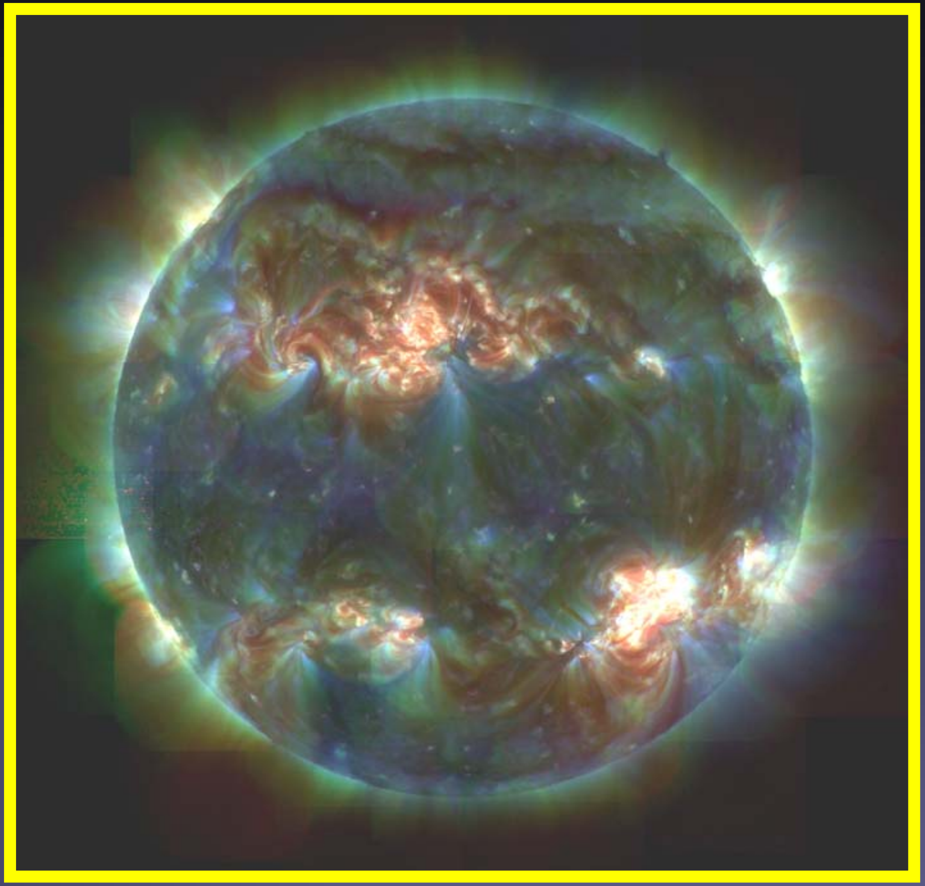
The Sun's Magnetic Field from Core to Corona



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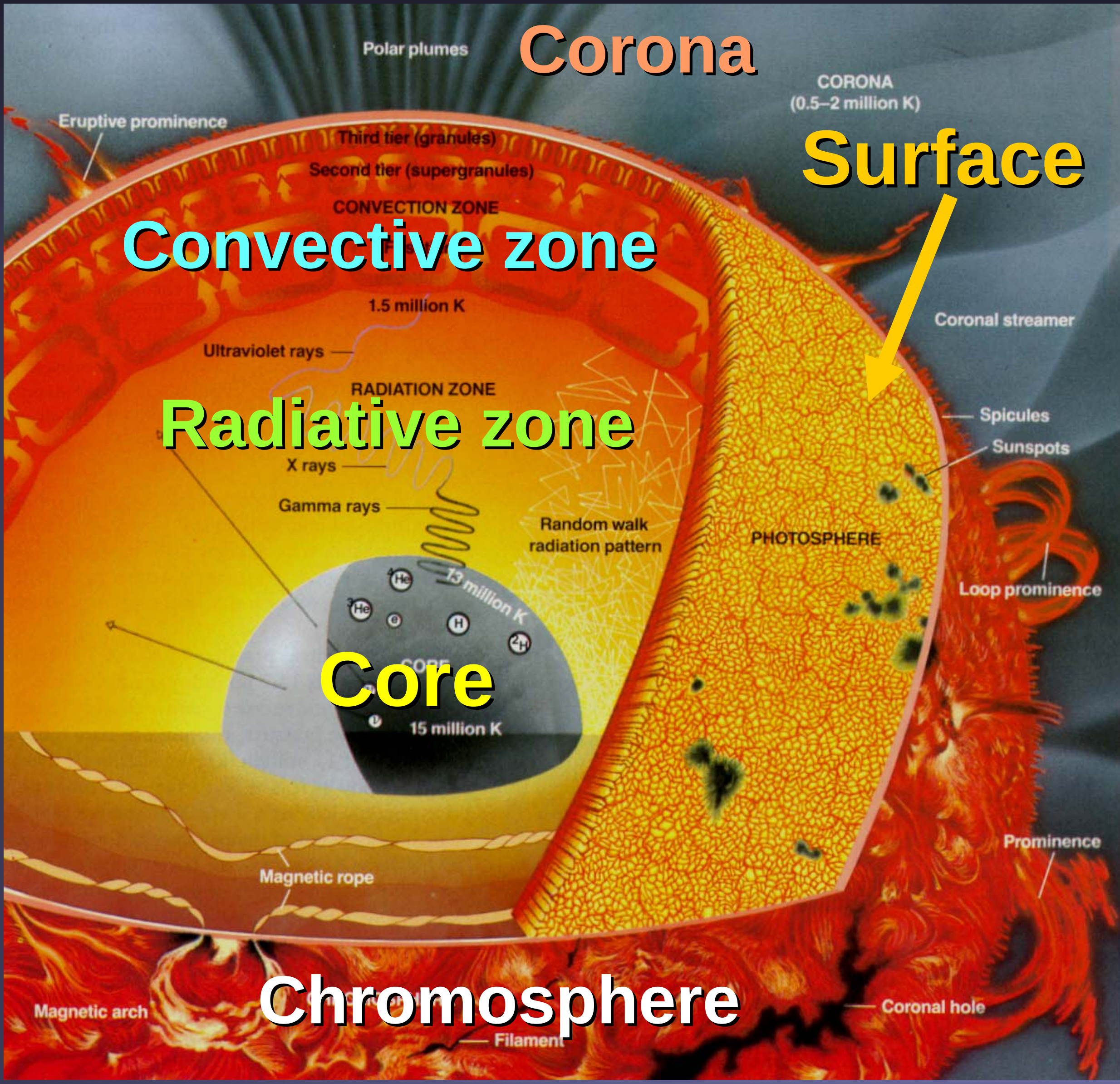
The Sun's Structure

Solar interior:

- Everything below the Sun's (optical) surface
- Divided into hydrogen-burning core, radiative and convective (energy transport) zones

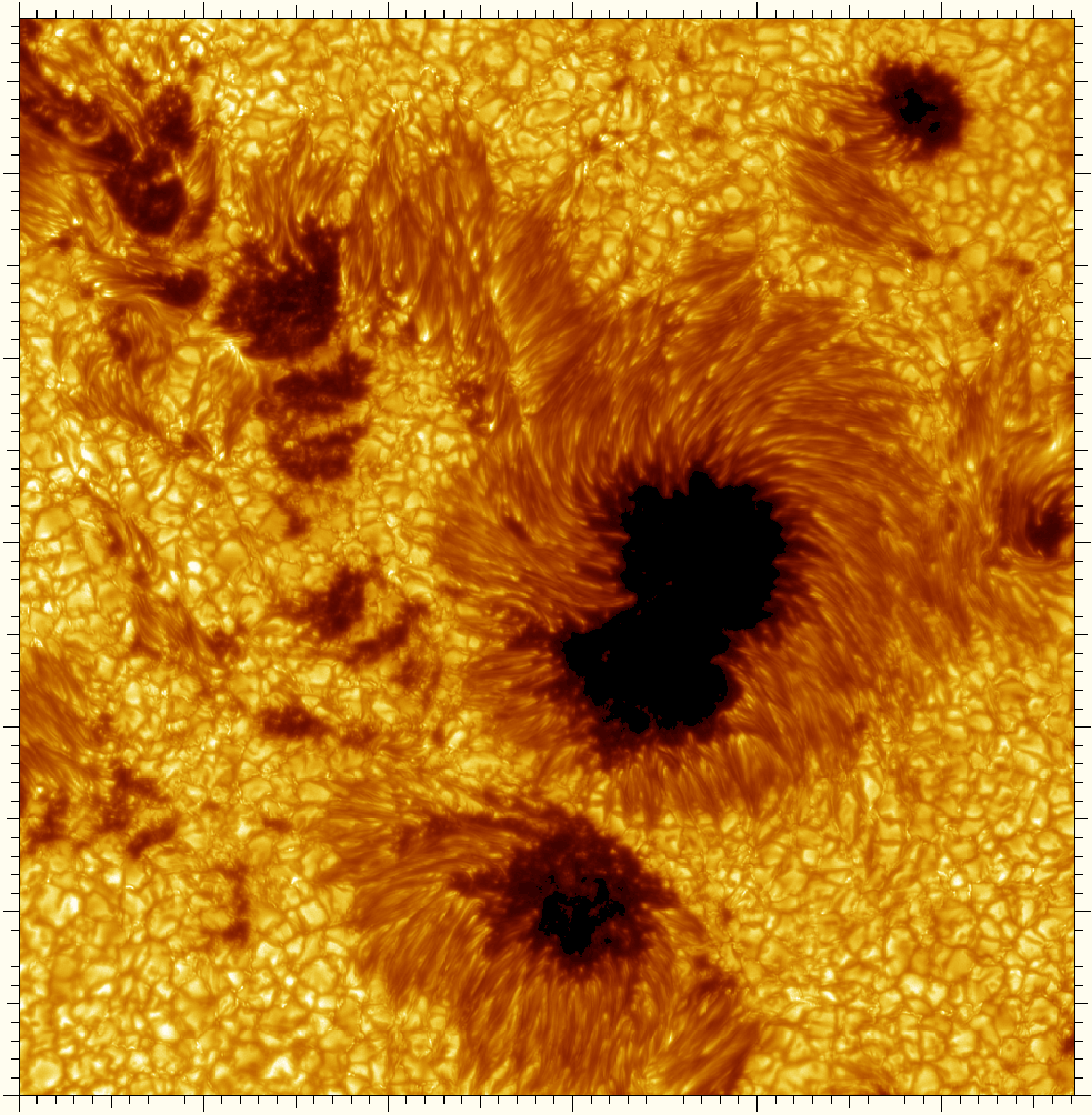
Solar atmosphere:

- Directly observable part of the Sun.
- Divided into photosphere, chromosphere, corona, heliosphere



