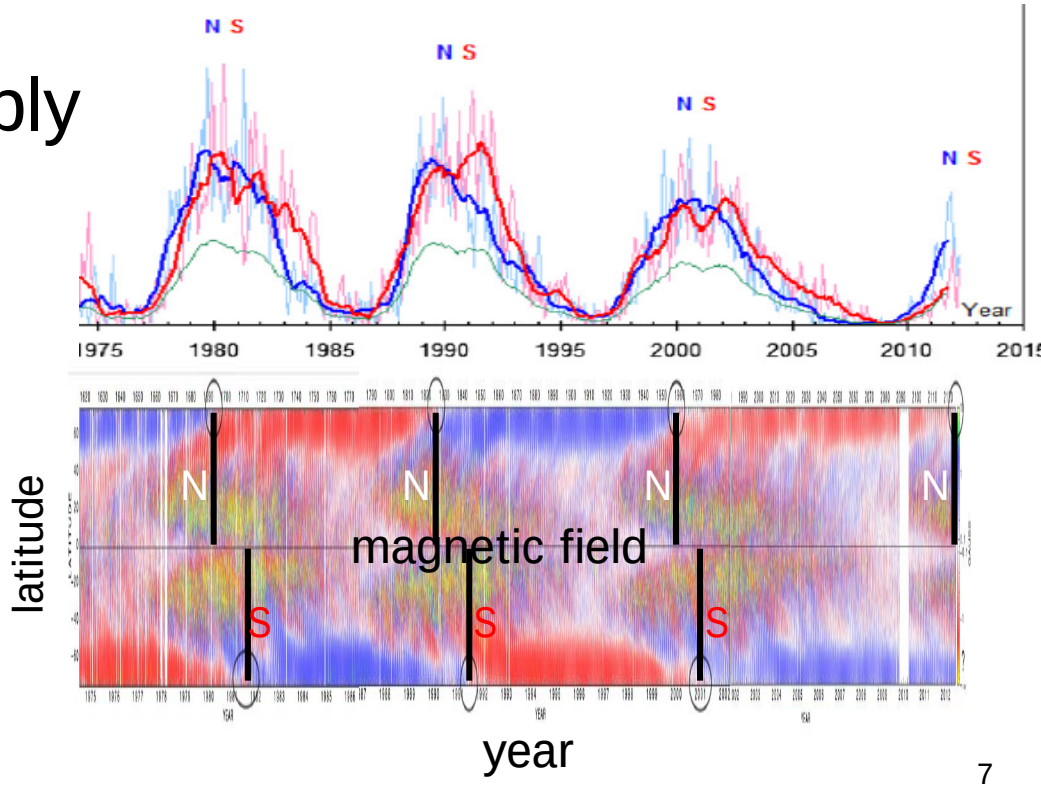
Polar Filed Reversal

- The polar field reversals have been at different times in the different hemispheres.

  Babcock & Babcock 1955, Babcock 1959, Babcock 1961

- The asymmetric polar field reversals are simply a consequence of the asymmetry of sunspot activity.

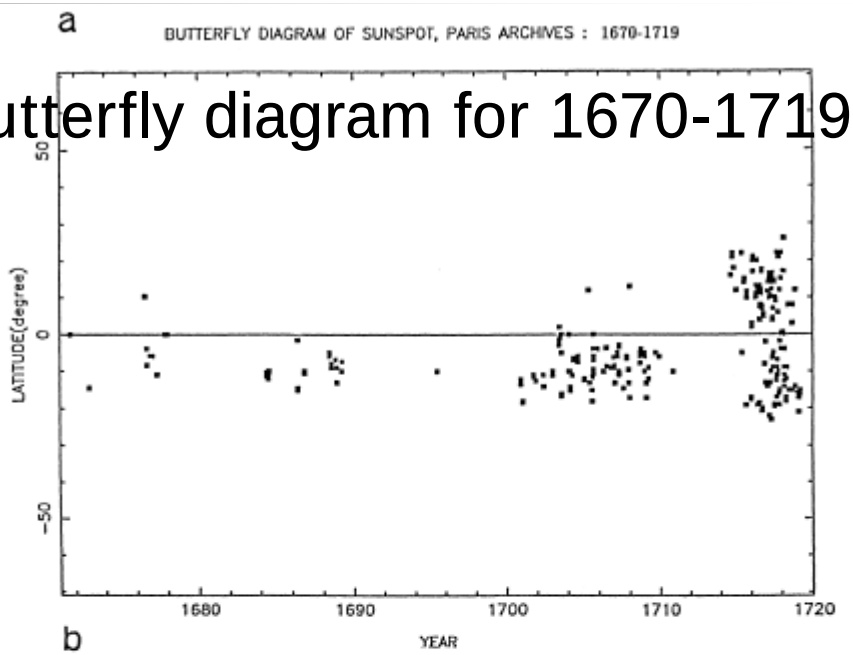
Svalgaad & Kamide 2013



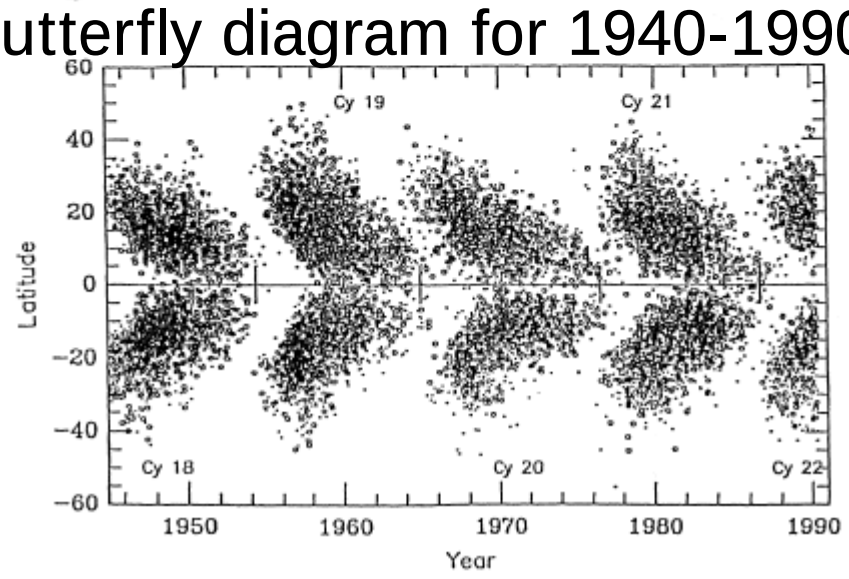
Strong Asymmetry in Maunder Min.

Sokoloff and Nesme-Ribes (1994)

Strong asymmetry b/w north and south hemisphere might be observed during the Maunder minimum.



