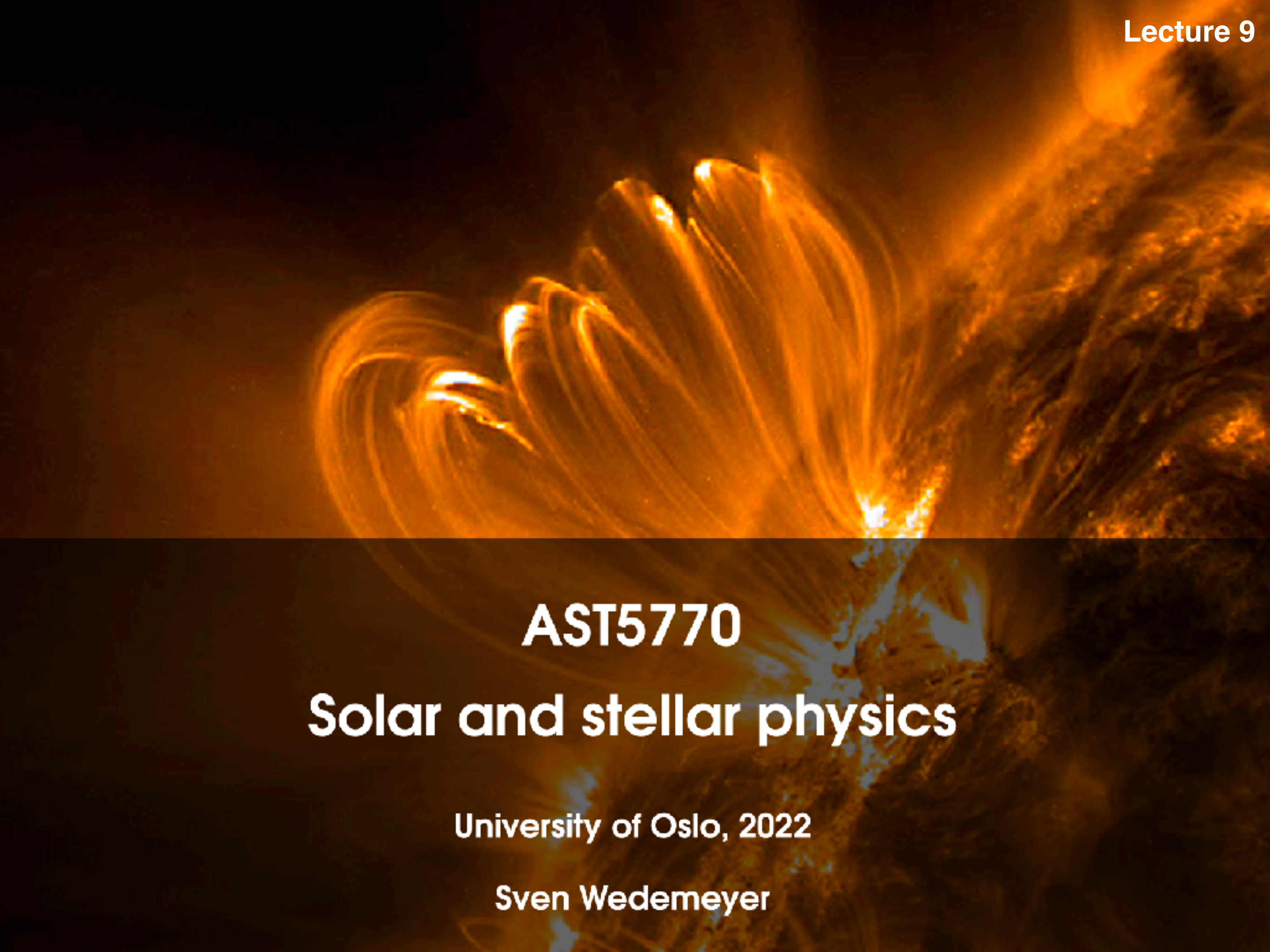




AST5770

Solar and stellar physics

University of Oslo, 2022

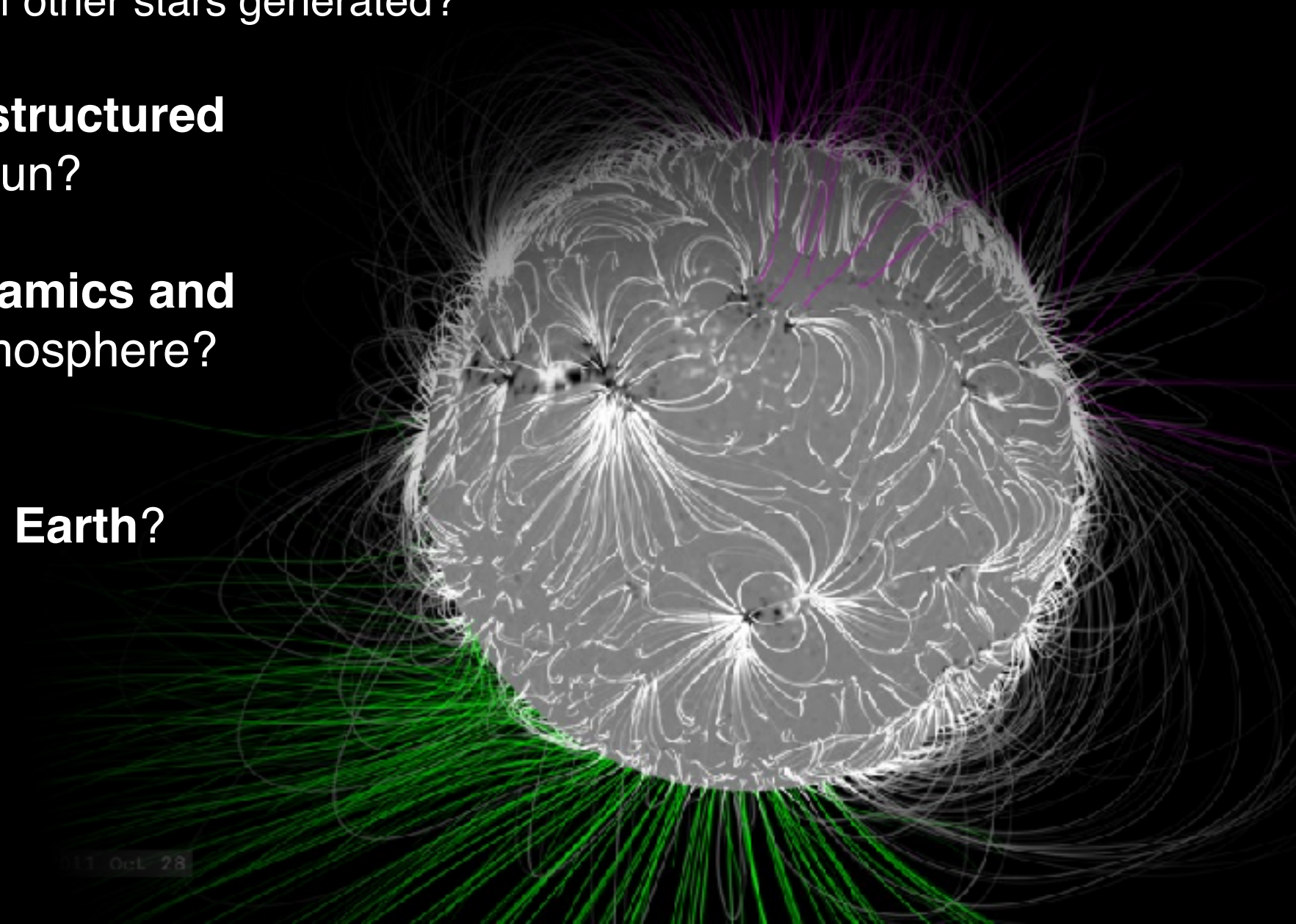
Sven Wedemeyer

Magnetism

Magnetism

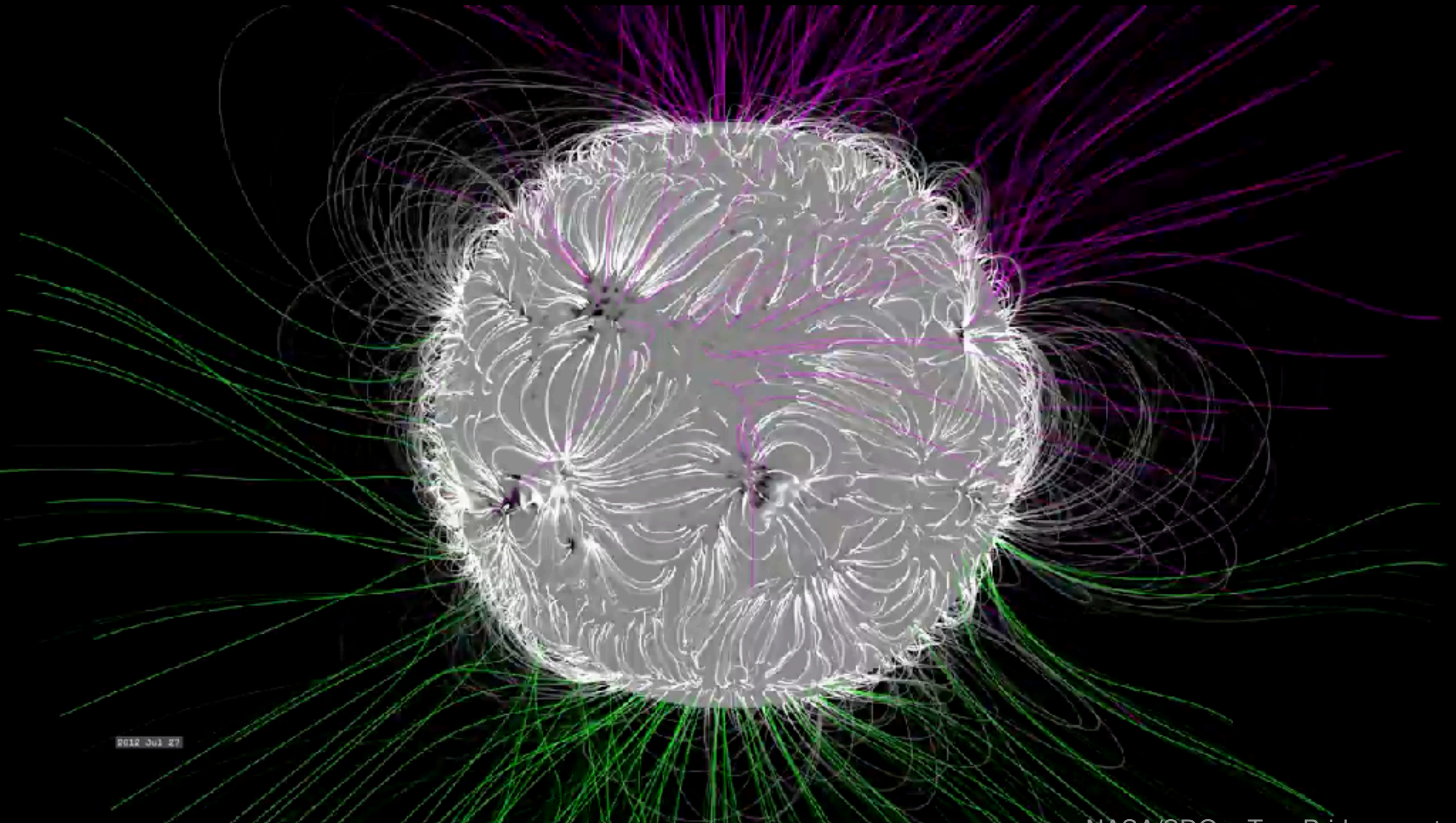
Many important questions ...

- **How is the magnetic field of the Sun generated?**
 - Is the Sun generating “new” magnetic field? Is there a dynamo process at work?
 - Or are those the remainders of a “primordial” magnetic field of the material from which the solar system and the Sun formed?
 - How is the magnetic field of other stars generated?
- How is the magnetic field **structured** in the atmosphere of the Sun?
- How does it affect the **dynamics and energy balance** of the atmosphere?
- And how does it affect the **interplanetary space and Earth?**



Magnetism

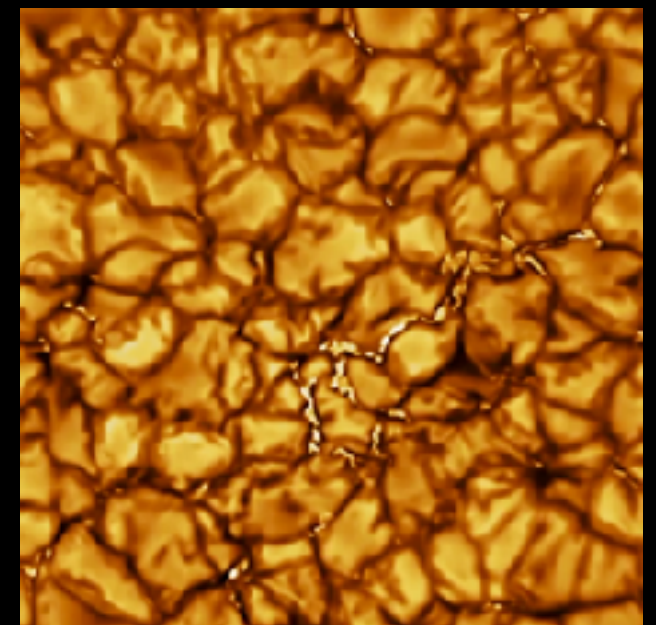
Magnetic fields on the Sun — Introduction



Magnetism

Captured through different scientific missions

- Ground-based instruments (on Earth)
 - Begin with Galileo Galilei and the refracting telescope (1611)
 - “Solar Tower” in Meudon (France)
 - Swedish Solar Telescope (SST) and THEMIS spectro-palorimeter (Canary)
 - Daniel K. Inouye Solar Telescope (DKIST) in Hawaii ...



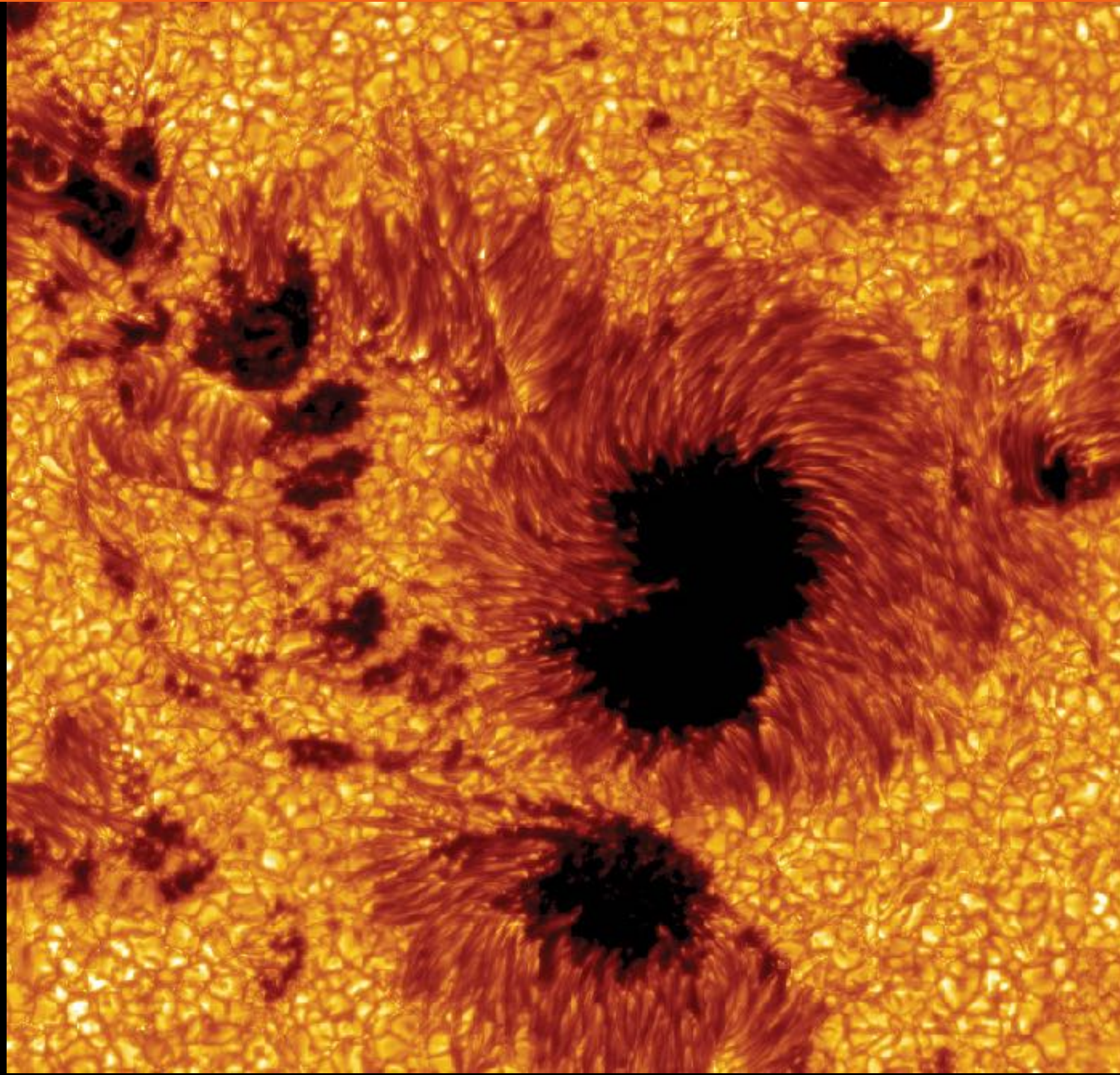
NSO DKIST

- Space missions
 - “Remote sensing” observations, especially for UV, X and γ -lights
 - “In situ” measurement of the ambient magnetised wind of particules
 - Ex : SOHO, SDO, HINODE, Solar Orbiter, Parker Solar Probe...

