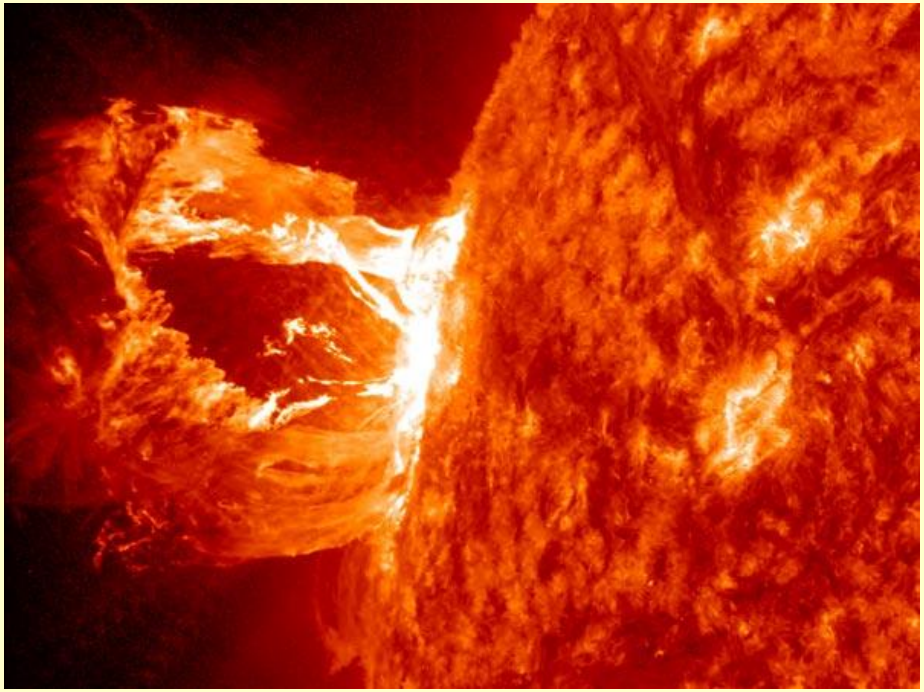
The Mysterious Magnetic Personality of our Sun



Arnab Rai Choudhuri

Department of Physics

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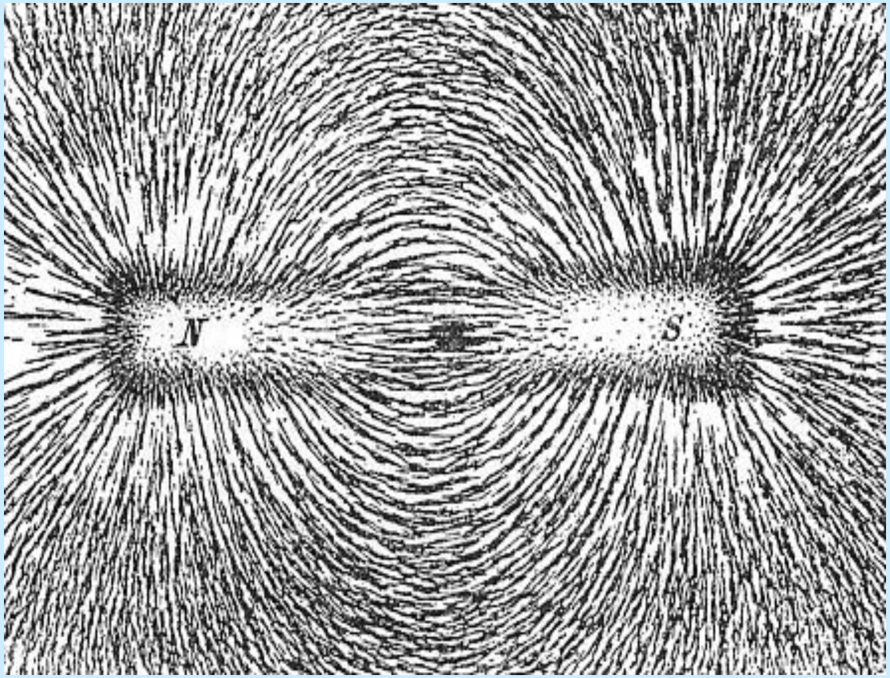
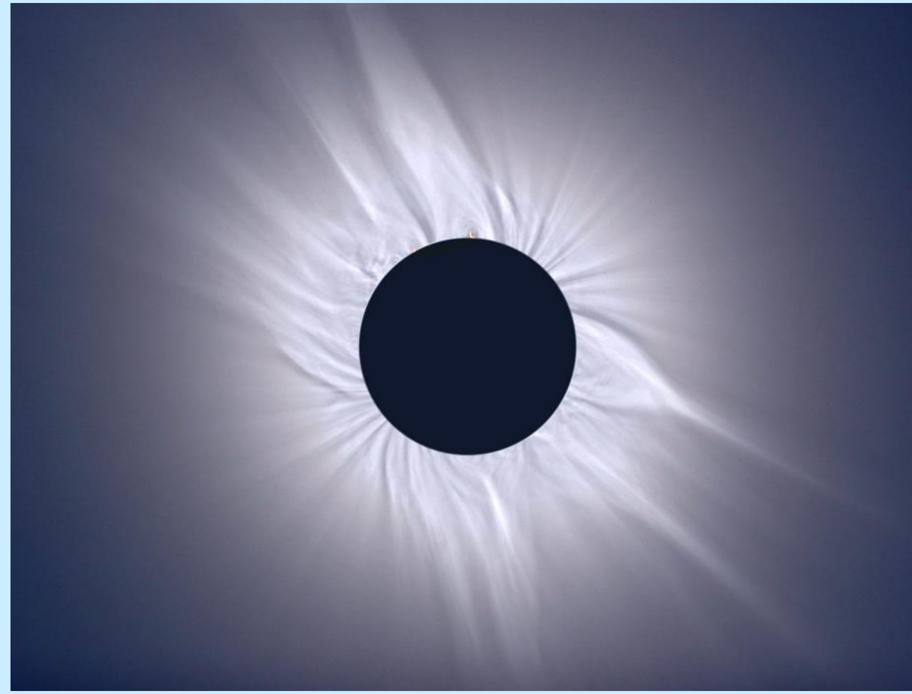




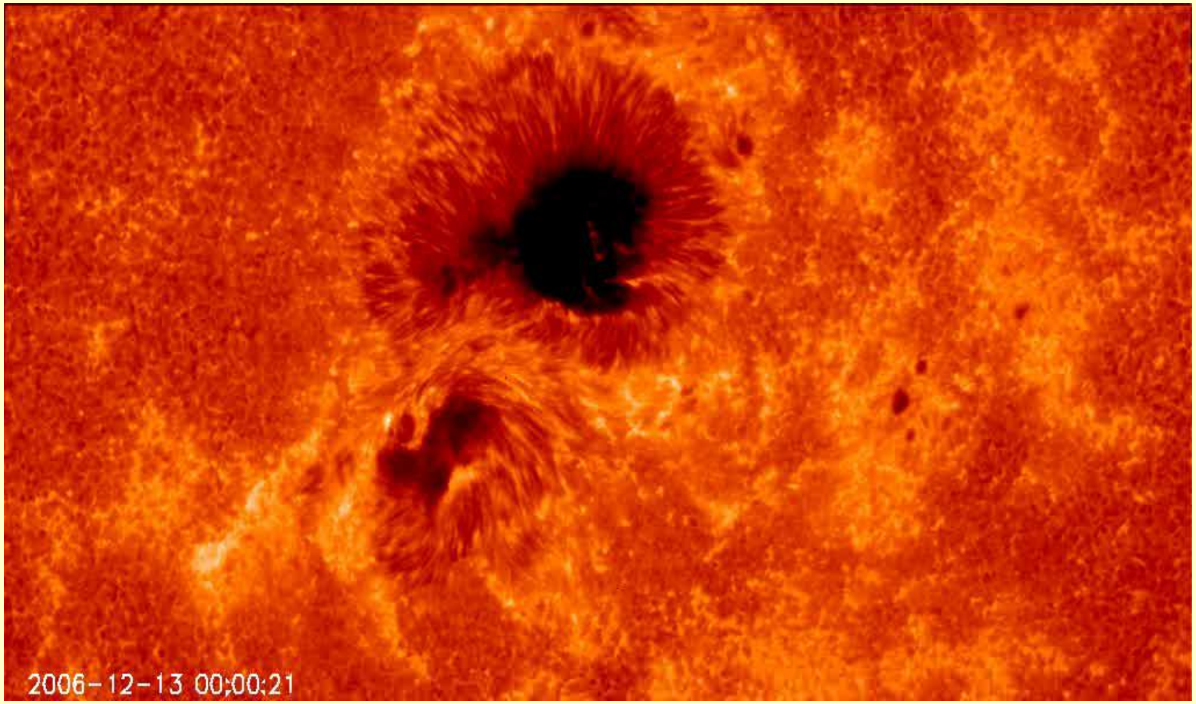
Iron filings around a bar magnet

Solar corona during a total solar eclipse

Solar magnetic fields do affect our lives!

March 13, 1989: About 6 million people in Quebec (Canada) were without electricity for 8 hours.

Cause: A major **solar flare** seen on March 9!



