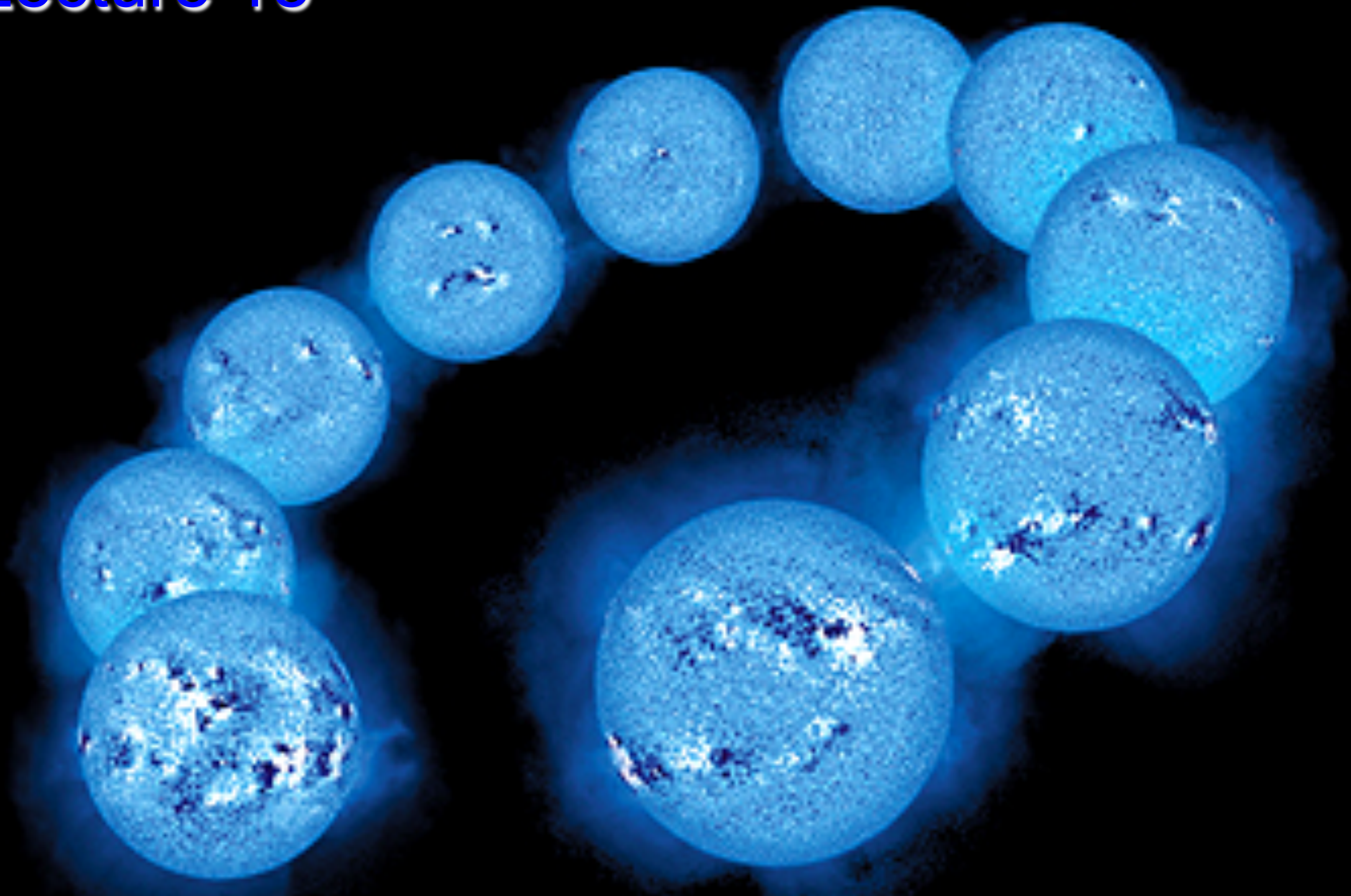
Lecture 18



Solar Magnetism - Dynamo

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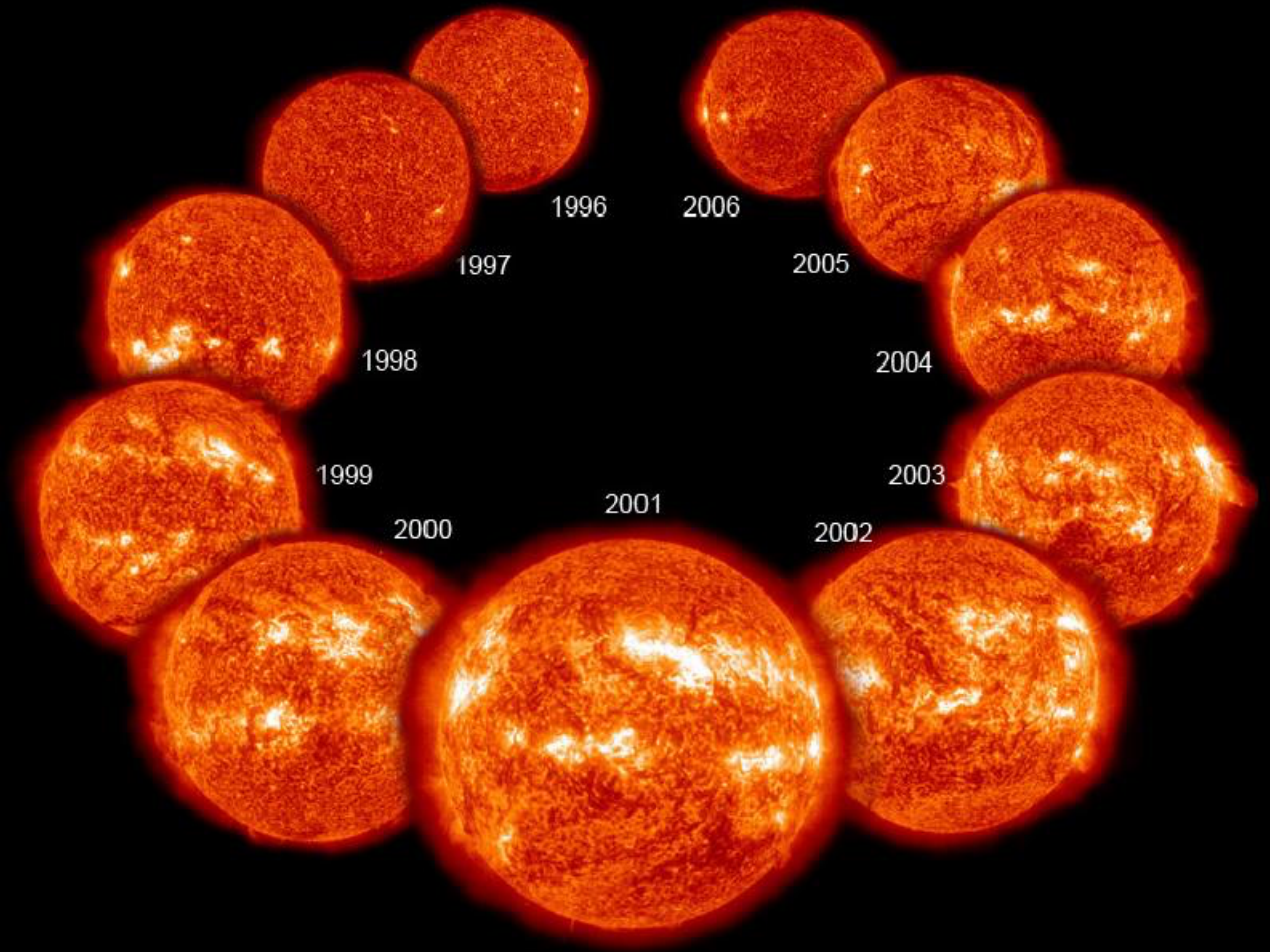
Karel J. Schrijver, NSO, NOAO and NSF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Guiding Questions

1. What is the sunspot cycle? What governs the cyclic variations in sunspot numbers and distribution?
2. Are there other solar activities exhibiting the 11-yr cycle?
3. What is the mechanism to generate the Sun's magnetic field and its cyclic behavior?
4. What roles do mass motions inside the Sun play in the solar dynamo?
5. What stars have global magnetic fields like the sun?
6. What is the technique to measure magnetic fields in celestial objects?

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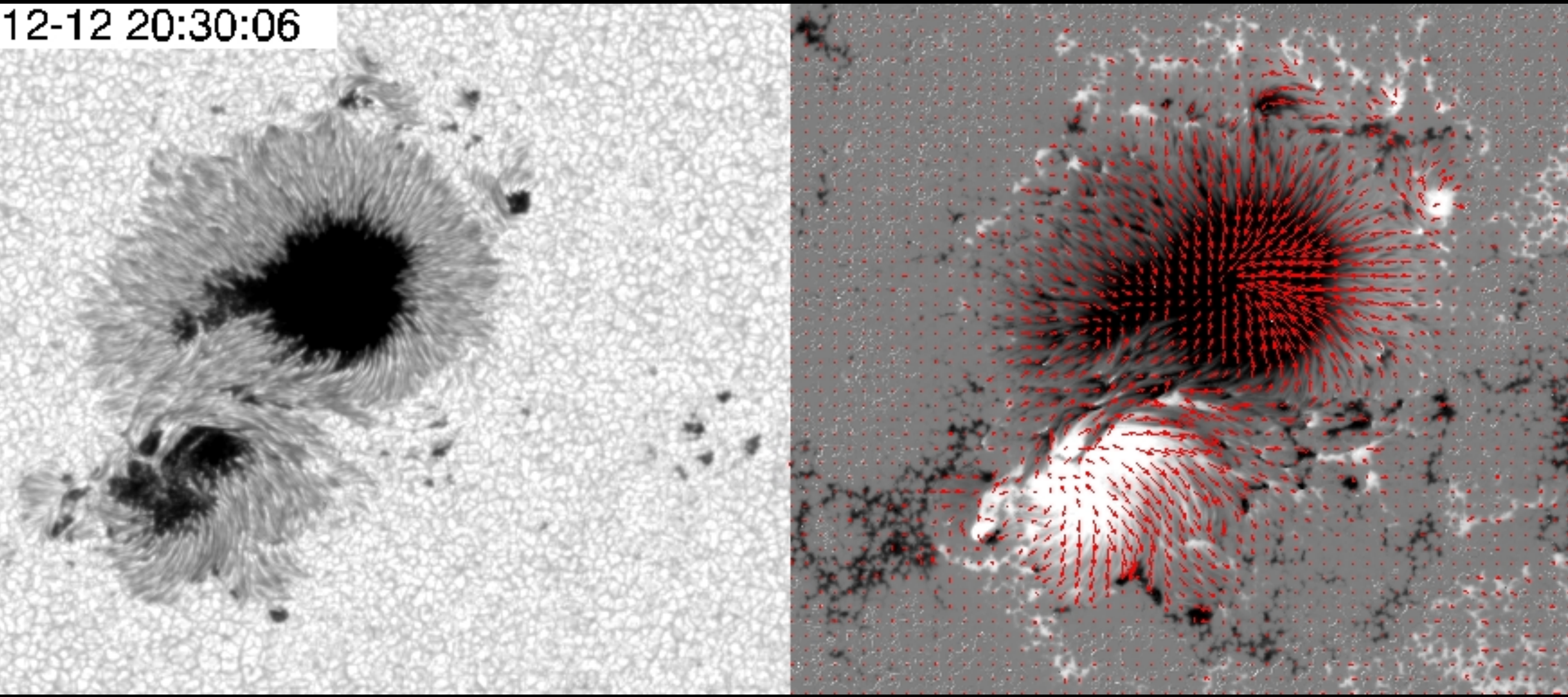
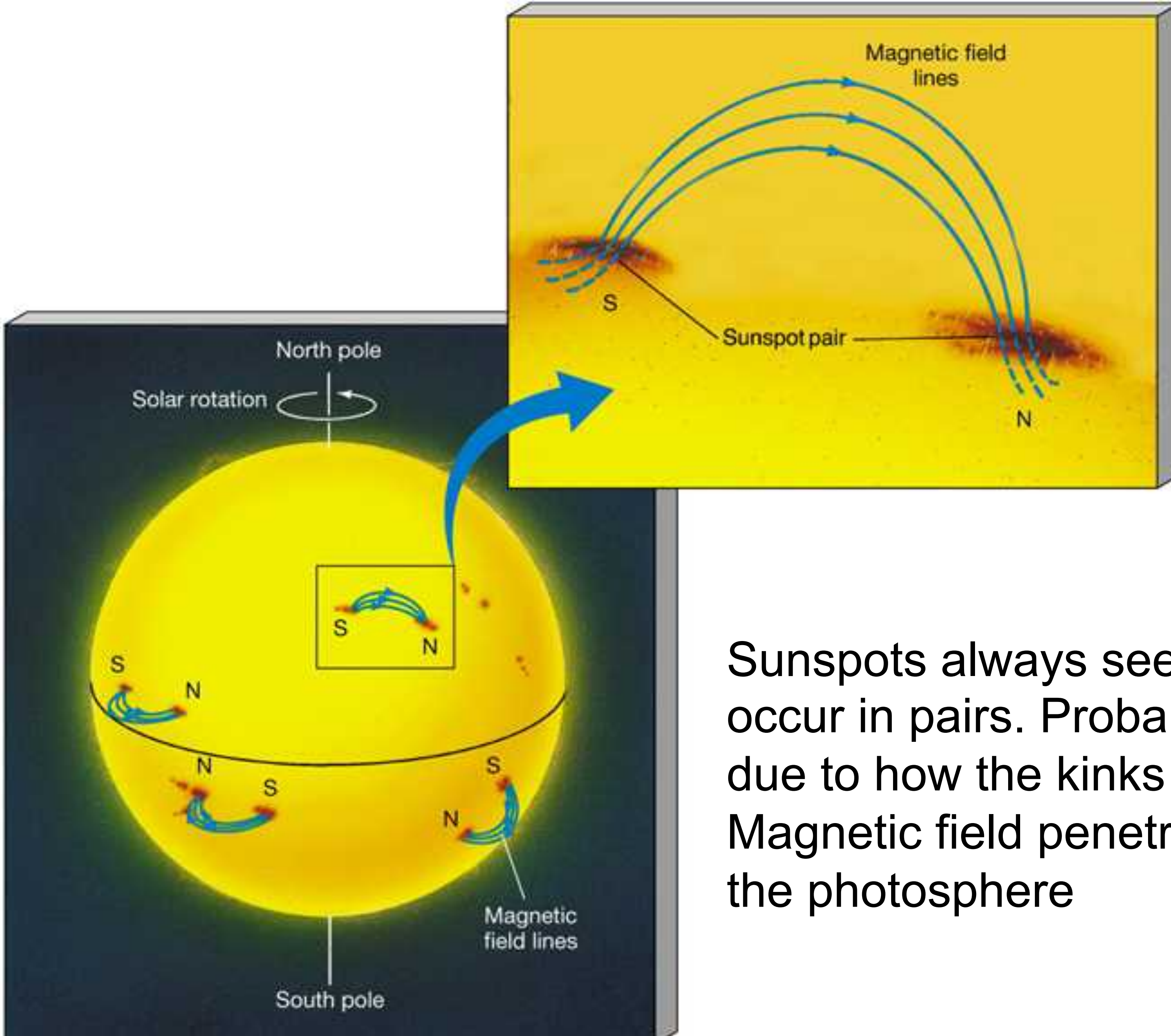
Sunspots are concentration of magnetic fields



