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LONG-TERM VARIATION IN THE SUN'S ACTIVITY CAUSED BY MAGNETIC ROSSBY WAVES IN THE TACHOCLINE

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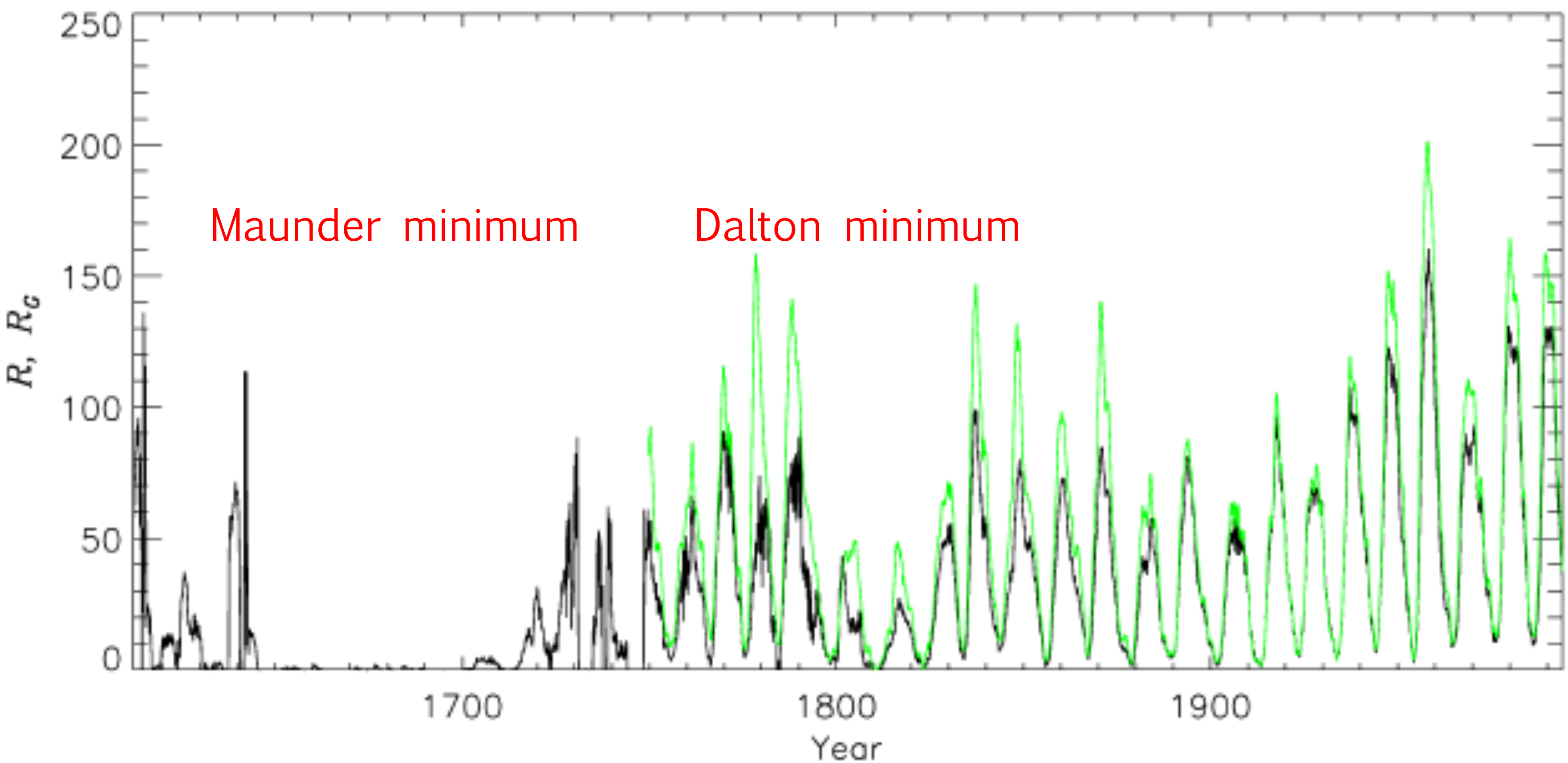
ABSTRACT

Long-term records of sunspot number and concentrations of cosmogenic radionuclides (10Be and 14C) on the Earth reveal the variation of the Sun's magnetic activity over hundreds and thousands of years. We identify several clear periods in sunspot, 10Be, and 14C data as 1000, 500, 350, 200, and 100 years. We found that the periods of the first five spherical harmonics of the slow magnetic Rossby mode in the presence of a steady toroidal magnetic field of 1200–1300 G in the lower tachocline are in perfect agreement with the timescales of observed variations. The steady toroidal magnetic field can be generated in the lower tachocline either due to the steady dynamo magnetic field for low magnetic diffusivity or due to the action of the latitudinal differential rotation on the weak poloidal primordial magnetic field, which penetrates from the radiative interior. The slow magnetic Rossby waves lead to variations of the steady toroidal magnetic field in the lower tachocline, which modulate the dynamo magnetic field and consequently the solar cycle strength. This result constitutes a key point for long-term prediction of the cycle strength. According to our model, the next deep minimum in solar activity is expected during the first half of this century.

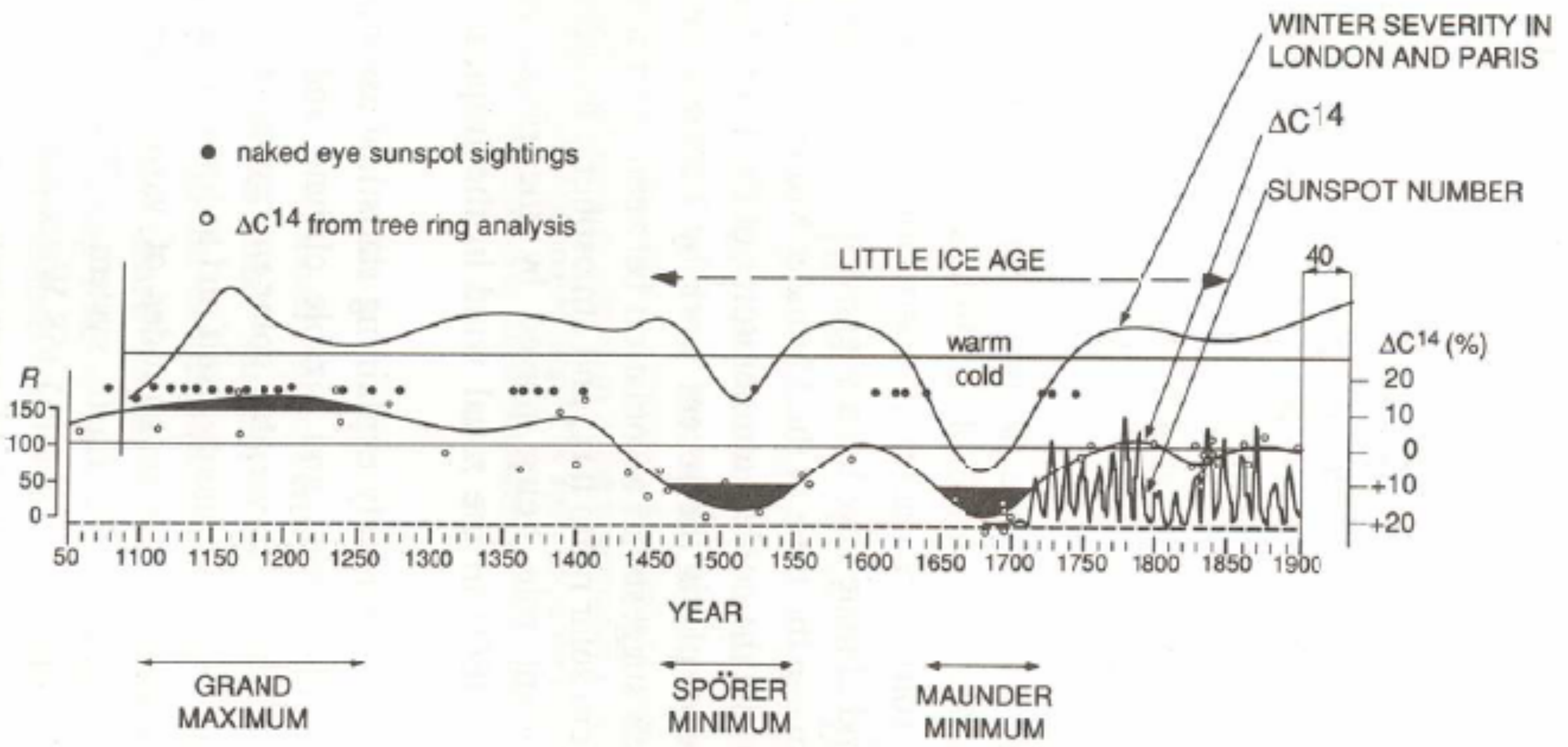
Key words: Sun: activity – Sun: interior – Sun: oscillations

