Rossby waves and solar activity variations

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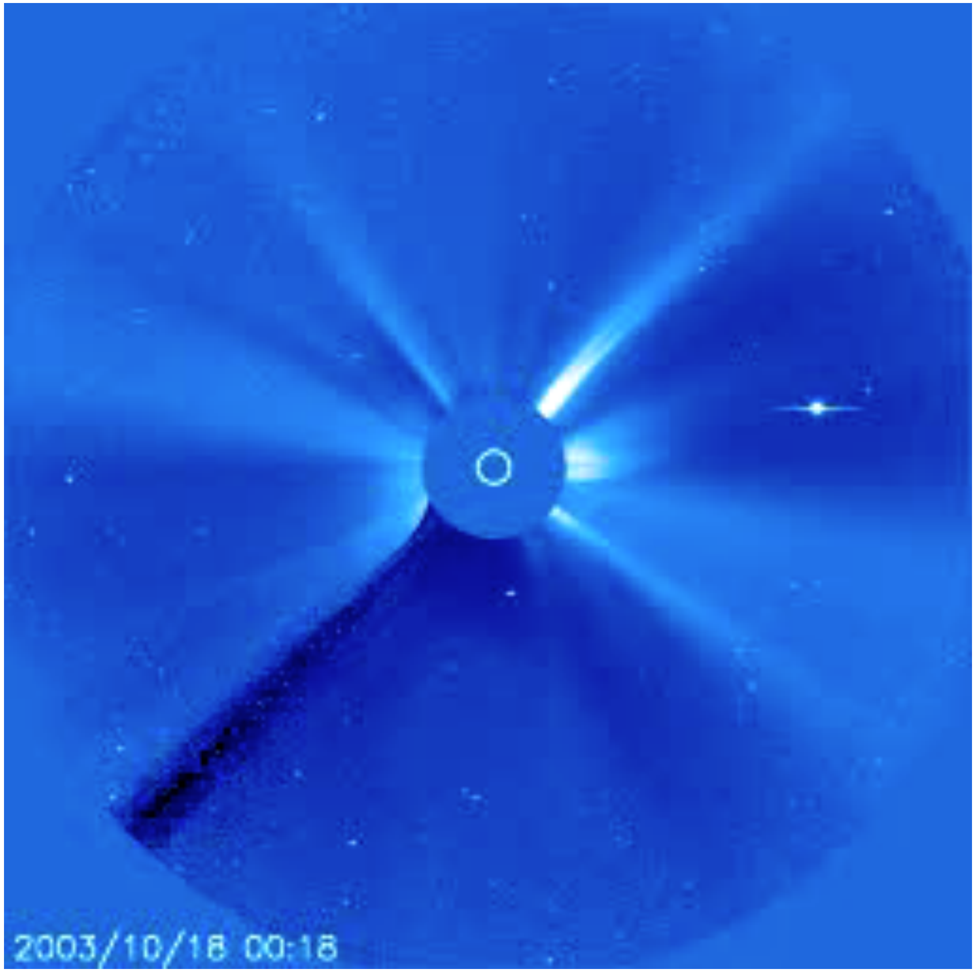
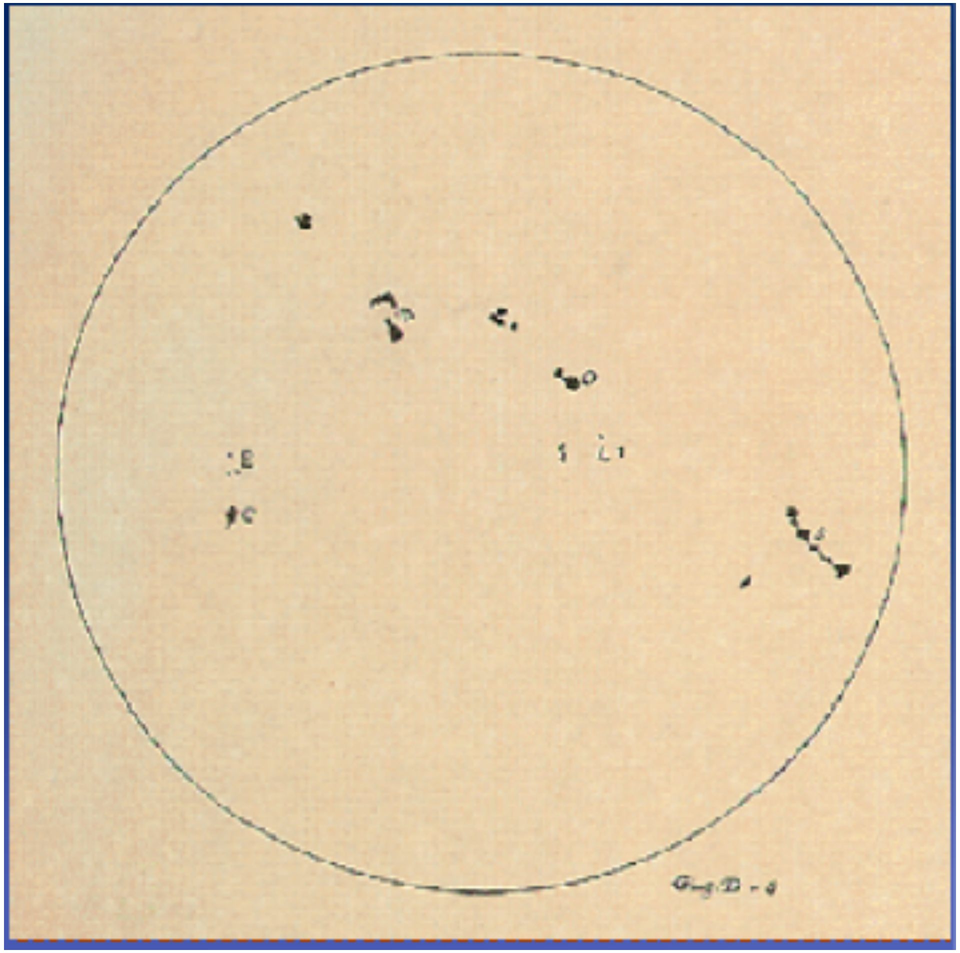
- Huge energy released during solar flares and coronal mass ejections causes magnetic storms in the Earth's magnetosphere.

- These storms may lead to damage of satellites and telecommunication systems.

