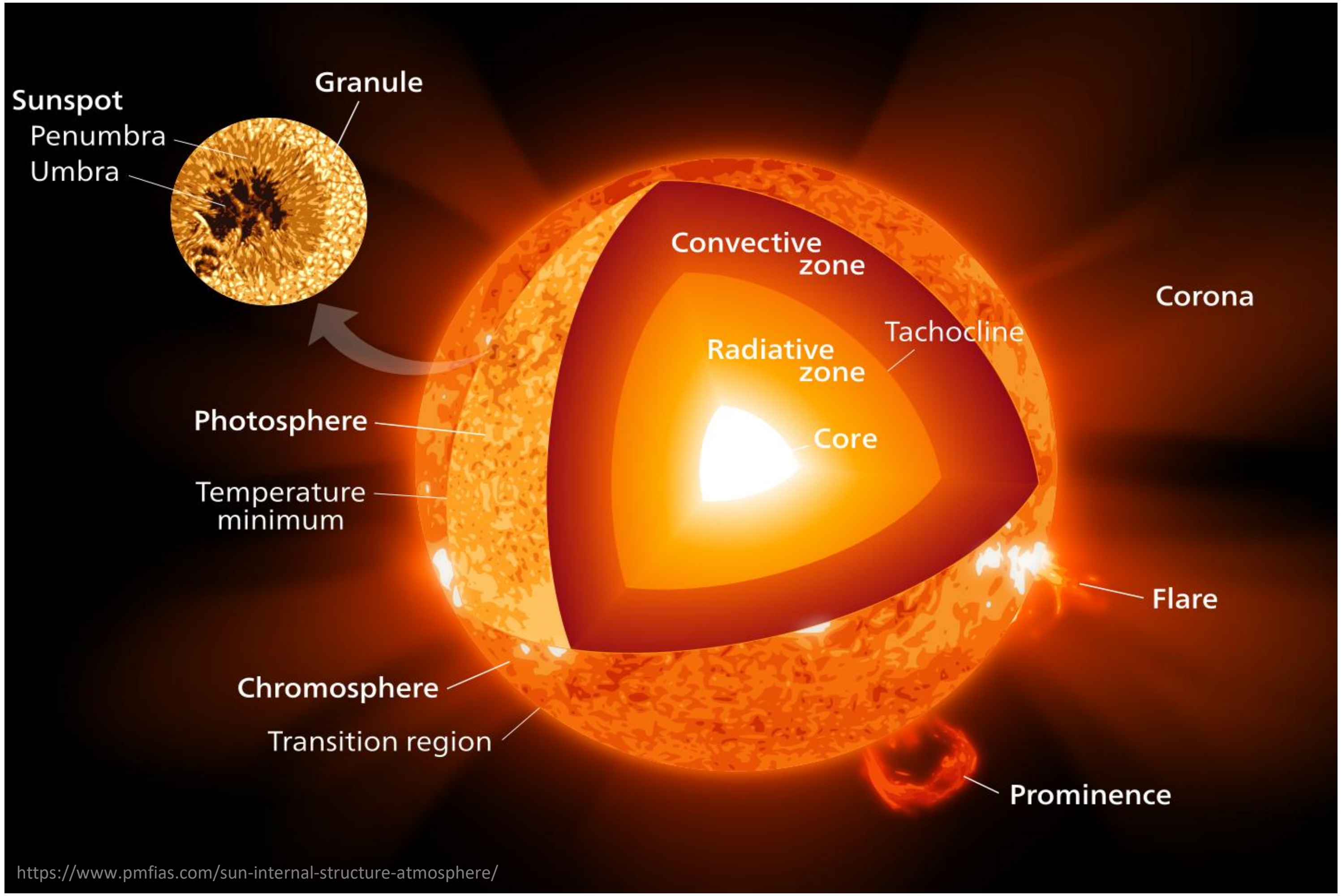
https://www.youtube.com/watch?v=2U3ucaVzRqQ

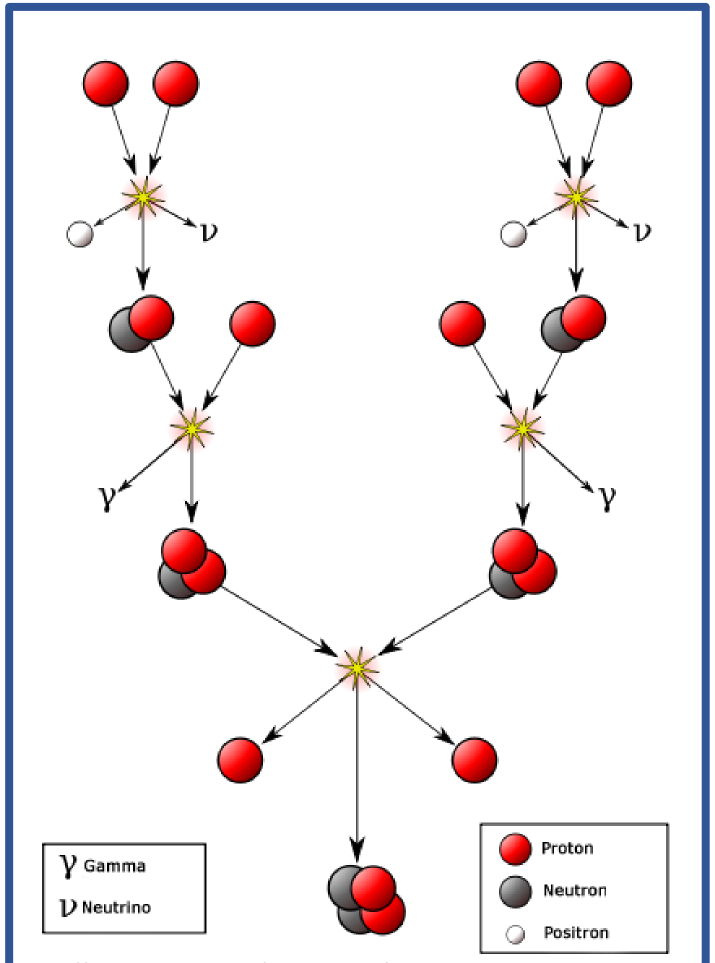
The Solar Magnetic Structure And Corona

Plasma Physics Seminar **Elias Hanser** **09.01.2024**

The Sun Is Structured In Several Layers



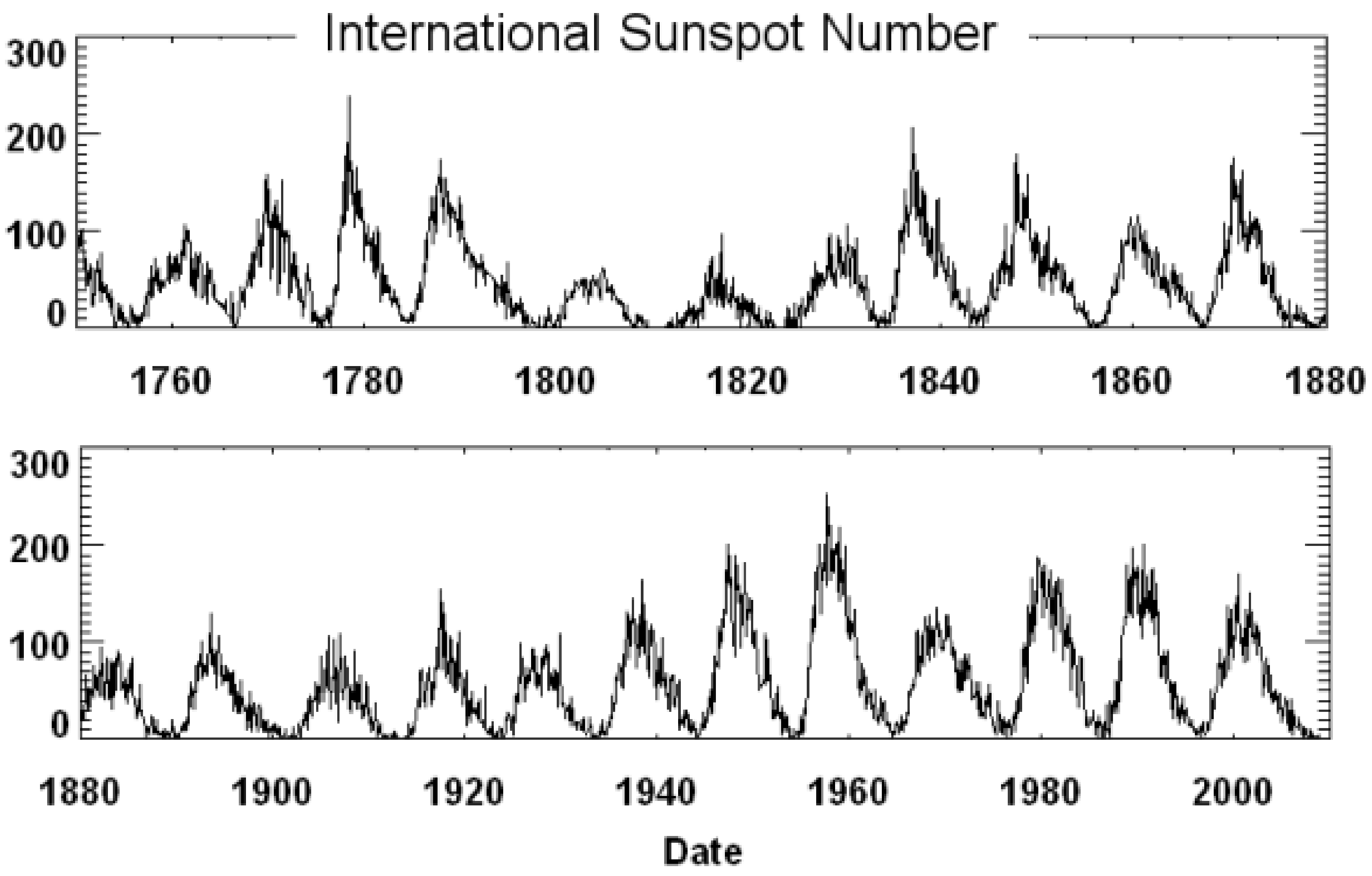
https://www.pmfias.com/sun-internal-structure-atmosphere/



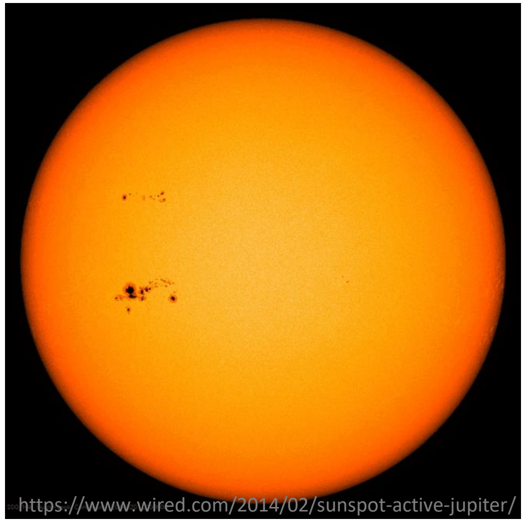
https://energyeducation.ca/encyclopedia/Nuclear_fusion_in_the_Sun

Why should we study the sun?