13-month sliding averages of the monthly average relative sunspot numbers R (green) and group sunspot numbers RG (black) for the period 1611 – 1998.

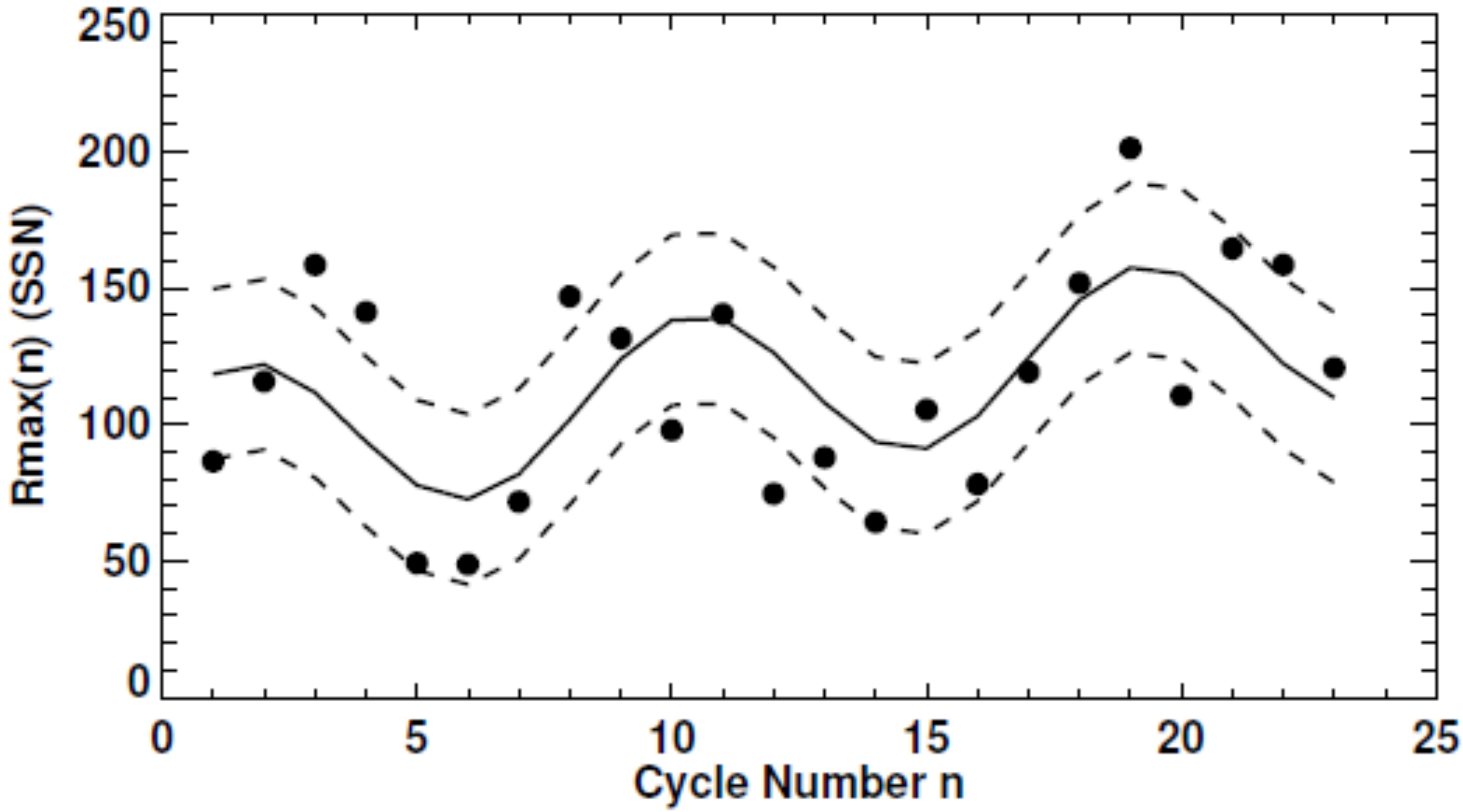


Petrovay (2010)

The Maunder minimum in the solar activity coincides to the little ice age in Europe.