$$\left(\frac{B^2}{8\pi} + nkT\right)_{In} = \left(\frac{B^2}{8\pi} + nkT\right)_{Out}$$

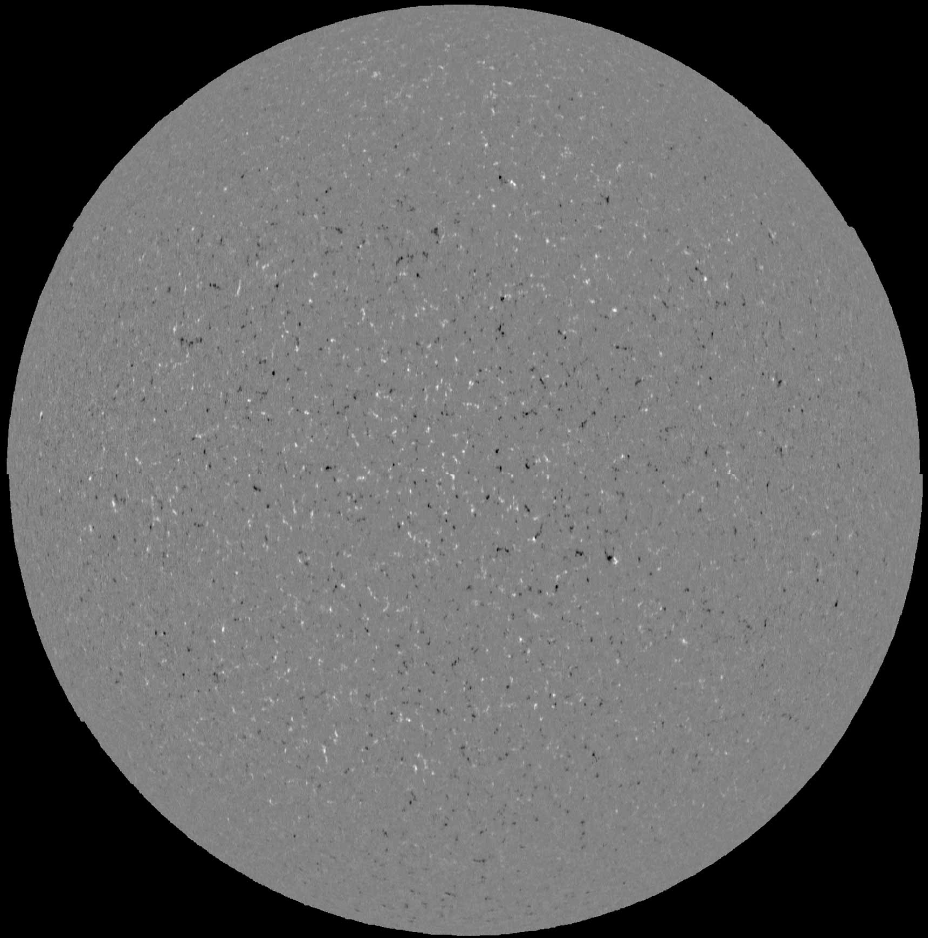
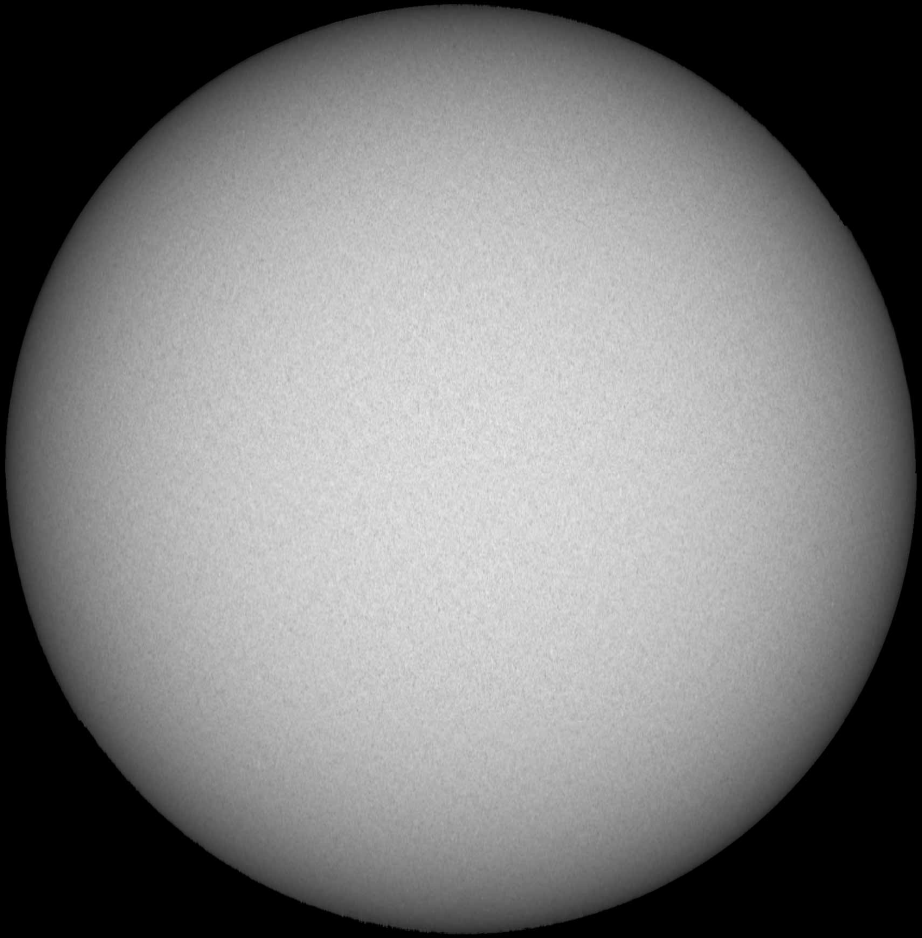


(a)

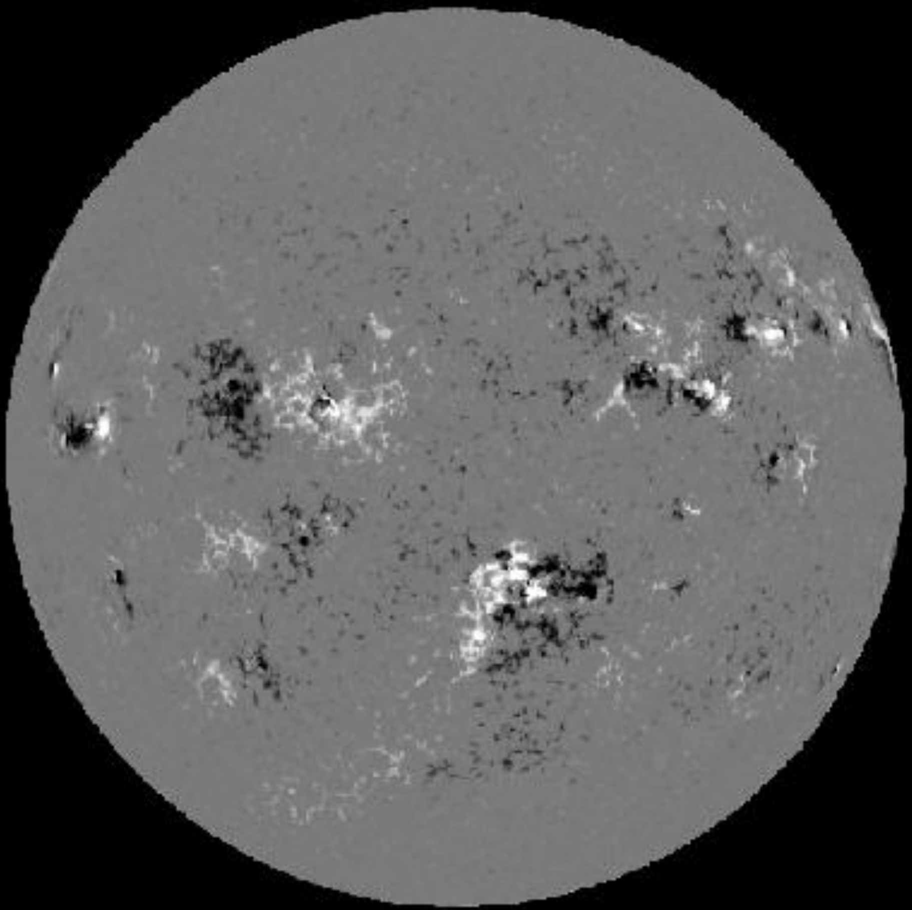
Sunspots always seem to occur in pairs. Probable due to how the kinks in Magnetic field penetrate the photosphere