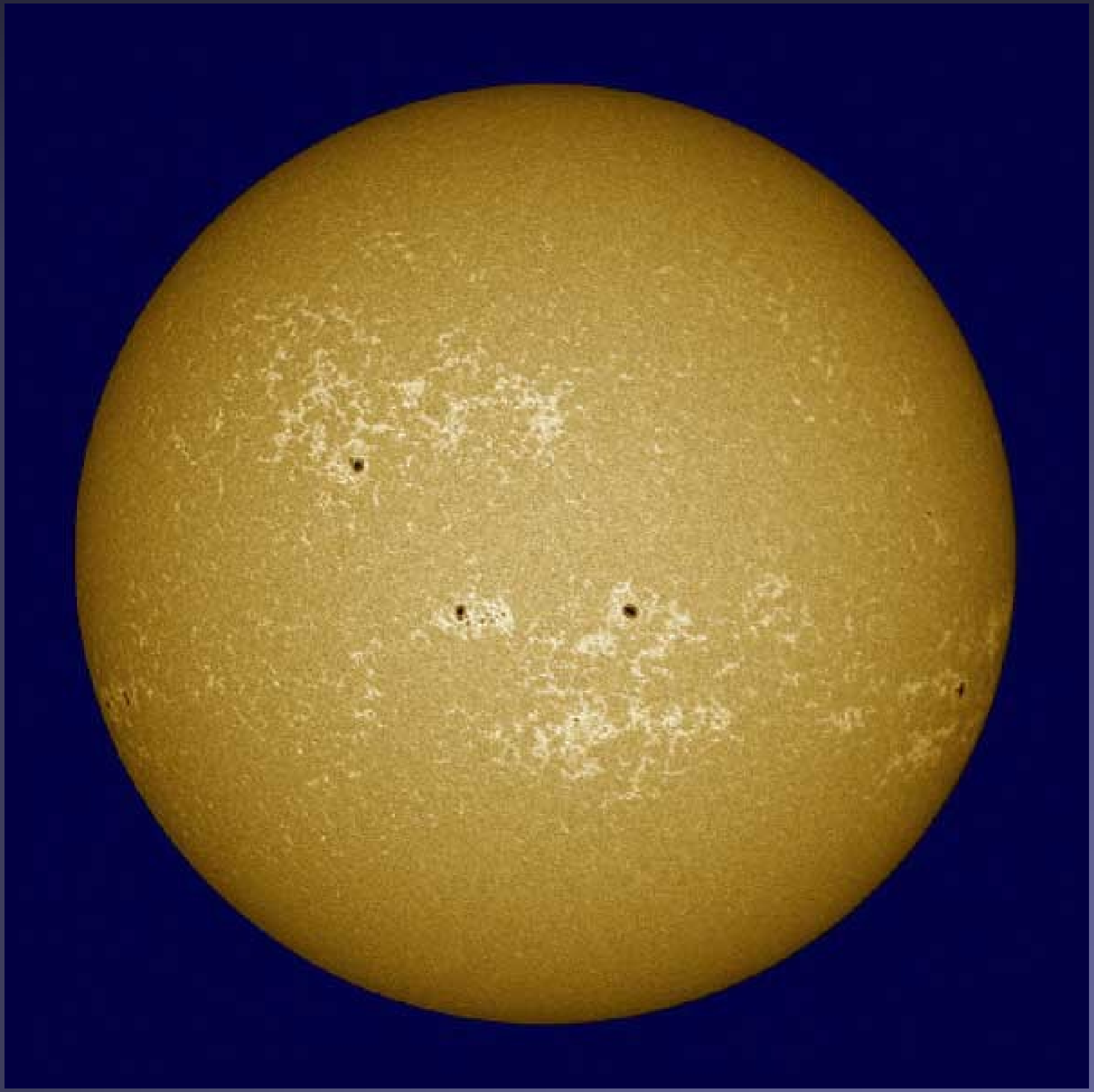
Part of the Sun in White Light

Gas at 5800 K



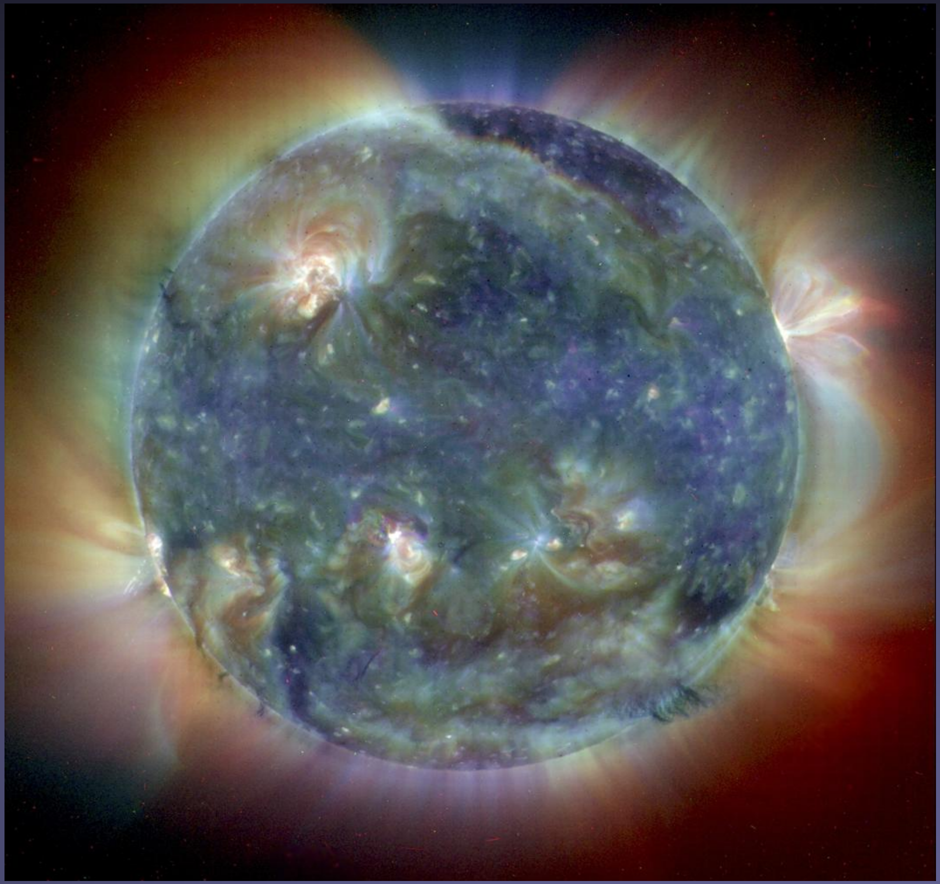
Chromosphere

Gas at 8000 K
(Ca II K)



The Hot and Dynamic Corona

Corona during an Eclipse



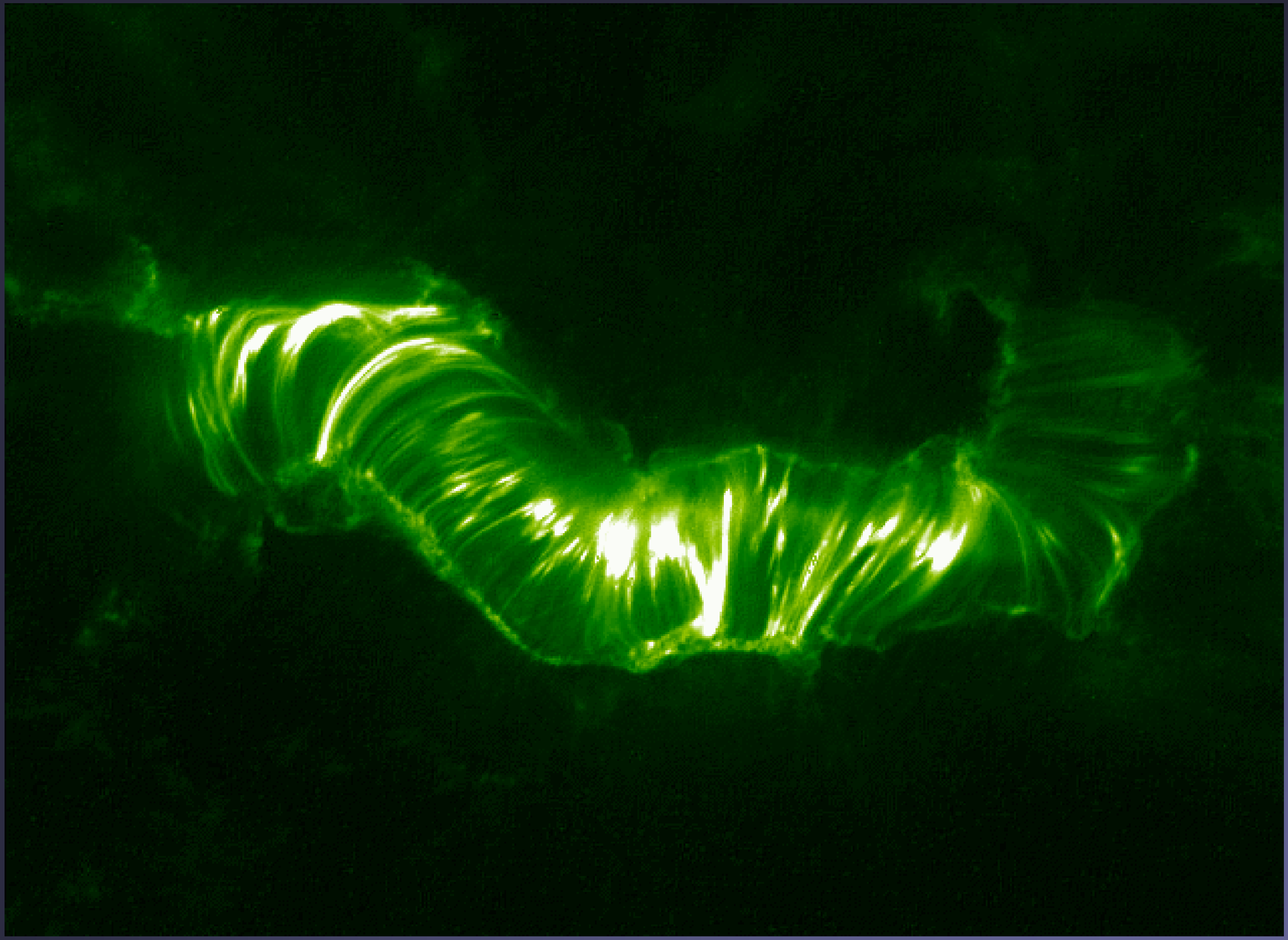
EUV Corona: $T = 1\text{-}2\ 10^6$ K
(different colours mean different temperatures)