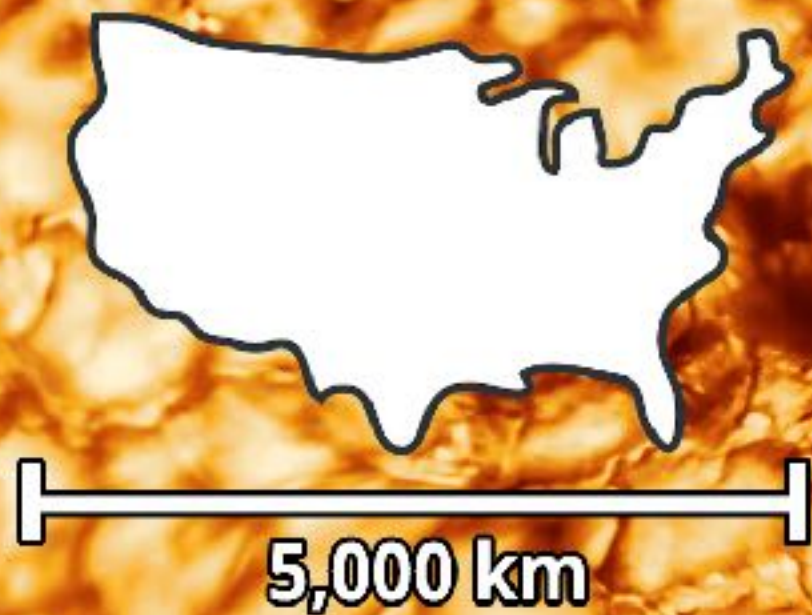
Magnetism

On the Sun

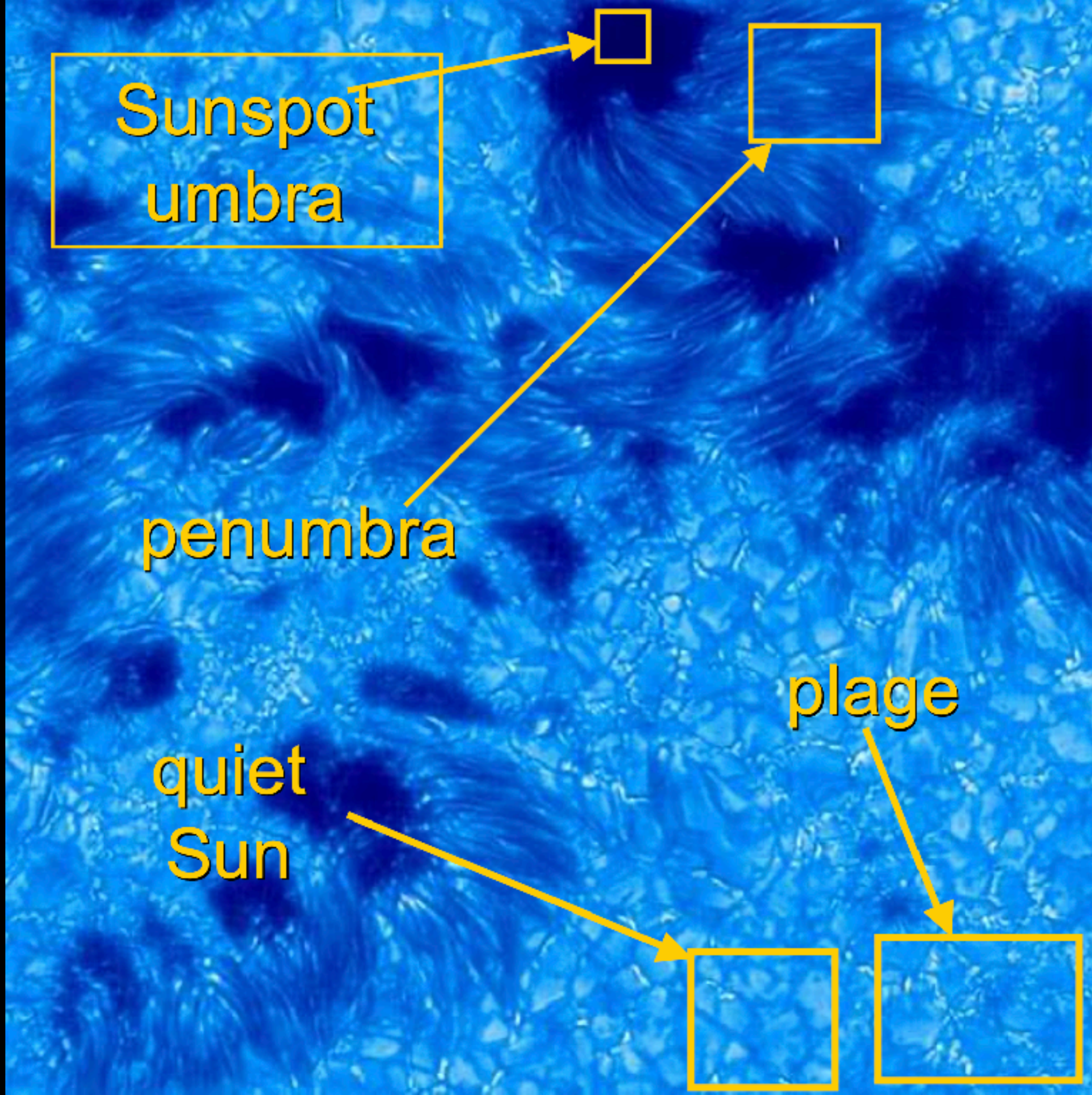
- Sunspots are clear imprints at the surface and in the atmosphere above
- Magnetism on the Sun occurs on all scales.
- Smallest features at or below spatial resolution limit of current telescopes
- Largest features on global scales
- Temporal scales between many years (activity cycle) to extremely short scales ($<1s$).



Sunspots



- Elongated “fibrilar” features
➔ Outlining magnetic field lines?



Magnetism

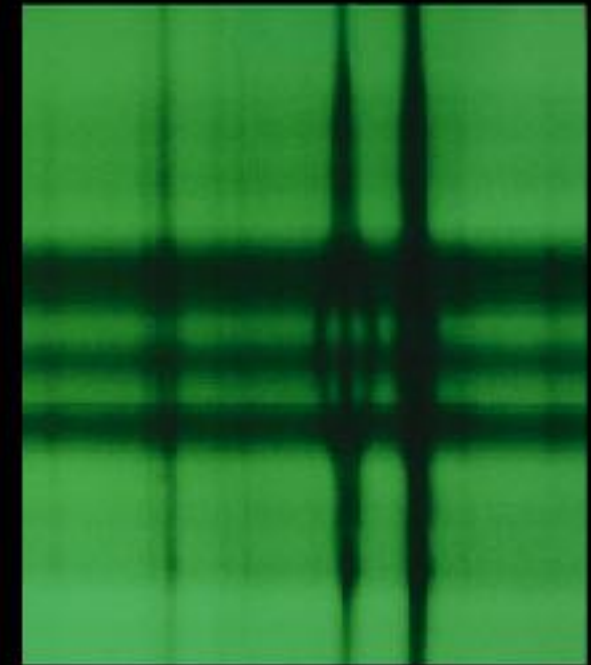
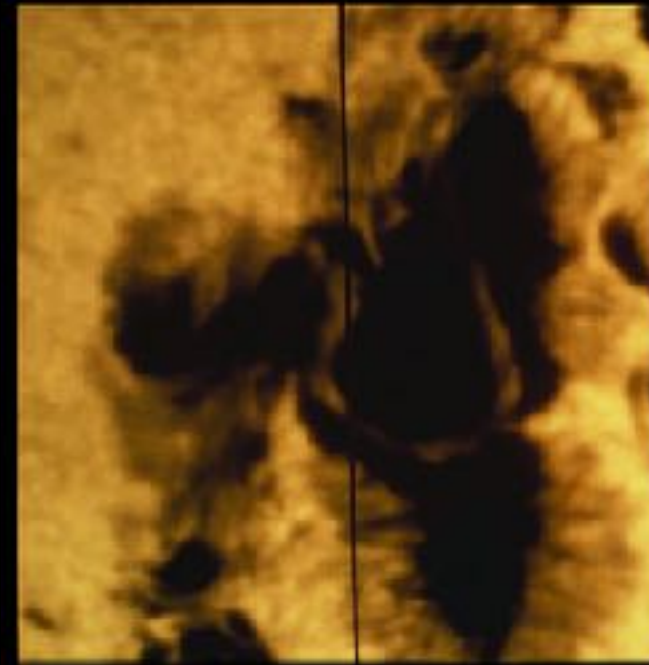
How to quantify it?

Through measurements :

Zemman effect on atomic rays

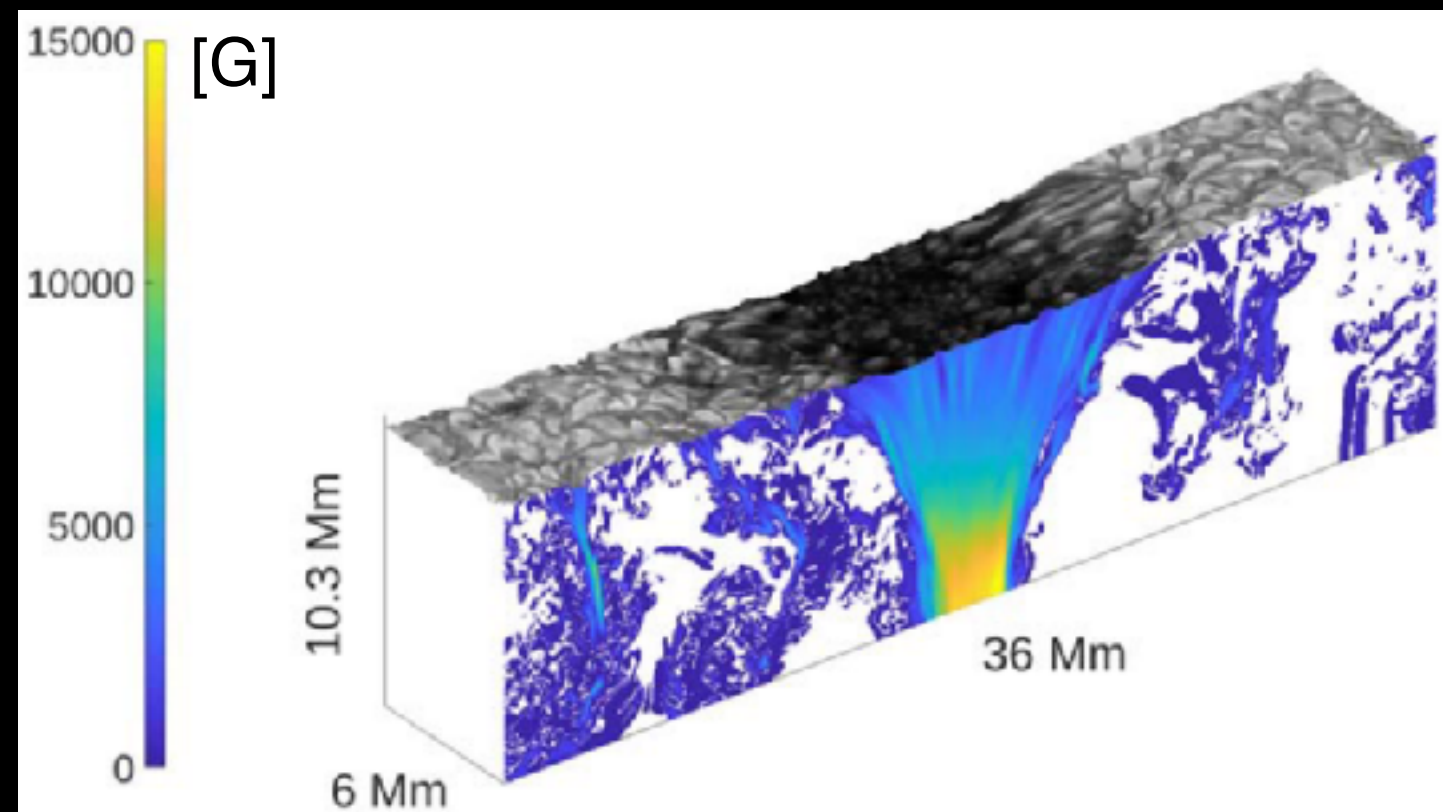
$$\Delta\lambda = 46.67 g_L \lambda_0^2 |B|$$

Kitt Peak National Observatory, NSO/AURA/NSF
See also Reiners et al. (2012)



help from reconstruction/simulations:

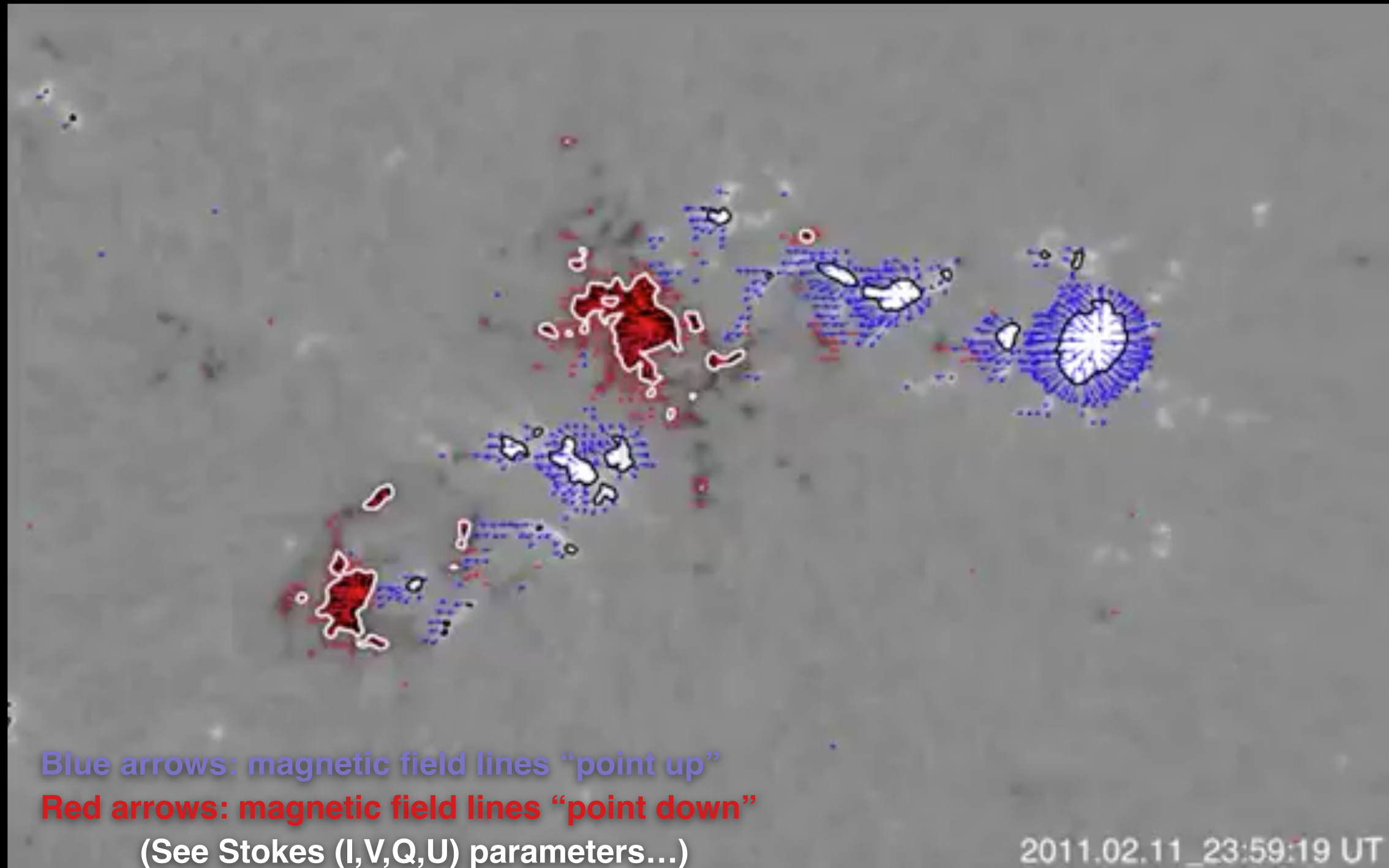
here Panja et al. (2020)



Magnetism

Photospheric magnetograms

- Observation of the Sun with SDO/HMI, 2/2011
- Evolution of magnetic field in an Active Region



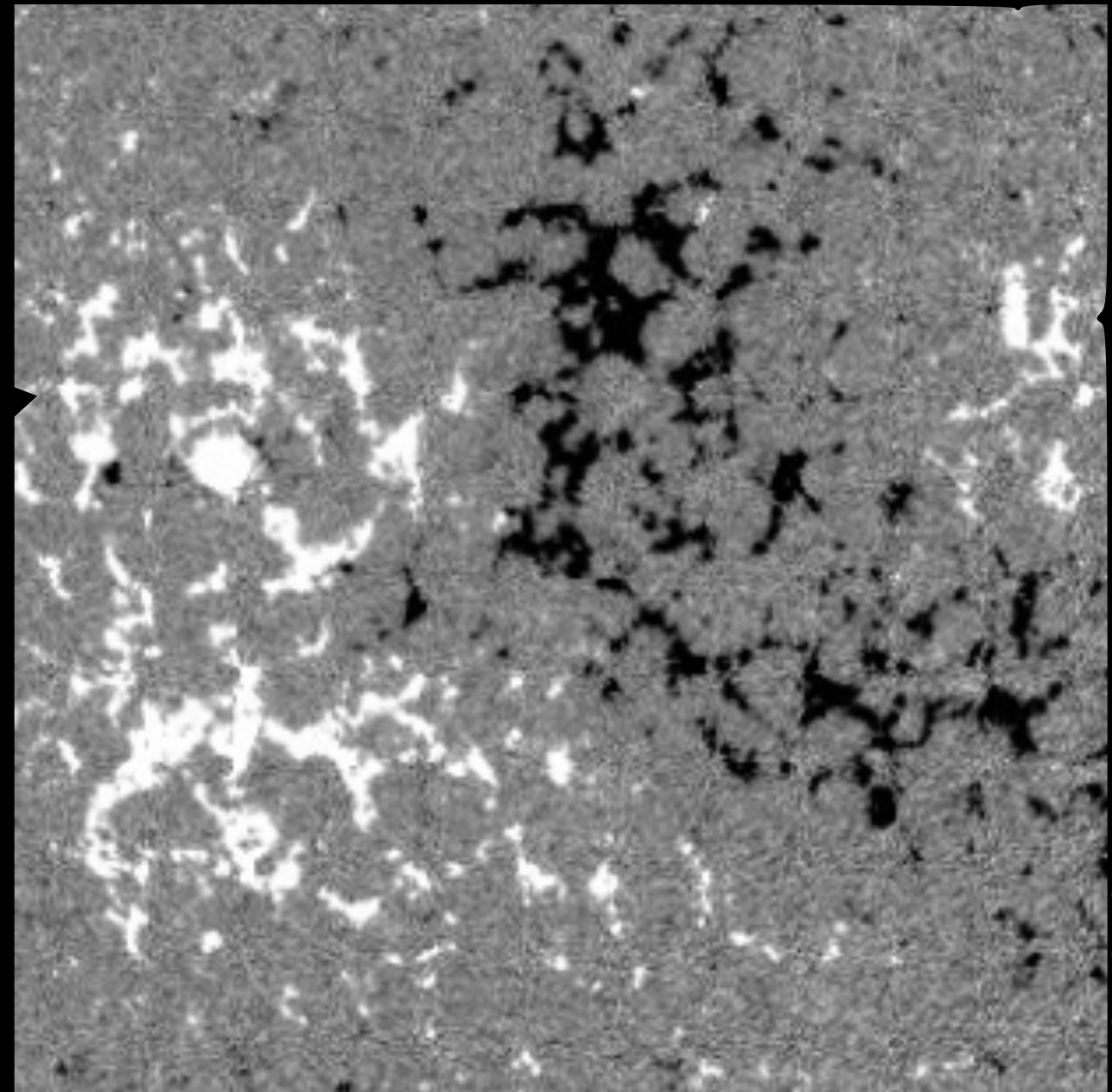
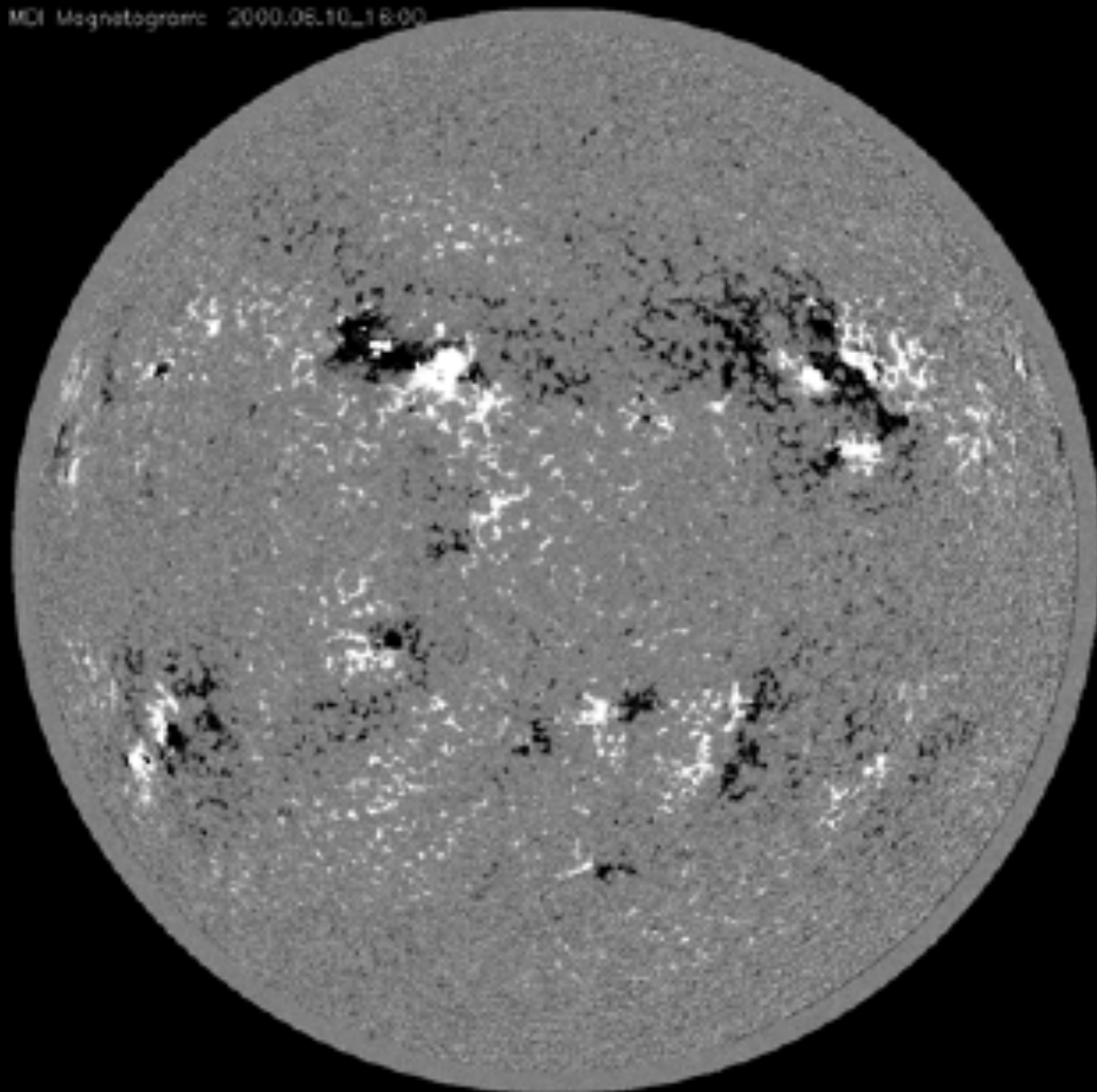
Observation follows target region,
removing effect of solar rotation