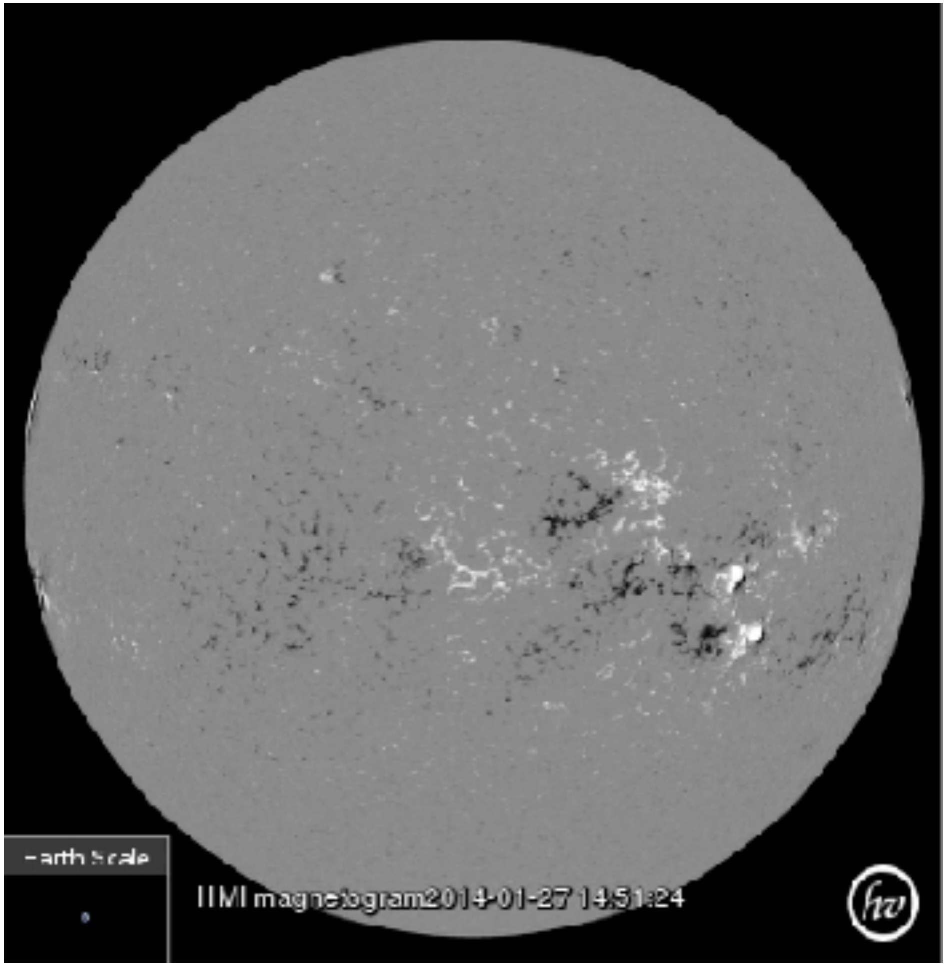


Sunspots were discovered by Galileo Galilei.

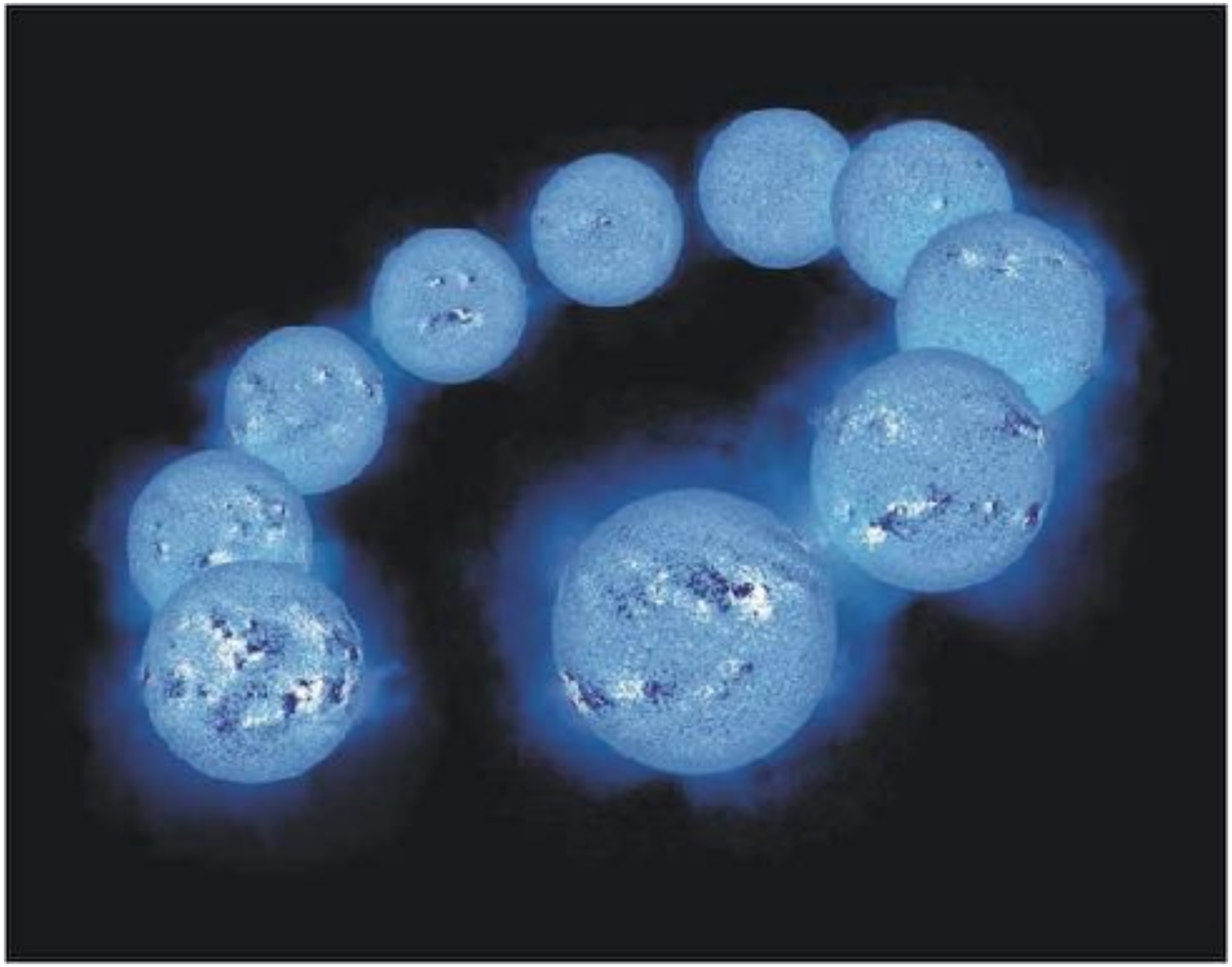

Galileo portrait in crayon by Leoni.



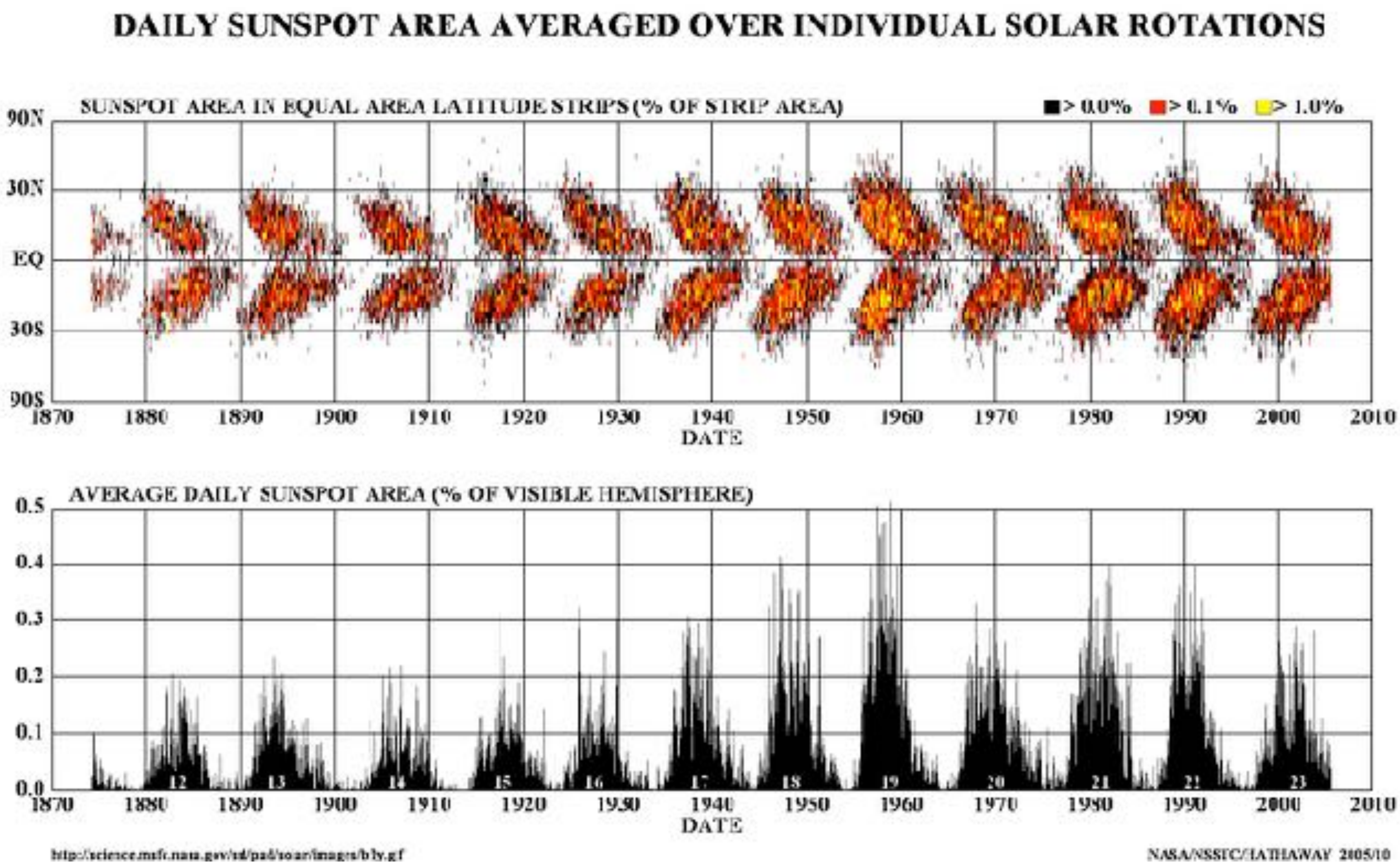
Sunspots are locations of strong magnetic field in the solar surface.