A Flare near the Solar Limb

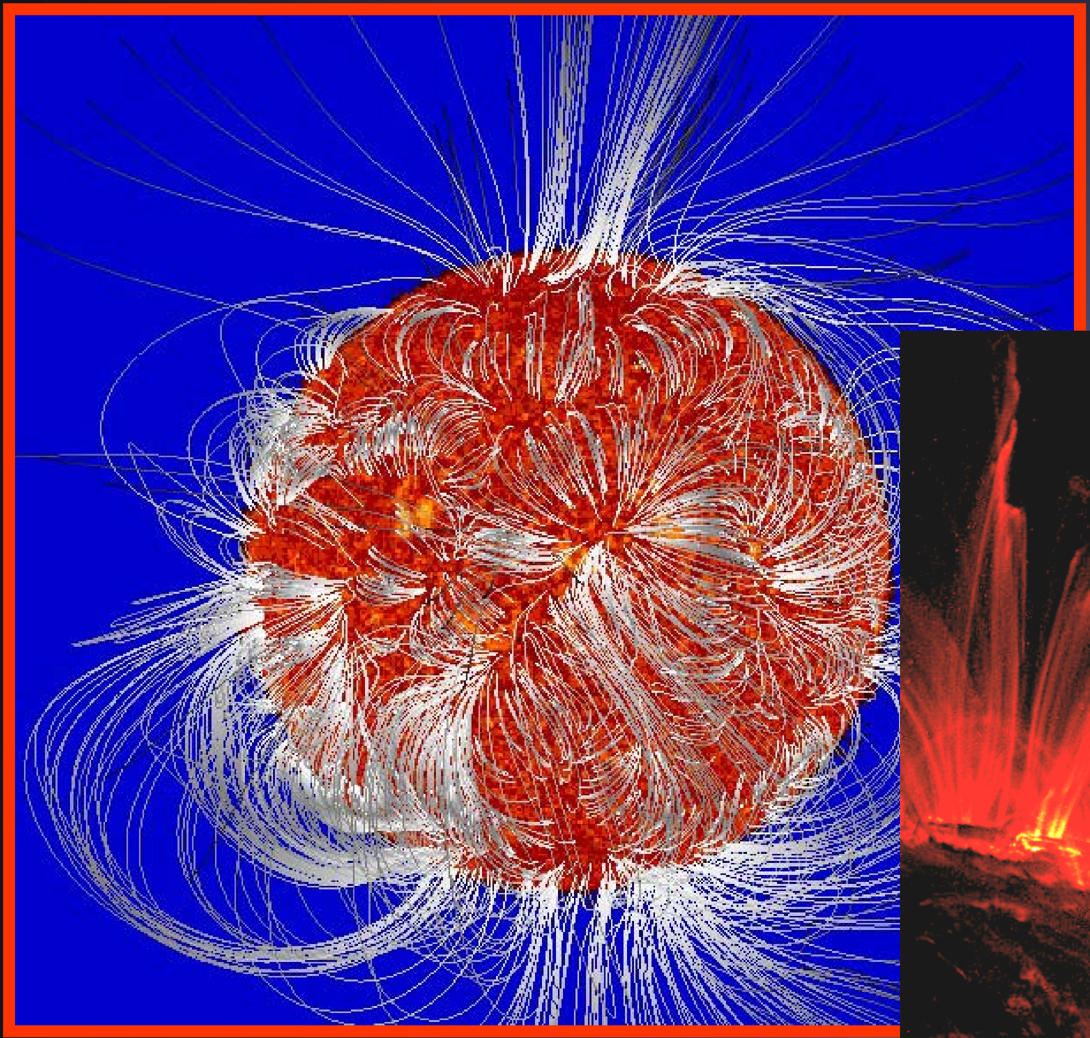
Gas at 10^6 K (Fe IX 171 Å)