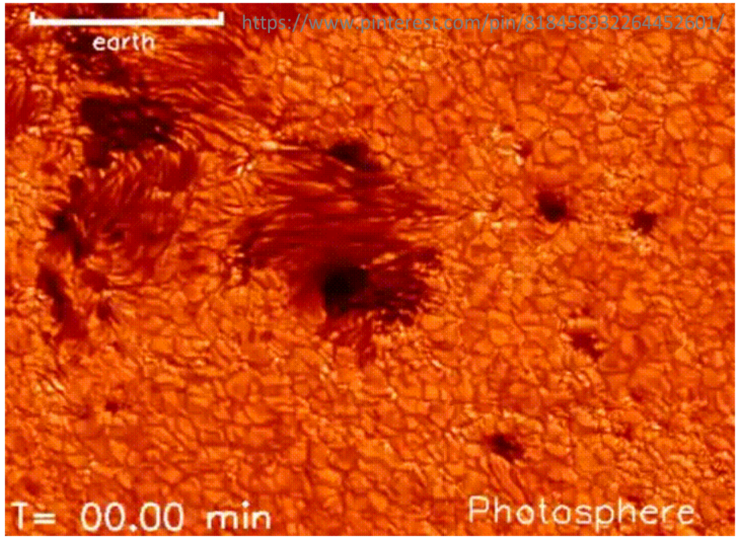
Observations - Sunspots Follow An 11 Year Cycle



https://spaceweather.com/glossary/sunspotnumber.html

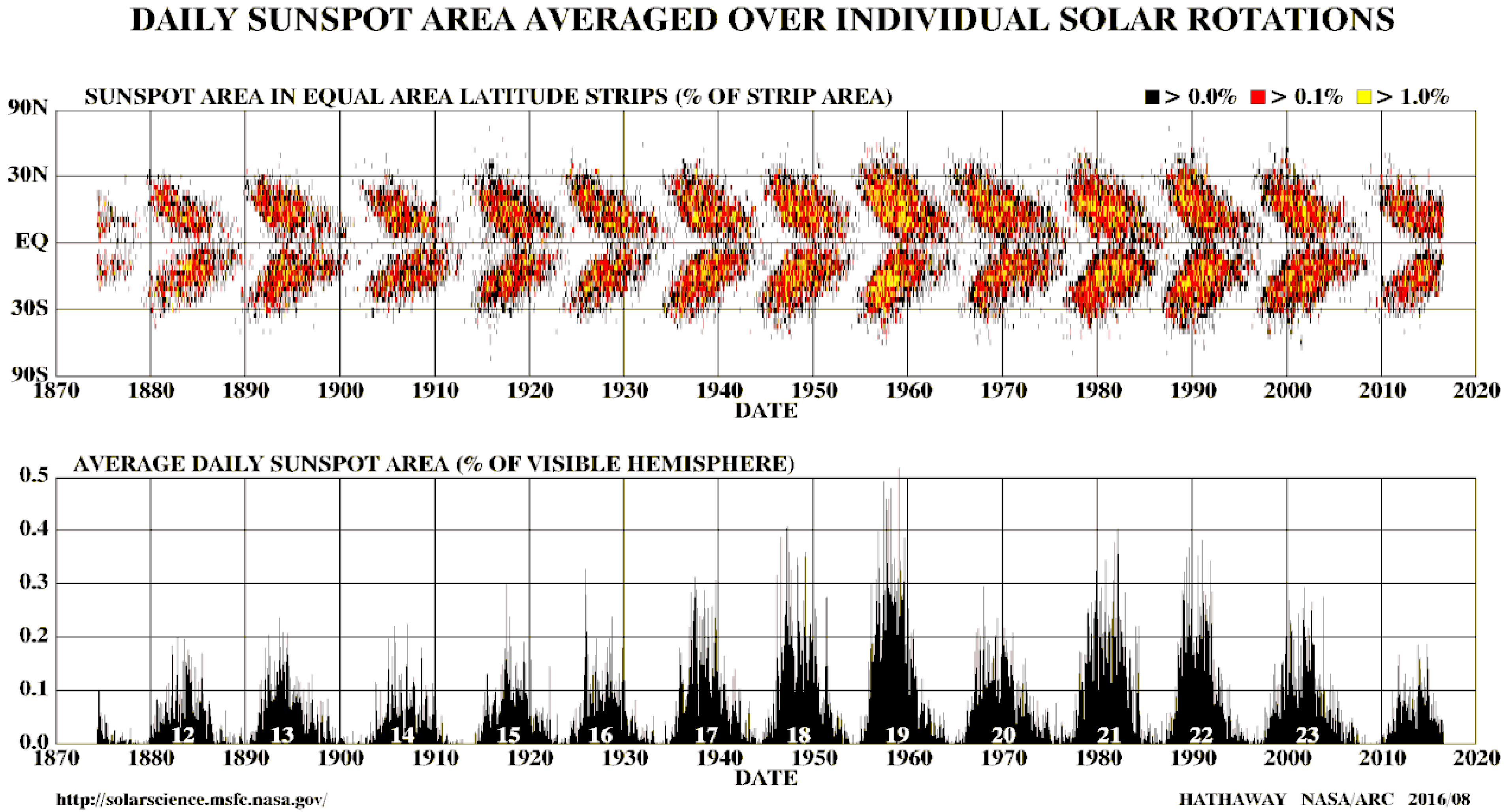


https://www.wired.com/2014/02/sunspot-active-jupiter/

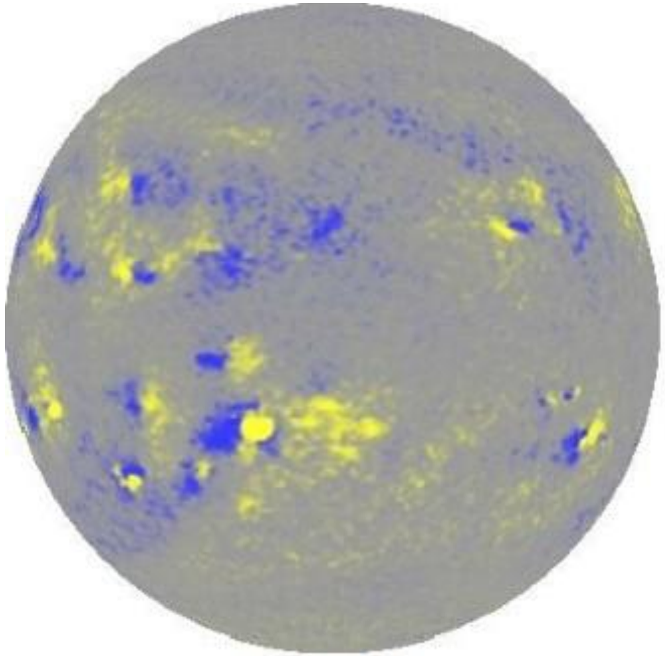


https://www.pinterest.com/pin/818458932264452601/

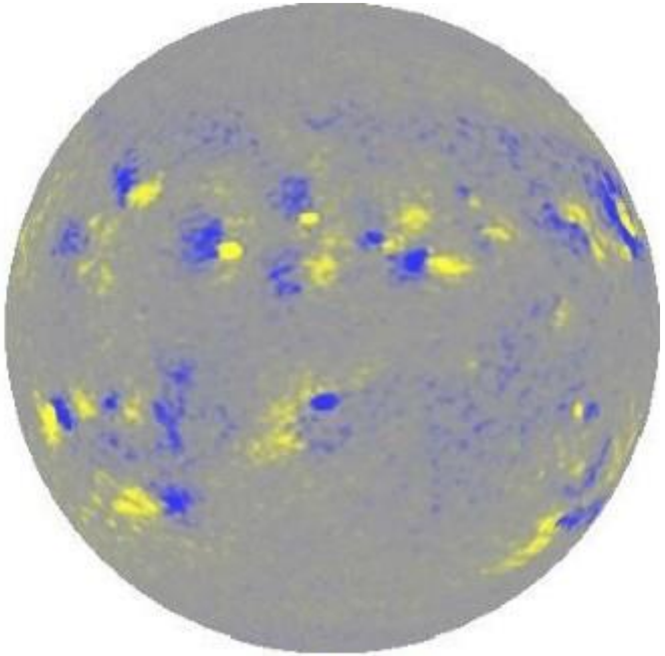
Observations – Throughout A Cycle Sunspots Appear Closer To The Equator (1861 Spörer’s Law)



Observations – Sunspots Show A Distinct Magnetic Behavior (1919 Hale's Law)