Flares occur above sunspots

Energy of a major flare ~ 10^{26} J

(Hiroshima atom bomb ~ 10^{14} J)

1859: Richard Carrington discovered the first solar flare

Energetic charged particles from flares can reach Earth's geomagnetic poles to produce **aurorae** and cause various geomagnetic disturbances

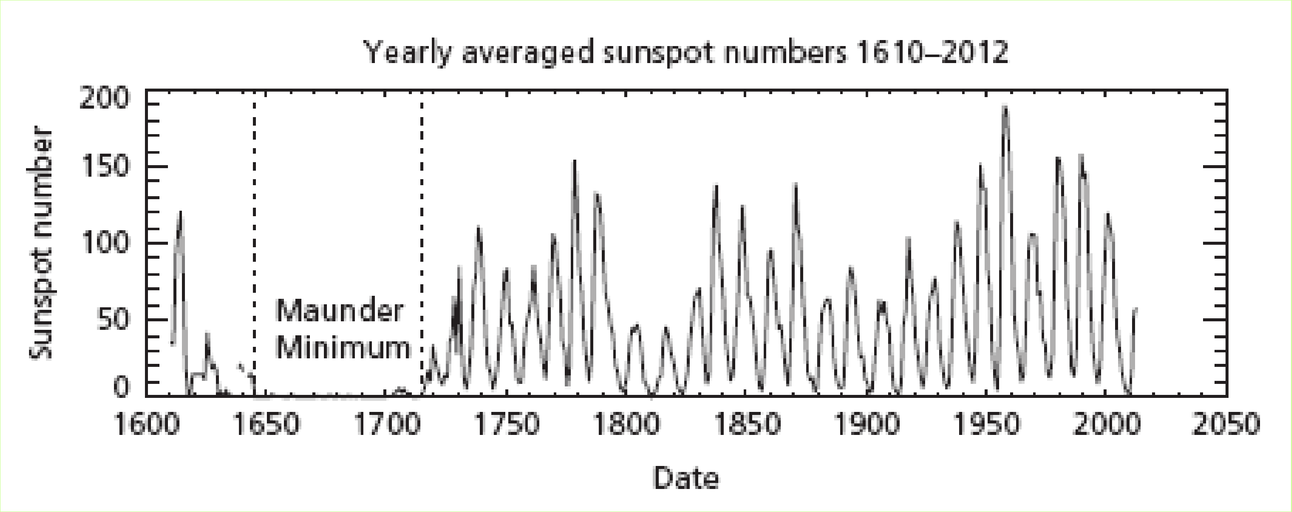
Damaging effects of solar disturbances

- Can disrupt radio communication by affecting the ionosphere
- Can damage electronic equipments in man-made satellites
- Can trip power grids
- Can make polar airlines routes dangerous

Can we figure out when more solar disturbances are likely to occur?

More sunspots => More solar disturbances

1844: Heinrich Schwabe discovered the 11-year sunspot cycle

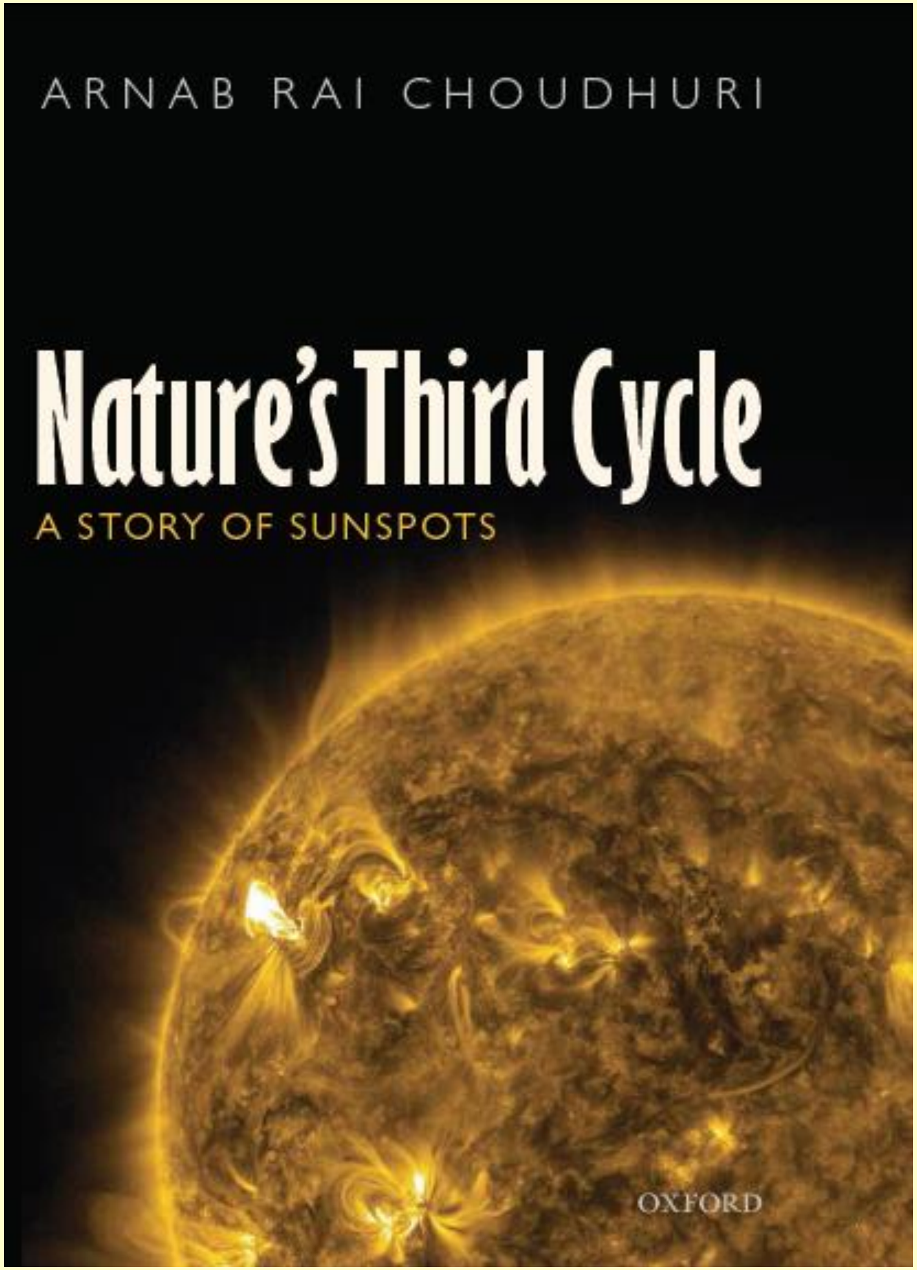


Nature’s third most important cycle for us, as we depend more on technology

The cycle has many irregularities

Maunder minimum 1640 – 1720

Little ice age!



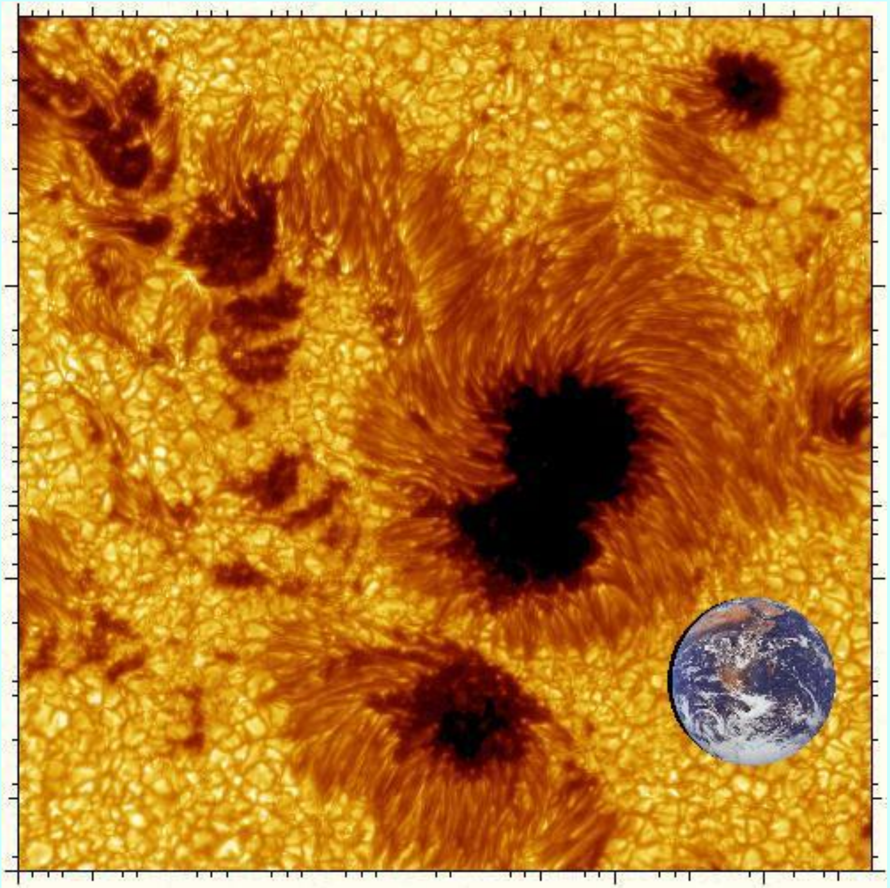
My recent popular science book published by Oxford University Press in January 2015