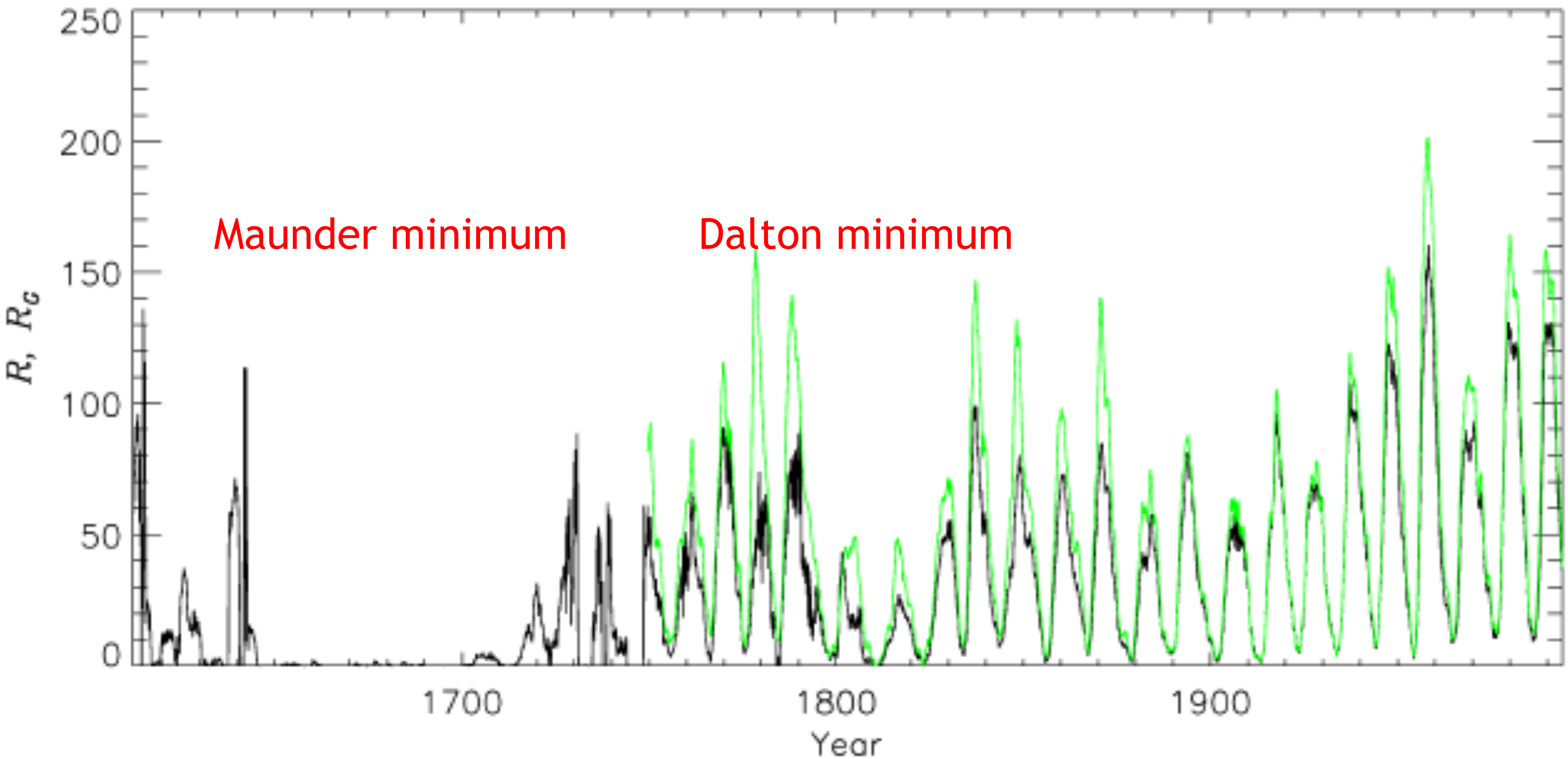
The solar activity has the main periodicity of 11 years.



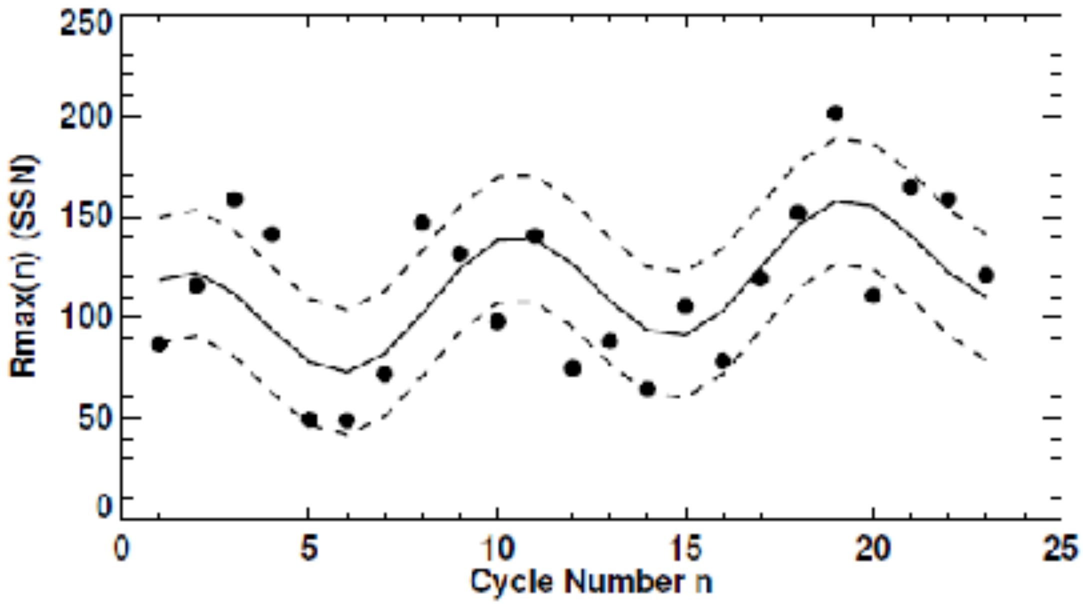
Solar activity undergoes the variations over shorter and longer time scales than the period of solar cycles.