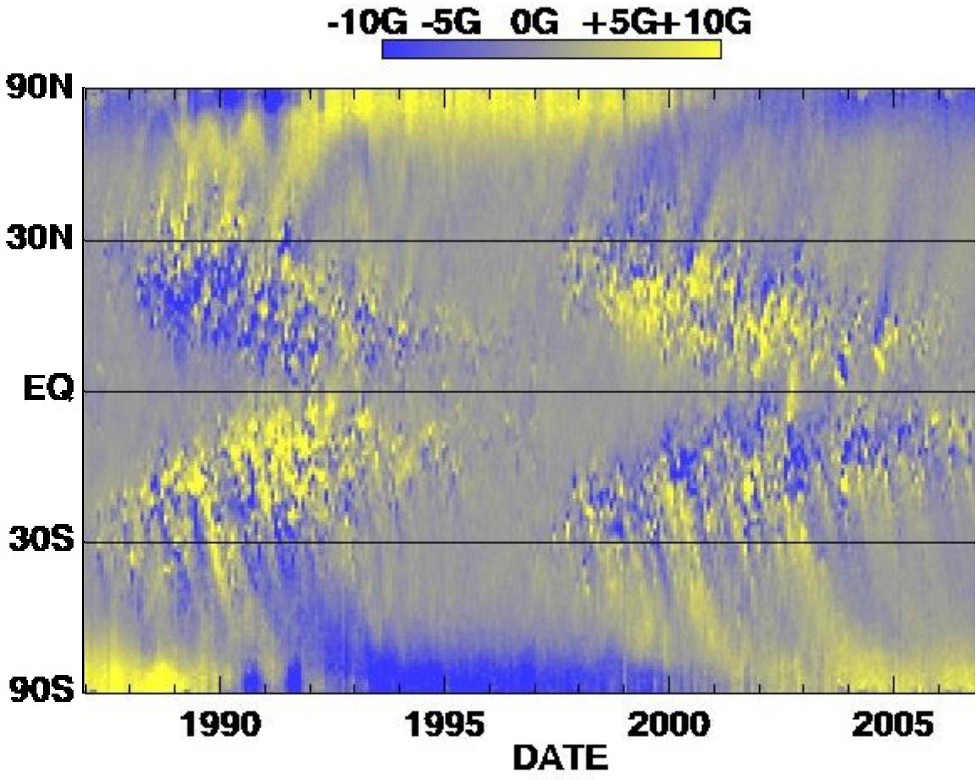


Cycle 22
1989 August 02



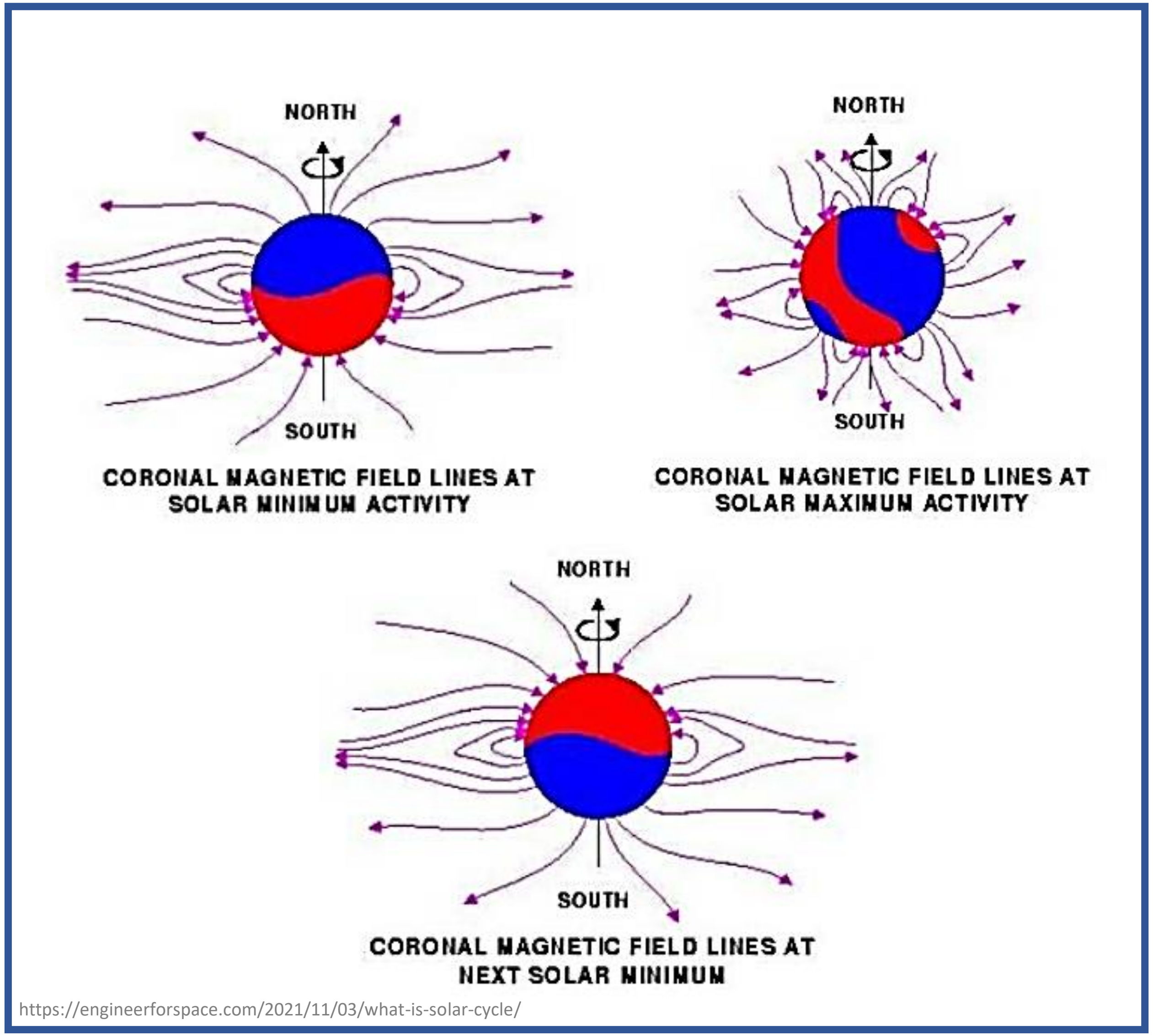
Cycle 23
2000 June 26

https://arxiv.org/pdf/1502.07020.pdf

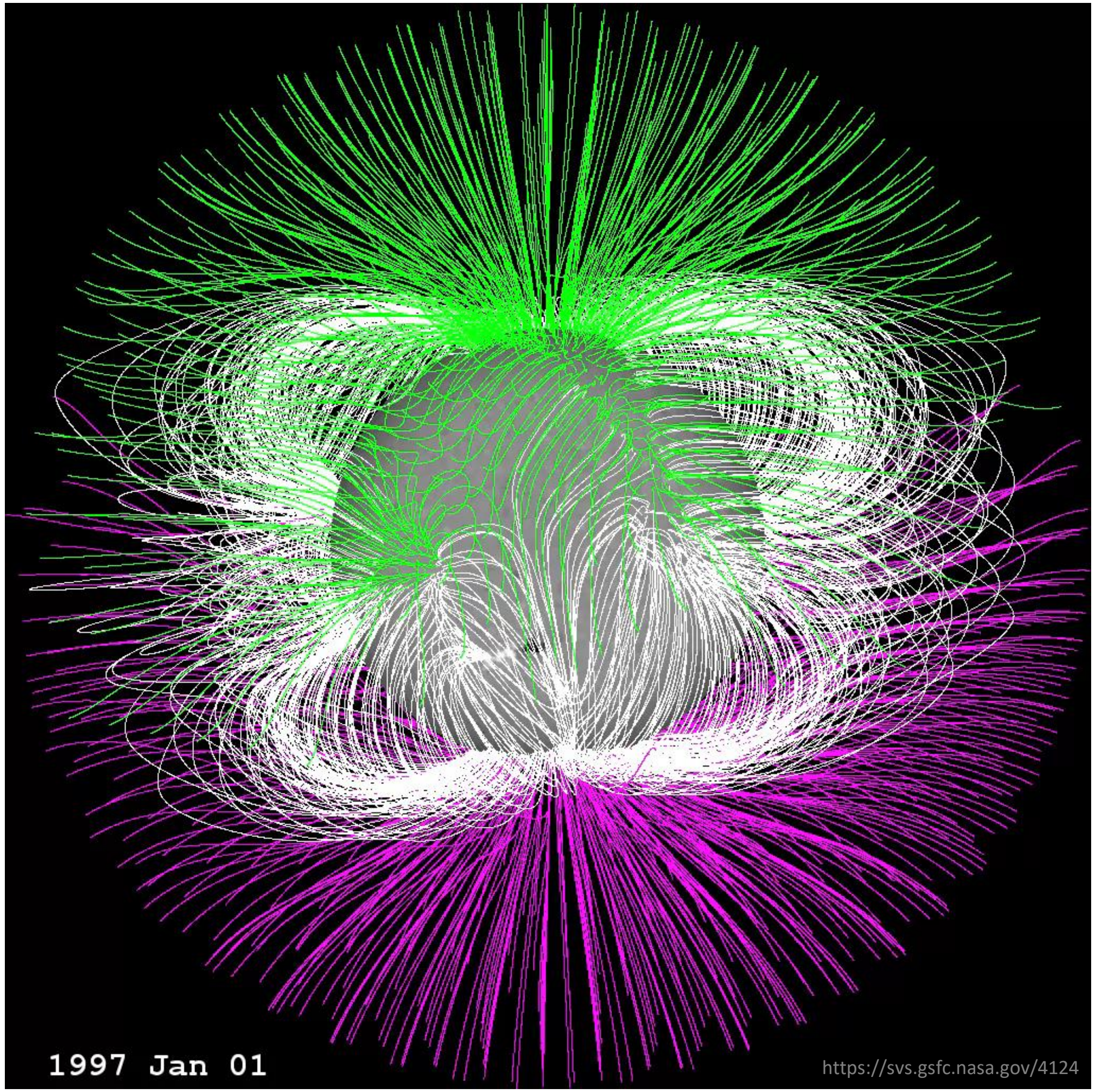


Hathaway NASA ARC 2016/10

Observations – Sun Shows An 11 Year Magnetic Reversal

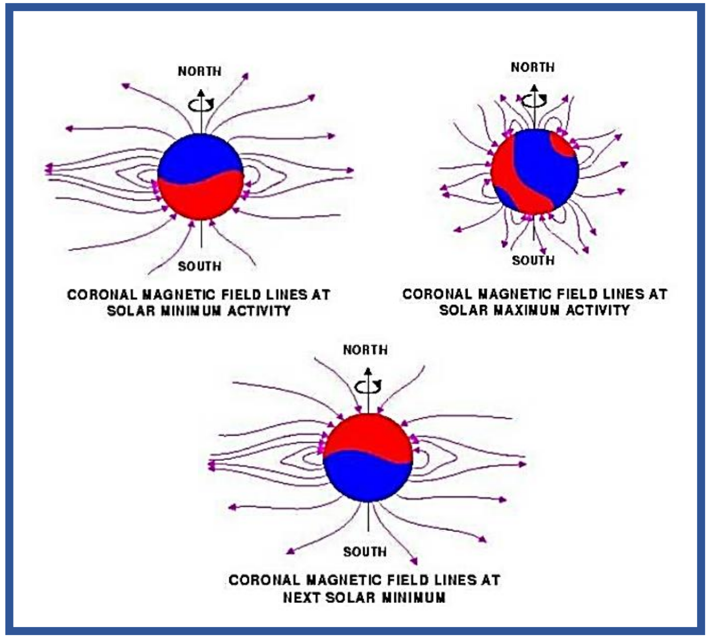


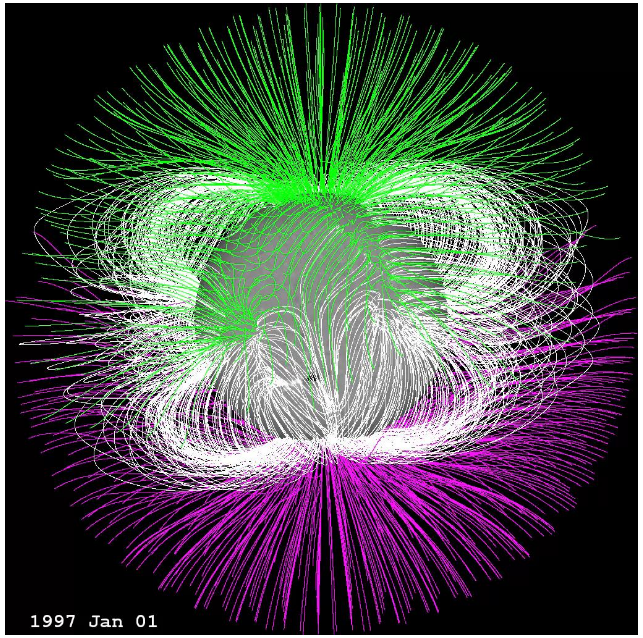
https://engineerforspace.com/2021/11/03/what-is-solar-cycle/



https://svs.gsfc.nasa.gov/4124

Observations – Sun Shows An 11 Year Magnetic Reversal





1. A dynamo model of the magnetic field has to **explain all observations**!

2. **Cowling’s anti-dynamo theorem**:

A **stationary axisymmetric magnetic field** with currents limited to a finite volume in space **cannot be maintained** by a velocity field with finite amplitude.

