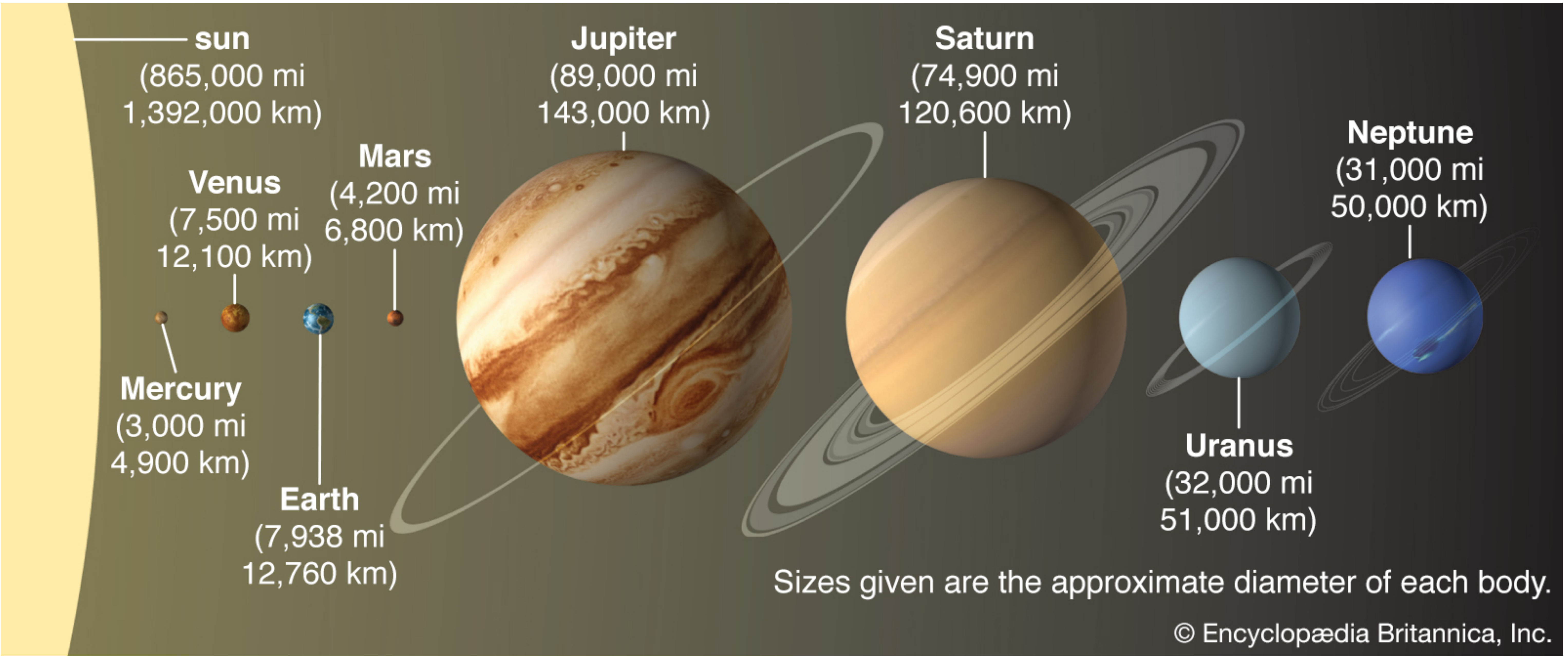
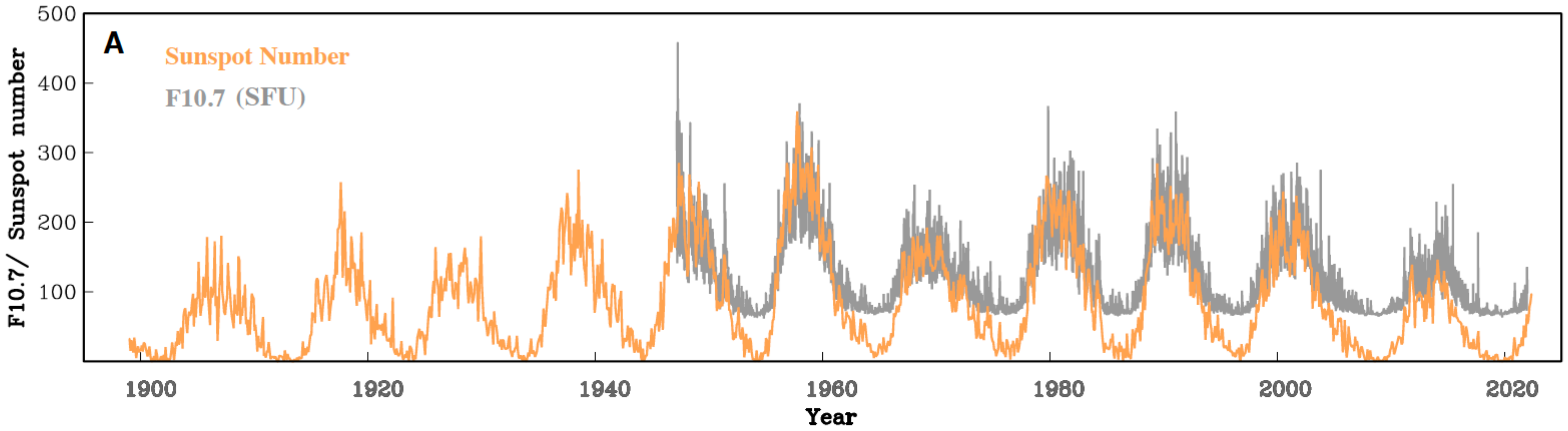
SIOG 231
GEOMAGNETISM AND ELECTROMAGNETISM

Lecture 19
The Solar Dynamo
3/12/2024

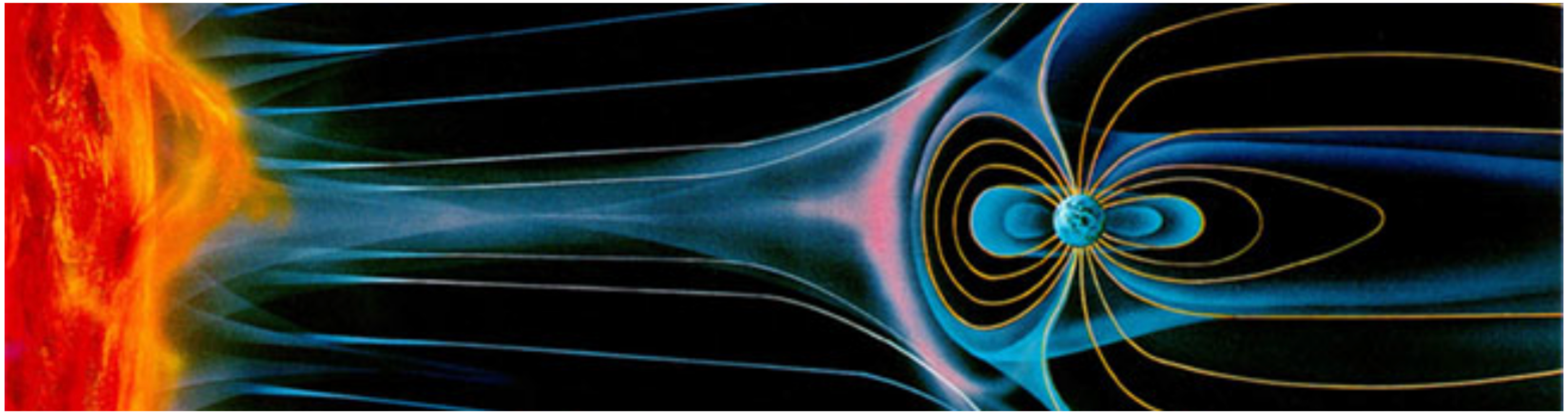
Not to mention other solar system bodies

Which of them have magnetic fields? dynamos?

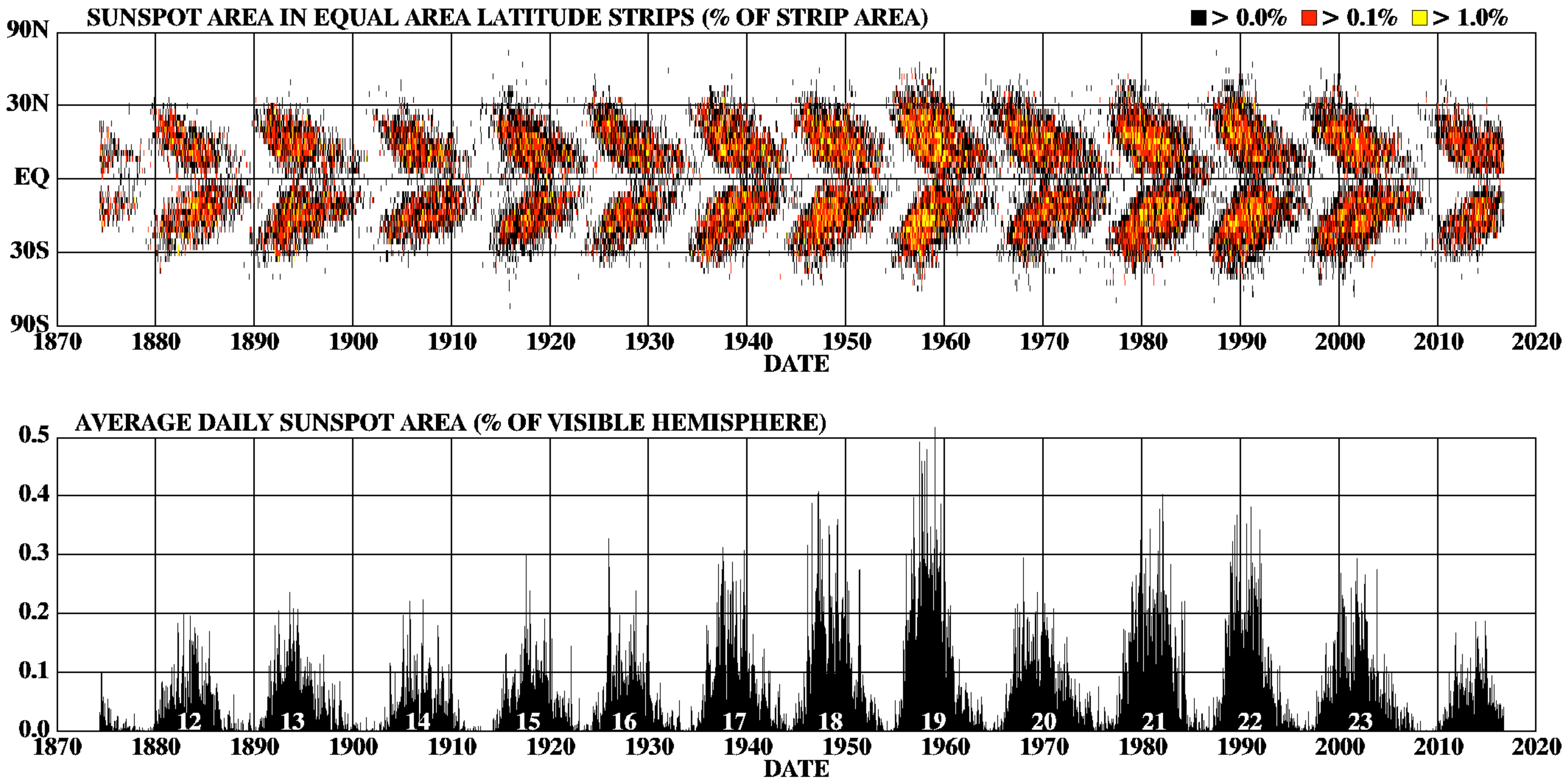




The solar magnetic field reverses approximately every 11 years, modulating sunspot number, radio flux, magnetic storms, and the strength of the ring current.



DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS



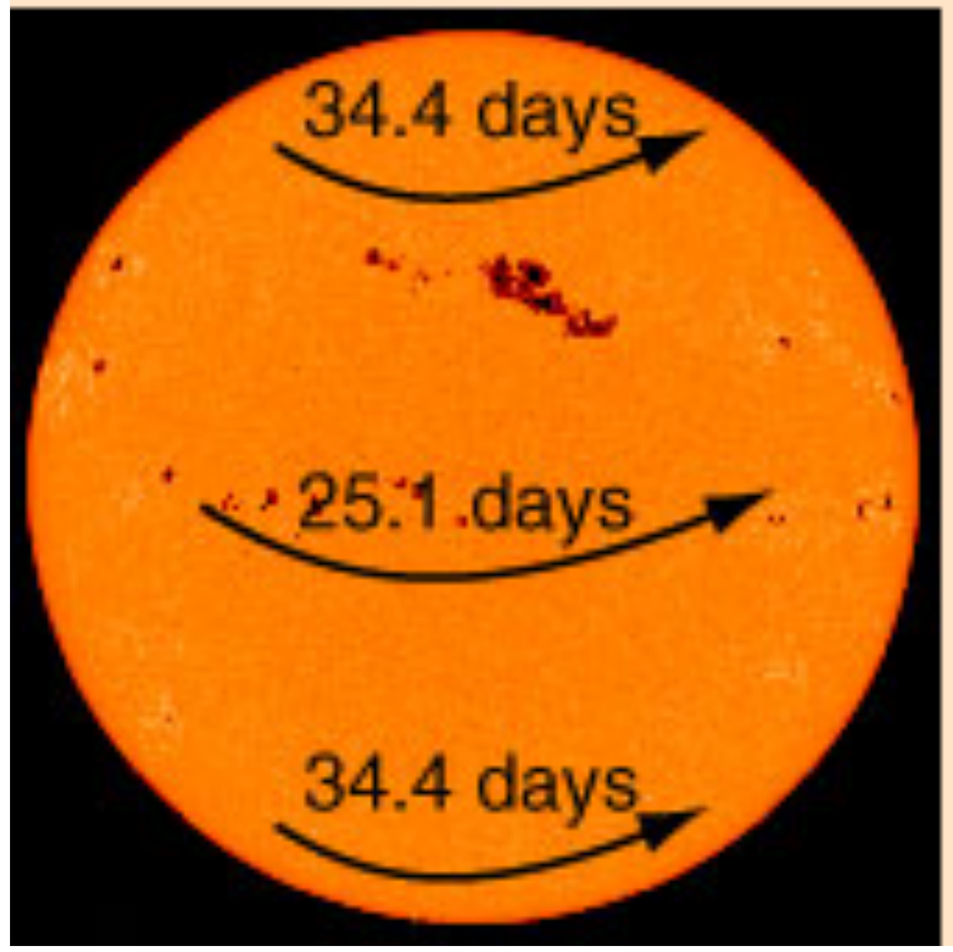
http://solarscience.msfc.nasa.gov/ HATHAWAY NASA/ARC 2016/10

The Sun is a self-sustaining dynamo that converts convective motion and **differential rotation** within the Sun to electric-magnetic energy.