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

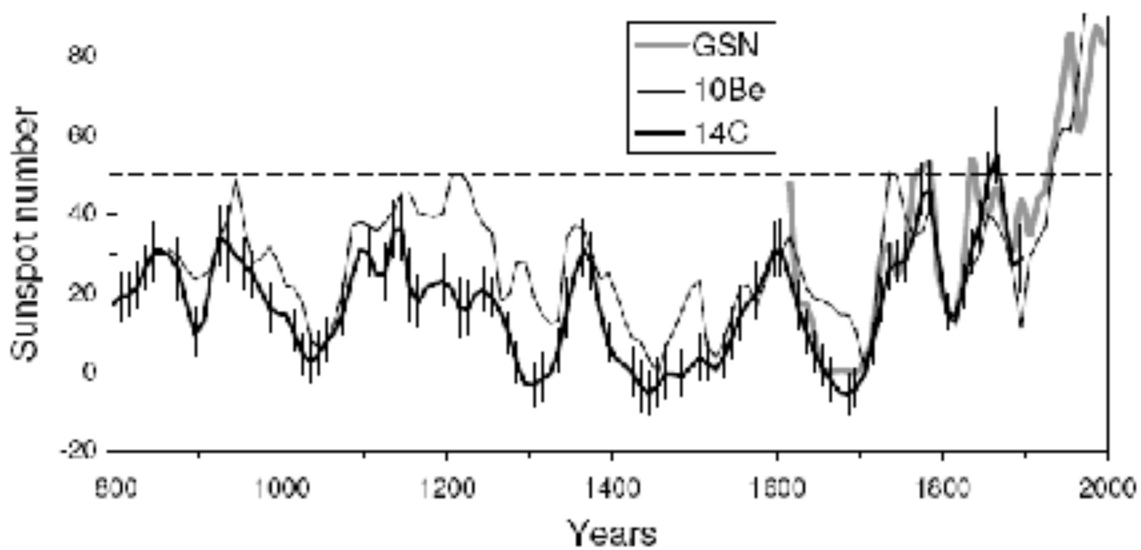


Petrovay (2010)



Gleissberg cycle
(~ 100 years)

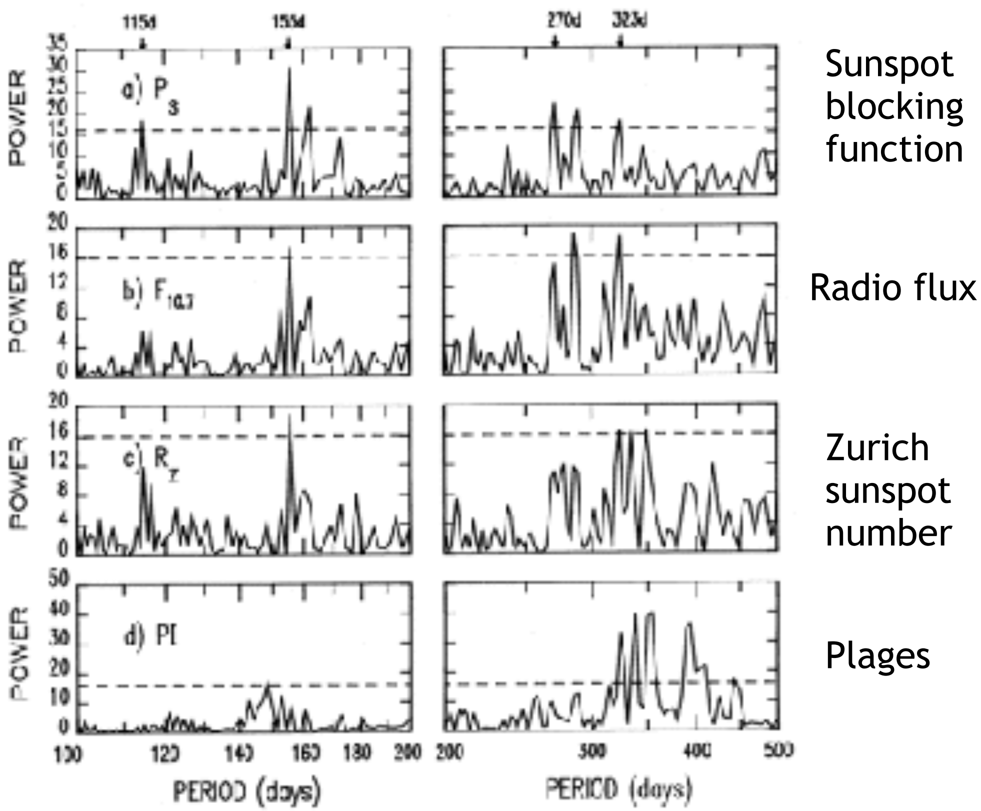
Hathaway (2010)



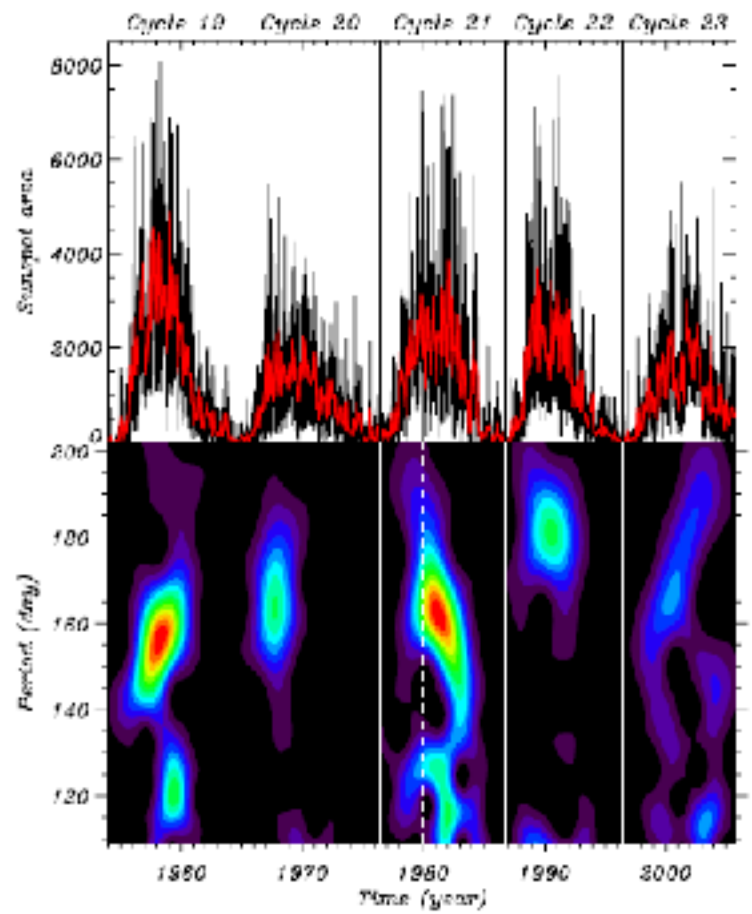
Usoskin (2008)

Rieger periodicity

Rieger et al. 1984, Lean and Brueckner 1989, Carbonell & Ballester 1990,92, Oliver et al. 1998, Ballester et al. 1999.