Some Theory – Magnetic Induction Equation

Magnetic field in an electrically **conducting and resistive fluid**:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boxed{\underset{\textbf{\textit{Diffusion Term}}}{\frac{1}{\mu_0\sigma}\boldsymbol{\nabla}^2\mathbf{B}}} + \boxed{\underset{\textbf{\textit{Convection Term}}}{\boldsymbol{\nabla} \times (\mathbf{v} \times \mathbf{B})}}$$

Diffusion dominated:

$$\frac{B}{\tau} = \frac{1}{\mu_0\sigma}\frac{B}{L^2} \implies \tau_\sigma = \mu_0\sigma L^2$$

Convection dominated:

$$\frac{B}{\tau} = \frac{vB}{L} \implies \tau_{ad} = \frac{L}{v}$$

Define **Magnetic Reynolds Number:**

$$R_m = \frac{\tau_\sigma}{\tau_{ad}} = \mu_0\sigma L v \sim 10^6 - 10^{10} \gg 1$$

Some Theory – Magnetic Induction Equation

Magnetic field in an electrically **conducting and resistive fluid**:

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

Define Magnetic Reynolds Number:

$$R_m = \frac{\tau_\sigma}{\tau_{ad}} = \mu_0 \sigma L v \sim 10^6 - 10^{10} \gg 1$$

Diffusion Negligible:

Frozen Flux Theorem:

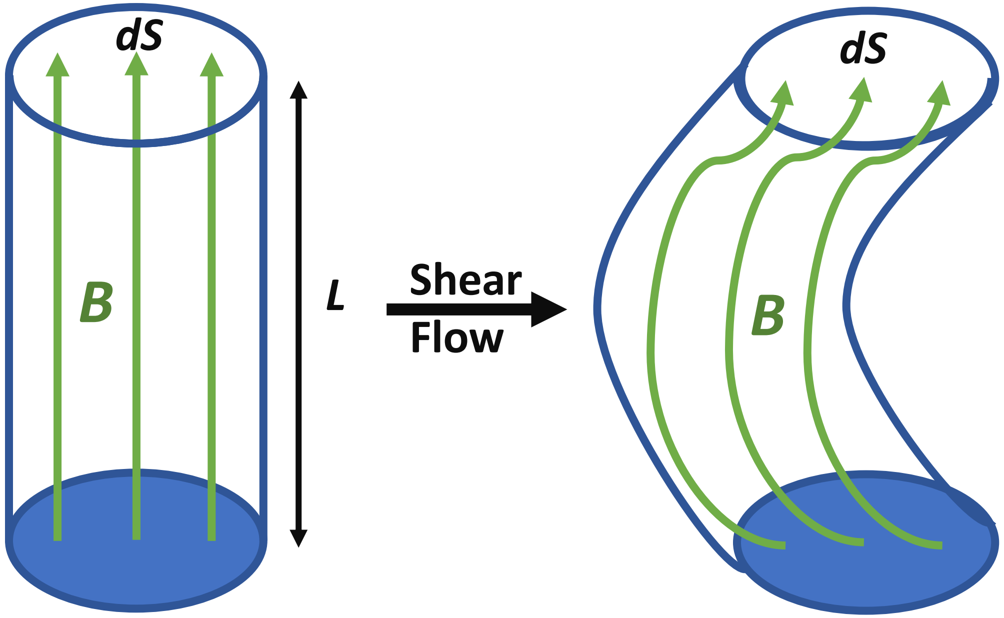
Magnetic fields embedded into highly conductive fluids are constrained to move together with the fluid in the limit of large magnetic Reynolds numbers.

Some Theory – Magnetic Induction Equation

Frozen Flux Theorem:

Magnetic fields embedded into highly conductive fluids are constrained to move together in the limit of large magnetic Reynolds numbers.

Sheared Magnetic Flux Tube



Conservation Laws

$$\Phi = BdS = const.$$

$$M = \rho LdS = const.$$

$$B \propto \rho L$$

Some Theory – Magnetic Buoyancy

MHD Equilibrium:

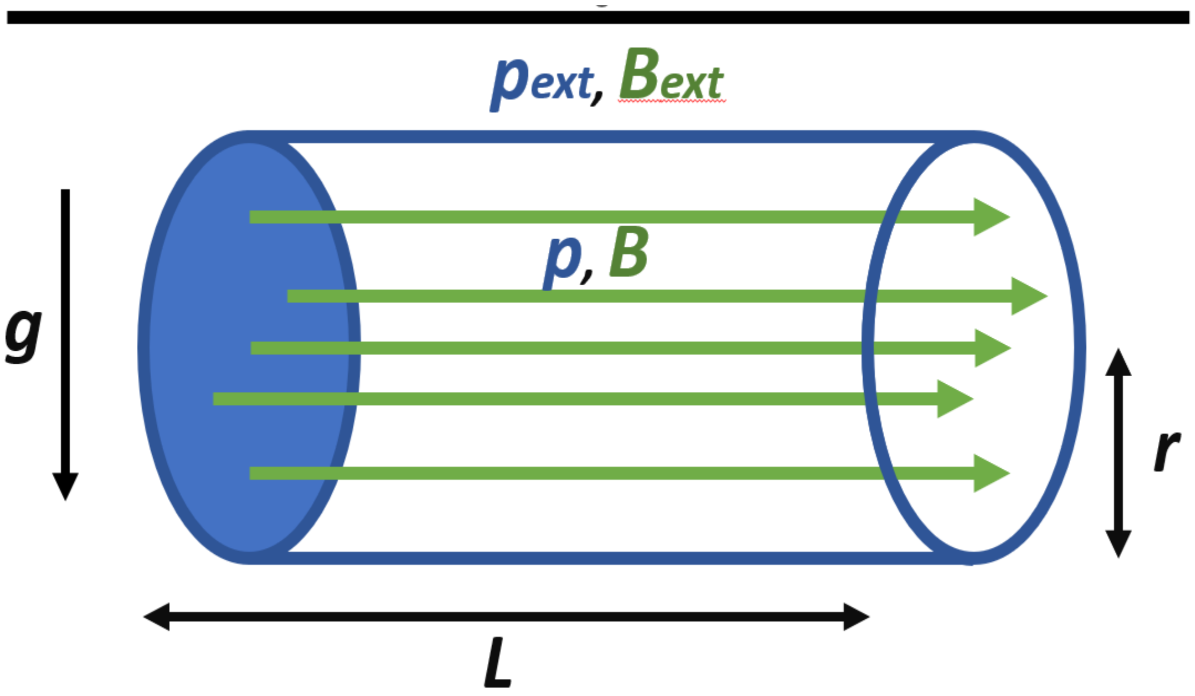
$$p + \frac{B^2}{2\mu_0} = p_{ext} + \cancel{\frac{B_{ext}^2}{2\mu_0}}$$

Equation of state:

$$pV = Nk_BT \implies p = \rho\frac{k_BT}{m_{e/i}}$$

Thermal Equilibrium:

$$T \sim T_{ext} \implies \rho_{ext} - \rho = \frac{m_{e/i}}{k_BT}\frac{B^2}{2\mu_0}$$



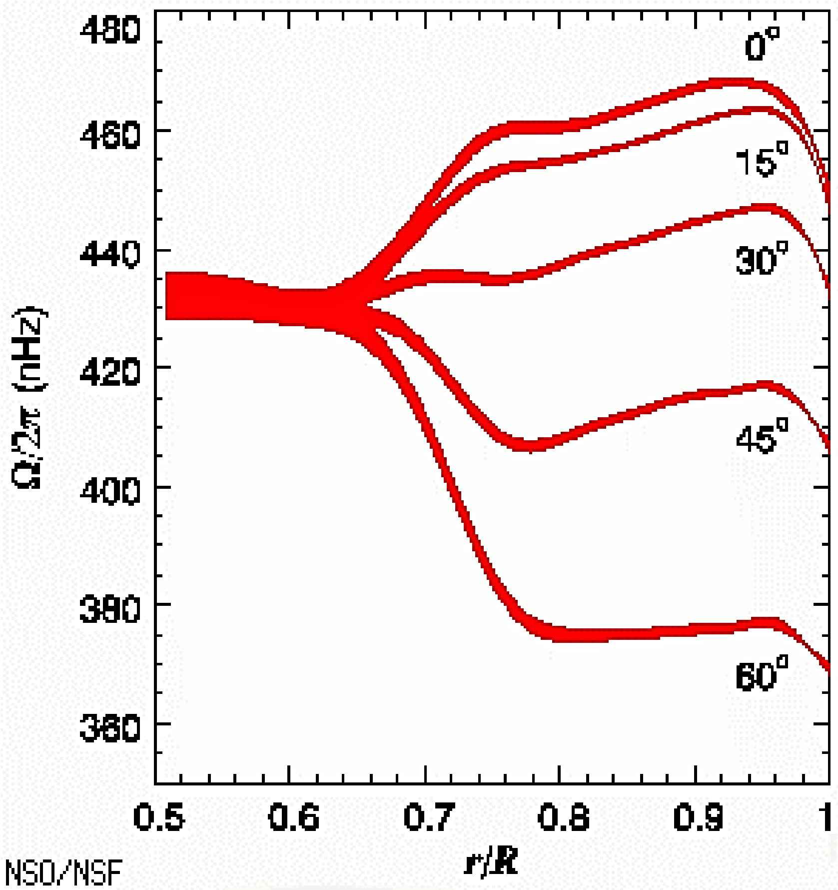
Buoyancy Force:

$$F = (\rho_{ext} - \rho)Vg \sim B^2$$

Magnetic flux tubes experience buoyancy!