Butterfly diagram for 1670-1719



Butterfly diagram for 1940-1990

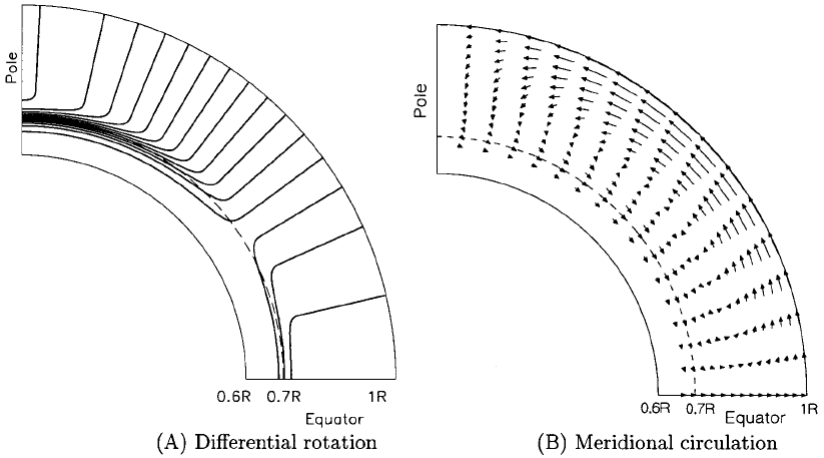
Other Asymmetric Features

- Mursula, Hiltula, Zieger 2002
  - Asymmetry of solar wind and heliospheric current sheets could be related to a persistent N-S asymmetry of solar dynamo.
- Feng, Deng, Xu 2013
  - Asymmetry of the flare index between the N-S hemispheres is about 6-7 months, which is near the time delay between flare activity and sunspot activity.
- Gopalswamy et al. 2012
  - Asymmetric behavior is revealed by microwave observations

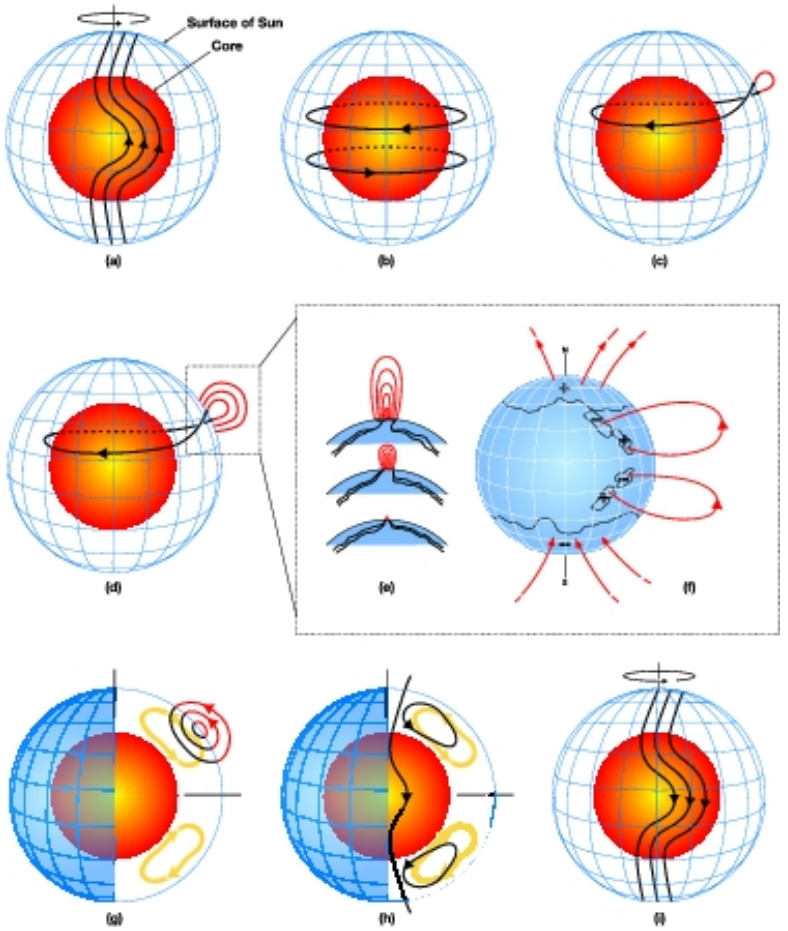
What is the cause of asymmetry?

Dynamo

The most of flux transport dynamo models just assumed the hemispheric symmetry.



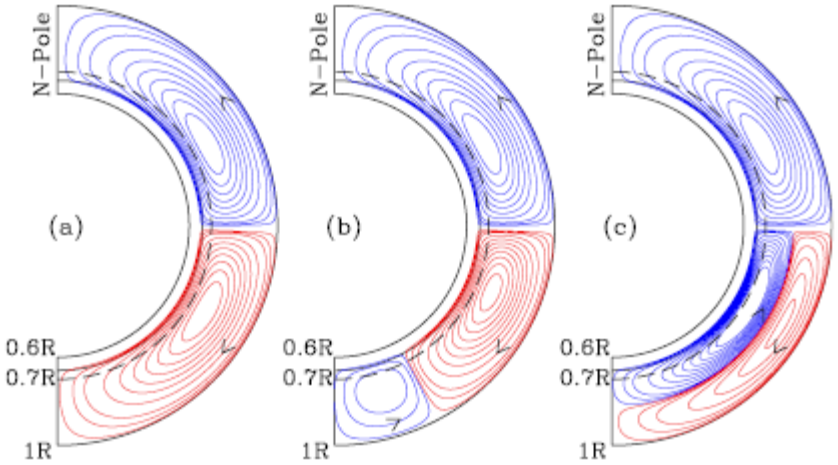
Dikpati & Charbonneau 1999
Babcock-Leighton Flux Transport Dynamo