Lean and Brueckner 1989

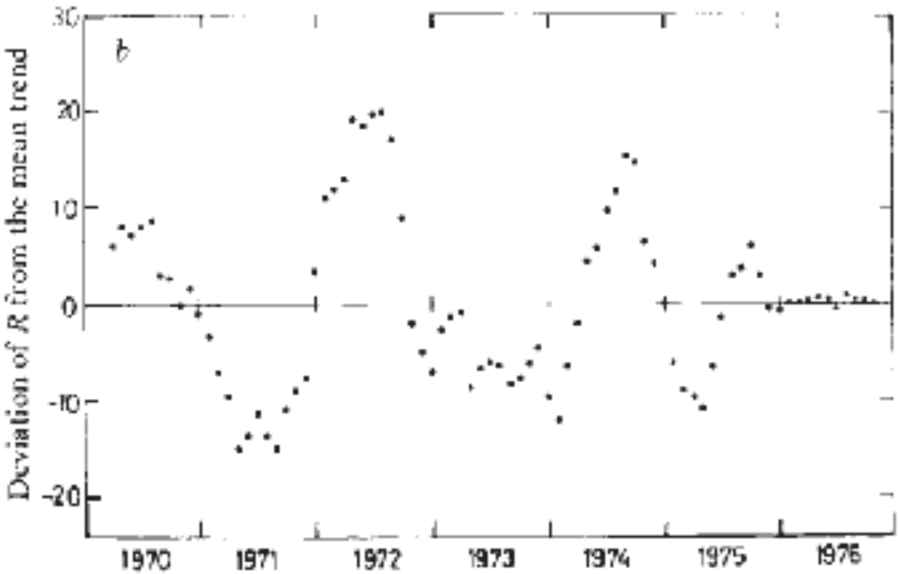


Zaqarashvili et al. 2010

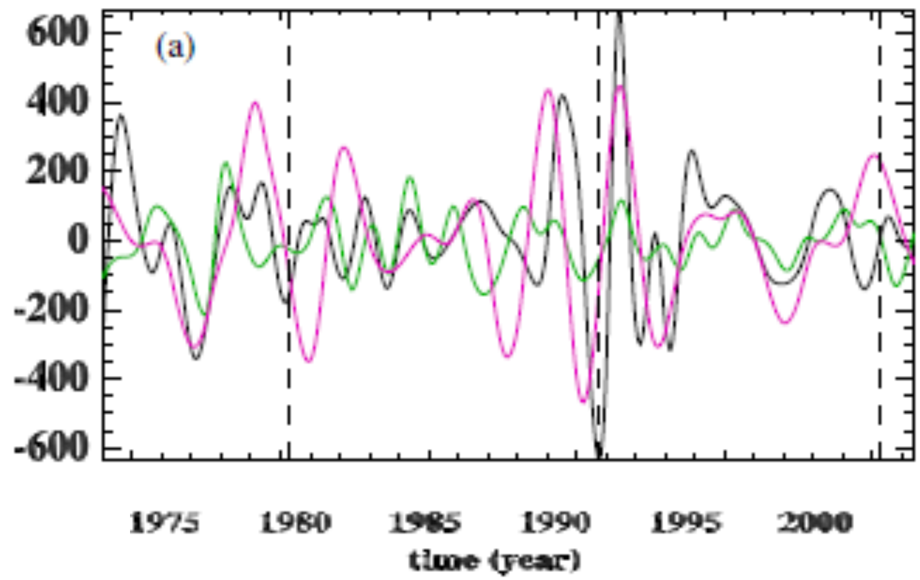
Quasi-biennial oscillations

The deviation of the relative sunspot numbers from the mean trend.

•Proton flux (black)
•coronal green line (green)
• sunspot area (purple).



Sakurai 1979



Vecchio et al. 2010

Annual oscillations: Scott's talk tomorrow!

Sturrock et al. (1999) made first suggestion to connect Rieger periodicity with Rossby waves. They suggested that 52, 78 and 154 day periodicities in solar activity could be connected to r modes (which are actually Rossby waves). They used the dispersion relation (Haurwitz 1940, Longuet-Higgins 1968, Papaloizou and Pringle 1978):

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

154 days: m=1, n=3

78 days: m=2, n=3

52 days: m=3, n=3

Lou (2000) made the second attempt to connect the Rieger periodicity with Rossby waves

$$\frac{\partial}{\partial t}\left[\frac{1}{c^2}\left(\frac{\partial^2}{\partial t^2}+f^2\right)-\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)\right]u_y-\frac{\partial f}{\partial y}\frac{\partial u_y}{\partial x}=0.$$

He used the beta-plane approximation, which gives the equation

$$\frac{\partial^2 v}{\partial y^2}+\left(\frac{\omega^2}{c^2}-k_x^2-\frac{k_x\beta}{\omega}-\frac{\beta^2}{c^2}y^2\right)=0.$$

$c=\sqrt{gH}$ is the surface gravity speed.

This is the equation of parabolic cylinder and its solutions can be expressed in terms of Hermite polynomials when

$$\frac{c}{\beta}\left(\frac{\omega^2}{c^2}-k_x^2-\frac{k_x\beta}{\omega}\right)=2n+1$$

It gives the dispersion relation for equatorially trapped waves

$$\omega^3 - \left[k_x^2 c^2 + (2n+1)\beta c\right]\omega - \beta k_x c^2 = 0$$

Equatorially trapped Rossby wave dispersion relation is (Lou 2000)

$$\omega \cong -\frac{\beta k_x c}{k_x^2 c + (2n+1)\beta}$$

Then using $k_x = m / R$ one gets

$$P \cong 25.1\left(\frac{|m|}{2} + 0.17\frac{2n+1}{m}\right) days$$

Observed Rieger-type periodicity of 155-160 days can be obtained for n=1, m=12 (152 days) or n=1, m=13 (164 days) harmonics.

However, equatorially trapped Rossby wave theory has two important problems.

1) Longuet-Higgins (1968) showed that shallow water waves are expressed by Weber equation and hence are confined to the equator when

$$\varepsilon = \frac{\beta^2}{c^2} = \frac{4\Omega^2 R^2}{gH} >> 1$$

In the opposite limit $\varepsilon << 1$ the waves are redistributed along whole latitude range.

In the case of solar parameters used by Lou (2000) $\varepsilon = 0.12 << 1$,

which means that the waves are not trapped near the equator.

Lou (2000) showed that the critical latitudes are $\pm 60^0$: they are significantly far from the equator.

Consideration of either reduced gravity or magnetic field may help the theory.

2) The wave numbers, which give Rieger periodicity are unrealistic. It is unclear why m=12,13 should be dominated over m=2-4.

Next, Zaqarashvili et al. (2010a,b) suggested that the instability of fast magnetic Rossby waves in the solar tachocline can be responsible for the observed mid-range periodicities.

They showed that the differential rotation and the toroidal magnetic field in the tachocline allows m=1 harmonic to grow exponentially.

Yellow – 2×10^3 G,

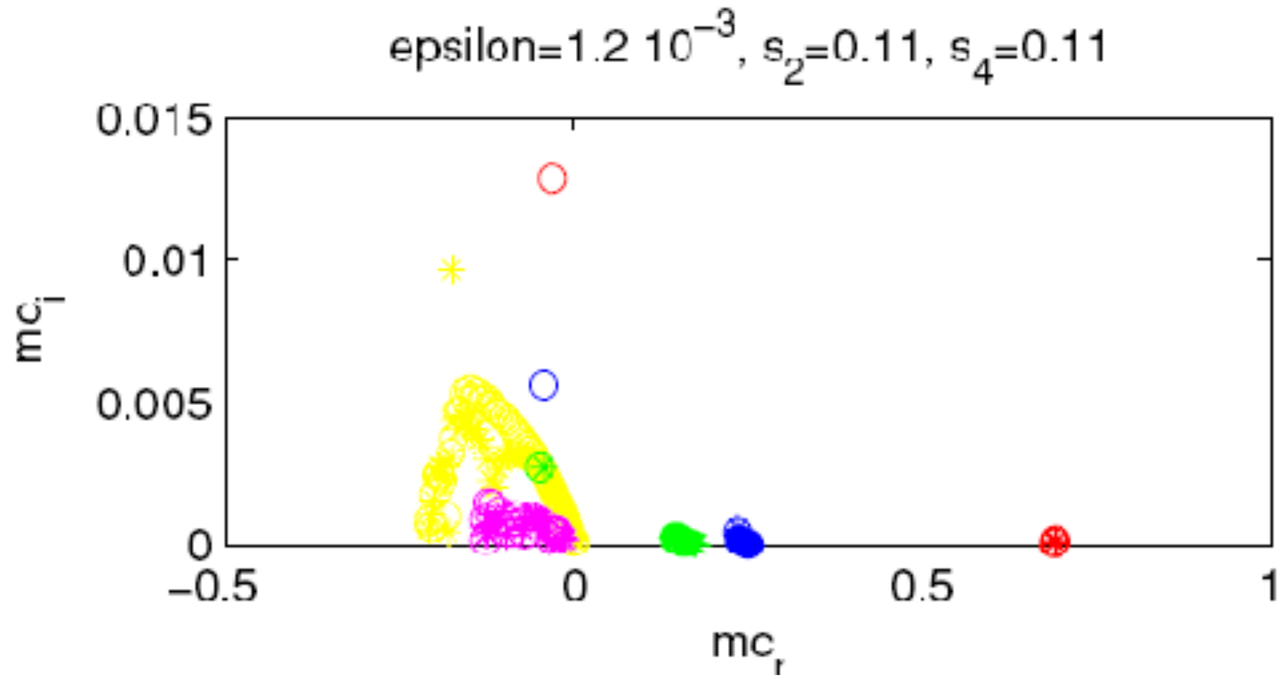
magenta - 2×10^4 G,

blue - 6×10^4 G,

green - 8×10^4 G,

dark blue- 10^5 G,

red - 2×10^5 G.