Amazon India is selling Kindle edition for less than Rs. 600/-

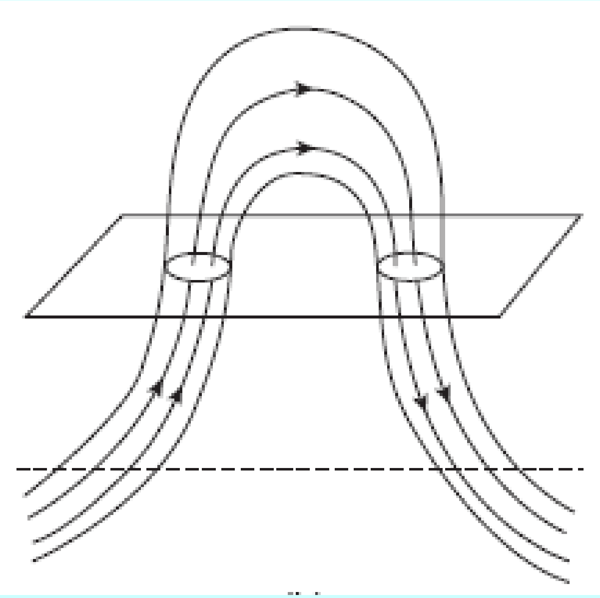
Paperback will come out in August 2017

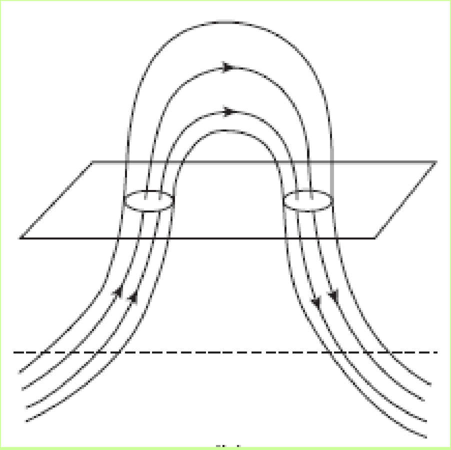
Hale (1908) discovered magnetic fields in sunspots from Zeeman splitting of magnetic fields (0.3 tesla)

Hale et al. (1919) – Often two large sunspots are seen side by side with opposite polarities



A strand of magnetic flux has come through the surface!



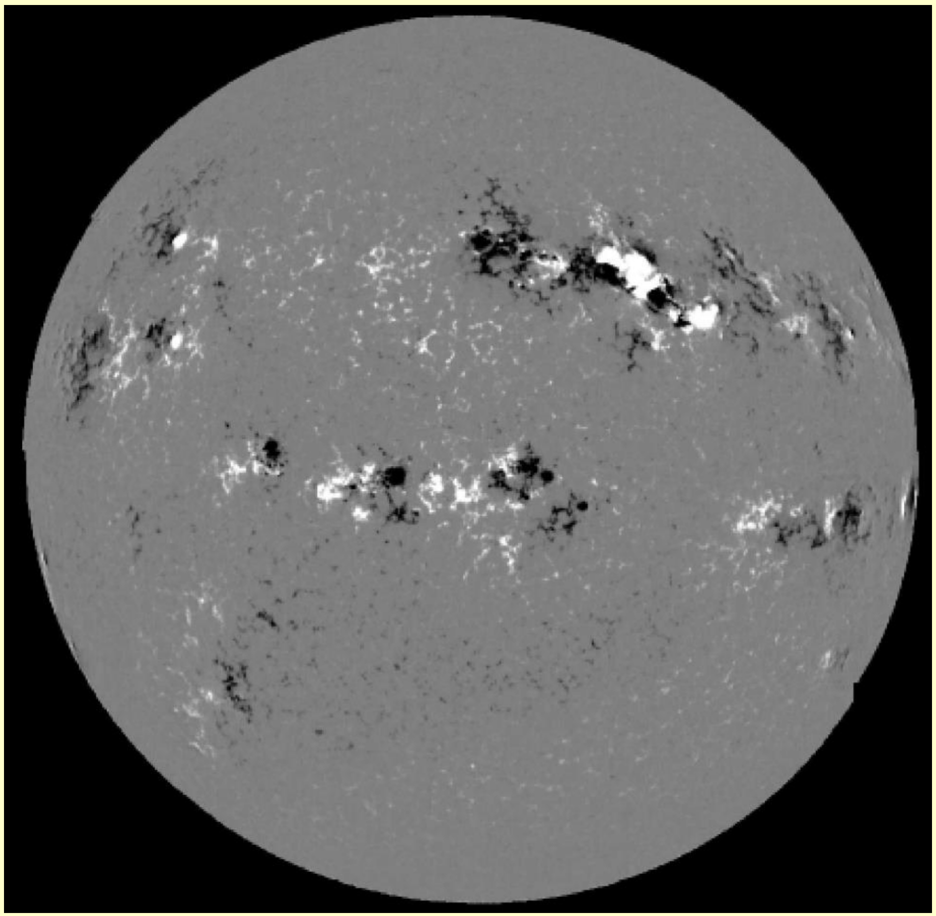


The solar corona is full of such magnetic loops

Loops emit in X-ray and Extreme ultra-violet (EUV)

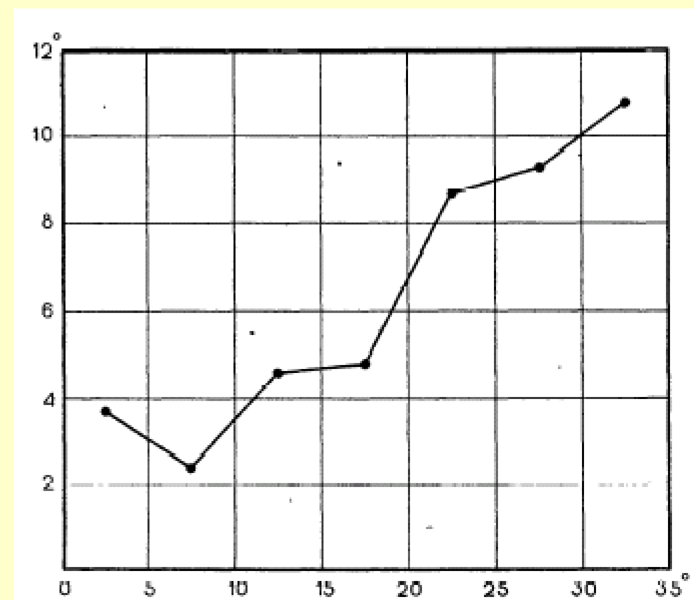
Magnetogram map (white +ve, black –ve)

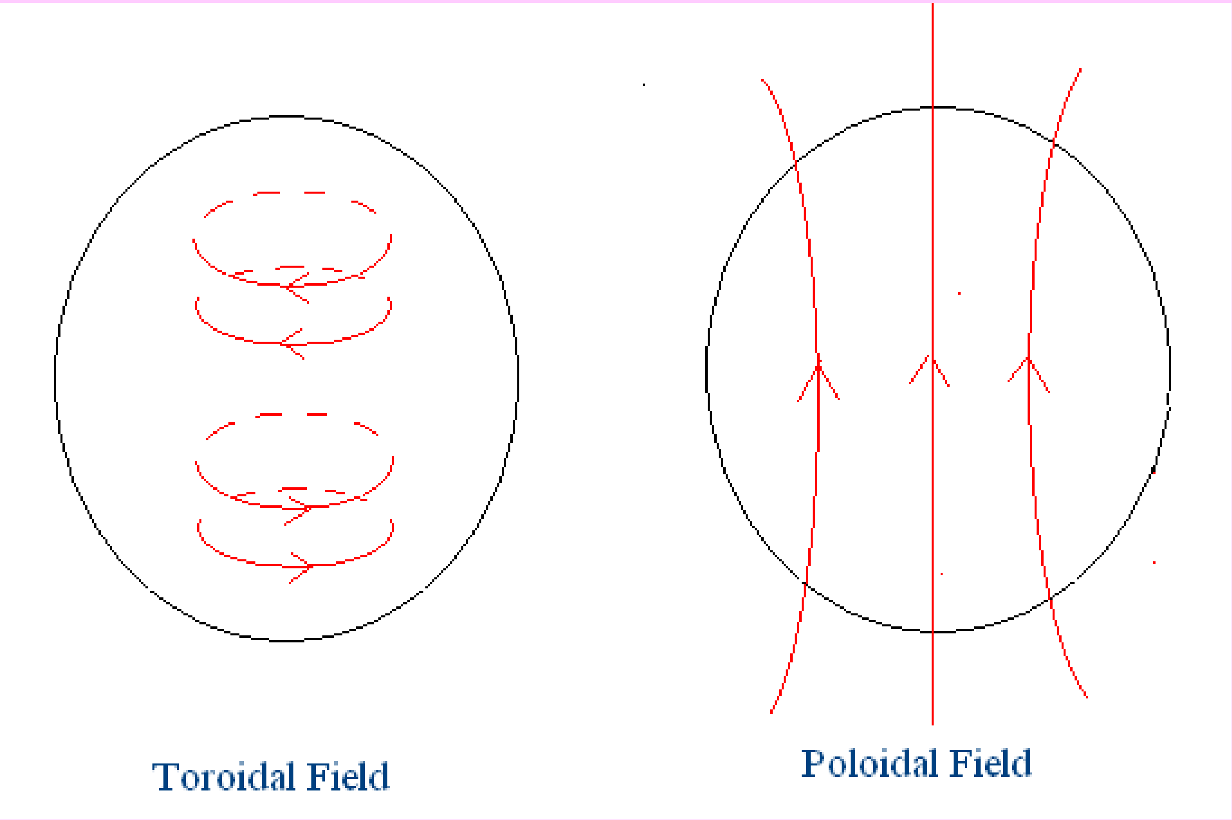
Polarity is opposite (i) between hemispheres; (ii) from one 11-yr cycle to next >> 22-yr period