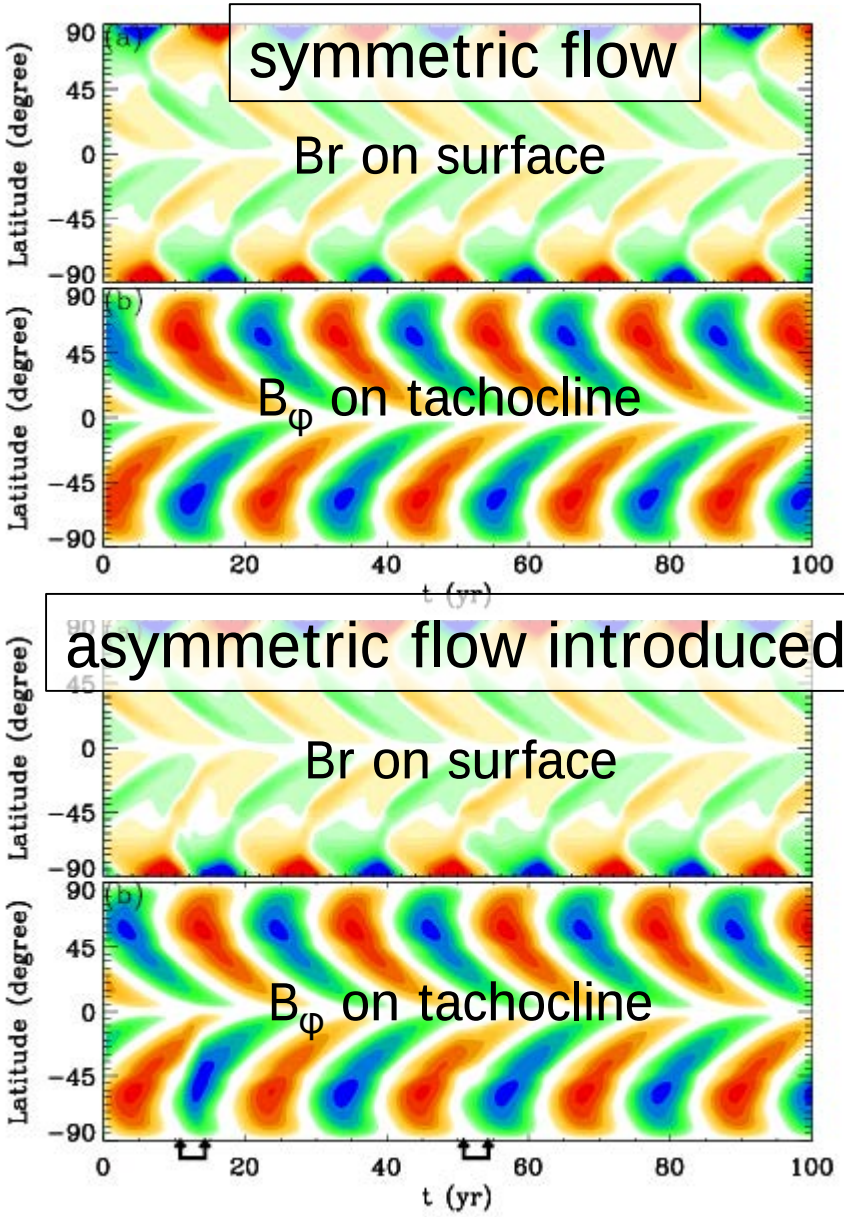


Effects of Asymmetric Flow

- Belucz & Dikpati 2013
  - Asymmetric meridional circulation
  - 2D flux transport model

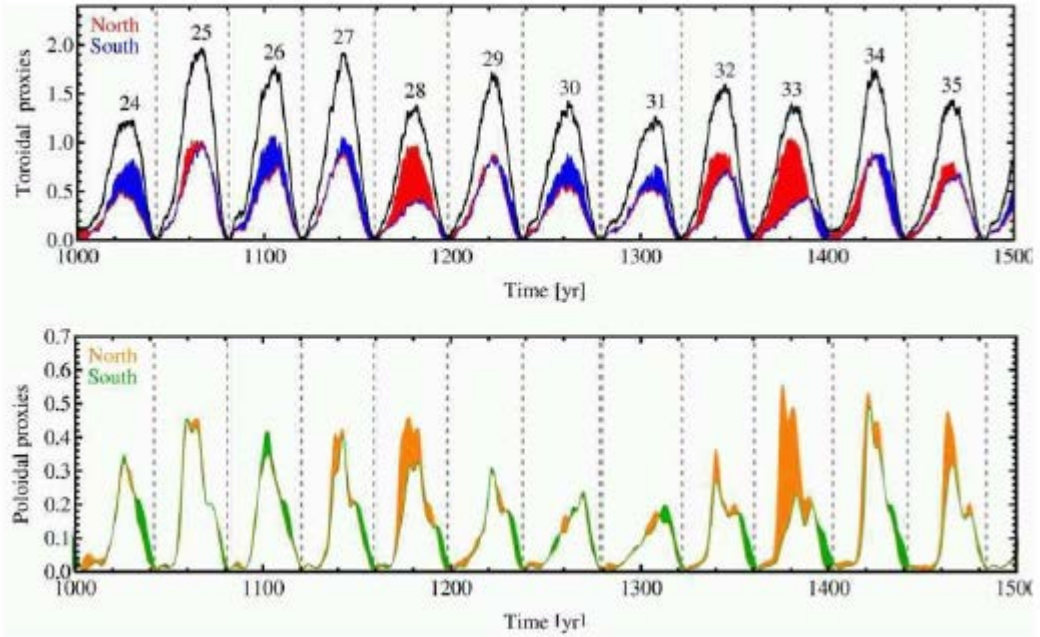
The asymmetry in meridional circulation produces differing cycles in the N-S hemispheres.





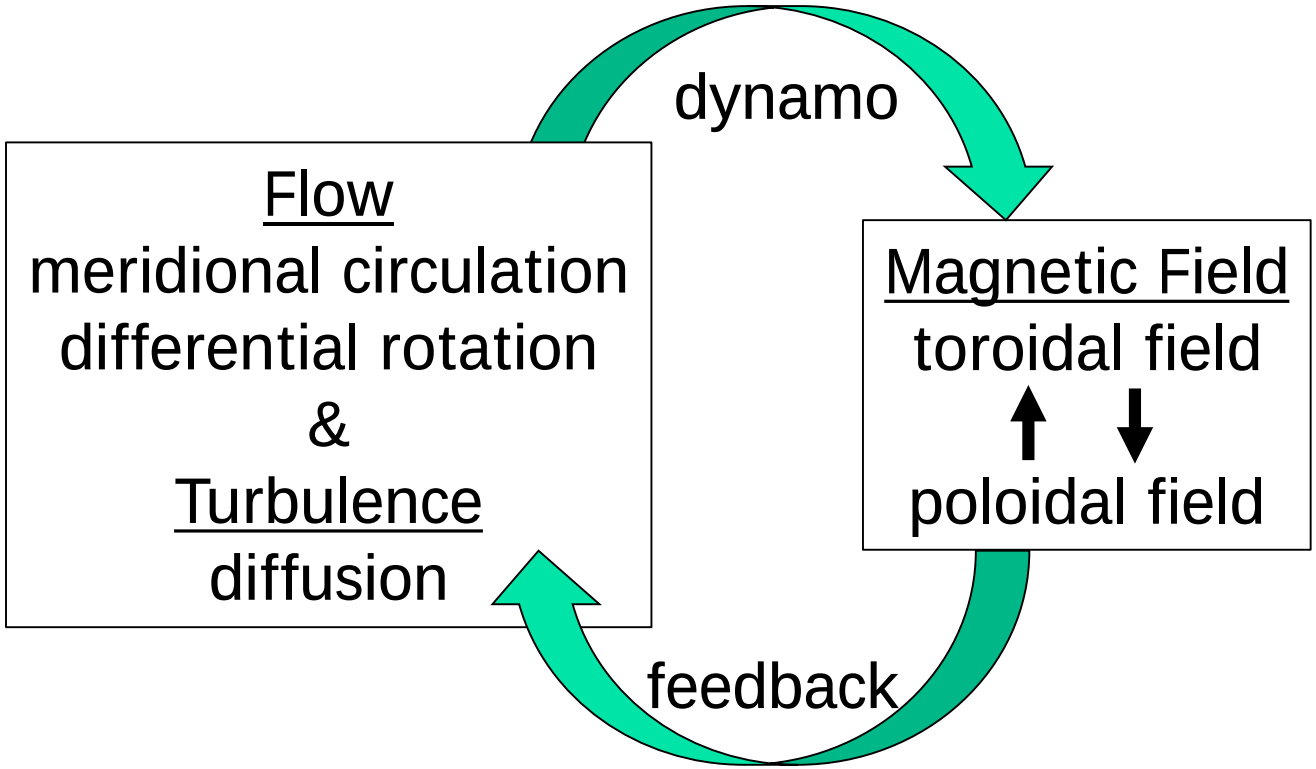
3D MHD Simulation

- Passos & Charbonneau 2014
- Norton, Charbonneau & Passos 2014



The N-S asymmetry is spontaneously generated, but the lag of cycle phase seems to execute a form of random walk rather than the trend of long-term persistence.

