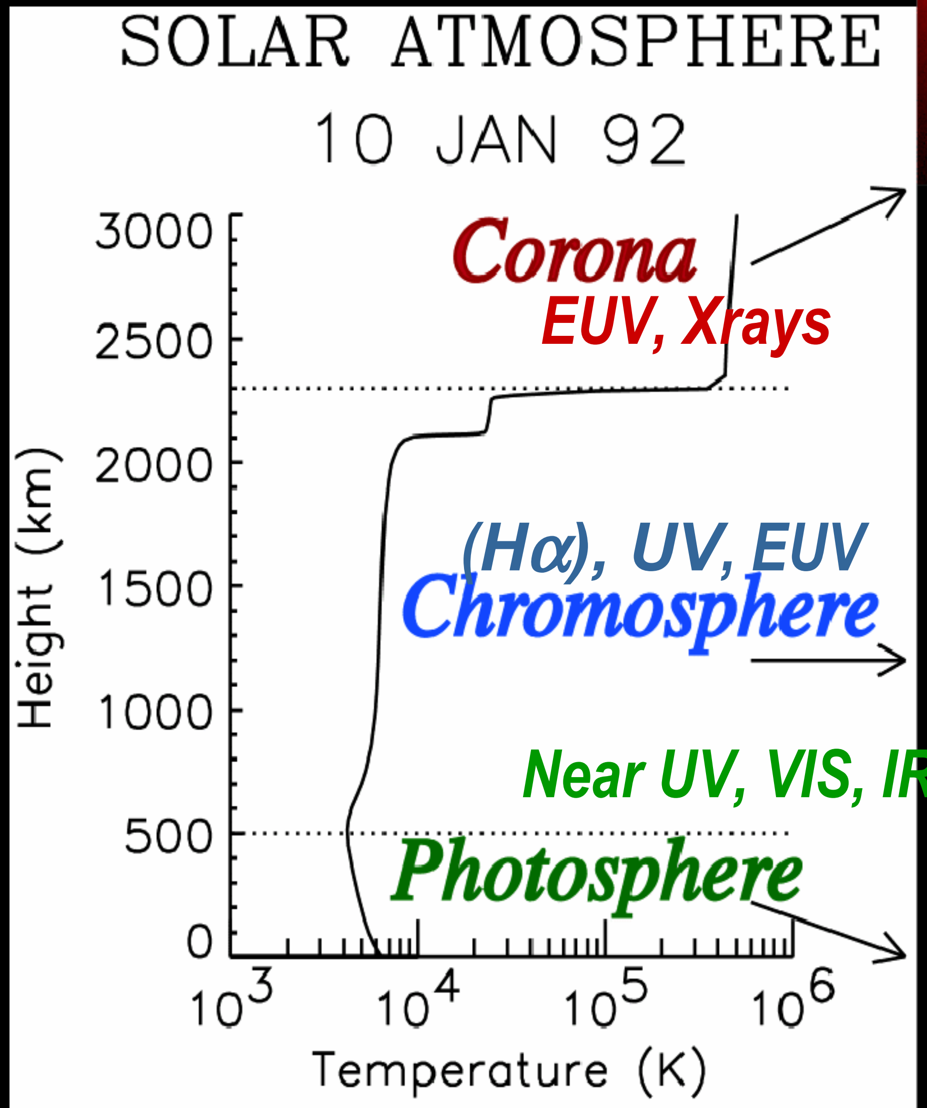
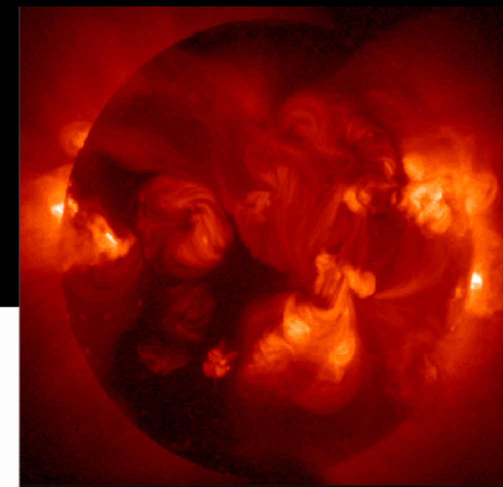
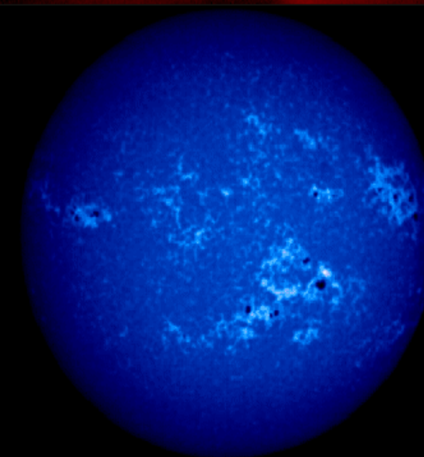
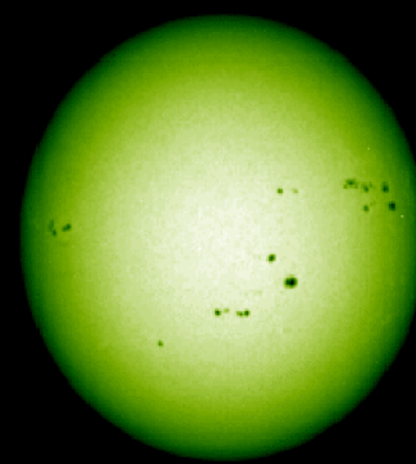
The Many Faces of the Sun

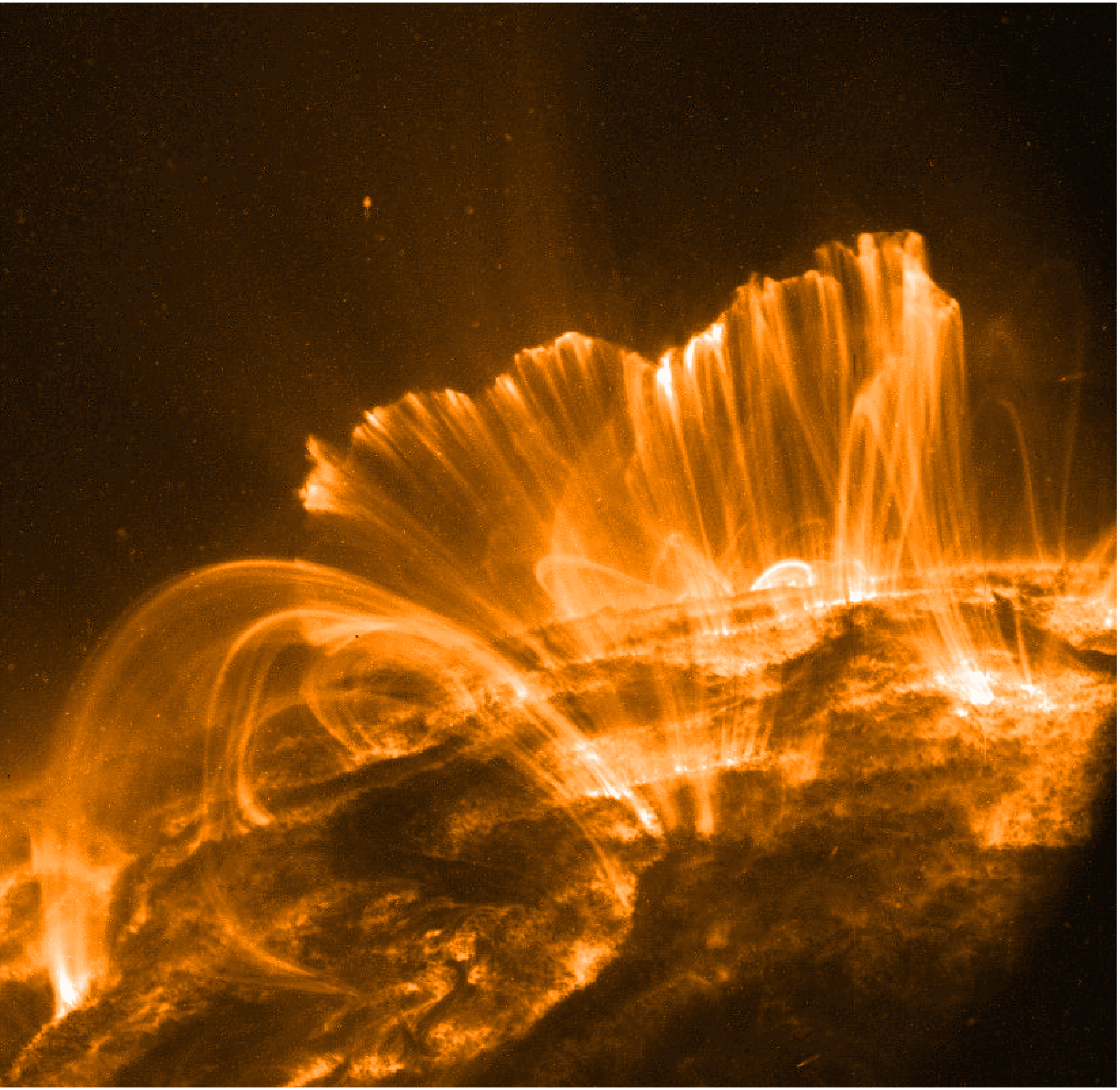






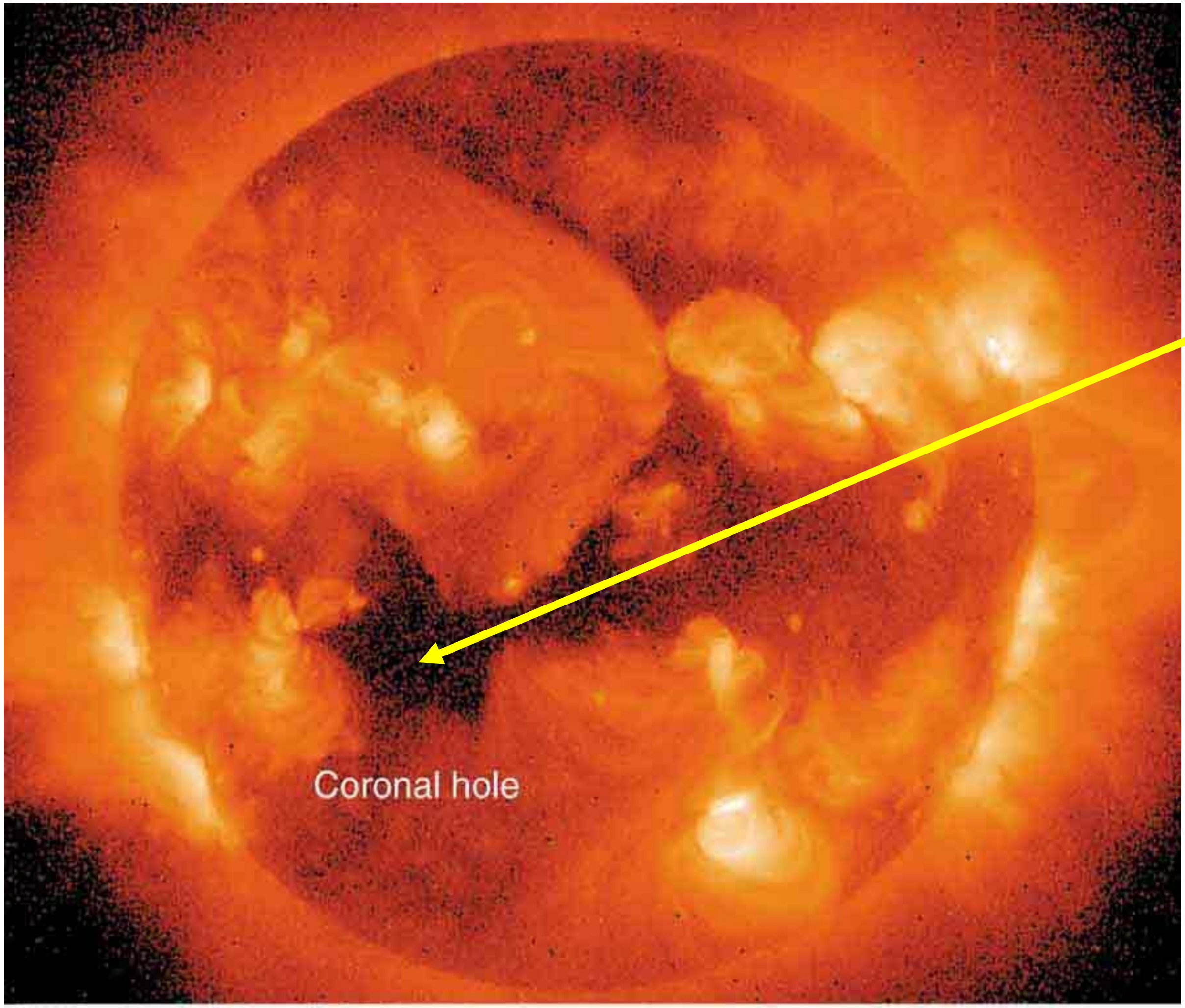


Coronal Loops



High resolution image of the corona obtained by TRACE satellite.

Corona and coronal Holes



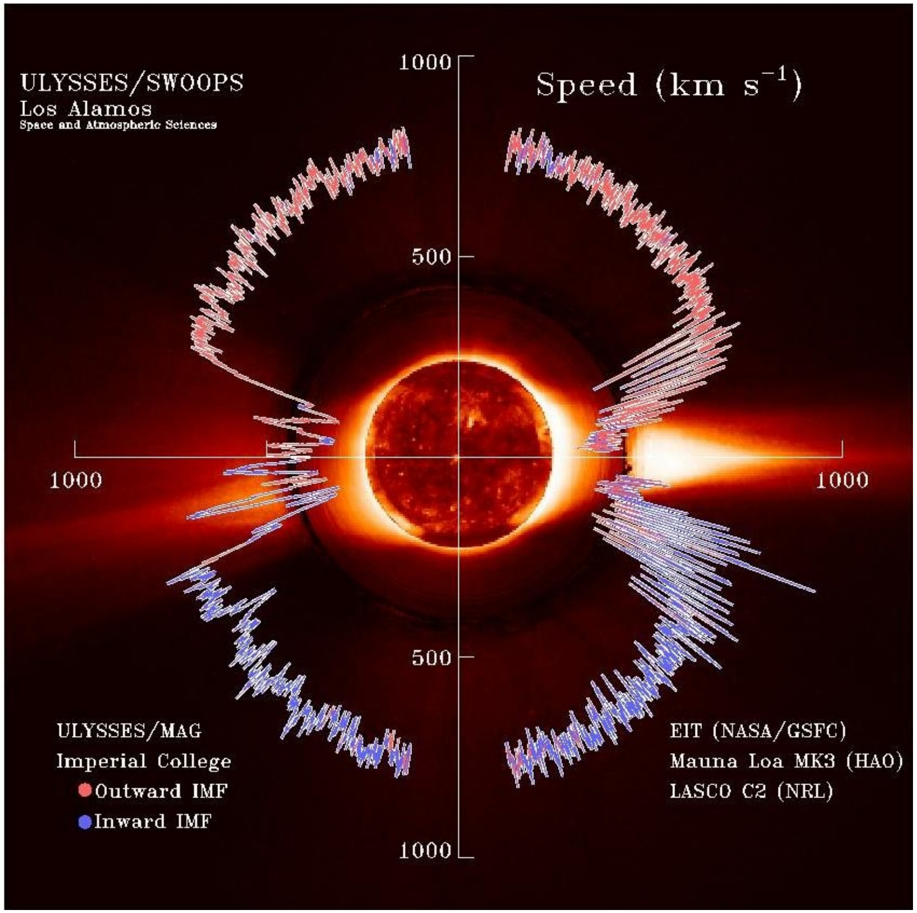
X-ray images of the sun reveal *coronal holes*.

These arise at the foot points of open field lines and are the origin of the solar wind.

The Solar Wind

Constant flow of particles from the sun.