Tilt of bipolar regions increases with latitude

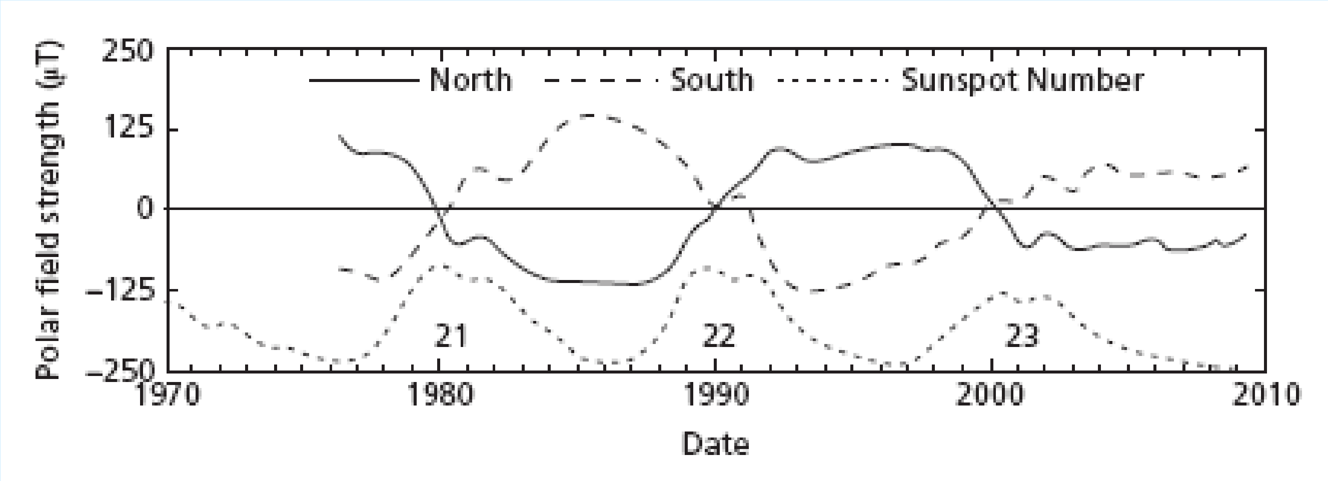
- Joy’s law (Joy 1919)





Parker (1955) suggested oscillation between the toroidal and poloidal fields.

Babcock & Babcock (1955) detected the weak poloidal field (~ 10^{-3} T)



The polar fields and the sunspot number as functions of time

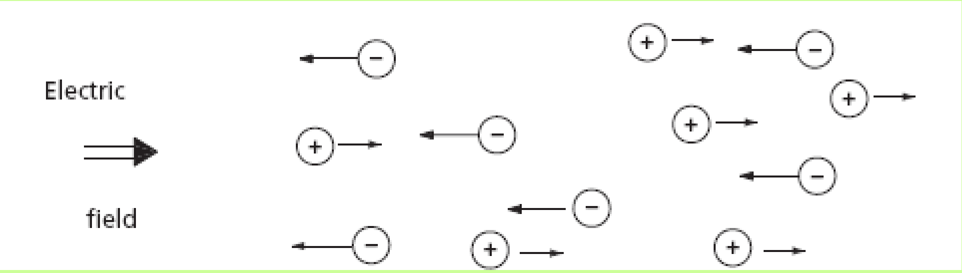
There is indeed an oscillation between toroidal magnetic field (indicated by sunspot number) and poloidal magnetic field (indicated by polar field), as envisaged by Parker (1955)

Central Dogma of solar dynamo theory

- The Sun’s magnetic field consists of both a toroidal component and a poloidal component
- Sunspots arise out of the toroidal field
- The polar field is a manifestation of the poloidal field
- There is a process producing toroidal field from poloidal field
- There is a process producing poloidal field from toroidal field, so that we get the cycle

The Plasma State: fourth state of matter

Saha (1920) studied how a gas gets ionized and converted into a plasma on increasing the temperature

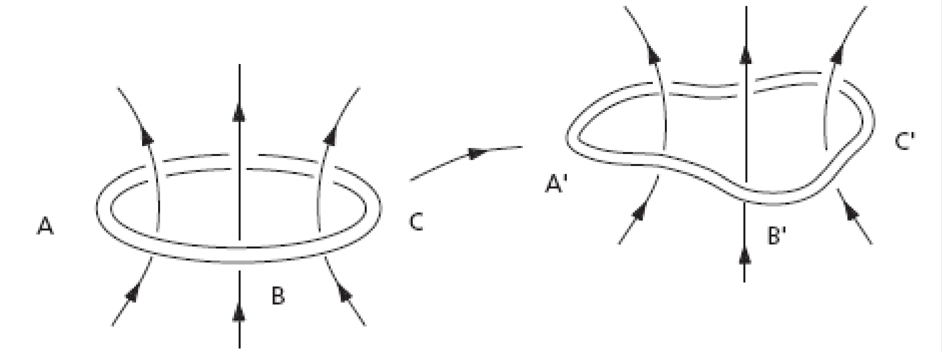


Plasmas can have strong currents and magnetic fields

Often we can treat a plasma as a continuum

Magnetohydrodynamics (MHD) – Electromagnetism + fluid mechanics

Alfven's theorem of flux freezing (Alfven 1942)



Flux through a loop of plasma remains conserved when the effect of resistance is negligible

Magnetic Reynolds number:

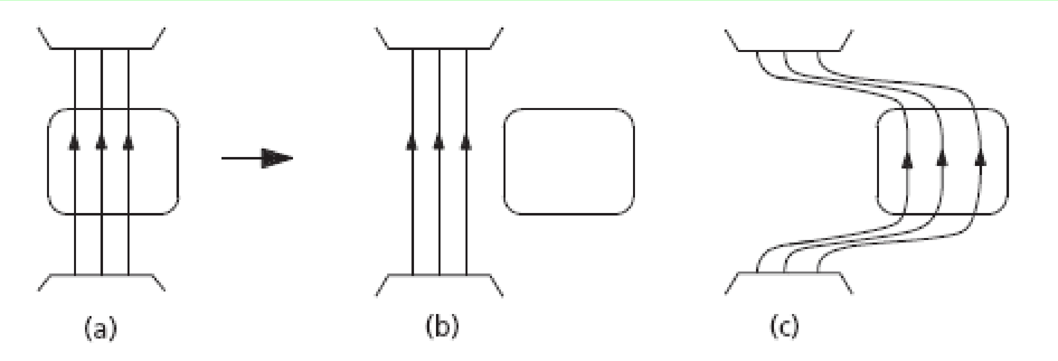
$$\mathcal{R}_{\mathrm{M}} = \frac{\mu_0 L V}{\rho},$$

μ_0 = electromagnetic constant,
L = size of system,
V = typical velocity,
ρ = resistivity.

Flux freezing condition:

$$\mathcal{R}_{\mathrm{M}} >> 1$$

Electrical resistance is less important for bigger systems! Flux freezing holds for astrophysical system =>
COSMICAL ELECTRODYNAMICS



$\mathcal{R}_M << 1$ $\mathcal{R}_M >> 1$

Magnetic field behaves like a plastic material in astrophysical systems

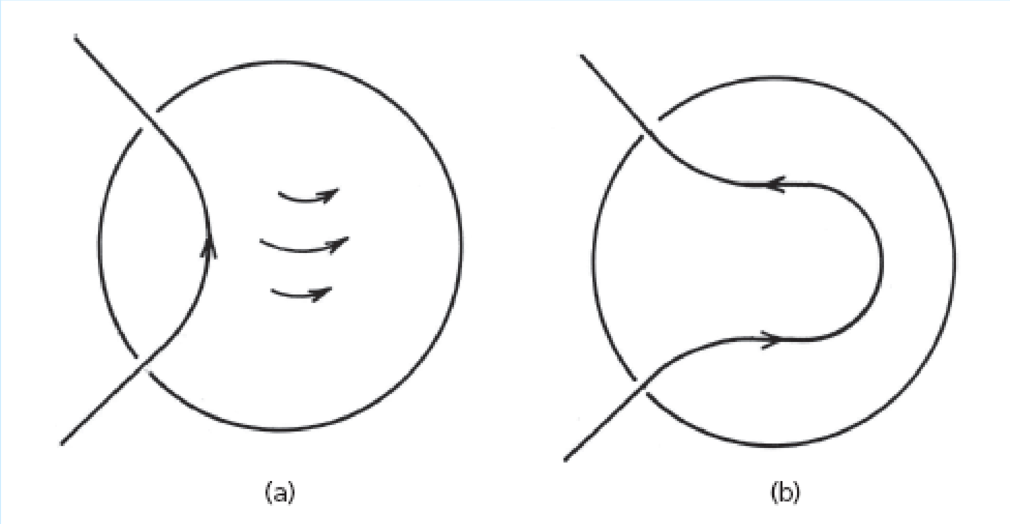
Symbiotic relation between MHD and solar physics