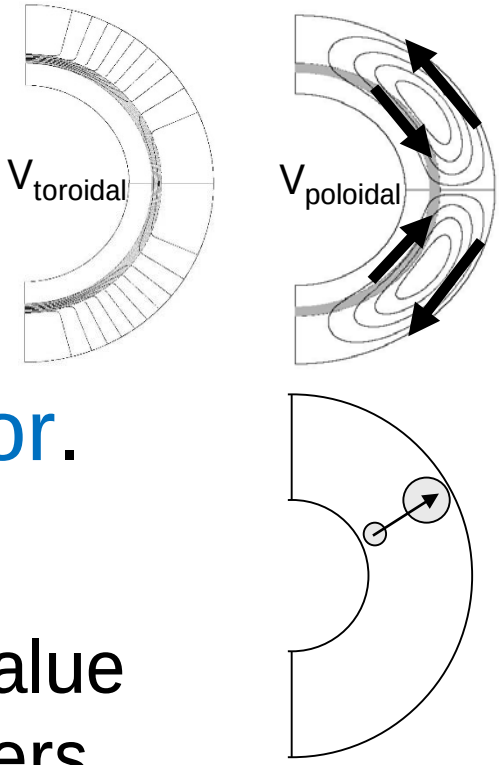
What is the cause of asymmetry?



Objective of our study: To find the minimal model to explain the N-S asymmetry of solar cycle.

Simulation model

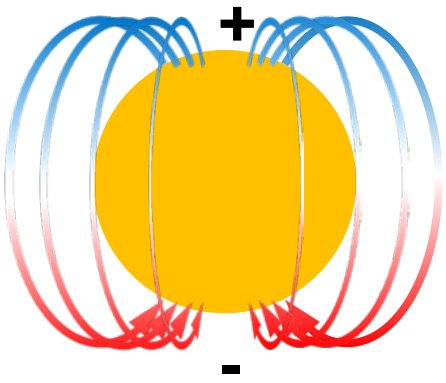
- Algorithm: Same as SURYA code (Chatterjee, Nandy, and Choudhuri 2004).
- Geometry: 2D (axisymmetric) full spherical shell.
- Dynamo model: αΩ-dynamo with differential rotation and meridional circulation, those are symmetric with respect to equator.
- Magnetic buoyancy effect:
  - Toroidal field exceeding a critical value is made to erupt to the surface layers.



Parity of Dynamo

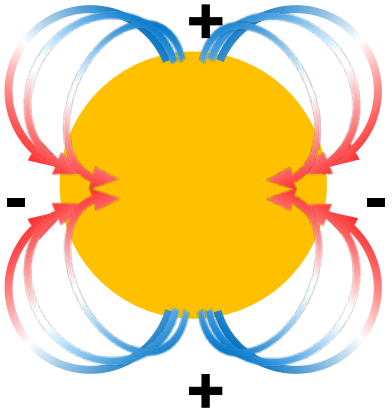
Ref. Jennings & Weiss (1991)

Nishikawa and Kusano (2008)



$\left(B_r^a, B_\theta^s, B_\phi^a\right)$

Dipole-type



$\left(B_r^s, B_\theta^a, B_\phi^s\right)$

Quadrupole-type

$$B_\phi^s(\theta) \equiv \left[B_\phi(\theta) + B_\phi(\pi-\theta)\right] / 2$$

$$B_\phi^a(\theta) \equiv \left[B_\phi(\theta) - B_\phi(\pi-\theta)\right] / 2$$

Equations

quadrupole type

$$\frac{\partial B_\phi^s}{\partial t} + s\boldsymbol{v}_p^s \cdot \nabla\left(\frac{B_\phi^s}{s}\right) + B_\phi^s \nabla \cdot \boldsymbol{v}_p^s$$
$$= \eta_t\left(\nabla^2 - \frac{1}{s^2}\right) B_\phi^s + \frac{1}{r}\frac{d\eta_t}{dr}\frac{\partial}{\partial r}\left(rB_\phi^s\right) + s\left(\boldsymbol{B}_p^s \cdot \nabla\right)\Omega^s$$

$$\frac{\partial A_\phi^a}{\partial t} + \frac{1}{s}\left(\boldsymbol{v}_p^s \cdot \nabla\right)\left(sA_\phi^a\right) = \eta_p\left(\nabla^2 - \frac{1}{s^2}\right) A_\phi^a + \alpha B_\phi^s$$

Magnetic buoyancy effect

dipole type

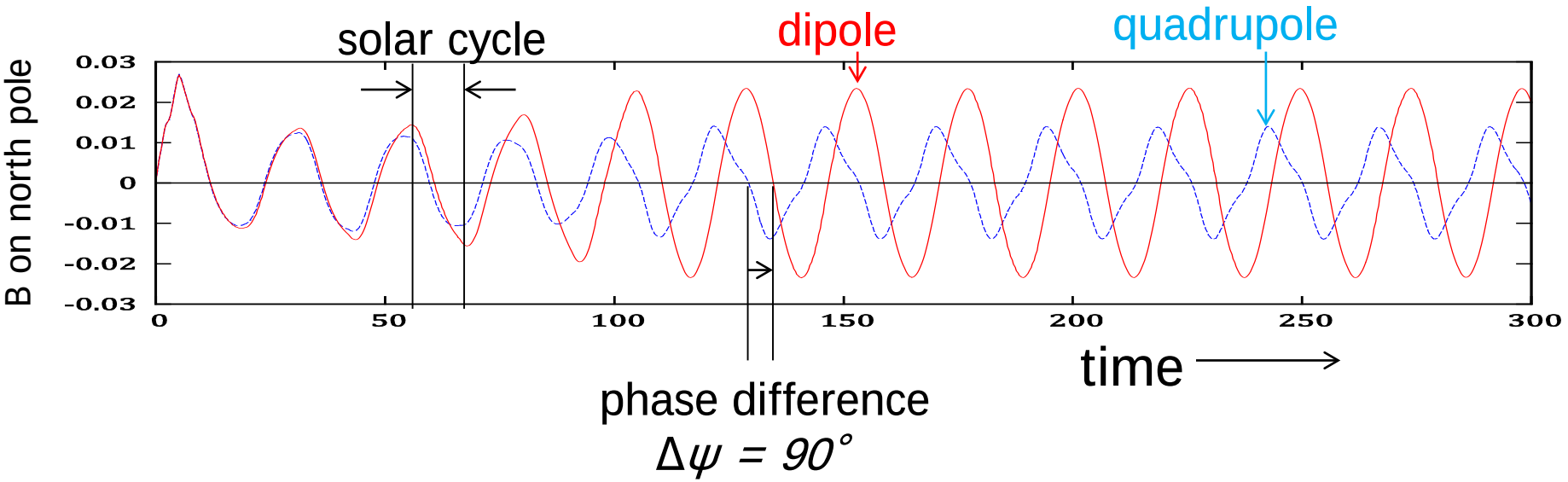
$$\frac{\partial B_\phi^a}{\partial t} + s\boldsymbol{v}_p^s \cdot \nabla\left(\frac{B_\phi^a}{s}\right) + B_\phi^a \nabla \cdot \boldsymbol{v}_p^s$$
$$= \eta_t\left(\nabla^2 - \frac{1}{s^2}\right) B_\phi^a + \frac{1}{r}\frac{d\eta_t}{dr}\frac{\partial}{\partial r}\left(rB_\phi^a\right) + s\left(\boldsymbol{B}_p^a \cdot \nabla\right)\Omega^s$$

$$\frac{\partial A_\phi^s}{\partial t} + \frac{1}{s}\left(\boldsymbol{v}_p^s \cdot \nabla\right)\left(sA_\phi^s\right) = \eta_p\left(\nabla^2 - \frac{1}{s^2}\right) A_\phi^s + \alpha B_\phi^a$$