Solar radius 695700 km ~109 times the Earth's

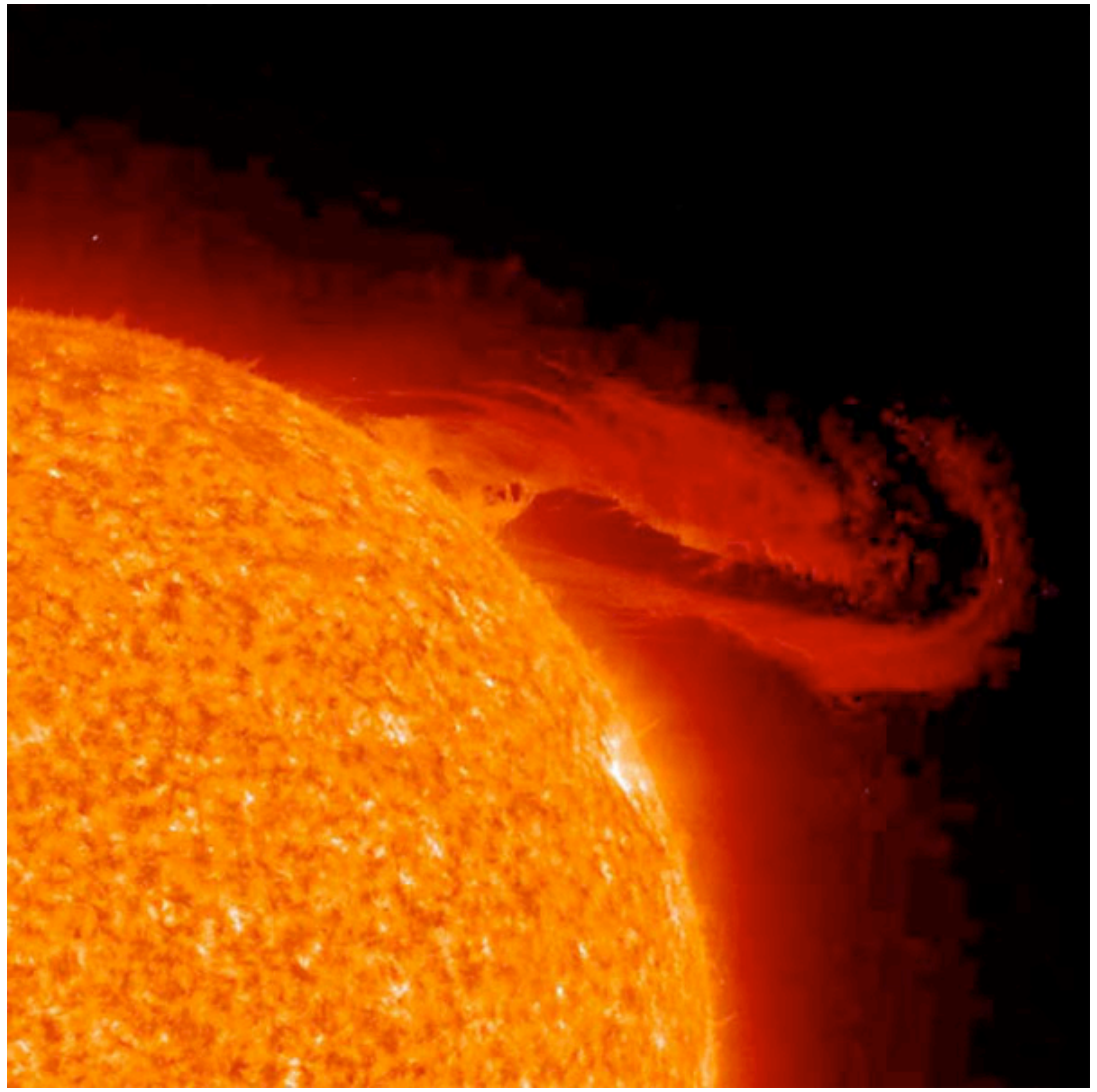
Its surface gravity is 274 m/s^2 or 28.0 times that of the Earth. Its mean density is 1410 kg/m^3 or 0.255 times the mean density of Earth. composition 71% hydrogen, 27.1 % helium. <2% others

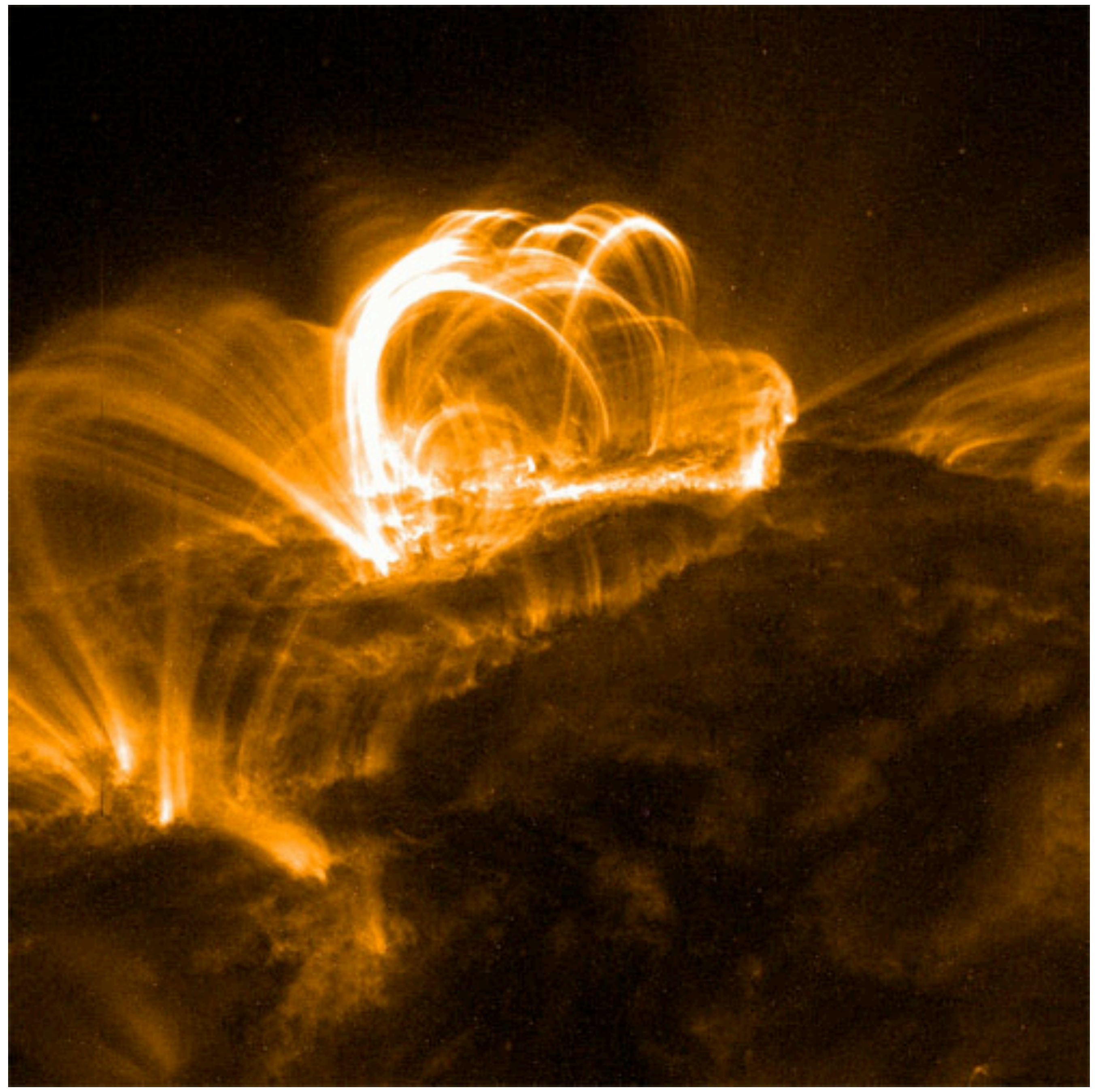
Escape velocity = 618 km/s
The center temperature is modeled to be 15.5 million K. The Sun is fueled by the proton cycle of nuclear fusion.



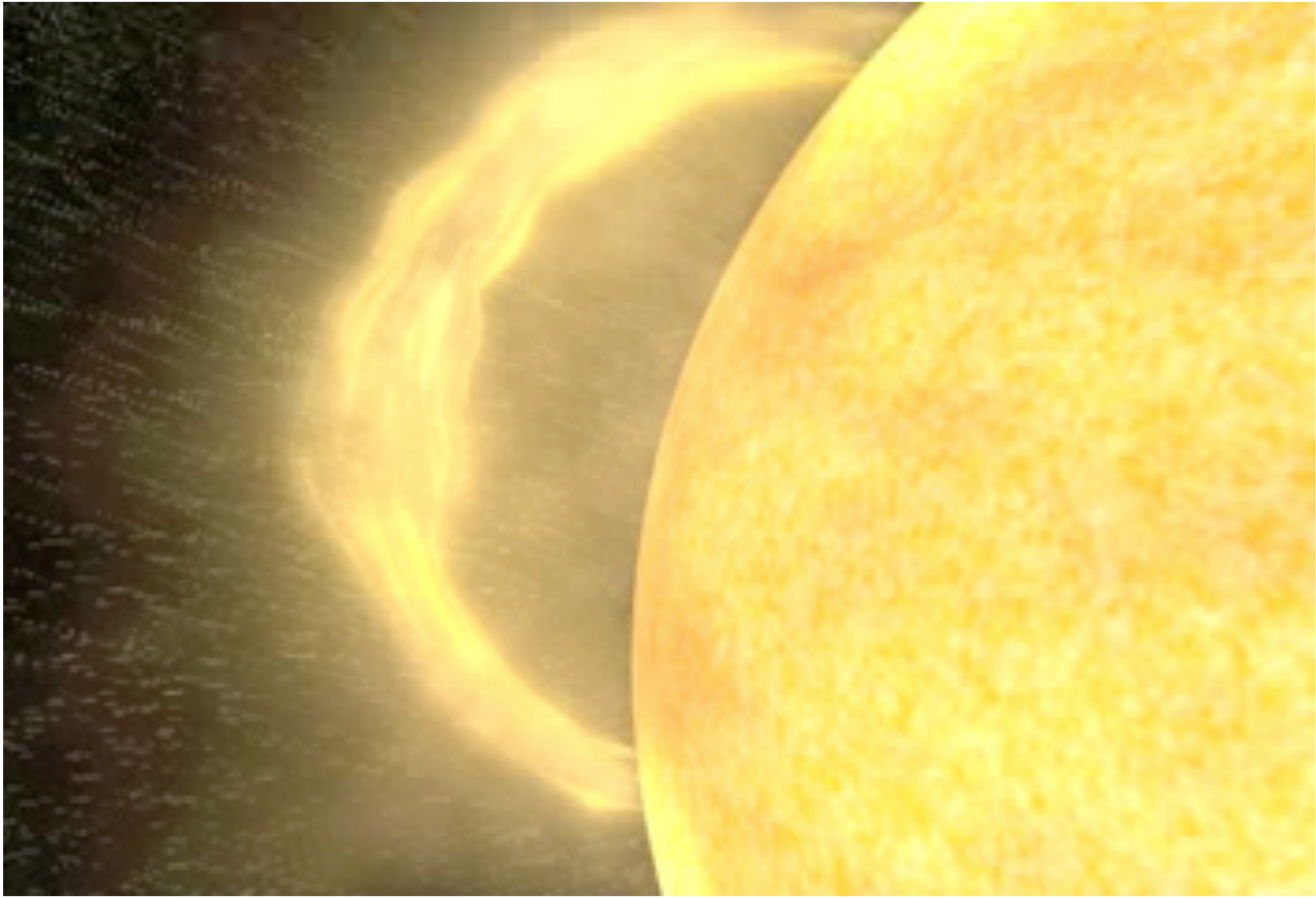
Being a gaseous body, the Sun does not have a single period of rotation like a rigid body. The sunspots provide a convenient reference for the measurement of the rotation period at different latitudes. The period of rotation averages 25.4 days, varying from 34.4 days at the poles to 25.1 days at the equator (Chaisson). Its axis is tilted 7.25° relative to the ecliptic.

Solar prominences - outflows of high energy particles



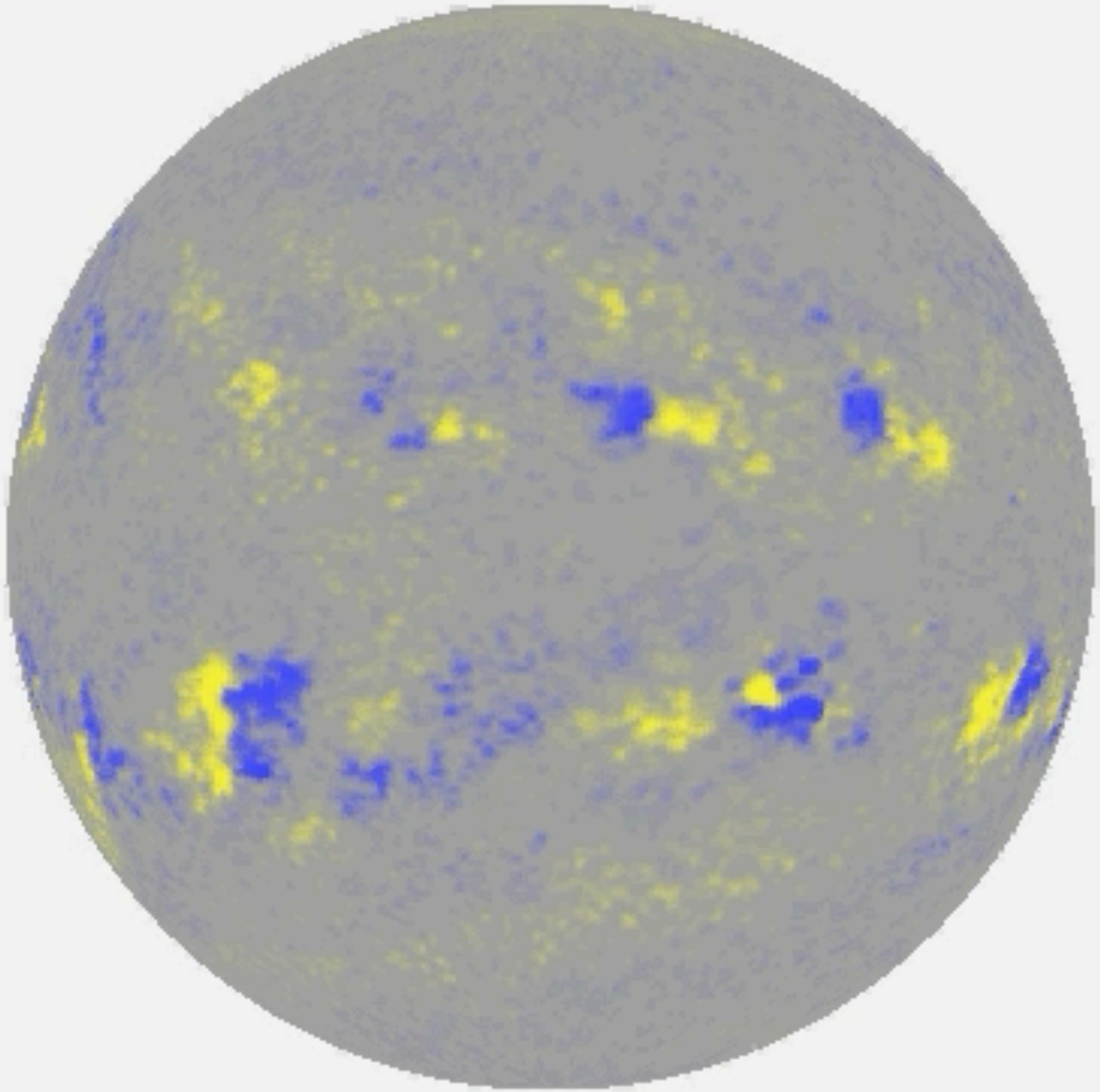


Solar flares release enormous amounts of energy and eject material out into space and cause magnetic storms.
Most famous example is the Carrington event in 1859 which released ~10^{25} Joules.