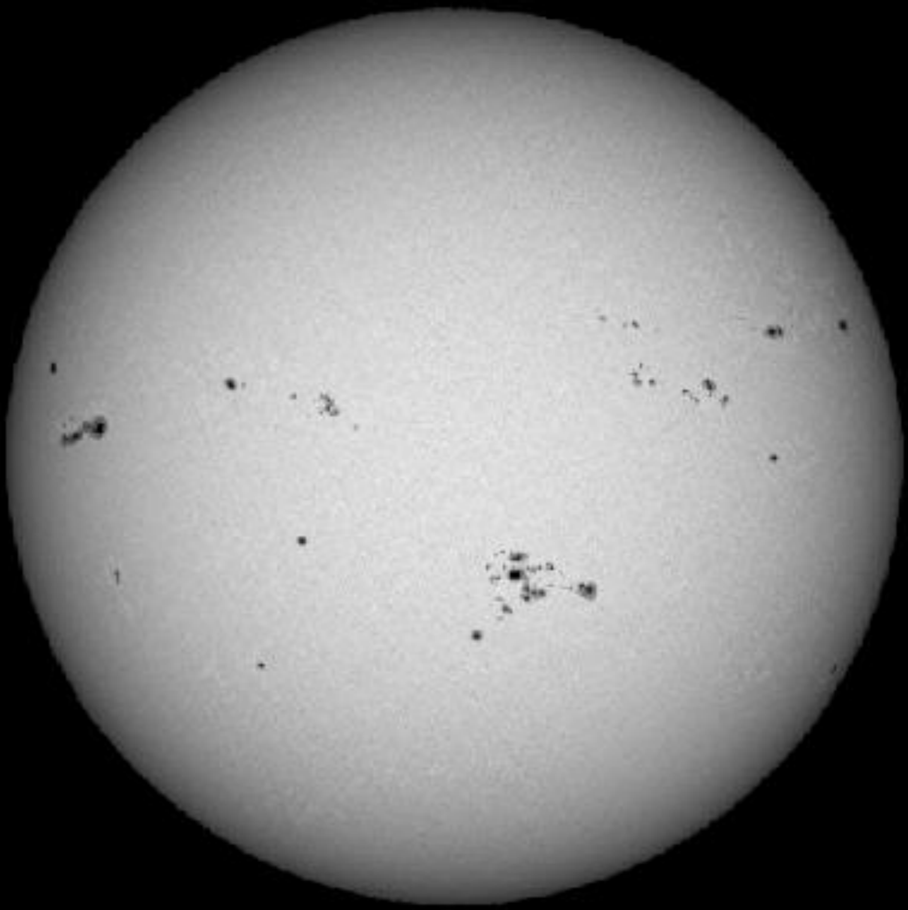

2001/03/27 12:48 UT

Solar Minimum

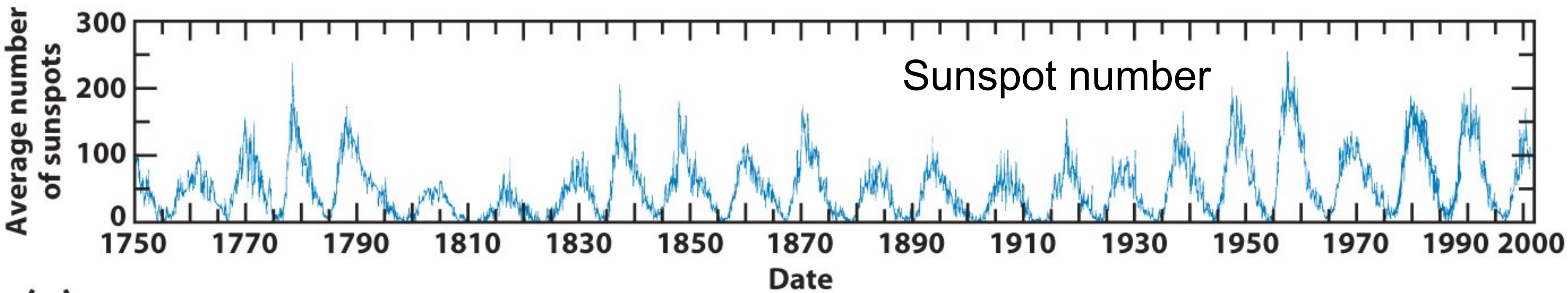
Solar Maximum



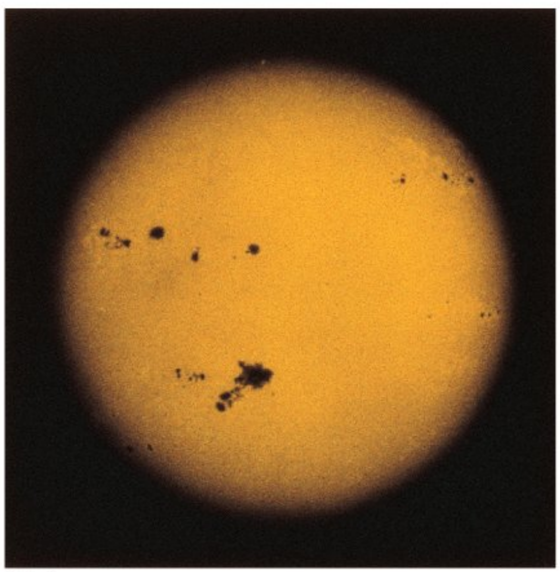


17.1 Solar cycle

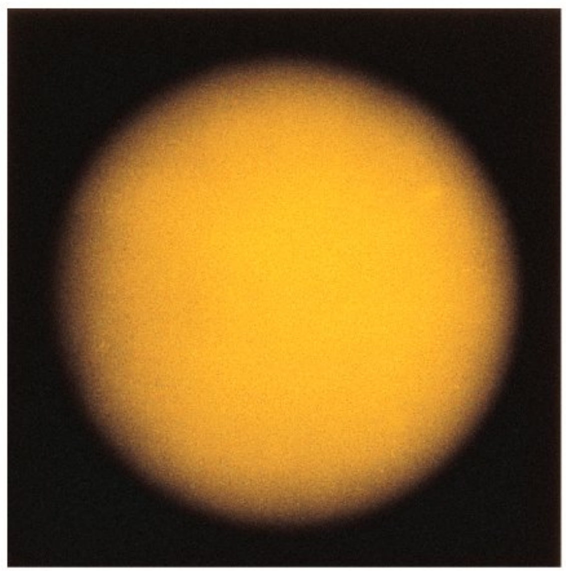
Sunspots are produced by a 22-year cycle in the Sun's magnetic field.



(a)



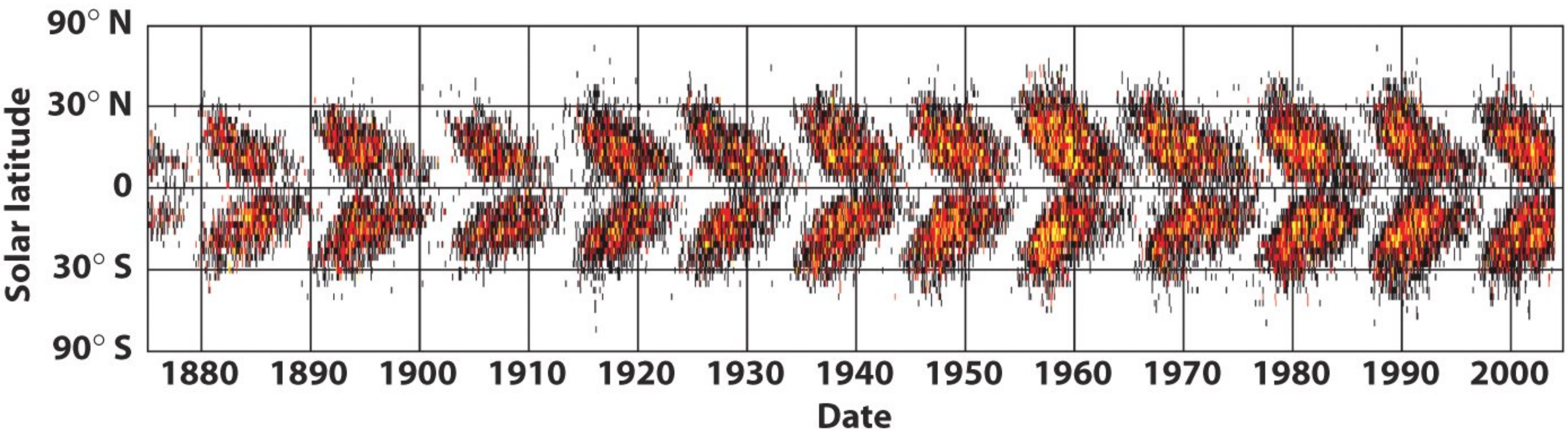
(b) Near sunspot maximum



(c) Near sunspot minimum

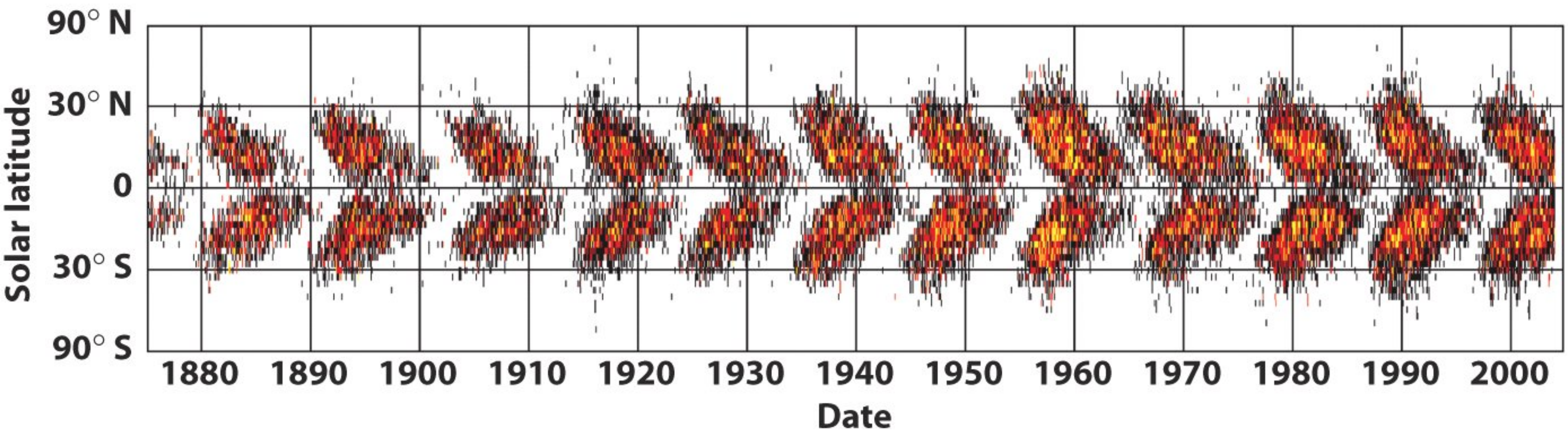
The number of sunspots is largest at the **solar maximum**, and the smallest at the **solar minimum**, so vary the **solar activities.**

Butterfly diagram: variation in the average latitude of sunspots.



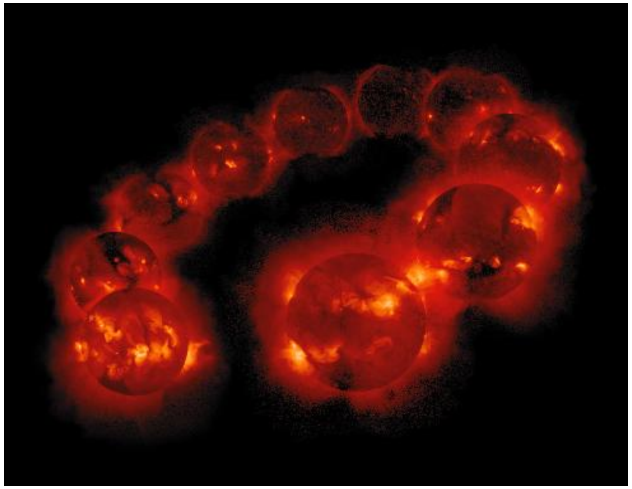
- At the start of each cycle, at the time of solar minimum, only a few spots are seen.
- Spots are generally confined to two narrow zones about 25 to 30 degrees north and south of the solar equator.
- Approximately 4 years into the cycle, around the time of solar maximum, the number of spots has increased markedly.
- Spots are found within about 15 to 20 degrees of the equator.
- Finally, by the end of the cycle, at solar maximum again, the total number has fallen again, and most sunspots lie within about 10 degree of the solar equator.
- The beginning of each new cycle appears to overlap the end of the last.