Result

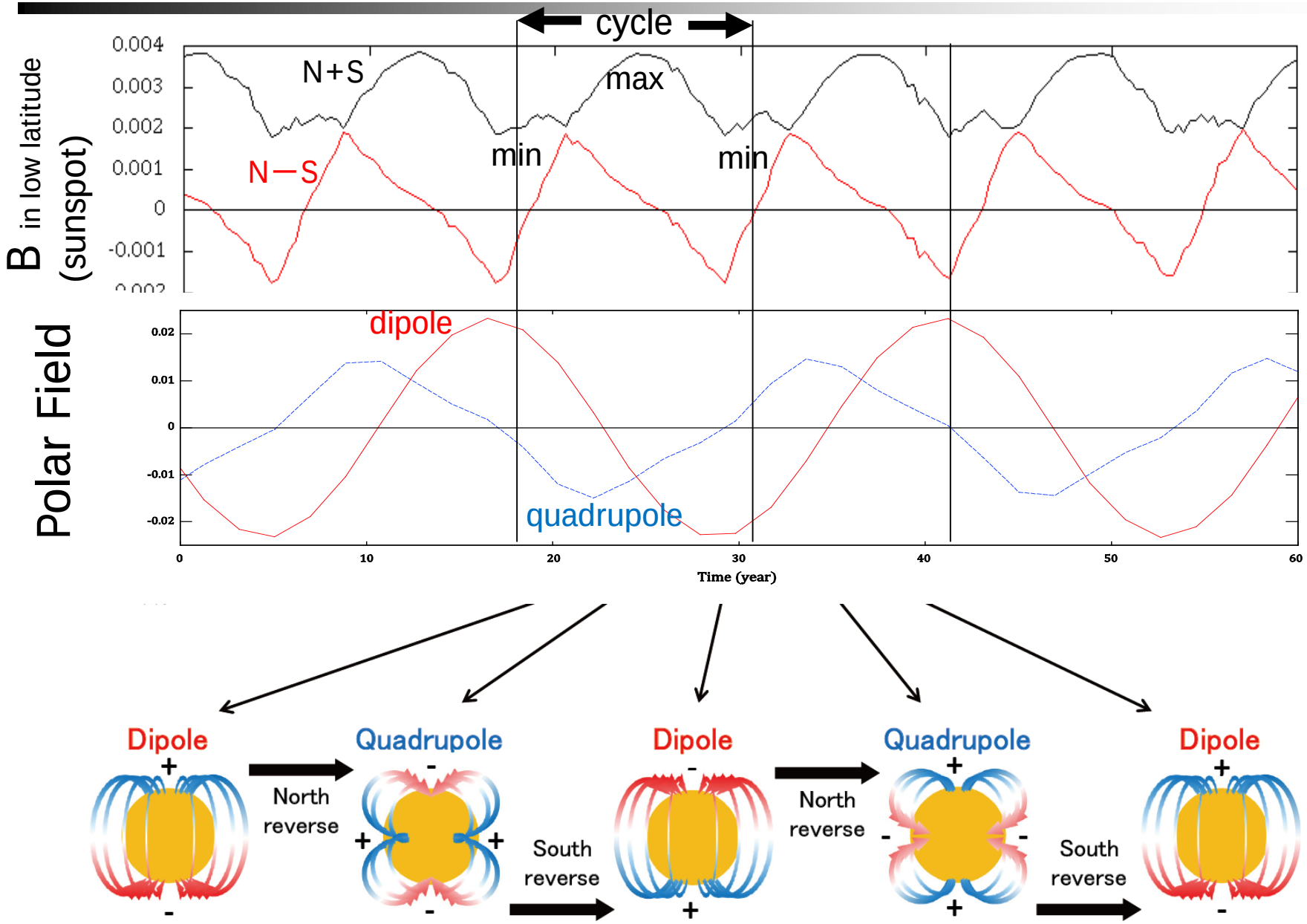
Result

- The cyclic oscillation of polar magnetic field

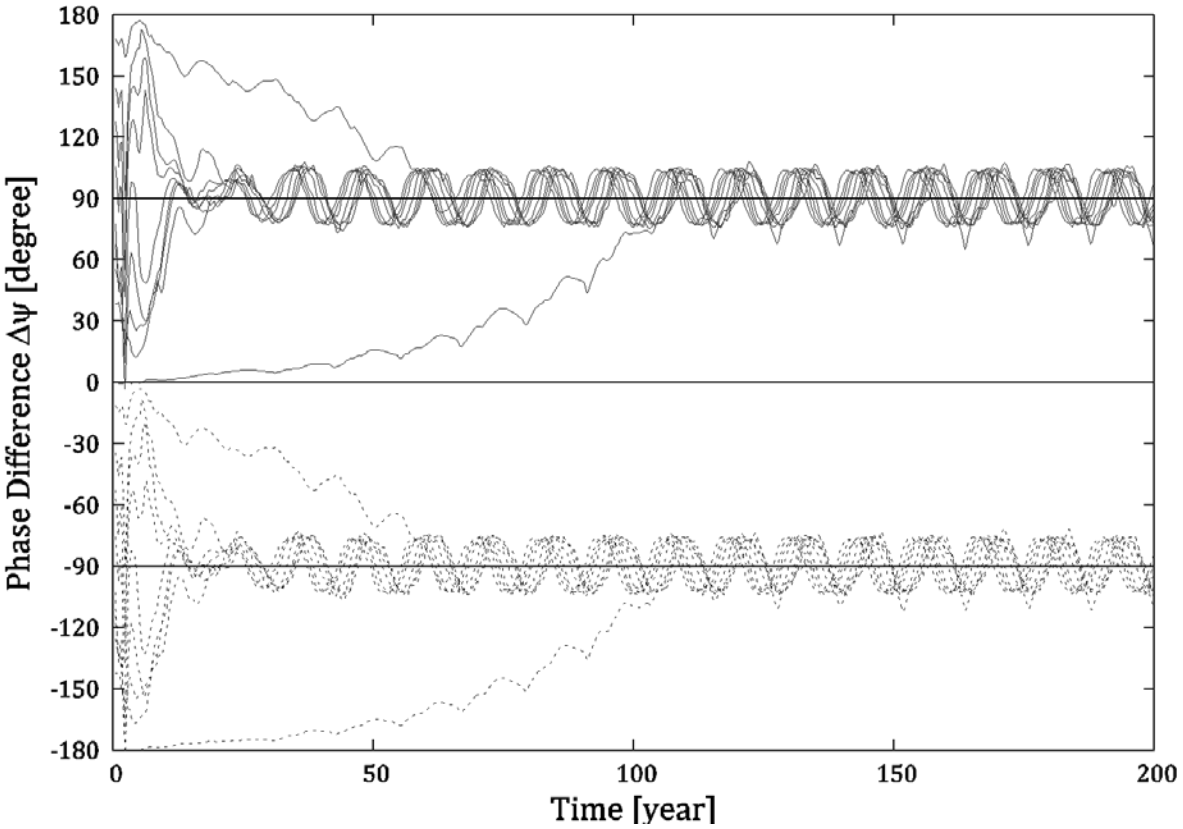


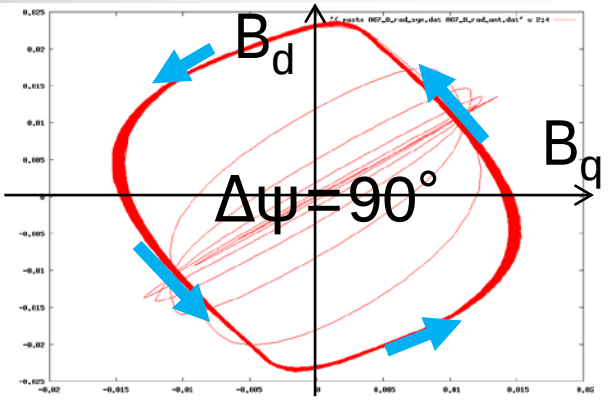
- Both the dipole and quadrupole-type fields oscillates with the same period corresponding to the double solar cycle.
- The phase difference b/w the two components spontaneously shifts to 90° and then is persistent.

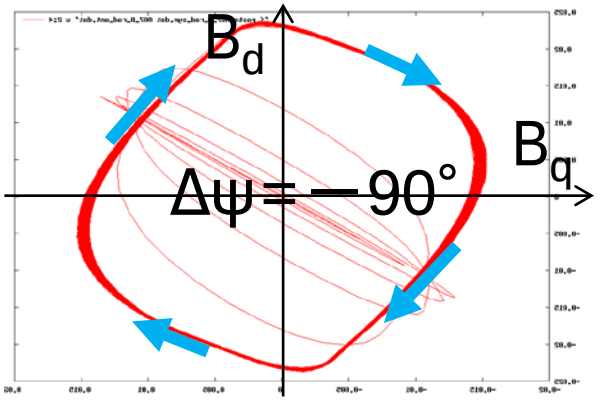