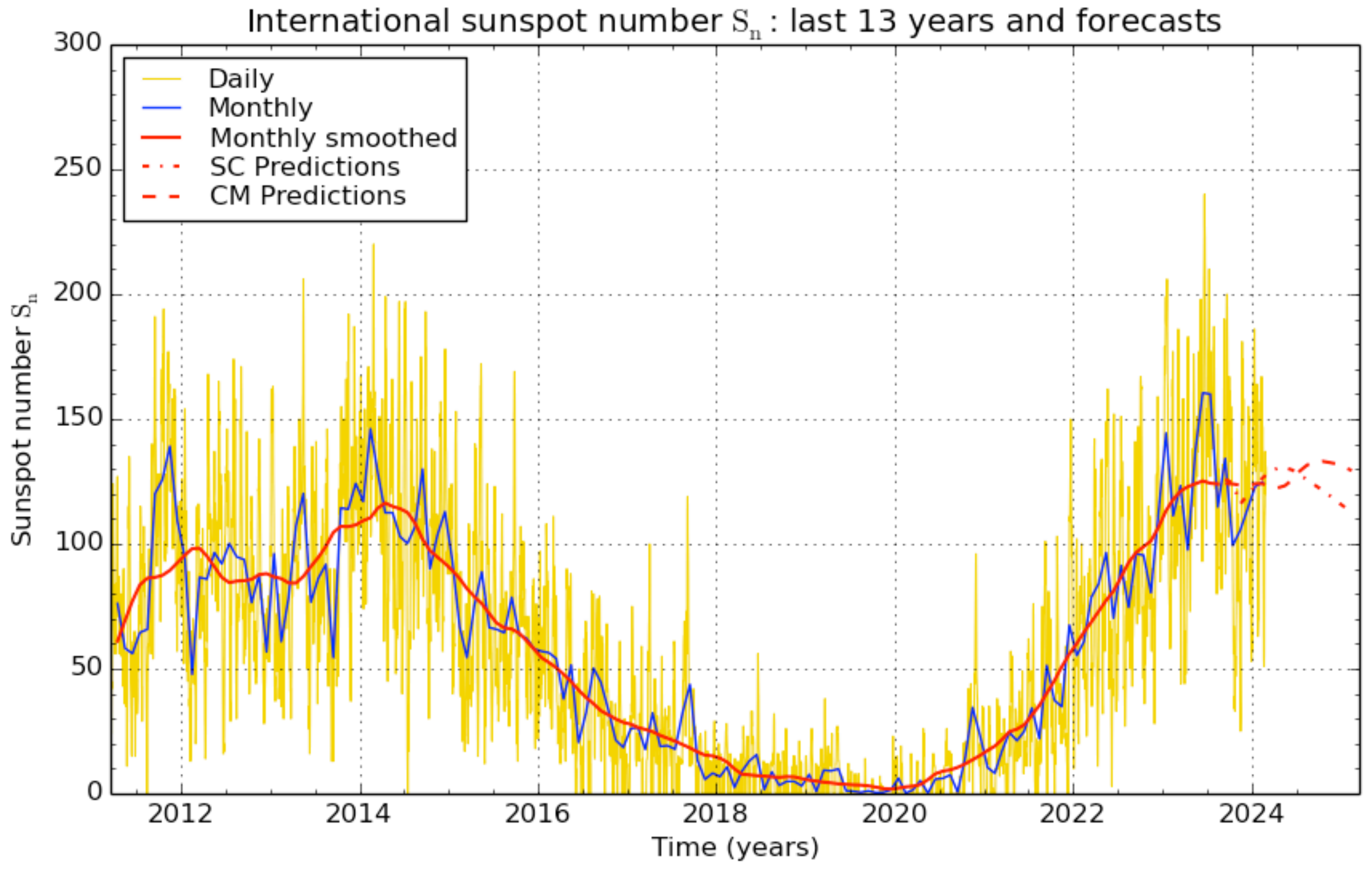
Solar Magnetic Field

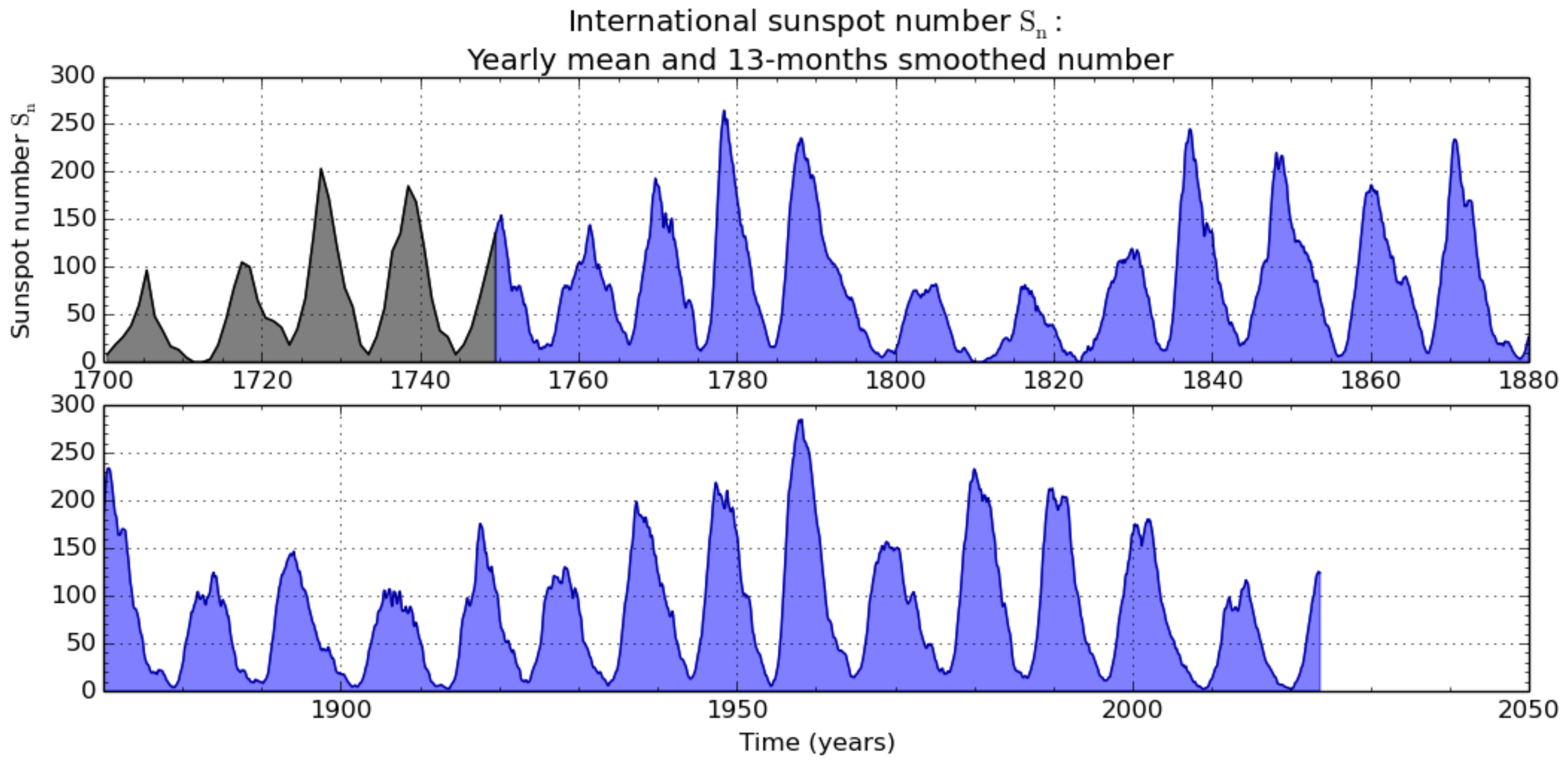
- 11 (actually 9-12) year solar sunspot cycle is a visible manifestation of solar magnetic activity
- Sunspots - cool (~3700K vs 5700K surroundings) dark patches on the solar surface lasting several days and associated with strong magnetic fields (~0.1–0.5 T)
- Usually paired positive and negative flux, appear at mid-latitudes early in cycle and migrate towards the equator
- Viewed by telescope since early 17th Century
- Radioisotopes (e.g., ^{10}Be and ^{14}C) extend the record back thousands of years



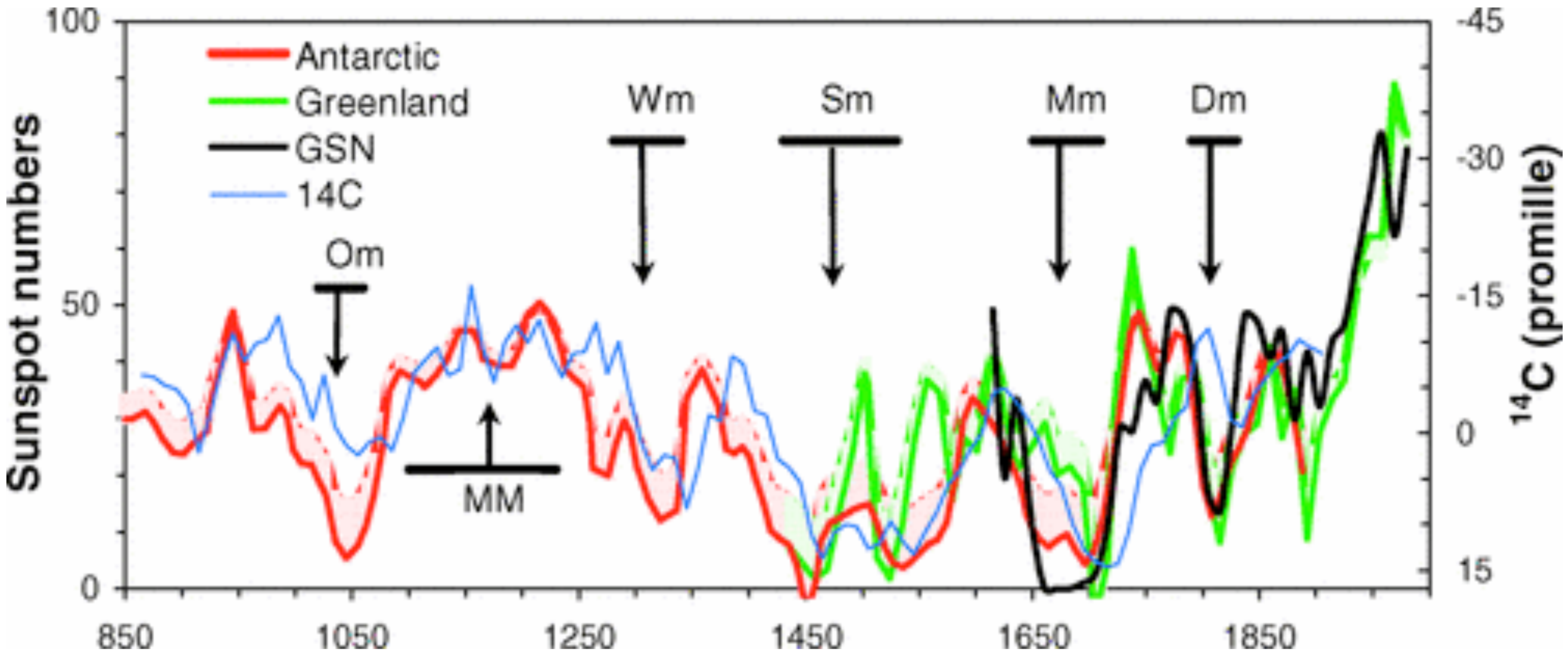
Note antisymmetry about the equator

Direct observations





Proxy observations

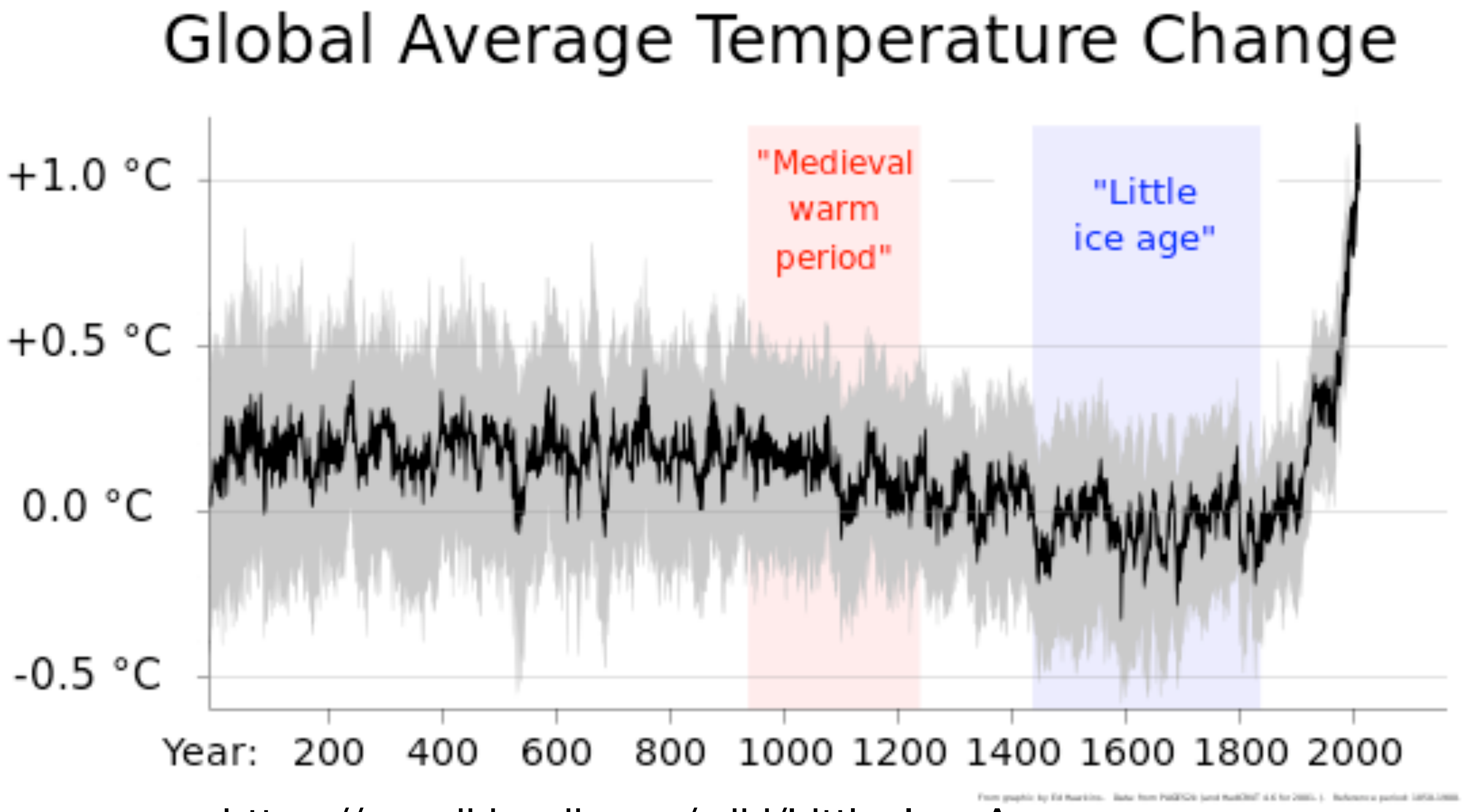


Time series of the sunspot number as reconstructed from ^{10}Be concentrations in ice cores from Antarctica (red) and Greenland (green). The corresponding profiles are bounded by the actual reconstruction results (upper envelope to shaded areas) and by the reconstructed values corrected at low values of the SN (solid curves) by taking into account the residual level of solar activity in the limit of vanishing SN (see Fig. 1). The thick black curve shows the observed group sunspot number since 1610 and the thin blue curve gives the (scaled) ^{14}C concentration in tree rings, corrected for the variation of the geomagnetic field [20]. The horizontal bars with attached arrows indicate the times of great minima and maxima [21]: Dalton minimum (Dm), Maunder minimum (Mm), Spörer minimum (Sm), Wolf minimum (Wm), Oort minimum (Om), and medieval maximum (MM). The temporal lag of ^{14}C with respect to the sunspot number is due to the long attenuation time for ^{14}C [19].