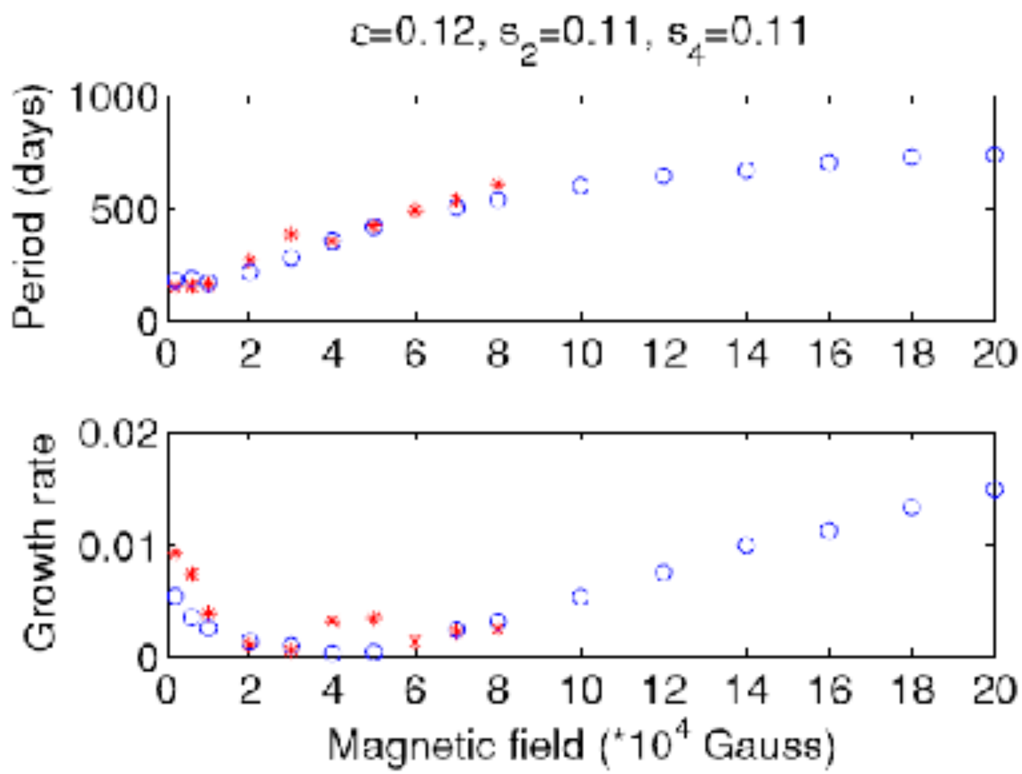
Zaqarashvili et al. 2010a

Unstable harmonics of fast magnetic Rossby waves for 10 kG magnetic field have periods of 150-160 days, which coincide to the Rieger-type periodicities.

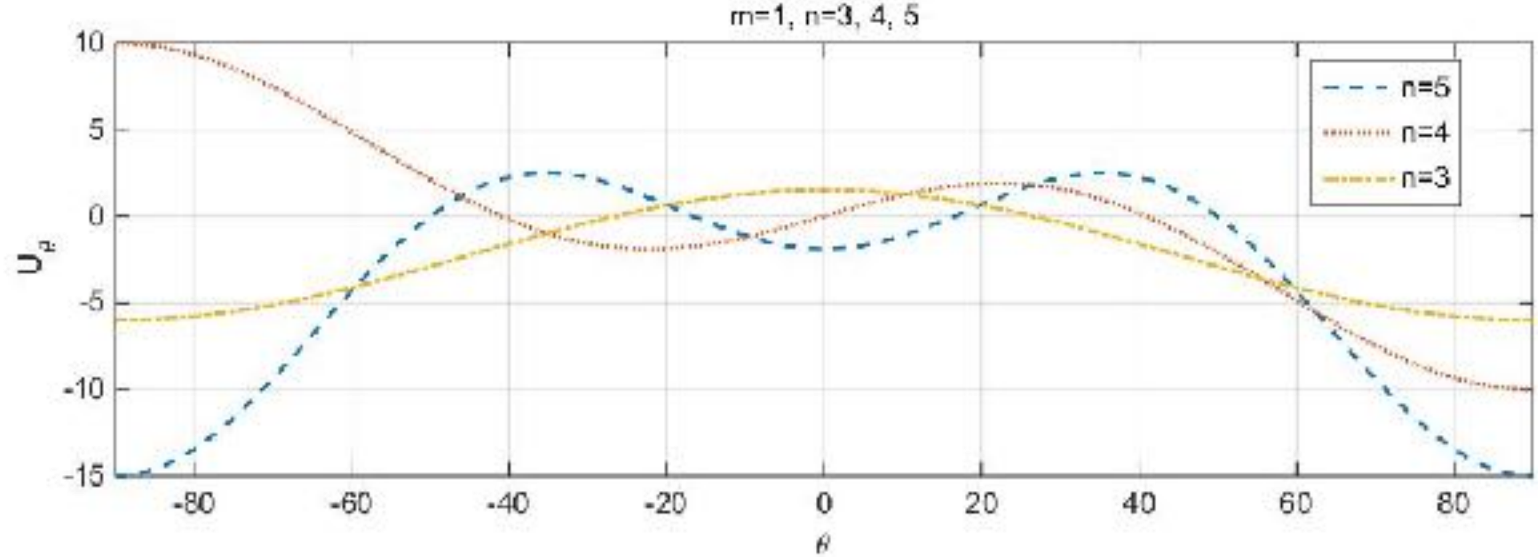
Unstable harmonics for 100 kG magnetic field have periods of ~2 years, which coincide to quasi-biennial oscillations.