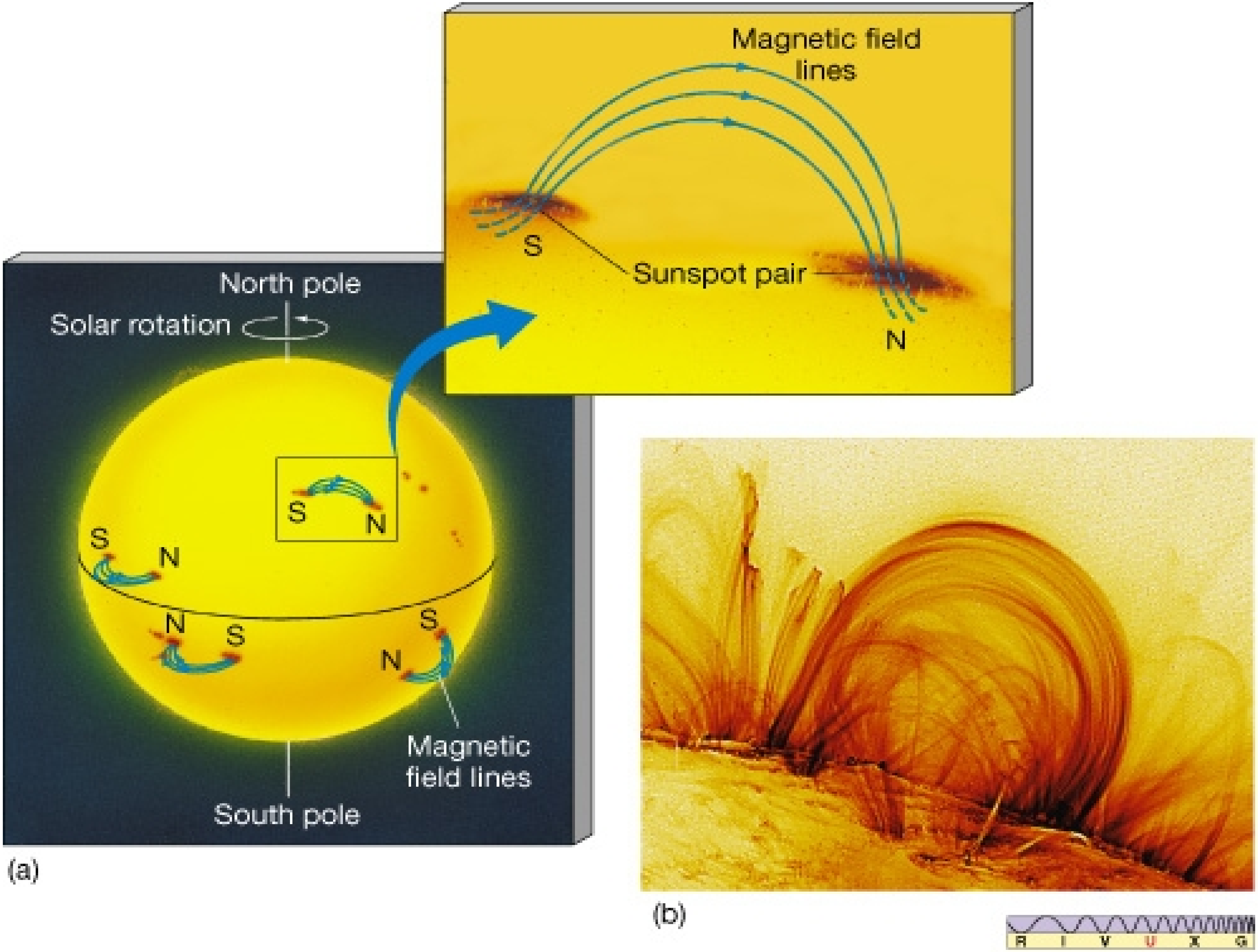
Velocity ≈ 300 – 800 km/s



⇒ Sun is constantly losing mass:

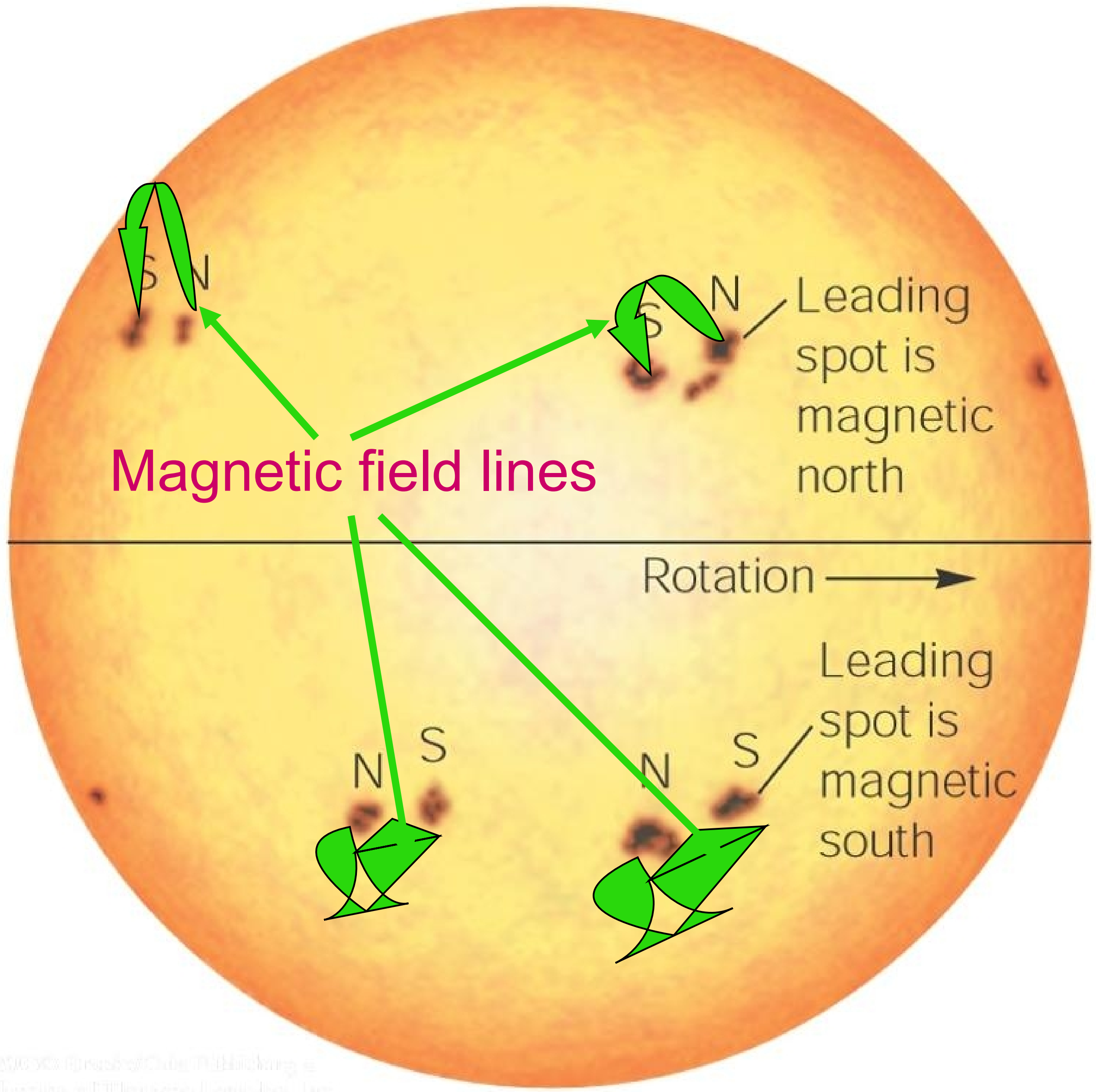
10^7 tons/year

(≈ 10^{-14} of its mass per year)

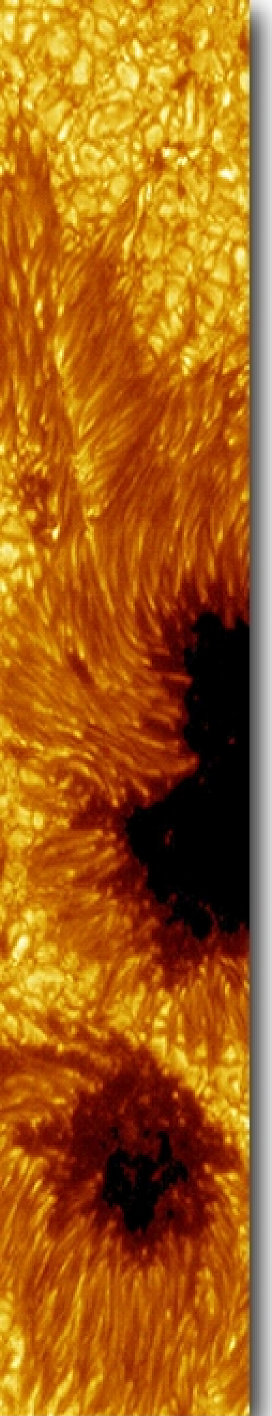


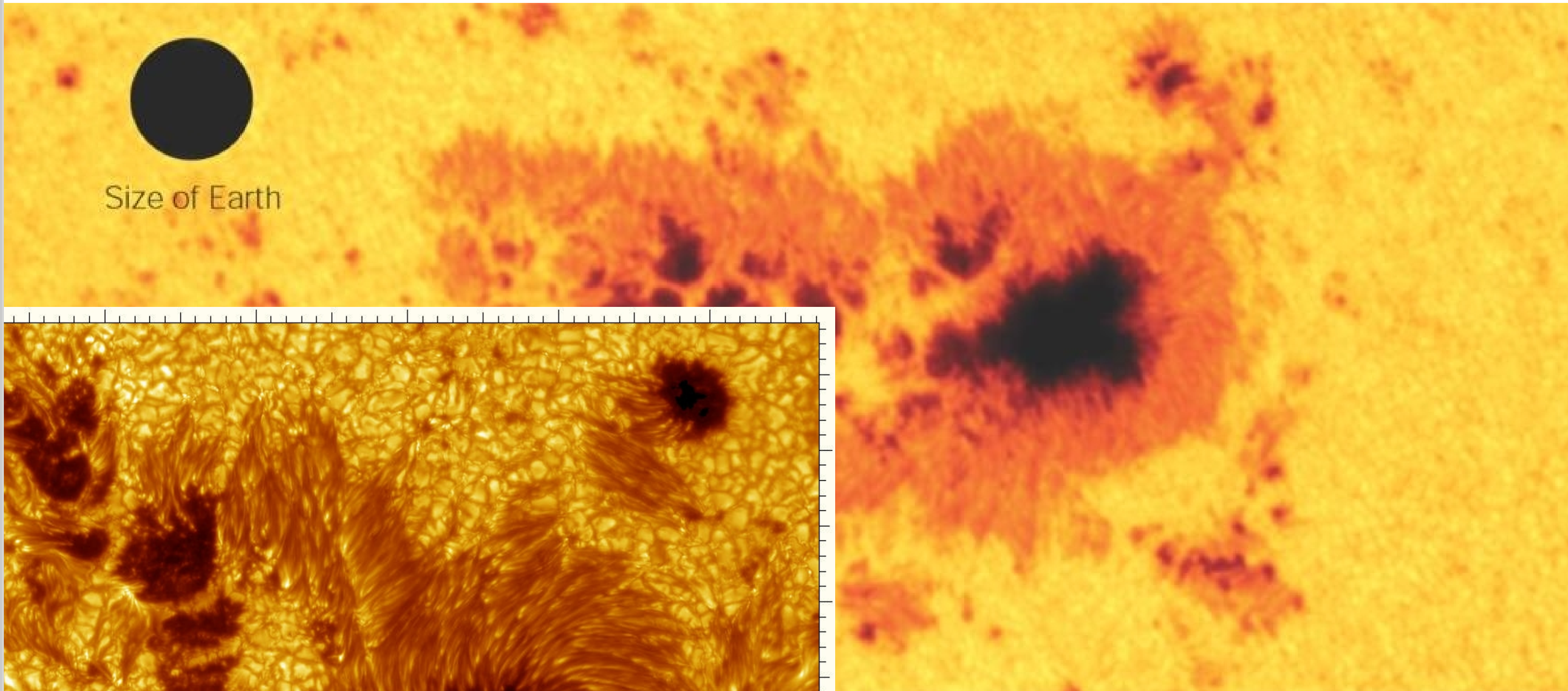
Magnetic field lines
S
Sunspot pair
N
North pole
Solar rotation
S
N
S
N
N
S
S
N
Magnetic field lines
South pole
(a)
(b)
R I V U X G

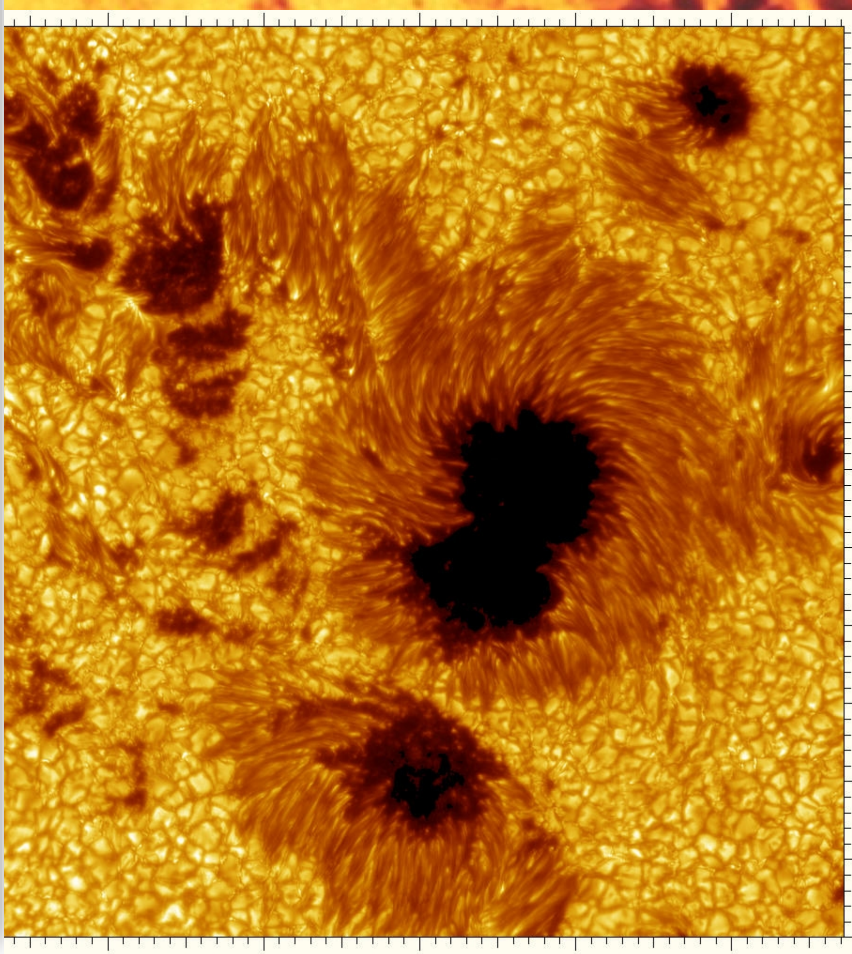
Magnetic Loops



Sun Spots





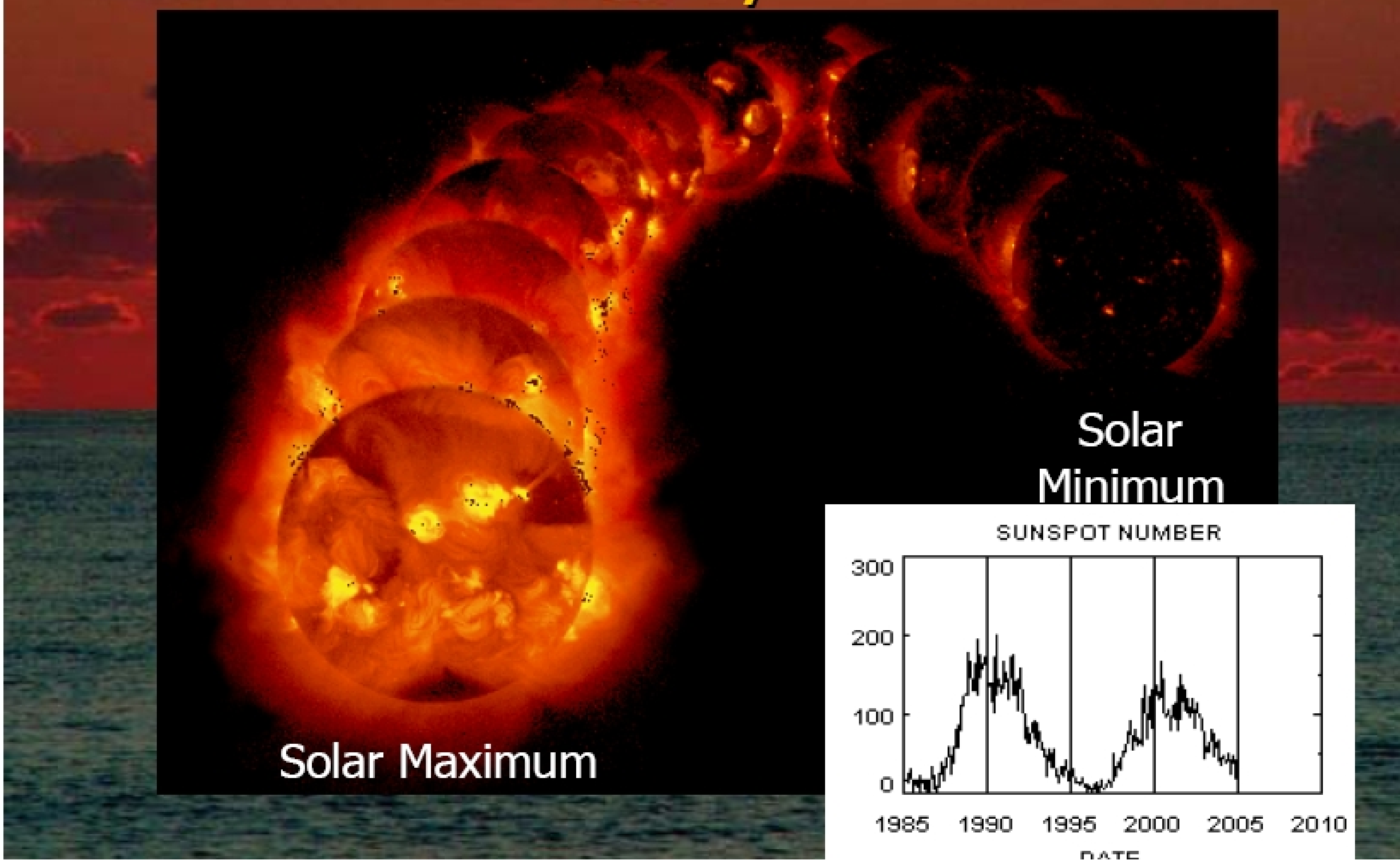


Cooler regions of the photosphere (T ≈ 4200 K).