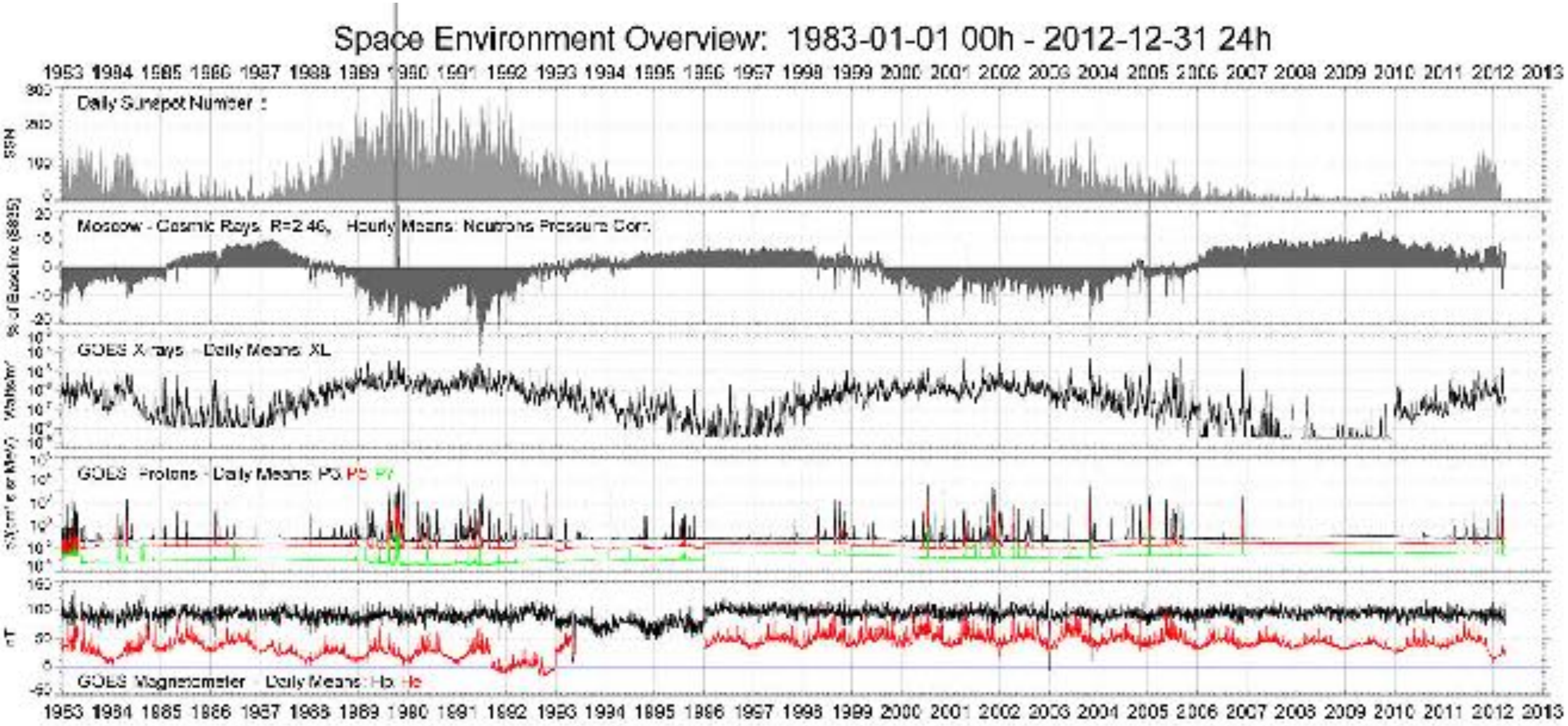


Gleissberg cycle (~ 100 years)

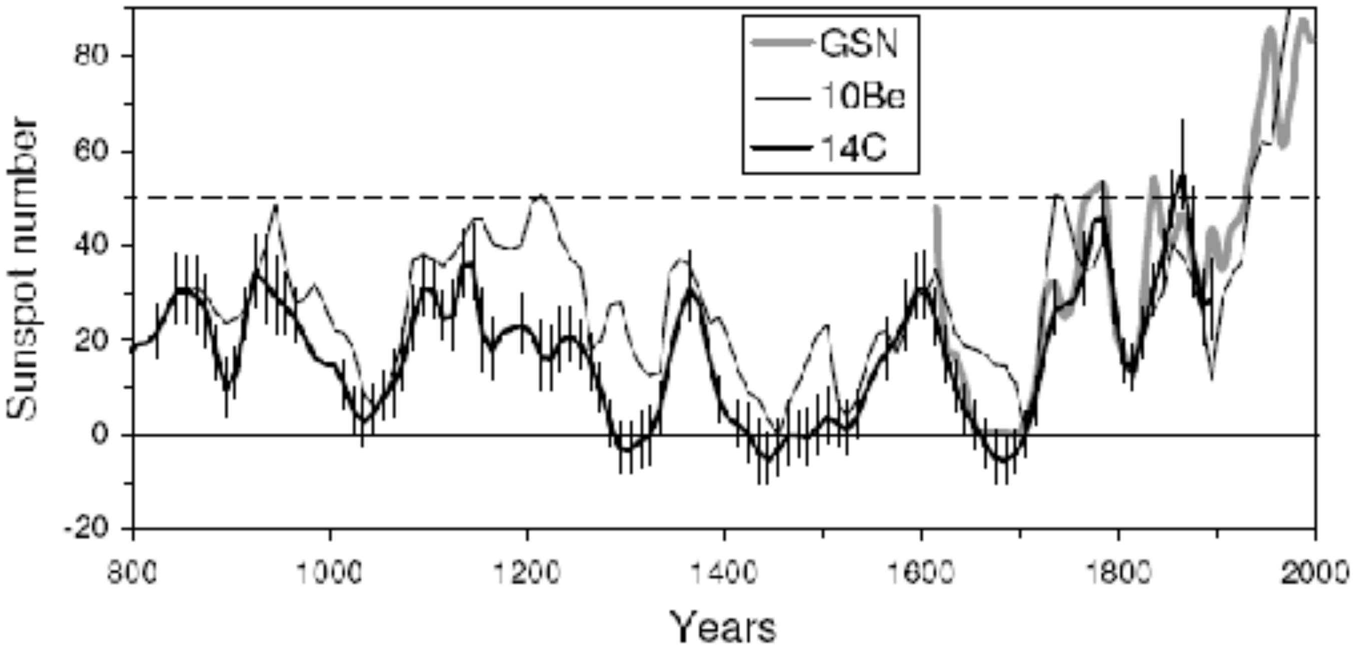


Hathaway (2010)