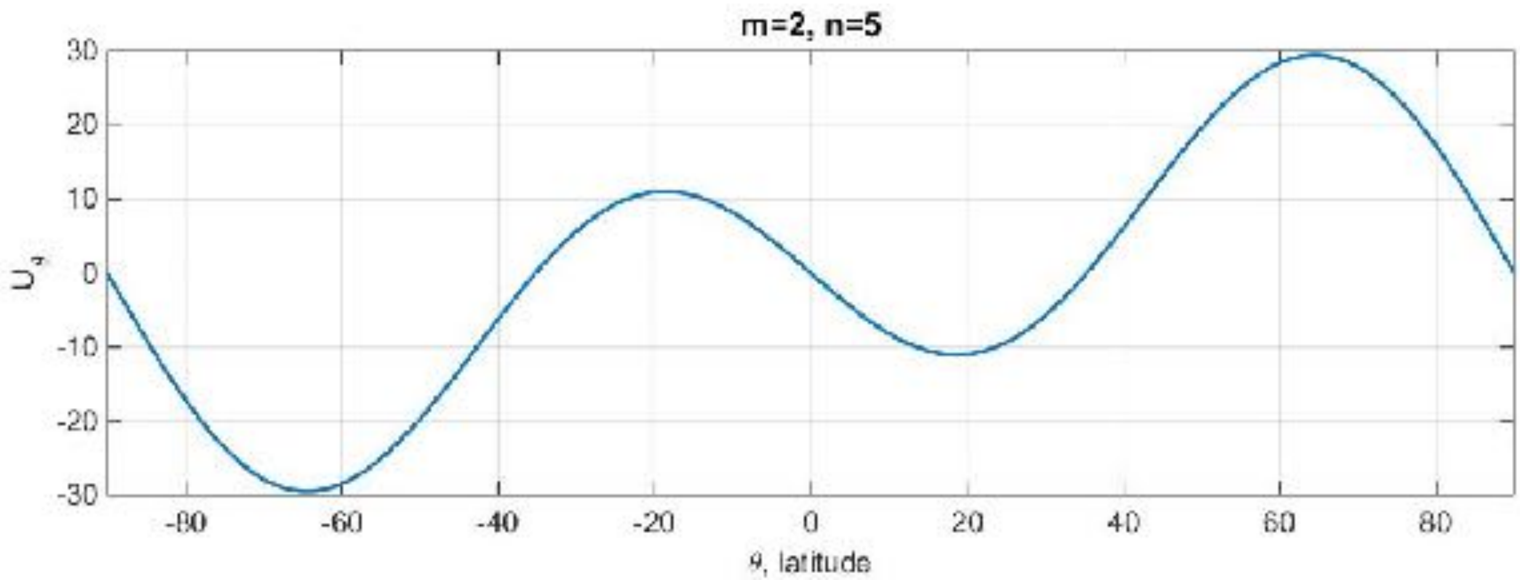
Asterisks: symmetric harmonics

Circles: anti-symmetric harmonics.

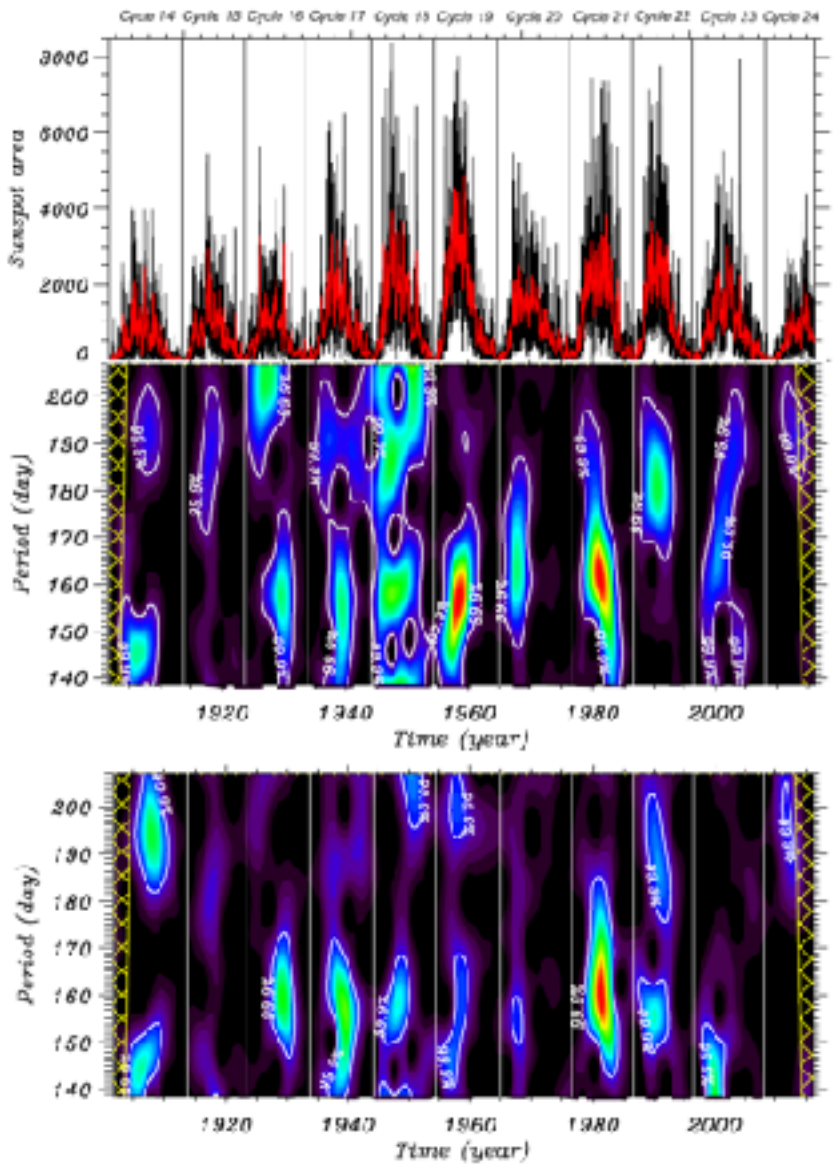


Zaqarashvili et al. 2010b


m=1, n=3, 4, 5
n=5
n=4
n=3
U_θ
θ
10
5
0
-5
-10
-15
-80
-60
-40
-20
0
20
40
60
80


m=2, n=5
U_ϕ
θ, latitude
30
20
10
0
-10
-20
-30
-80
-60
-40
-20
0
20
40
60
80

Gurgenashvili et al. 2016



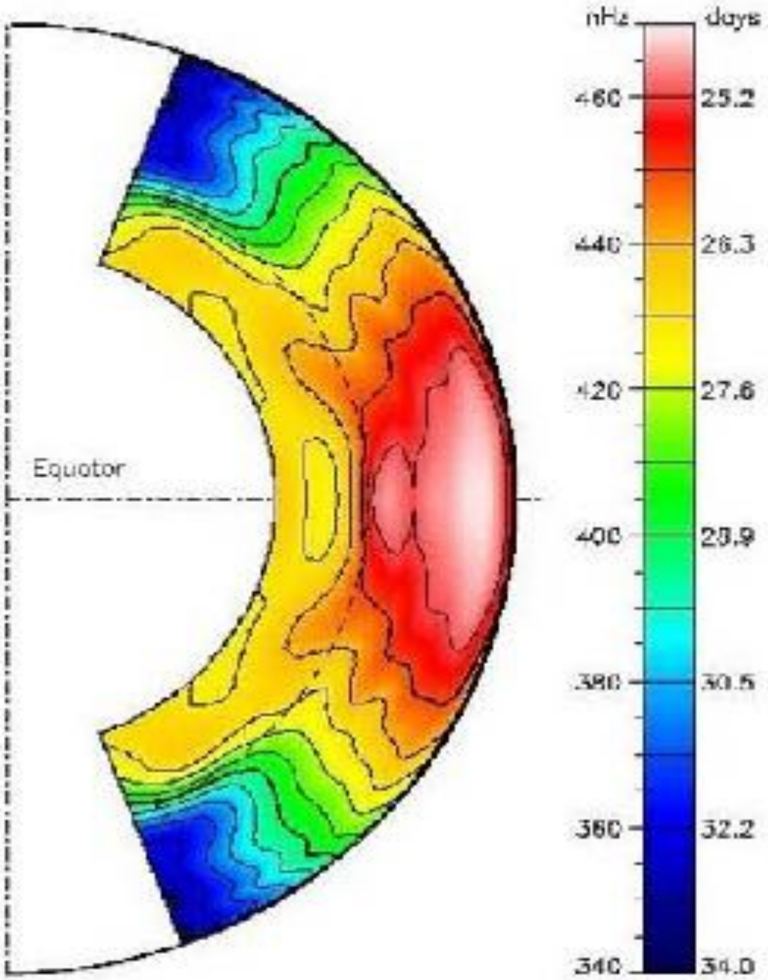
Greenwich Royal Observatory sunspot data

Royal Observatory of Belgium sunspot number data

Rieger periodicity is correlated with solar cycle strength: stronger cycles yield shorter periods!

The location of dynamo layer in the solar interior is an open question.