Only appear dark against the bright sun. Would still be brighter than the full moon when placed on the night sky!

Solar cycle

Solar Cycle

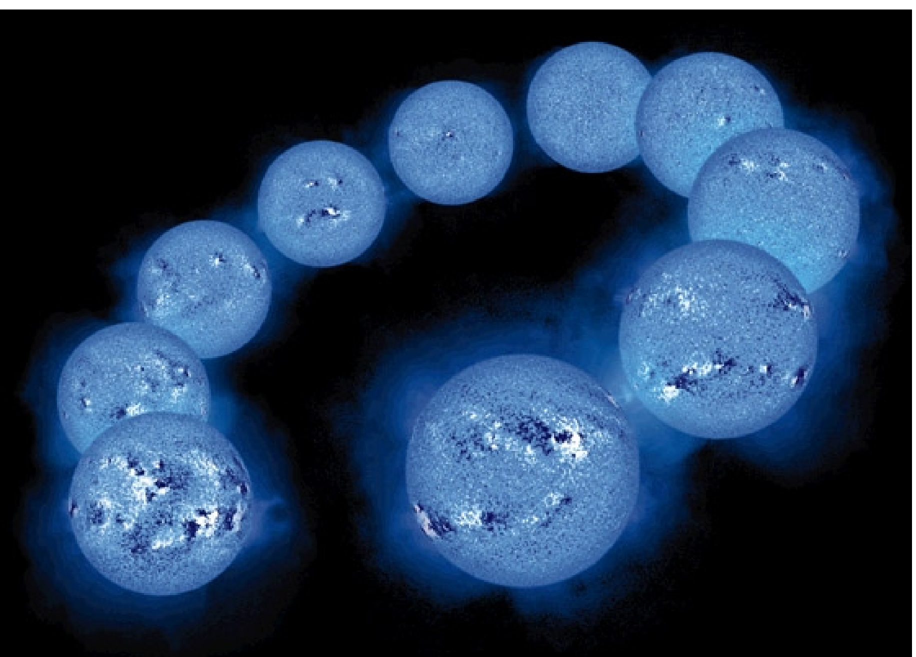

Solar Minimum
Solar Maximum
SUNSPOT NUMBER
300
200
100
0
1985
1990
1995
2000
2005
2010

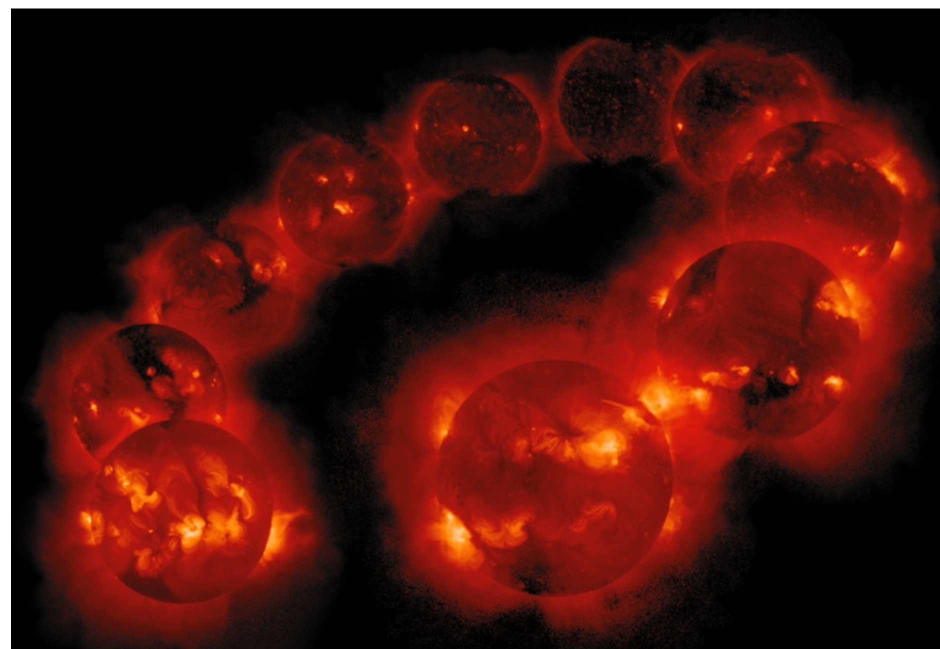
Magnetic Field and X-Ray Variation Through one Solar Cycle

The black-and-white patterns show the surface magnetic field variation through one sunspot cycle (11 years).

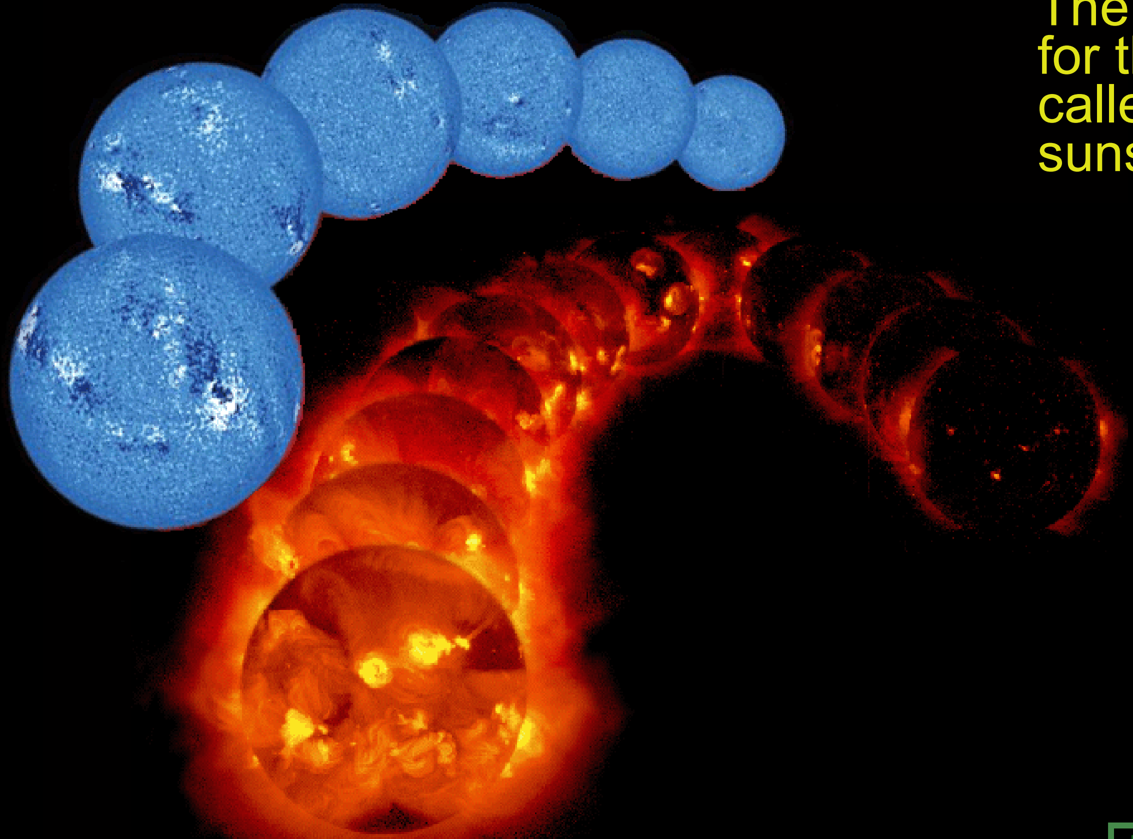
The activities in the solar corona also follow the solar cycle.

In fact, the level of almost every aspect of solar activities (flares, coronal mass ejections, etc.) follows the solar cycle.

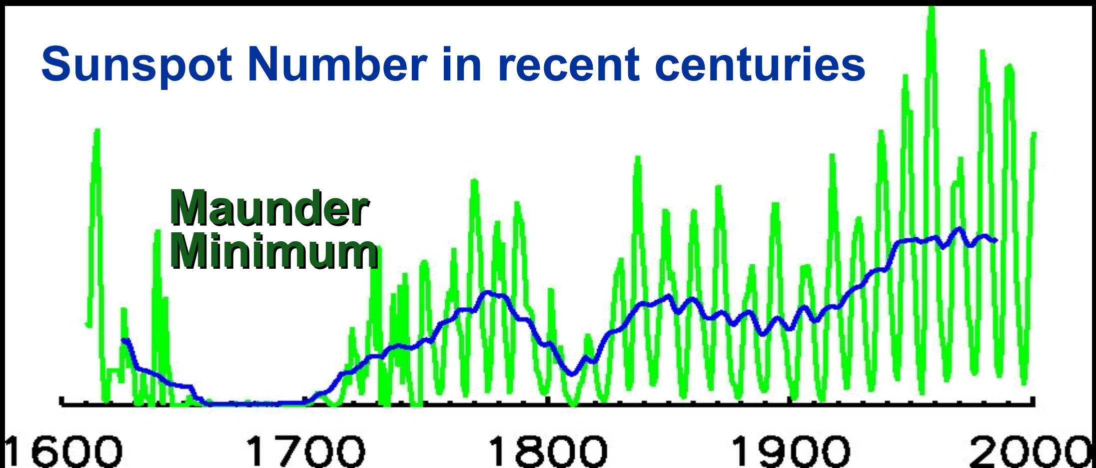




The solar dynamo is responsible for the 11-year solar cycle (also called the 22-year solar cycle, the sunspot cycle, magnetic cycle)



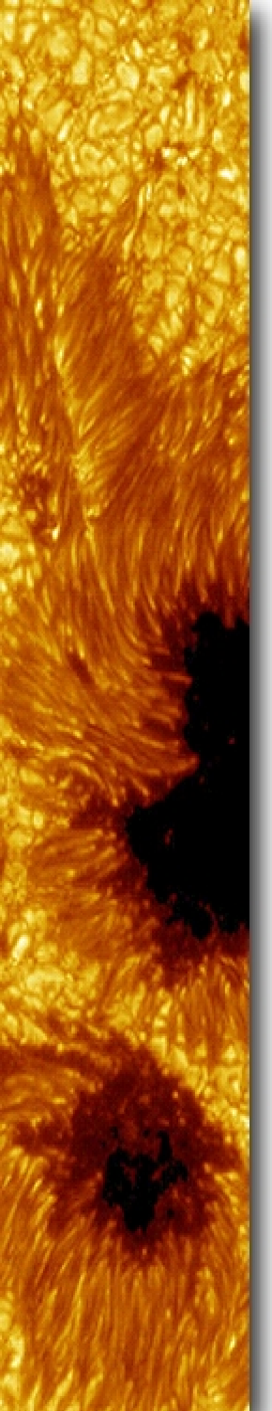
SUNSPOT CYCLES



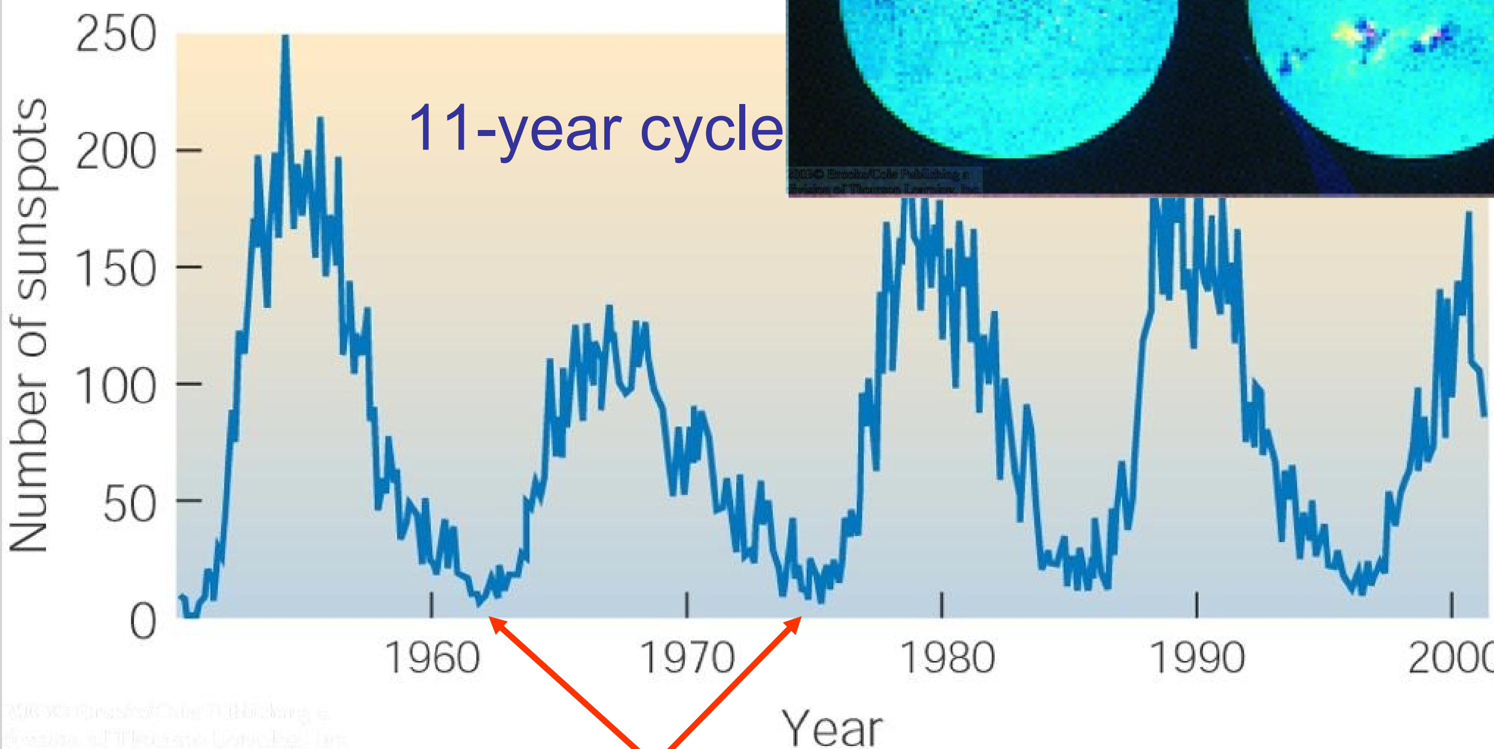
Two important points:

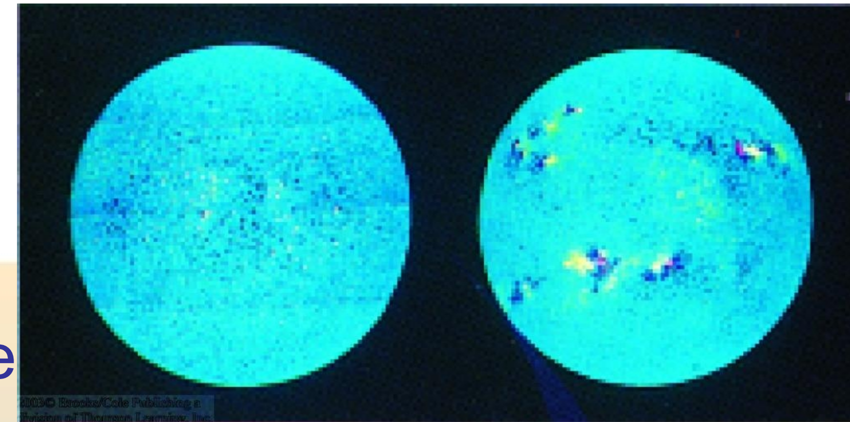
- The sunspot cycle itself varies
- All of the types of energy input to Earth exhibit greater fluctuations on shorter timescales (flares, CMEs)