Butterfly diagram: variation in the average latitude of sunspots.

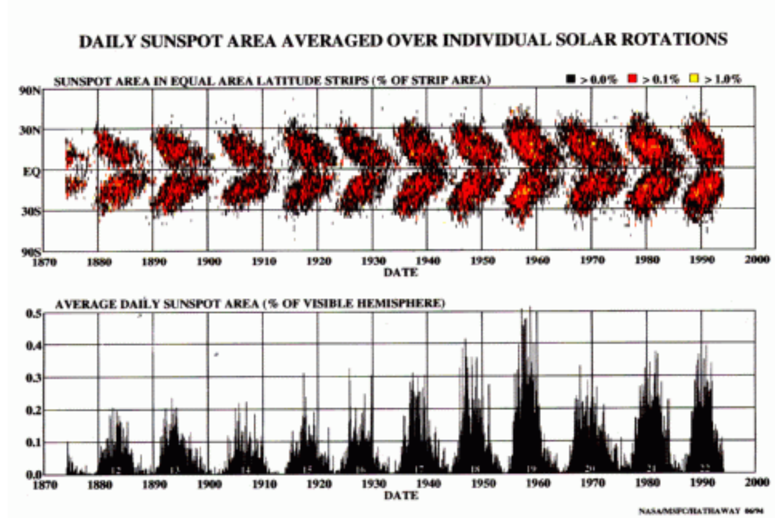


- The Sun's surface features vary in an 11-year cycle
- This is related to a 22-year cycle in which the surface magnetic field increases, decreases, and then increases again with the opposite polarity
- The average number of sunspots increases and decreases in a regular cycle of approximately 11 years, with reversed magnetic polarities from one 11-year cycle to the next
- Two such cycles make up the 22-year solar cycle

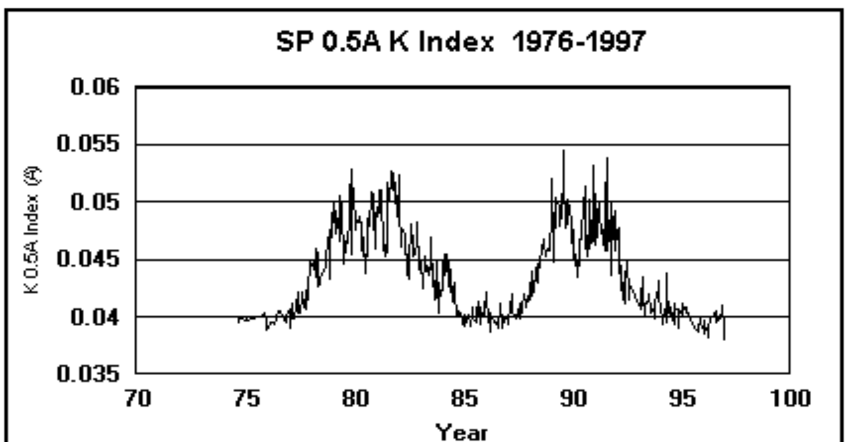
The solar cycle is manifested in many aspects: sunspot cycle, radiation cycle, all reflecting the magnetic cycle.



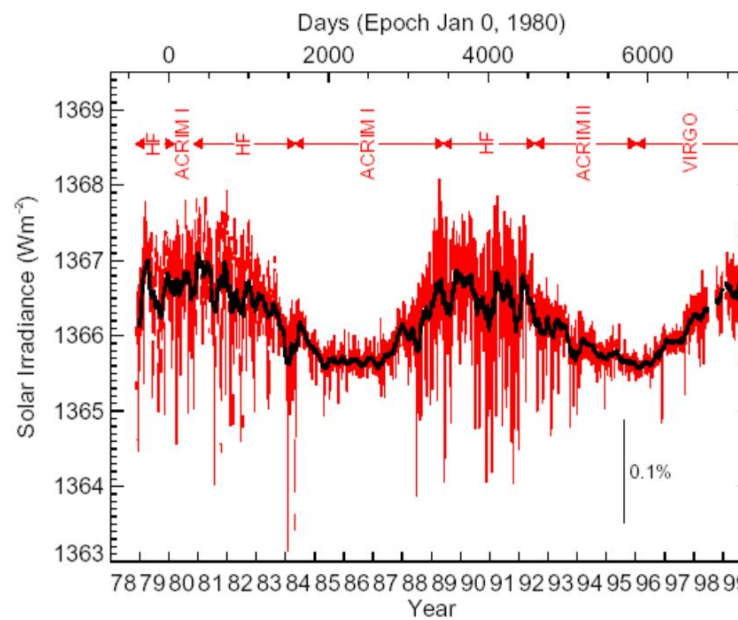
X-ray view of the solar cycle



Sunspot disk distribution pattern and total area

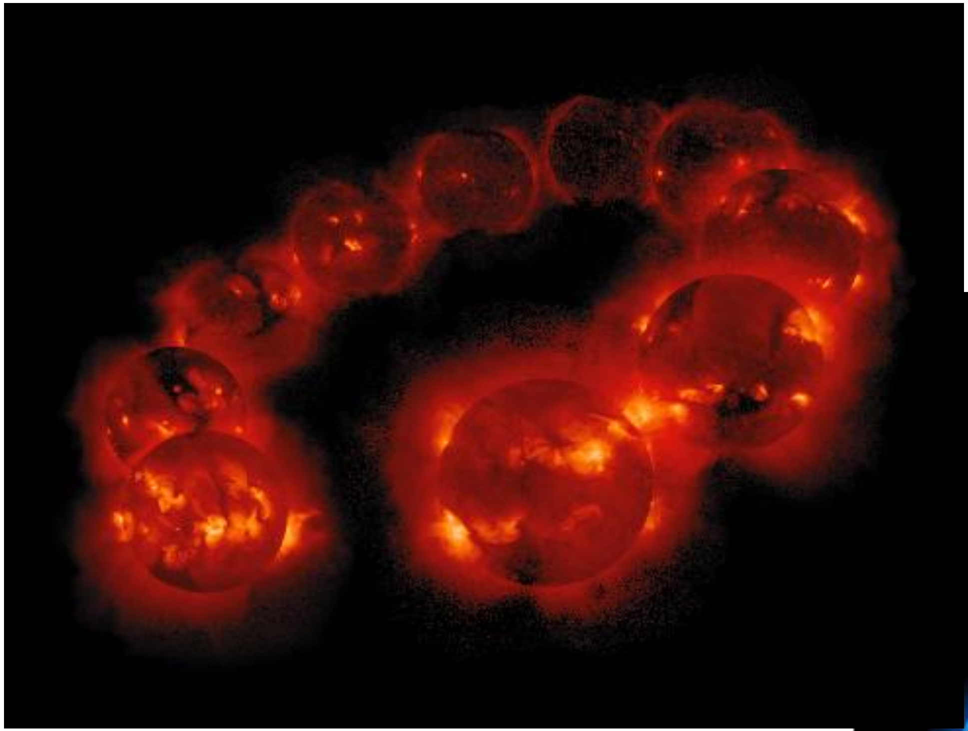


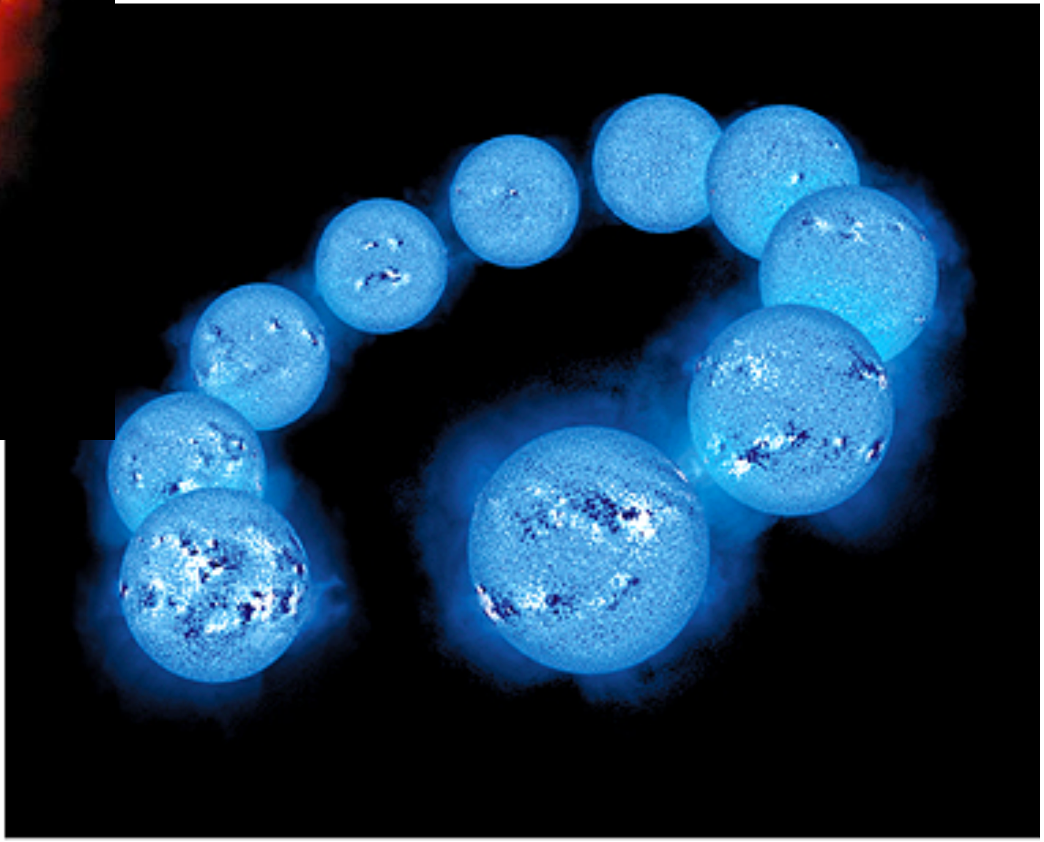
Ca II K index: chromospheric activity



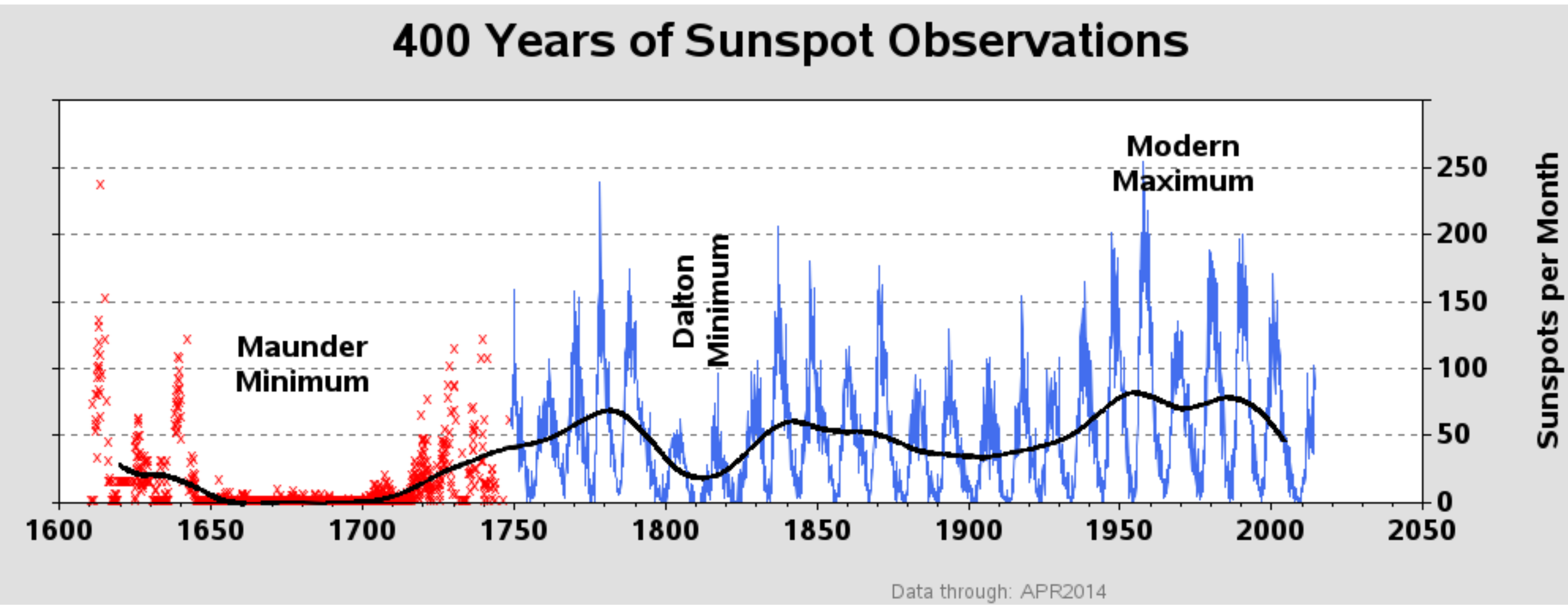
solar irradiance variations

Ex.1: when the sun spot cycle reaches the maximum, what do you think is the phase of the radiation cycle? Maximum? Minimum? Or else?