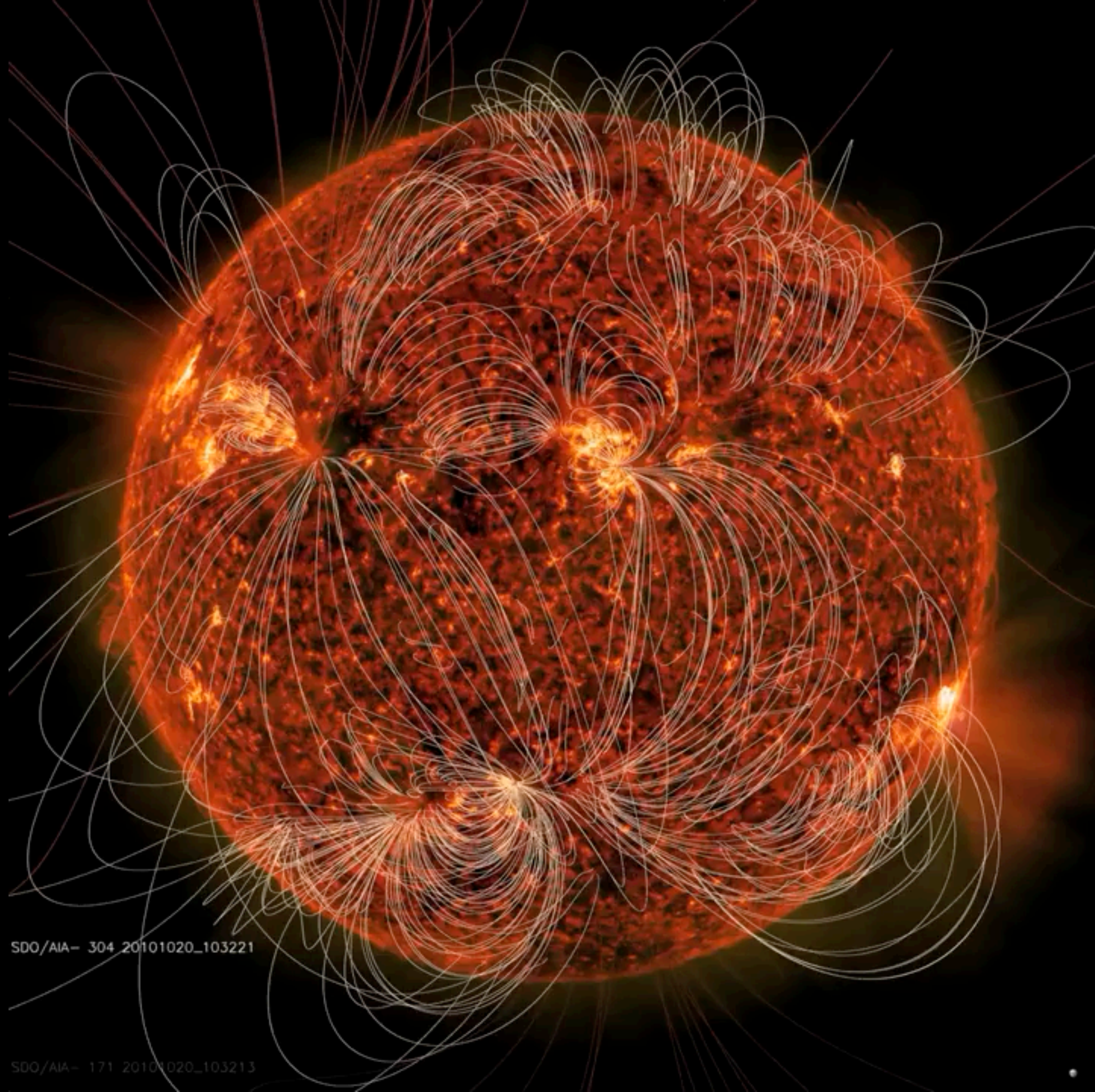
Magnetism

Photospheric magnetograms

- Active regions, bi-polarity systematic east-west orientation opposite in the south

MCI Magnetogram 2000.08.10_18:00





SDO/AIA- 304 20101020_103221

SDO/AIA- 17 20101020_103213

Magnetism

So far — Radiative-Hydrodynamic Equations

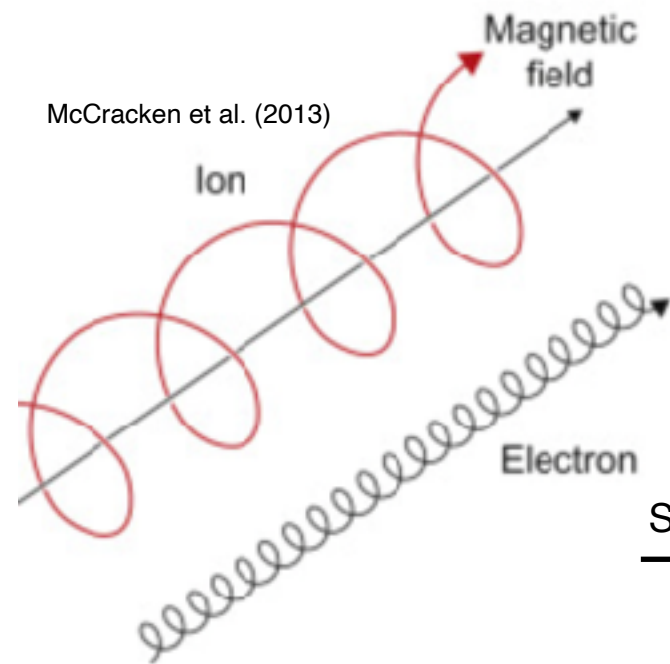
- Hydrodynamic equations:
 - Conservation of mass (density):
(*mass continuity equation*) $\partial_t \rho = -\nabla \cdot (\rho \mathbf{v}),$
 - Conservation of momentum: $\partial_t \rho \mathbf{v} = -\nabla \cdot (\rho \mathbf{v} \mathbf{v} + \underline{\tau}) - \nabla p + \rho \mathbf{g},$
 - Conservation of energy: $\partial_t e = -\nabla \cdot (e \mathbf{v}) - p \nabla \cdot \mathbf{v} + q_{\text{rad}} + q_{\text{visc}},$
- Coupling with the radiation field is give by the radiative cooling and heating term
(as derived from the radiative transfer equation)

$$q_{\text{rad}} = 4\pi\rho \int_{\lambda} \kappa_{\lambda} (J_{\lambda} - S_{\lambda}) d\lambda,$$
- Equation of state $P = c_s^2 \rho = \frac{\rho k_B T}{\mu}$ perfect gas approximation

Additional equations needed when dealing with charged particles (plasma) and magnetic and electric fields

Magnetism

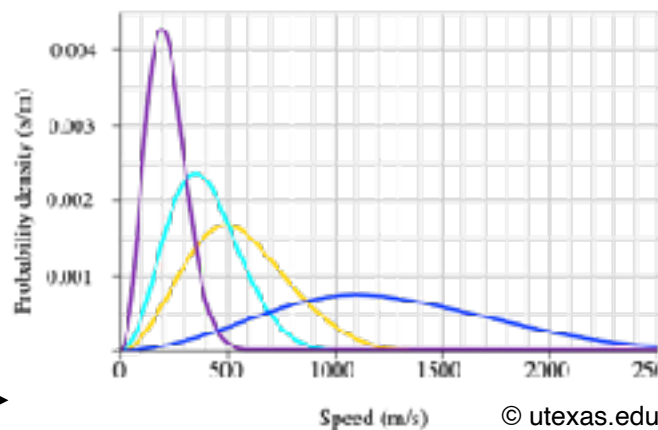
From particles to MHD



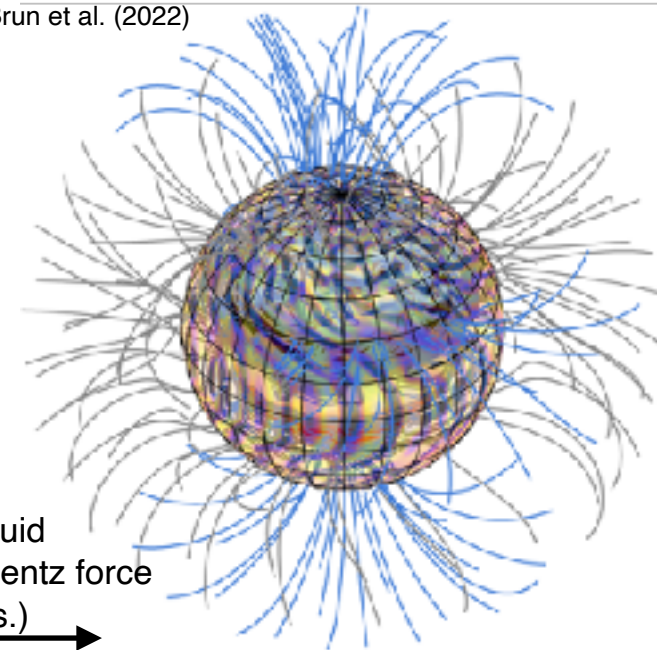
Particles approach

Statistical Physics

Maxwell-Boltzmann Molecular Speed Distribution for Noble Gases



Continuous fluid
(Navier-stokes, Lorentz force
Maxwell Eqs.)



Kinetic

Hybrid

Fluid

high frequencies

low frequencies

f

ω_{pe}

electron
plasma

ω_{pi}

ion
plasma

ω_{ci}

ion
gyrofrequency

ω_a

Alfvén

ω_{ei}

electron-ion
collision

Larger spatial/temporal scales

Magnetism

Magnetohydrodynamics (MHD)

- MHD equations describe how a magnetic field interacts with a continuous plasma (ionized gas).
 - “Like hydrodynamics”, but with extra equations (Lorentz-force etc.)
- **Ideal MHD**
 - Simplifying assumption: infinite conductivity (no resistance), perfectly conducting (and thus fully ionised) plasma, no dissipation of electro-magnetic energy
 - Currents are present, but no charge densities
 - Applicable in the solar interior and in good approximation in the solar atmosphere (note that there will be deviations)
- **Non-ideal MHD conditions:**
 - Ions and neutrals slip past each other (ambipolar diffusion)
 - Magnetic reconnection (localized events, flares)
 - Turbulence induced reconnection

Magnetism

Magnetohydrodynamics (MHD)

- MHD equations describe how a magnetic field interacts with a continuous plasma (ionized gas).
- primary variables $\mathbf{v}$, $\mathbf{B}$, p , ρ and T

Conservation of mass (density) (mass continuity equation)	$\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0$
Conservation of momentum — extra term	$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B} + \mathbf{F}_g + \mathbf{F}_v$
Conservation of energy	$\frac{\rho^\gamma}{\gamma - 1} \frac{d}{dt} \left(\frac{p}{\rho^\gamma} \right) = -\nabla \cdot \mathbf{q} - L_r + j^2/\sigma + F_H$
Equation of state	$p = \frac{k_B}{m} \rho T \quad \left(= \frac{\tilde{R}}{\tilde{\mu}} \rho T \right)$

$\mathbf{j} \times \mathbf{B}$: Lorentz force per unit volume — describes the interaction between the magnetic field and the plasma

j^2/σ : Ohmic dissipation

q : heat flux due to particle conduction

L_r : net radiation

Magnetism

Magnetohydrodynamics (MHD)

- MHD equations describe how a magnetic field interacts with a continuous plasma (ionized gas).
- primary variables $\mathbf{v}$, $\mathbf{B}$, p , ρ and T

Conservation of mass (density) (mass continuity equation)	$\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0$
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Conservation of energy	$\frac{\rho^\gamma}{\gamma - 1} \frac{d}{dt} \left(\frac{p}{\rho^\gamma} \right) = -\nabla \cdot \mathbf{q} - L_r + j^2 / \sigma + F_H$
Equation of state	$p = \frac{k_B}{m} \rho T \quad \left(= \frac{\tilde{R}}{\tilde{\mu}} \rho T \right)$
Induction equation	$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$
Ohm's Law	$\mathbf{j} = \sigma (\mathbf{E} + \mathbf{v} \times \mathbf{B})$

- Further reading: *Solar Magnetohydrodynamics*, E. Priest (2014), downloadable via UiO bib.

Magnetism

Magnetohydrodynamics (MHD)

- MHD equations describe how a magnetic field interacts with a continuous plasma (ionized gas).

primary variables: $\mathbf{v}$, B , p , ρ , T

- Numerical simulations need to account for a lot physics — computationally very challenging
- Certain terms can be neglected depending on the simulated scenario in order to make problem computationally feasible
 - Validity of resulting model then limited by these simplifying assumptions
- Numerical simulations have historically developed from simplified cases to increasingly more complex and

$$\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0$$

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B} + \mathbf{F}_g + \mathbf{F}_v$$

$$\frac{\rho^\gamma}{\gamma - 1} \frac{d}{dt} \left(\frac{p}{\rho^\gamma} \right) = -\nabla \cdot \mathbf{q} - L_r + j^2 / \sigma + F_H$$

$$p = \frac{k_B}{m} \rho T \quad \left(= \frac{\tilde{R}}{\tilde{\mu}} \rho T \right)$$

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

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

- Further reading: *Solar Magnetohydrodynamics*, E. Priest (2014), downloadable via UiO bib.

Magnetism

Magnetohydrodynamics (MHD)

- Additional equation can be derived from the Maxwell Equations and the Lorentz force

Maxwell's Equations	Gauss's law	$\nabla \cdot \mathbf{E} = \frac{\rho_q}{\epsilon_0}$
	Gauss's law of magnetism	$\nabla \cdot \mathbf{B} = 0$
	Maxwell–Faraday equation (Faraday's law of induction)	$\nabla \times \mathbf{E} = - \frac{\partial \mathbf{B}}{\partial t}$
	Ampère's circuital law (with Maxwell's addition)	$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t}$
Lorentz force (electromagnetic force) <i>Charged particle moving in electric and magnetic fields.</i>		$\mathbf{F} = q\mathbf{E} + q(\mathbf{v} \times \mathbf{B})$

- Further reading: *Solar Magnetohydrodynamics*, E. Priest (2014), downloadable via UiO bib.

Magnetism

Fundamental plasma properties

- **Electrical conductivity** σ

For a fully ionised,
collision-dominated plasma
(see “Drude model”...)

$$\sigma = n_e e^2 \tau_{ei} / m_e$$

n_e : number density of electrons
 e : electric charge
 m_e : electron mass
 τ_{ei} : electron-ion collision time

- **Magnetic diffusivity** η

$$\eta = 1/(\mu\sigma)$$

μ : magnetic permeability;
*magnetic field production due
to moving electric charge
(current)*

- **Charge conservation:** MHD “charge continuity equation”

$$\frac{\partial \rho_q}{\partial t} + \nabla \cdot (\rho_q \mathbf{v}) = 0 \quad \Rightarrow \quad \frac{\partial \rho_q}{\partial t} + \nabla \cdot \mathbf{j} = 0$$

$$\rho_q = q n$$

$$\rho_q \mathbf{v} = \mathbf{j}$$

$\mathbf{v}$: Velocity

ρ_q : Charge density

q : Charge per particle

n : Number density

$\mathbf{j}$: Current

- **Ohm’s law:**

(From Lorentz force of a large number of particles, moving at a non-relativistic velocity $\mathbf{v}$ in the presence of a magnetic field)

➡ Electric field ($\mathbf{v} \times \mathbf{B}$) in addition to the electric field ($\mathbf{E}$) which would act on material at rest.

➡ Current density $\mathbf{j} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B})$

Magnetism

Generalized Ohms Law (For a plasma that consists of a mix of electrons, protons and neutral atoms)

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{j}$$

Electric field
in a moving
plasma

Resistive
term (cf
 $V=IR$; η =
resistivity)

- **Ideal MHD:** $\eta = 0 \Rightarrow \mathbf{E} + \mathbf{v} \times \mathbf{B} = 0$
 - A very good approximation for many applications (incl. solar interior)
 - ‘frozen-in flux’ approximation
 - Simplifies computations!