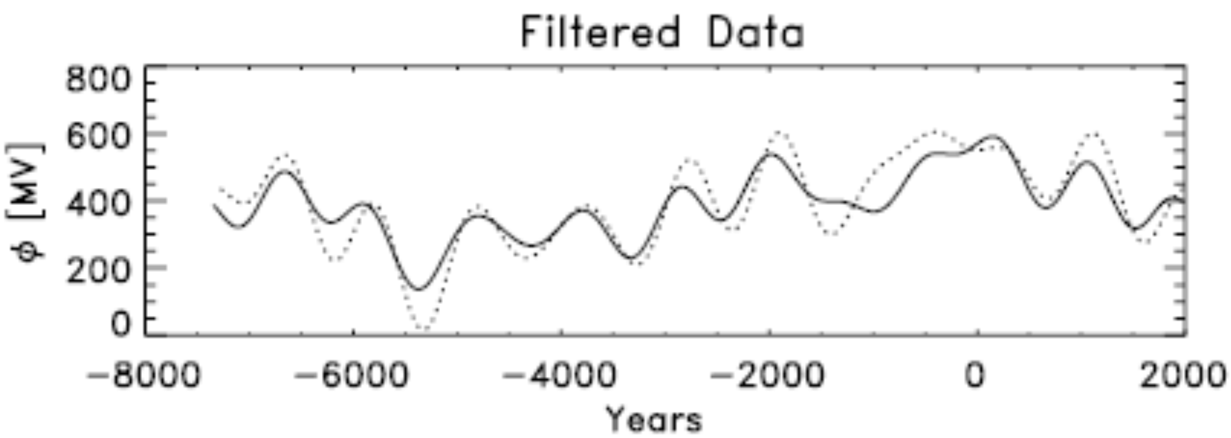
Cosmic rays and solar activity



Long periodicity: cosmogenic nuclide intensity in tree rings and polar ice core

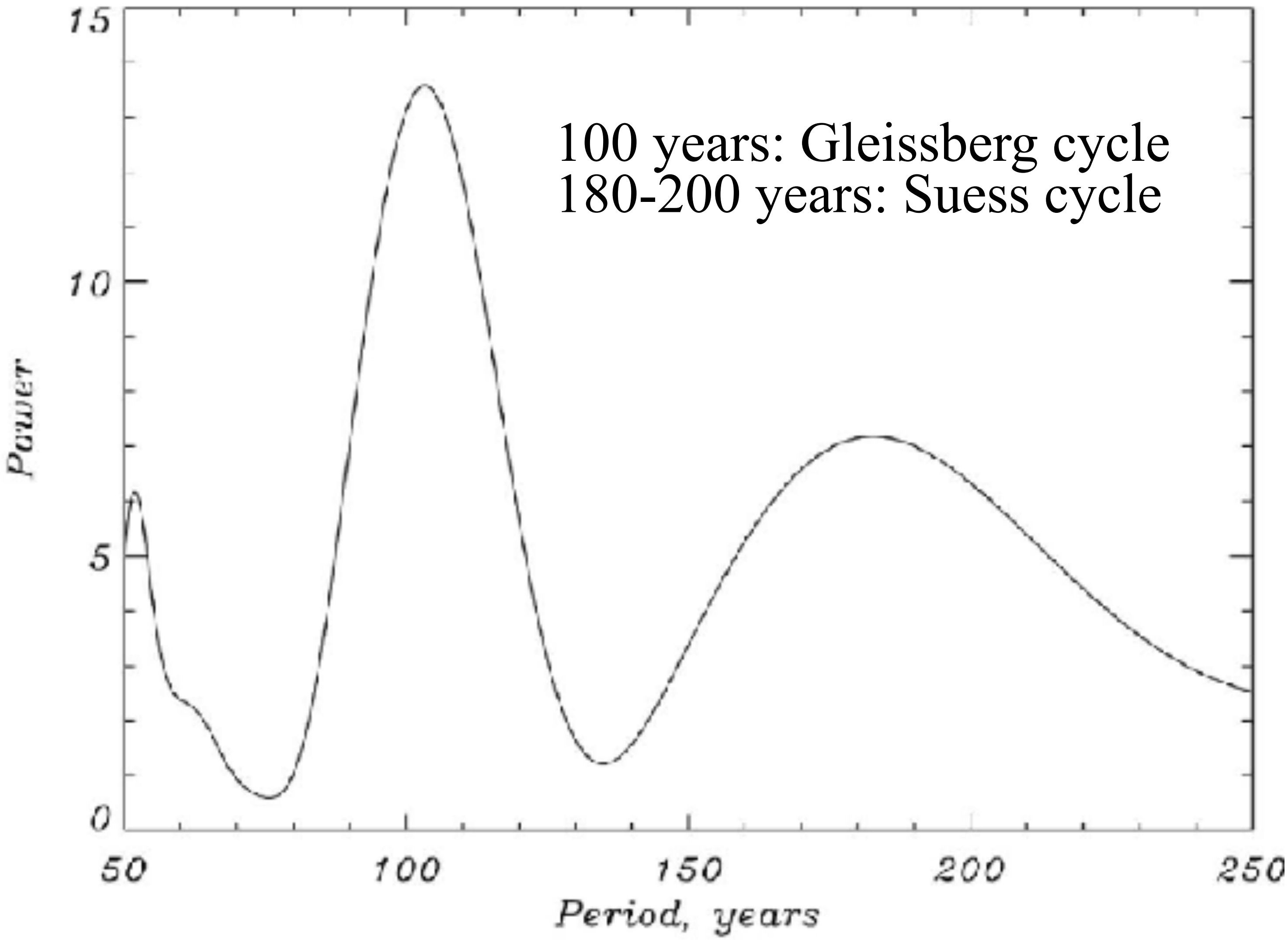


Usoskin (2008)



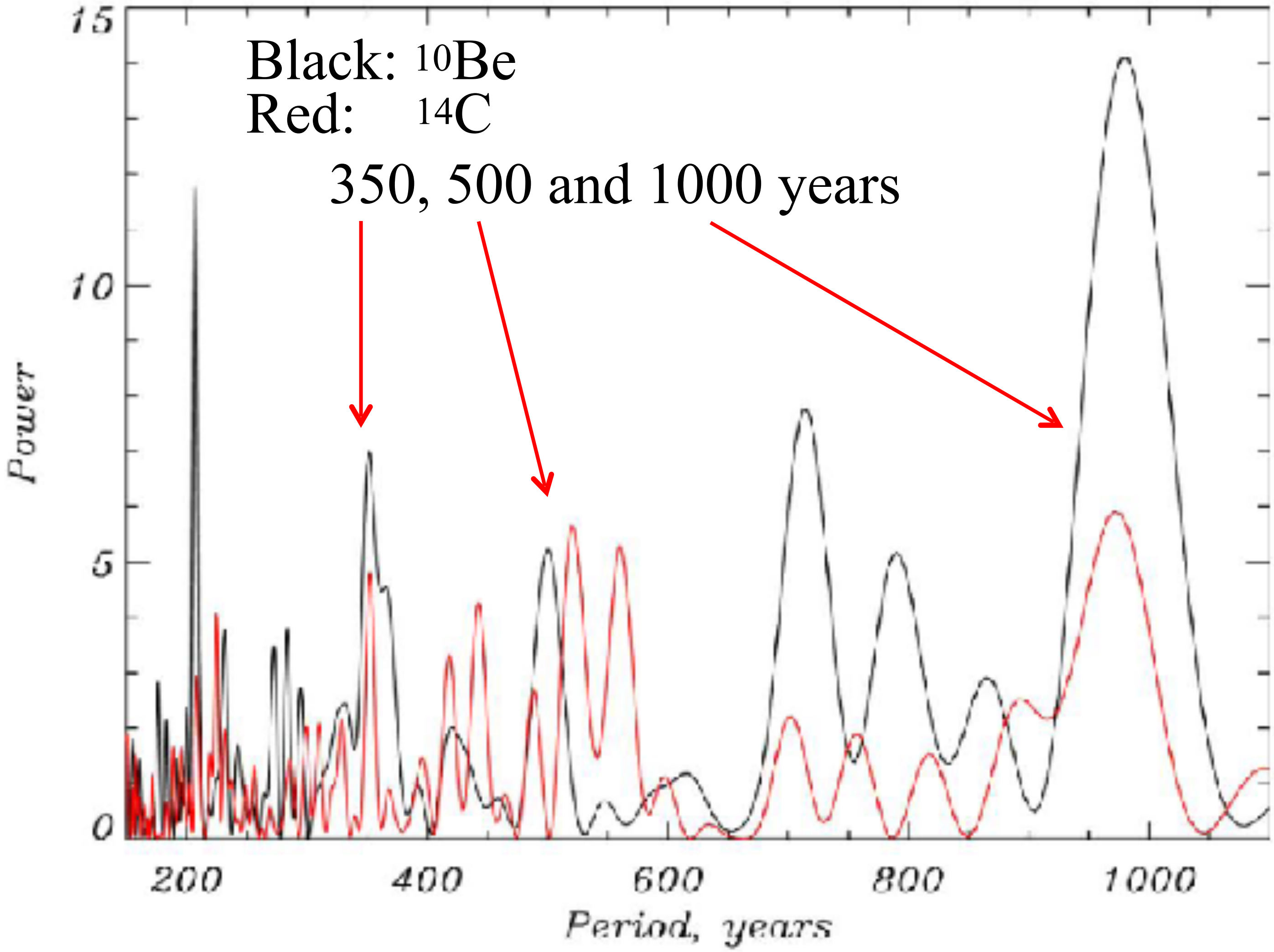
Hanslmeier at al. (2013)

Periodicity in sunspot numbers



Zaqarashvili et al. (2015)