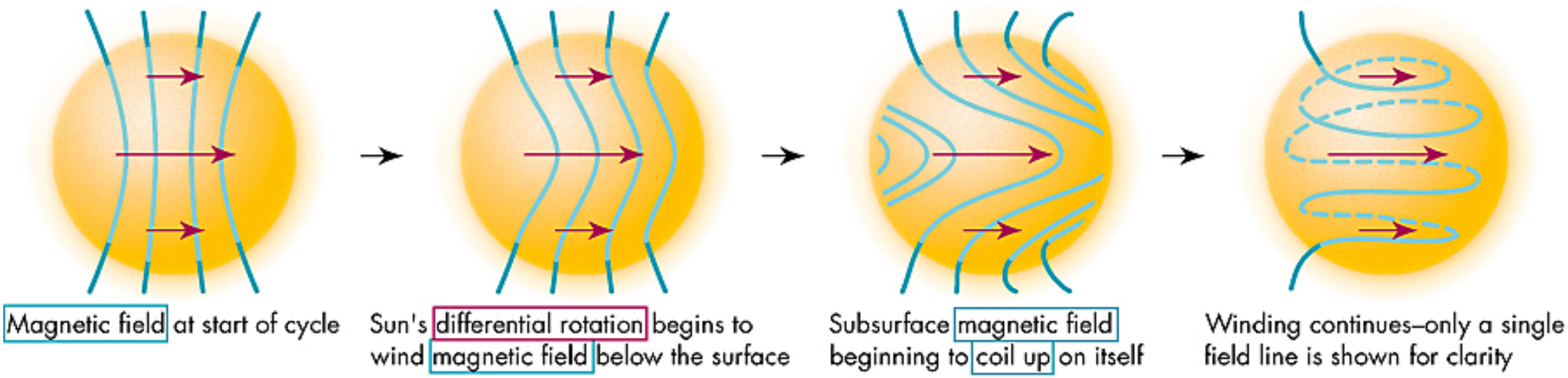


Maunder Minimum



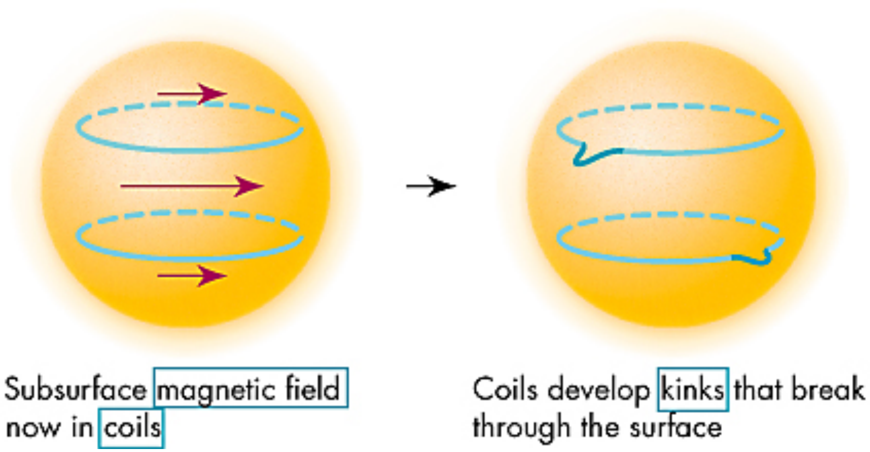
17.2 Magnetic dynamo

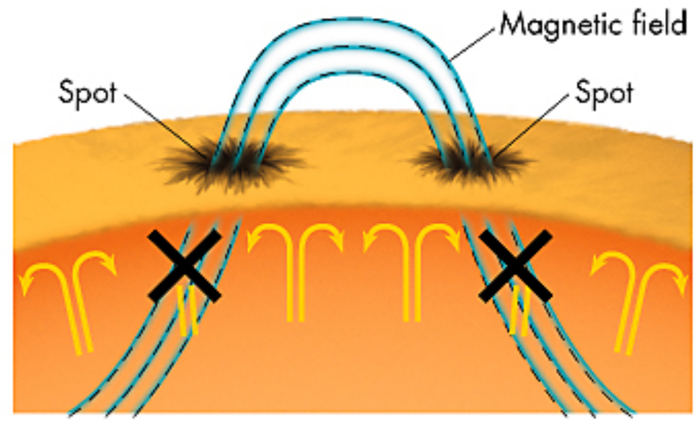
The solar magnetism and its activity are generated by **differential rotation** (Ω **effect**) and **convection** (α **effect)** - **solar dynamo.**



<u>The Ω **effect** converts poloidal field to toroidal field by differential rotation.</u> The α **effect** refers to twisting of the toroidal field by Coriolis as it rises with convection cells.

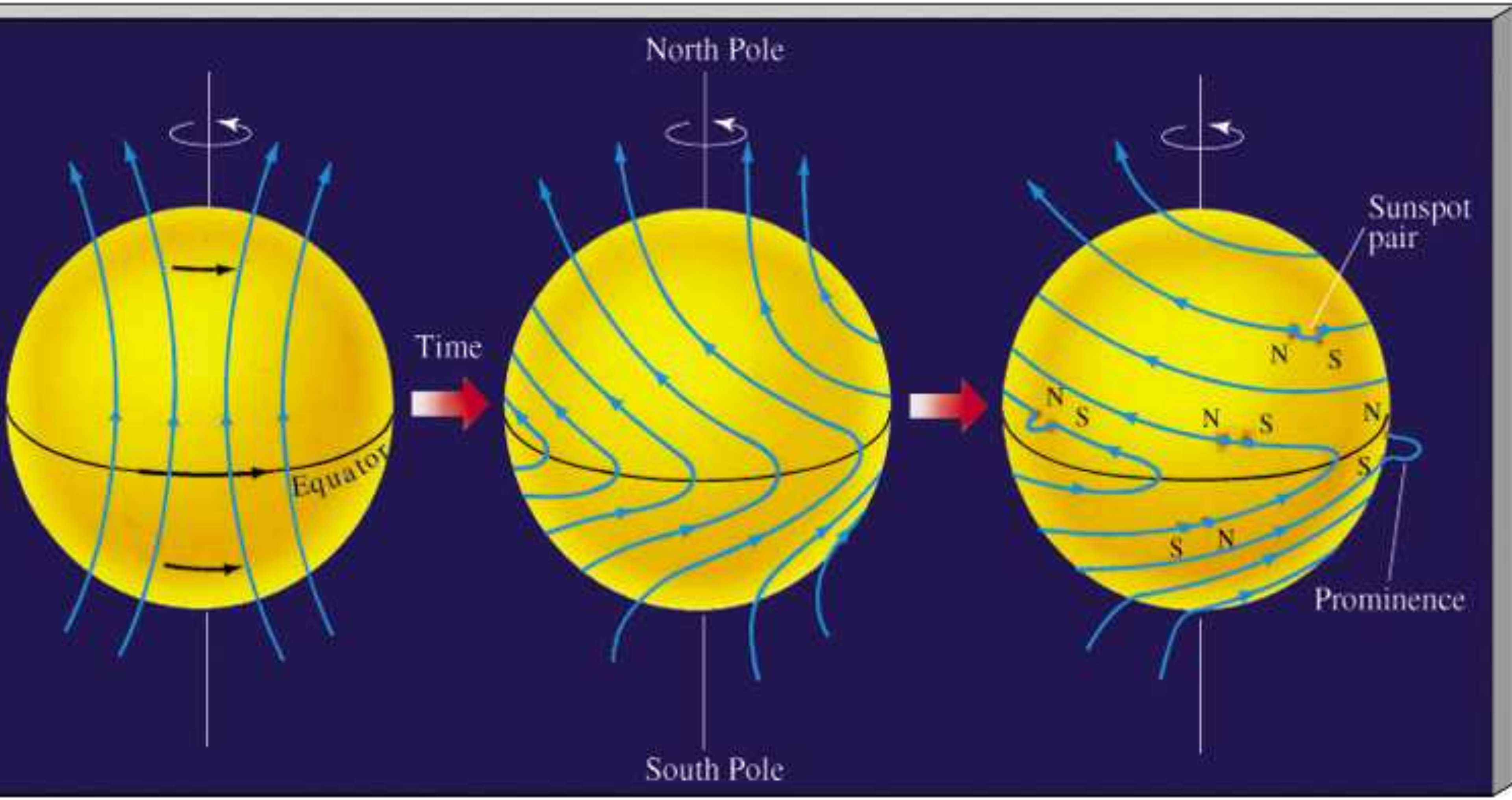
The solar magnetism and its activity are generated by **differential rotation** (Ω **effect**) and **convection** (α **effect) - solar dynamo.**



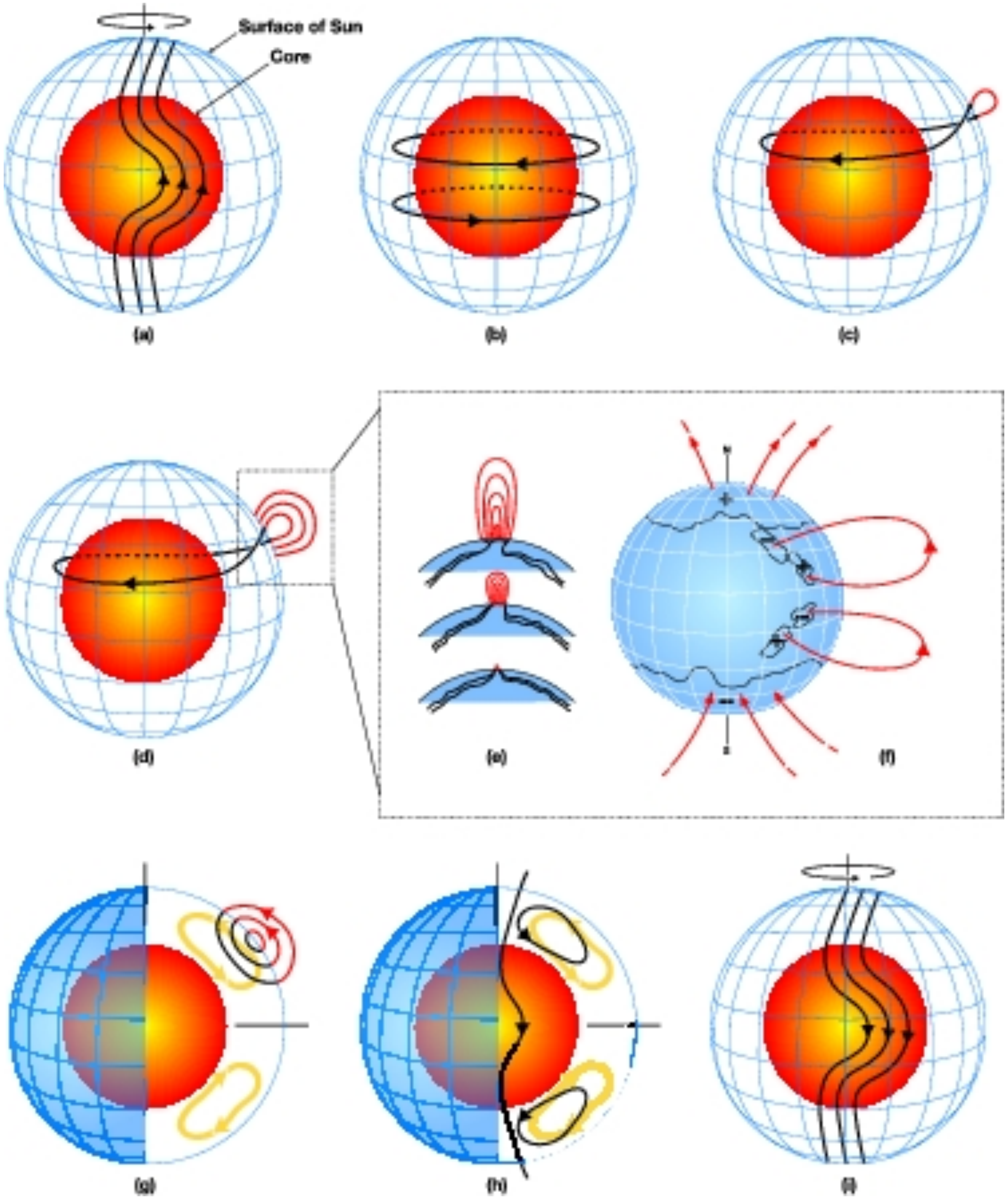


The α **effect** refers to twisting of the toroidal field by Coriolis as it rises with convection cells.