Magnetism

Momentum Equation

- Conservation of momentum — the MHD equation of motion

$$\underbrace{\rho \left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) \mathbf{v}}_{\text{convective derivative of the momentum}} = \underbrace{-\nabla \cdot \underline{\underline{\mathbf{P}}} + \rho_q \mathbf{E} + \mathbf{j} \times \mathbf{B}}_{\text{sources and sinks of momentum (forces)}} + \text{any other forces acting on the plasma (e.g. gravity)}$$

- $\nabla \cdot \underline{\underline{\mathbf{P}}}$: plasma pressure gradient
- $\rho_q E$: electric field force (can be neglected if no net charge density in plasma)
- $\mathbf{j} \times \mathbf{B}$: Lorentz force

Magnetism

Magnetic pressure

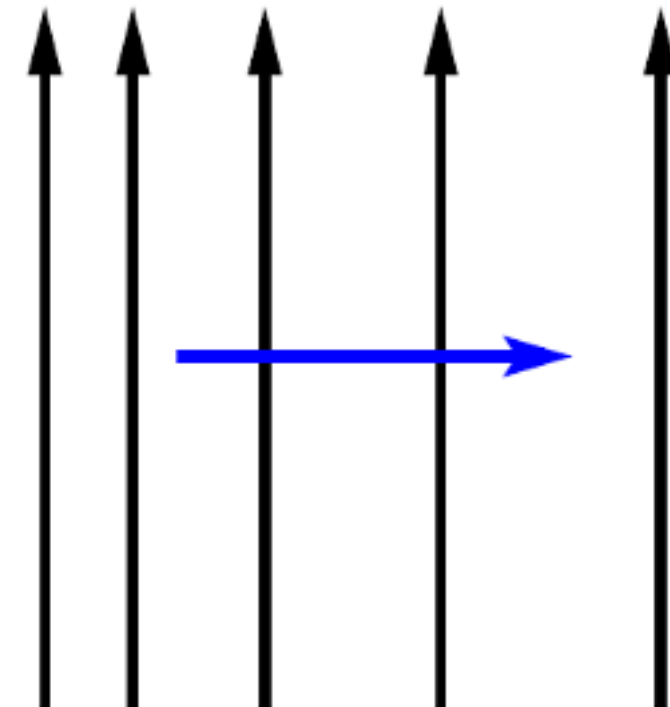
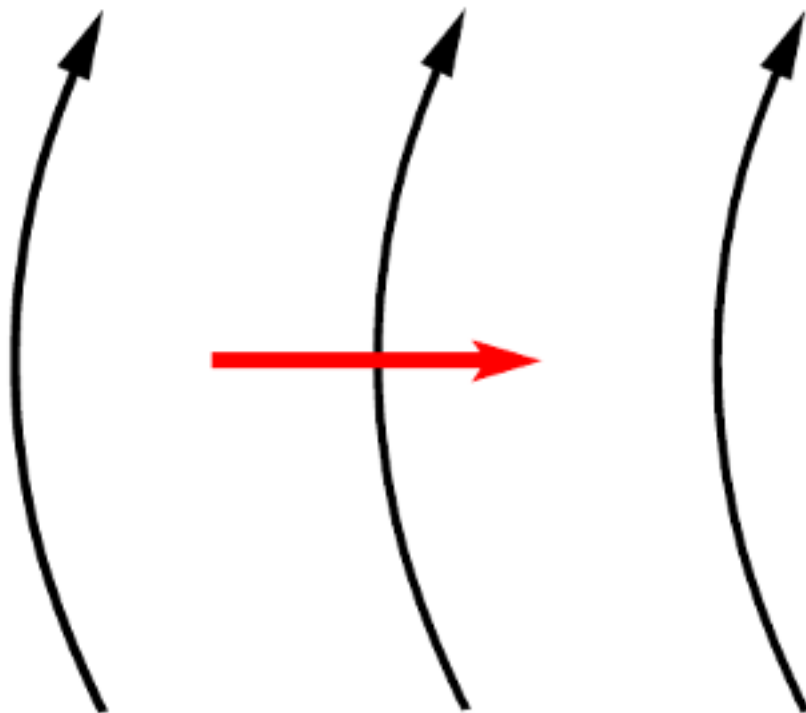
$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B} + \mathbf{F}_g + \mathbf{F}_v$$

Lorentz force

$$\mathbf{j} \wedge \vec{B} = \frac{(\vec{B} \cdot \nabla) \vec{B}}{\mu_0} - \nabla \left(\frac{B^2}{2\mu_0} \right)$$

magnetic tension

magnetic pressure



Magnetism

Force-free fields

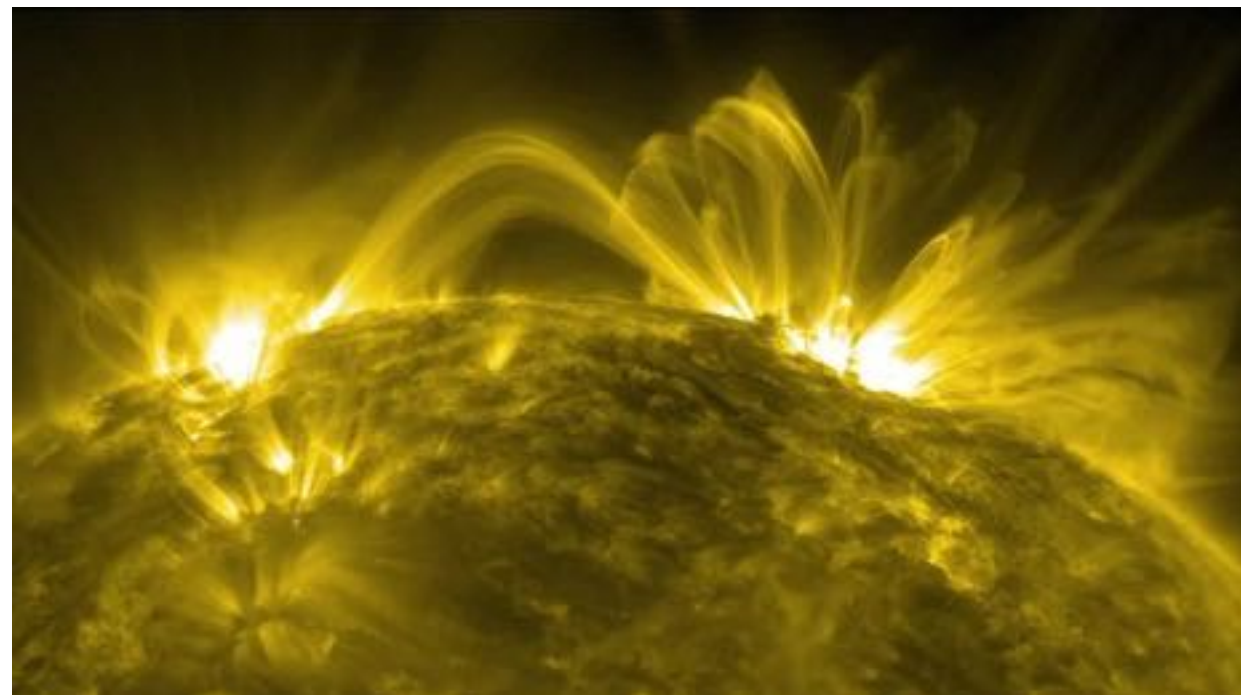
- Magnetic field configuration for which Lorentz force is zero ($\vec{j} \times \vec{B} = 0$) called **force-free**

$$\rho \left(\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \vec{\nabla}) \vec{v} \right) = \rho \vec{g} - \vec{\nabla} p + \vec{j} \wedge \vec{B}$$

Static high in the atmosphere $\beta \ll 1$

$$\begin{aligned} \vec{j} \wedge \vec{B} &= 0 \\ \vec{\nabla} \wedge \vec{B} &= \mu_0 \vec{j} \\ \alpha &= \frac{\mu_0 j}{B} \end{aligned}$$

$$\vec{\nabla} \wedge \vec{B} = \alpha \vec{B}$$

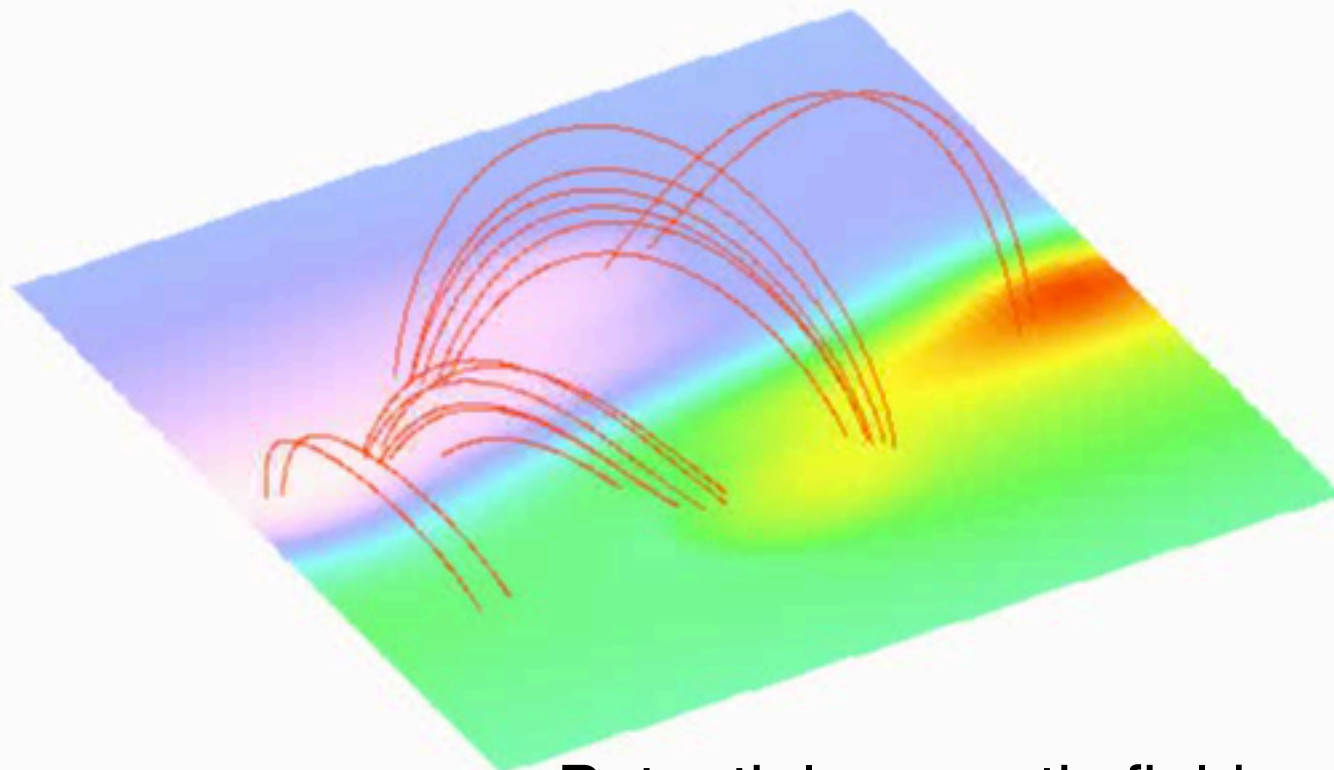


AIA/SDO

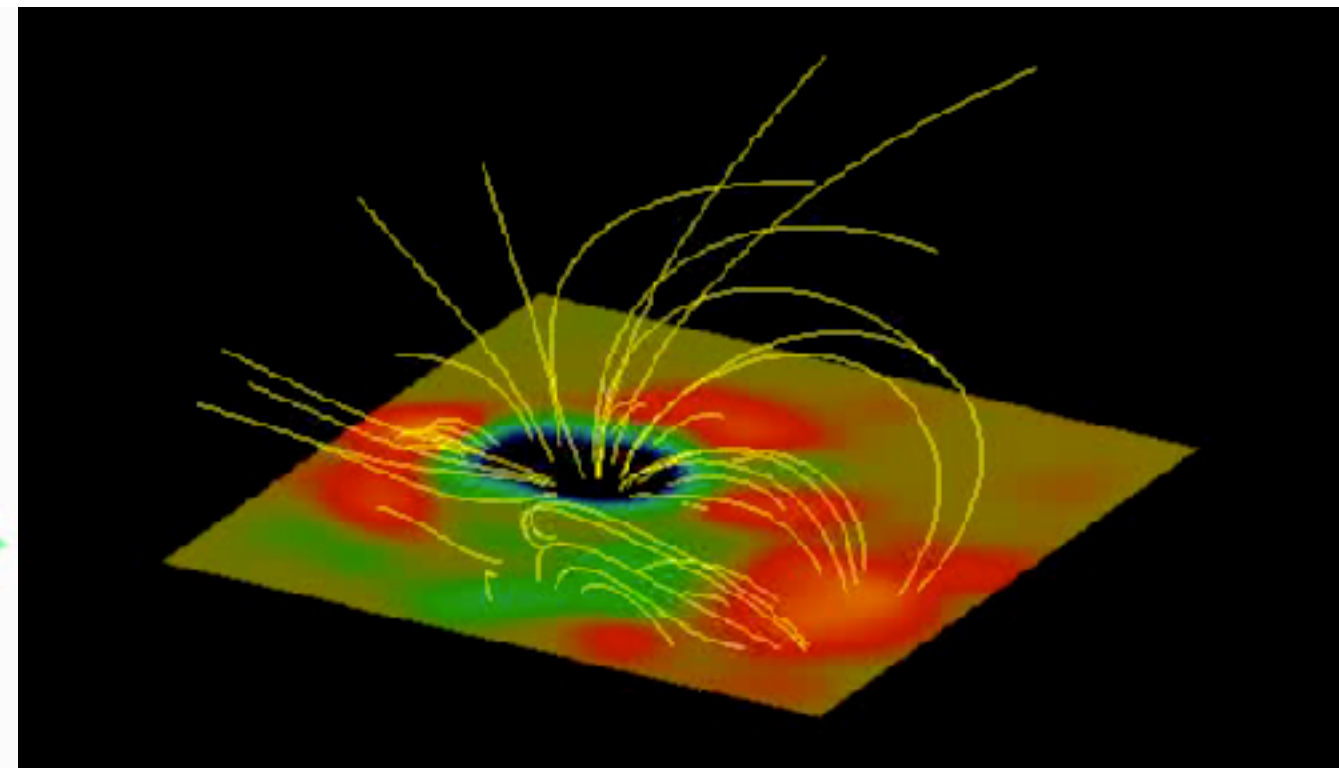
Magnetism

Force-free fields

- Magnetic field configuration for which Lorentz force is zero ($\mathbf{j} \times \mathbf{B} = 0$) called **force-free**
- **Example 1:** magnetic tension and pressure are in balance
- **Example 2:** potential magnetic field configuration with no electric current
 $\mathbf{j} = 0 \rightarrow \nabla \times \mathbf{B} = 0 \rightarrow \mathbf{B} = \nabla \Psi$ Ψ : magnetic (scalar) potential



Potential magnetic field extrapolation



See Alissandrakis (1981) ; Wiegmann

Magnetism

Magnetic pressure

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B} + \mathbf{F}_g + \mathbf{F}_v$$

- Assume a static case, no net charge, ignore gravity and viscosity $\Rightarrow \mathbf{j} \times \mathbf{B} = \nabla p$
- Magnetic field exerts a pressure force, for short: **magnetic pressure**.

- In SI units:
T, μ_0 in H/m

$$P_{\text{mag}} = \frac{B^2}{2\mu_0}$$

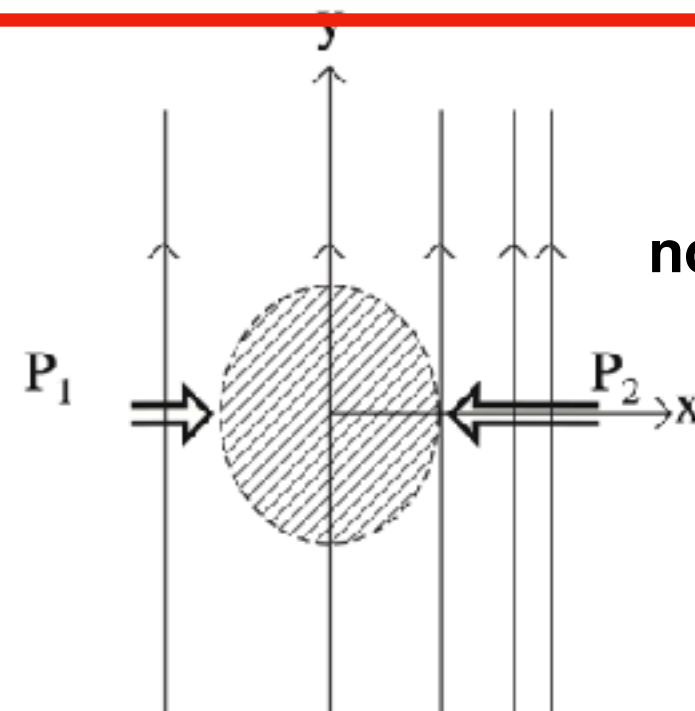
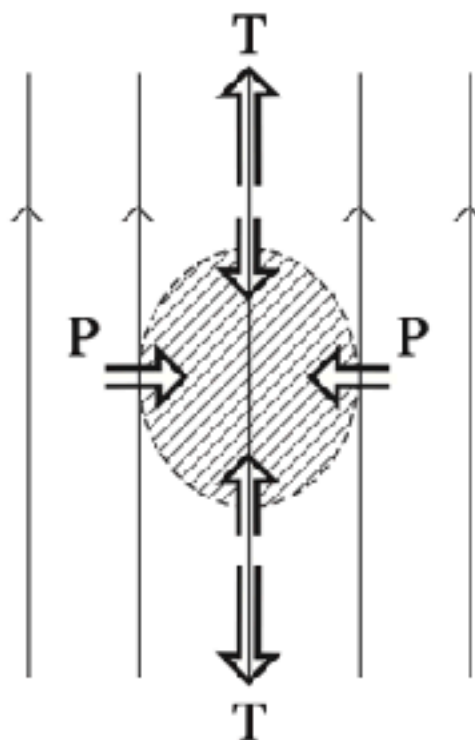
SI units: P in Pa, B in T
 μ_0 : magnetic permeability in vacuum

- In cgs units
cm², B in G

$$P_{\text{mag}} = \frac{B^2}{8\pi}$$

cgs units: P in dyn/cm²

uniform field:
magnetic pressures (P) and tensions (T) are in balance



non-uniform field:

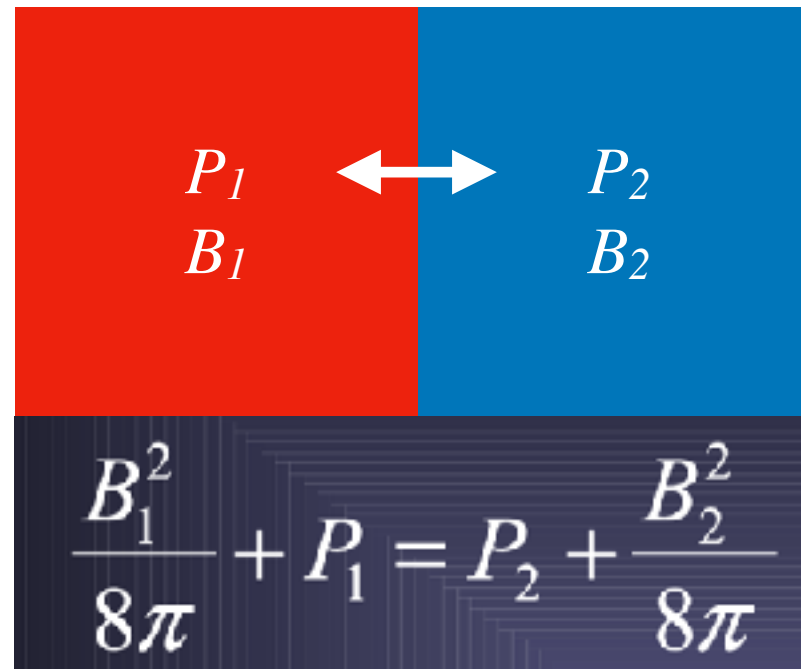
$$dB/dx > 0$$

Imbalance:

$$P_2 > P_1$$

Magnetism

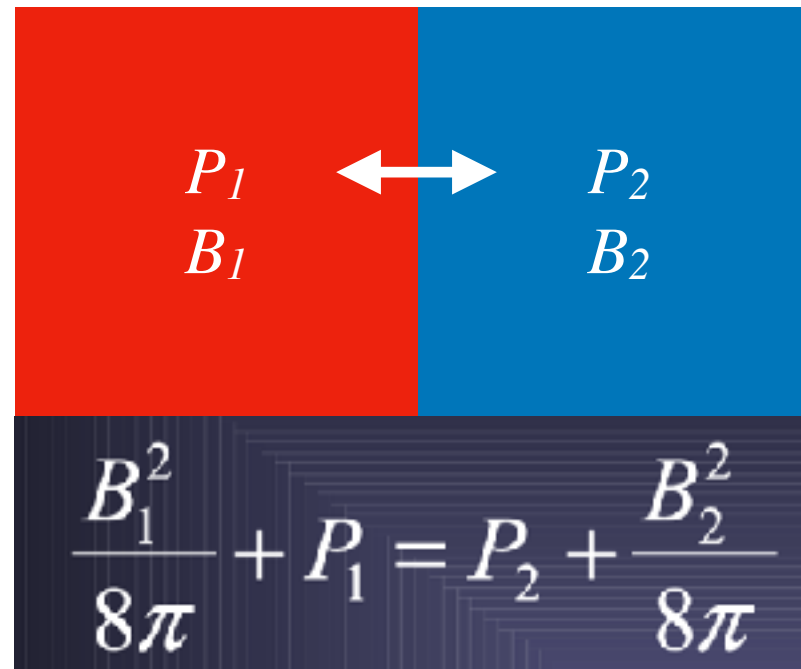
Magnetic pressure



- **Pressure balance** between two different plasma domains (1 and 2):
- If $B_2 = 0$:
 - Extreme case: Component 1 is evacuated: $P_1 = 0 \Rightarrow B_1^2 / 8\pi = P_2$
 - Sets a maximum field strength for region 1 to be in balance with the (surrounding) region 2: **equipartition field strength** $B_{eq} = (8\pi P_2)^{1/2}$
 - If $B > B_{eq}$: Not in pressure balance, overpressure in component 1, tends to expand