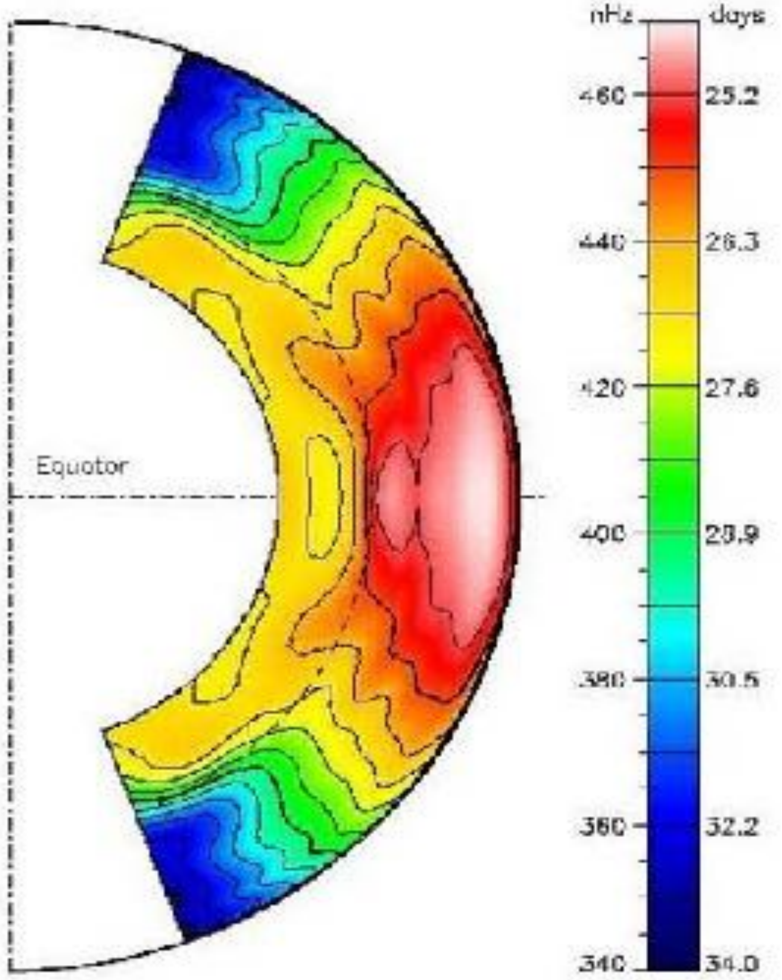
Periodicity in cosmogenic nuclides



Zaqarashvili et al. (2015)

Sunspots are formed in the solar interior

This periodicity could be related to the tachocline.



- Tachocline is the thin layer below the convection zone.
- It is important for angular momentum redistribution and for the solar dynamo.

Existing mechanisms

- Nonlinear solar dynamo permits a transition from periodic oscillations to chaotic behaviour with a long period modulation of magnetic field strength (Weiss et al. 1984).

- Random fluctuations in the dynamo parameters, which may mimic the main features of the long-term variations in the activity (Choudhuri and Karak 2012).

- The tidal influence of solar system planets may modulate the temperature gradient and consequently the magnetic storage capacity in the solar tachocline (Abreu et al. 2012).

MHD Rossby waves: dispersion relation

It defines the dispersion relation for spherical magnetic Rossby waves

$$\left(\frac{\omega}{\Omega_0}\right)^2 + \frac{2m}{n(n+1)}\frac{\omega}{\Omega_0} + \frac{B_0^2 m^2}{\mu\rho\Omega_0^2 R^2}\frac{2-n(n+1)}{n(n+1)} = 0.$$

In nonmagnetic case it reduces to the HD Rossby wave solution.

The magnetic field causes the splitting of ordinary HD mode into the fast and slow magnetic Rossby waves.

MHD Rossby waves: spherical coordinates

In the nonmagnetic case it transforms into HD Rossby wave solution

$$\omega = -\frac{2m\Omega_0}{n(n+1)}.$$

For the slow magnetic Rossby waves

$$\omega = -m\Omega_0 \frac{B_0^2}{\mu\rho\Omega_0^2 R^2} \frac{2 - n(n+1)}{2}.$$

Different spherical harmonics have different periodicity.

The period of particular harmonics depend on the magnetic field Strength.

Long-period modulation and slow Rossby mode

If unperturbed magnetic field in the tachocline is 1300 G or 0.13 T then the dispersion relation of slow magnetic Rossby modes gives the following periods for different harmonics:

m	n	Theoretical	Observed
1	2	~1150 years	~ 1030 years (^{10}Be, ^{14}C)
1	3	~450 years	~ 500 years (^{10}Be, ^{14}C)
1	4	~250 years	~ 350 years (^{10}Be, ^{14}C)
1	5	~180 years	~ 200 years (sunspots)
1	6	~100 years	~ 100 years (sunspots)

Very good coincidence between observed and theoretical periods!

Instability of MHD Rossby waves

We use the observed profile of the differential rotation

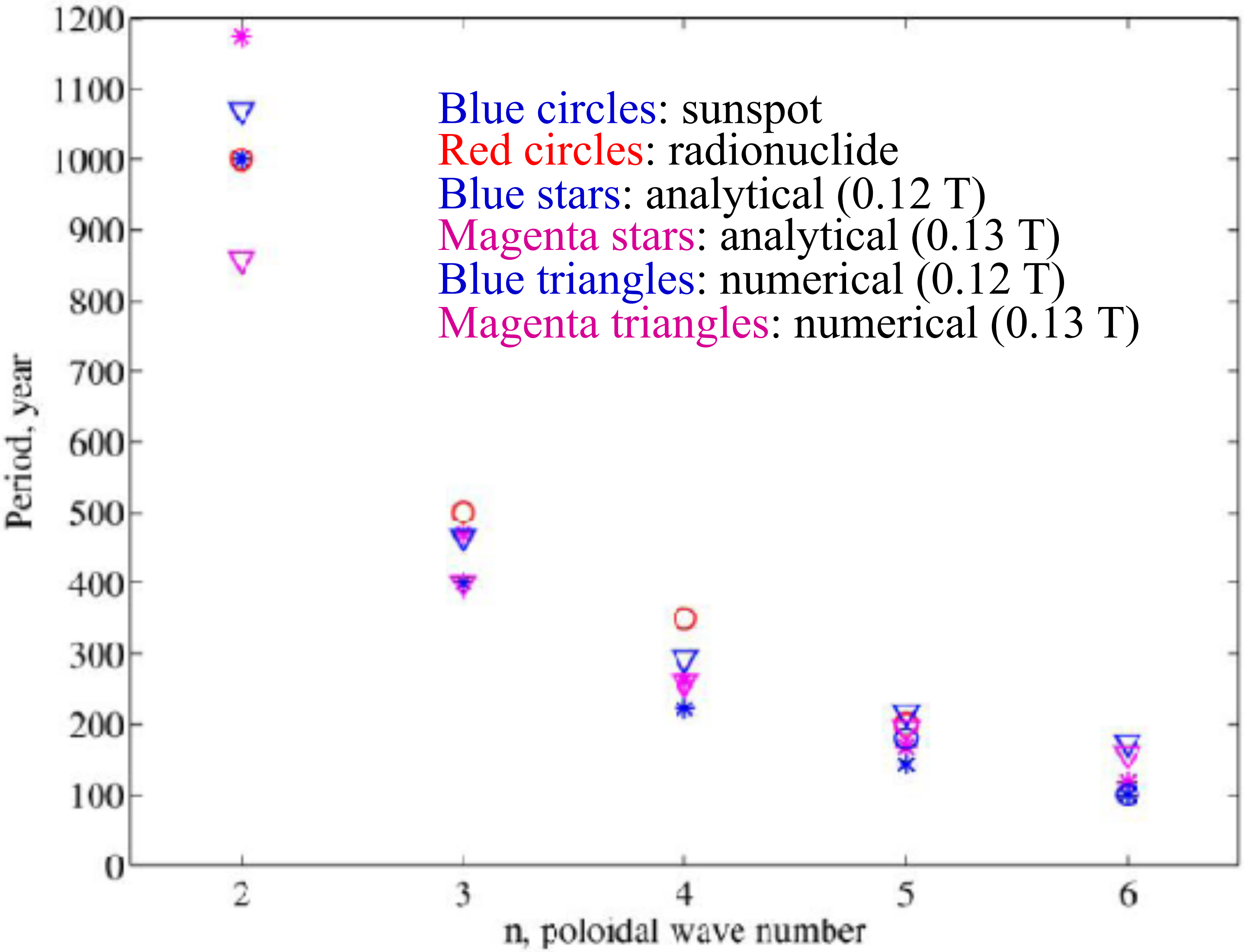
$$\Omega(\theta) = \Omega_0 \left[1 - s_2 \cos^2\theta - s_4 \cos^4\theta\right],$$

which is symmetric with regards to the equator.