As the result, the initial polar fields are turned into magnetic “kinks” in the rising cycle.

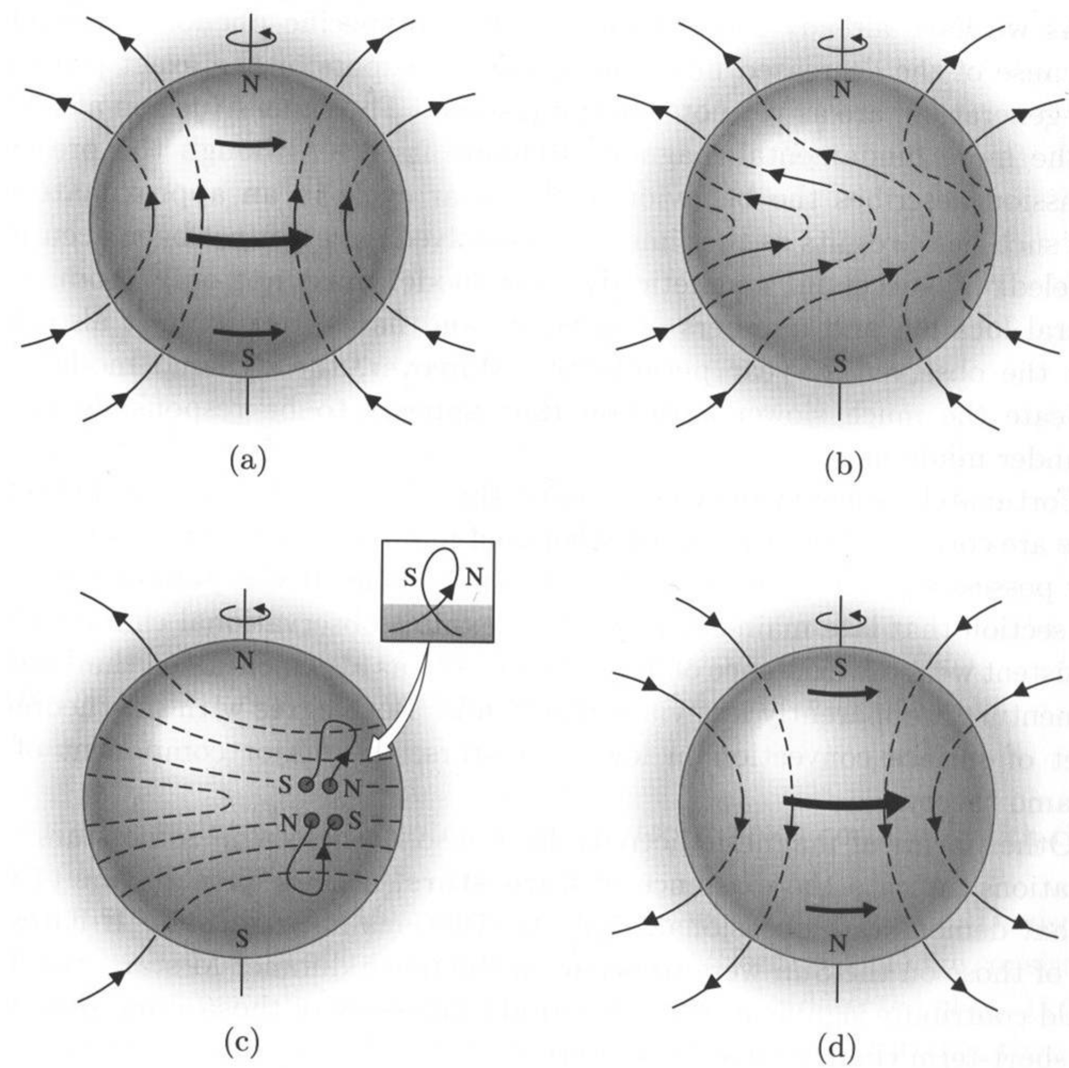


How Sunspots form



http://www.ucar.edu

After the solar maximum, flux transfer by meridional flow and flux cancellation eventually change the toroidal field back to poloidal field with reversed polarity.



As this decaying occurs, a flux loop forms connecting the leader and follower spots. The magnetic axis between leader and follower is tilted towards the equator. If the leader and follower spots move apart as the flux loop is decaying, the follower flux will move polewards and the leader flux will move equatorwards. These fluxes would then cancel with the existing polar fields, and a trans-equatorial poloidal loop would form, connecting follower flux from one hemisphere with that of the other.

Magnetism critically depends on interior flow.

rotation of electrically conductive fluid → poloidal global field

differential rotation → toroidal field

convection + rotation → merging kinked field close to equator

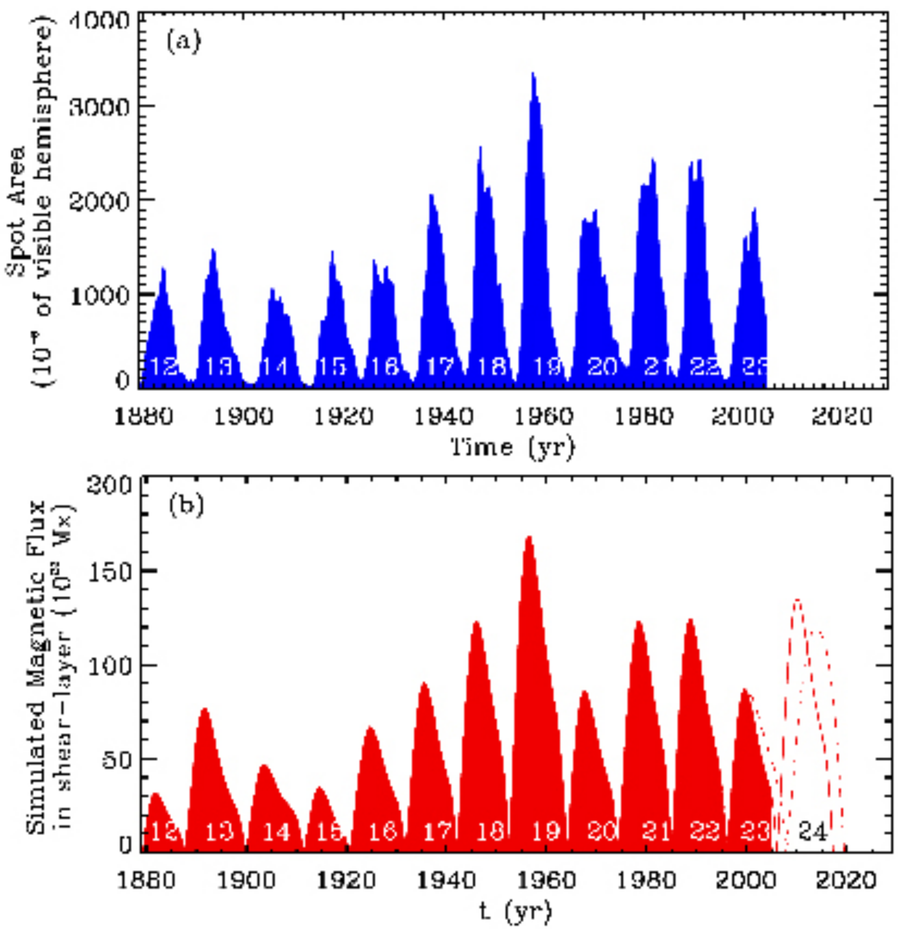
meridional convection flow → polar field

flux cancellation → polarity reversal

Helioseismology determines the flow patterns beneath the surface. Helioseismology studies sound waves generated by the convective turbulence, reflected at the surface, and refracted inside the Sun, to find the temperature and density structure of the interior. It also reveals the motion patterns inside.

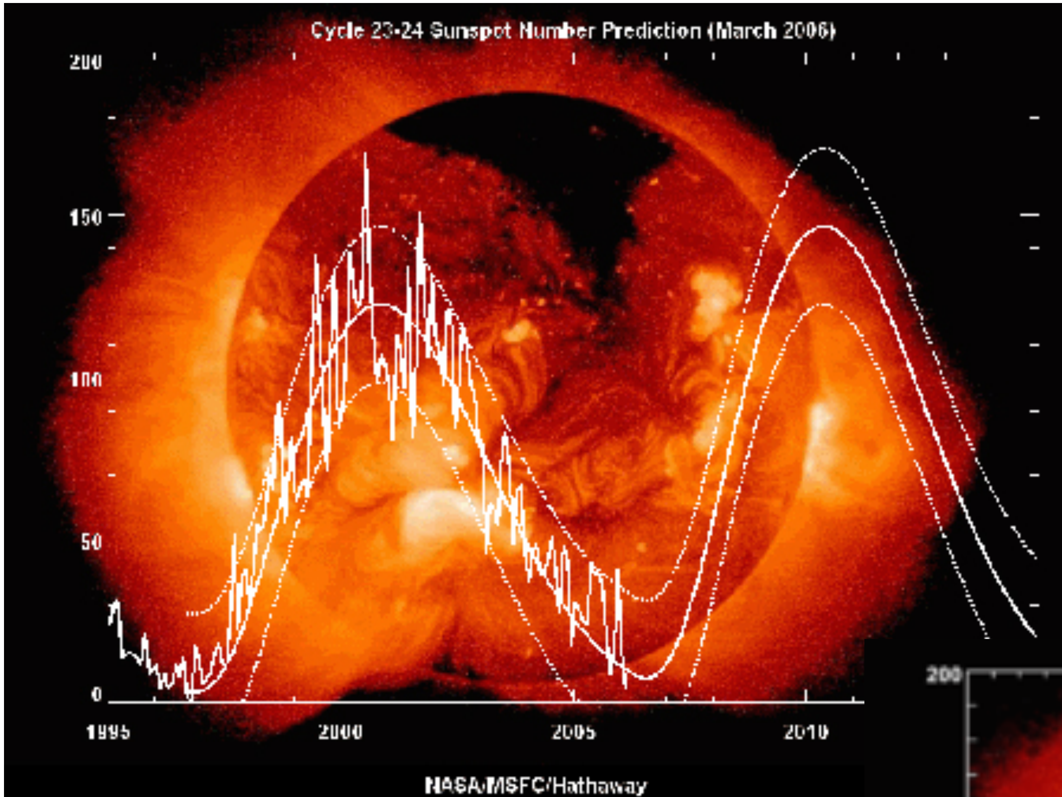
- Astronomers now believe that the Sun’s magnetic field is generated and amplified by the constant stretching, twisting, and folding of the field lines that results from the combined effects of differential rotation and convection.
- This theory is called solar dynamo, which predicts that the Sun’s magnetic field should rise to a maximum, then fall to zero and reverse itself in a more-or-less periodic way.
- Solar surface activity, such as sunspot cycle, simply follows the variations in the magnetic field.
- The changing numbers of sunspots and their migration to lower latitudes are both consequences of the strengthening and eventual decay of the field lines.

Ex.3: in the photosphere and convective zone, the gas pressure dominates the magnetic pressure, so magnetic fields are carried along by mass motion.