- Many solar phenomena require MHD for explanation
- Sun is the best place for testing many theoretical predictions of MHD

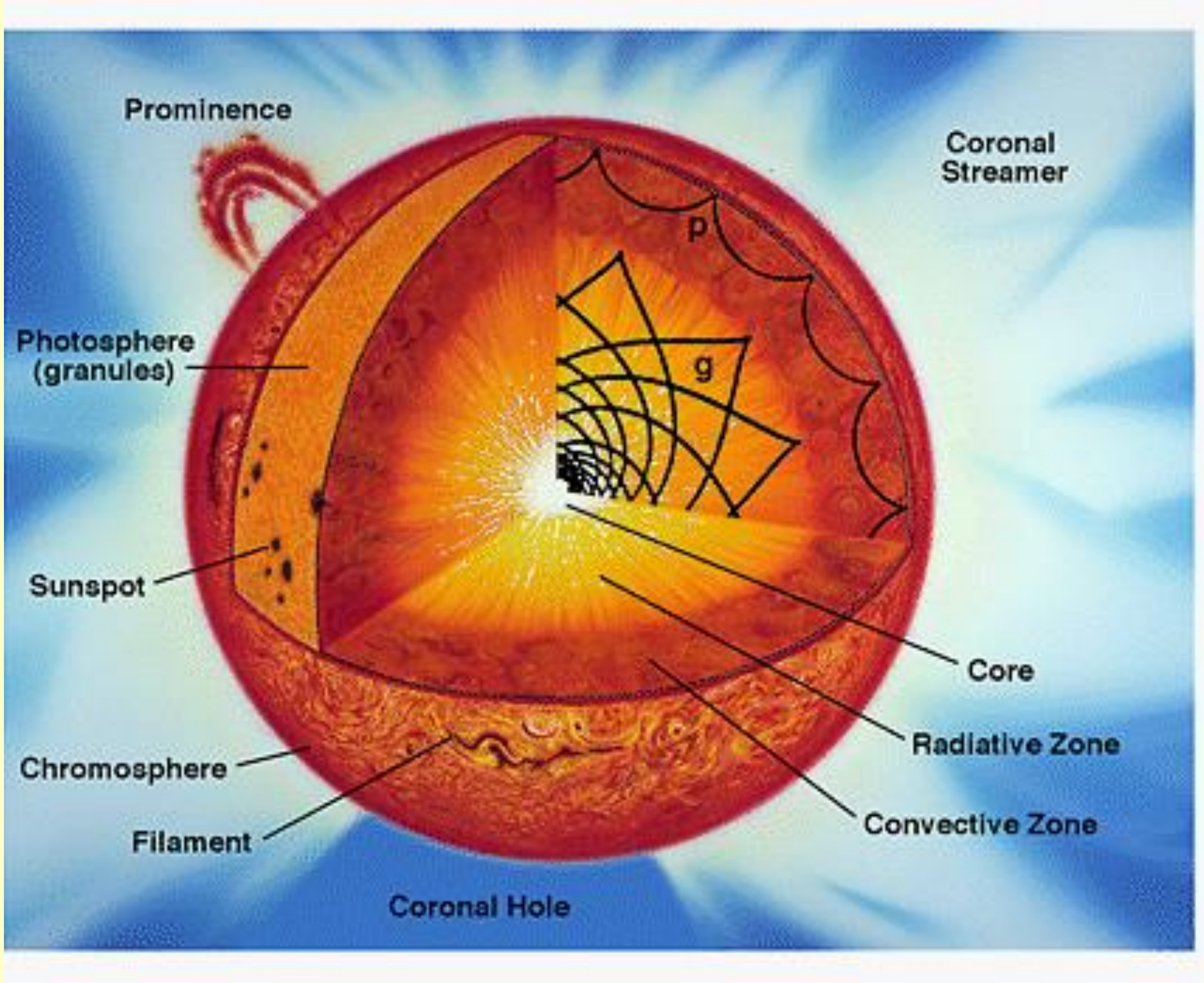
Solar MHD – The Sun is the best laboratory for high-$\mathcal{R}_M$ MHD!

The Sun rotates around its axis in about 27 days, but does not rotate like a solid body

Equatorial regions rotate faster => Differential rotation



The toroidal magnetic field is stretched by the differential rotation to generate the poloidal magnetic field



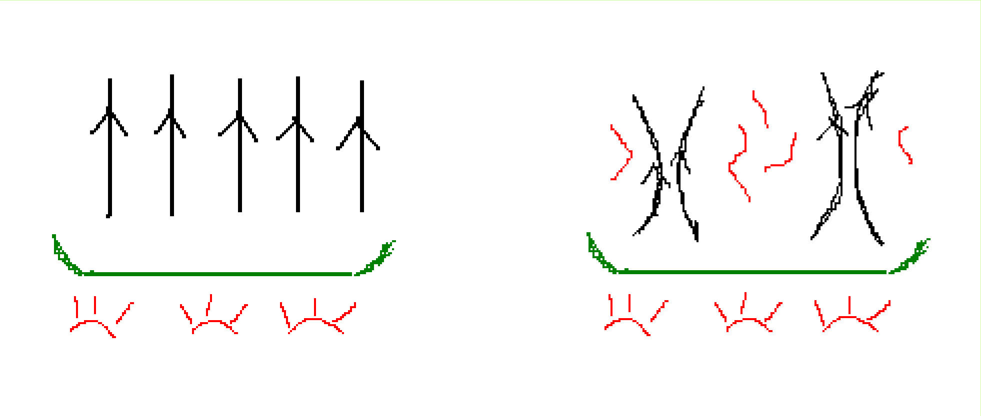
Sunspots are magnetic field concentrations in turbulent plasma

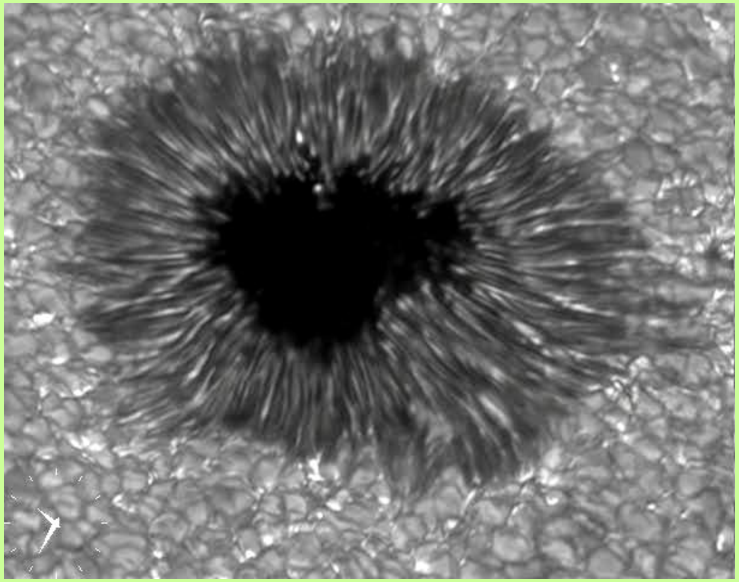
Heat is transported outward by radiative transfer till $0.7R$ and then by convection in the zone $0.7R$ – R

Magnetoconvection

Linear theory – Chandrasekhar 1952

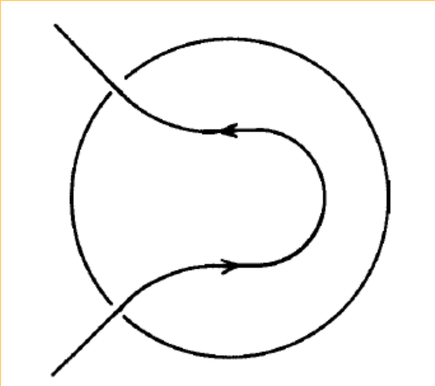
Nonlinear evolution – Weiss 1981; . . .





Sunspots are magnetic field concentrations with suppressed convection

Magnetic field probably exists as flux tubes within the solar convection zone



Why do parts of the toroidal magnetic field float up?