The Solar Cycle



After 11 years, North/South order of leading/trailing sun spots is reversed

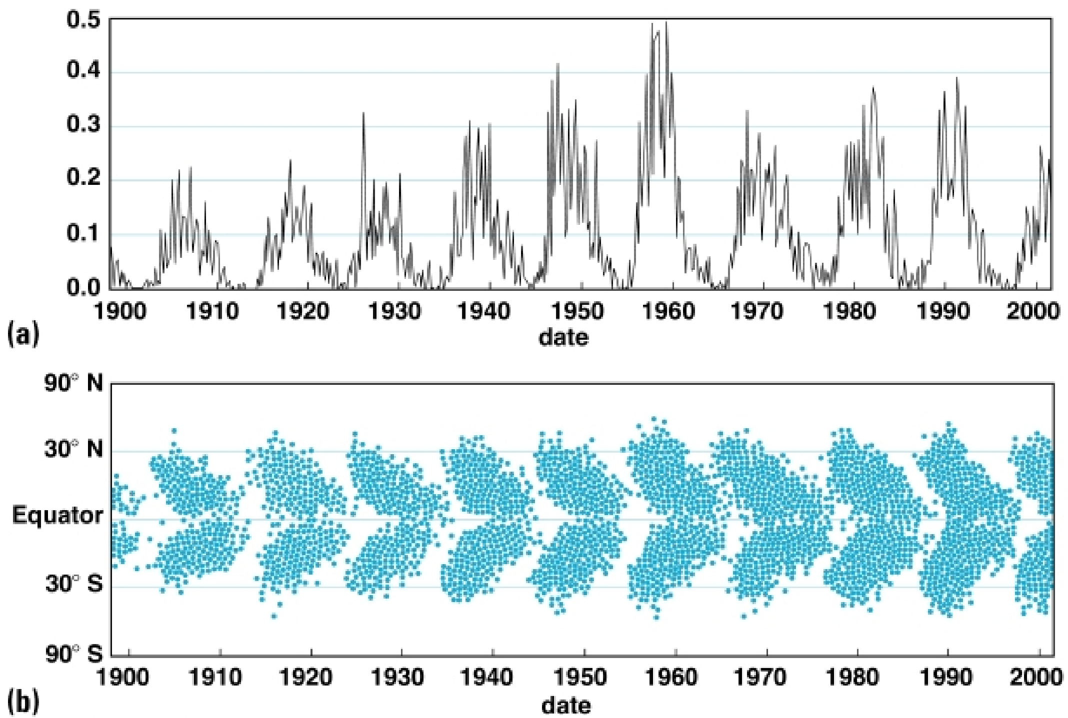




Reversal of magnetic polarity

=> Total solar cycle = 22 years

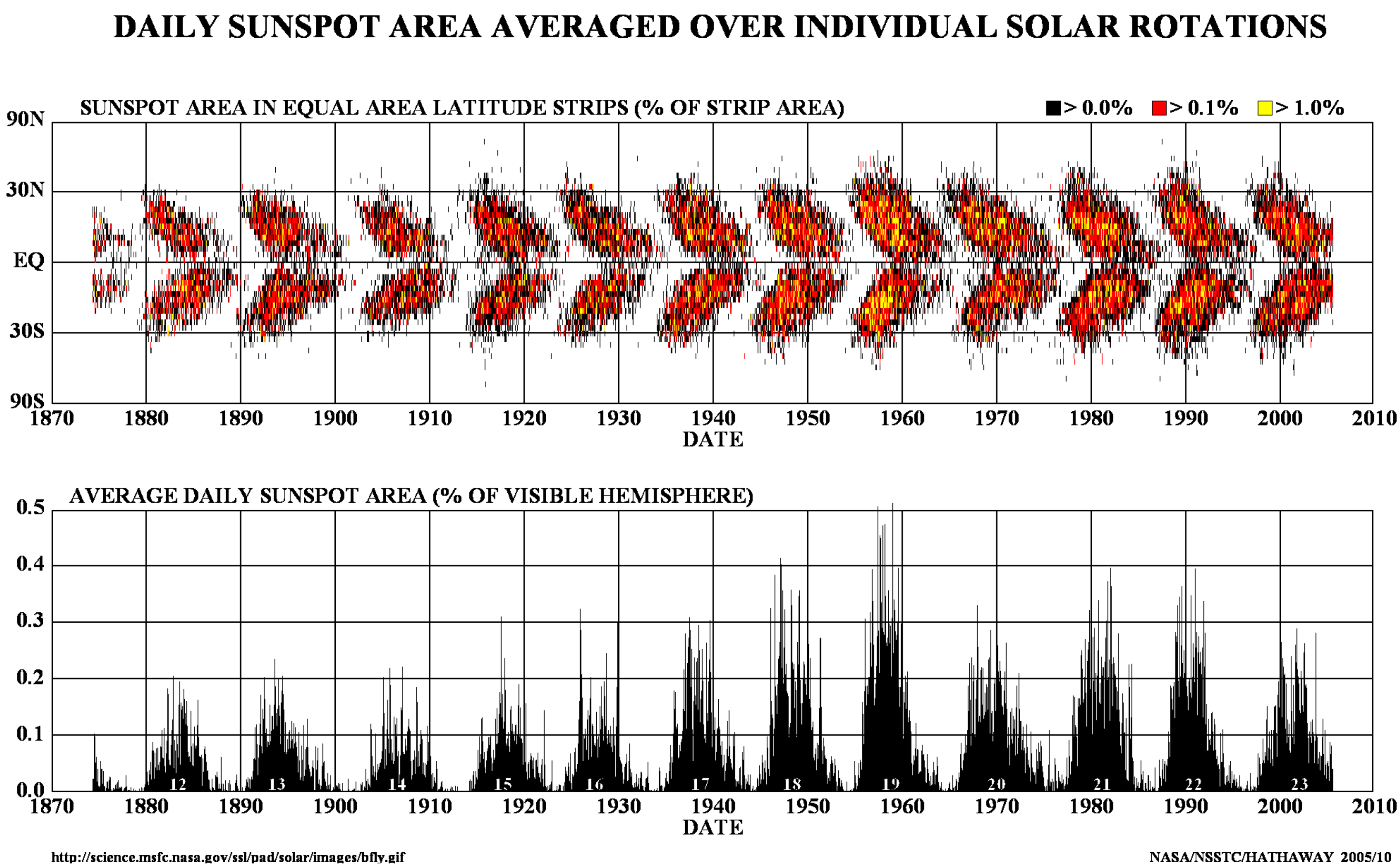
Solar Cycle---Sunspot Numbers and the Butterfly Diagram



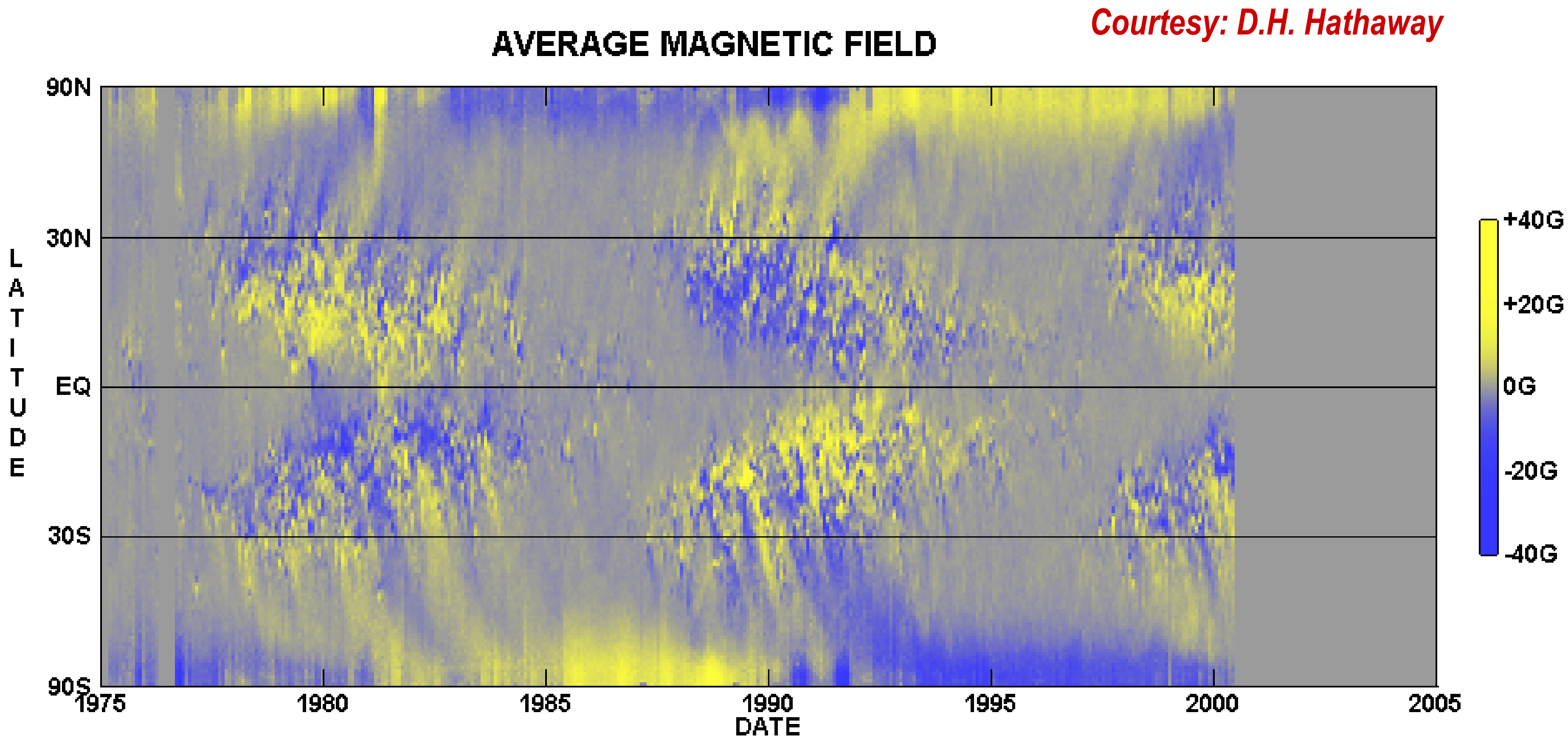
Solar Cycle
The **number** of sunspots on the surface of the Sun follows a 11-year cycle.

Butterfly diagram
Sunspots appear at higher latitude at the beginning of the solar cycle, and migrate toward the equator as the cycle evolves. So, when we plot the latitude of the sunspots as a function of time, the patterns looks like a series of butterfly… therefore it is referred to as the *butterfly diagram'*

Classical Signature of Solar Cycle



Properties of Solar Cycle



- Equatorward migration of sunspot-belt
- Poleward drift of large-scale radial fields, from follower spots
- Polar field reversal at sunspot maximum

Solar Atmosphere

Photosphere

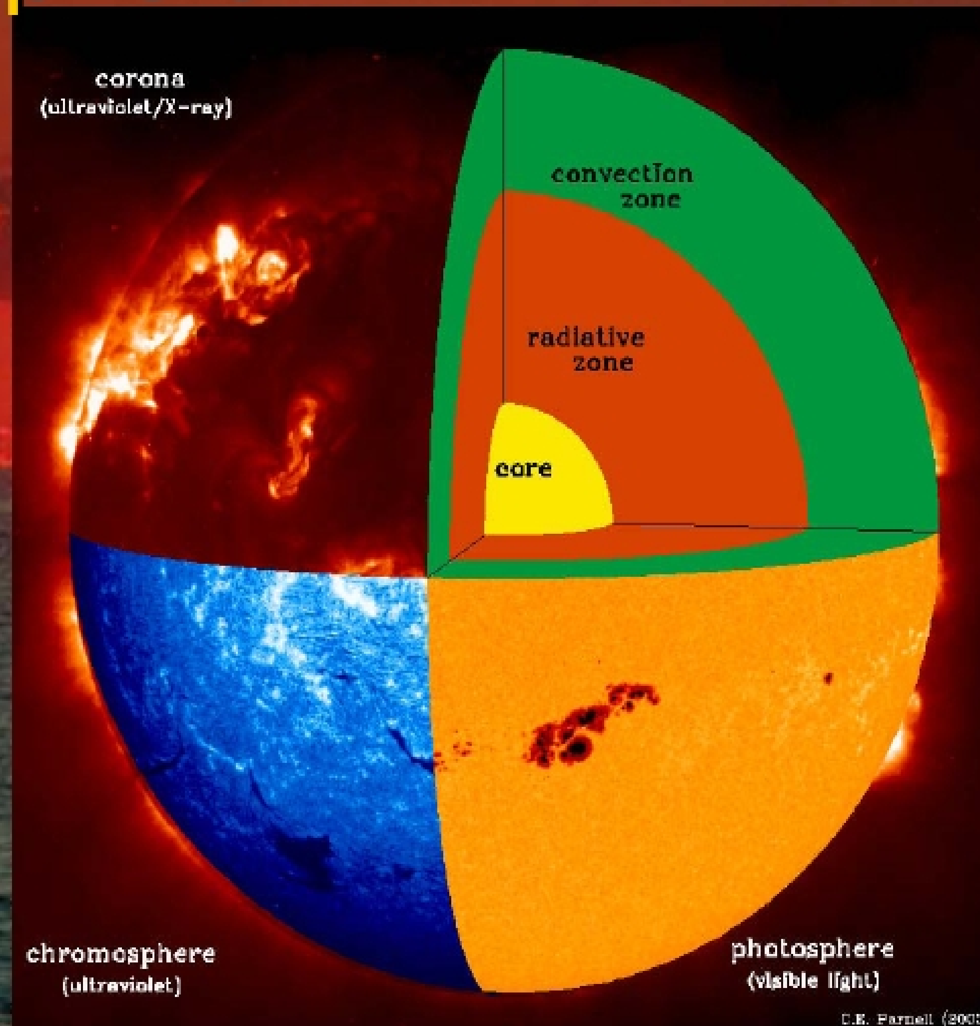
↓

Chromosphere

↓

Corona

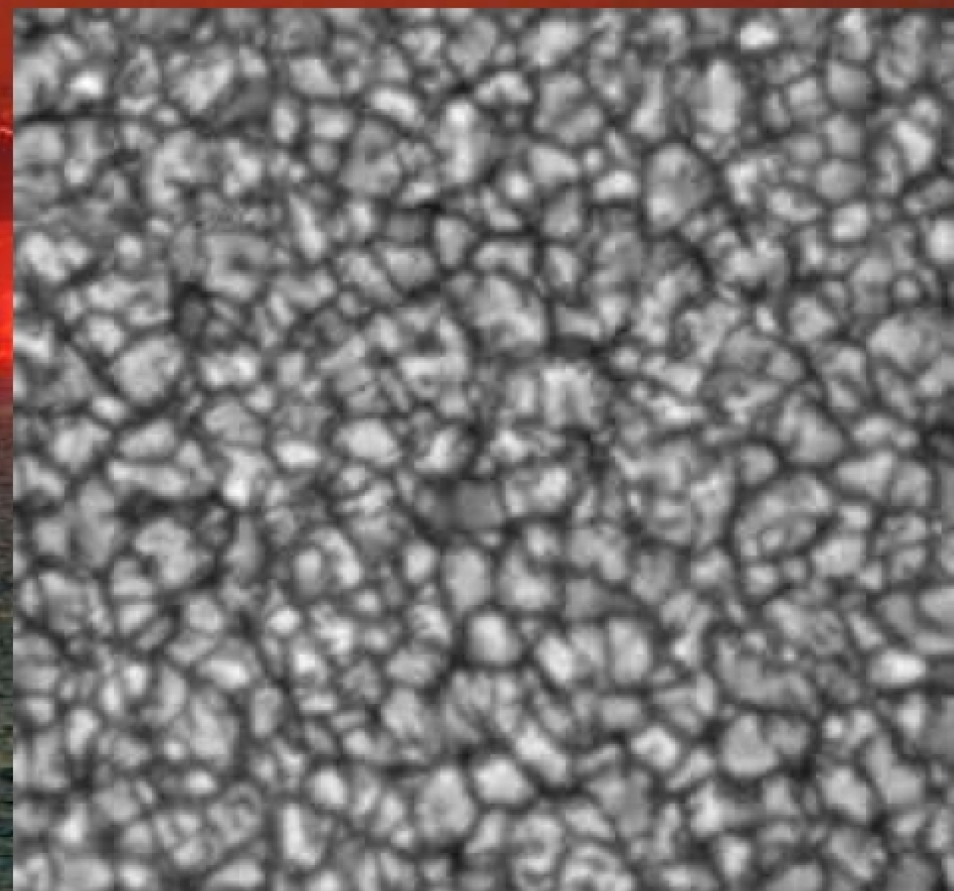
highly ionised gas: plasma



Photospheric Features: Granulation

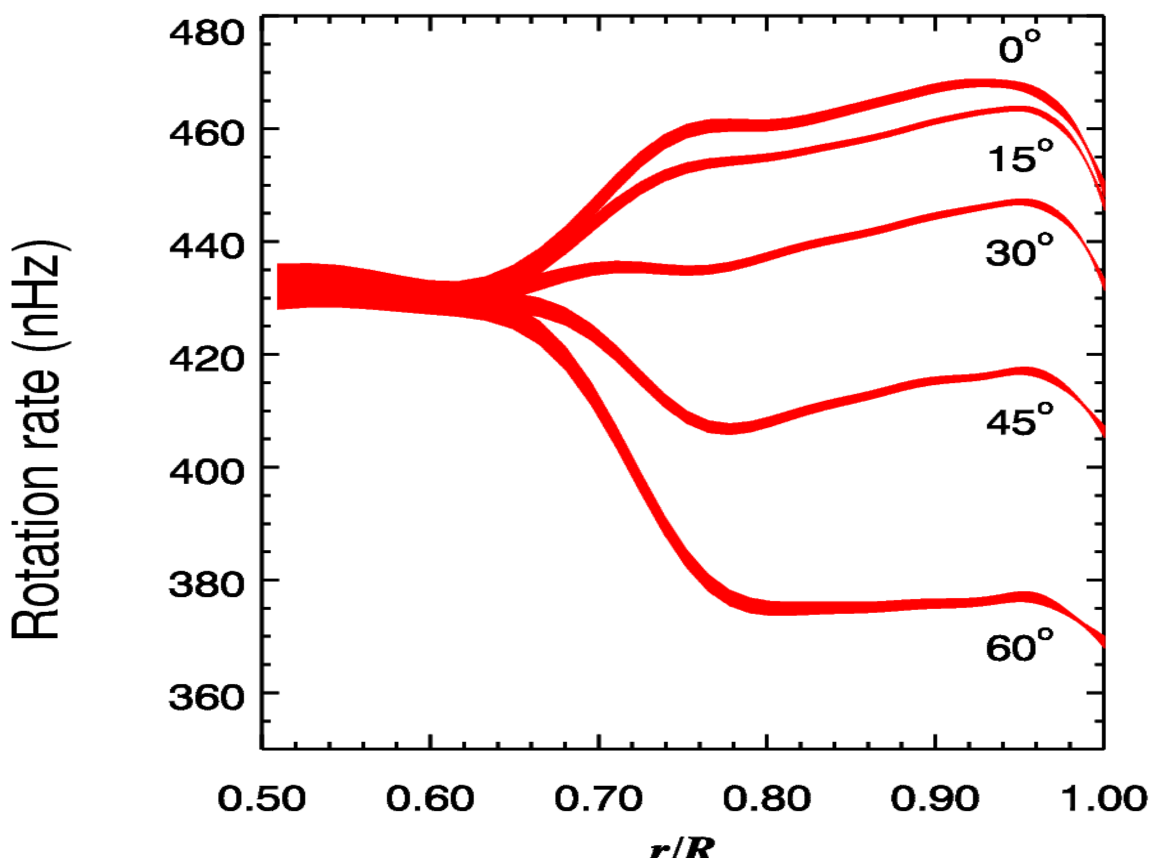
- Size of granulation cell ~ 1000km
- manifestation of convection