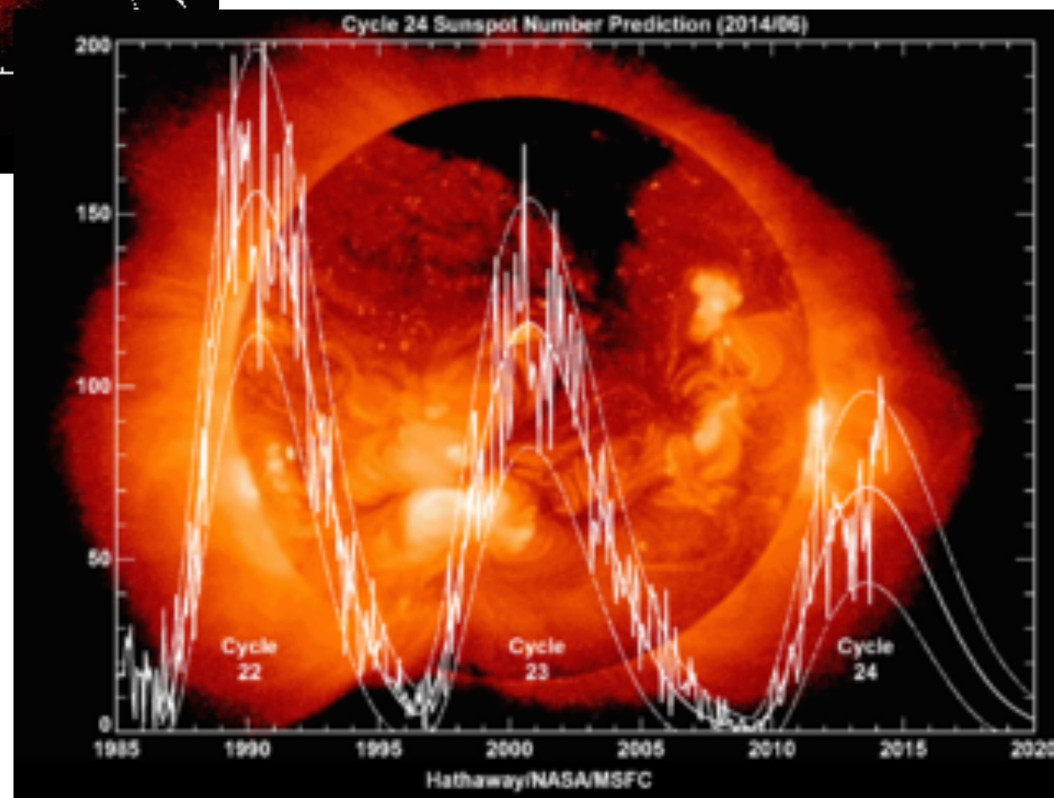


Recent progress in numerical simulation using a **flux-transport** model and knowledge of flows inside the Sun by **helioseismology** aims at predicting the timing and strength of the upcoming solar cycles.

http://www.nasa.gov/vision/universe/solarsystem/solar_cycle_graphics.html



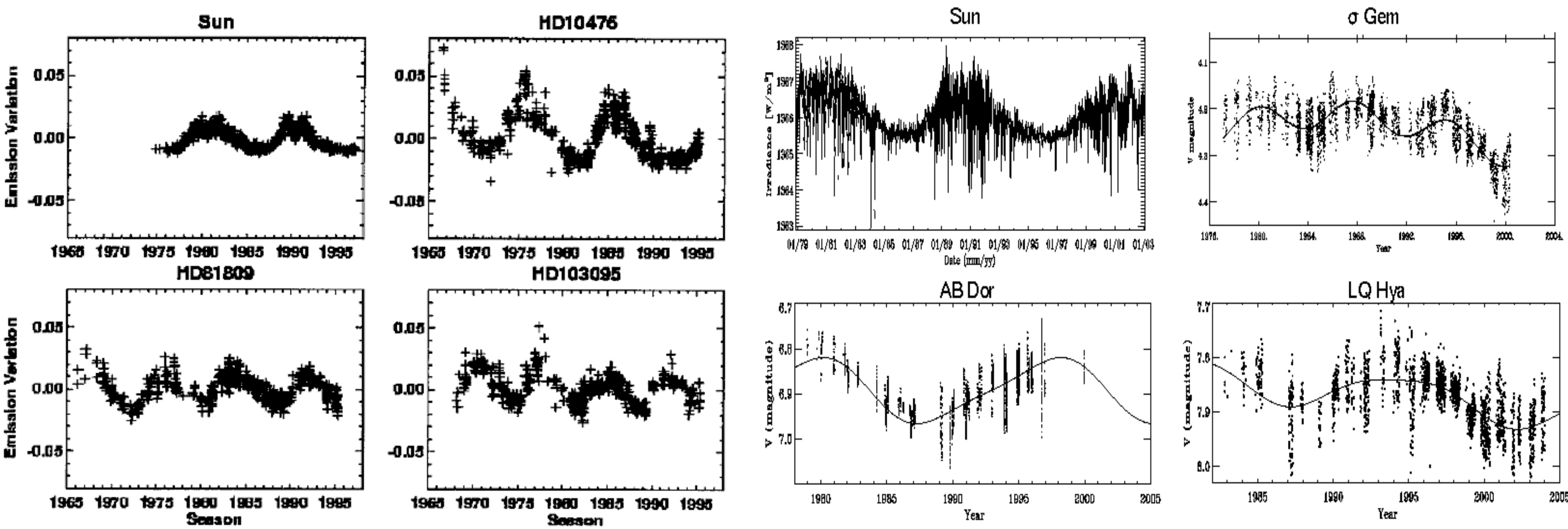
predicted solar cycle 24 in 2006, as comparable to cycle 23.



observed solar cycle 24 in 2014, with a totally unexpected deep minimum at the end of cycle 23, and a very weak cycle 24 – more to learn!

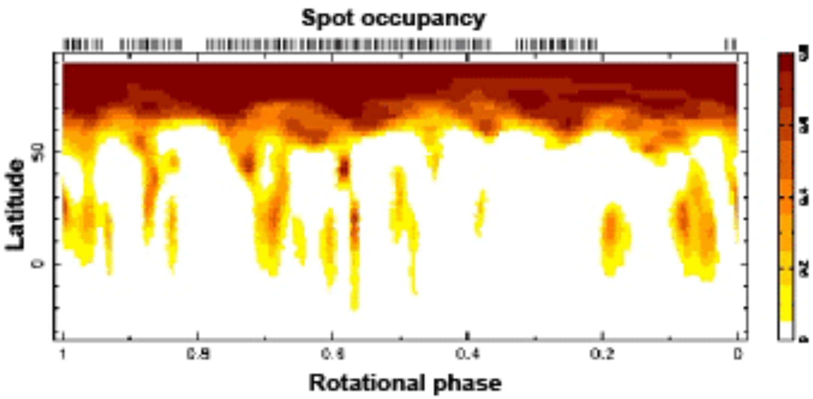
17.3 Stellar Magnetism

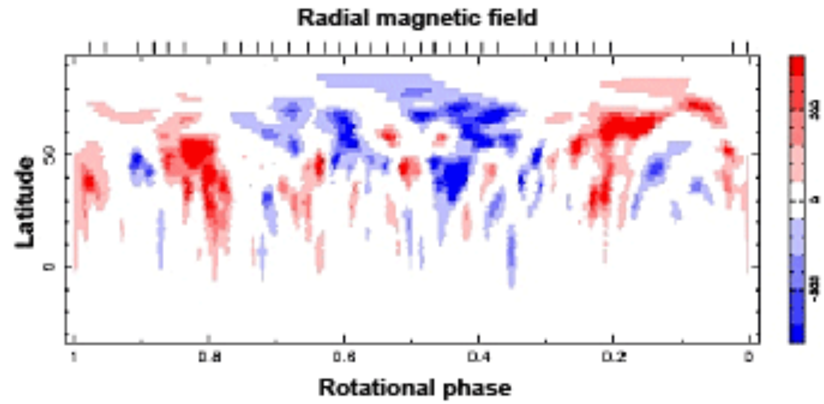
Solar type activity phenomena exist on cool stars with outer convection zones. Studying stellar magnetic activity provides tests of solar dynamo models and ways to understand stellar magnetic evolution.



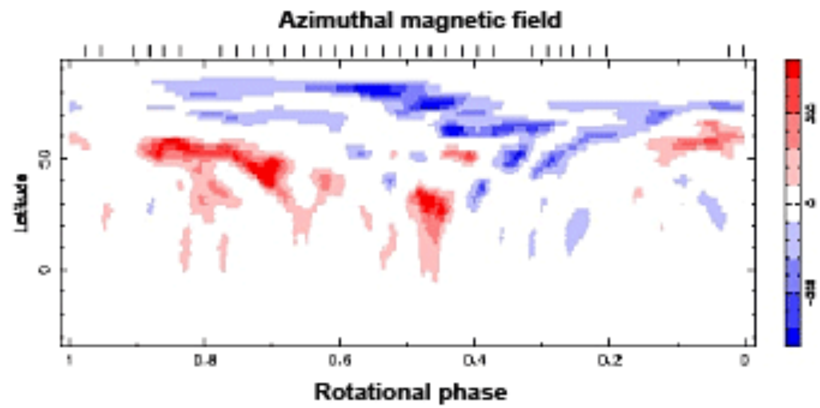
chromospheric Ca II H K cycle

A variety of stars along and beyond the H-R diagram exhibit magnetic activities. Evident cyclic patterns have been observed.



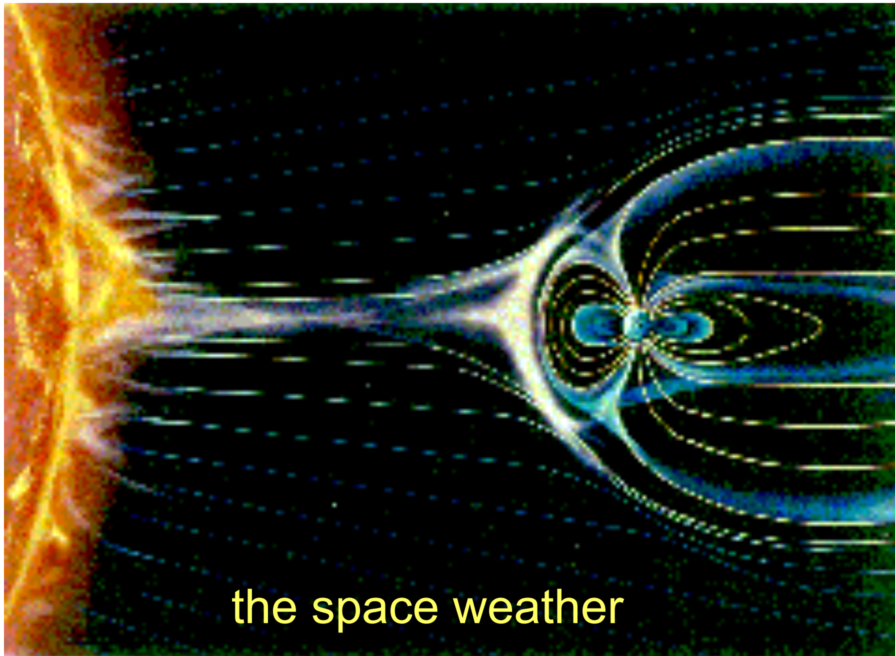


Zeeman-Doppler effect: measuring stellar magnetic fields on fast rotators.