Magnetism

Magnetic pressure



- **Pressure balance** between two different plasma domains (1 and 2)
- If $B_2 = 0$ and $T_1 = T_2$, then also $\rho_1 < \rho_2$ (Equation of state!)
 - ➡ Magnetic features (here 1) are buoyant compared to the surrounding gas.
- In the convection zone:
 - Lower density inside magnetic flux bundles compared to surrounding plasma
 - Magnetic flux bundle becomes buoyant and rises towards the surface (down the gradient) unless stopped by other forces

Magnetism

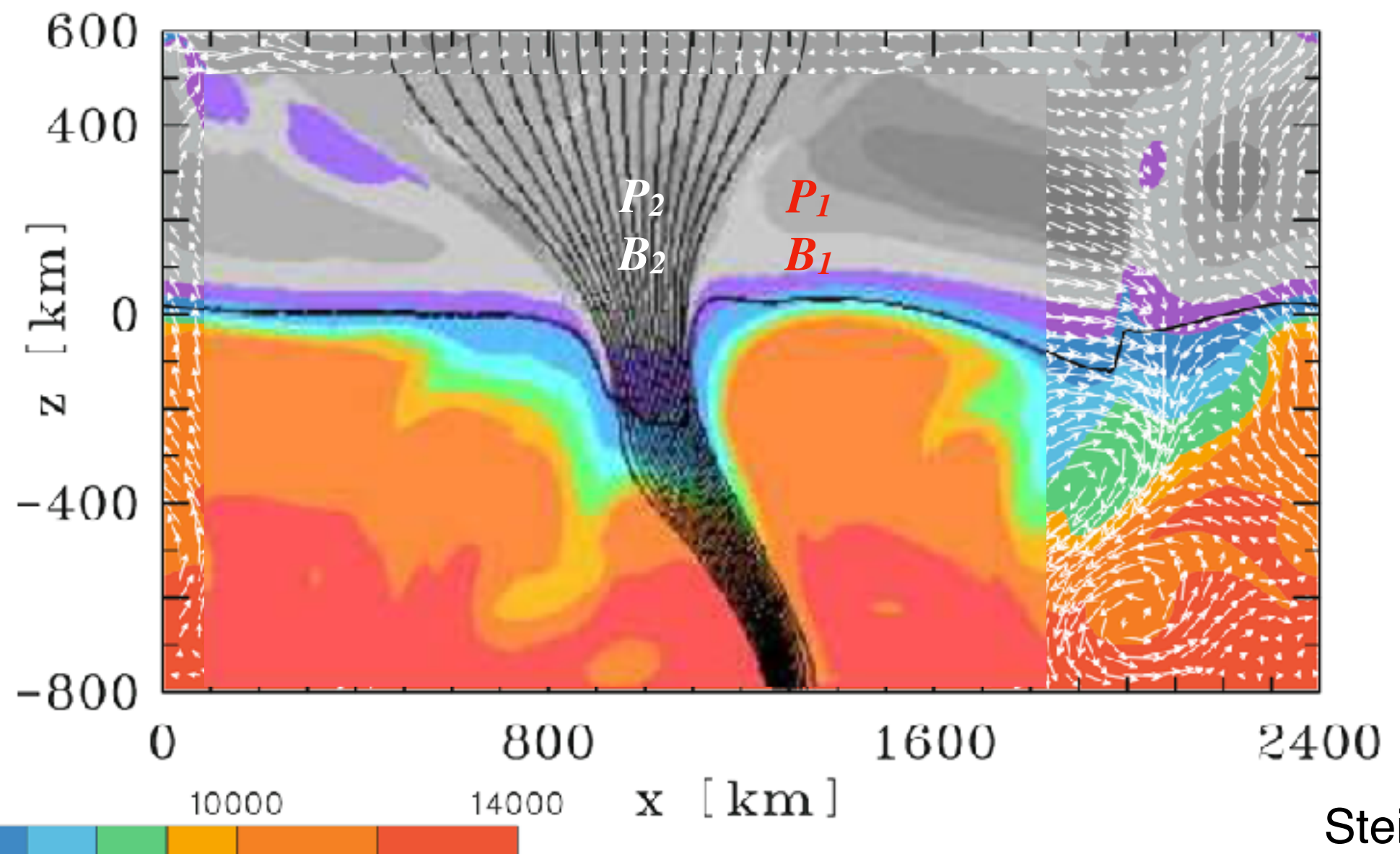
Magnetic pressure

- Additional contributions from magnetic pressure inside magnetic flux concentration
- Pressure balance $\Rightarrow$ lower gas pressure inside the flux concentration than outside
- Gas pressure of surrounding drops with height $\Rightarrow$ Magnetic structure funnels out (wine-glass shape)

- $B_2 > B_1$

- $\Rightarrow P_2 < P_1$

- $\Rightarrow \rho_2 < \rho_1$



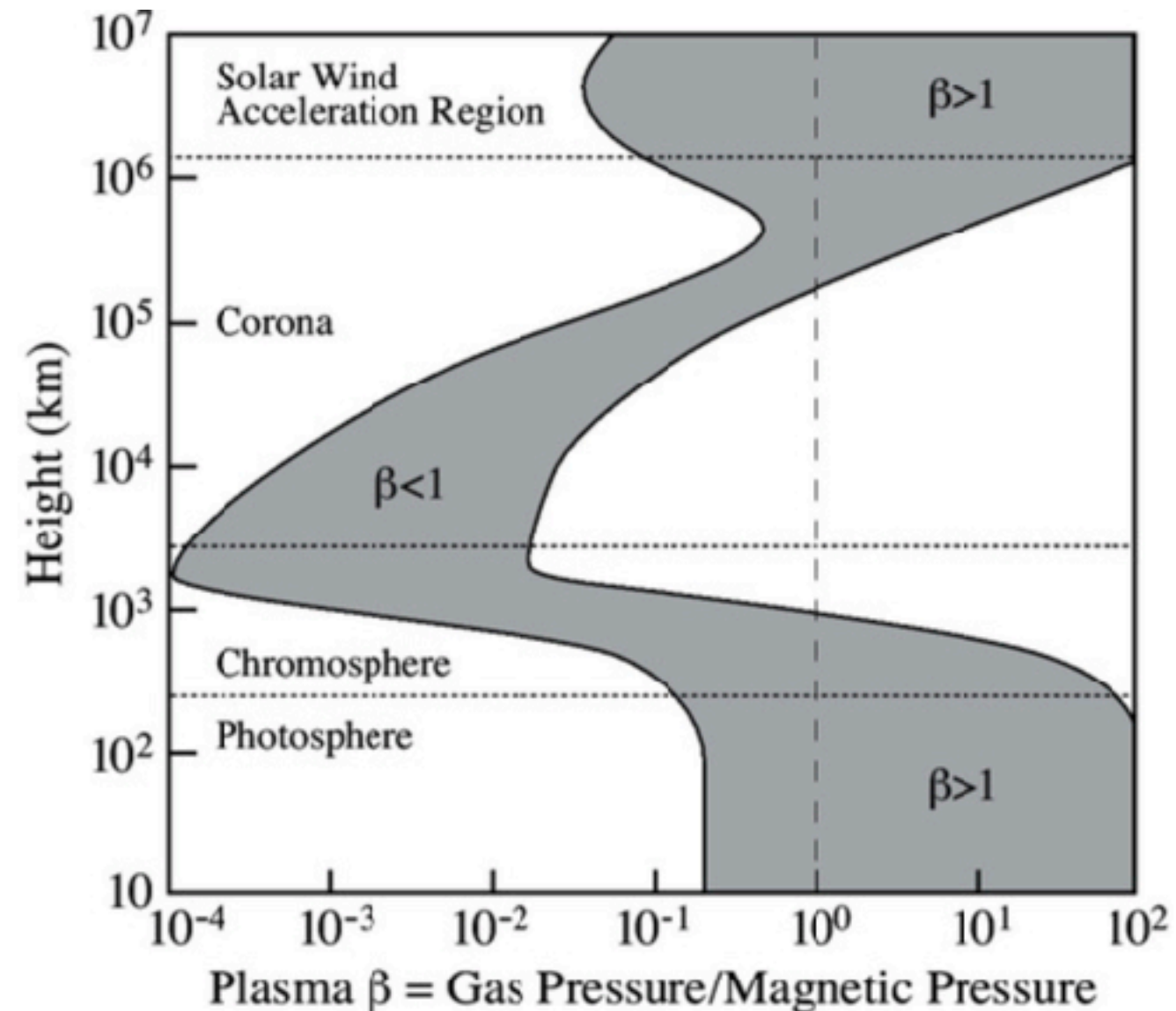
Magnetism

Plasma-Beta

- Plasma- β describes the ratio of thermal to magnetic pressure

$$\beta = \frac{P_g}{P_m} = \frac{8\pi P_g}{B^2} \text{ (cgs)}$$

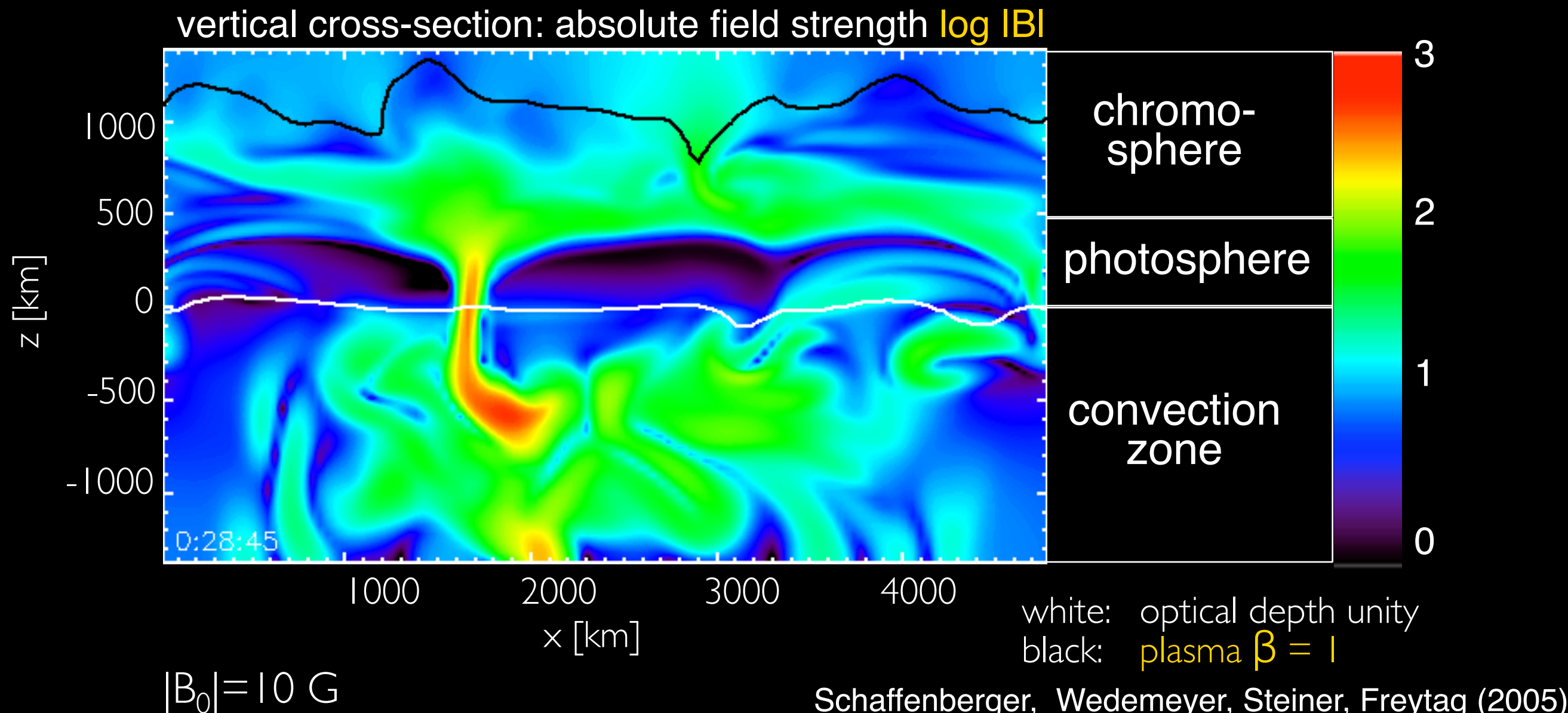
- $\beta < 1$: **Magnetic field dominates** and dictates the dynamics of the gas
- $\beta > 1$: **Thermal gas dynamics dominate** and forces the field to follow (—> If **ideal-MHD**, the magnetic field does not diffused and is said “**frozen-in**” the plasma.)
- β is a local quantity but the typical range of values changes with radius:
 - Convection zone: $\beta > 1$
 - Lower atmosphere (outside strong magnetic field concentrations): $\beta > 1$
 - Chromosphere: transition to $\beta < 1$
 - Corona: $\beta \ll 1$



Magnetism

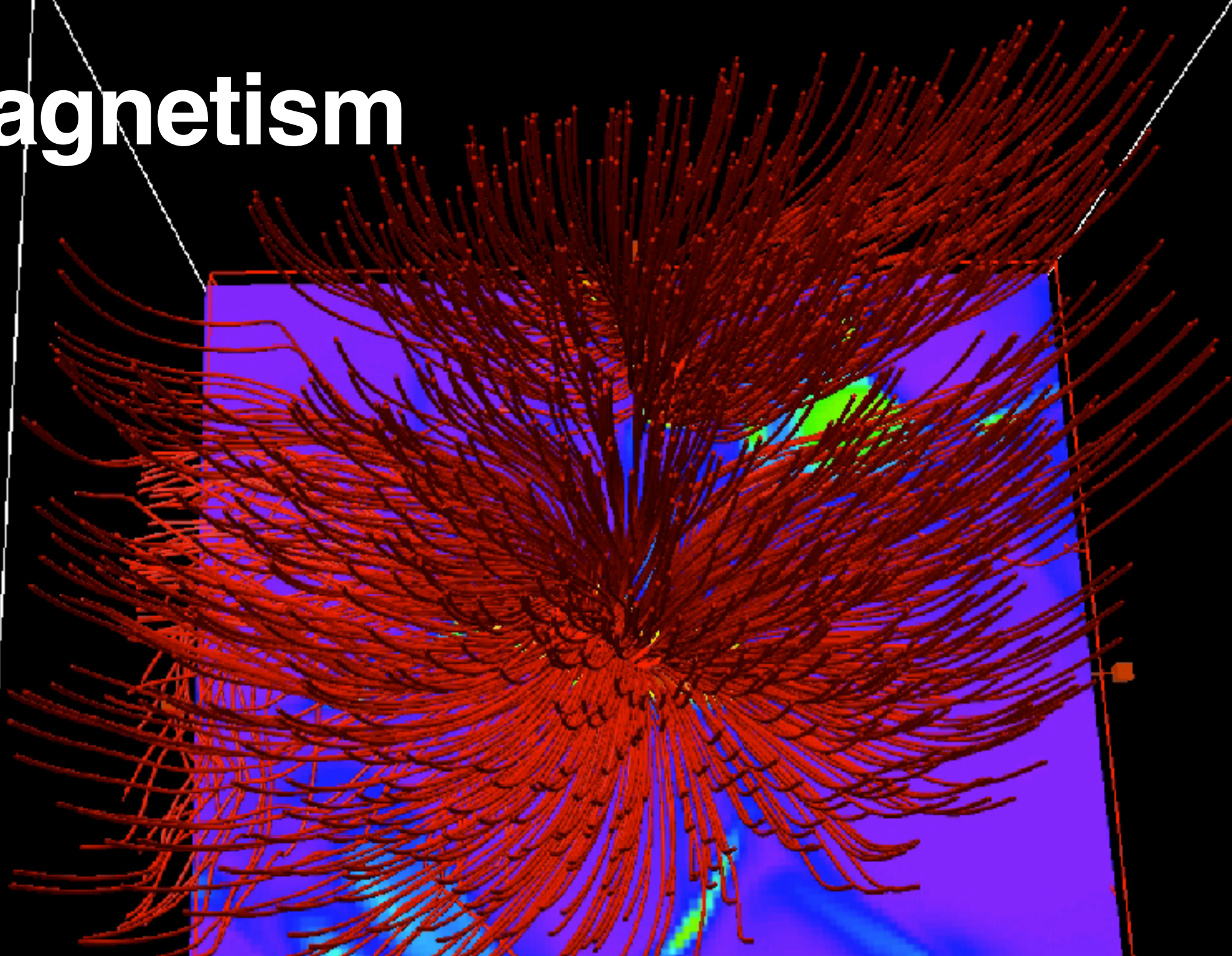
Plasma-Beta

- Magnetic field in chromosphere is highly dynamic
 - Propagating shock waves compress magnetic field
 - Fast moving filaments of enhanced field



Magnetism

CO⁵BOLD
(close-up)

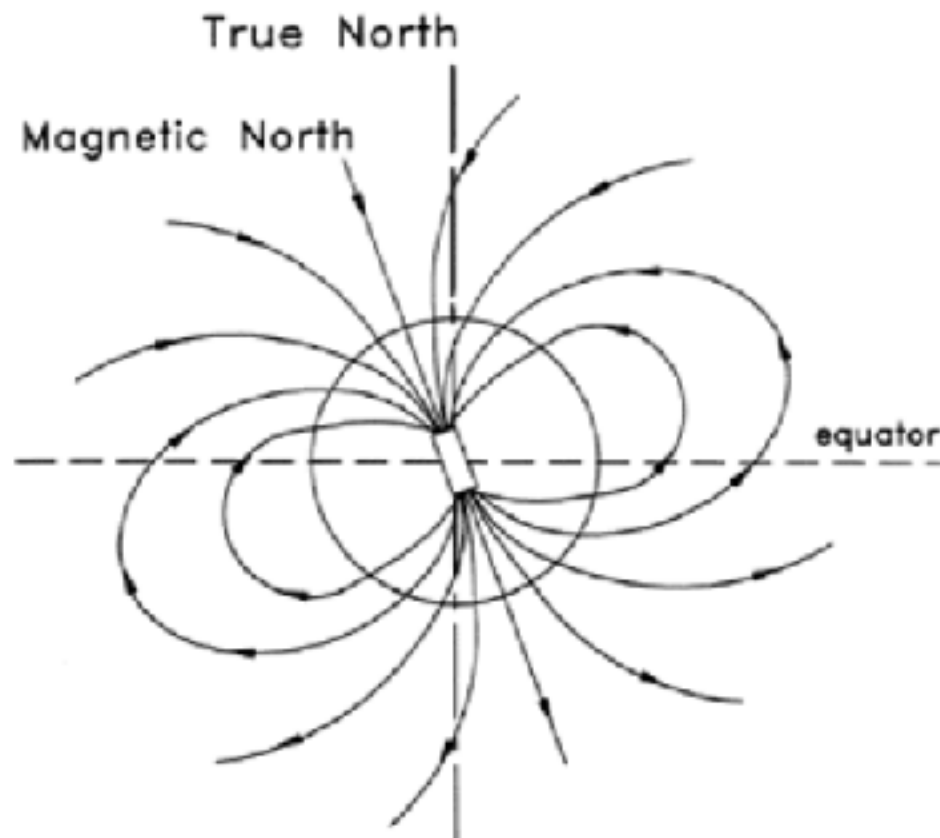


- Complicated field structure with rotating and/or swaying subgroups
- Continuous reorganisation of structure
- More complicated than individual “flux tubes”