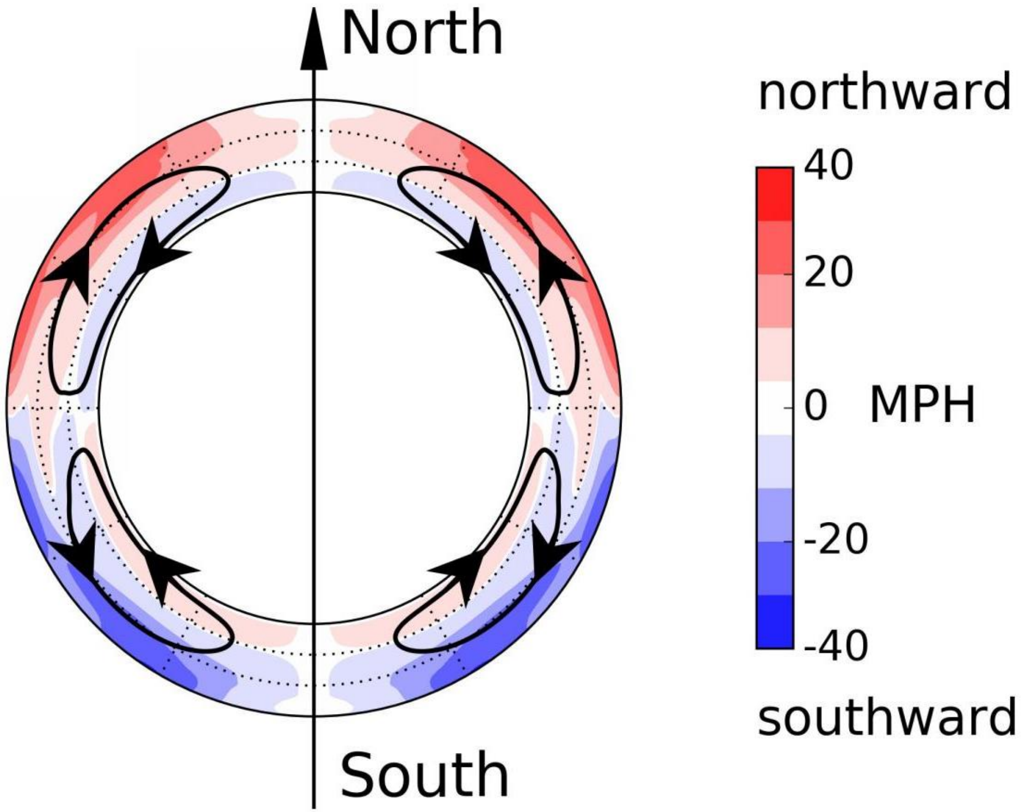
Some Theory – Solar Plasma Flow Speed

Rotational Flow



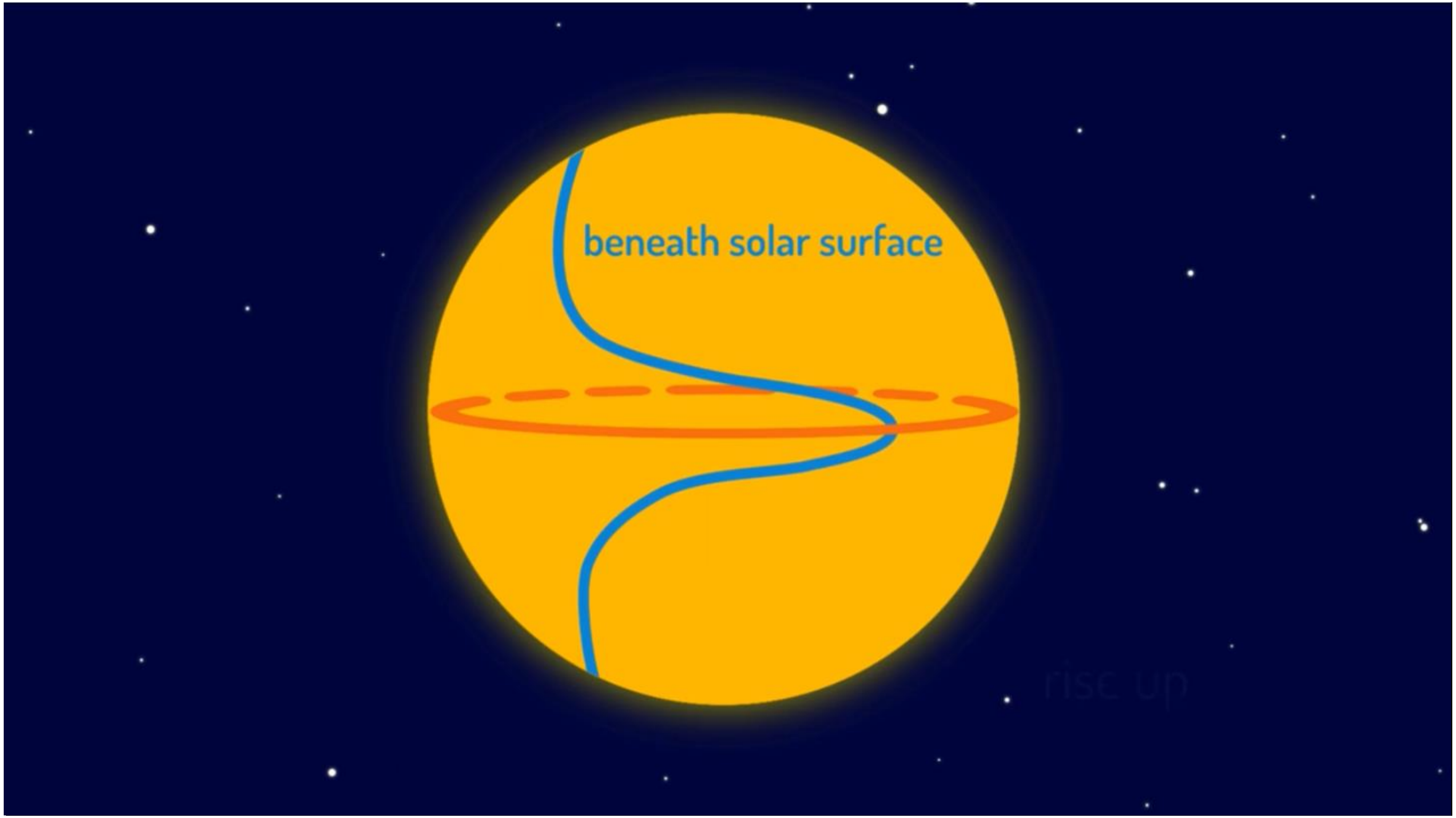
https://en.wikipedia.org/wiki/Tachocline#/media/File:Tachocline.svg

Meridional Flow



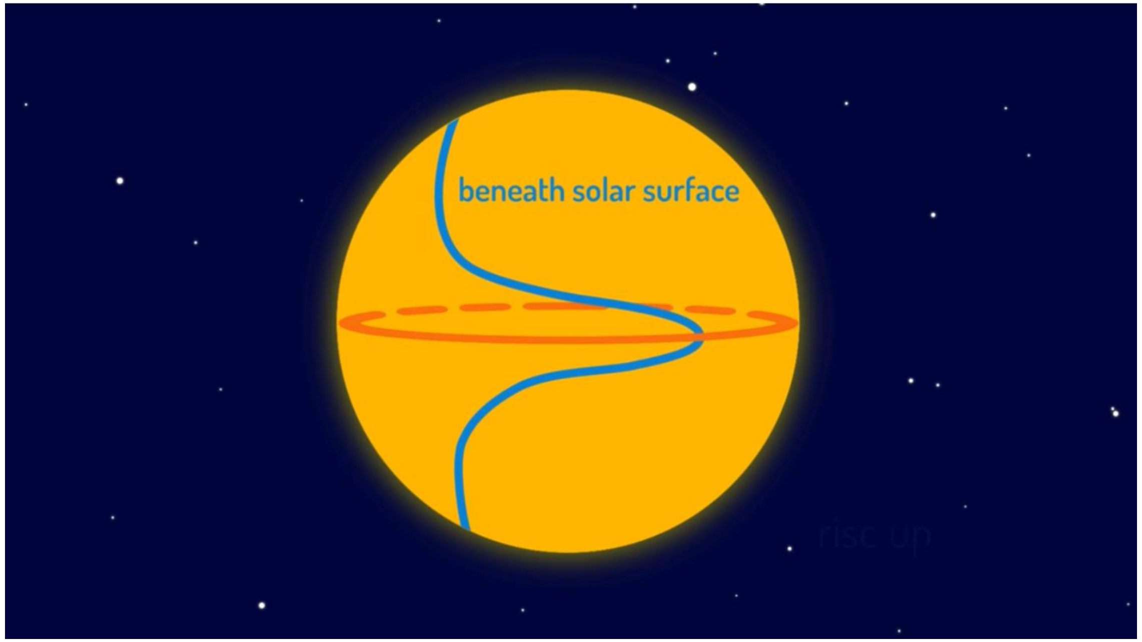
https://www.eurekalert.org/news-releases/590318