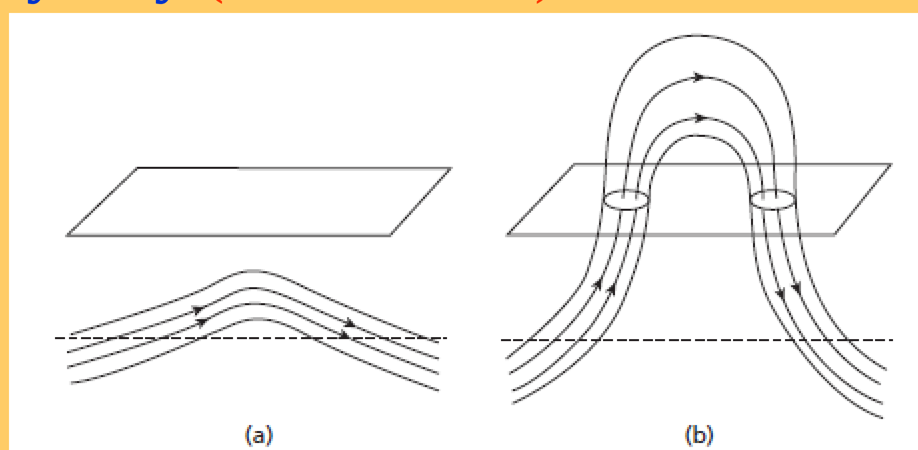
Horizontal Magnetic Flux Tube

$$p_{\rm out} = p_{\rm in} + \frac{B^2}{2\mu} \longrightarrow p_{\rm in} \le p_{\rm out}$$

Usually the inside is under-dense

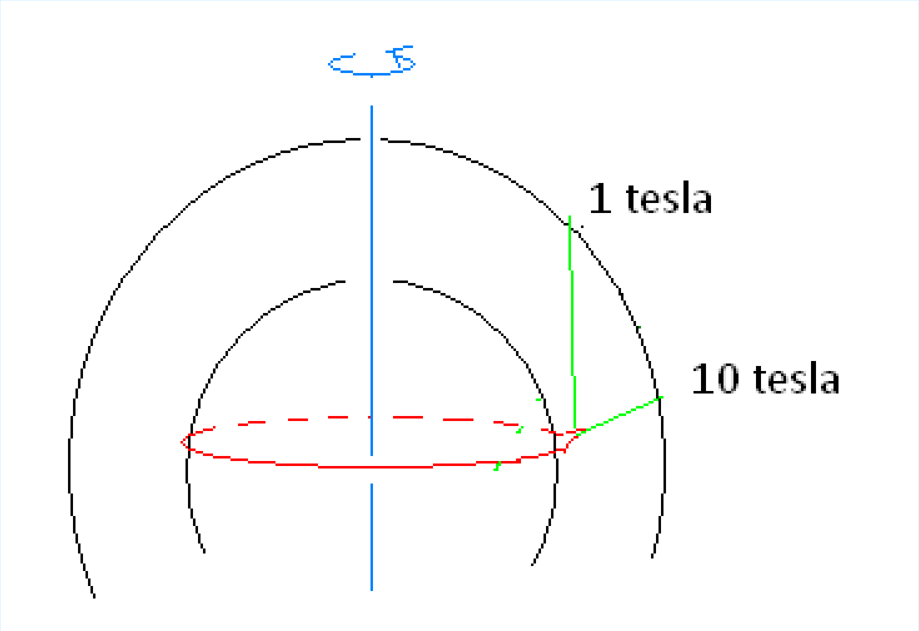
Magnetic buoyancy (Parker 1955)

Very destabilizing within the convection zone, but much suppressed below its bottom



3D dynamics of flux tubes in solar convection zone

(Choudhuri & Gilman 1987; Choudhuri 1989; D’Silva & Choudhuri 1993; Fan et al. 1993; Caligari et al. 1995)



Early dynamo models suggested B at bottom to be 1 tesla, but such fields are diverted by Coriolis force (Choudhuri & Gilman 1987)

Only 10 tesla fields can emerge at sunspot latitudes

Joy's Law (1919) – Tilts of bipolar sunspots increase with latitude

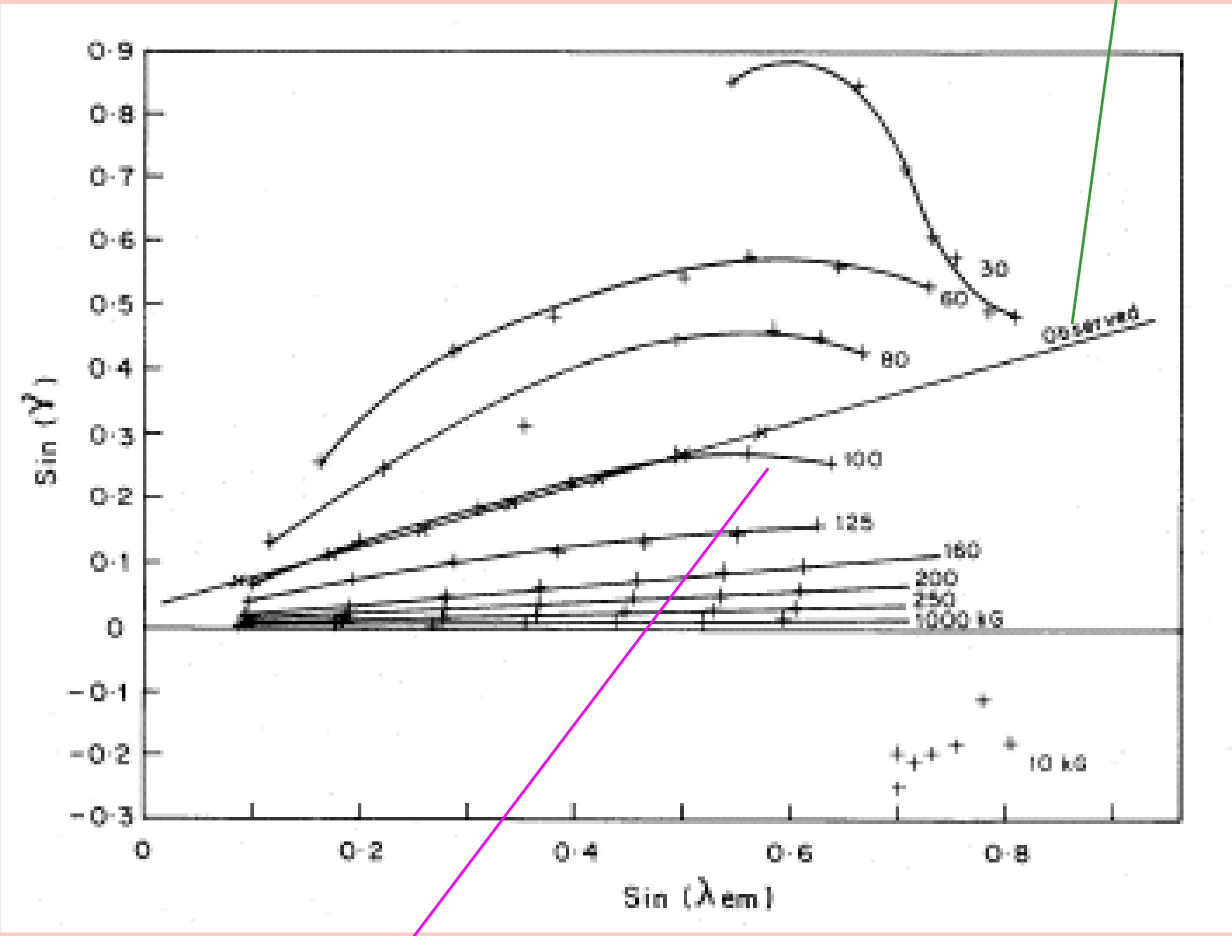


Figure from D'Silva & Choudhuri (1993) – First quantitative explanation!

Only 100 kG = 10 tesla fields match observations!

Early models of solar dynamo could not work with magnetic fields stronger than 1 tesla

Invoking some early ideas of Babcock (1961) and Leighton (1964), flux transport dynamo model for the sunspot cycle was developed to allow for much stronger fields

The workability of this model was demonstrated by Choudhuri, Schussler & Dikpati (1995)

Basic Equations

Magnetic field

$$\boldsymbol{B} = B(r,\theta)\boldsymbol{e}_\phi + \nabla \times [A(r,\theta)\boldsymbol{e}_\phi],$$

Velocity field

$$\Omega(r,\theta)\, r \sin\theta\, \mathbf{e}_\phi + \mathbf{v}$$

$$\frac{\partial A}{\partial t} + \frac{1}{s}(\boldsymbol{v}.\nabla)(sA) = \eta_\mathrm{p}\left(\nabla^2 - \frac{1}{s^2}\right)A + \alpha B,$$

$$\frac{\partial B}{\partial t} + \frac{1}{r}\left[\frac{\partial}{\partial r}(rv_r B) + \frac{\partial}{\partial \theta}(v_\theta B)\right] = \eta_\mathrm{t}\left(\nabla^2 - \frac{1}{s^2}\right)B + s(\boldsymbol{B}_\mathrm{p}.\nabla)\Omega + \frac{1}{r}\frac{\mathrm{d}\eta_\mathrm{t}}{\mathrm{d}r}\frac{\partial}{\partial r}(rB)$$

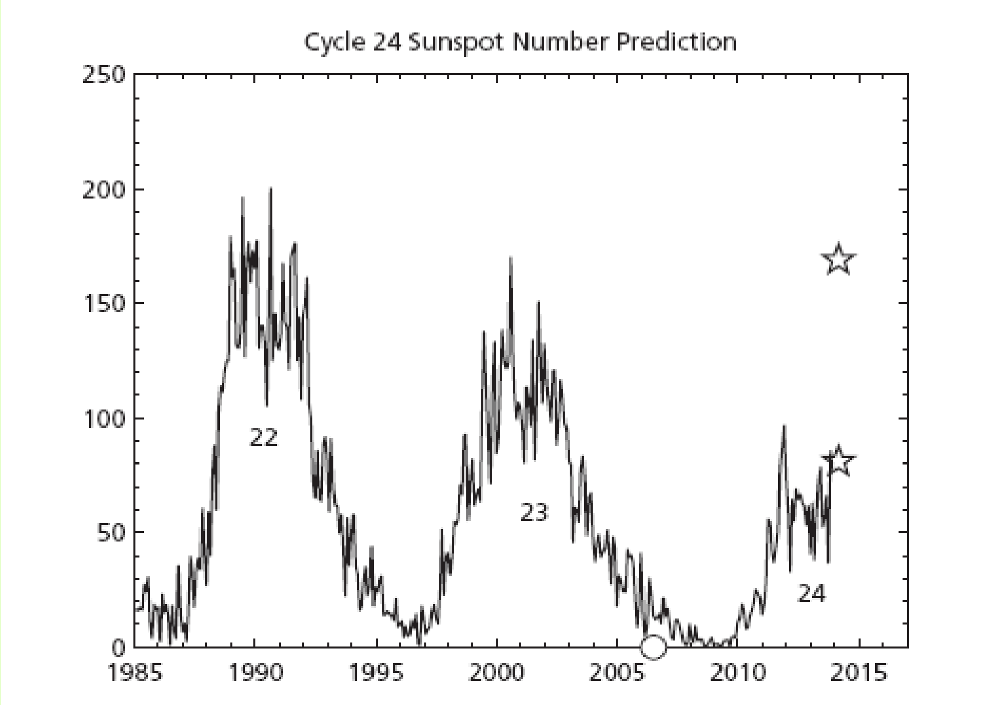
The code *Surya* solves these equations

For a range of parameters, the code relaxes to periodic solutions (Nandy & Choudhuri 2002, *Science* **296**, 1671)

Can we predict the strength of a sunspot cycle before its advent?