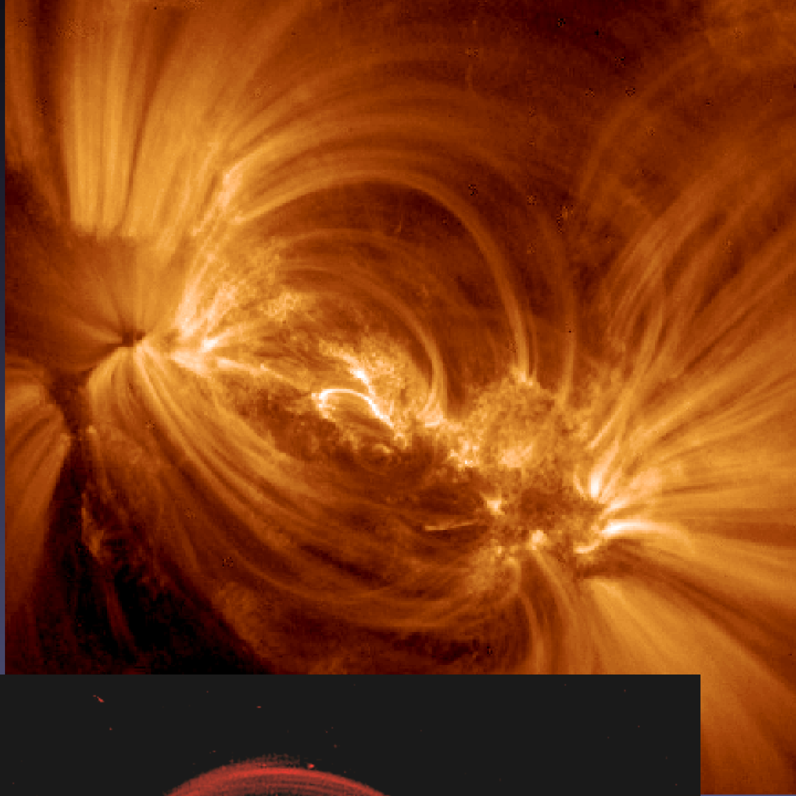
Movie covers 4 hours

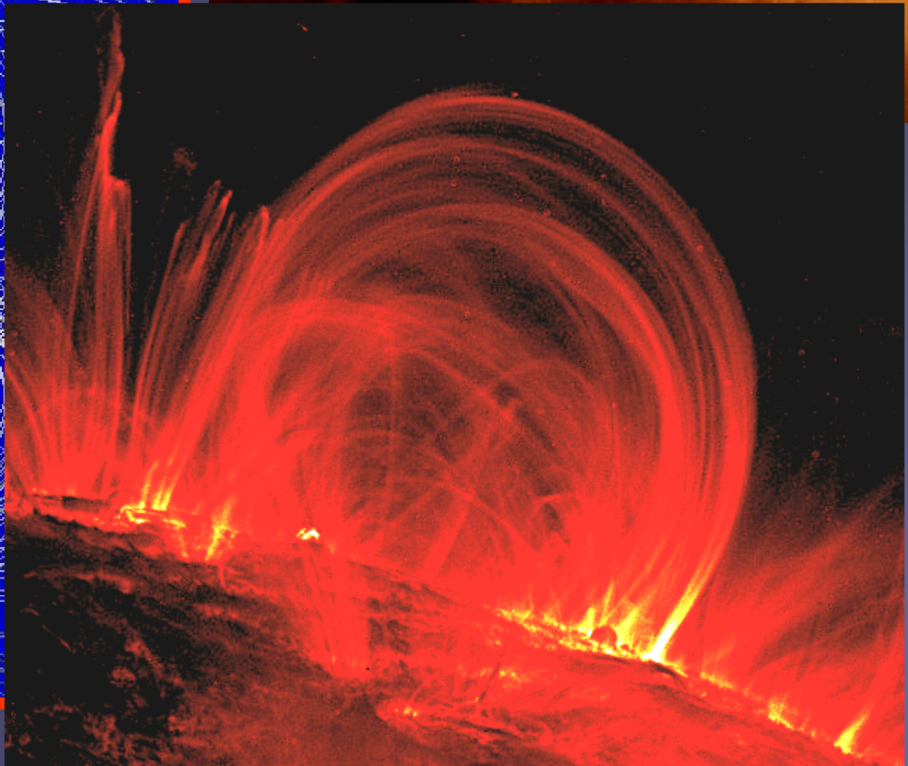
Size of Earth



The solar physicist's view: Sun's activity is driven by its magnetic field



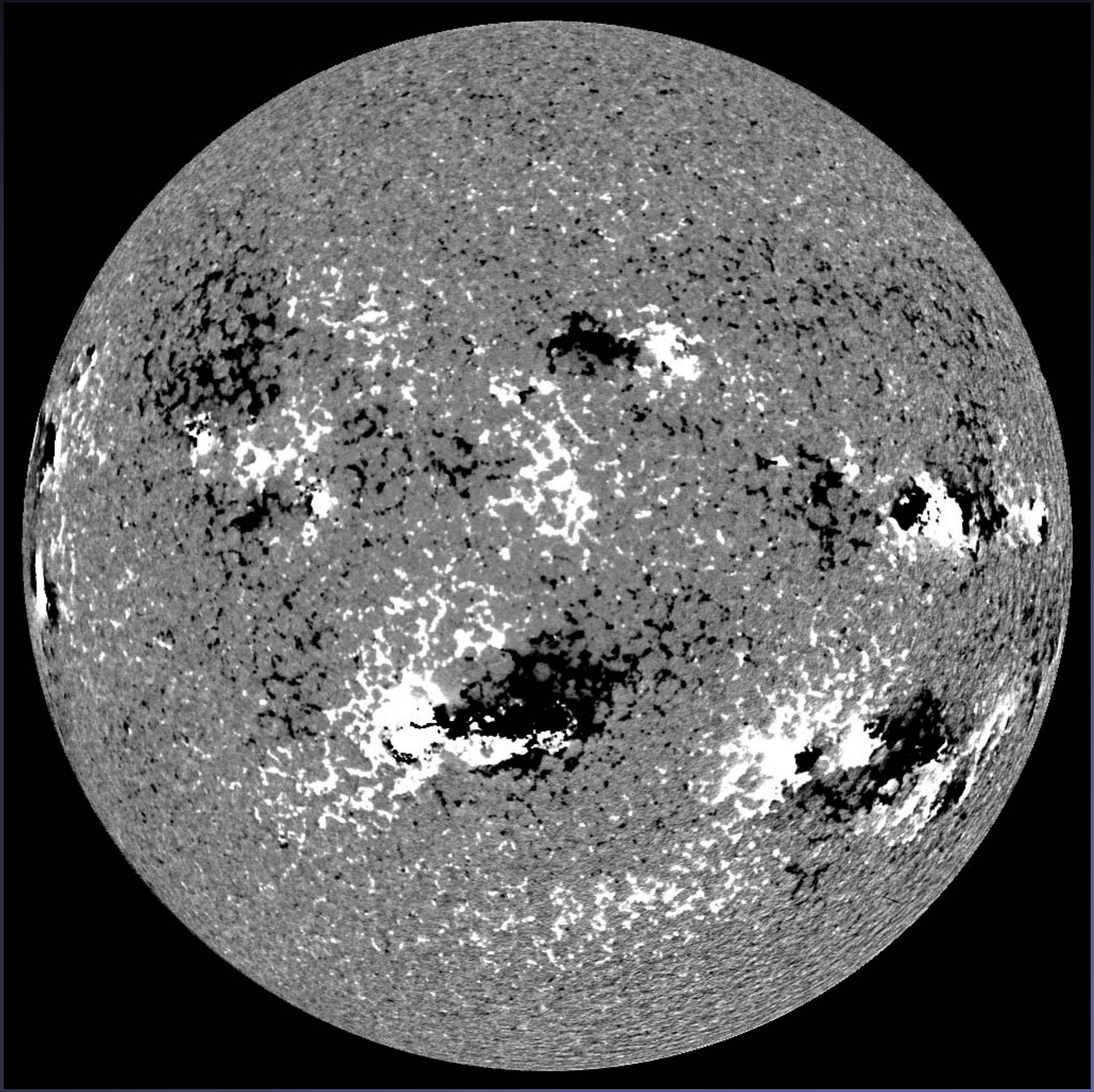




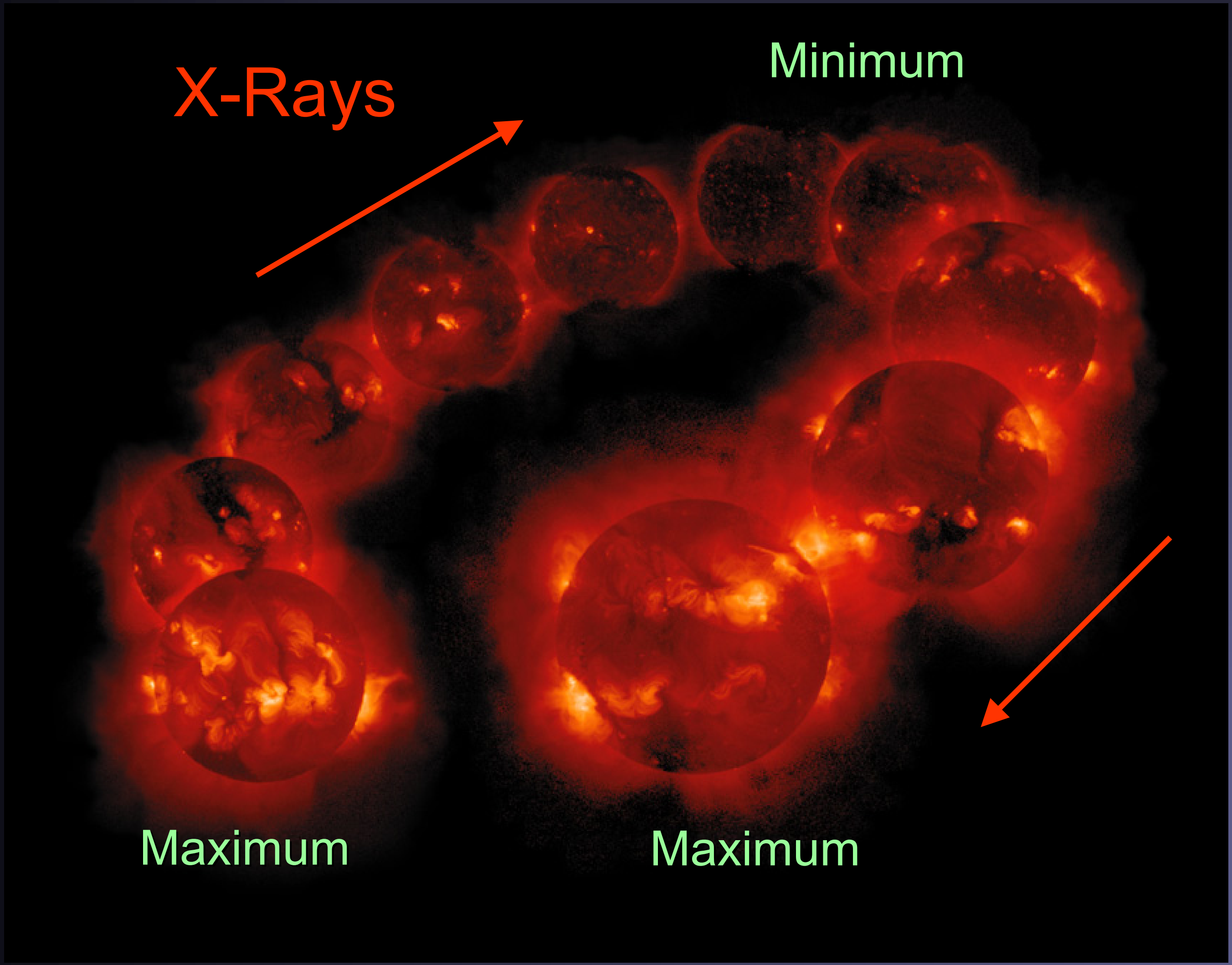
Magnetic Field Measured at Solar Surface

Sequence of Magneto-grammes over a Solar rotation

MDI/SOHO

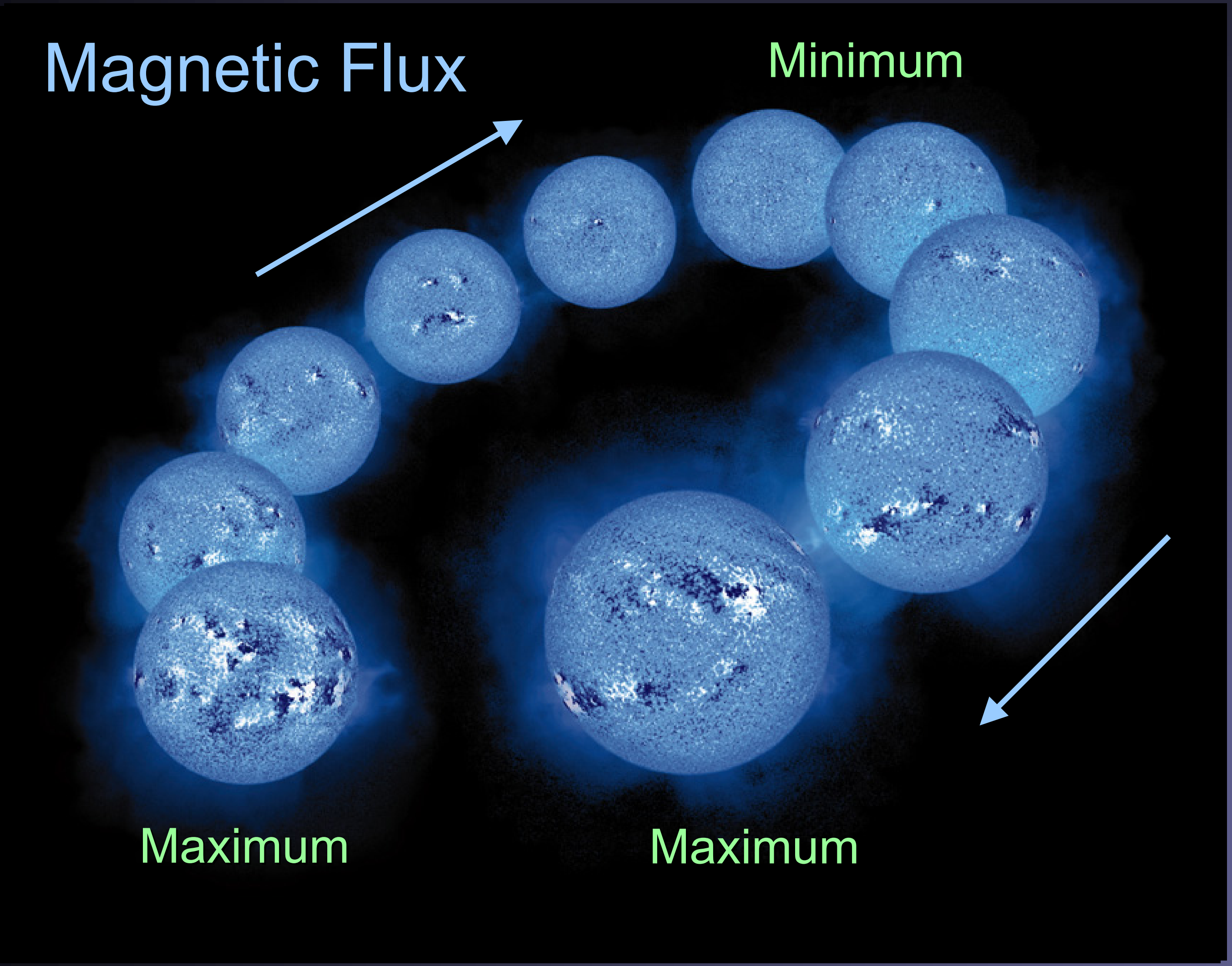


Activity Cycle of the Sun



Energetic radiation from the Sun varies by a large amount over the solar cycle: by a factor of 2 in the EUV, by a factor of 100 in X-rays.

Activity Cycle of the Sun



The magnetic flux of the Sun also varies over the 11-year solar cycle.

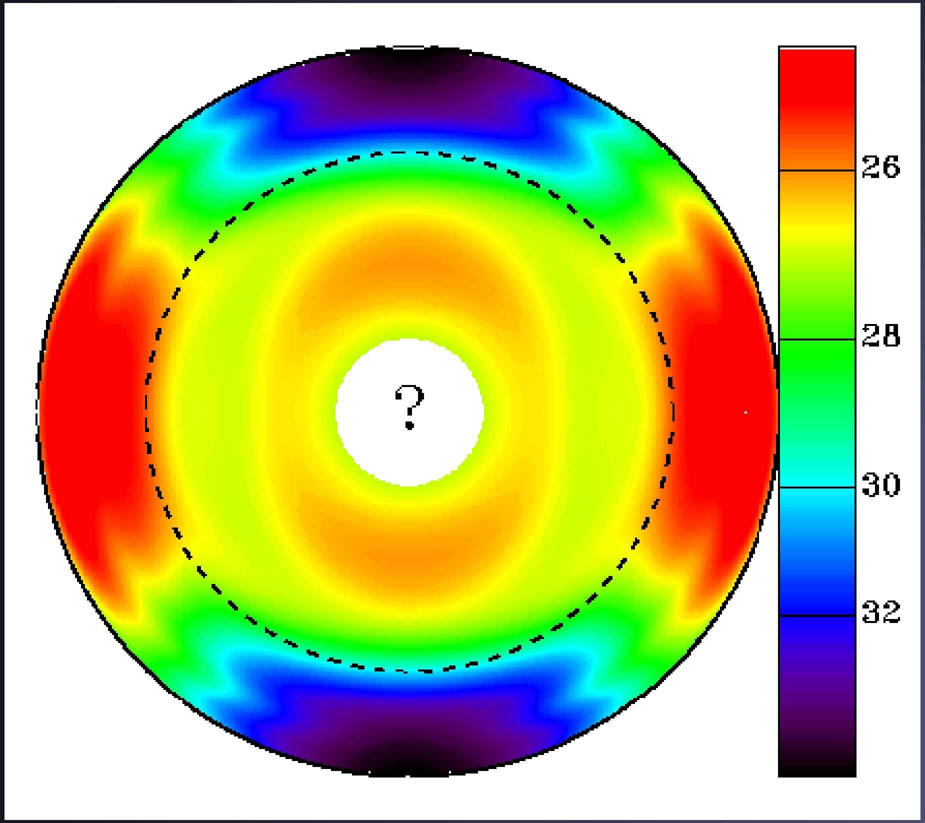
At the same time the number of sunspots and other indicators of solar activity also fluctuate.