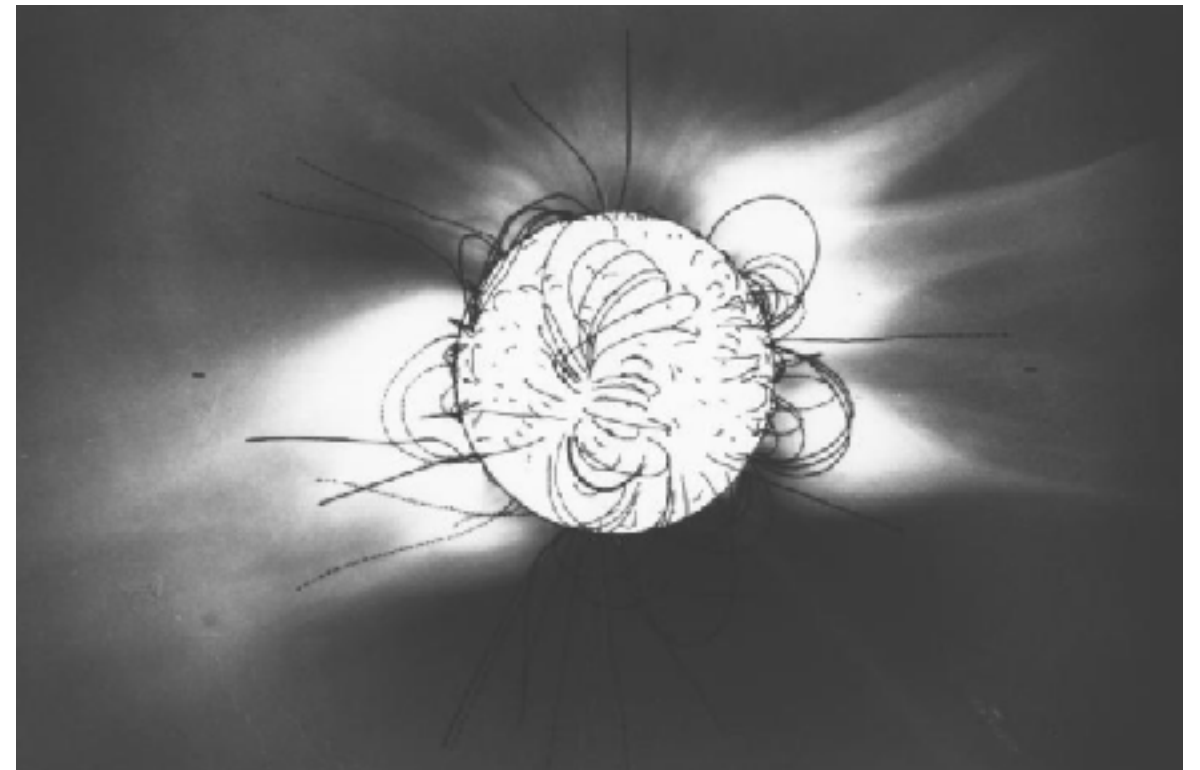
Magnetism

Global magnetic field configurations

Earth — dipole field



Sun — more complicated

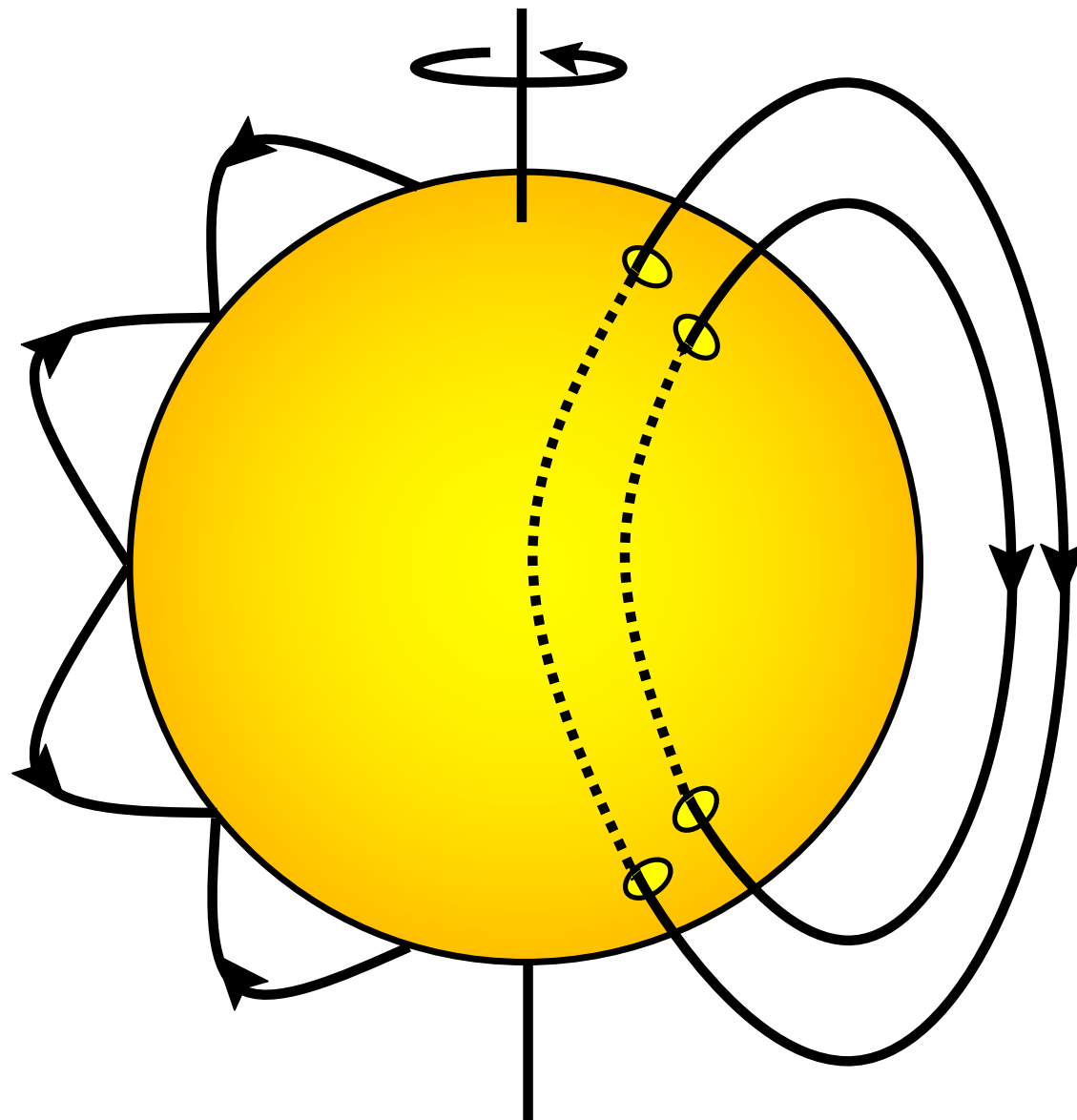


- Like Earth, also the Sun is permeated by a dipole field but with much more complicated additional field geometry that changes over time (solar cycle)

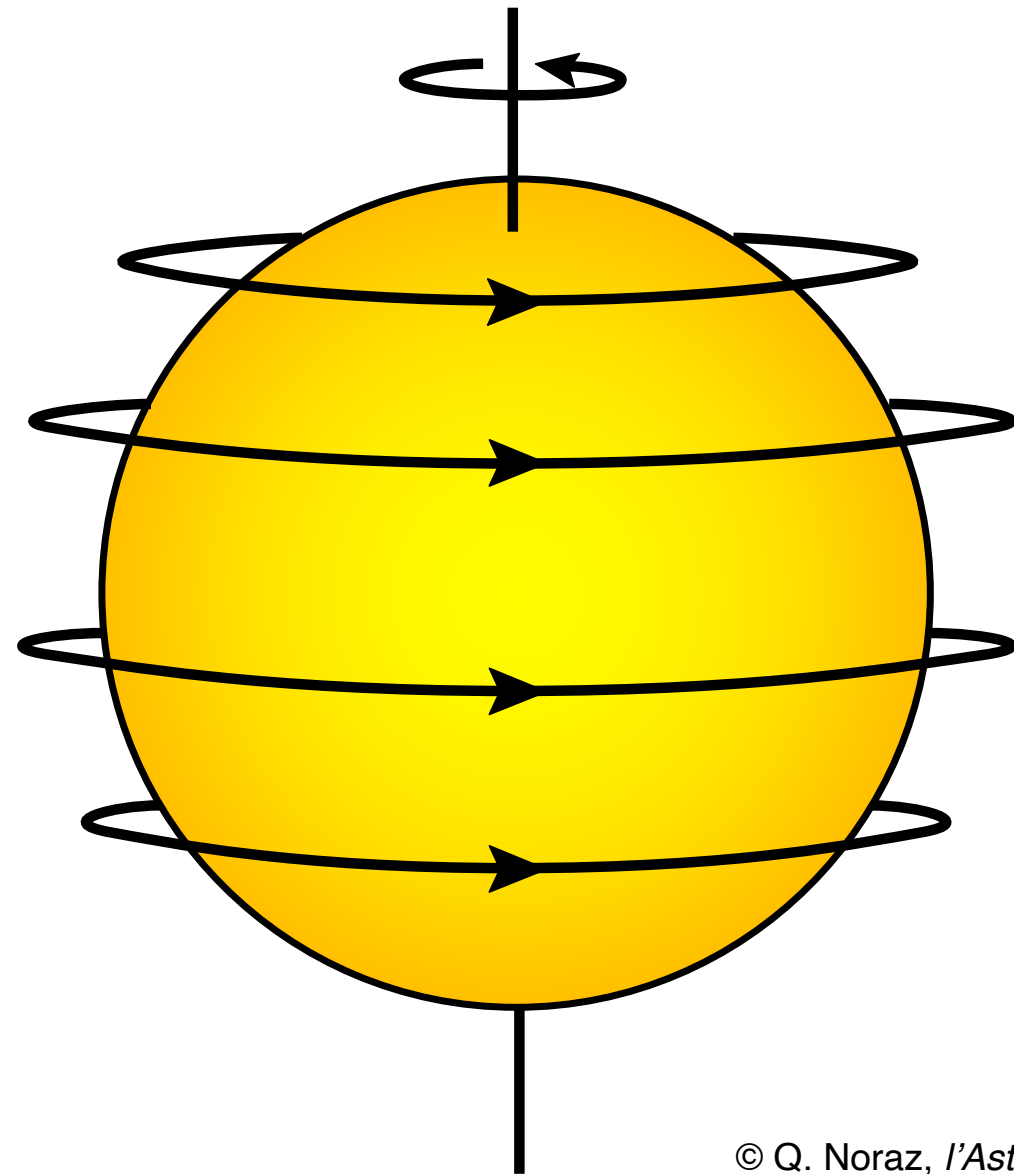
Magnetism

Global magnetic field configurations

Poloidal



Toroidal



Multi-pole
(here “hexadecapole”,
see also spherical harmonics for details...)

dipole

Magnetism

Take aways

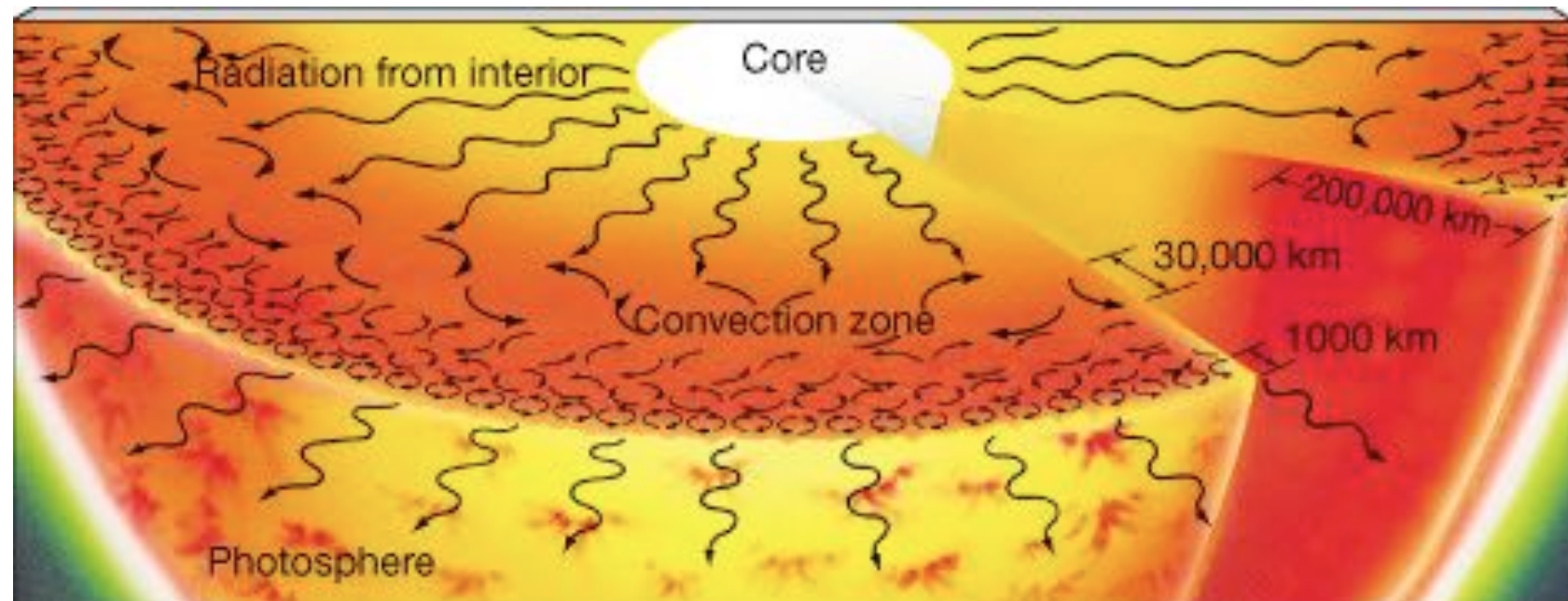
- Ionised gas (plasma) in motion — electric and magnetic fields need to be considered
- Magnetic pressure arises — impacts structure and dynamics of the plasma
 - Higher magnetic field means lower thermal pressure and lower density with respect to the surrounding
- Plasma- β parameter = ratio of thermal to magnetic pressure
 - $\beta < 1$: **Magnetic field dominates** and dictates the dynamics of the gas
 - $\beta > 1$: **Thermal gas dynamics dominate** and forces the field to follow

The solar dynamo

Dynamo

Overview

- Interior of the Sun: plasma (ionized gas) — charged particles
- Convection moves around the plasma (turbulence)
 - ➡ Moving charged particles generate electric currents
 - ➡ Electric currents generate magnetic fields (via Ampere's law).
 - ➡ Changing magnetic fields induces electric currents (Faraday's law).
 - ➡ **Self-reinforcing dynamo process**
- Continuous generation of magnetic dipole fields
- Convection currents **stretch and twist** the magnetic field lines, increases magnetic tension (*analogy for magnetic field lines: rubber bands*)
- Magnetic field gets stronger in some locations and/or orientation of field varied
- Magnetic field decays on time scales much shorter than the Sun's life time
 - ➡ **New field is generated** continuously



Dynamo

Induction equation

Dynamo effect:

The ability of a conductive fluid (plasma) to **amplify and maintain a magnetic field against its ohmic dissipation.**

Convert kinetic energy into magnetic energy

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

$$R_m = \frac{vL}{\eta} \sim \frac{\text{induction or advection of a magnetic field due to the motion of a conducting medium}}{\text{magnetic diffusion}}$$

- Small R_m : Advection is unimportant, magnetic field is diffusive.
- Large R_m : Diffusion unimportant -> **frozen-field** (Alfvén theorem)

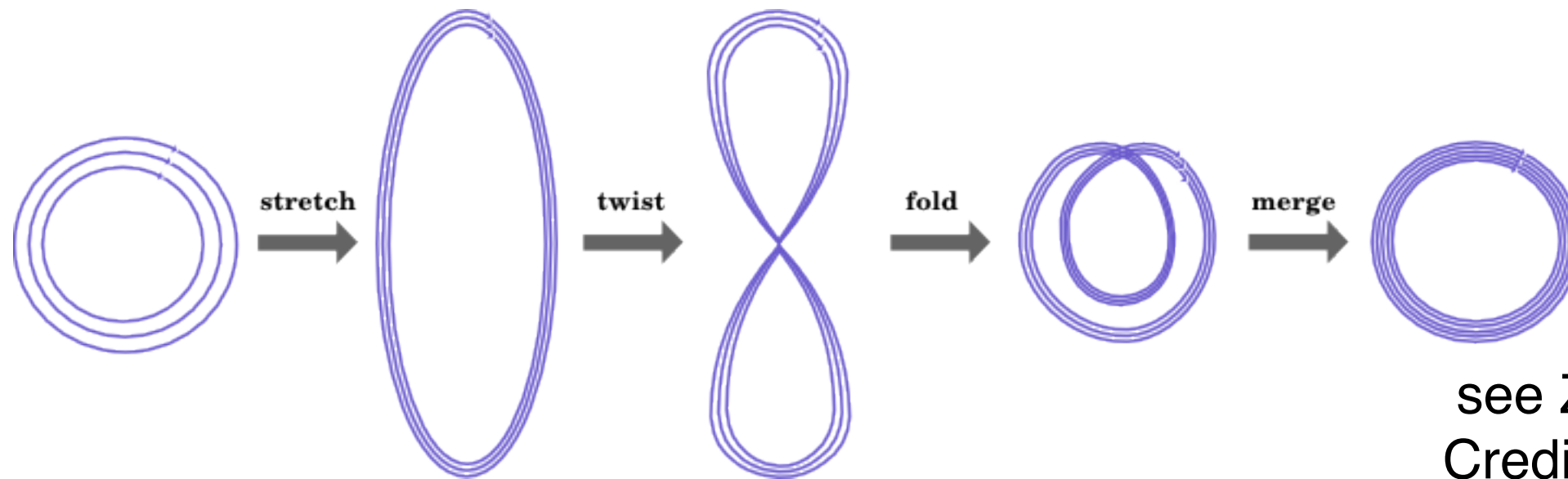
Magnetic field advected with the fluid flow and sustained by dynamo process.

- In the Sun: $R_m \sim 10^6$ (very large) —
Diffusion and related dissipation of magnetic field unimportant.