Usoskin et al., 2003, https://doi.org/10.1103/PhysRevLett.91.211101

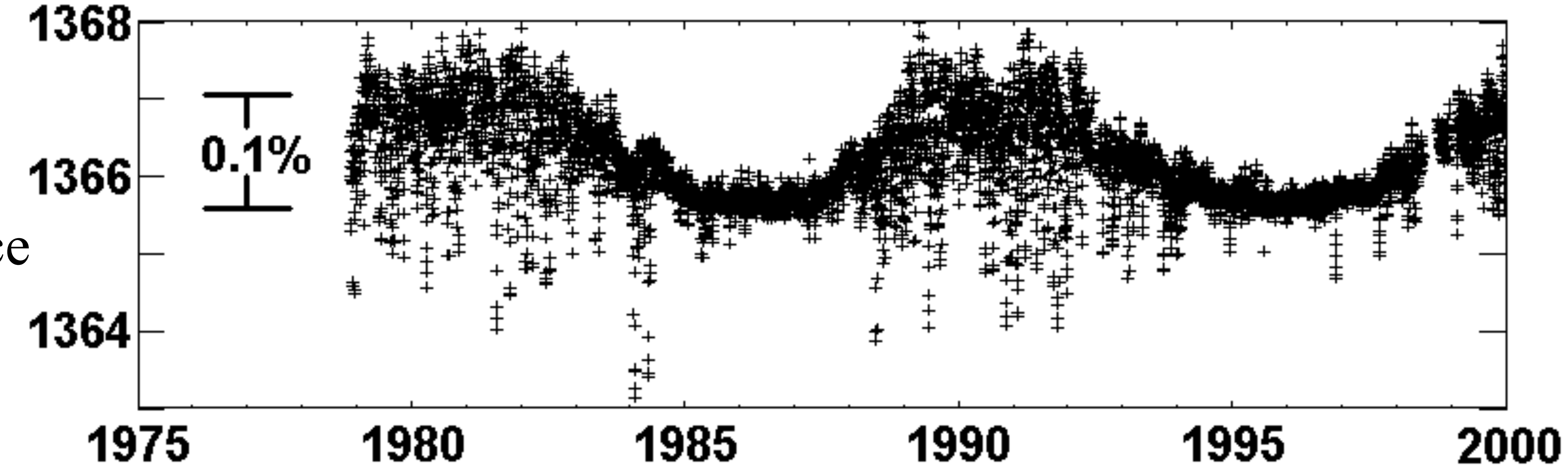
- Grand minima such as 17th Century Maunder Minimum (1645-1715) are times of reduced activity - coincidence with Little Ice Age has led to research on links between solar activity and climate change - but that is a complex question.

The Frozen Thames, 1677
Abraham Hondius - Original painting in the collection of the Museum of London



https://en.wikipedia.org/wiki/Little_Ice_Age

Total Solar Irradiance



https://solarscience.msfc.nasa.gov/whysolar.shtml

A lot of what we know about the Sun comes from Helioseismology

- Differential rotation is measured in much more detail by helioseismology - measuring Sun’s structure and dynamics through its normal modes of oscillation

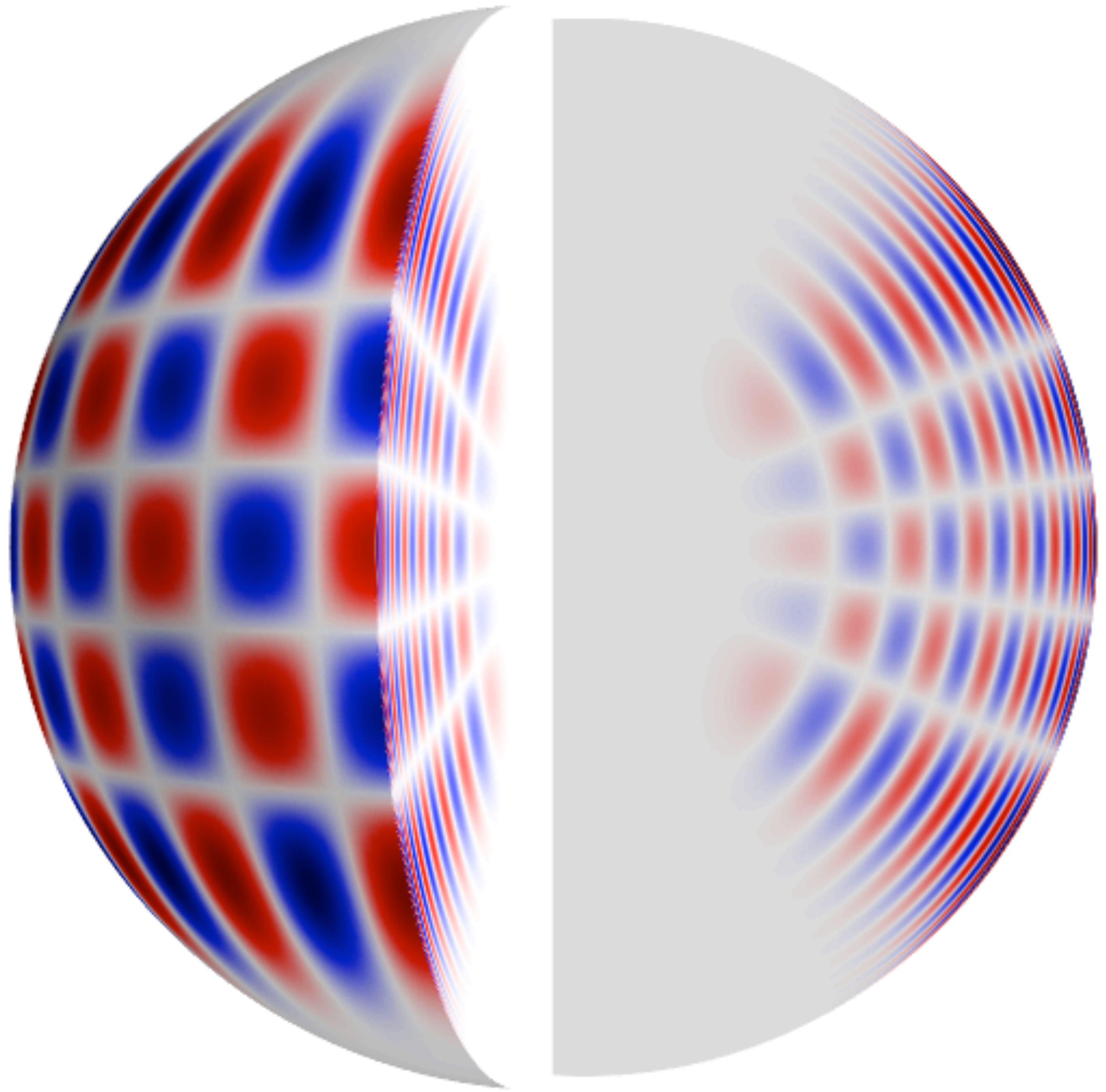
- both local (near surface) and global seismology (resonant modes) are important

- global rotation profile reveals rigidly rotating core and differentially rotating envelope

- Boundary layer between them is the **tachocline,** which has meridional flow connected with the convection zone

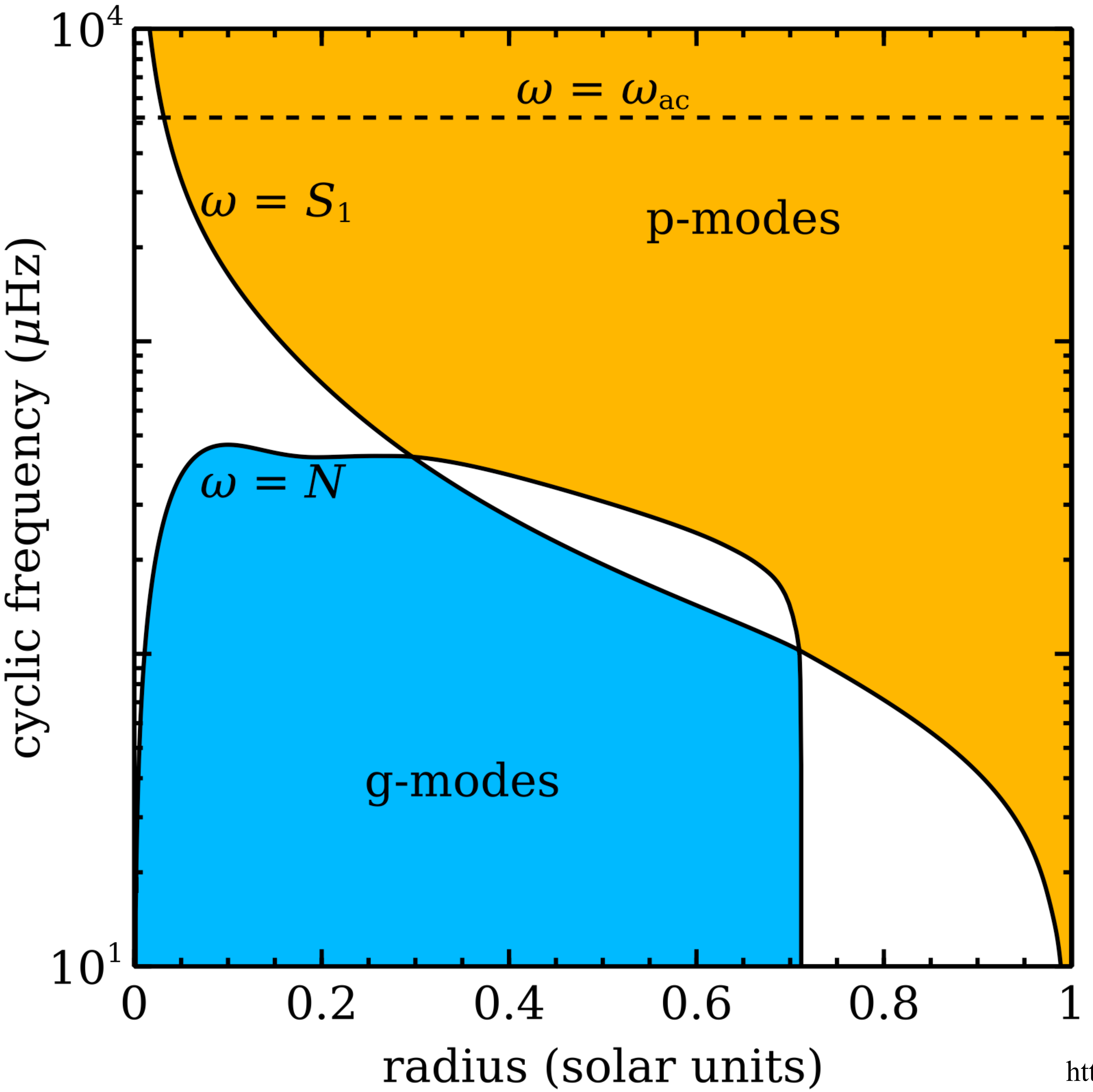
Helioseismology II

- No solid surface - so no shear waves
- Pressure Modes (p modes) - standing sound waves, frequencies 1-5 mHz, sample outer region of Sun
- Gravity Modes (g modes) - confined to convectively stable regions
- Surface gravity modes (f modes)



a solar pressure mode (p-mode) with radial order n=14, angular degree l=20 and azimuthal order m=16. The surface shows the corresponding spherical harmonic. The interior shows the radial displacement computed using a standard solar model

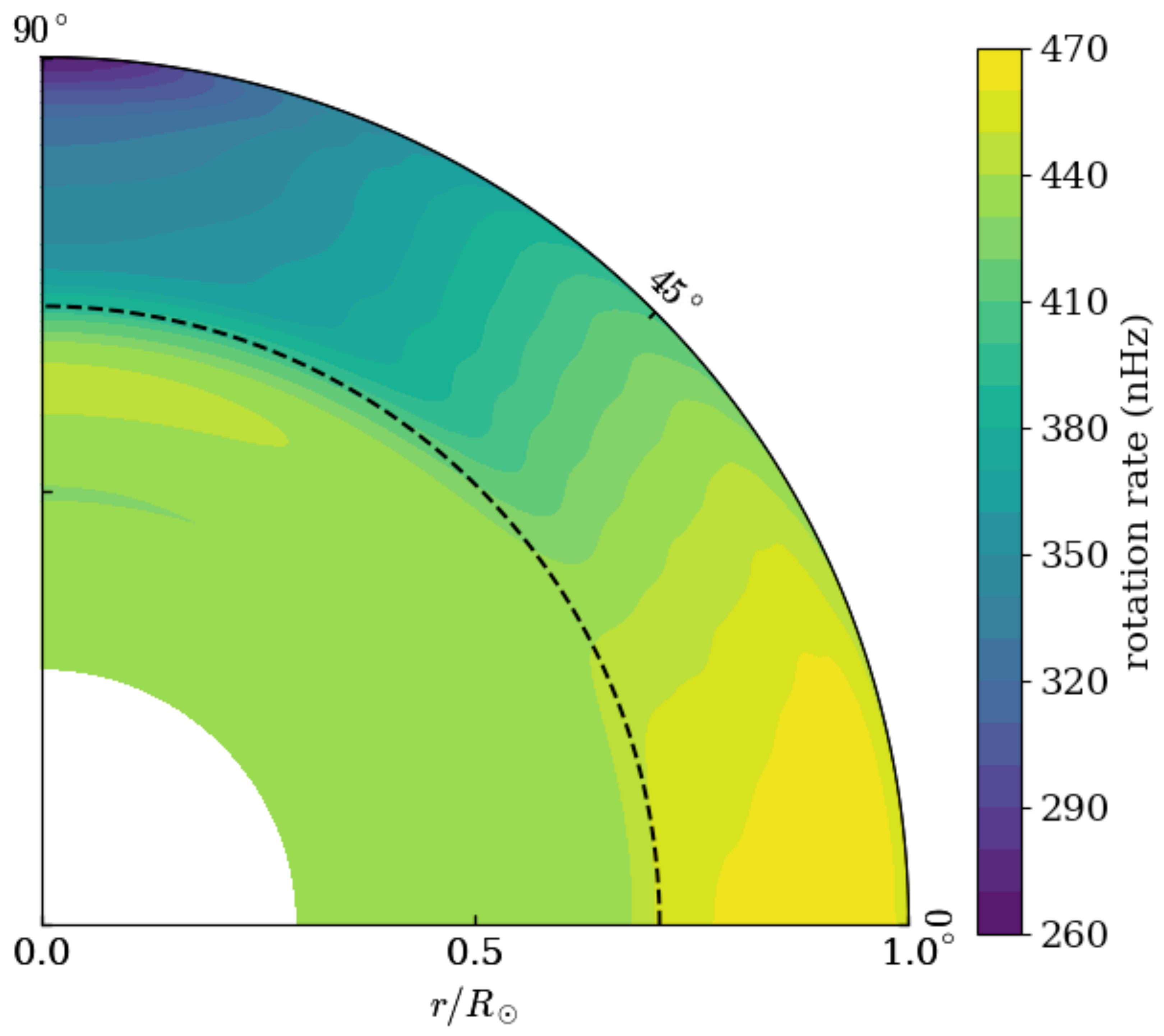
https://en.wikipedia.org/wiki/Helioseismology