Magnetic field is taken to be

$$B_\varphi = B_0 \cos\theta \sin\theta .$$

It is anti-symmetric with regards to the equator.



Zaqarashvili et al. 2015

- ➢ In order to get the observed periodicity, the strength of the toroidal magnetic field needs to be 0.12-0.13 T.

- ➢ However, dynamo magnetic field in the tachocline is believed to be 1-10 T!

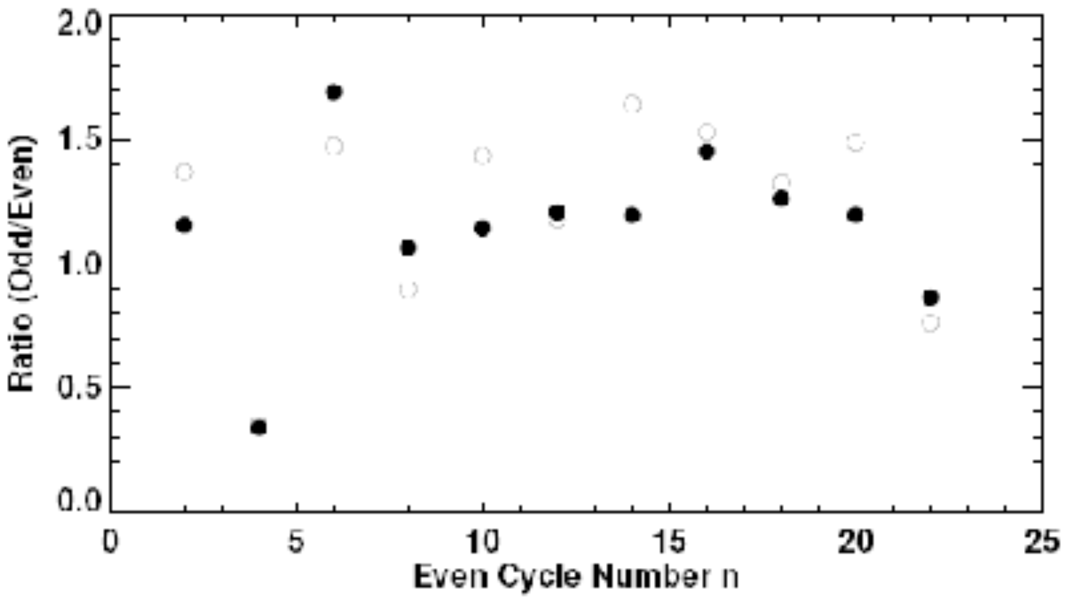
- ➢ Hence, dynamo generated magnetic field can not be responsible to explain the observed periodicity.

- ➢ If one averages the dynamo magnetic field over longer time interval then the cycle length (11 years), then it is zero due to consecutive sign reversals.

- ➢ Therefore, it is clear that the dynamo magnetic field can not influence the long-term dynamics of the tachocline.

➢ However, the fossil (primordial) magnetic field, which is formed during the Sun's collapse, could remain in the interior.

➢ This magnetic field is one of mechanisms which supports the observed solid body rotation of the radiative interior.



Hathaway (2010)

➢ The primordial magnetic field may explain Gnevyshev-Ohl rule (Gnevyshev and Ohl 1948) that the odd cycles are generally stronger than even cycles (Boyer and Levy 1984).

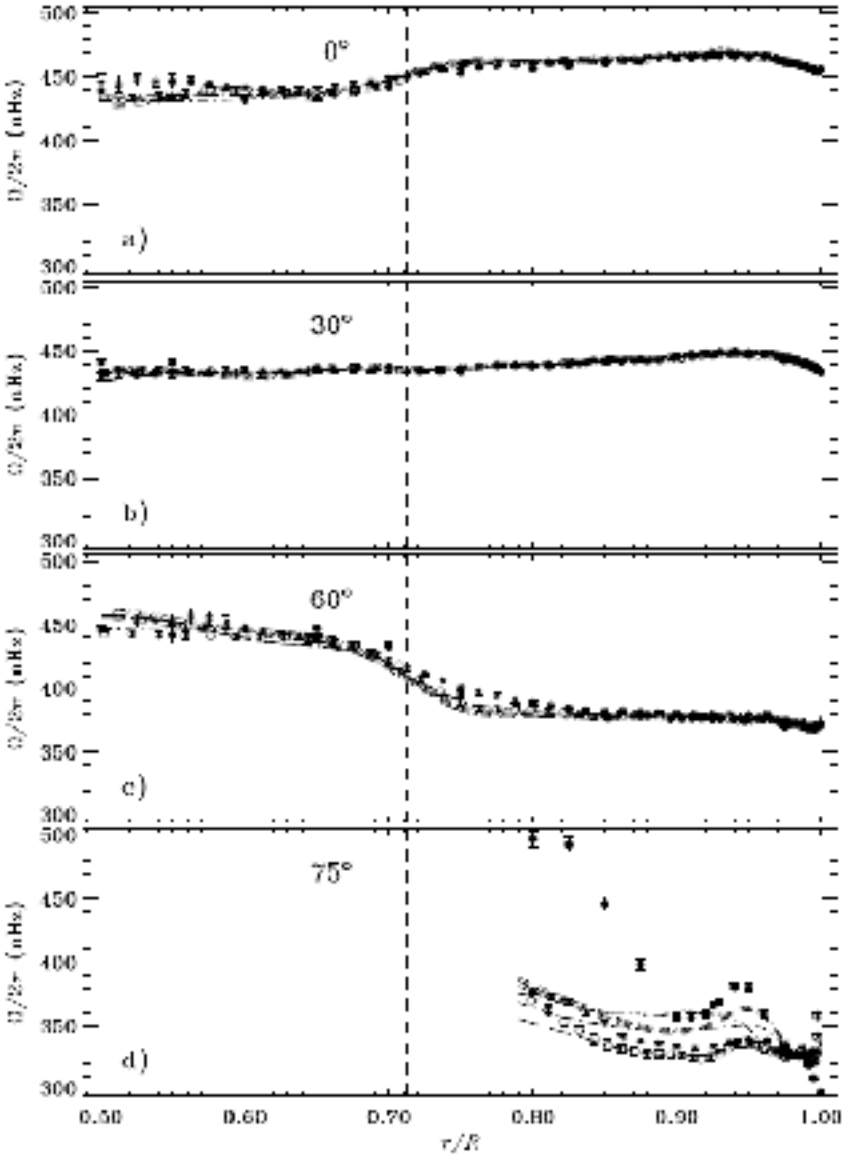
- The strength of primordial magnetic field in the interior is controversial.

- The field strength deep in the radiative interior was estimated as 0.1 T (Gough and McIntyre 1998), which is very close to the required value.

- The strength of magnetic field in the upper part of radiative interior, which is in equipartition with the kinetic energy of turbulent pumping from the convection zone, is about 0.1 T.

- The toroidal field strength in the upper part of radiative interior in equipartition with the energy of latitudinal differential rotation is 0.1 T if the differential rotation parameters s_2 and s_4 are 0.01.

- But, solar differential rotation parameters are around 0.14, which gives the equipartition field strength of 1 T.