Dikpati & Gilman (2006) predicted a strong cycle 24

Choudhuri, Chatterjee & Jiang (2007) predicted a weak cycle 24



Our prediction is the first successful prediction of a sunspot cycle from a theoretical dynamo model!!

Two papers from our group had been selected as "Editors' suggestion" in *Physical Review Letters*

PRL **98,** 131103 (2007) PHYSICAL REVIEW LETTERS week ending 30 MARCH 2007

Predicting Solar Cycle 24 With a Solar Dynamo Model

Arnab Rai Choudhuri,[1,2,*] Piyali Chatterjee,[1] and Jie Jiang[2]

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(Received 9 January 2007; published 29 March 2007)

PRL **109,** 171103 (2012) PHYSICAL REVIEW LETTERS week ending 26 OCTOBER 2012

Origin of Grand Minima in Sunspot Cycles

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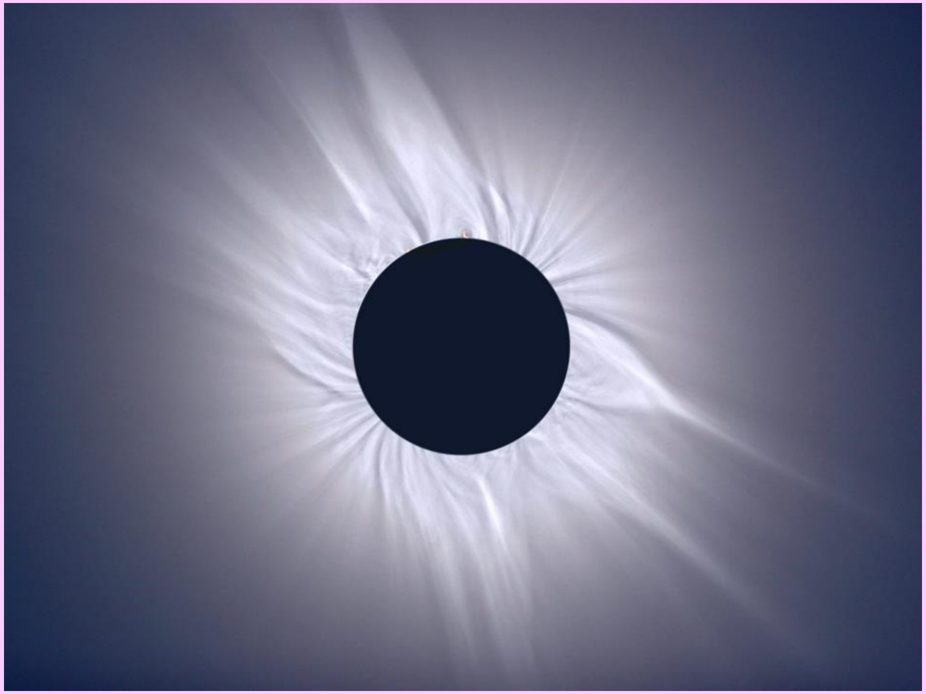
(Received 30 March 2012; published 25 October 2012)

Although Sun's surface has a temperature of about 6000 K, the temperature of the corona is millions of degrees!!!



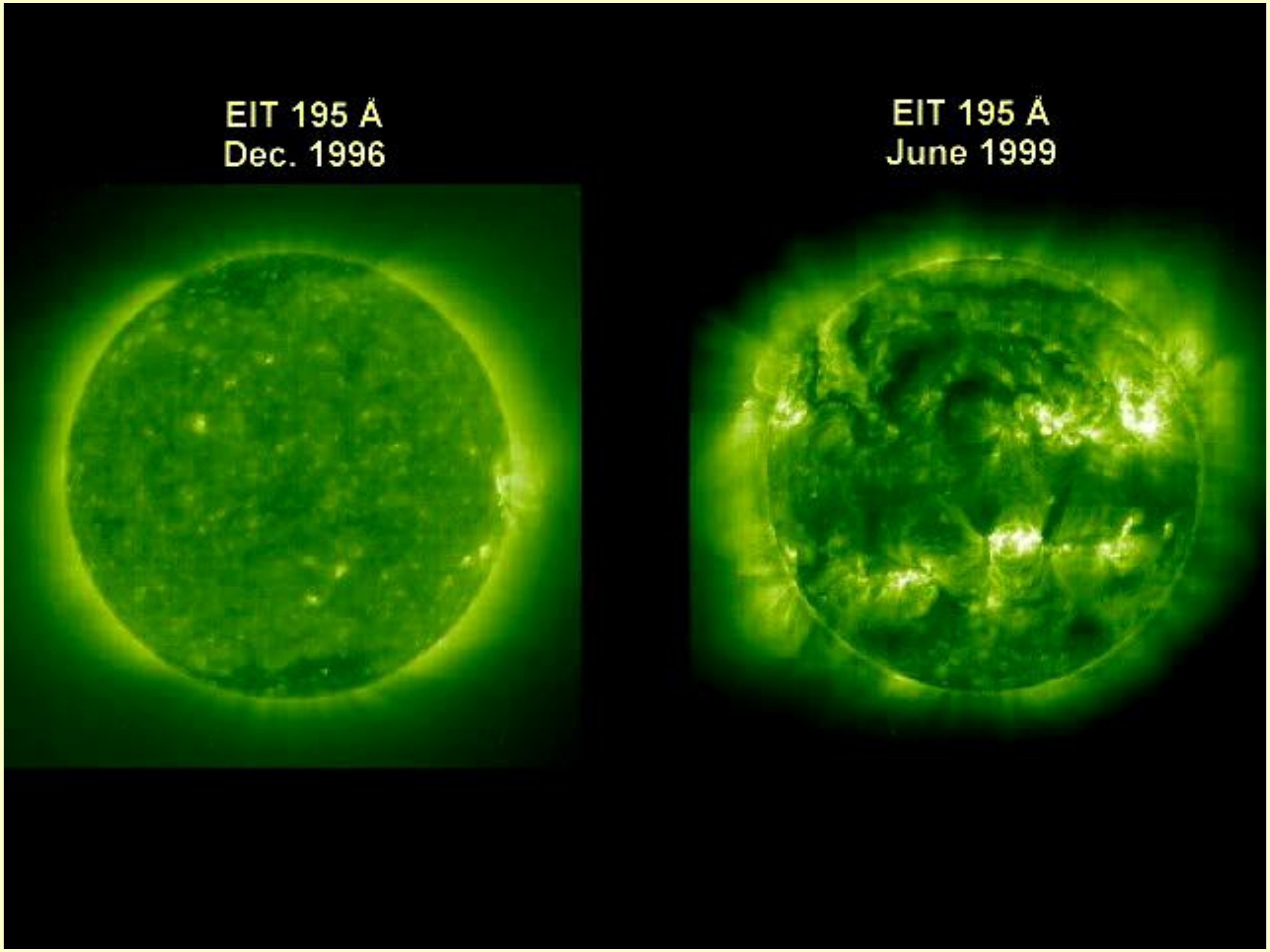
First inferred from spectral lines of the corona (Edlen 1943)

Do we have a violation of the second law of thermodynamics?