A propagation diagram for a standard solar model showing where oscillations have a g-mode character (blue) or where dipole modes have a p-mode character (orange). The dashed line shows the acoustic cut-off frequency, computed from more precise modelling, and above which modes are not trapped in the star, and roughly-speaking do not resonate.

https://en.wikipedia.org/wiki/Helioseismology

Helioseismology III

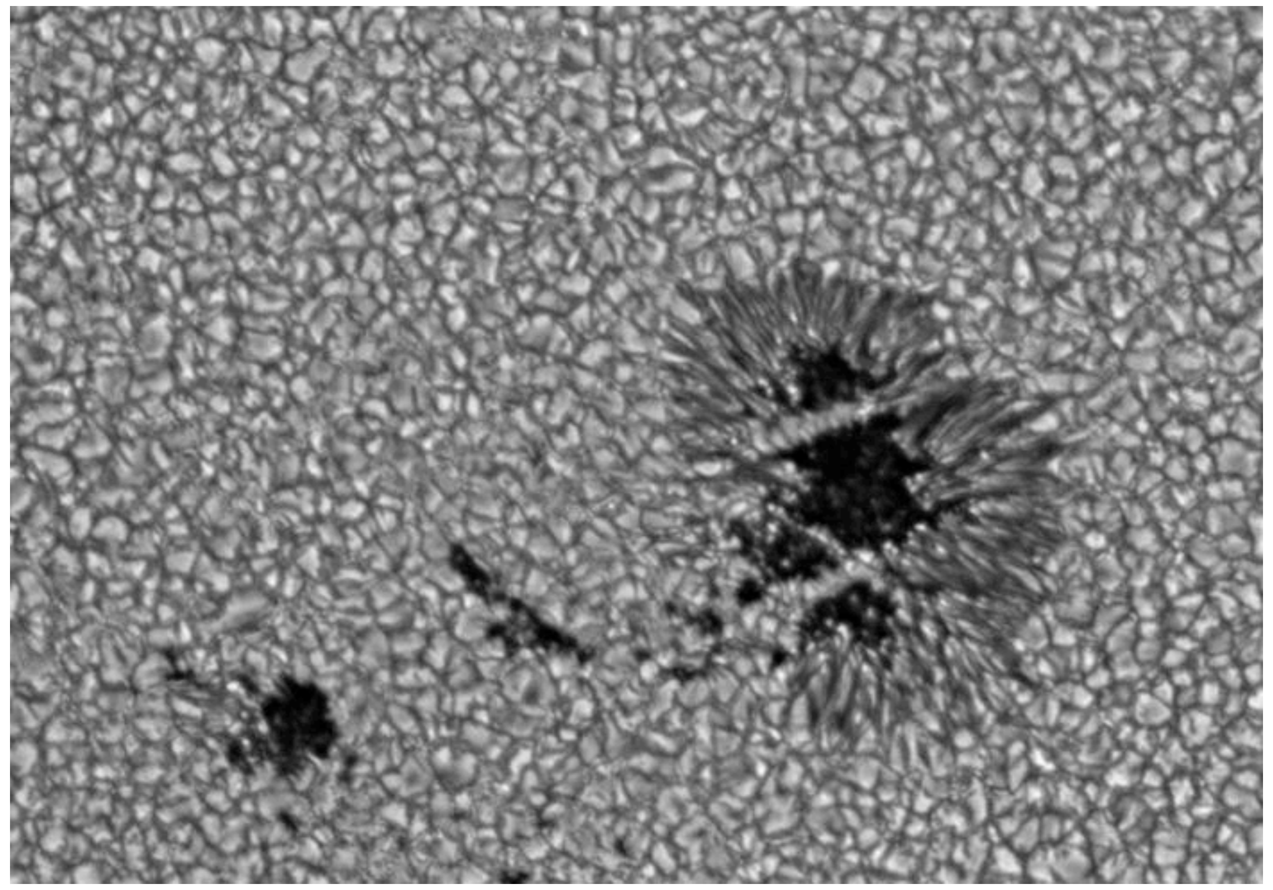


https://en.wikipedia.org/wiki/Helioseismology

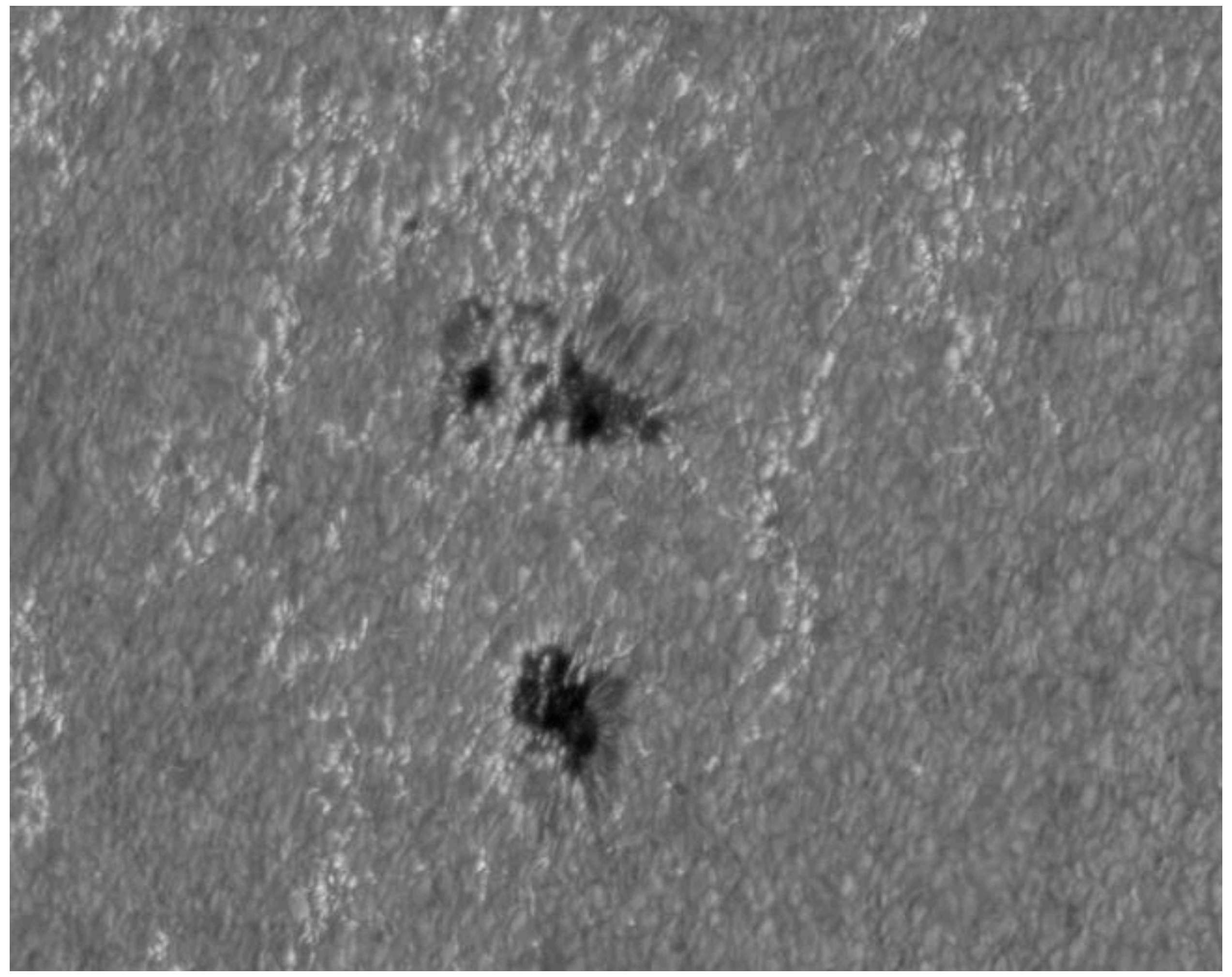
Sun has a rotation profile with several features:

- a rigidly-rotating radiative (i.e. non-convective) zone, though the rotation rate of the inner core is not well known;
- a thin shear layer, known as the ***tachocline***, which separates the rigidly-rotating interior and the differentially-rotating convective envelope;
- a convective envelope in which the rotation rate varies both with depth and latitude; and
- a final shear layer just beneath the surface, in which the rotation rate slows down towards the surface.

Sunspots - dark areas

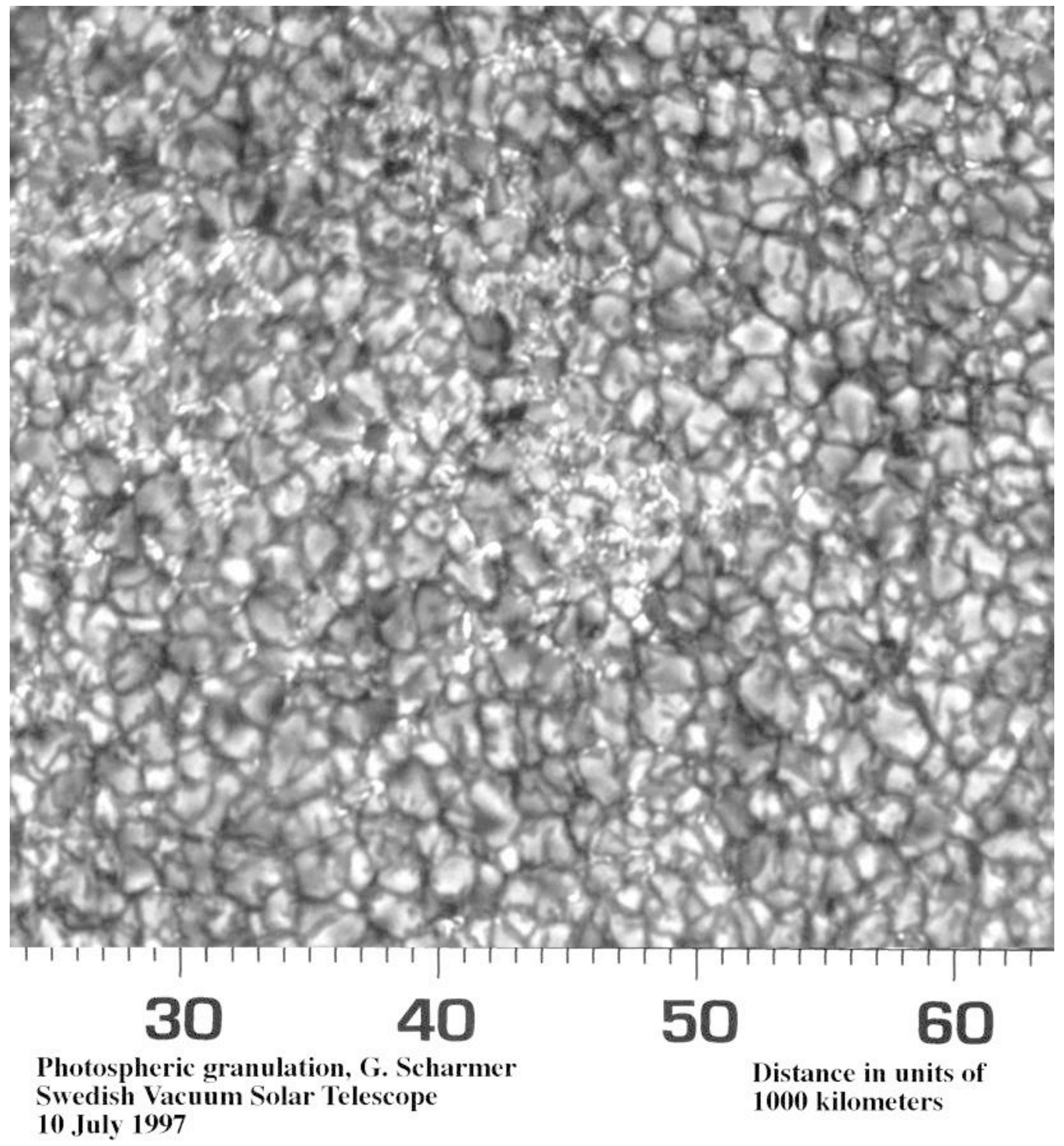


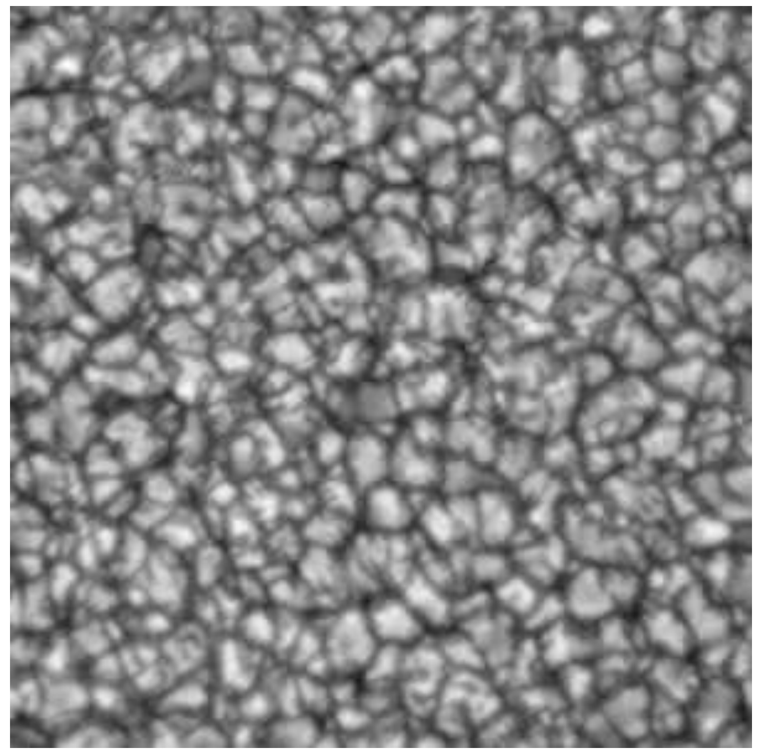
Faculae, bright areas, smaller magnetic bundles



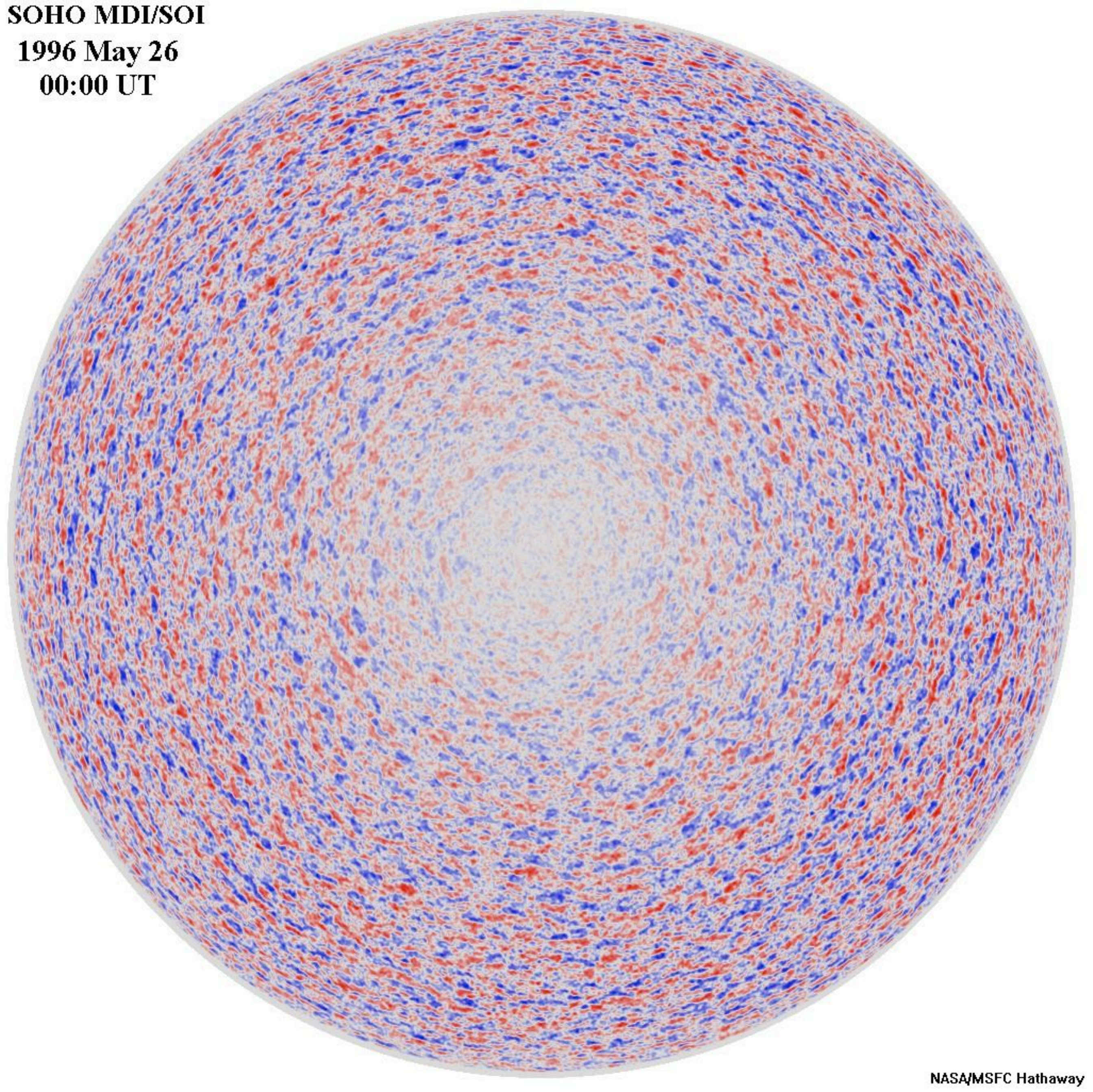
Scale invariance!