Solar Dynamo Models – Parker and Babcock

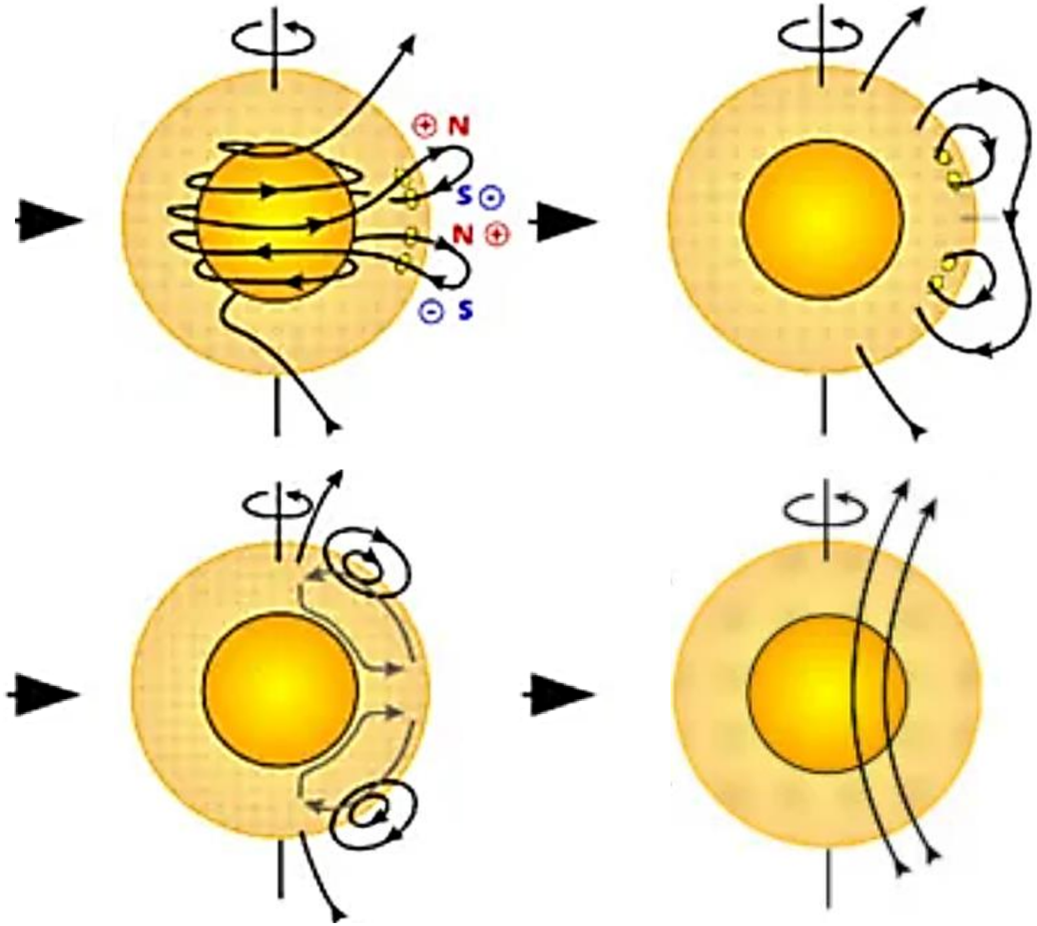


Solar Dynamo Models – Parker and Babcock

Parker Model:



Babcock-Leighton Model:

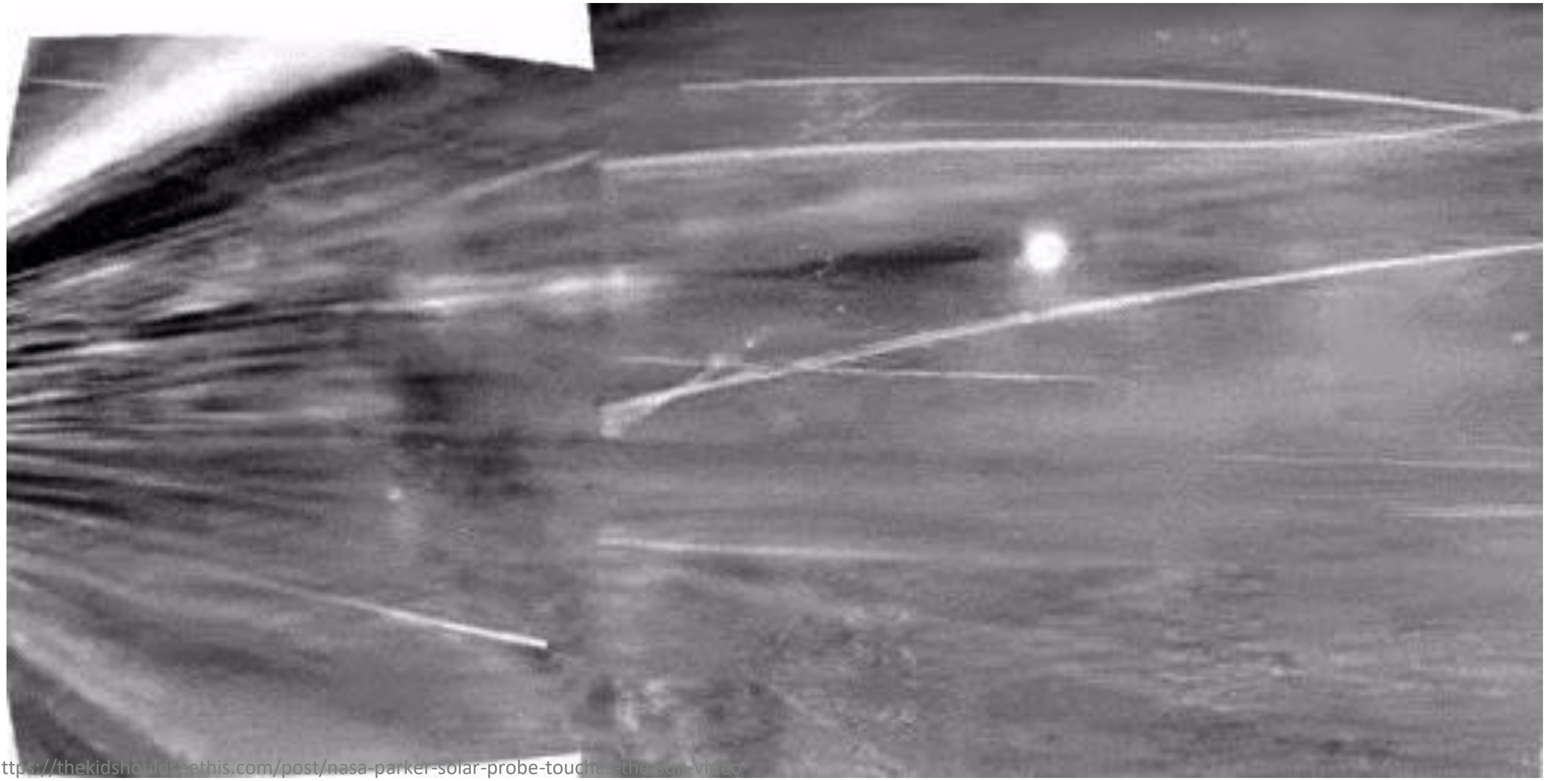


https://doi.org/10.1051/0004-6361/202141946

The Solar Corona - Touching The Sun

https://www.sdsc.edu/News%20Items/PR20211203_solar_corona.html

Corona As Seen From Earth



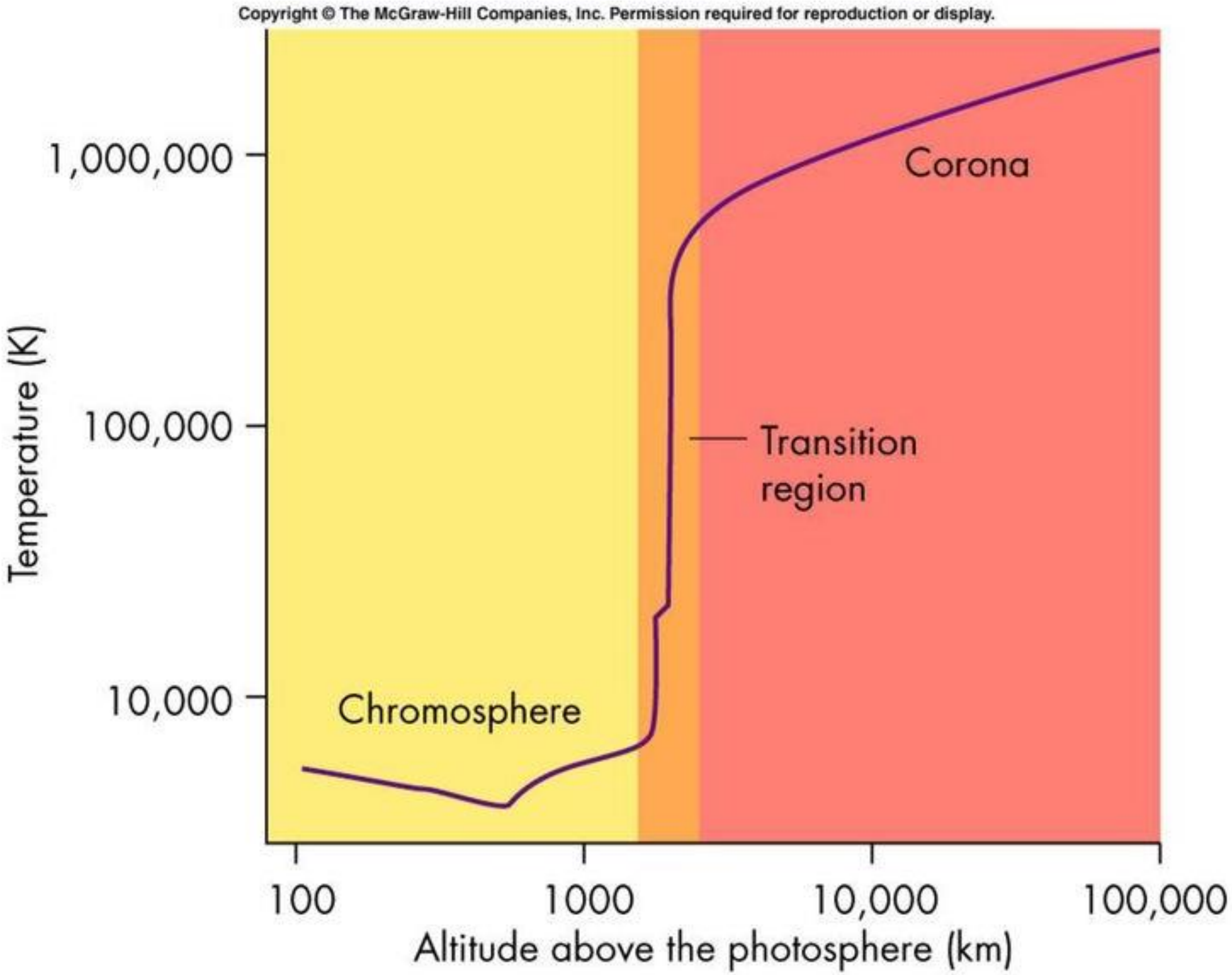
https://thekidshouldseethis.com/post/nasa-parker-solar-probe-touches-the-sun-video

Parker Solar Probe Touching The Sun (2021)

The Corona Heating Problem

Quiet Corona:
1.5 Million K

Active Corona:
> 4.0 Million K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The Corona has to be heated by a magnetic field mechanism!