Schou et al. (1998)

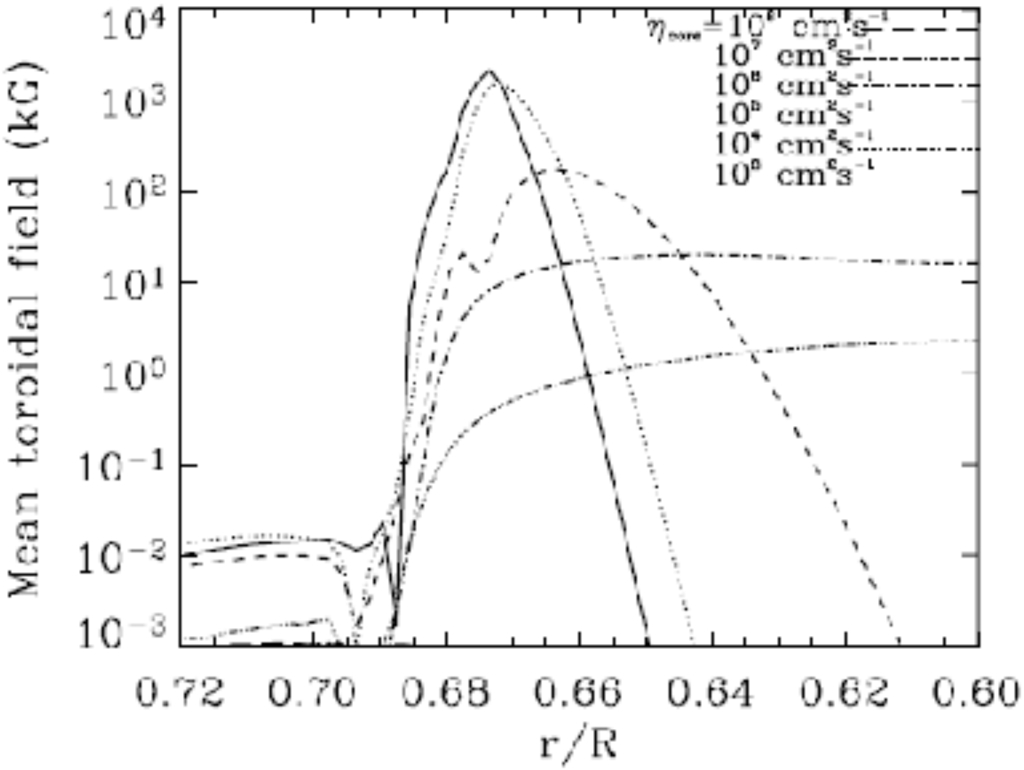
➢ The center of the tachocline is located at 0.7-0.71 R and it has negligible thickness of 0.05 R.

➢ At 0.7 R (middle tachocline) differential rotation parameter s_2 =0.1, which is closer to the main value of differential rotation.

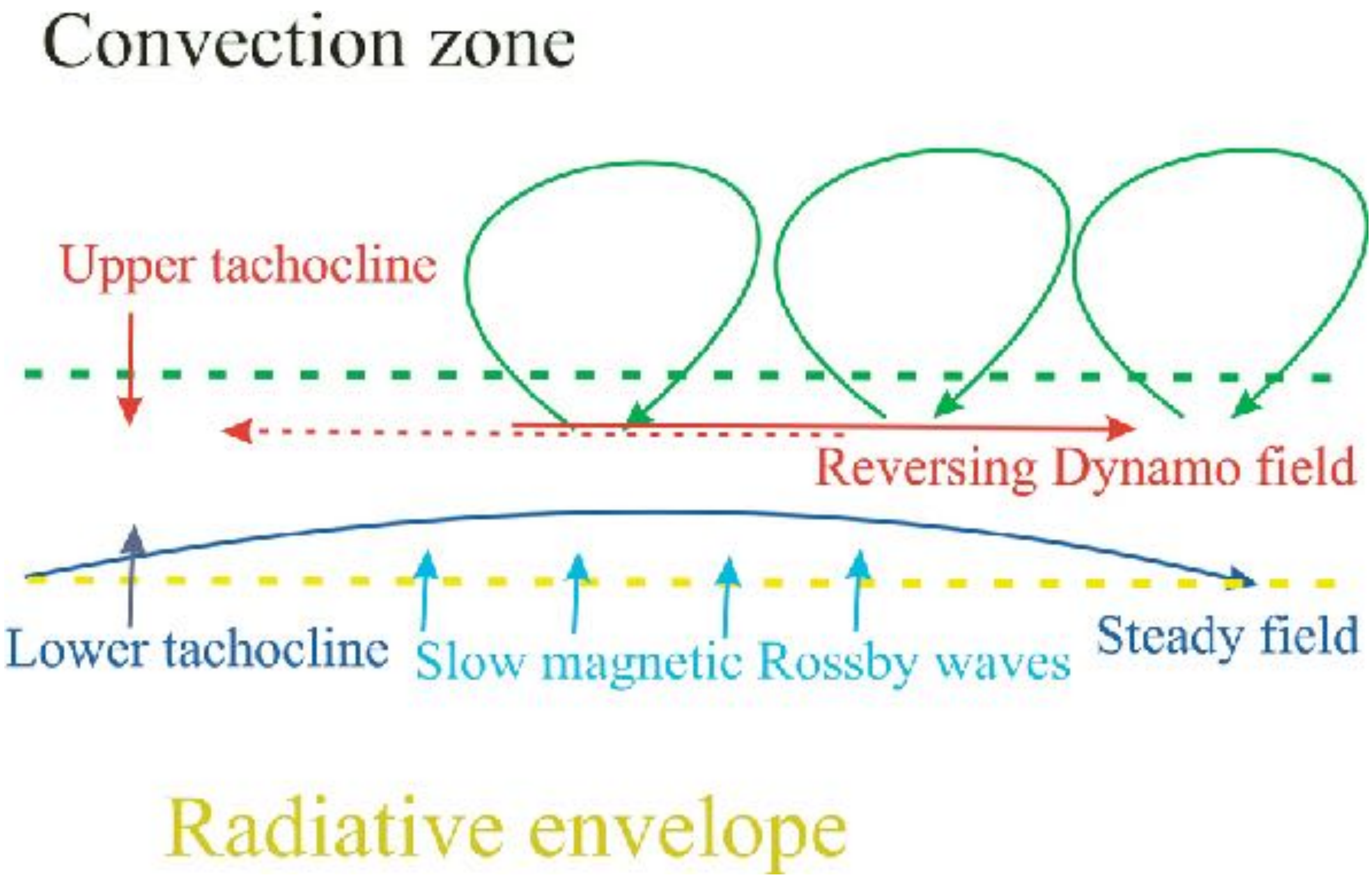
➢ At 0.68 R (lower tachocline) the differential rotation parameter s_2 =0.015, which is almost the value which we need!

In order to get the observed periodicity, the strength of steady toroidal magnetic field needs to be 1.2-1.3 kG.