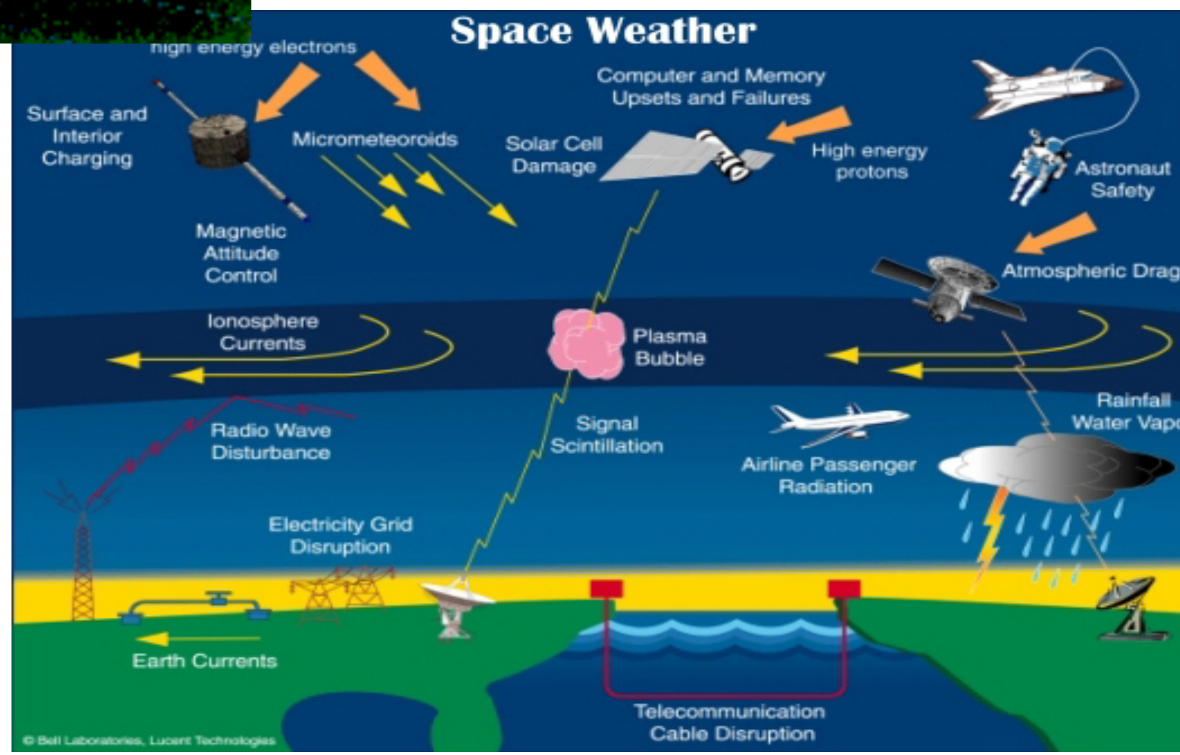


There is a strong correlation between stellar <u>rotational properties</u> and <u>magnetic activity indicators</u>:

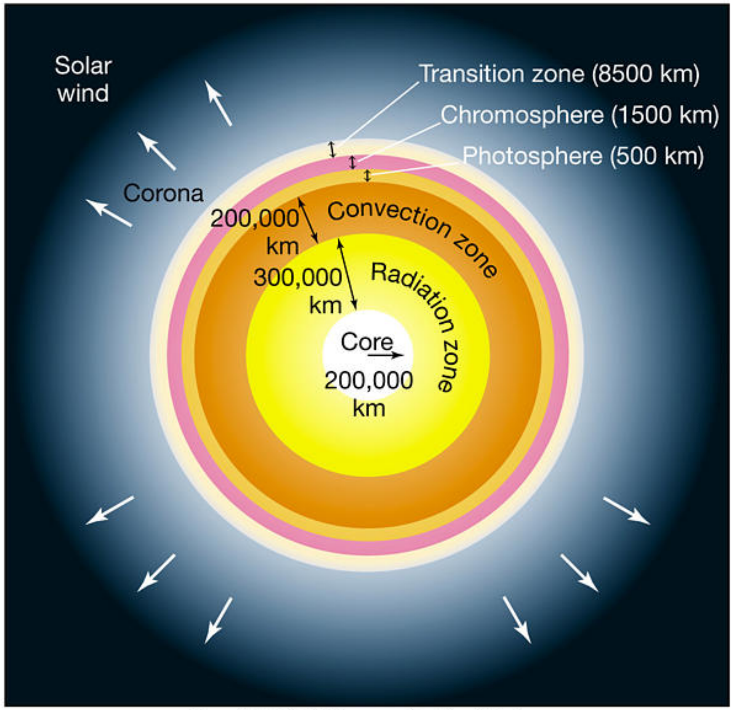
rapid rotation <==> higher activity



Why study the sun?
Streams of charged particles from the Sun lead to adverse **space weather** and pose threat to our ambition to explore the outer space and solar system.

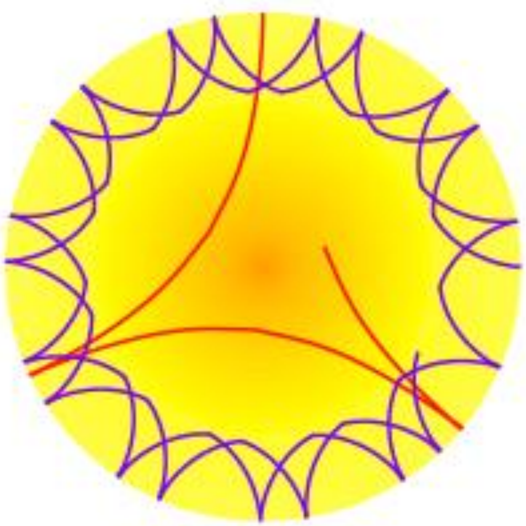


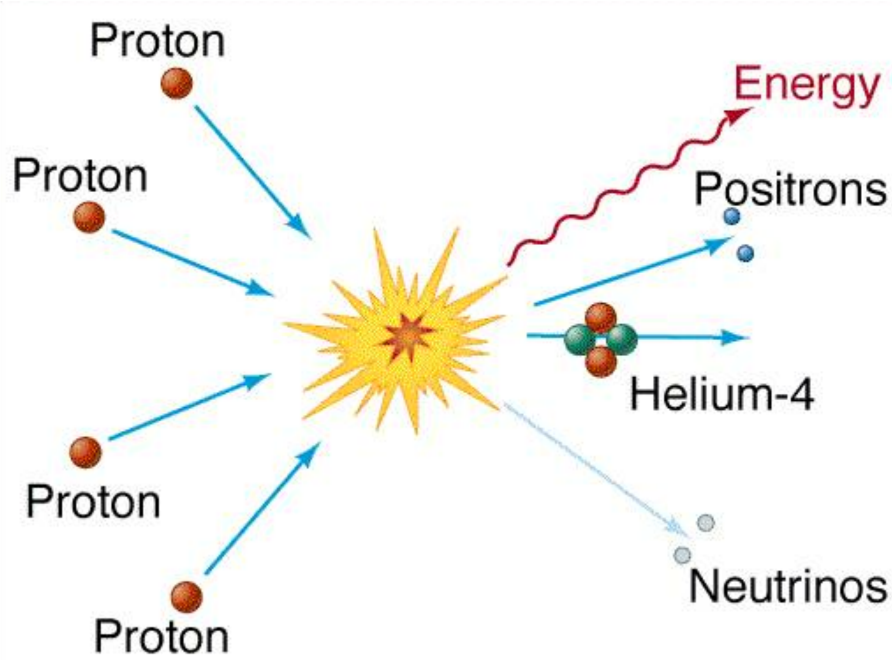
We may predict space weather by a good understanding of the Sun's magnetic field and its evolution.



Why study the Sun?

The Sun is an average main-sequence star and the only one of which we know great details of the interior, atmosphere, and magnetic field.

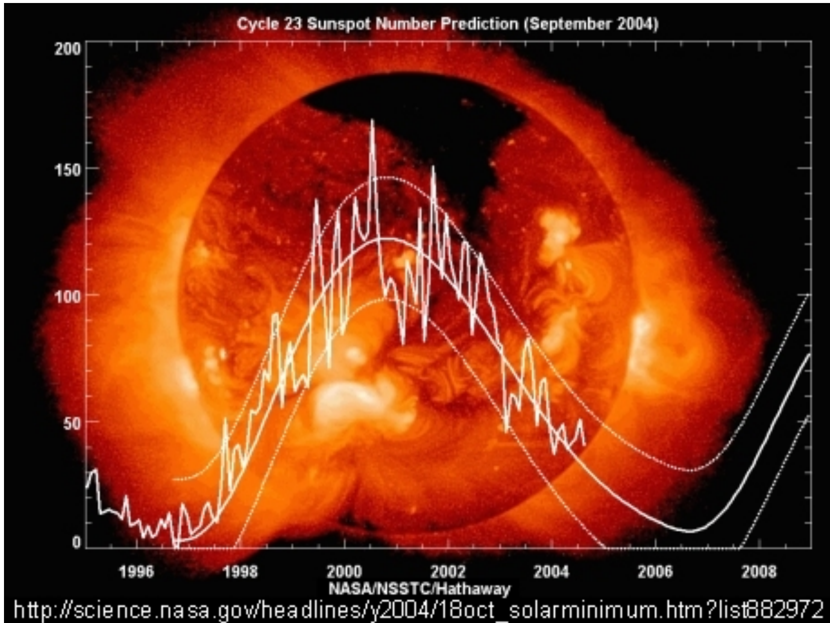




Why study the Sun?

Thermonuclear reactions in the core of the Sun as well as billions of stars generate enormous amount of energy. Such fusion energy is the future of clean energy.

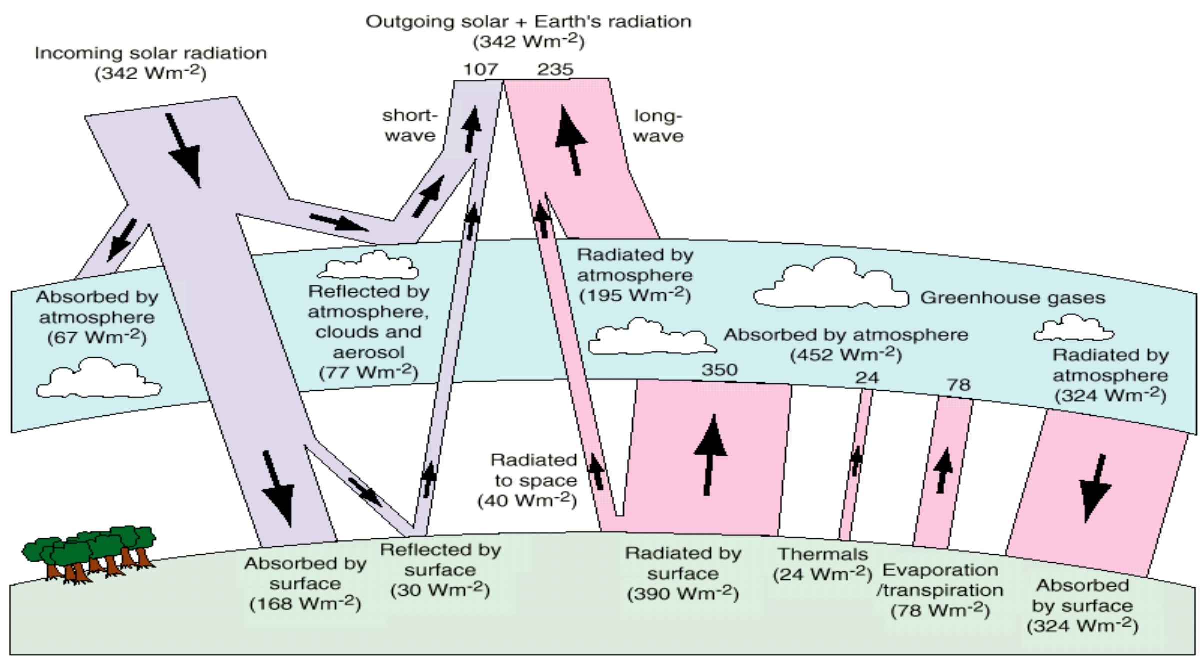
"Every time you look up at the sky, every one of those points of light is a reminder that fusion power is extractable from hydrogen and other light elements, and it is an everyday reality throughout the Milky Way Galaxy."



Why study the Sun?

The Sun is the energy source of human life and activities. The global change on the Earth may be modulated by the Sun's activity.

the climate connection



Key Words

- 22-year solar cycle
- butterfly diagram
- convection
- differential rotation
- flux transport model
- magnetic dynamo model
- meridional flow
- solar maximum
- solar minimum

summary

- Solar activities, such as sunspot number, area, and distribution, and solar radiation in various wavelength, exhibit a 22-year cycle, which reflects the **magnetic cycle.**
- The solar magnetism and its cycle are generated by magnetic dynamo through **differential rotation**, **convection**, and **meridional flows**.
- Latest progress in numerical simulations using flux transport models and observed flow patterns inside the Sun may improve our understanding and prediction of solar cycle.