The Corona Heating Problem – Heating Mechanisms

Wave Heating (AC)	Magnetic Heating (DC)
• MHD waves are produced by turbulence in convection zone • Waves dissipate in corona in the form of heat	• Stress is continuously built up by photospheric motion • Release by **magnetic reconnection** in the form of **flares/nanoflares**
• Hard to explain the active sun's temperatures	• Hard to yield to achieve the average quiet sun's temperature

Solving The Heating Problem – Magnetic Reconnection

Magnetic field in an electrically **conducting and resistive fluid**:

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

Magnetic Reynolds Number:

$$R_m = \frac{\tau_\sigma}{\tau_{ad}} = \mu_0 \sigma L v$$

Opposed Magnetic Fields:

Solving The Heating Problem – Magnetic Reconnection

Magnetic field in an electrically **conducting and resistive fluid**:

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

Magnetic Reynolds Number:

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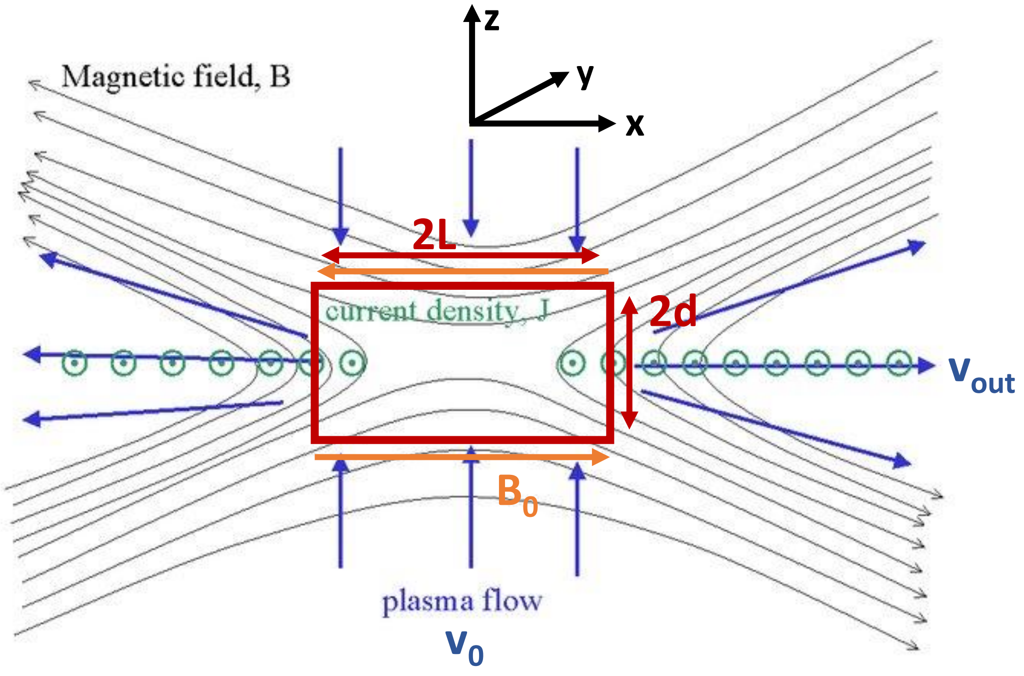
Opposed Magnetic Fields:


https://nasa.tumblr.com/post/612502266197557248/weird-magnetic-behavior-in-space

Solving The Heating Problem – Magnetic Reconnection



Continuity Equation:

$$\cancel{\frac{\partial \rho}{\partial t}} + \nabla \cdot (\rho \mathbf{v}) = 0 \implies \cancel{\rho} v_0 L \Delta y = \cancel{\rho} v_{out} d \Delta y$$

Steady State

Constant Density

$$\boxed{v_0 L = v_{out} d}$$

Ohm's Law: $\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{J}$

Sheet Edge: $J_y = 0 \implies E_y = v_0 B_0$

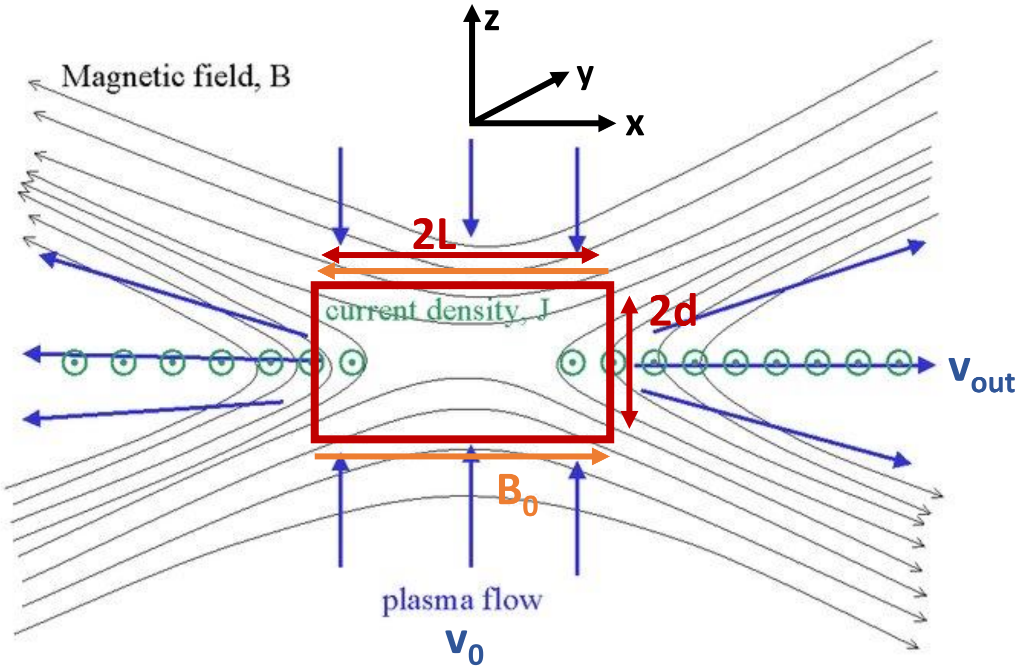
Sheet Center: $v_z = 0 \implies E_y = \eta J_y$

$$\boxed{v_0 B_0 = \eta J_y}$$

Ampere's Law:

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} \implies \boxed{\frac{B_0}{d} = \mu_0 J_y}$$

Solving The Heating Problem – Magnetic Reconnection



v_{out}/v_0-Relationship:

$$\boxed{v_0 L = v_{out} d}$$

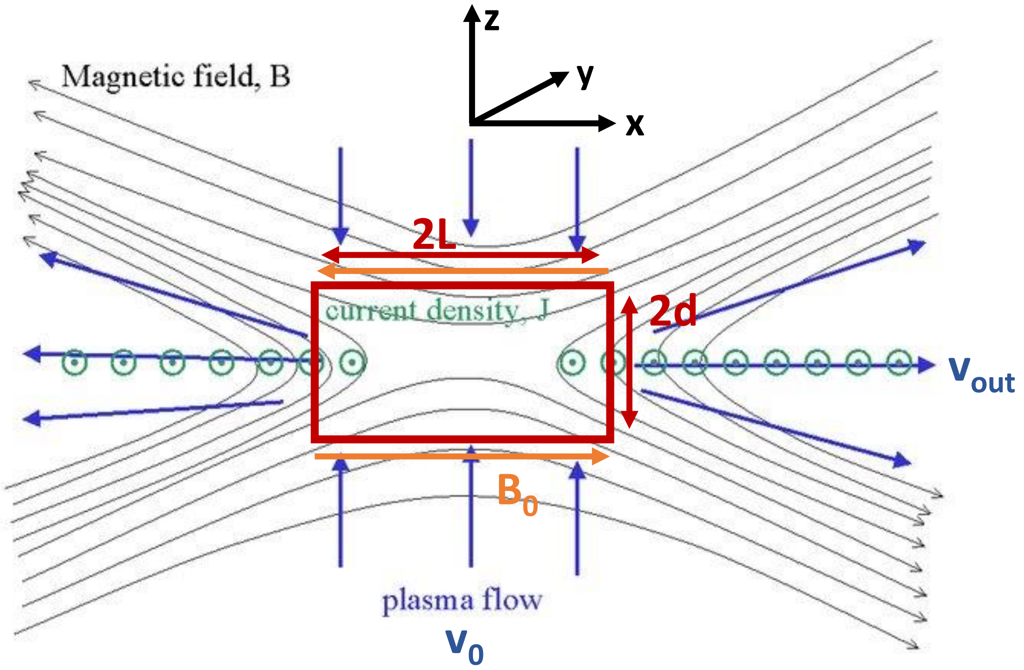
$$\boxed{v_0 B_0 = \eta J_y}$$

$$\boxed{\frac{B_0}{d} = \mu_0 J_y}$$

$$\boxed{v_0 B_0 = \frac{\eta B_0}{d \mu_0}}$$

$$\boxed{v_{out} = \frac{\mu_0 L}{\eta} v_0^2}$$

Solving The Heating Problem – Magnetic Reconnection



v_{out}/v_0-Relationship:

$$\boxed{v_{out} = \frac{\mu_0 L}{\eta} v_0^2}$$

MHD Eq. of Motion:

$$\rho(\mathbf{v} \cdot \nabla)\mathbf{v} = -\nabla p + \mathbf{J} \times \mathbf{B}$$