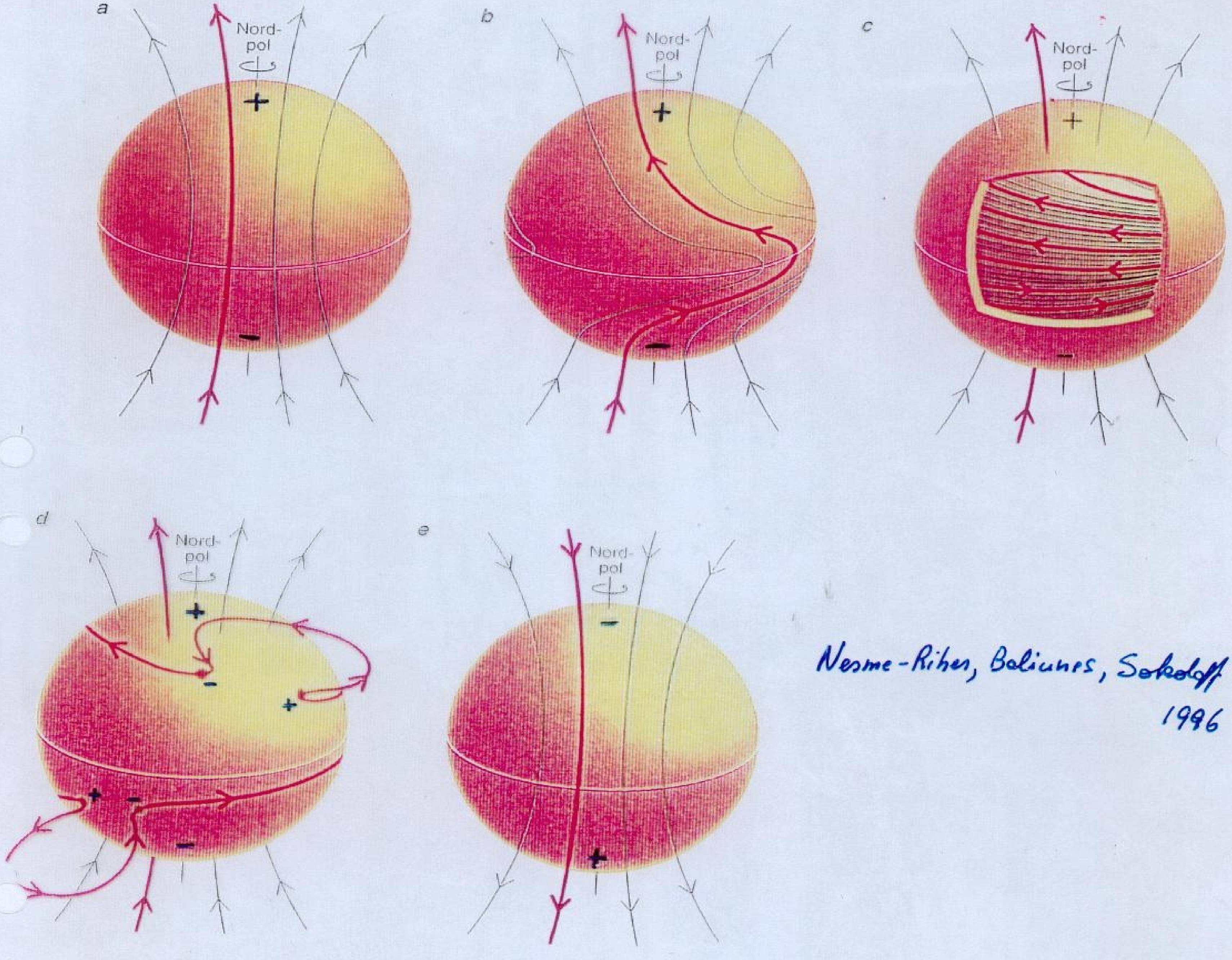
(bubbling up and down...)



Differential Rotation of the Sun

The Sun does not rotate like a solid body. It rotates every 25 days (1/462 nHz) at the equator and takes progressively longer to rotate one revolution at higher latitudes, up to 35 days (1/330 nHz) at the poles. differential rotation.





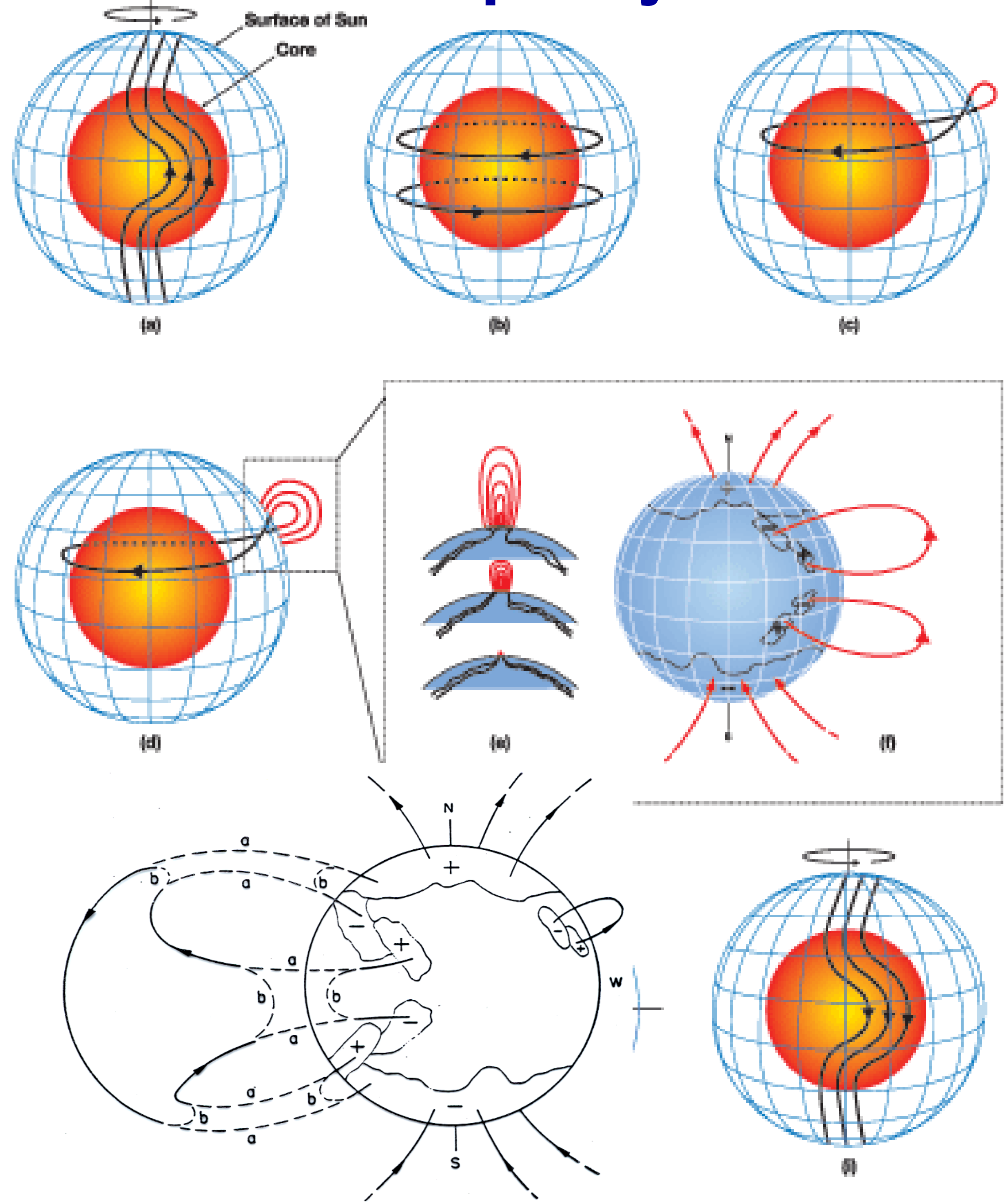
Nesme-Ribes, Baliunas, Sokoloff
1996

Schematic summary of predictive flux-transport dynamo model

Shearing of poloidal fields by differential rotation to produce new toroidal fields, followed by eruption of sunspots.

Because, leading sunspots are slightly equatorward of their following ones, there is more cancellation of leading-polarity fux than following-polarity flux by diffusion across the equator.

This leaves a surplus of following-polarity flux in each hemisphere, north and south. Over the course of the cycle, in each hemisphere meridional flow sweeps the remnant flux toward the pole and builds up a polar cup of predominantly following-polarity flux (Moore 1990).



Induction Equation

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\mathbf{j} = \sigma_0(\mathbf{E} + \mathbf{v} \times \mathrm{B})$$

$$\nabla \times \mathrm{B} = \mu_0 \mathbf{j}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathrm{B}) + \frac{1}{\mu_0 \sigma_0} \nabla^2 \mathbf{B}$$

Induction equation

Faraday's law in combination with the simple phenomenological ***Ohm's law***, relating the electric field in the plasma frame with its current:

$$\mathrm{j} = \sigma_0(\mathrm{E} + \mathrm{v} \times \mathrm{B})$$

Using ***Ampere's law*** for slow time variations, without the displacement current and the fact that the field is free of divergence ($\nabla \cdot \mathbf{B} = 0$),

yields the induction equation (with conductivity σ_0):

$$\frac{\partial \mathrm{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathrm{B}) + \frac{1}{\mu_0 \sigma_0} \nabla^2 \mathrm{B}$$

Induction equation

Evolution of a magnetic field in a plasma, with conductivity σ, moving at velocity v

$$\frac{\partial B}{\partial t} = \nabla \times (v \times B) + \frac{1}{\mu_0 \sigma} \nabla^2 B$$

- The first term of the right hand side describes the behaviour (coupling) of the magnetic field with the plasma
- The second term on the right hand side represents diffusion of the magnetic field through the plasma.

Schrijver and Zwan

Solar and Stellar Magnetic Activity

Cambridge, Univ. Press 2000

If the scale length of the plasma is L, the gradient term is (approximately)

$$\nabla \sim 1/L$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

$$\mathcal{O}\left(\frac{B}{\hat{t}}\right) \sim \mathcal{O}\left(\frac{v B}{\ell}\right) + \mathcal{O}\left(\frac{\eta B}{\ell^2}\right) \qquad (4.7)$$

local change by advection and diffusion

$$\partial \mathbf{B}/\partial t = \nabla^2 \mathbf{B} / (\sigma\mu_0) + \text{curl}\,(\mathbf{v} \times \mathbf{B})$$

Rate of change of field in a flare volume =

diffusive term + **convective term**.

Get an order-of-magnitude estimate of quantities by approximating $\partial/\partial t = 1 / t$, $\text{curl} = 1 / L$, $\nabla^2 = 1 / L^2$:

If there is no convective term, then: $B/\tau_D = B / (L^2 \sigma \mu_0)$

or **diffusion time**, $\boldsymbol{\tau_D = L^2 \sigma \mu_0}$. **(4)**

Solar Flare

- A solar flare is a **sudden brightening** of solar atmosphere (photosphere, chromosphere and corona)

- Flares release 10^{27} - 10^{32} ergs energy <u>in tens of minutes.</u>

(Note: one H-bomb: 10 million TNT = 5.0×10^{23} ergs)

- A flare produces enhanced emission in all wavelengths across the EM spectrum, including radio, optical, UV, soft X-rays, hard X-rays, and γ-rays

- Flare emissions are caused by
  - hot plasma emitting in: radio, visible, UV, soft X-ray
  - **non-thermal** energetic particles emitting in: radio, hard X-ray, γ-rays

Energy Source

$E_{th} \approx 3nkTV = 10^{28}$ erg for pre-flare $T = 10^6$K

$E_{mag} \approx (B^2/2\mu)V \approx$ **10^{32} erg**

Only **magnetic energy** (E_{mag}) is of the right order for the energy released in a large flare.