Granules, tops of convection cells, light upwelling, dark downwelling



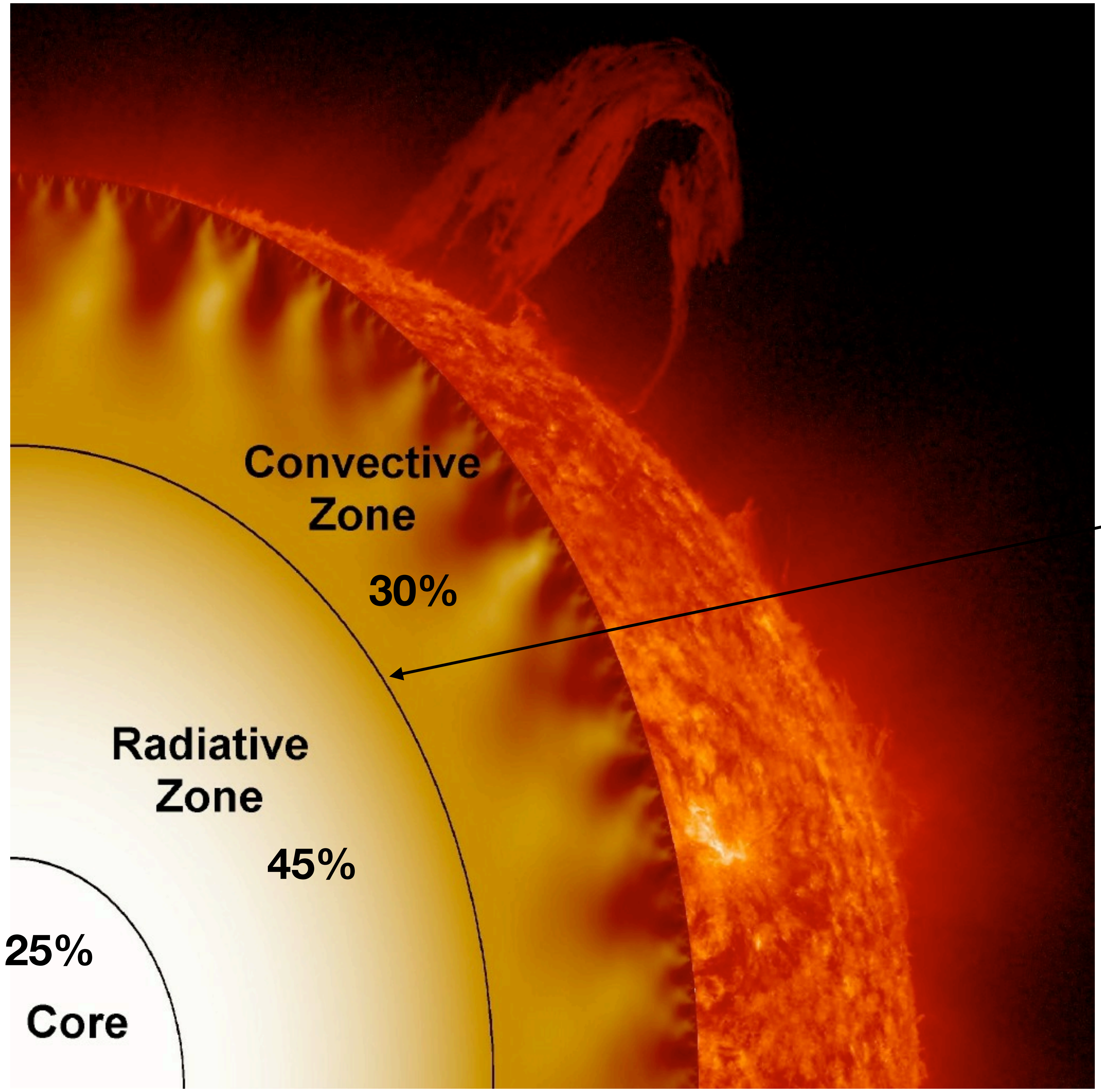


Super granules, tops of convection cells, blue moving towards, red away from us.



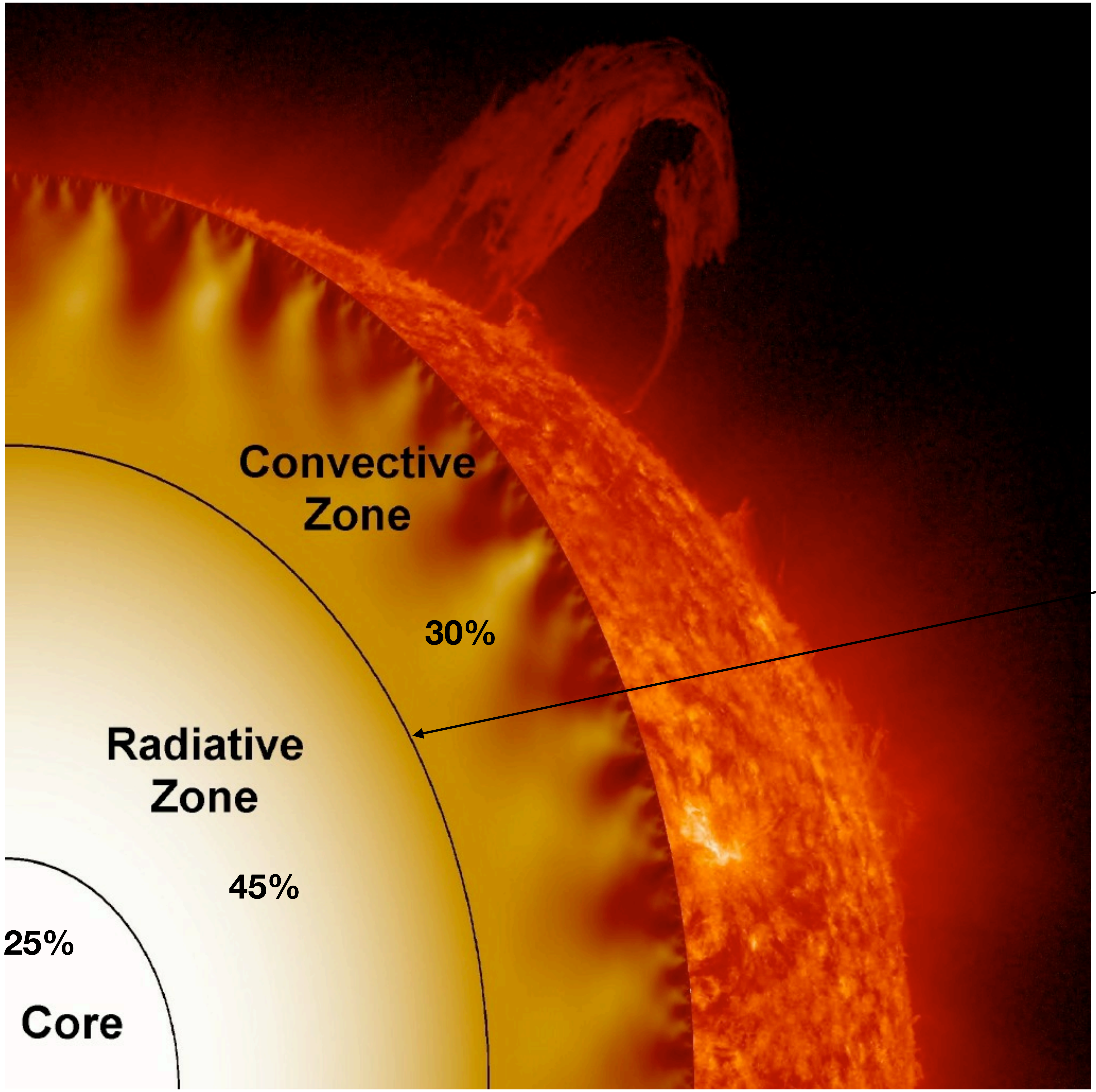
The Sun is a self-sustaining dynamo that converts convective motion and **differential rotation** within the Sun to electric-magnetic energy.

Currently, the geometry and width of the **tachocline** are hypothesized to play an important role in models of the solar dynamo by winding up the weaker poloidal field to create a much stronger toroidal field. However, recent radio observations of cooler stars and brown dwarfs, which do not have a radiative core and only have a convection zone, have demonstrated that they maintain large-scale, solar-strength magnetic fields and display solar-like activity despite the absence of tachoclines. This suggests that the convection zone alone may be responsible for the function of the solar dynamo??



Solar structure
Energy generated in core diffuses out ward by radiation and then convection

Tachocline - field is generated by dynamo action
changes in fluid flow velocities across the layer (shear flows) can stretch magnetic field lines of force and make them stronger.



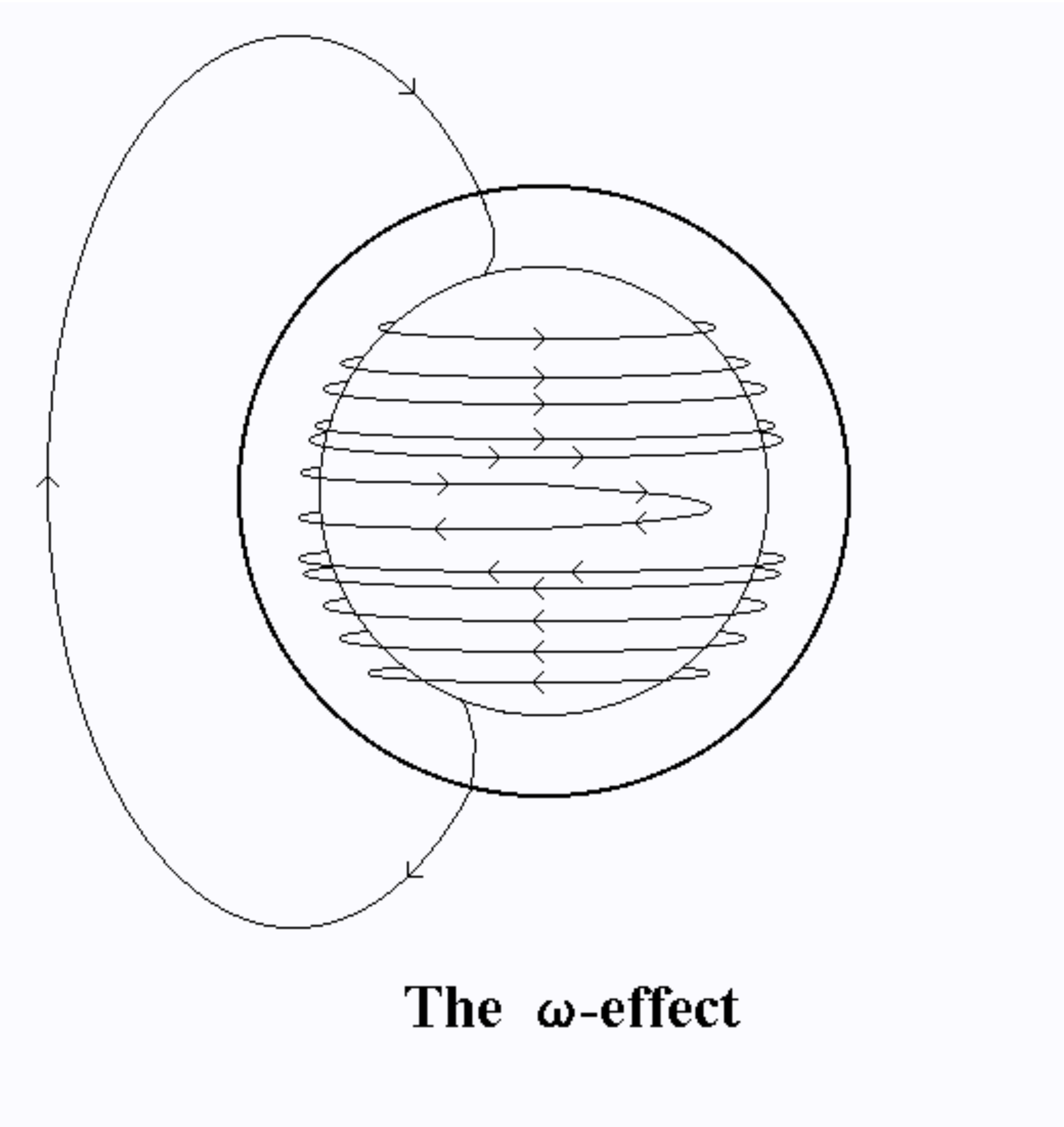
Solar structure
Energy generated in core diffuses outward by radiation and then convection