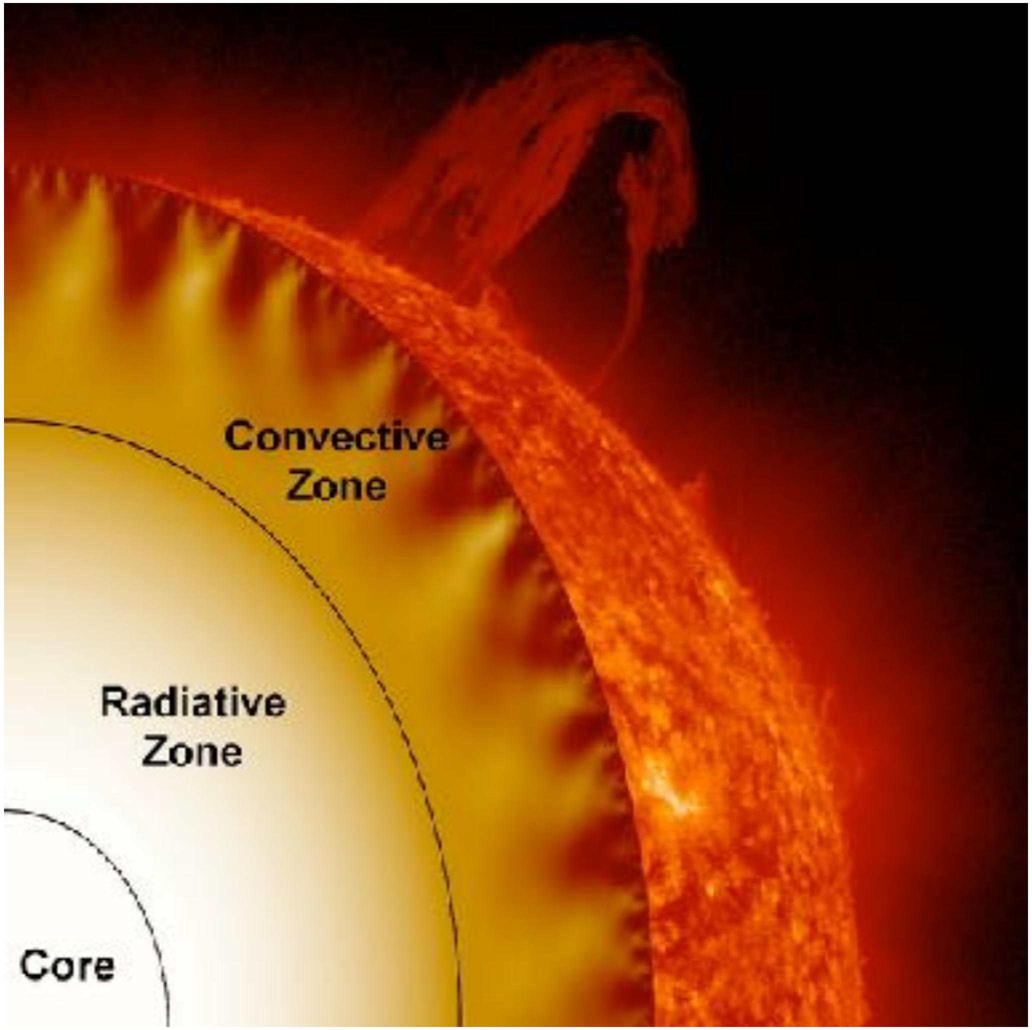
Most of dynamo models suggest that the amplification of magnetic field occurs in the tachocline (Parker 1993, Ferriz-Mas et al. 1994).



Tachocline: thin layer below the convection zone.

Importance: angular momentum redistribution and solar dynamo.

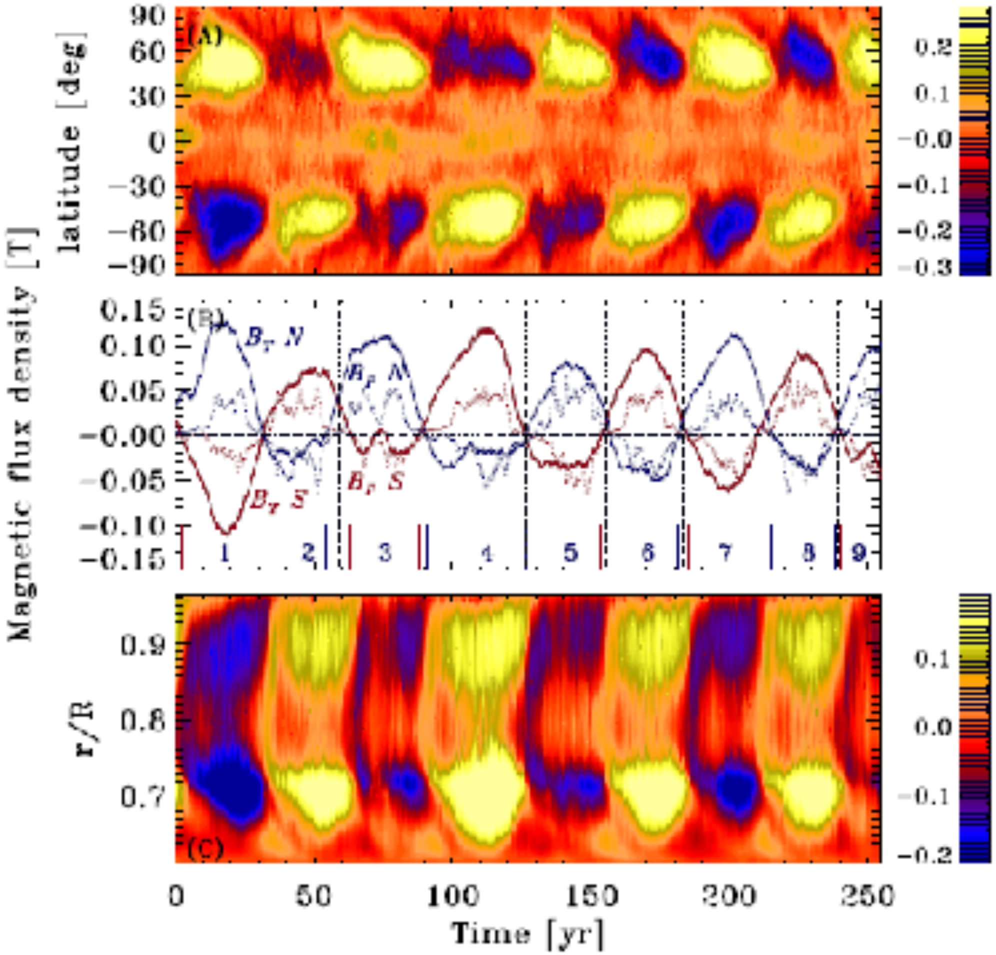
Magnetic flux tubes arise due to the magnetic buoyancy and appear at the surface as sunspots



The magnetic field strength can be estimated from simulations of rising flux tubes, which yield values of 10-100 kG (Schüssler et al. 1994, Rempel 2006).

courtesy to Marshall Space Flight Center

Recent 3D numerical simulations including convection, rotation and magnetic field showed that the stable toroidal field can be formed in the convection zone without considering the tachocline (Brown et al. 2010, 2011, Ghizaru et al. 2010, Nelson et al. 2011).



Ghizaru et al. 2010

Solar dynamo models with and without tachocline predict strong 10-100 kG (Schüssler et al. 1994, Rempel 2006) and weak 2.5 kG (Ghizaru et al. 2010) toroidal fields, respectively.

The field strength in the dynamo layer is crucial for dynamo models.

The estimation of the field strength in the solar interior may test the validity of different dynamo models.

Observed Rieger-type periodicity and magnetic Rossby wave dispersion relation may help us to estimate magnetic field (Next talk by Eka).

We need to know which harmonic(s) is actually responsible for the periodicity i.e. we need spatial structure over the sphere.

Scott's talk tomorrow!

Open questions:

1) Which Rossby model (spherical harmonics, equatorially trapped etc.) is responsible for Rieger-type periodicities? We need more theory.

2) Which harmonic(s) are responsible for the periodicity? We need spatially resolved oscillations and more theory.

3) What is the role of MHD instabilities in the excitation of Rieger periodicity? We need more numerical simulations.

4) Rieger periodicity + magnetic Rossby wave theory: seismology of solar interior? We need more observational results+ theory.