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flare
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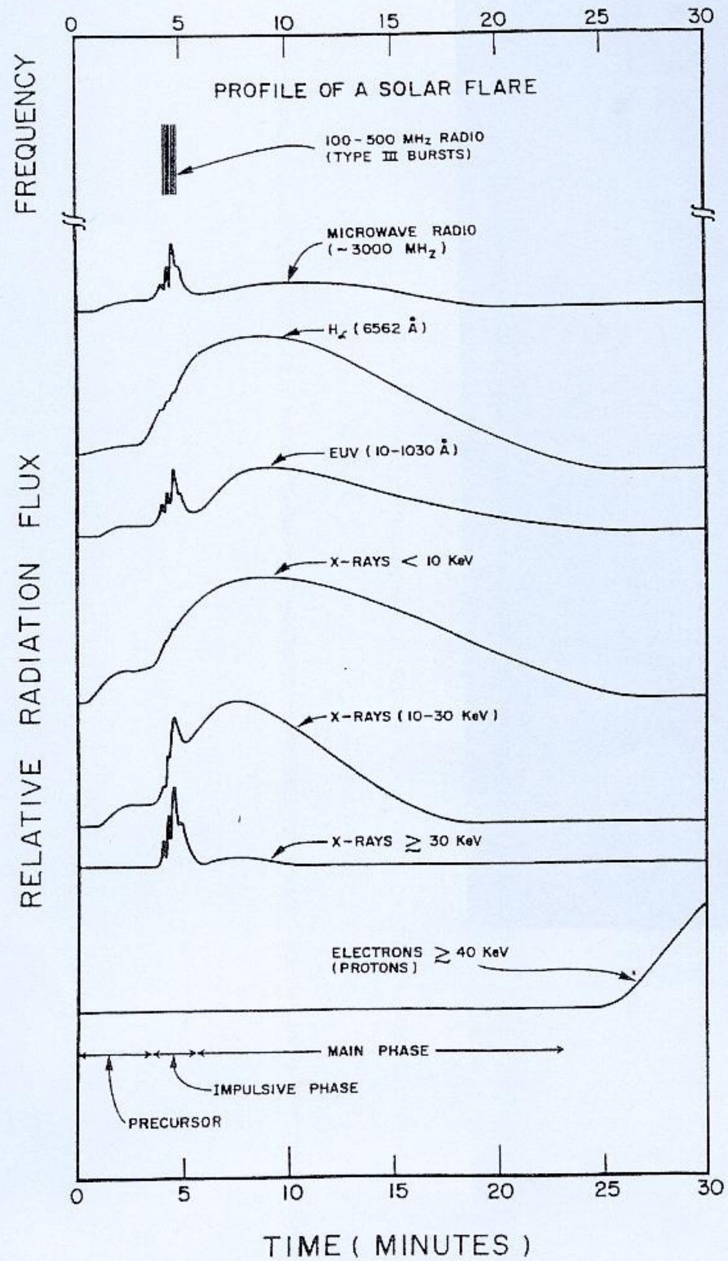
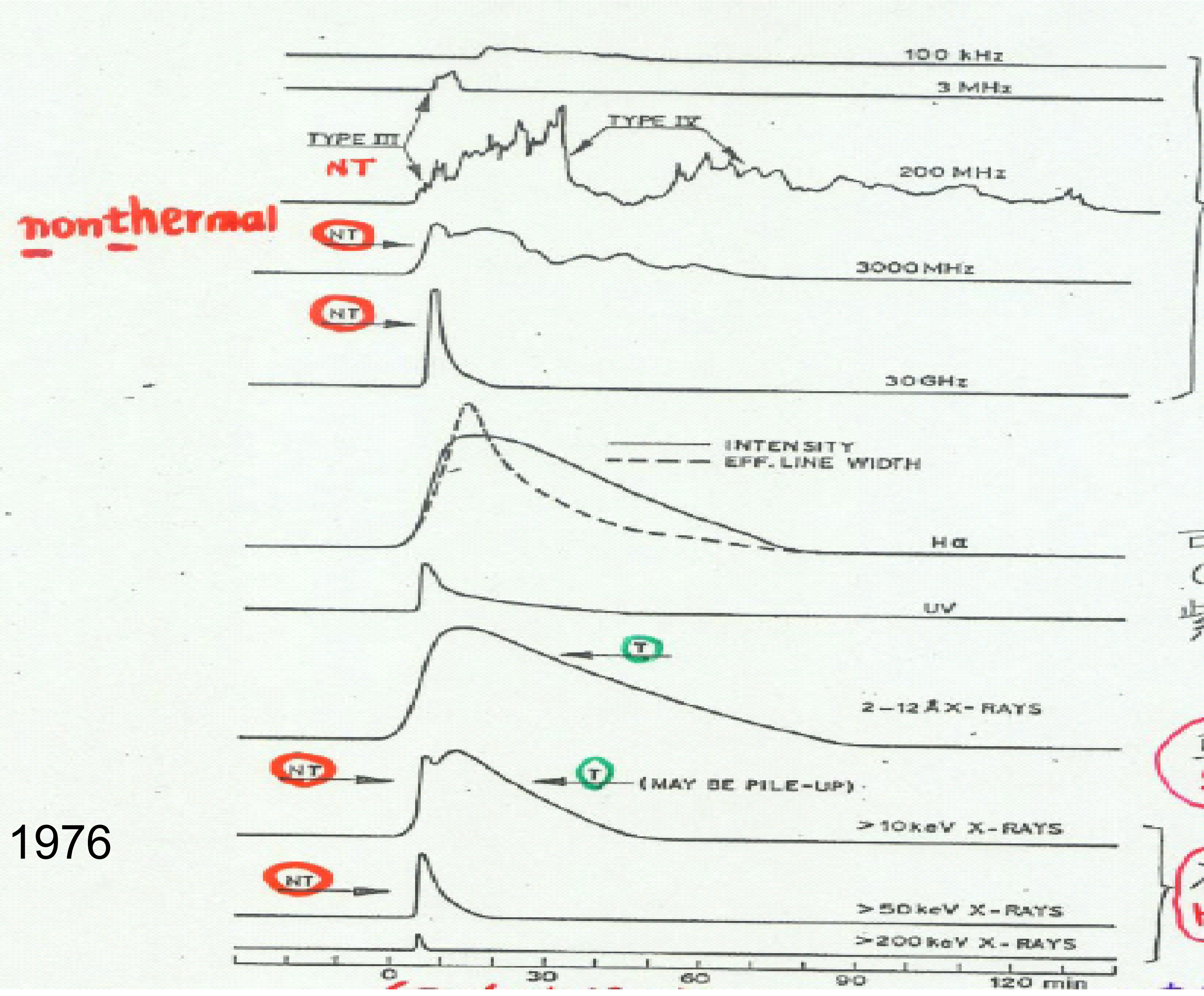




Svestka 1976

Flare radiation and emission mechanisms

Radio – microwave to metre wavelengths, produced by **gyrosynchrotron, bremsstrahlung** and collective plasma processes.

Optical emission – lines and continua, Hα line is seen in emission (due to collisional excitation in hot, flare-produced plasma).

White-light continua are probably produced by hydrogen recombination following electron bombardment and H^- emission.

UV lines and continua – excitation by hot flare-produced plasma, with an “impulsive contribution” due to nonthermal electrons.

Flare radiation and emission mechanisms (contd.)

•**EUV line emission**.

•**Soft X-ray – lines and continua** (thermal e^- - p^+ bremsstrahlung, bound-free continuum).

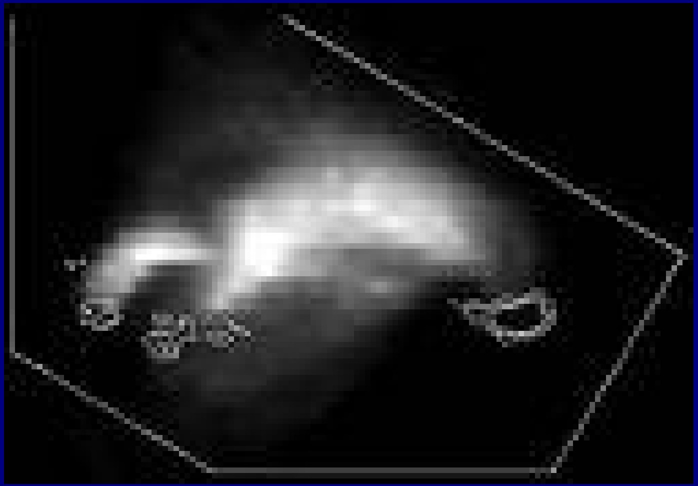
•**Hard X-rays**– non-thermal e^- - p^+ bremsstrahlung.

∀**γ-ray lines and continua**:
- continuum up to 1 MeV produced by non-relativistic electron bremsstrahlung
- >10 MeV continuum is due to relativistic electron bremsstrahlung.

Flare radiation and emission mechanisms (contd.)

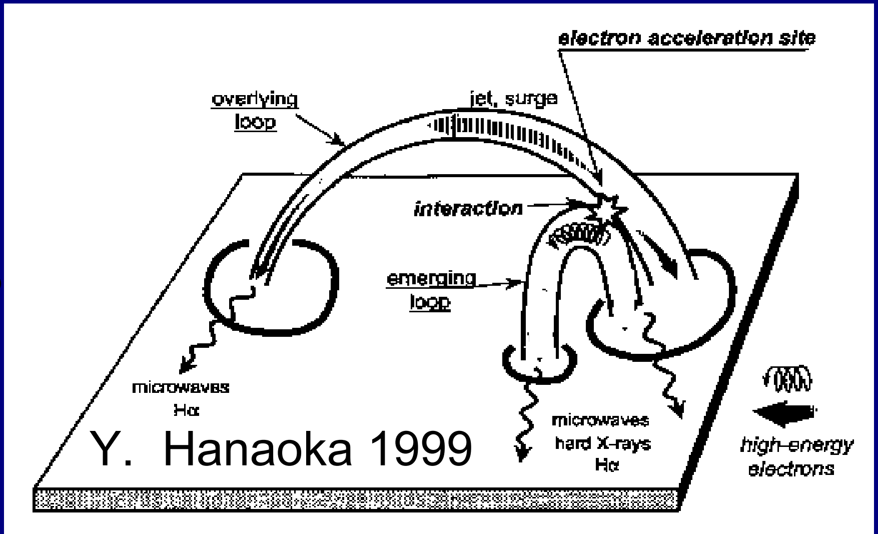
γ-ray emission (contd.)

- narrow lines in 4-7 MeV range produced when accelerated p^+ and α particles interact with ambient heavy nuclei.
- **strongest γ-ray line** is the neutron capture line at **2.23 MeV**, with another strong line at **0.511 MeV** due to positron annihilation.

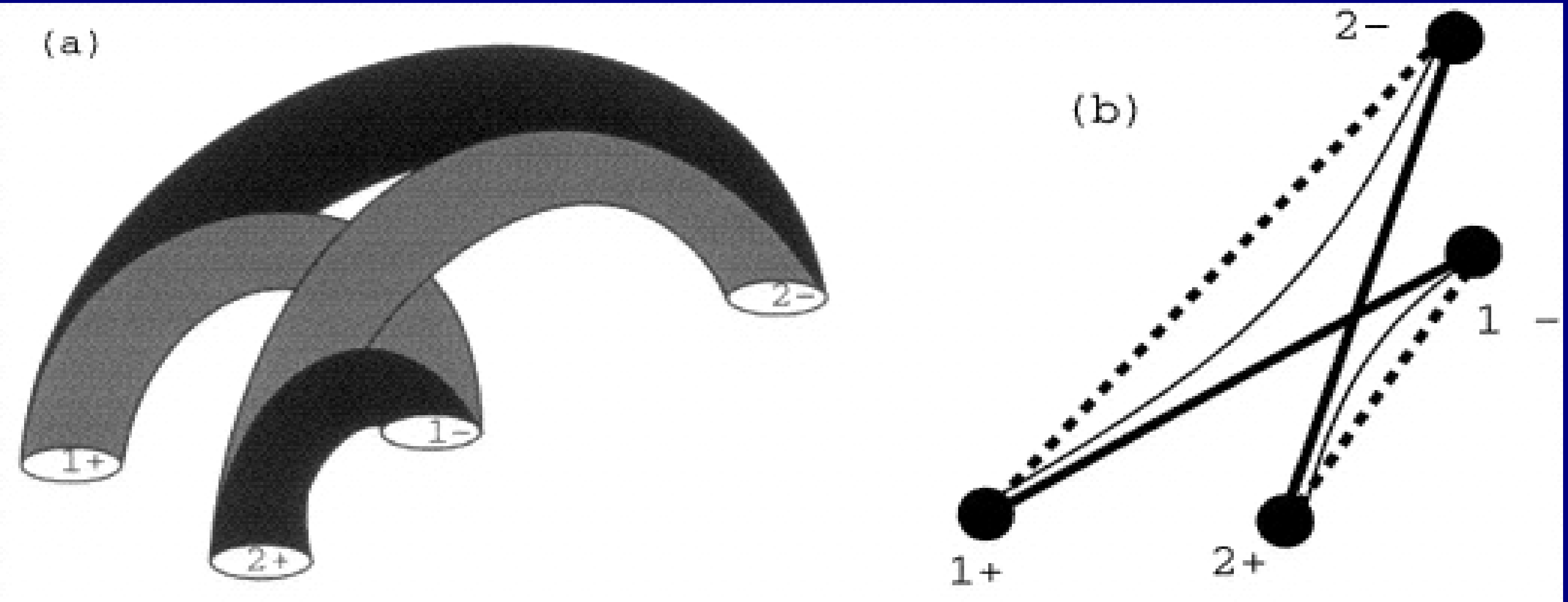


Loop-Loop interactions

www.astro.uni.wroc.pl/nauka/helpap/rf/1093

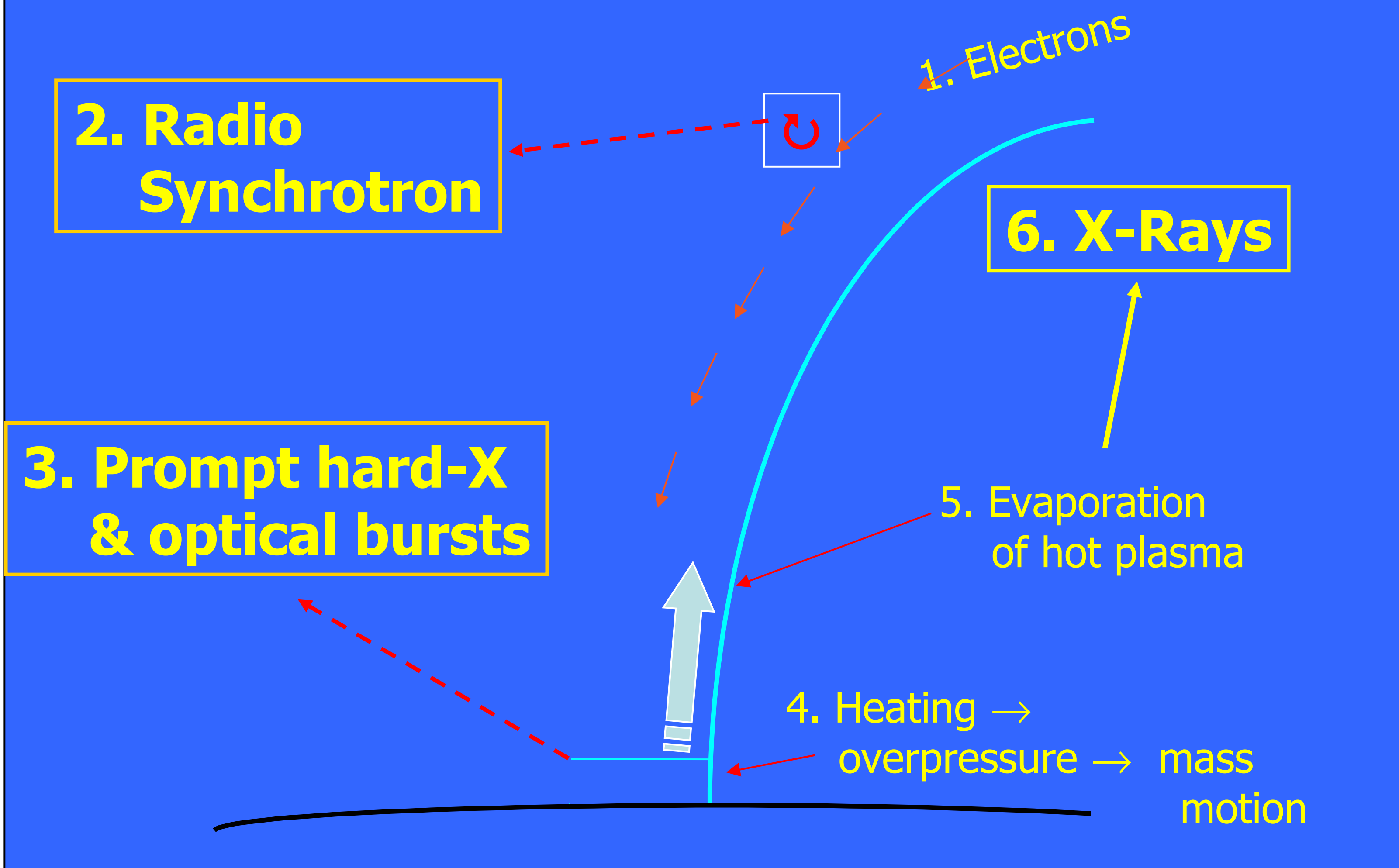


Magnetic-reconnection

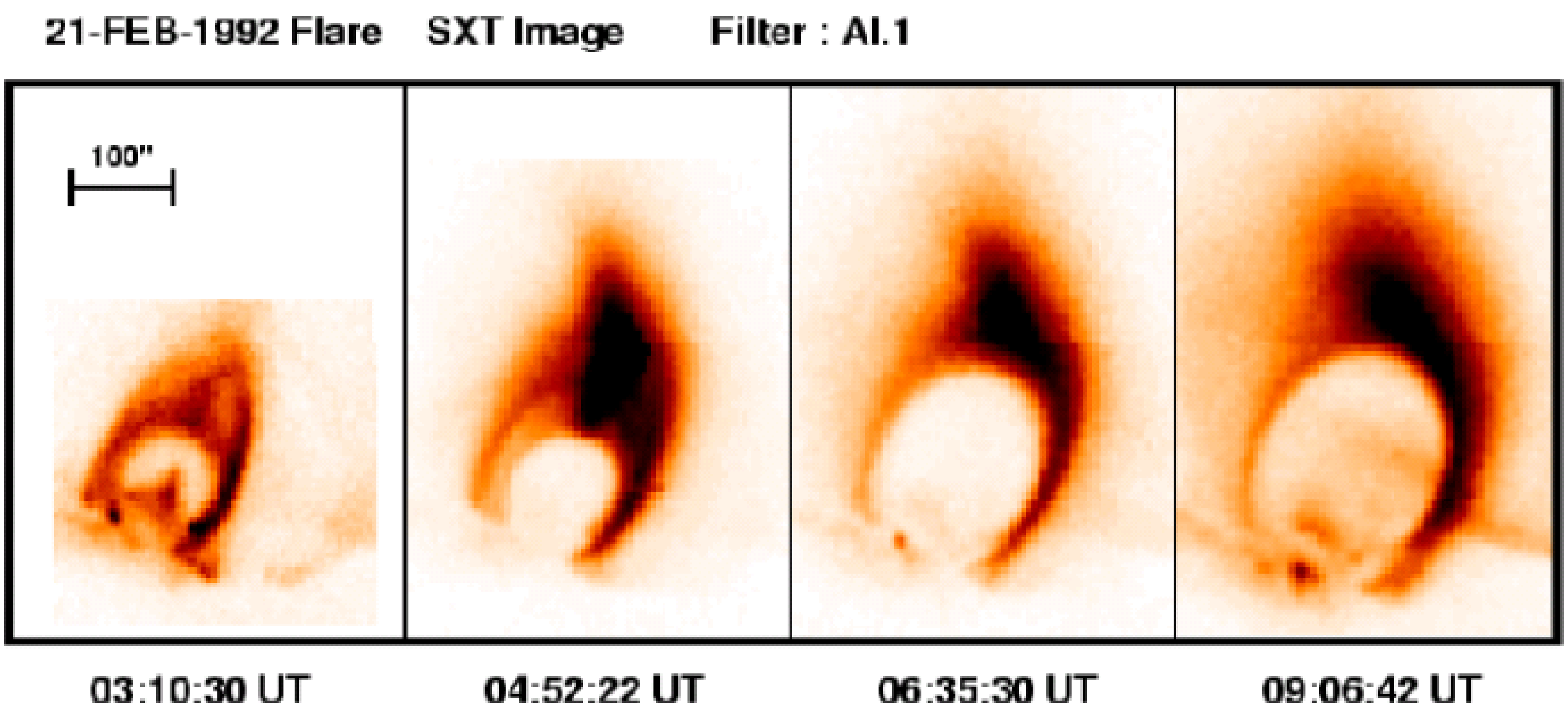


Standard flare scenario after reconnection

0. Build-up of non-potential fields $\rightarrow$ field annihilation $\rightarrow$ reconnection $\rightarrow$ particle acceleration