Dynamo

Fast & Small-Scale

- SFT mechanism: ***stretch-twist-fold***



see Zeldovich et al. 1983
Credit : Jennifer Schooner

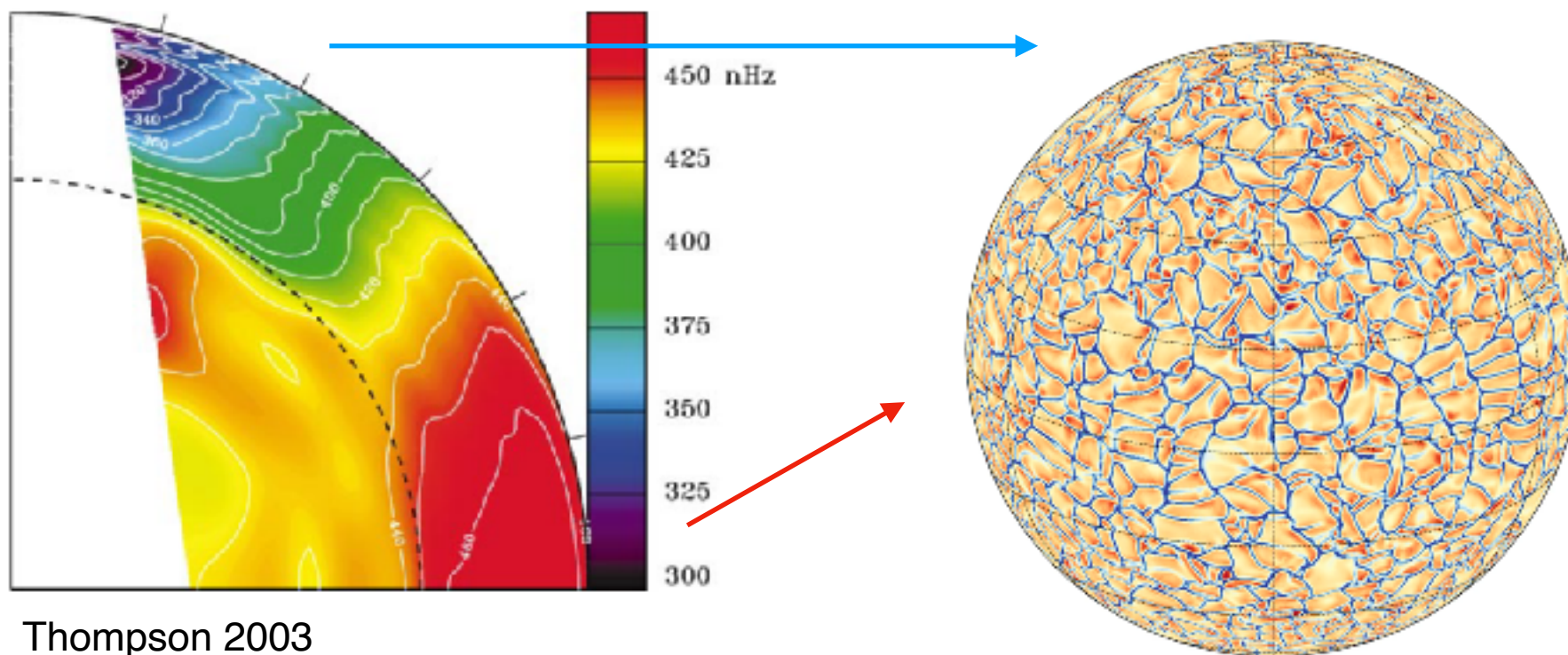
- $R_m \gg 1$: frozen-in field
- Stretch : increase radius of loop ($V=cte$)
-> section decreases, B increases (Maxwell-flux)
- Twist/fold : increases magnetic tension
- Merge : Relaxation of magnetic geometry with reconnection ($\eta \neq 0 \rightarrow R_m \neq \infty$)

=> **Magnetic energy increased**, for a final geometry similar to the initial one

Dynamo

Large-scales : Ω -effect (Omega effect)

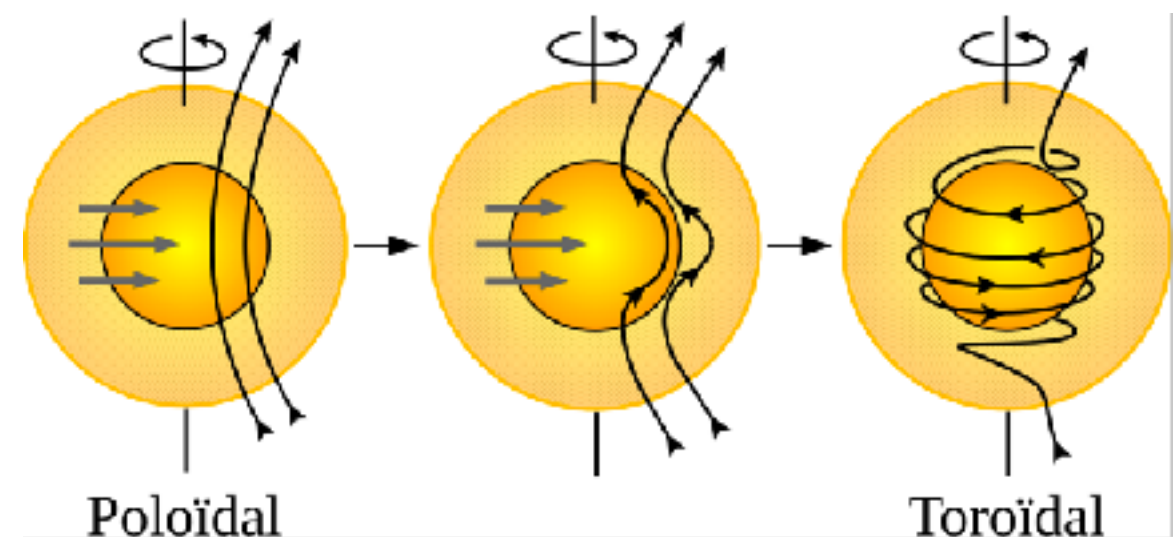
- Omega effect converts initially meridional (poloidal) magnetic field into azimuthal (toroidal) magnetic field due to **differential rotation**



Differential Rotation (DR)

- Radiative interior: **solid-body rotation**
- Convective envelope: differential rotation with **slow poles** and a **fast equator**

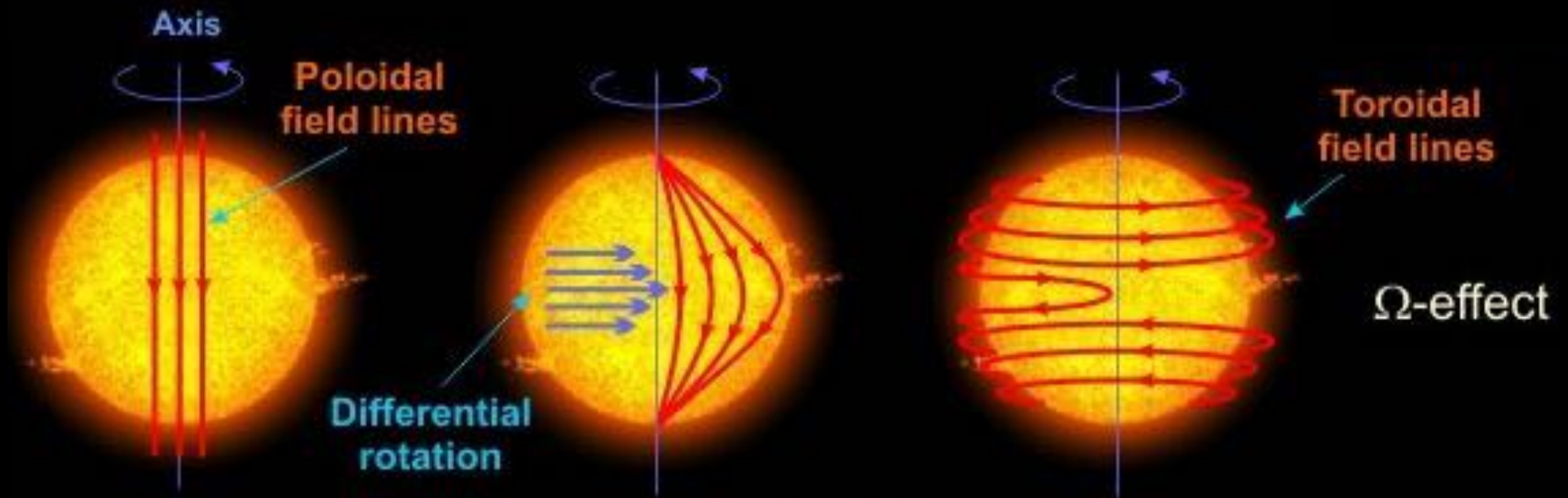
Ω -effect



Dynamo

Ω -effect (Omega effect)

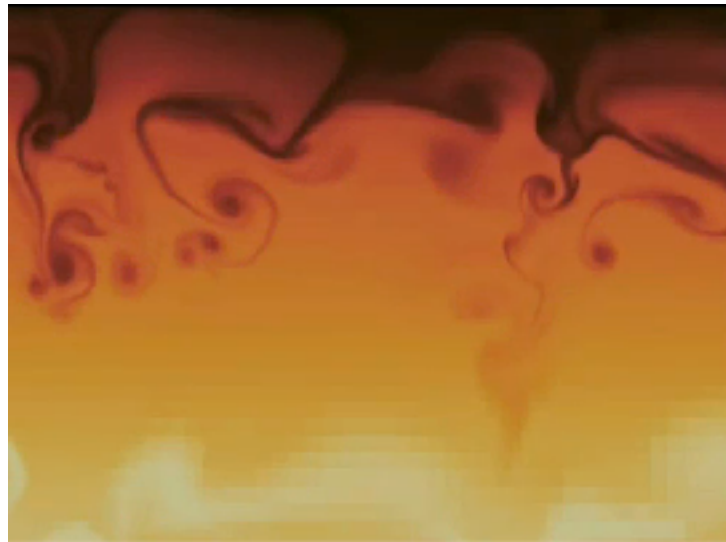
- Omega effect converts initially meridional (poloidal) magnetic field into azimuthal (toroidal) magnetic field
- ➔ Initial meridional magnetic field is twisted and coiled around the Sun due to **differential rotation**
- ➔ Creates magnetic flux strands in the azimuthal (toroidal) direction in shallow depths and low latitudes



Dynamo

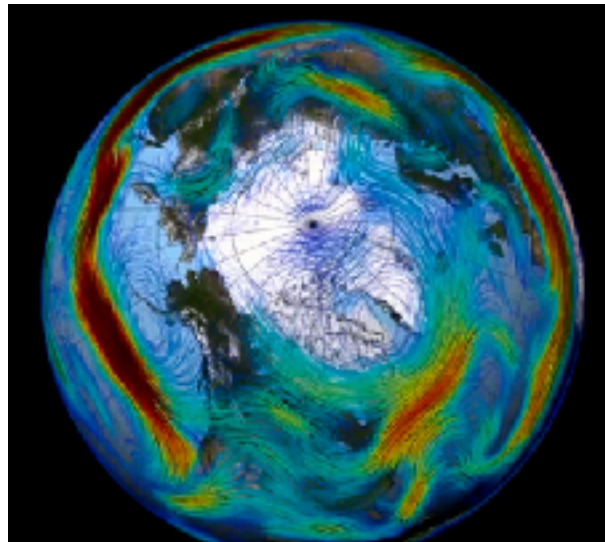
Large-scale : α -effect (Alpha effect)

Convection

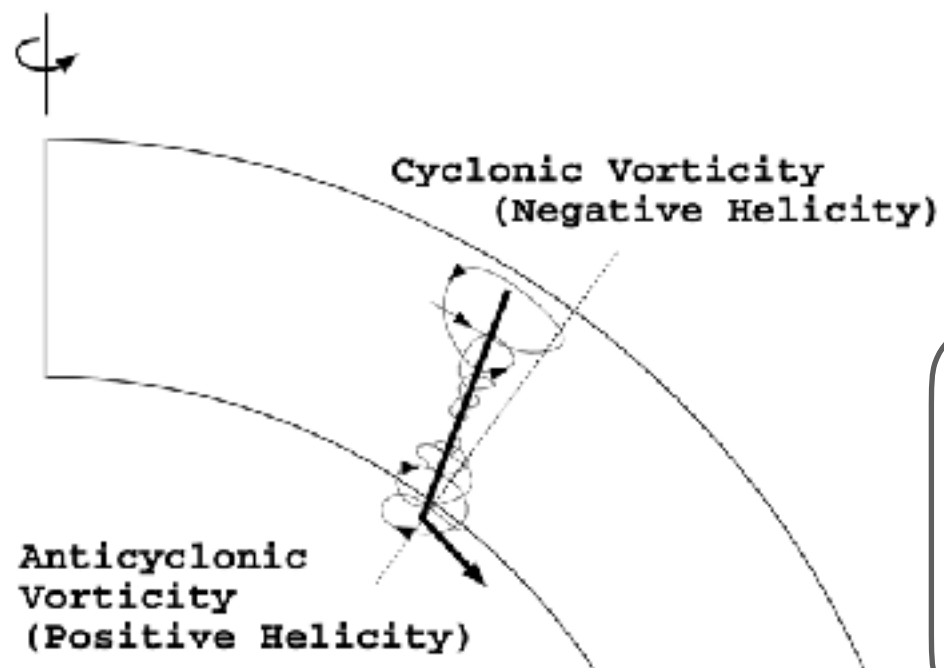


© M. Delorme, Dyablo-WholeSun

Rotation

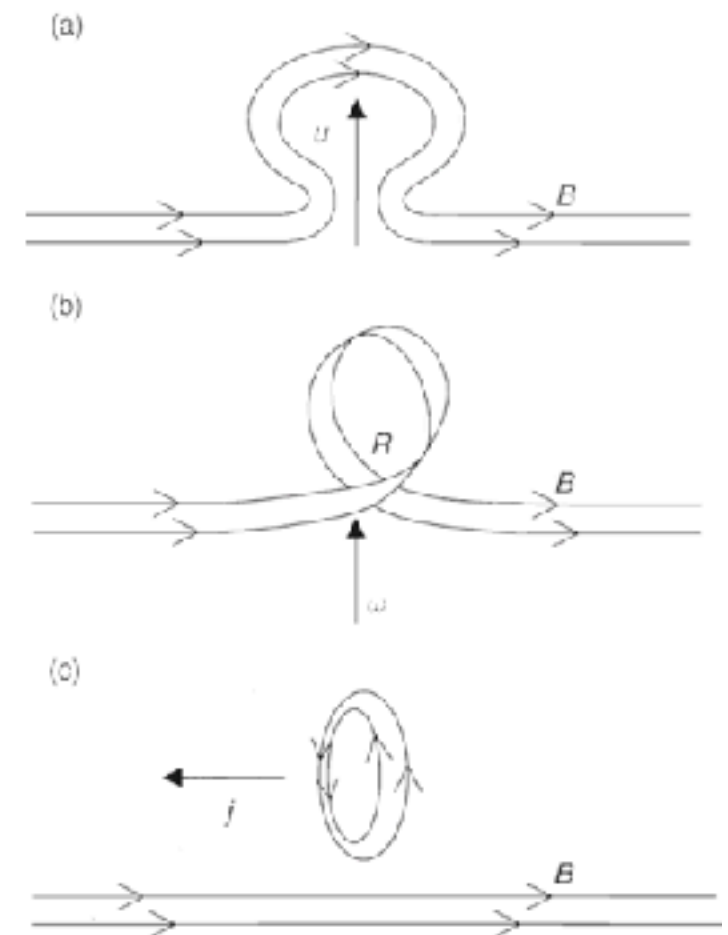


© NASA's Goddard Space Flight Center



Miesch et al. (2000)

velocity u
vorticity $\omega = \nabla \times u$
helicity $H = u \cdot \omega$

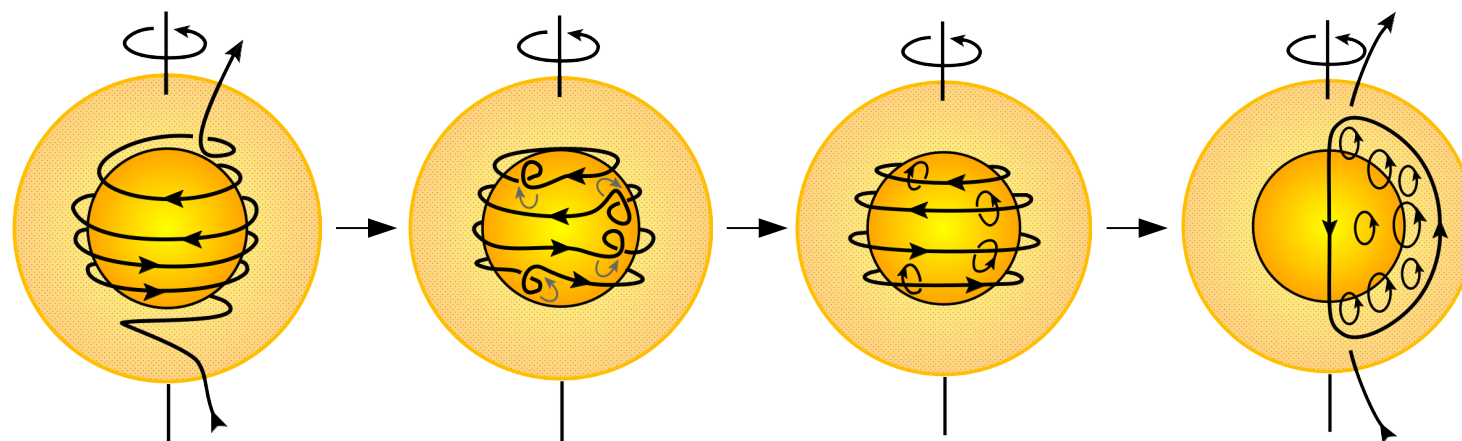


Parker 1955

Dynamo

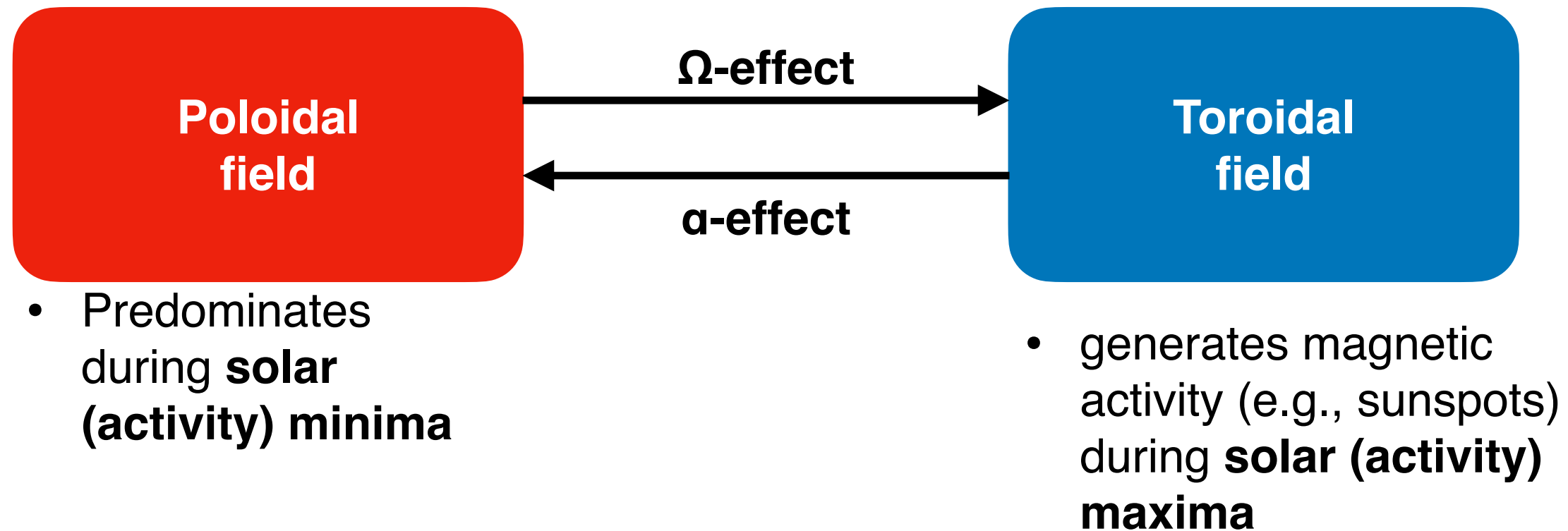
Large-scale : α -effect (Alpha effect)

- High gas pressure (deep) in the convection zone: $P_g \gg P_m \Rightarrow \beta \gg 1$
 - ➡ **High plasma-beta** conditions, magnetic field frozen in
 - ➡ Toroidal magnetic field gets partially dragged along by the moving plasma
- Solar rotation induces **Coriolis force** ($\omega \times v$) on convective motions
- Note: Signs of both the Coriolis force and toroidal magnetic field are reversed in the northern versus the southern hemisphere!
 - ➡ Small-scale magnetic field loops of the same polarity in both hemispheres
- Small-scale loops gradually merge due to magnetic diffusivity
 - ➡ **Generates a large scale poloidal magnetic field** (Parker 1955).