Magnetic field in Sun's core and radiative zone

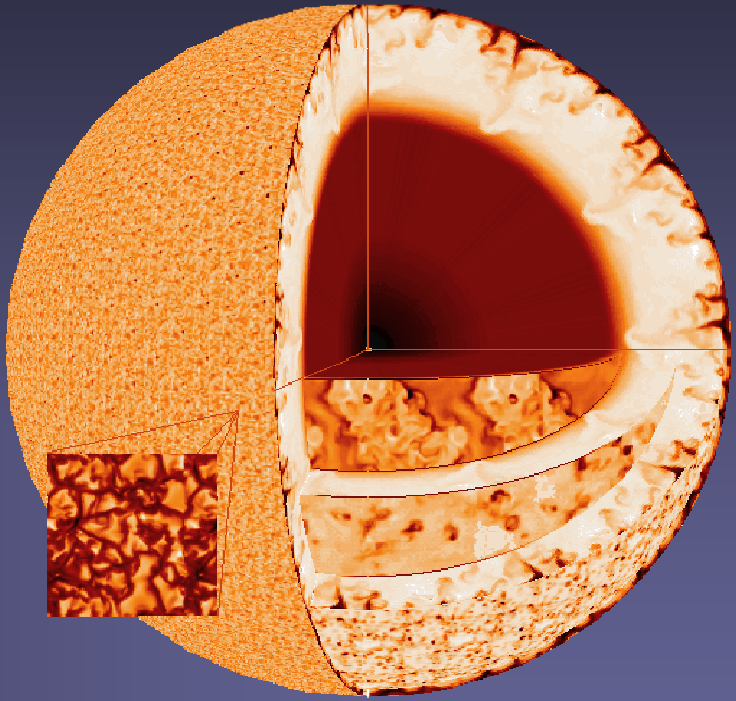
- So far only upper bounds
  - 7 MG on toroidal field around core from oblateness of Sun (Friedland and Gruzinov 2004)
  - 10^3-10^4 G on poloidal field through core from asymmetry of solar global dipole at solar surface (Boyer & Levy 1984; Boruta 1996)
- g-modes: sensitive diagnostics. Possible discovery reported by Garcia et al. (2007)
  - Field strengths of toroidal fields as low as ~10^4 G may be detected (Rashba et al. 2007)

Flow Fields Relevant to Solar Dynamo

Support for an overshoot-layer dynamo (Ω effect)



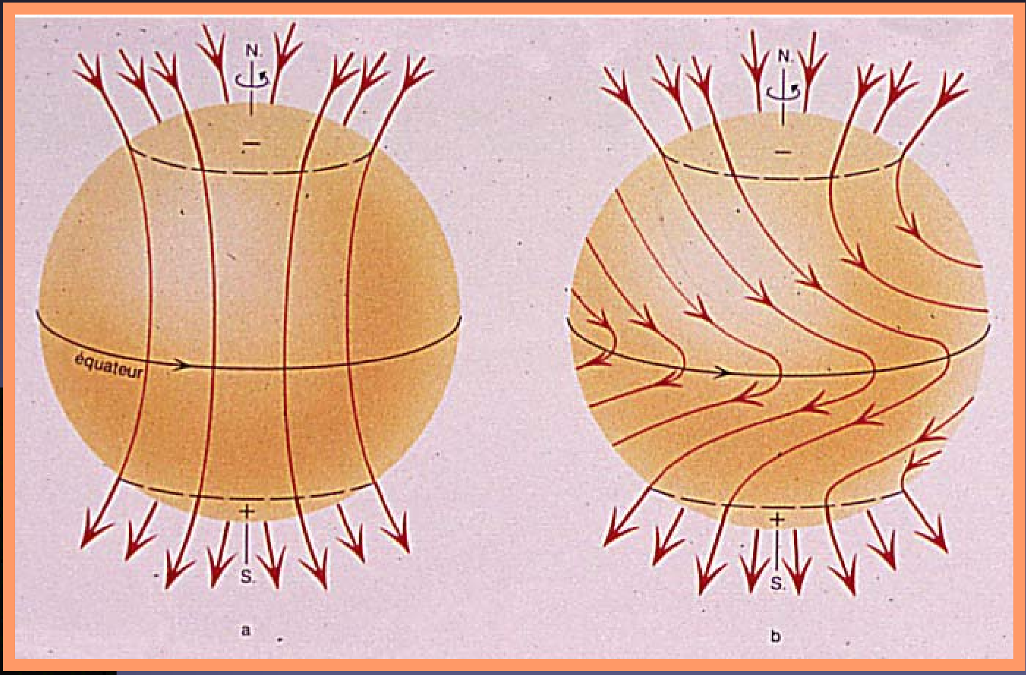
Large scale flow fields: Differential rotation + meridional circulation (MDI + GONG)

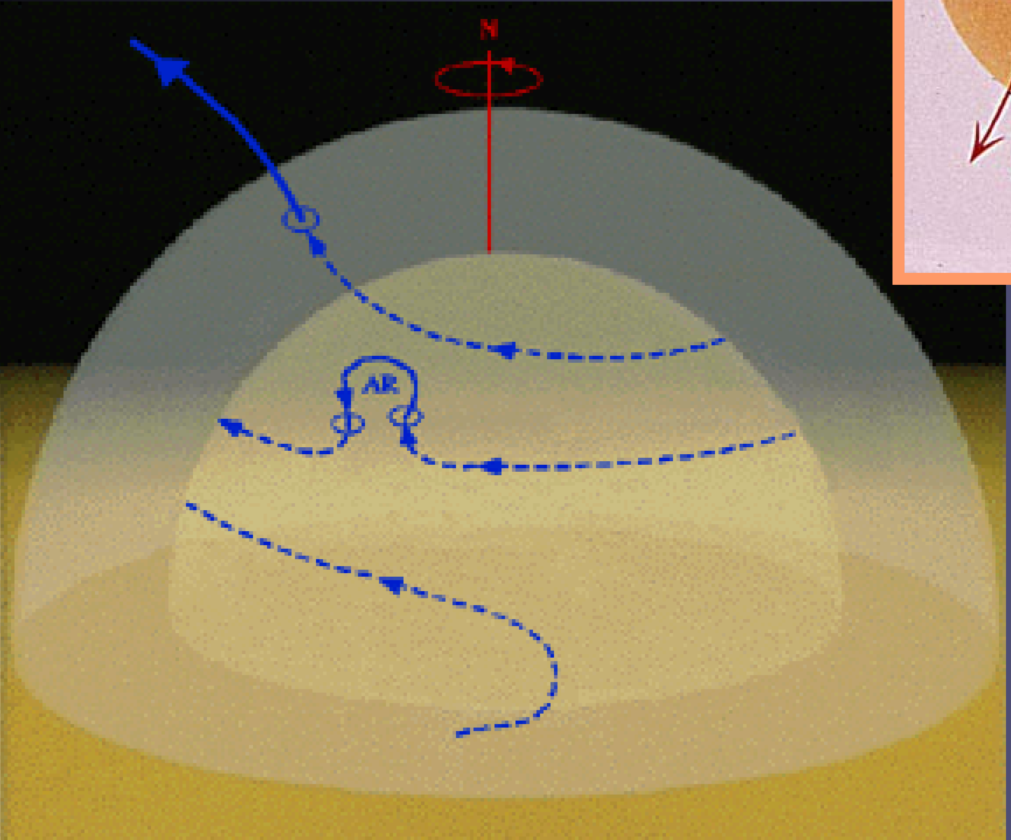


Small scale flow fields: Convection (Nordlund et al.; Miesch)

Sketch of the Solar Dynamo I

Omega effect: winding up of field lines due to differential rotation





Emergence of flux due to magnetic buoyancy once field is strong enough (Parker instability)

Magnetic field in the convection zone

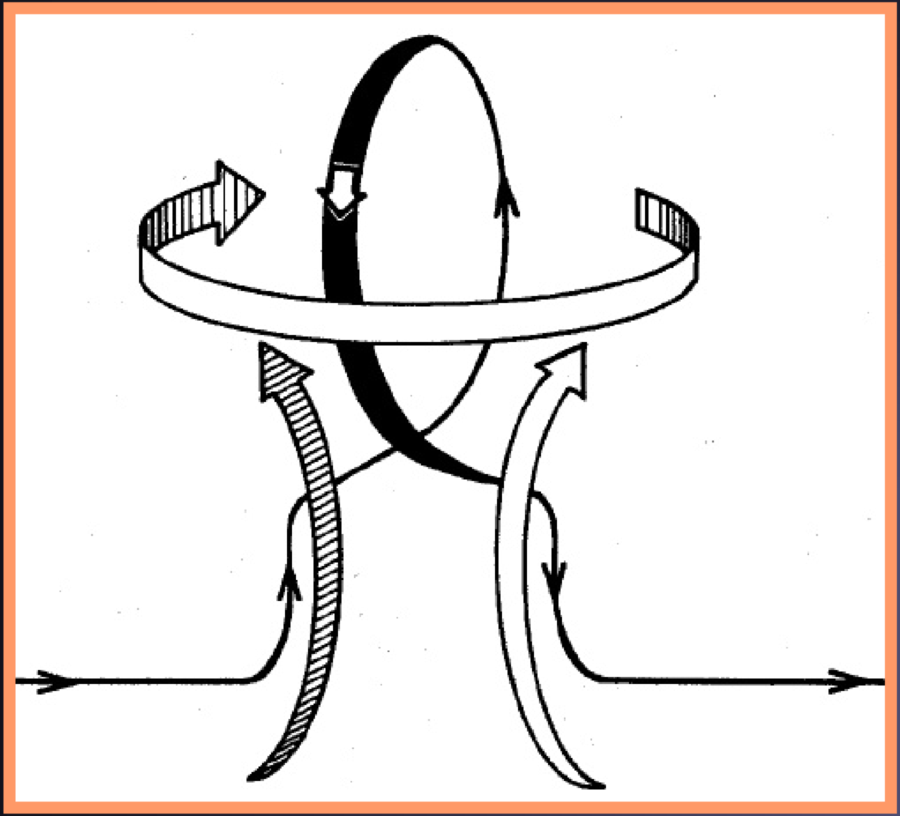
- Magnetic field is produced by dynamo located near bottom of convection zone (in overshoot layer).