Solar Cycle for Δψ=90°



Dependency on the Initial Phase

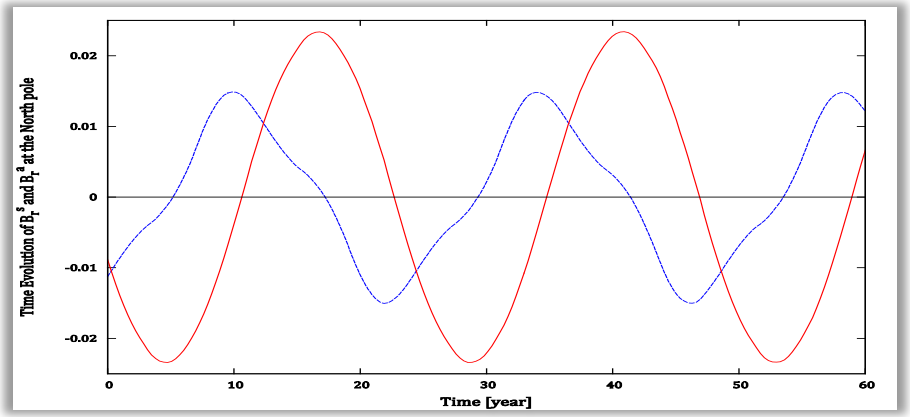






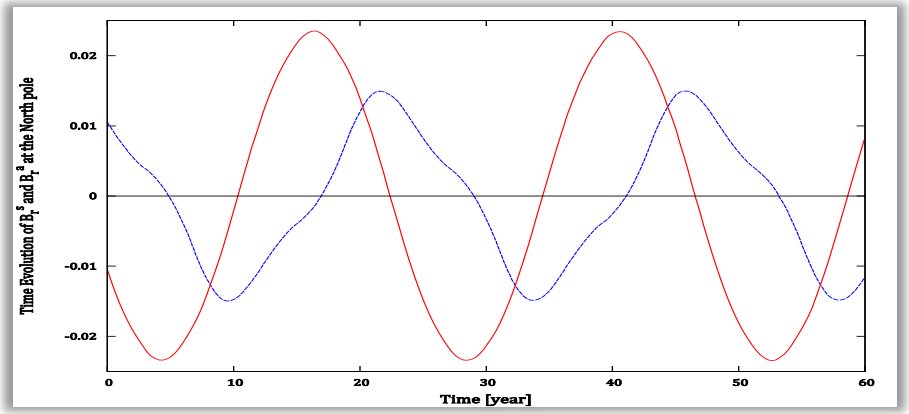
- Regardless of the initial condition, the phase difference Δψ always falls into 90° or −90° .
- They correspond to two attractors.

Properties of the Two Attractors



The attractor for $\Delta\psi = 90^\circ$

Sunspot in the north is more active in the early phase and the polar field in the north is first reversed.