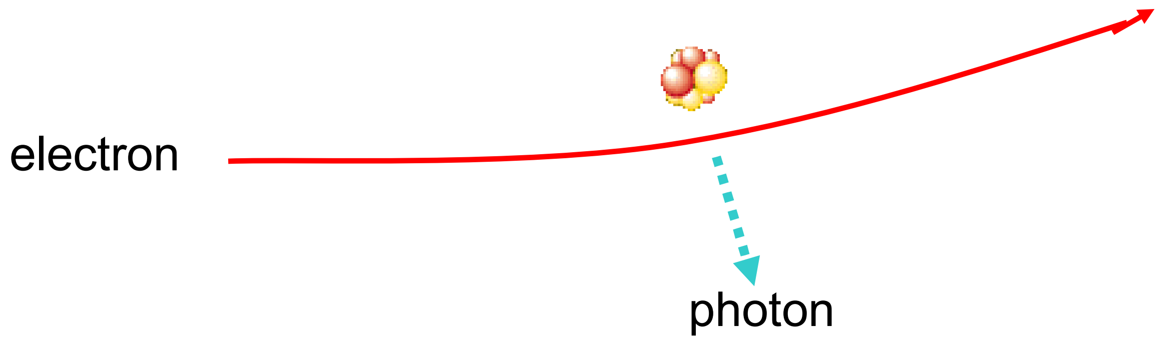


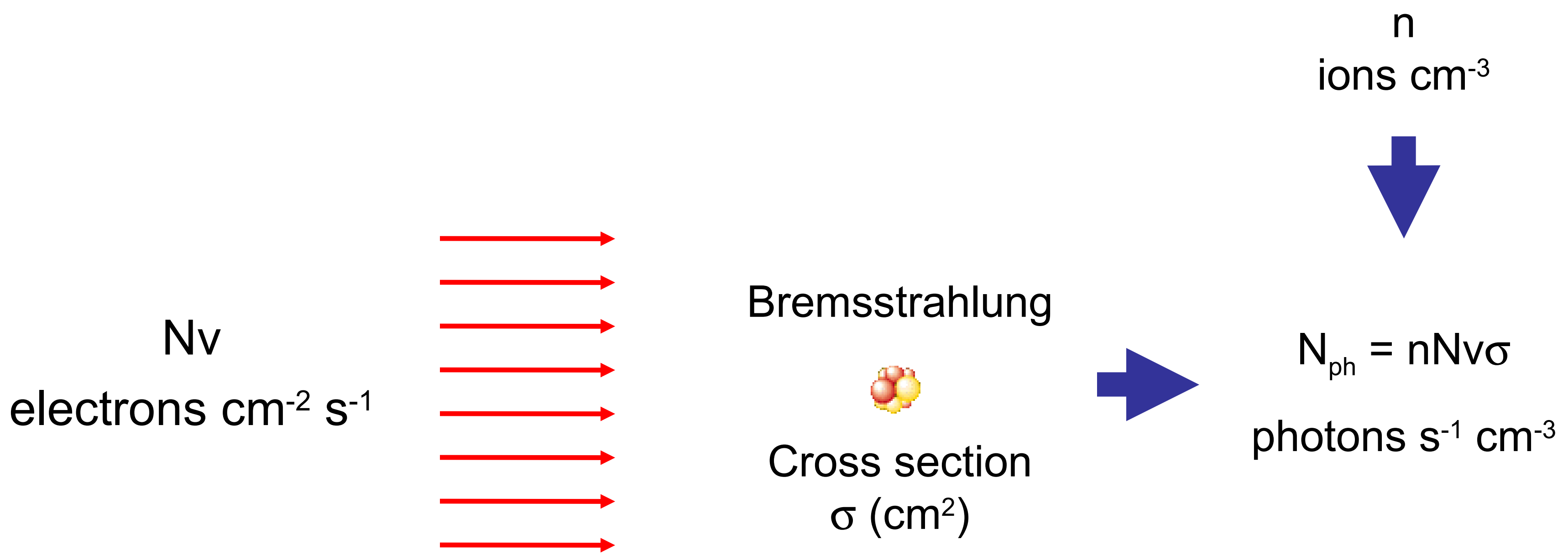
LDE (long duration event) flare
(SXT, ～ 1 keV、 Tsuneta et al. 1992)



electron temperature ～１０＾７ K、
electron density～１０＾（１０）ｃｍ＾（－３）

From Fast Electrons to Bremsstrahlung Photons





Thick-target bremsstrahlung

Thick-target bremsstrahlung occurs when an electron enters a thick material, loses energy by multiple collisions with the atoms and electrons in the material, and may eventually come to rest.

The rapid deposition of nonthermal kinetic energy causes an explosive pressure increase in the chromosphere such that heated material "evaporates" into the corona (e.g., Antonucci, Gabriel, & Dennis 1984).

Magnetic Activity:

Flaring activity (radio wavelenghts , X-rays)

Spots

Cromospheric activity

The Phenomenon of Stellar Activity

1 Red dwarfs

2 Solar-type stars

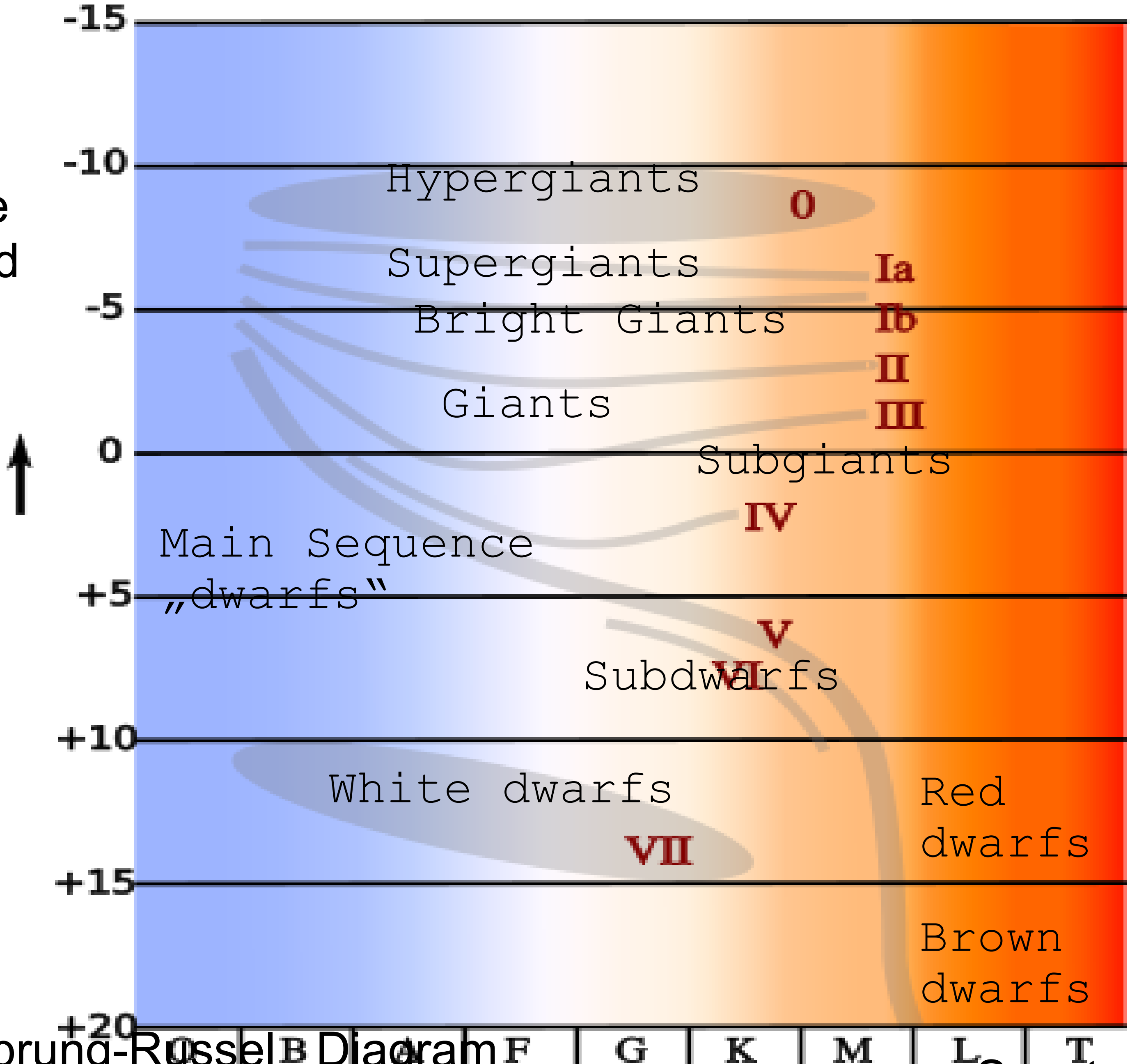
3 RS CVn stars

4 T Tauri stars

Svetlana V. Berdyugina:

http://solarphysics.livingreviews.org/Articles/lrsp-2005-8/

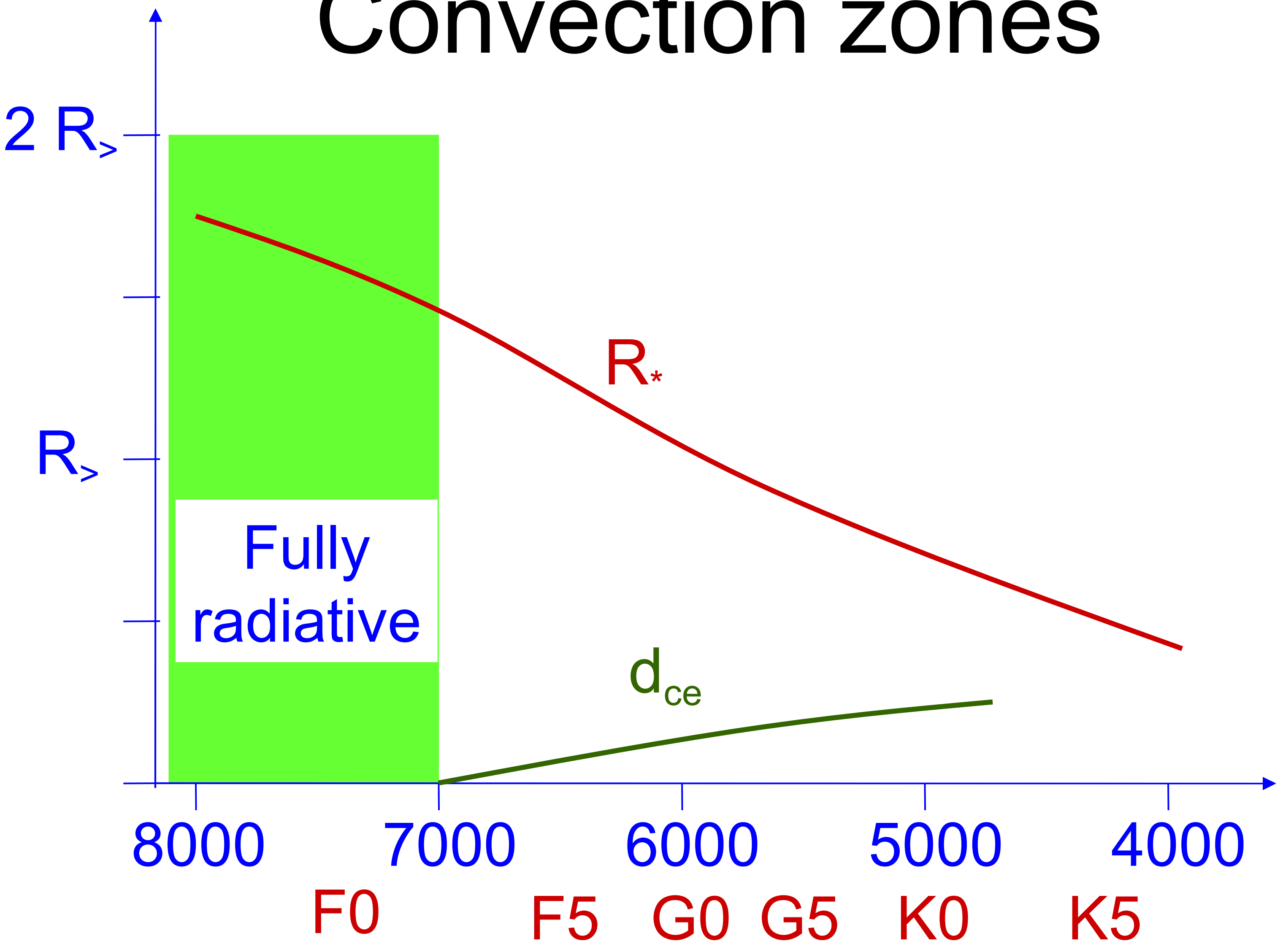
Absolute Magnitude (M_v)