$$\Longrightarrow \boxed{v_{out} = \frac{B_0}{\sqrt{\rho \mu_0}} = v_{Alfven}}$$

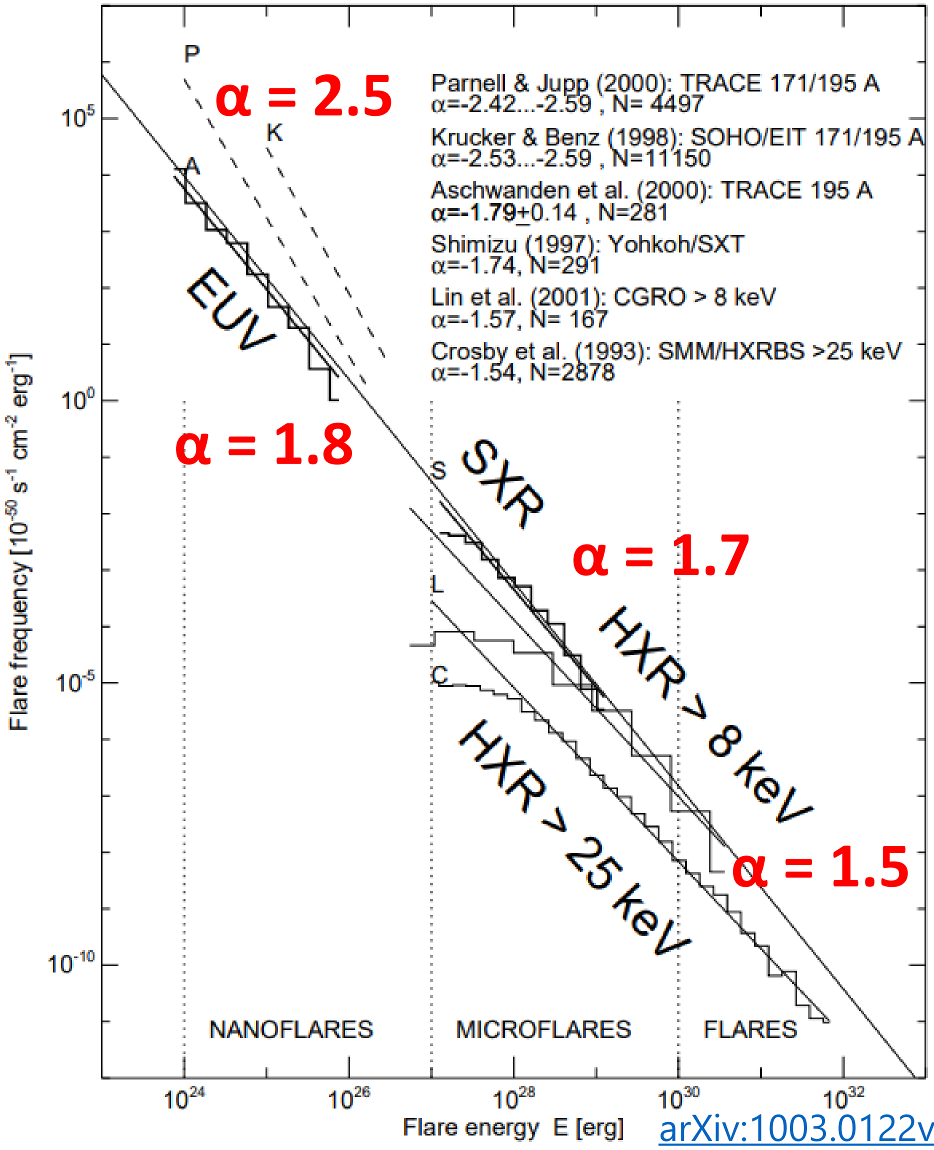
Energy Dissipation:

$$\frac{\mathrm{E}_{\mathrm{kin,out}}}{\mathrm{E}_{\mathrm{EM,in}}} = \frac{\frac{1}{2}\rho v_{out}^2 \cdot d\Delta y}{\frac{B_0^2}{\mu_0} \cdot L\Delta y} = \frac{1}{2}\frac{v_{out}^2}{v_{Alfven}^2} = \frac{1}{2}$$

Reconnection events are a source of fast, hot plasma!

Solving The Corona Heating Problem – Nano Flares

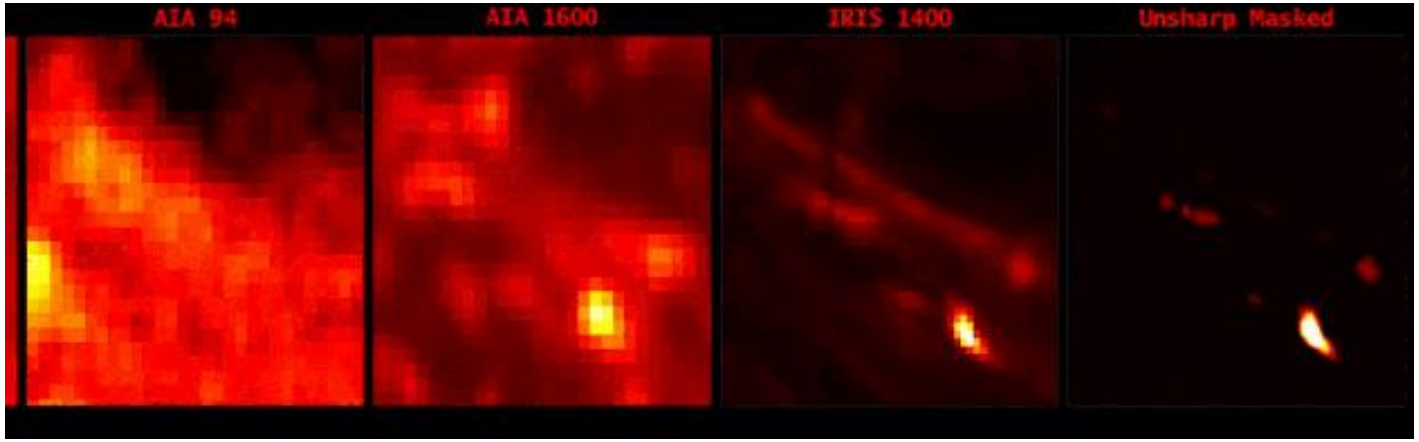
- Power-law coefficient for sufficient coronal heating: **$\alpha \gtrsim 2.0$**
- Only **nanoflares** could explain heating
- Problem: Very hard to observe!



arXiv:1003.0122v1

Solving The Corona Heating Problem – Nano Flares

Potential First Nano Flare Observation:




nature astronomy
LETTERS
https://doi.org/10.1038/s41550-020-01263-2

Check for updates

The origin of reconnection-mediated transient brightenings in the solar transition region

Shah Mohammad Bahauddin[1]✉, Stephen J. Bradshaw[2] and Amy R. Winebarger[3]

The ultraviolet emission from the solar transition region is dominated by dynamic, low-lying magnetic loops. The enhanced spatial and temporal resolution of the solar observation satellite Interface Region Imaging Spectrograph (IRIS) has made it possible to study these structures in fine detail. IRIS has observed 'transient brightenings' in these loops, associated with strong excess line broadenings[1,2] providing important clues to the mechanisms that heat the solar atmosphere. However, the physical origin of the brightenings is debated. The line broadenings have been variously interpreted as signatures of nanoflares[3], magneto-hydrodynamic turbulence[4], plasmoid instabilities[5] and magneto-acoustic shocks[6]. Here we use IRIS slit-jaw images and spectral data, and the Atmospheric Imaging Assembly of the Solar Dynamics Observatory spacecraft, to show that the brightenings are consistent with magnetic-reconnection-mediated impulsive heating at field-line braiding sites in multi-stranded transition-region loops. The spectroscopic observations present evidence for preferential heating of heavy ions from the transition region and we show that this is consistent with ion cyclotron turbulence caused by strong currents at the reconnection sites. Time-dependent differential emission measure distributions are used to determine the heating frequency[7-9] and to identify pockets of faintly emitting 'super-hot' plasma. The observations we present and the techniques we demonstrate open up a new avenue of diagnostics for reconnection-mediated energy release in solar plasma.

IRIS has observed small-scale (a few million metres, Mm) loop-like structures with intermittent brightenings in the Sun's active regions, which are associated with excess line broadenings[1,2]. These rapidly evolving brightenings are remarkably consistent with previous High-Resolution Coronal Imager (Hi-C) observations of reconnection-mediated heating in coronal loops[10]. Figure 1 (and Supplementary Fig. 1) shows information revealed by IRIS regarding the geometries and the evolution of the brightened loops. Although Atmospheric Imaging Assembly (AIA) images and Helioseismic and Magnetic Imager (HMI) magnetograms from the Solar Dynamics Observatory (SDO) present these loops as singular, monolithic structures, having opposite polarity at their foot-points, unsharp masking applied to IRIS 1,400 Å slit-jaw images demonstrates the existence of substructures within the brightening regions, which we interpret to mean that the loops are multi-stranded. The 131 Å and 94 Å SDO/AIA passbands detect a signature of the aftermath of heating at the braiding sites: 'super-hot' plasma. The observations presented in Figs. 2 and 3 show a pixel-by-pixel analysis of the brightenings labelled 1 and 3 in Fig. 1, and the evolution of their spectra. The IRIS 1,400 Å channel is the primary mode for this analysis owing to its fast cadence and high spatial resolution, and because it contains several lines readily available for plasma diagnostics. The intensity of Si ɪv 1,403 Å emission varies strongly on the 50–100-s timescales over which the loops in Figs. 2 and 3 were rastered. This implies the presence of even faster variations below the timescale limit imposed by the rastering process. The density-sensitive O ɪv line ratio (1,399.766 Å/1,401.157 Å, Supplementary Table 1) finds number densities of 10^{11} cm^{-3} in the brightenings and densities of 10^{13} cm^{-3} in the darker regions, which are more characteristic of the upper chromosphere (Extended Data Fig. 1).

The Si ɪv 1,403 Å line changes profoundly in the bright regions; it becomes multi-peaked (Fig. 1, lower panel) and broadens substantially (full-width at half-maximum $\Delta\lambda \approx 300$ km s^{-1}). We decomposed the Si ɪv 1,403 Å profiles into two Gaussian components and found strong bi-directional flows with a maximum speed of 100 km s^{-1} towards and away from the observer. The two components of the bi-directional flows feature non-thermal components as large as 100 km s^{-1} (Figs. 2 and 3, see panels for Si ɪv(a) for the blue-shifted component and Si IV(b) for the red-shifted component). Strong Doppler shifts with broad non-thermal components are also observed in the S ɪv 1,404 Å line profile. The downwards (surfacewards) flow observed in Si ɪv 1,403 Å is somewhat slower than the upwards flow to conserve momentum, since the atmosphere is gravitationally stratified. However, the O ɪv 1,401 Å line profile is only ever weakly red-shifted (maximum 25 km s^{-1}) with a single component and no non-thermal broadening is observed.

We conjecture that the explanation for these different line profiles may lie in the formation temperatures of Si ɪv ($10^{4.8}$ K) and O ɪv (10^5 K). The bi-directional jet material cools as it expands and so a stronger signature of the flow is observed in the lower-temperature line; if the emission from O ɪv emanates from the slower, inner (and thus warmer) region of the reconnection jet, the Doppler-shifted components may not be sufficiently separable to resolve. Spectroscopic observations across a broader range of line formation temperatures than are currently available, and/or modelling and predictions of line profiles in non-equilibrium conditions for strong outflows, should address this matter in detail.

To further investigate the differences between the heavier (silicon and sulfur) ions, and lighter (oxygen) ion and their underlying causes, the ratio of the peak Si ɪv 1,403 Å and O ɪv 1,401 Å intensities is plotted for each pixel in Figs. 2 and 3 (top-right panels). This ratio is a strong diagnostic for non-equilibrium ionization and models show that enhanced values are induced by impulsive heating when density-dependent dielectronic recombination is included in the line-formation process and ions with enhanced lifetimes are transported into denser layers of the atmosphere[11]. Large Si/O peak

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2020

Summary - Solar Magnetics And The Corona

- The Sun Has Many Layers With **Different Transport Behavior**
- The Sun Has A **22 Year** Magnet Field **Turnover Cycle**
- This Causes **High Solar Activity** (Sun Spots, Prominences, …)
- The Corona Is **Hotter Than It Should Be**, But We Gradually Understand Why
- The Sun Is Still A ***Hot* Scientific Topic**

Any Burning Questions?