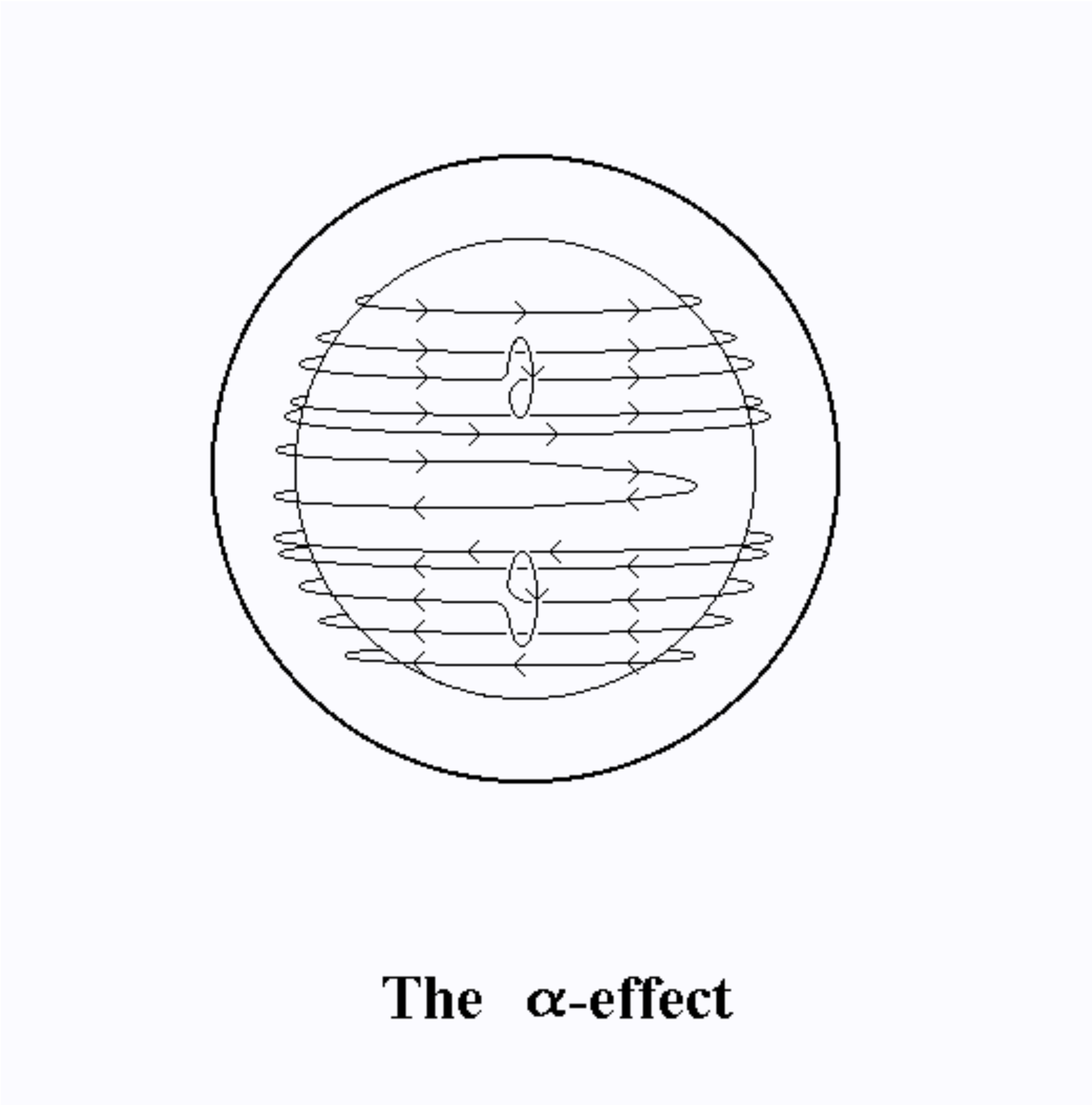
Tachocline - field is generated by dynamo action in this region.

This inference comes from realization that

- Magnetic fields in convection zone would rise too rapidly to experience α or ω effect
- Radiative zone is stable and does not produce buoyancy
- Interface layer is where there are rapid changes in rotation rate

The Sun's differential rotation with latitude can take a north-south oriented magnetic field line and wrap it once around the Sun in about 8 months.



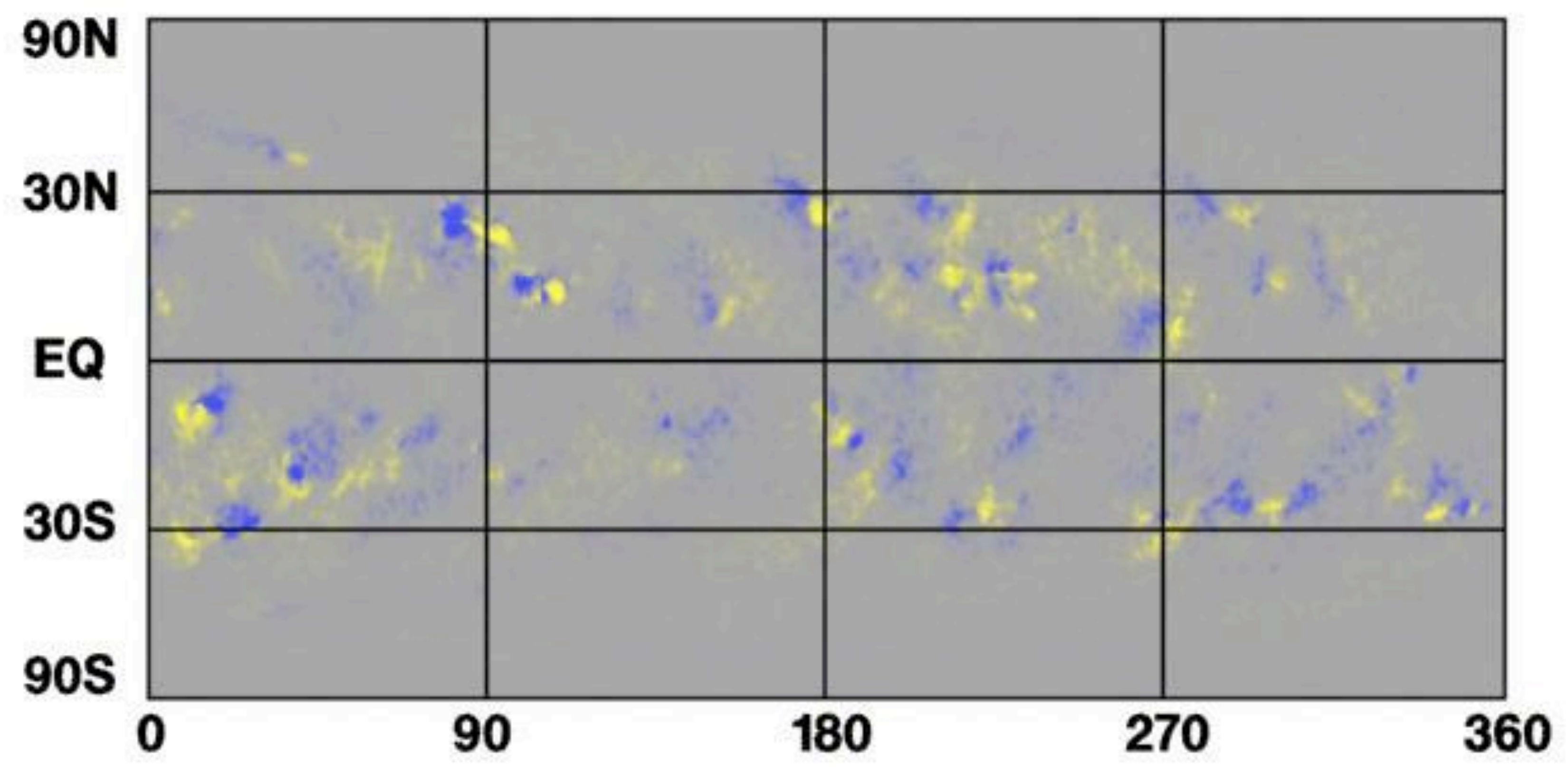


Early models of the Sun's dynamo assumed that the α effect twisting is produced by the effects of the Sun's rotation on very large convective flows that carry heat to the Sun's surface. This assumption produces too much twisting and produces magnetic cycles that are only a couple years in length.

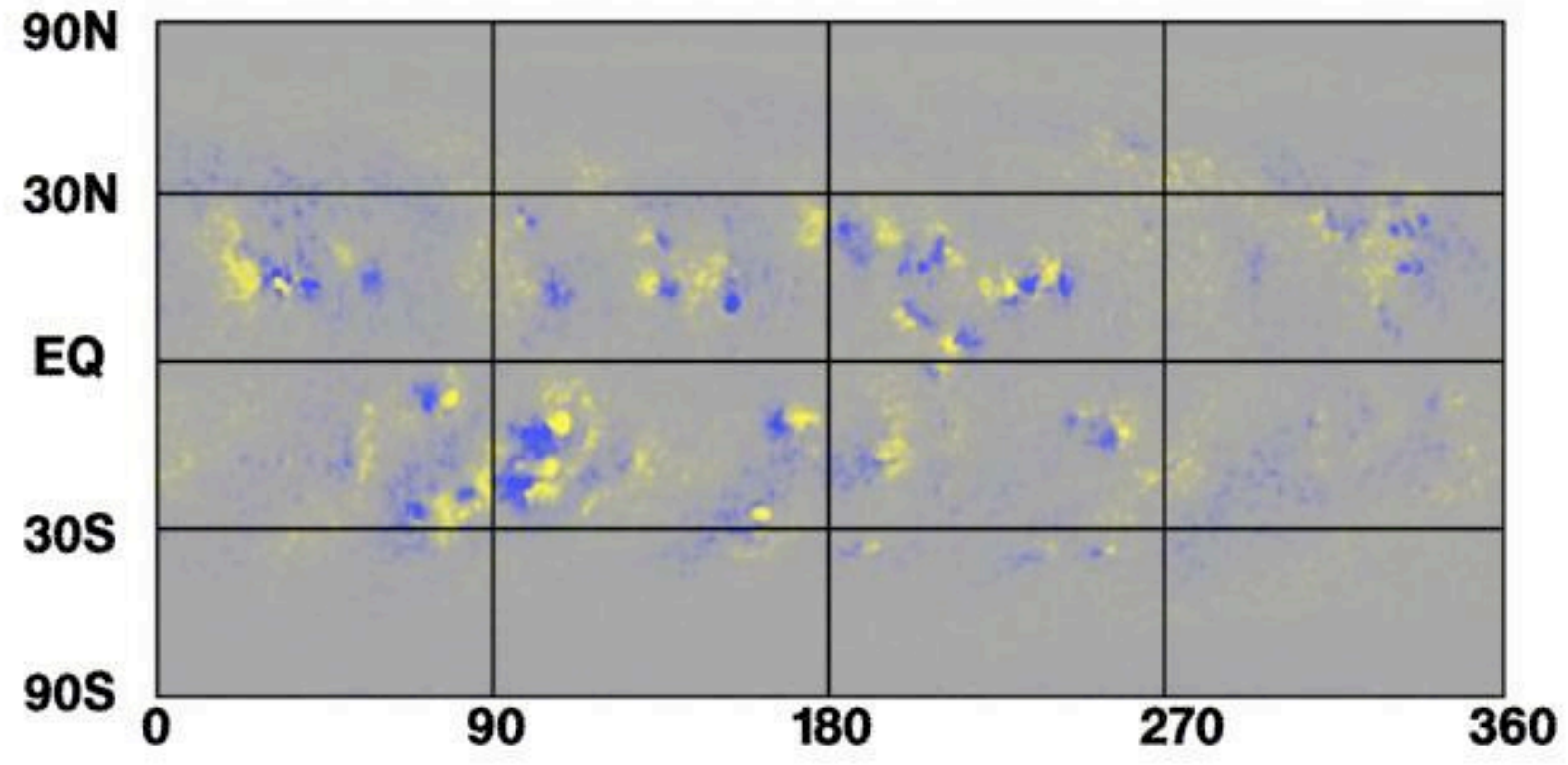
Hale's Polarity Law:

The polarity of the leading spots in one hemisphere
is opposite that of the leading spots in the other hemisphere
and the polarities reverse from one cycle to the next.

Cycle 21



Cycle 22



Observations to explain:

- 11 year period of sunspot cycle
- butterfly diagram- tilt and equatorward drift
- Hale's polarity law
- polarity reversal

Surface Flows observed by

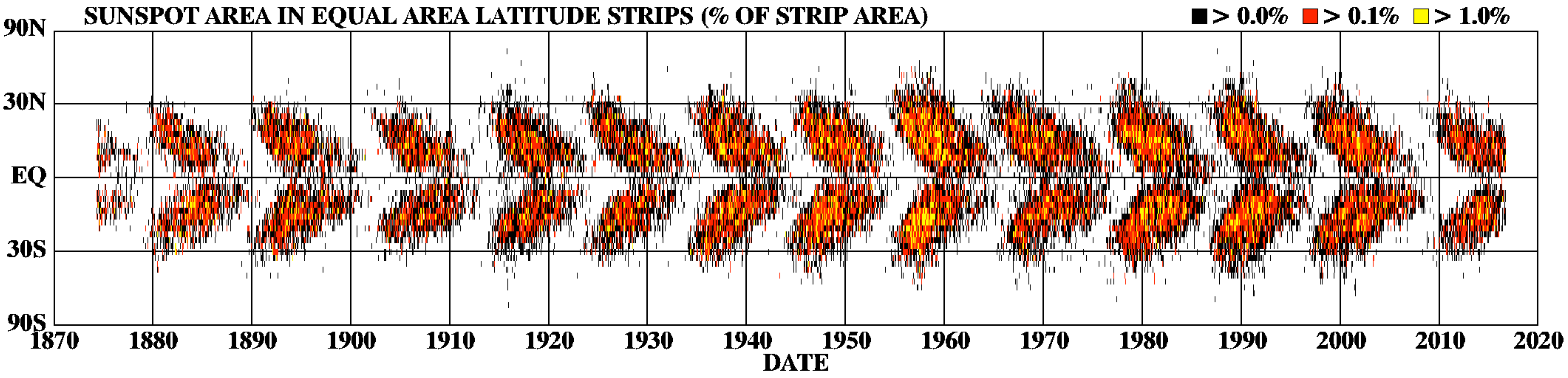
Global Oscillation Network Group (GONG) instruments and Michelson Doppler Imager (MDI) on the SOHO Mission.