Dynamo

α and Ω

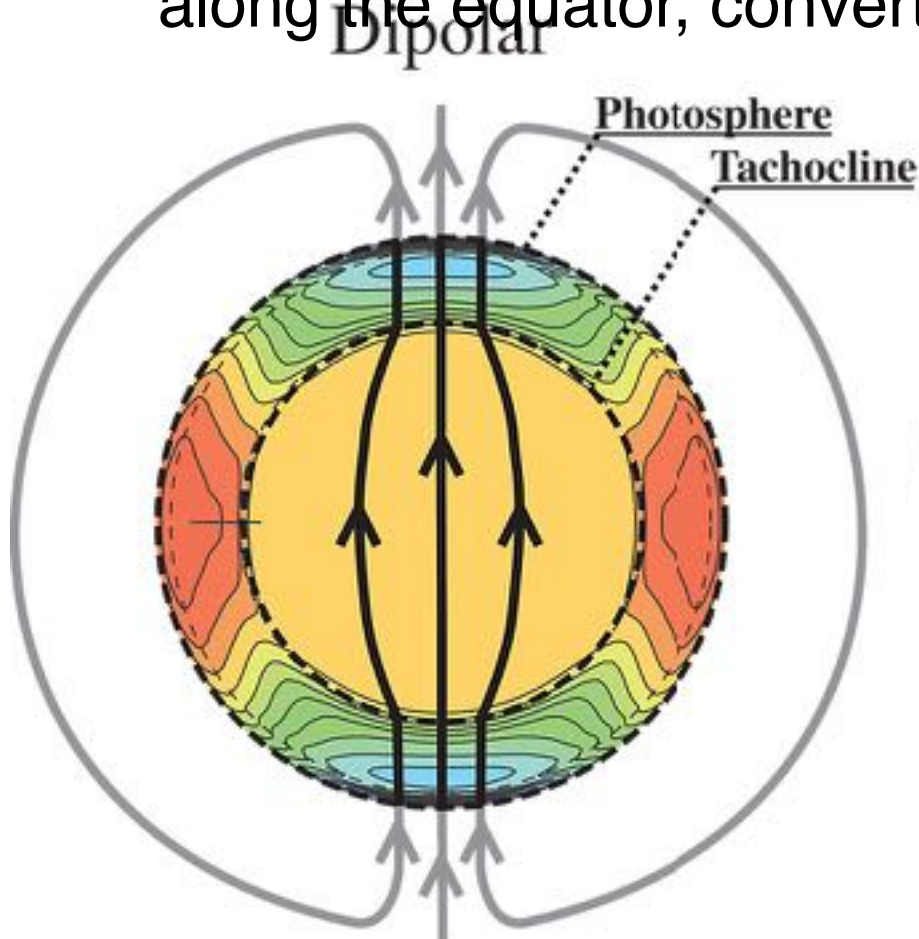


- **Solar cycle:** Change between these extreme configurations, forming a solar activity cycle
 - One cycle period ~ 11 year
 - Global polarity of the Sun's magnetic field (N-S) swaps during that period
 - Complete cycle back to the same polarity = $2 \times 11 \text{ yr} = 22 \text{ yr}$

Dynamo

Solar cycle — change of magnetic field configuration

- Below tachocline: Rotation as solid body
- Above tachocline: differential rotation — faster rotation near equator, slower at poles
- Magnetic dipole field (poloidal) at solar minimum
- Over time: differential rotation shears magnetic field at the tachocline, drags it along the equator, converts into toriodal configuration.

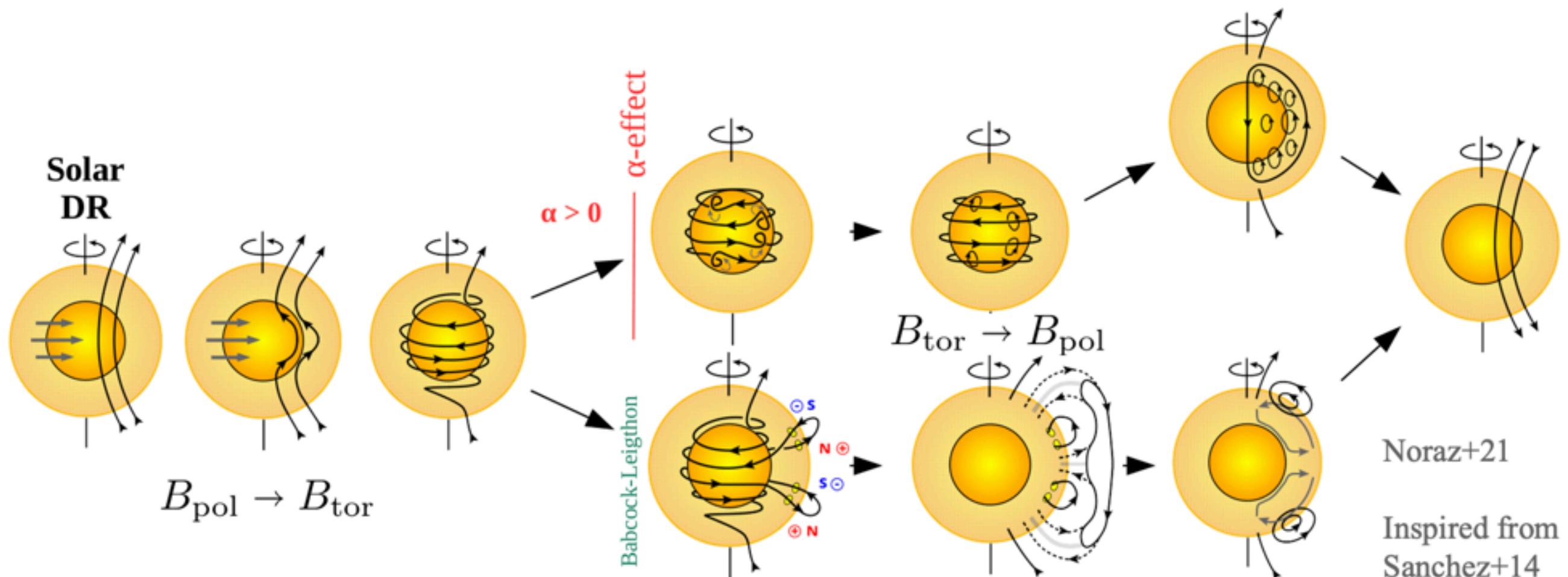


Solar Minimum

Dynamo

Solar cycle — change of magnetic field configuration

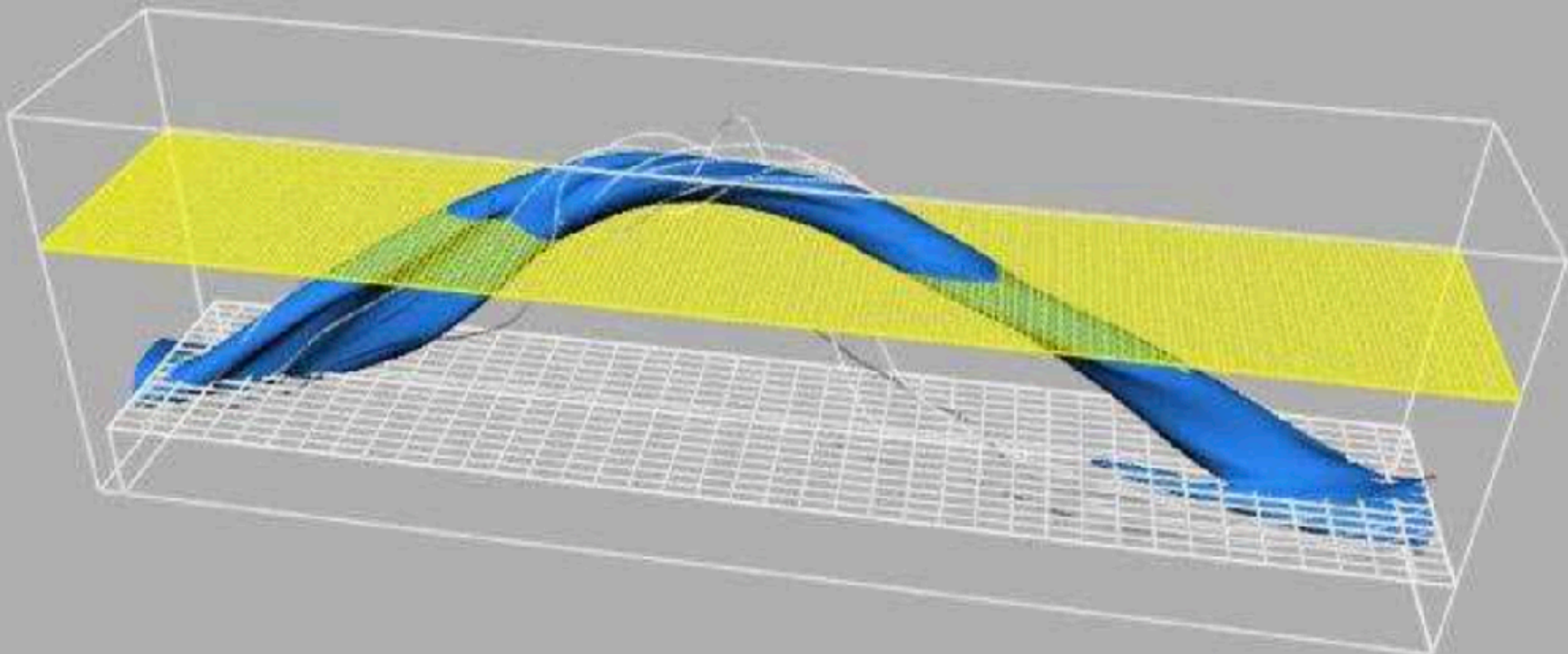
- Below tachocline: Rotation as solid body
- Above tachocline: differential rotation — faster rotation near equator, slower at poles
- Magnetic dipole field (poloidal) at solar minimum
- Over time: differential rotation shears magnetic field at the tachocline, drags it along the equator, converts into toroidal configuration
- Toroidal generation either with α -effect or Babcock-Leighton



Dynamo

Emergence of a magnetic flux tube

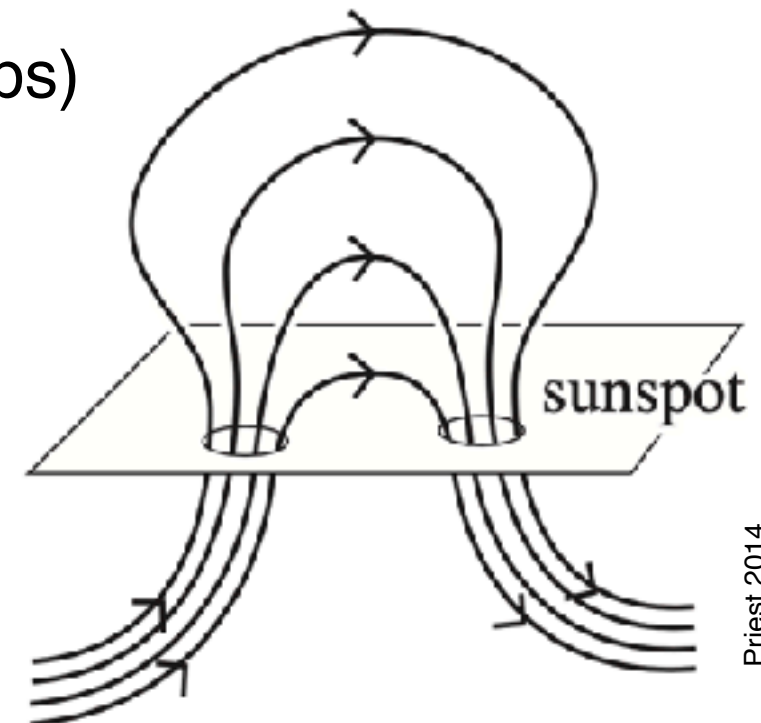
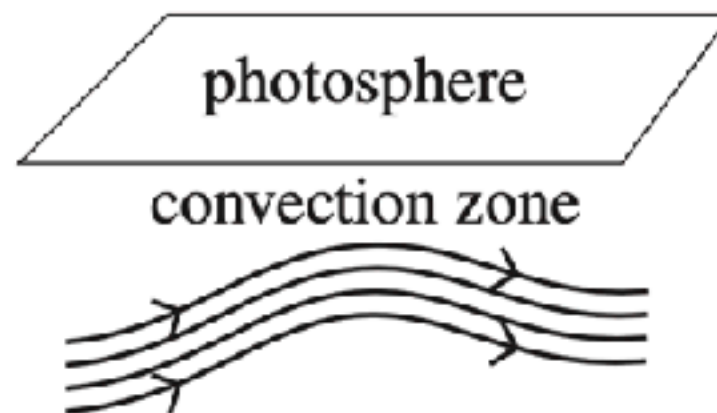
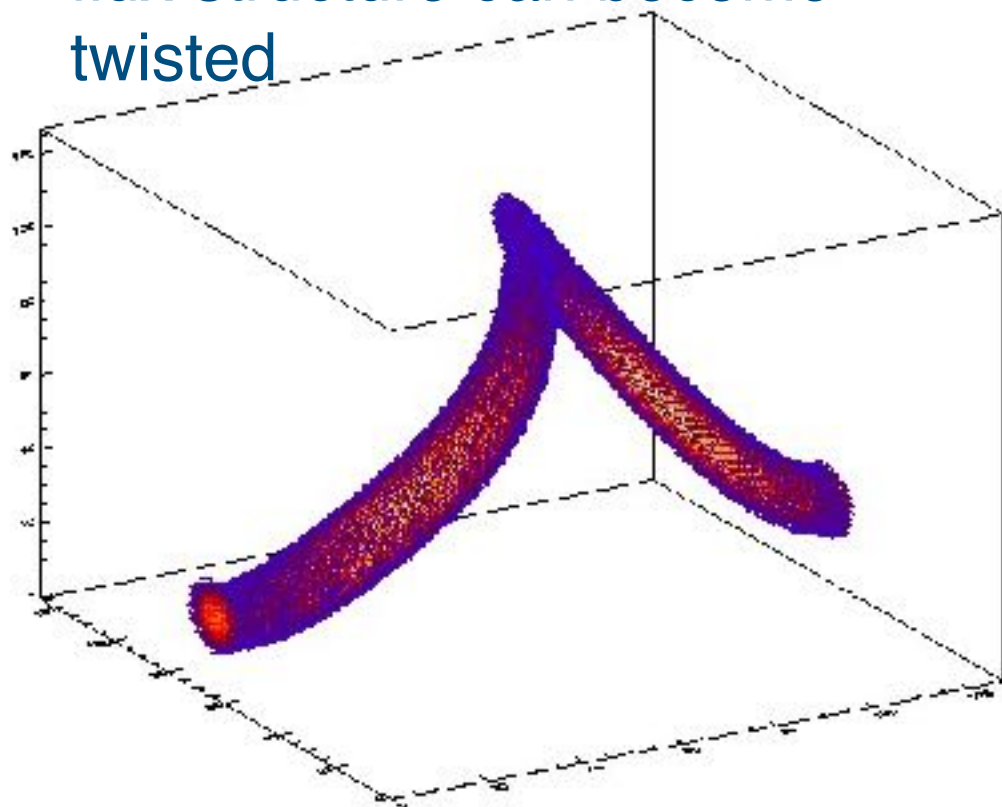
- Magnetic field generated mainly in the tachocline near bottom of convection zone
- **Magnetic pressure** inside flux rope — lower density inside than in the surrounding plasma
 - ➡ Magnetic flux rope becomes **buoyant, rises upwards** (Parker instability)



Dynamo

Emergence of a magnetic flux tube

- Magnetic flux rope rises to surface due to its buoyancy (Parker instability)
- Flux rope reaches surface eventually
- The two points where the loop breaks through the surface are sunspots of opposite polarity
- Flux rope produces a bipolar active region at the surface
 - In reality often more complicated topology (sunspot groups)
- While rising, the magnetic flux structure can become twisted



Dynamo

Magnetic fields at the surface — Active Regions

2012 March - Sunspot evolution

HMI CONTINUUM NOAA 1429



NASA's Solar Dynamics Observatory

by Paolo Porcellana

Dynamo

Magnetic fields at the surface — Active Regions

Backyard Video Astronomy by Paolo Porcellana

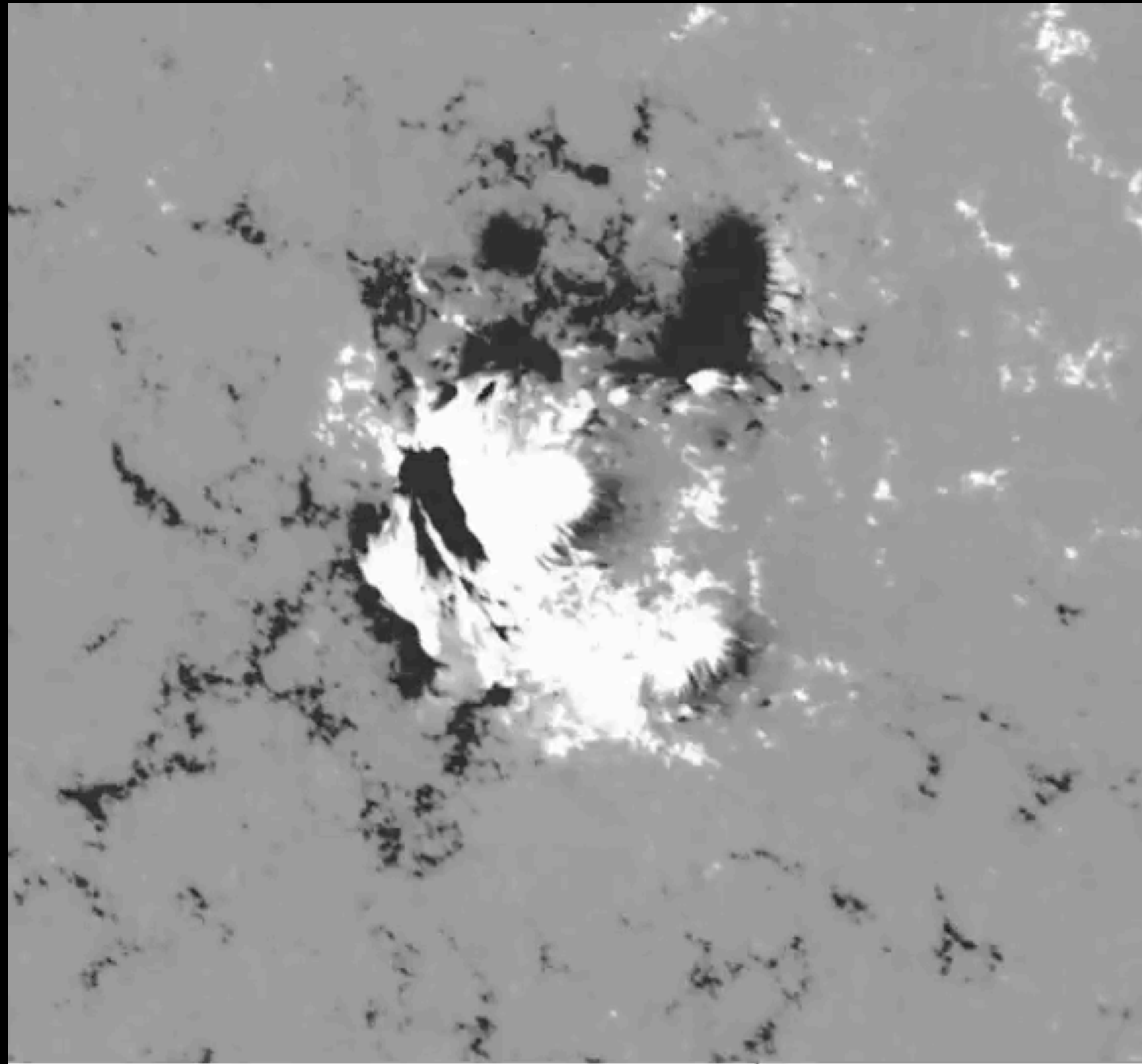
Earth

NOAA 1785 Sunspot Evolution

Dynamo

Magnetic fields at the surface — Active Regions

- Magnetogram (HMI)



Dynamo

Overview

- Requirements for an efficient dynamo
 - **Properties of the flows** in the solar interior
 - convection
 - differential rotation
 - meridional flow
 - ★ **Tachocline:** Strong radial change in rotation speed, exhibits a strong radial shear
- Plasma motions must convert meridional (poloidal) magnetic field into an azimuthal (toroidal) magnetic field, and vice versa (Large-scale).
- **Induction** has to overcome magnetic diffusion (large magnetic Reynolds number)

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

Magnetic diffusivity Velocity

Dynamo

Overview

- Current understanding: Magnetic field generated by a dynamo located near the bottom of the convection zone (overshoot layer, tachocline)
- Produces toroidal flux bundles
- Once magnetic field sufficiently strong, flux bundles become buoyant (Parker instability)
 - ➡ Rise towards surface
 - ➡ Break through surface, visible as sunspots etc.