➔ toroidal flux tubes in pressure balance with surroundings:

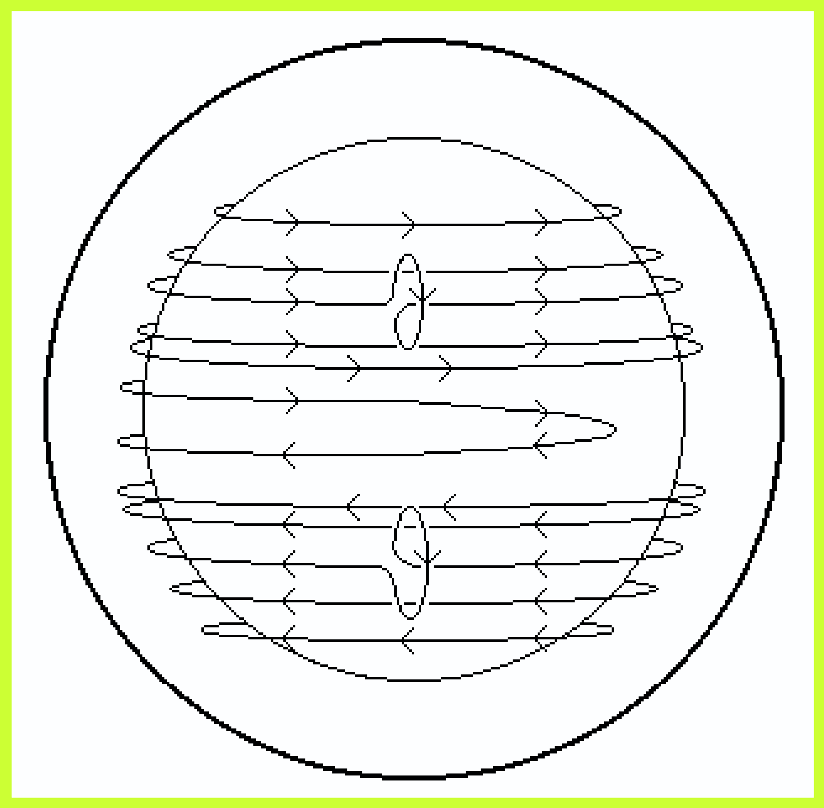
$$\frac{B_1^2}{8\pi} + P_1 = P_2 + \frac{B_2^2}{8\pi}$$

- If $B_1 > B_2$ and $T_1 = T_2$, then $\rho_1 < \rho_2$ ➔ intense magnetic fields are evacuated and buoyant relative to surrounding gas. Buoyancy dominates over curvature for B ≥ 10^5 G (Parker instability)
- A loop-like structure moves towards the solar surface and breaks out.

Sketch of the Solar Dynamo II



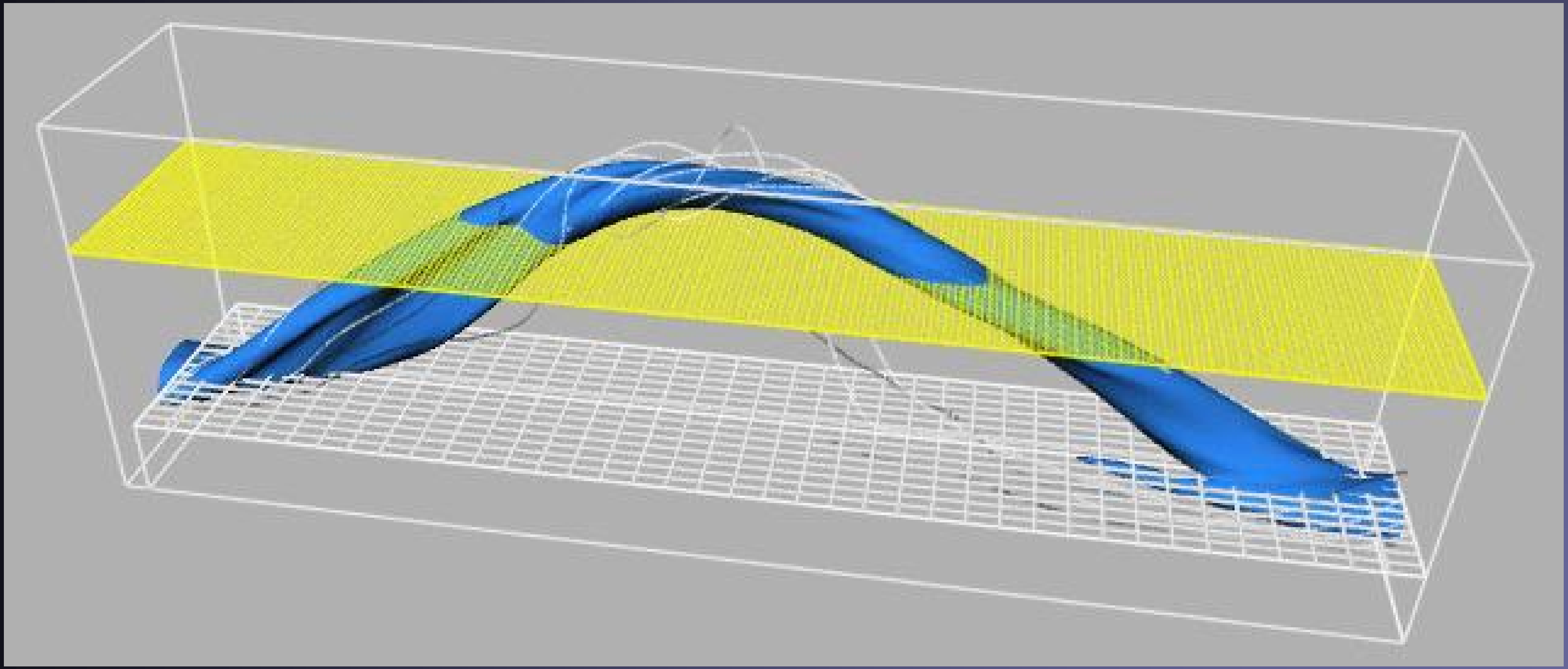
Poloidal field from toroidal field: α-effect (due to Coriolis force)



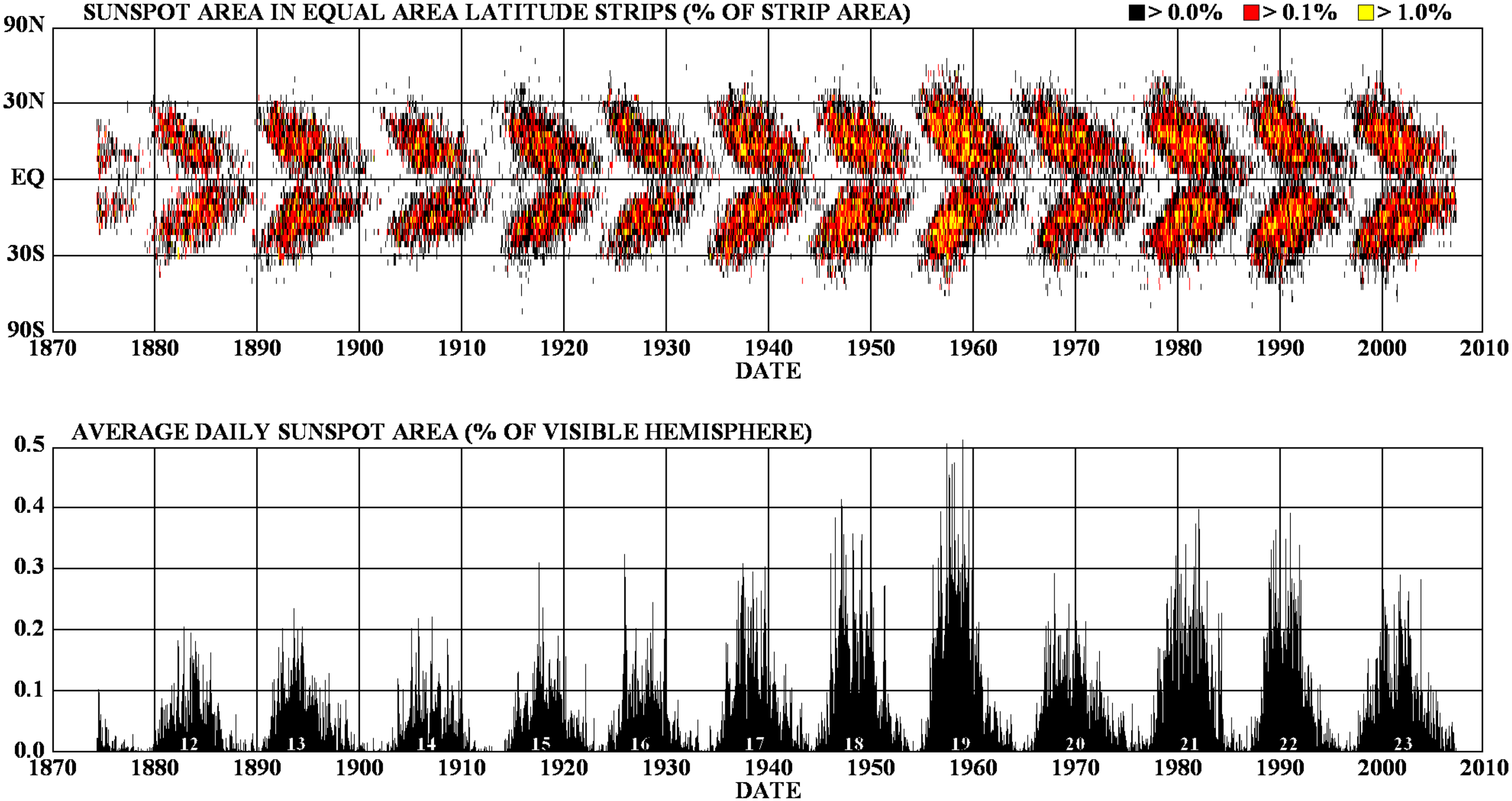
New poloidal field has opposite polarity to original poloidal field

Emergence of a magnetic flux tube

Magnetic field is believed to be generated mainly in the Tachocline near bottom of convection zone.
Due to its buoyancy (see earlier slide; Parker instability), a magnetic field will rise towards the solar surface. At the solar surface it will produce a bipolar active region.



DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS



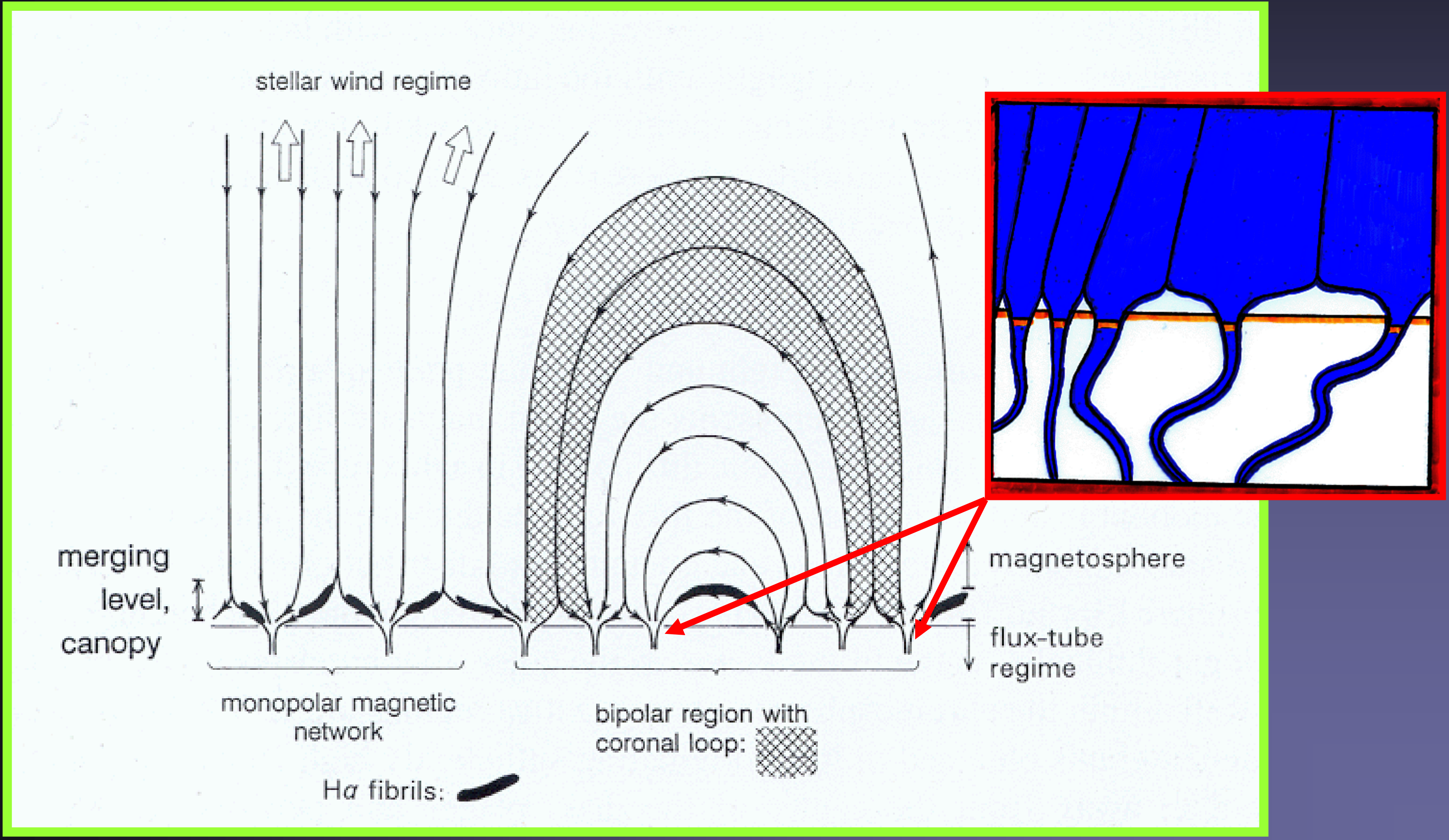
http://solarscience.msfc.nasa.gov/

NASA/MSFC/NSSTC/HATHAWAY 2007/05

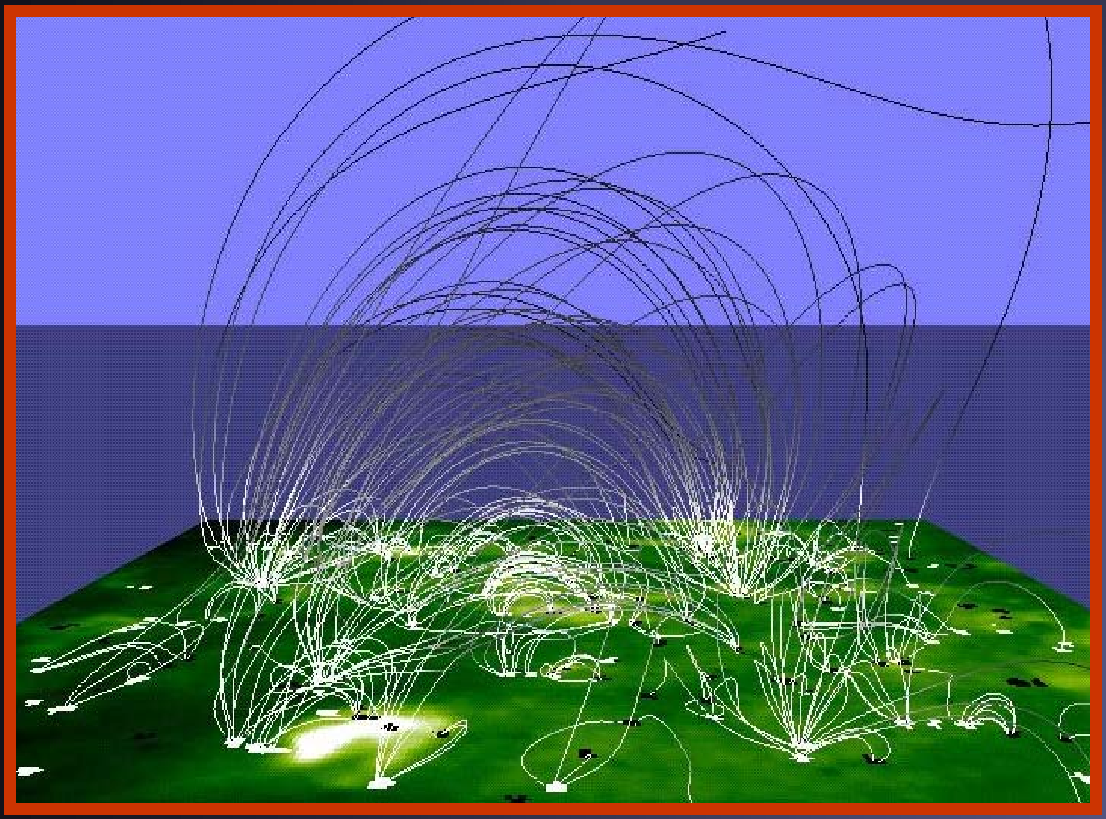
Change of B-field with height

- Plasma β describes the ratio of thermal to magnetic energy density: $$\beta = \frac{8\pi P}{B^2}$$
- $\beta > 1$ ➔ Thermal energy, i.e. gas dominates & forces the field to follow: in solar interior
- $\beta < 1$ ➔ Magnetic field dominates and dictates the dynamics of the gas: in atmosphere, corona: $\beta \approx 10^{-3}$
- *B* ≈ 1500 G at solar surface, $B \sim \exp(-z/2H)$, due to horizontal pressure balance and $P_g \sim \exp(-z/H)$
- Due to flux conservation, $$\iint B(x, y, z)\,dxdy = \text{const}$$ field expands exponentially with height, until it fills all the available space above a given height.

Flux Tubes, Canopies, Loops and Funnels



Coronal Heating: Driven by Magnetoconvection?



Energy dissipation & magn. reconnection at current sheets

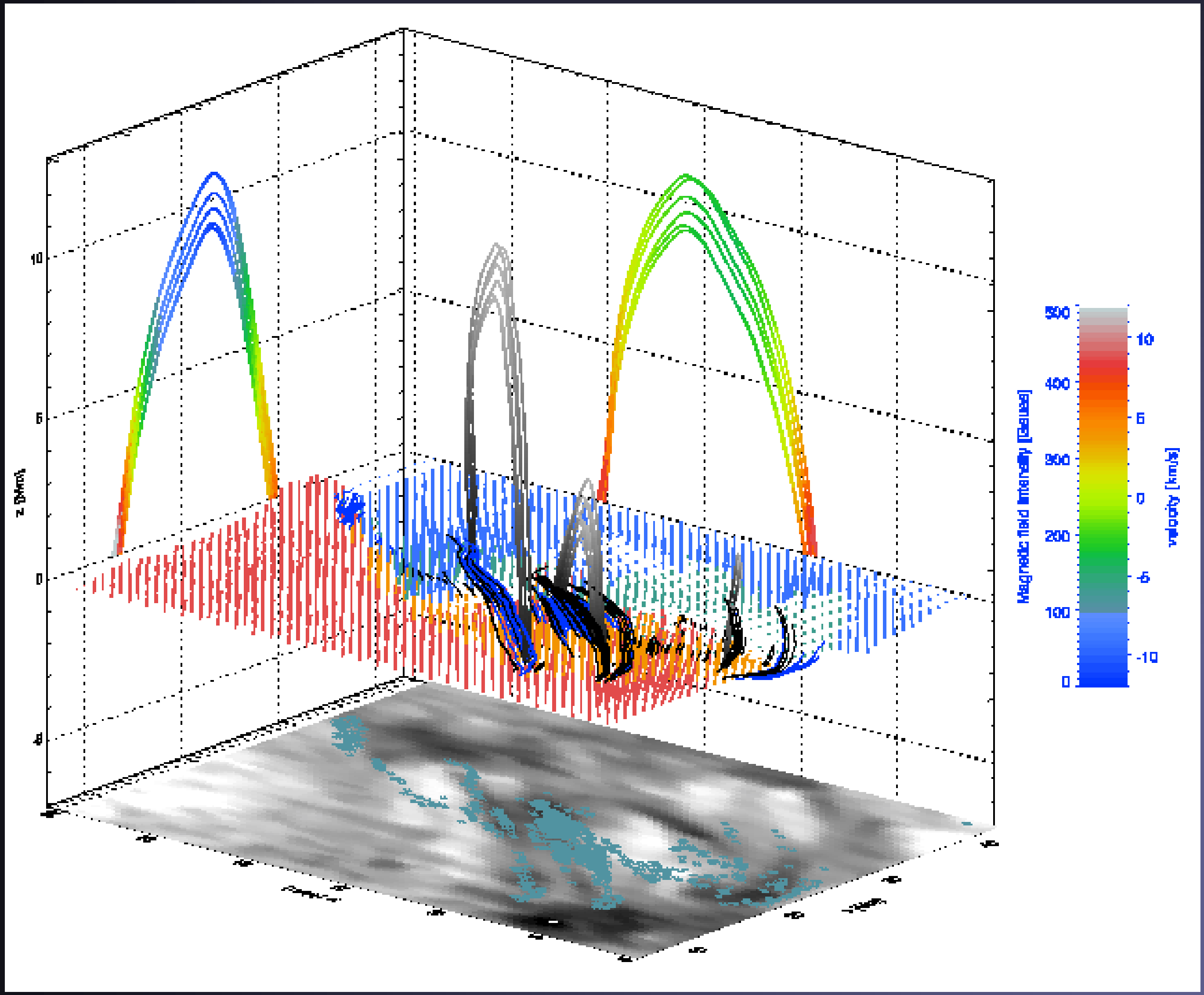
↑

Complex & tangled coronal magnetic structure

↑

Dynamic interaction of magnetic flux with convection

First measurement of the magnetic field in coronal loops



Magnetic loops deduced from measurements of He I 10830 Å

Stokes profiles in an emerging flux region.