Caused by:

- solar rotation
- cellular convection
- meridional flow

Meridional flow

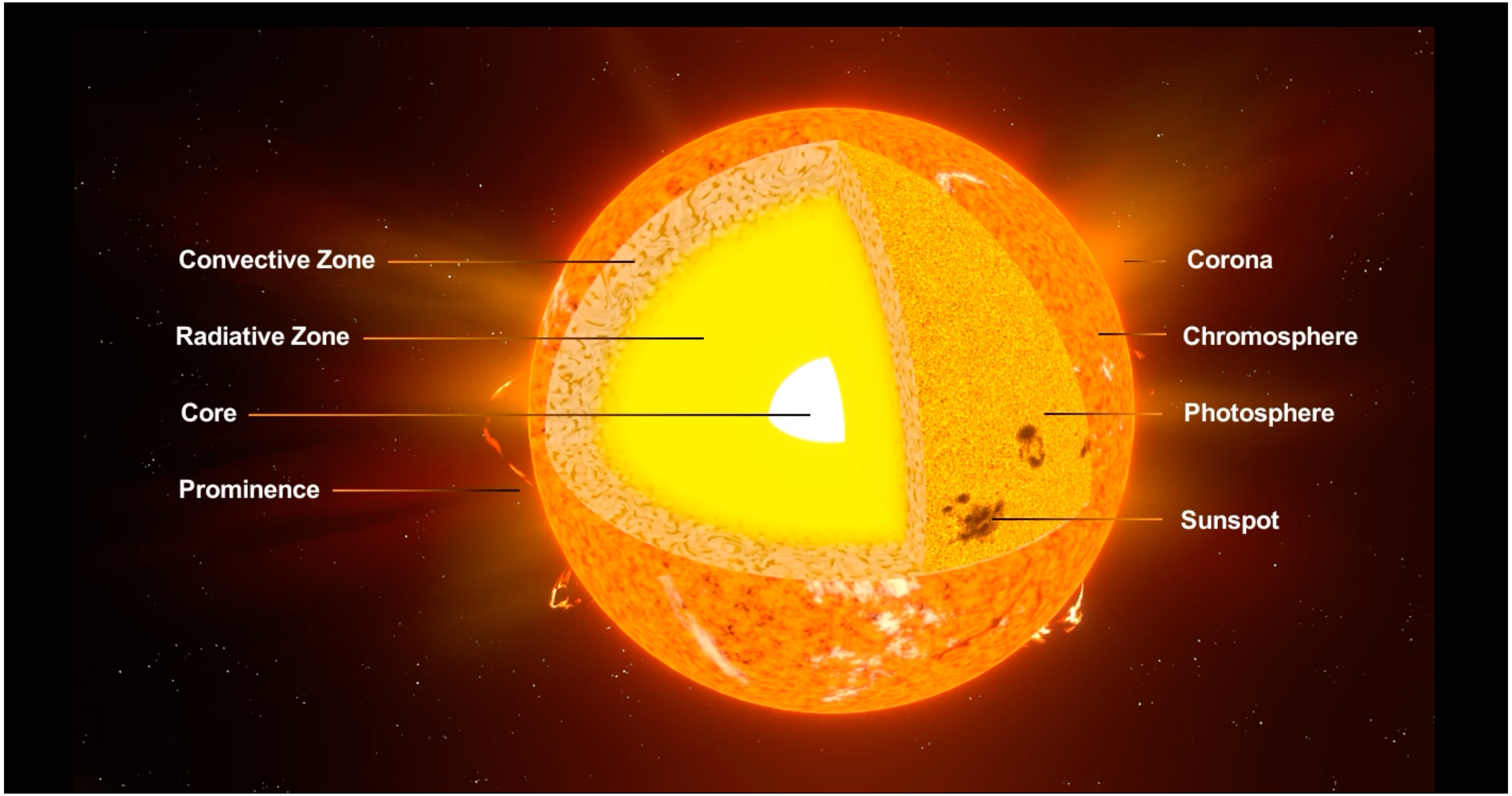
The Sun's meridional flow - the flow of material along meridian lines from the equator toward the poles at the surface and from the poles to the equator below the surface - must also play an important role in the Sun's magnetic dynamo. At the surface the poleward flow is ~10 m/s but the return flow toward the equator inside the Sun where the density is much higher must be much slower still - maybe 1 to 2 m/s. This slow return flow which is poorly determined would carry material from the mid-latitudes to the equator in about 11 years.



variations in the meridional circulation are suggested to be the source of variations in sunspot cycle amplitudes

Animation of Interior Flows

https://solarscience.msfc.nasa.gov/movies/Sun_Animation_Mar23A.mp4



Solar Dynamo Theory

Significant advances have been made in recent years:

- global magnetohydrodynamical simulations of convection and magnetic cycles,
- the turbulent electromotive force and the dynamo saturation problem, and
- flux transport dynamos, and their application to model cycle fluctuations and grand minima and to carry out cycle prediction.

Charbonneau (2014) doi: 10.1146/annurev-astro-081913-040012

MHD induction equation again

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

and

$Rm = \dfrac{UL}{\eta}$ will again very large. Ohmic dissipation is very inefficient at length scale of the system (solar radius). Two time scales are

$$\tau_{circ} = \frac{L}{U} \qquad\qquad \tau_{mag} = \frac{L^2}{\eta} \sim 10^{10} \text{ years}$$

Need **u** to explain the ~decadal cycle period down to minutes for small photospheric magnetic flux concentrations. Short term stuff is ok for advective surface convection ($L \sim 10^6$ m and $U \sim 10^3 \text{m s}^{-1}$) yielding $\tau_{circ} \sim$ 15 minutes. But large scale is hard — magnetic self-organization problem.

MHD equations for solar dynamo - conservation of mass, momentum, energy, magnetic induction

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \tag{6}$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\frac{1}{\rho}\nabla p - 2\boldsymbol{\Omega} \times \mathbf{u} + \mathbf{g} + \frac{1}{\mu_0 \rho}(\nabla \times \mathbf{B}) \times \mathbf{B} + \frac{1}{\rho}\nabla \cdot \boldsymbol{\tau}, \tag{7}$$

$$\frac{\partial e}{\partial t} + (\gamma - 1)e\, \nabla \cdot \mathbf{u} = \frac{1}{\rho}\left\{\nabla \cdot [(\chi + \chi_r)\nabla T] + \phi_u + \phi_B\right\}, \tag{8}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B} - \eta \nabla \times \mathbf{B}). \tag{9}$$

Here ρ is the fluid density; e is internal energy; p is gas pressure; $\boldsymbol{\tau}$ is the viscous stress tensor; χ and χ_r are the kinetic and radiative thermal conductivities, respectively; ϕ_u and ϕ_B are the viscous and Ohmic dissipation functions, respectively; and other symbols have their usual meaning. In the solar dynamo context it is customary to write the MHD equation in a rotating reference frame; the centrifugal force is absorbed in the gravitational term so that only the Coriolis force appears on the right-hand side of Equation 7. Equations 6–9 need to be augmented by an equation of state (typically the perfect gas law), and the magnetic field needs to be subjected to the solenoidal constraint $\nabla \cdot \mathbf{B} = 0$. The specification of appropriate boundary conditions completes the mathematical specification of the problem.

Solar dynamo Simulations

- MHD equations are a set of nonlinear PDEs to be solved in thick rotating stratified fluid of electrically conducting fluid subject to thermal forcing producing convection.
- Gilman (1983), Glatzmaier (1984,1985) used strong dissipation effects but produced rapidly rotating equatorial region, the buildup of large-scale magnetic fields (but showing strong hemispheric asymmetries), magnetic field migration (but poleward rather than equatorward), and polarity reversals (although quite irregular).
- Increased computing power led to higher resolution, potent dynamos with strong B fields, but no large scale B component.
- Stable mechanically forced underlying fluid layer produced large scale field but no reversals (Browning et al, 2006; Brown et al., 2010)
- Recent developments include solar-like cycle reversals of large scale magnetic component.

Three newer simulations are compared in Charbonneau 2015

doi: 10.1146/annurev-astro-081913-040012

- PENCIL code (www.nordita.org/pencil-code) - pseudo global simulations in a spherical wedge, fixed values for dissipative coefficients
- ASH anelastic spherical harmonic code - massively parallel spectral code in spherical geometry, explicit sub grid model for dissipation
- EULAG-MHD parallel multiscale flow solver - dissipation in numerical advective scheme
- All show self-organization of large-scale magnetic fields impacted by various factors: rotation, differential rotation, sub grid models, magnetic Prandtl Number, tachocline

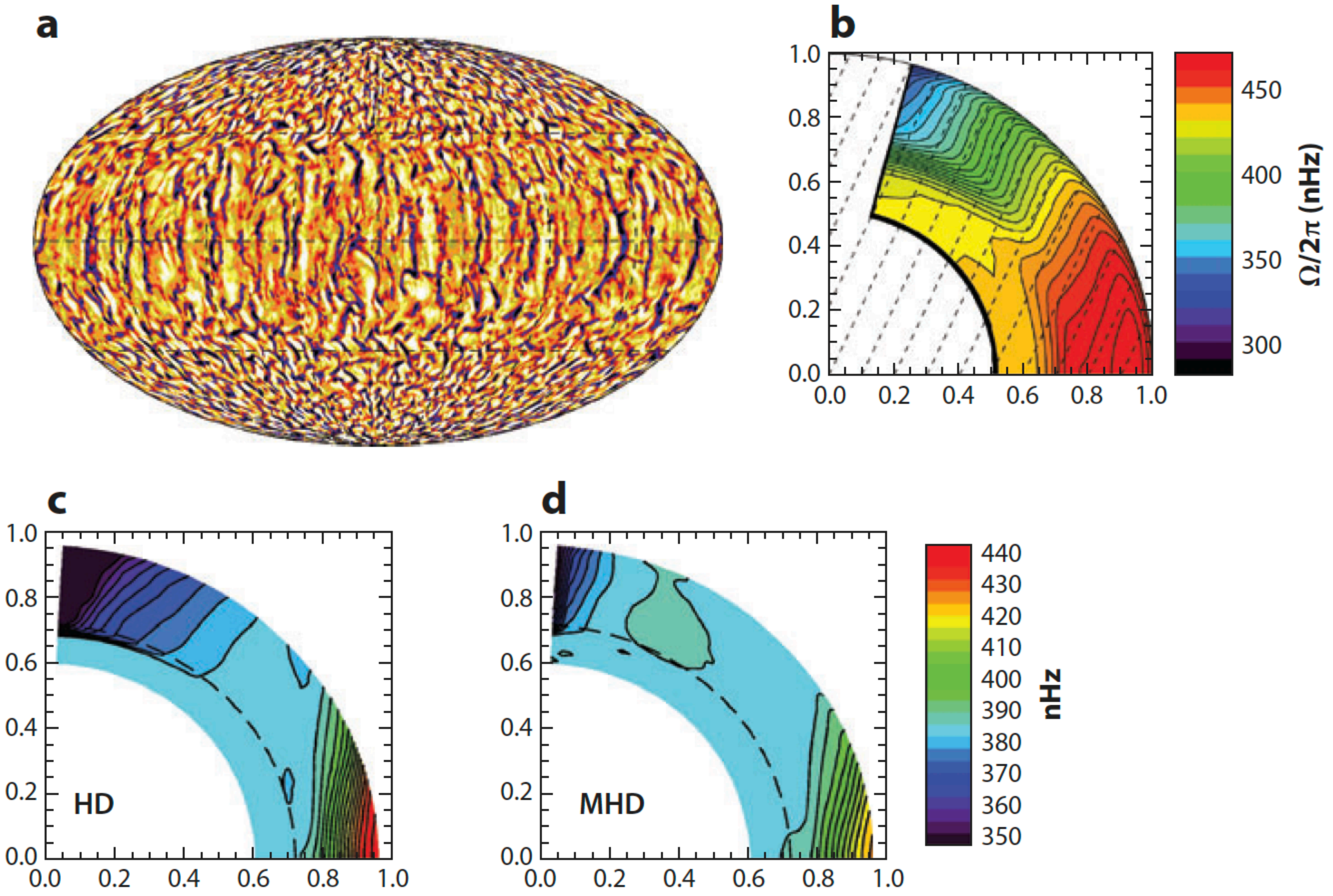
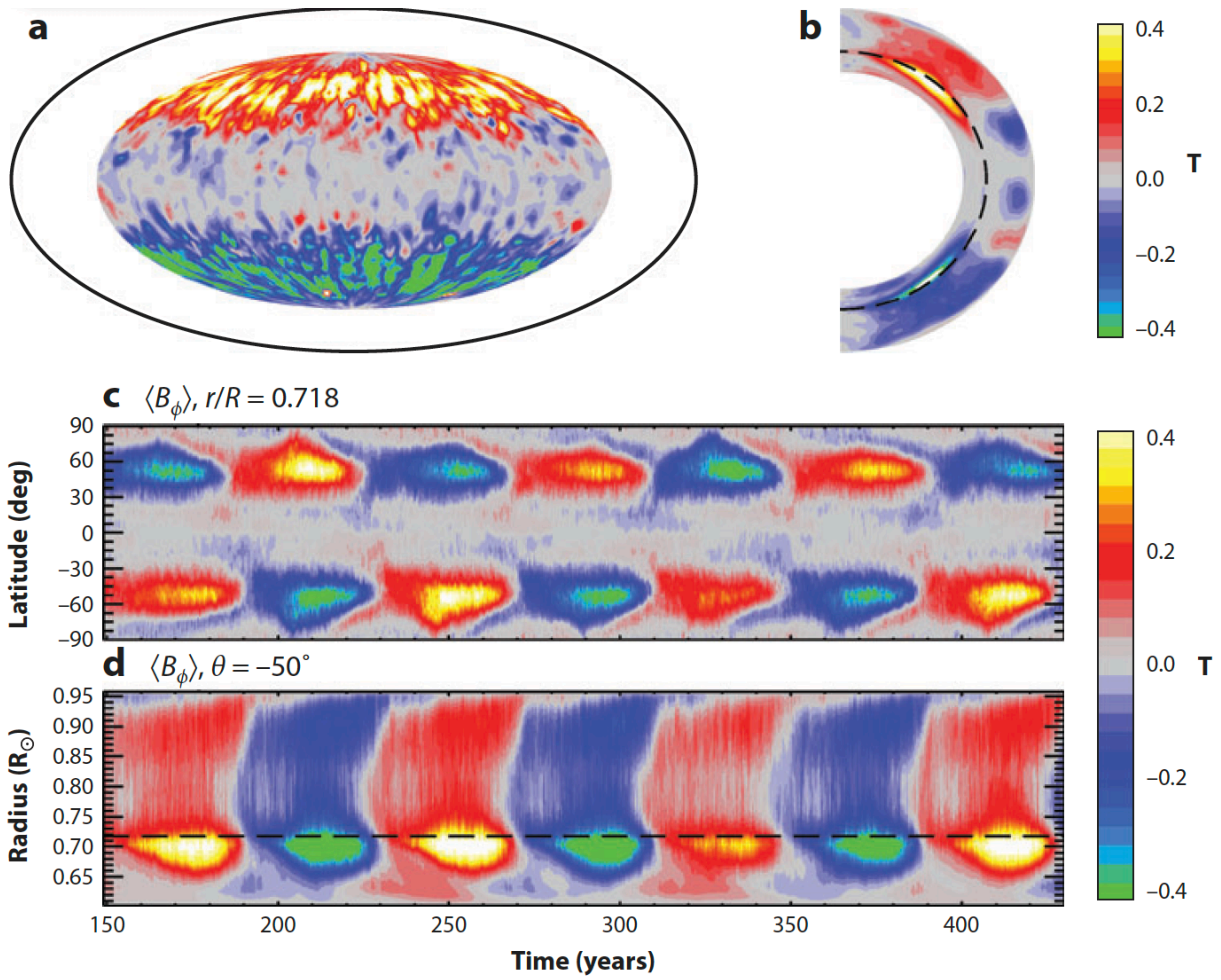


Figure 2

Plasma flows in the solar interior: (*a*) vertical flow velocities in subsurface layers, as produced by a high-resolution EULAG simulation, courtesy of Guerrero et al. (2013); (*b*) helioseismic inversion of the solar internal differential rotation, taken from Howe (2009); and differential rotation in (*c*) a purely hydrodynamical (HD) EULAG numerical simulation and (*d*) a EULAG numerical simulation obtained in the magnetohydrodynamic (MHD) regime. The dashed line indicates the base of the convection zone.



https://www.annualreviews.org/do/10.1146/do.multimedia.2014.06.10.274/abs/

Video 1

Magnetic cycles in a global EULAG-MHD anelastic simulation, essentially identical to those by Ghizaru et al. (2010) and Racine et al. (2011). To view the video, access this article on the Annual Reviews website at **http://www.annualreviews.org**. This simulation includes a convectively stable fluid layer underlying the convecting layers. (*a*) A snapshot in Mollweide projection of the toroidal (zonal) magnetic component at depth $r/R_\odot = 0.718$; (*b*) a snapshot of the zonally averaged toroidal field in a meridional plane taken at the same time as panel *a*. (*c*) Time-latitude and (*d*) radius-latitude diagrams of the zonally averaged toroidal field, the former at depth $r/R_\odot = 0.718$ and the latter at latitude +25°. The dashed lines in panels *b* and *d* indicate the bottom of the convectively unstable layers. This is a moderate-resolution simulation, rotating at the solar rate but subluminous with respect to the Sun.