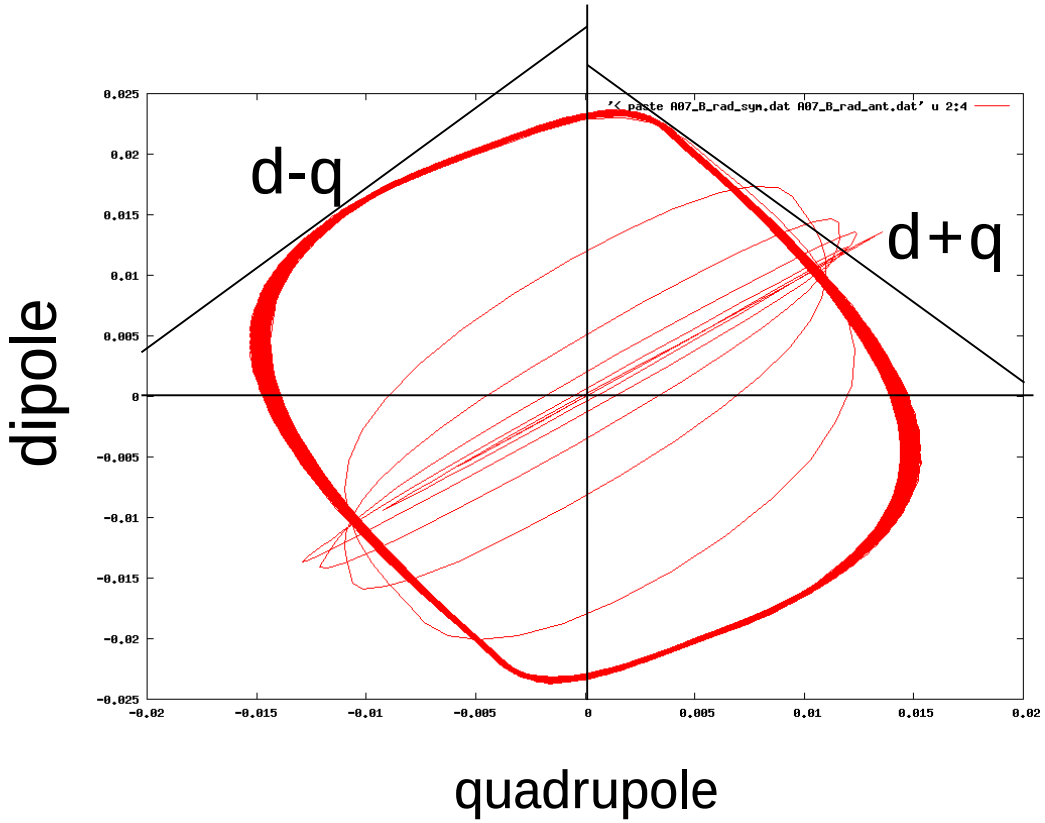


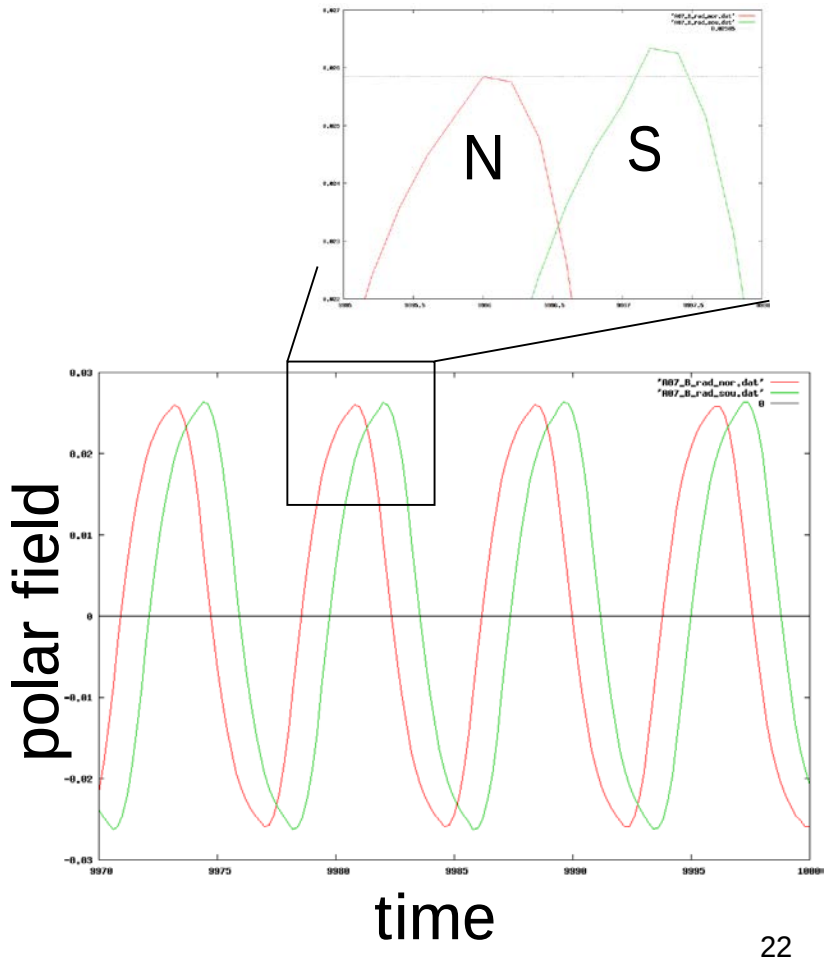
The attractor for $\Delta\psi = -90^\circ$

Sunspot in the south is more active in the early phase and the polar field in the south is first reversed.

Asymmetry in polar field intensity

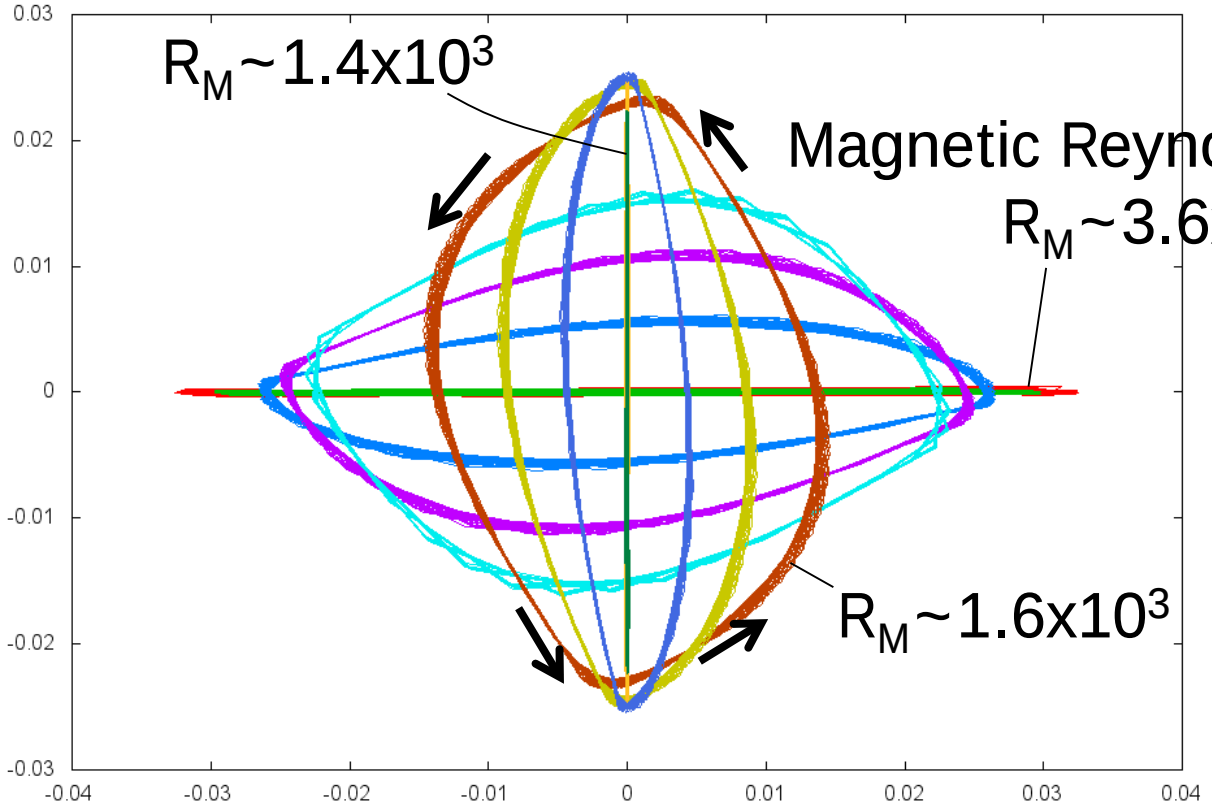
- The squashed factor of attracter causes the difference of polar field max intensity between the north and south pole