Left projection: Field strength

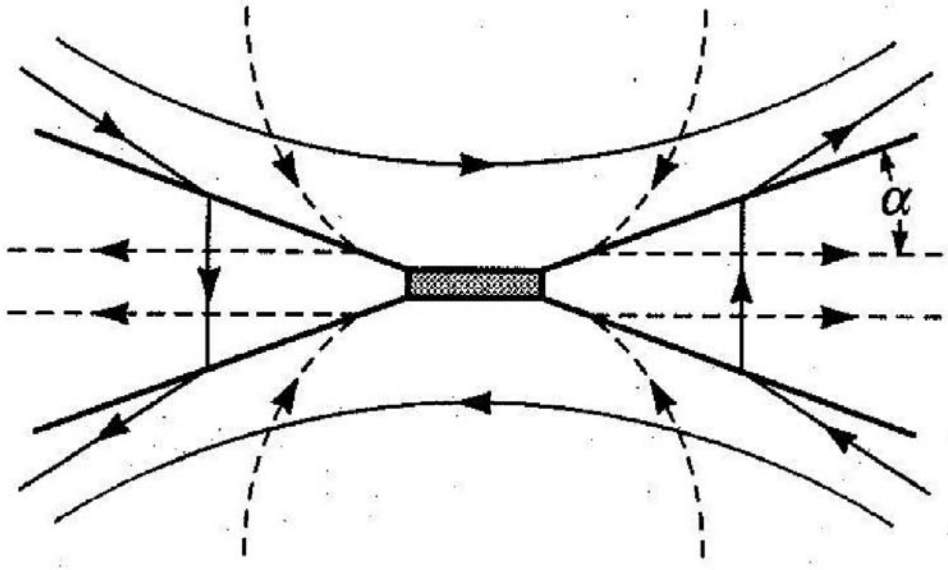
Right projection: Vertical velocity

Solanki et al. 2003, Nature

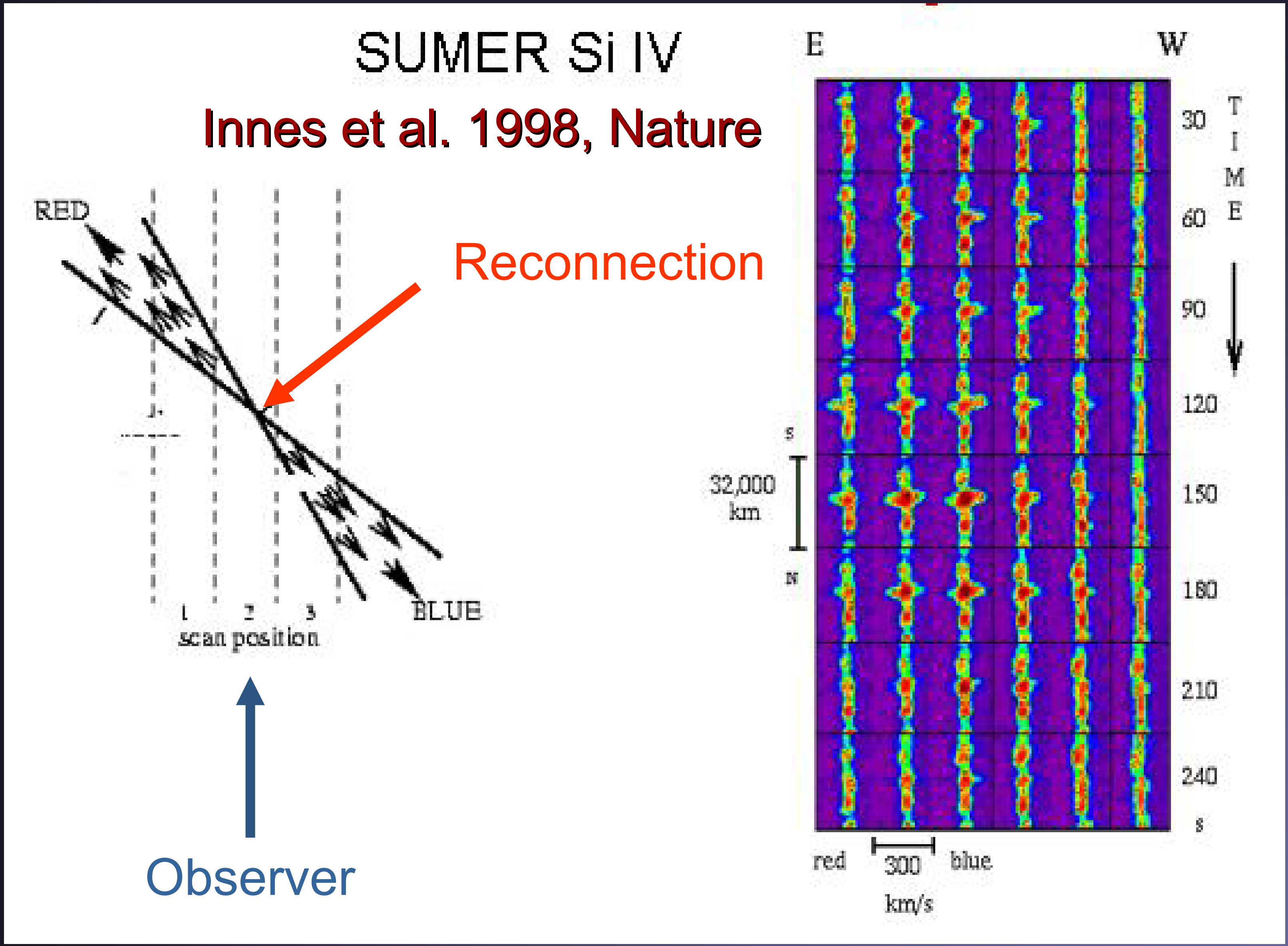
Magnetic reconnection

Petschek Model Gives Fast Reconnection

Petschek's configuration has an X-point caused by shocks:

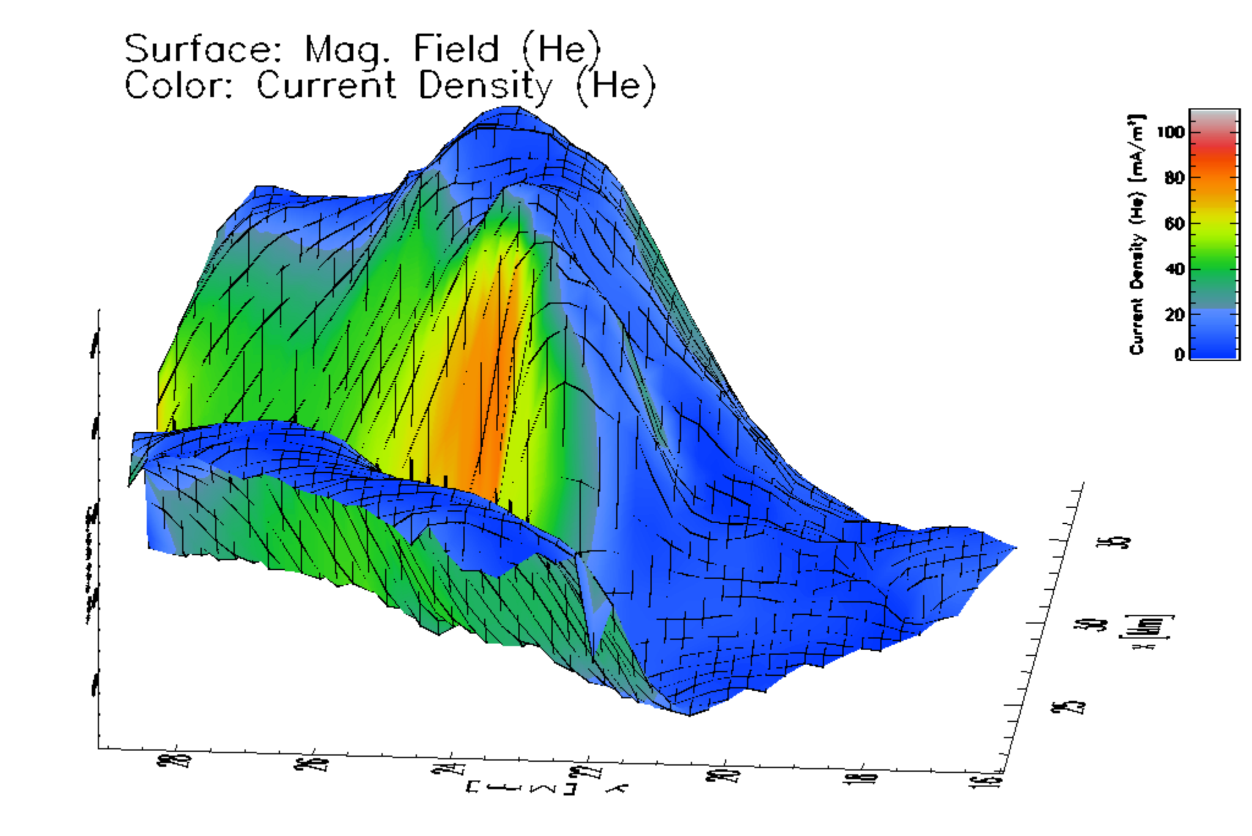


Evidence for reconnection



Electric Current Sheet at Coronal Base

He I 10830 Å reveals electric current sheet (tangential discontinuity of magnetic vector) at coronal base



Observed in emerging flux region

Surface: magnetic field strength (note the valley)

Colour: current density

Solanki et al. 2003, Nature