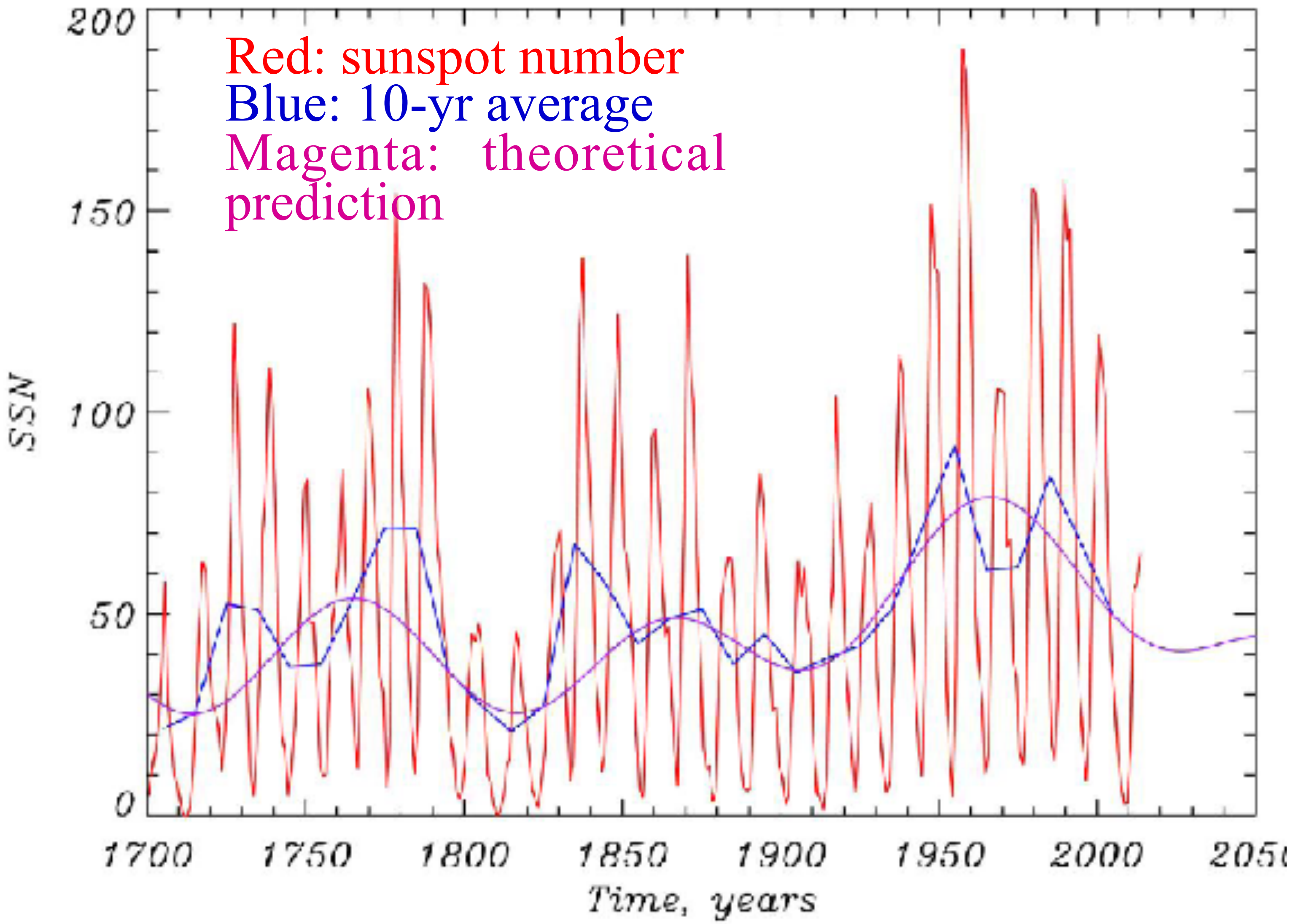
Dikpati et al. (2006) showed that a steady (nonreversing) dynamo for a low magnetic diffusivity may generate steady toroidal field with strength of 1 kG in the lower tachocline.



Dikpati et al. (2006)

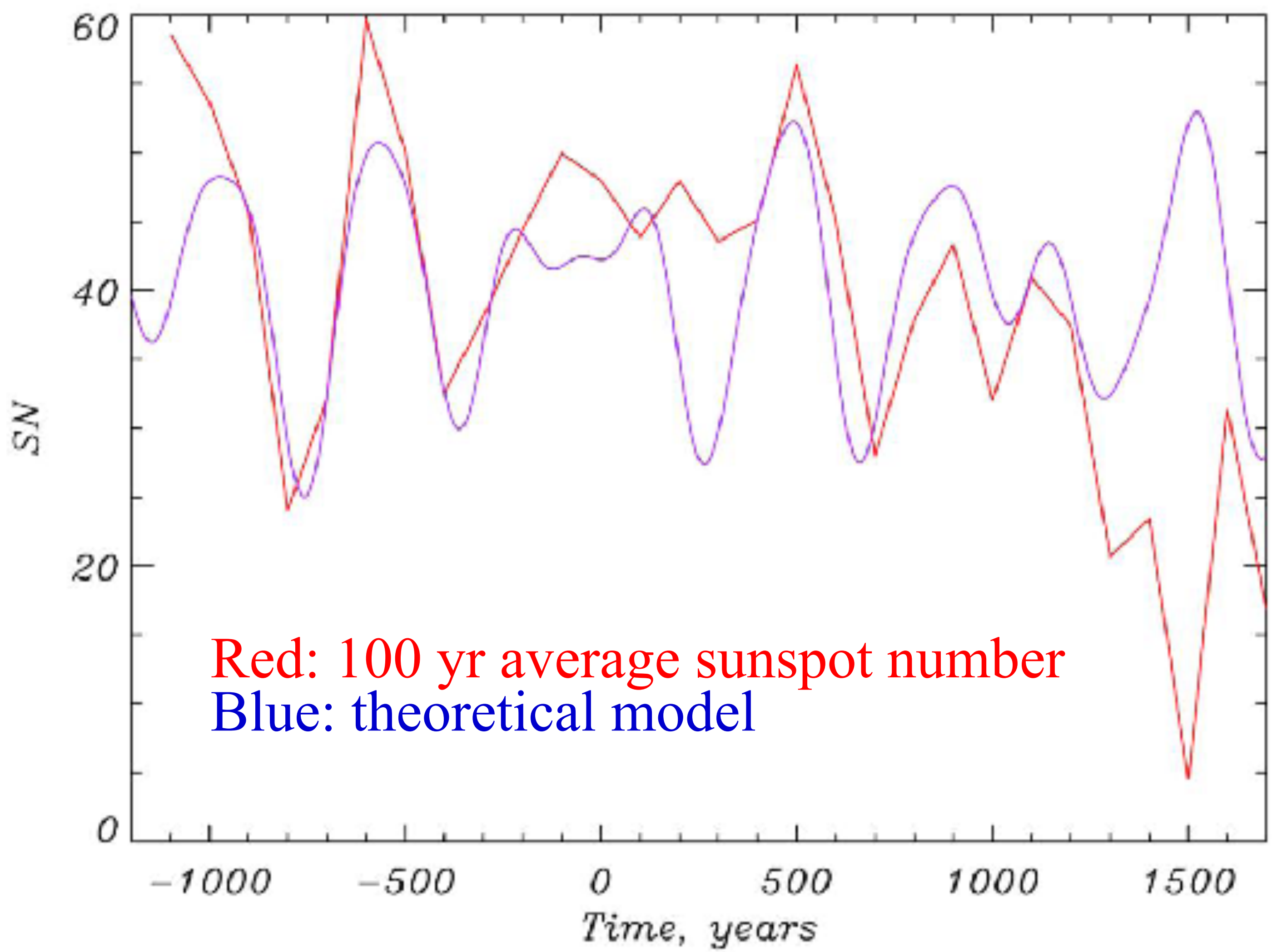

Convection zone
Upper tachocline
Reversing Dynamo field
Lower tachocline
Slow magnetic Rossby waves
Steady field
Radiative envelope

Predictions of future solar activity



Zaqarashvili et al. (2015)

Modeling of past solar activity



Zaqarashvili et al. (2015)

Conclusions

➢ Sunspot numbers and concentration of cosmogenic radionuclide on the Earth show the variation of solar activity with periods of 1000, 500, 350, 200, 100 years.

➢ These periods correspond to the periods of slow magnetic Rossby wave spherical harmonics if the fossil magnetic field has strength of 0.12-0.13 T.

➢ The theory of magnetic Rossby waves allows the long-term prediction of solar cycle strength.

➢ According to our model, the next deep minimum in the solar activity will occur near 2030 year.