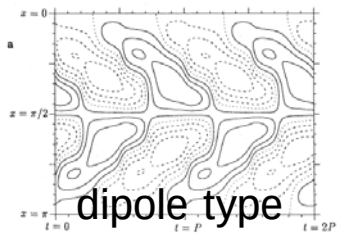
Dependency of attractors on R_M

dipole

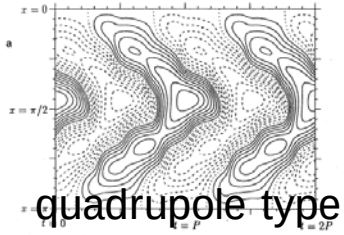


quadrupole

Jennings & Weiss 1991

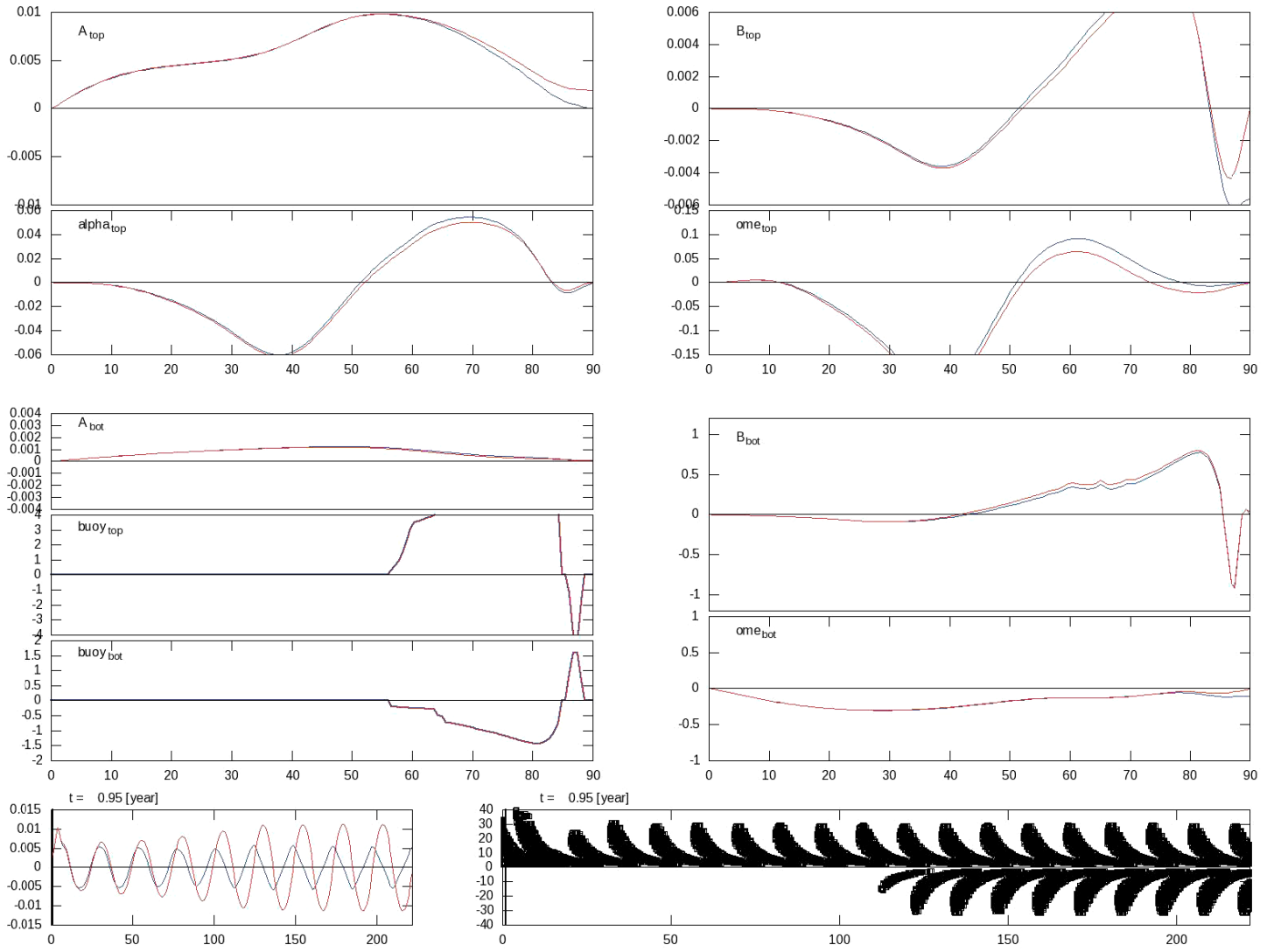


dipole type

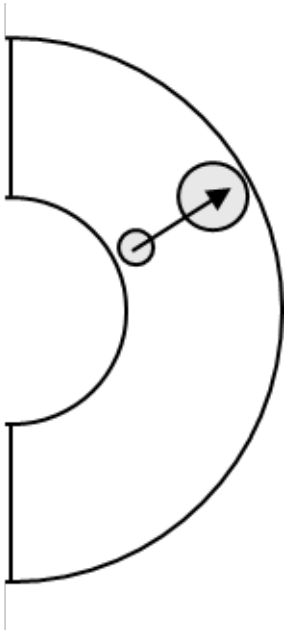


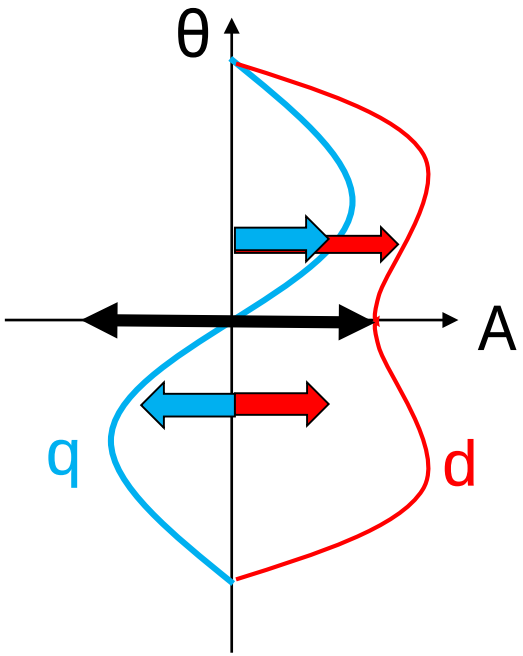
quadrupole type

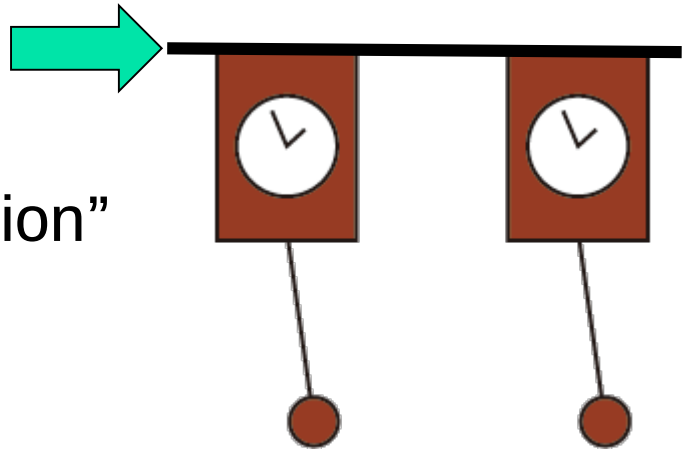
Why attracters for Δψ= ±90°



Mechanism of attractors







“Stochastic synchronization”

Summary

- The flux transport dynamo model well explains the asymmetric reversal of polar field as well as the lag of solar cycle between the N-S hemisphere, even if the flow is symmetric.
- There are two attractors in which the dipole and quadurapole field coexist and the phases are shifted (+ or -) 90 degrees.
- It means that the asymmetry of spherical dynamo can be inherently generated.
- However, the simple flux transport model cannot reproduce the transition b/w the different attracters, which corresponds to the switch of different hemispheric parity (NS $\rightleftarrows$ SN).