Hertzsprung-Russel Diagram

Spectral type

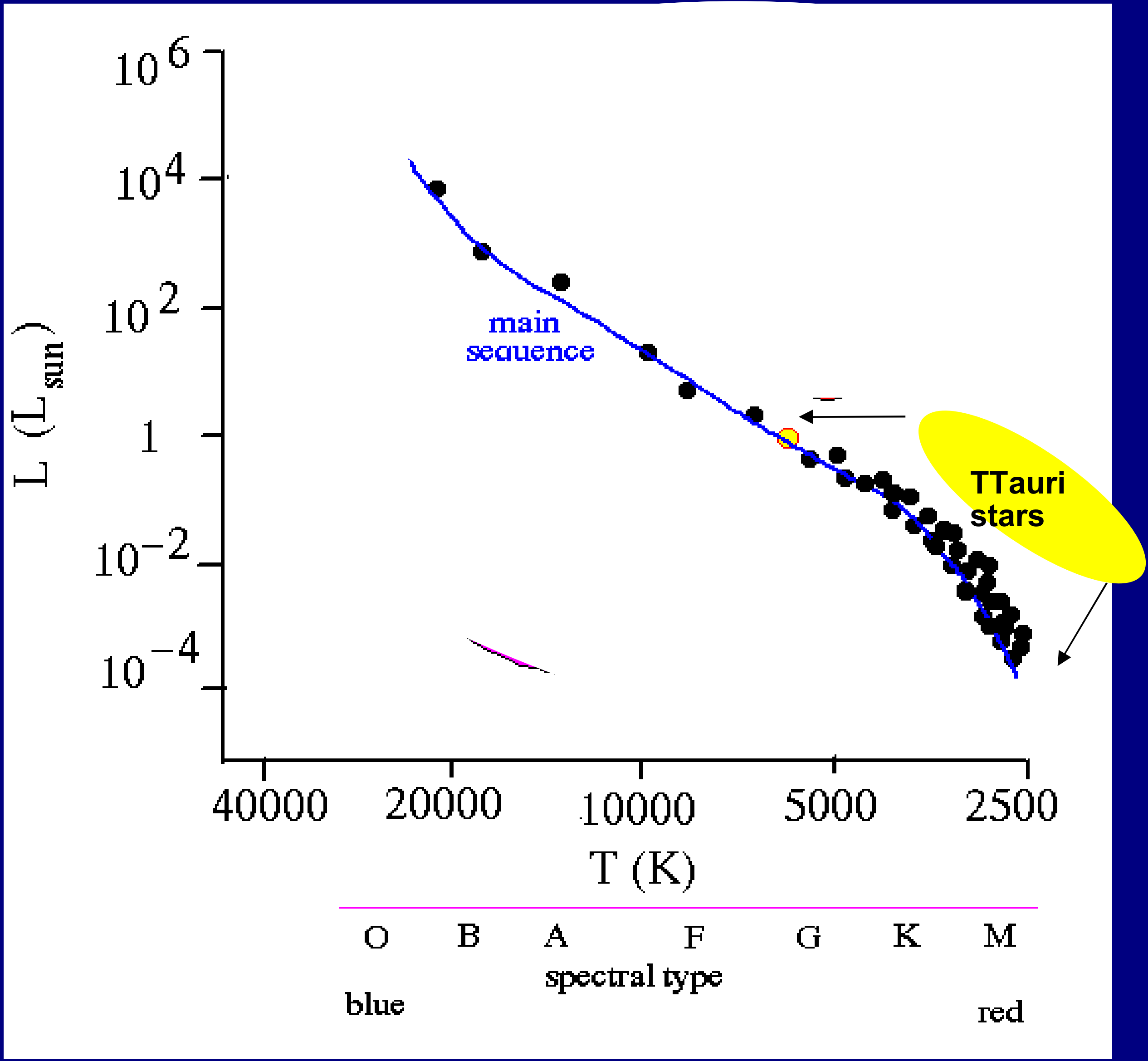
Convection zones



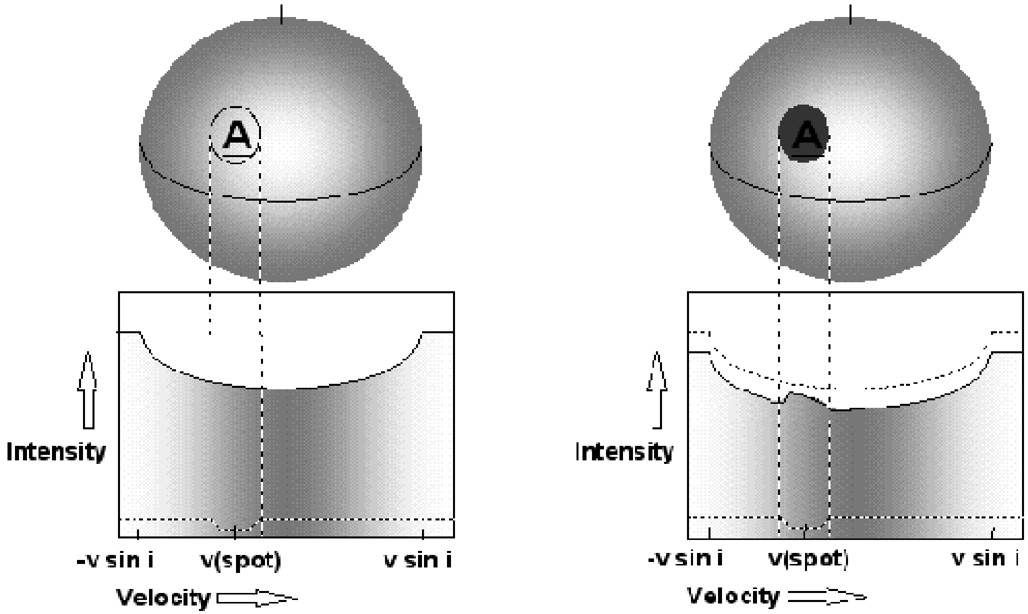
Weak-line T Tauri Stars

are pre-main sequence objects,

where the radiative zone either is still missing or is deeply embedded and therefore corresponds to a very different situation with respect to the thin convective shell of the Sun.

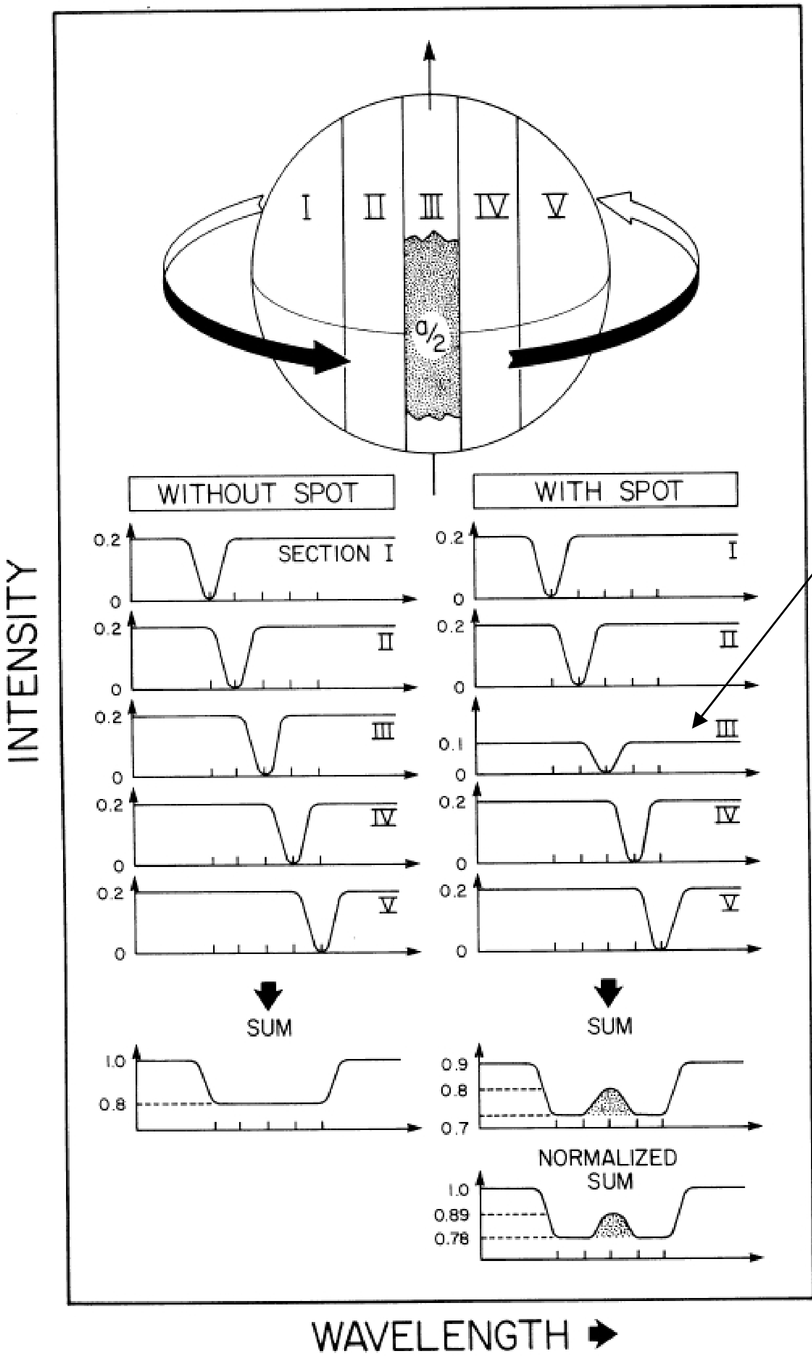


Principle of Doppler imaging



K.G. Strassmeier

Doppler imaging is a technique, which uses a series of spectral line profiles, of a rapidly rotating star, to compute the stellar surface temperature distribution.



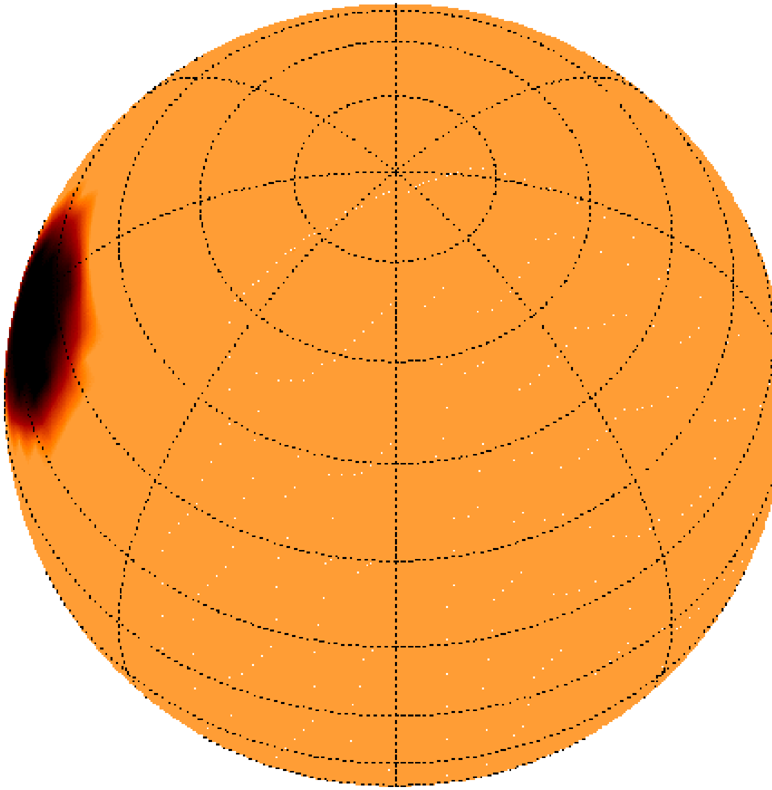
Doppler Imaging from Vogt & Penrod 1983

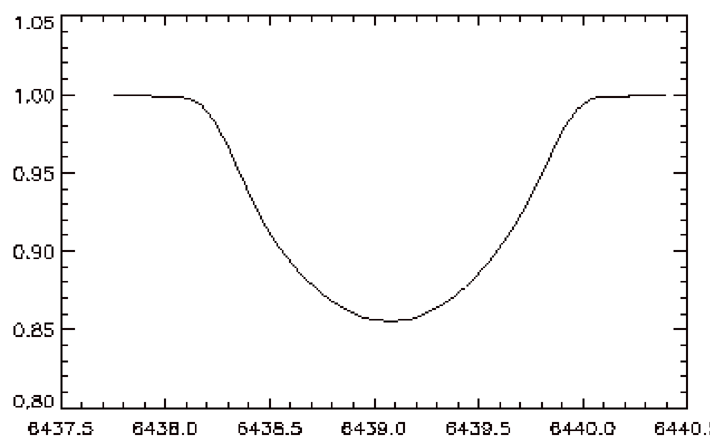
lower continuum

As a spot moves across the star the line profile changes. From an observed line profile, one can construct an image of the surface of the star. This technique has been applied to many different types of stars.

Doppler imaging$_1$

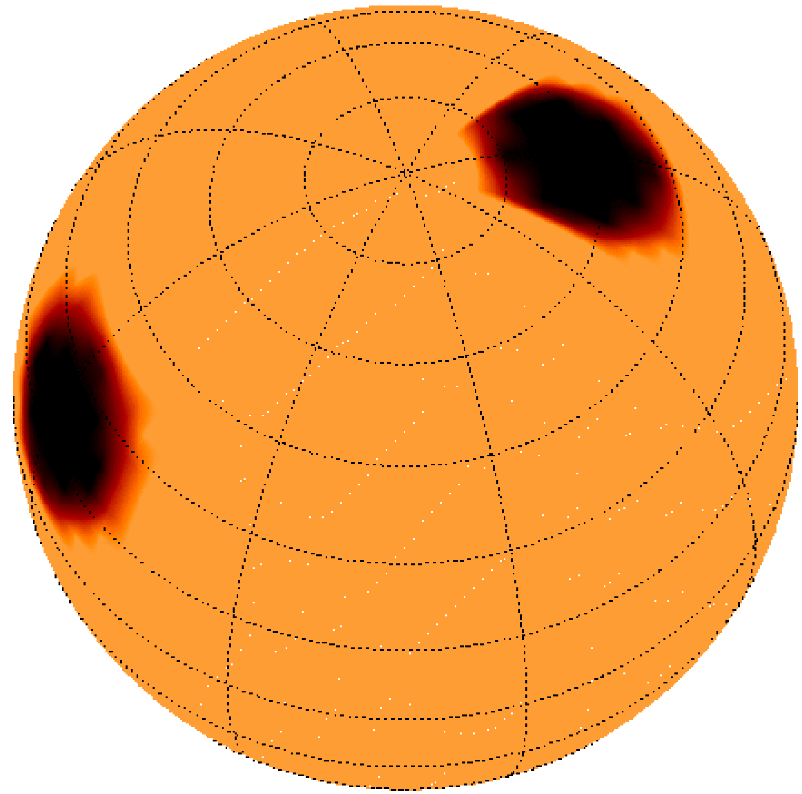
- Missing flux from spots produce line profile deformations
- 'bumps' move from blue to red wing of the profile due to the 'Doppler' effect.
- Position of spots correspond to spot longitudes

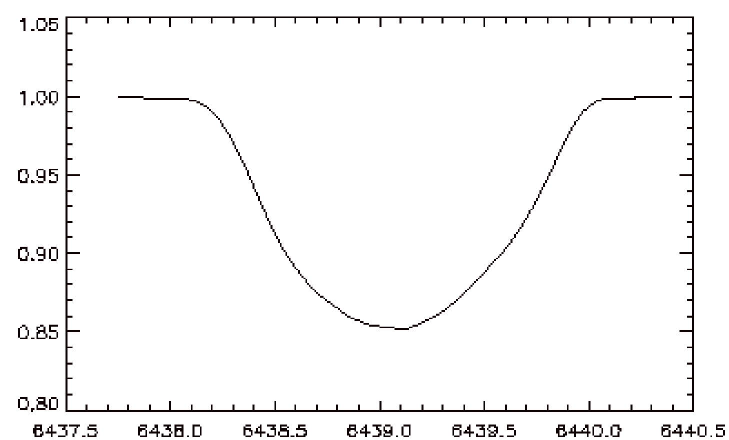




Doppler imaging$_2$

- Speed of spots give indication of the latitude (more uncertain than the longitude)
- 'bumps' from high latitude spots start out somewhere in the middle of the line wing, low latitude spots at the line shoulder





The Phenomenon of Stellar Activity

1 Red dwarfs and BY Dra phenomenon

2 Solar-type stars

3 RS CVn stars

4 T Tauri stars

.2 Solar-type stars

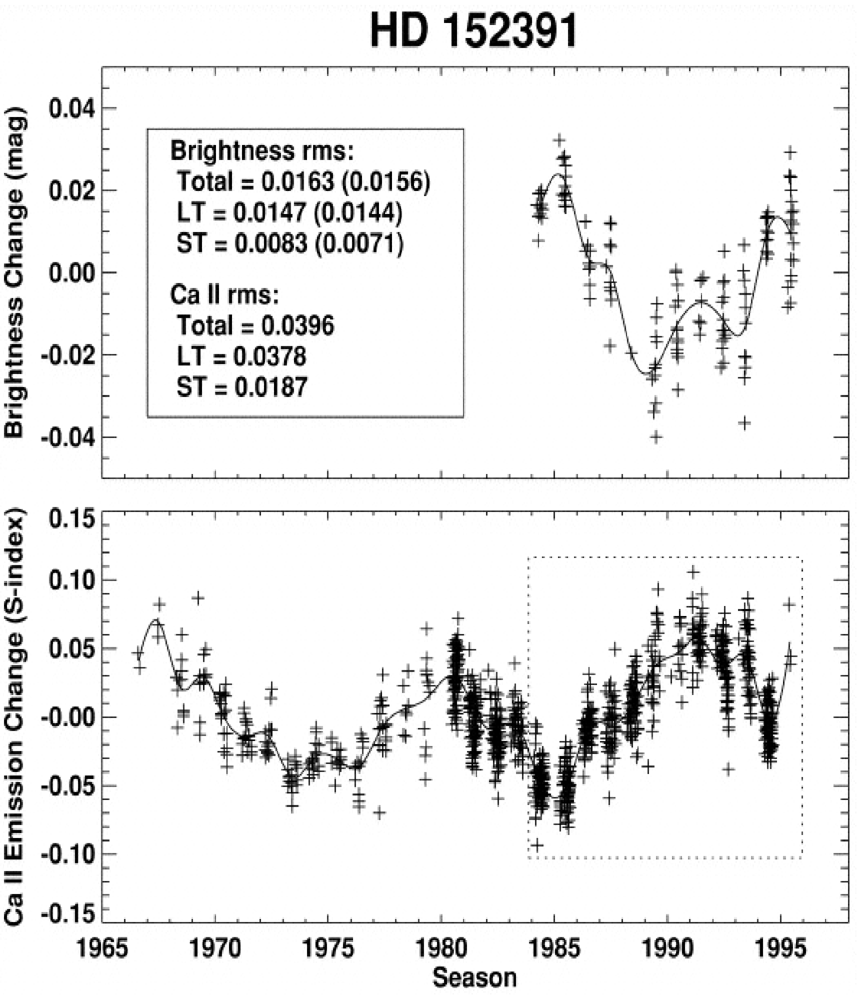
Stars on the lower main-sequence are known to show chromospheric activity similar to that on the Sun which is detected, e.g., in the Ca II H & K emission (Wilson, 1978).

Svetlana V. Berdyugina:

http://solarphysics.livingreviews.org/Articles/lrsp-2005-8/

Monitoring of stellar activity (CaII H&K)

- Extension of the Mt. Wilson survey
- Search for activity cycles
- Surveys to search for active stars



Activity Cycles

- Long term chromospheric activity indices for several stars showing different patterns of activity cycles