Hottest regions of the corona should emit X-rays and Extreme UV

Has to be detected from space

Rotating Sun seen in Extreme UV



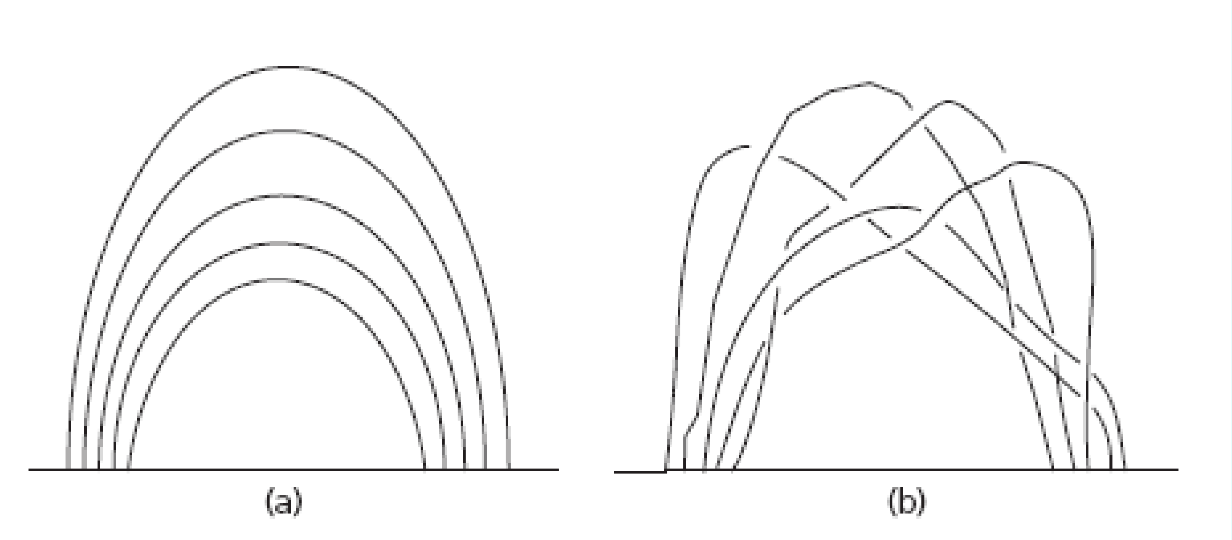
Solar Minimum

Solar Maximum

Magnetic fields in the coronal loops imply currents

Can the heat generated by the currents produce the high tempature of the corona? – Only if the currents flow through narrow regions!

Parker (1972) – disturbances of footpoints by convection tangles up magnetic fields

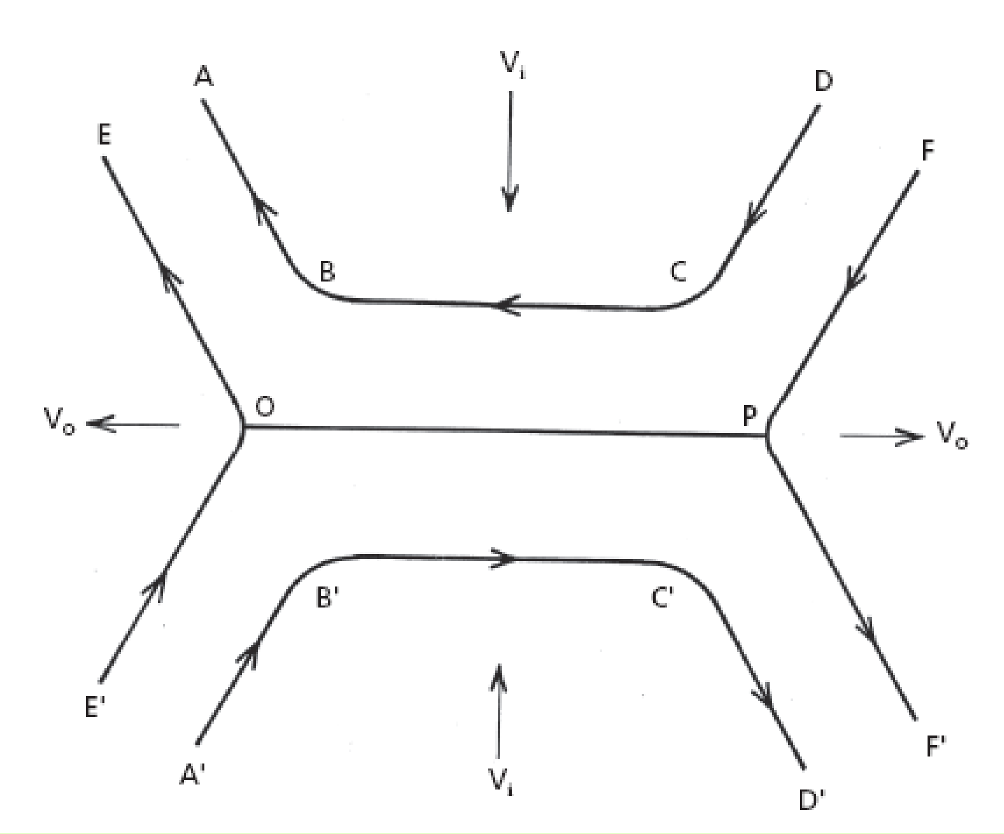


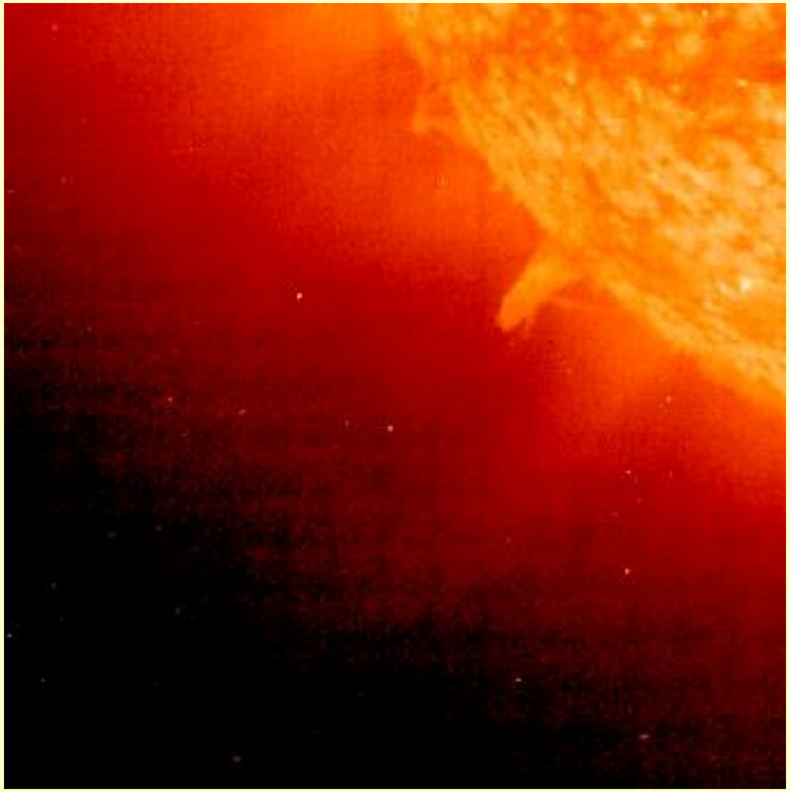
Currents flow through narrow regions and heat the corona

Magnetic reconnection – Sweet 1958, Parker 1957, Petschek 1964

Heating goes as j^2 and is important in the central region where current density j is high

Solar flares are caused by magnetic reconnection in gigantic regions where often two flux systems come across each other





Eruptive Prominence

Coronal Mass Ejection (CME)

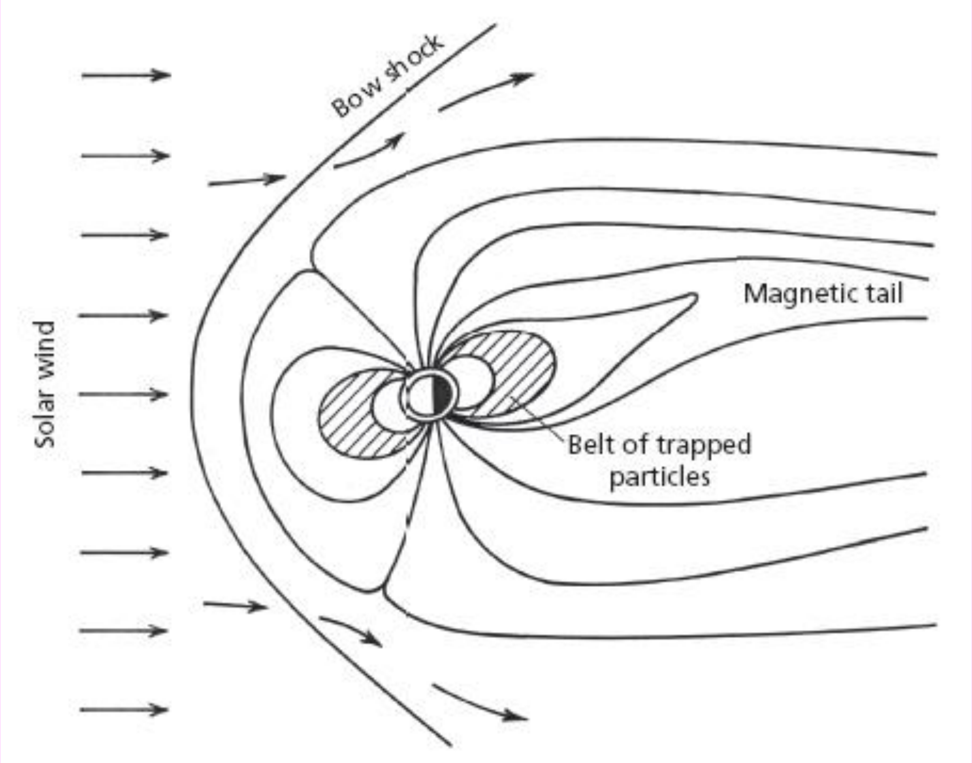
More flares, eruptive prominences and CMEs occur when there are more sunspots

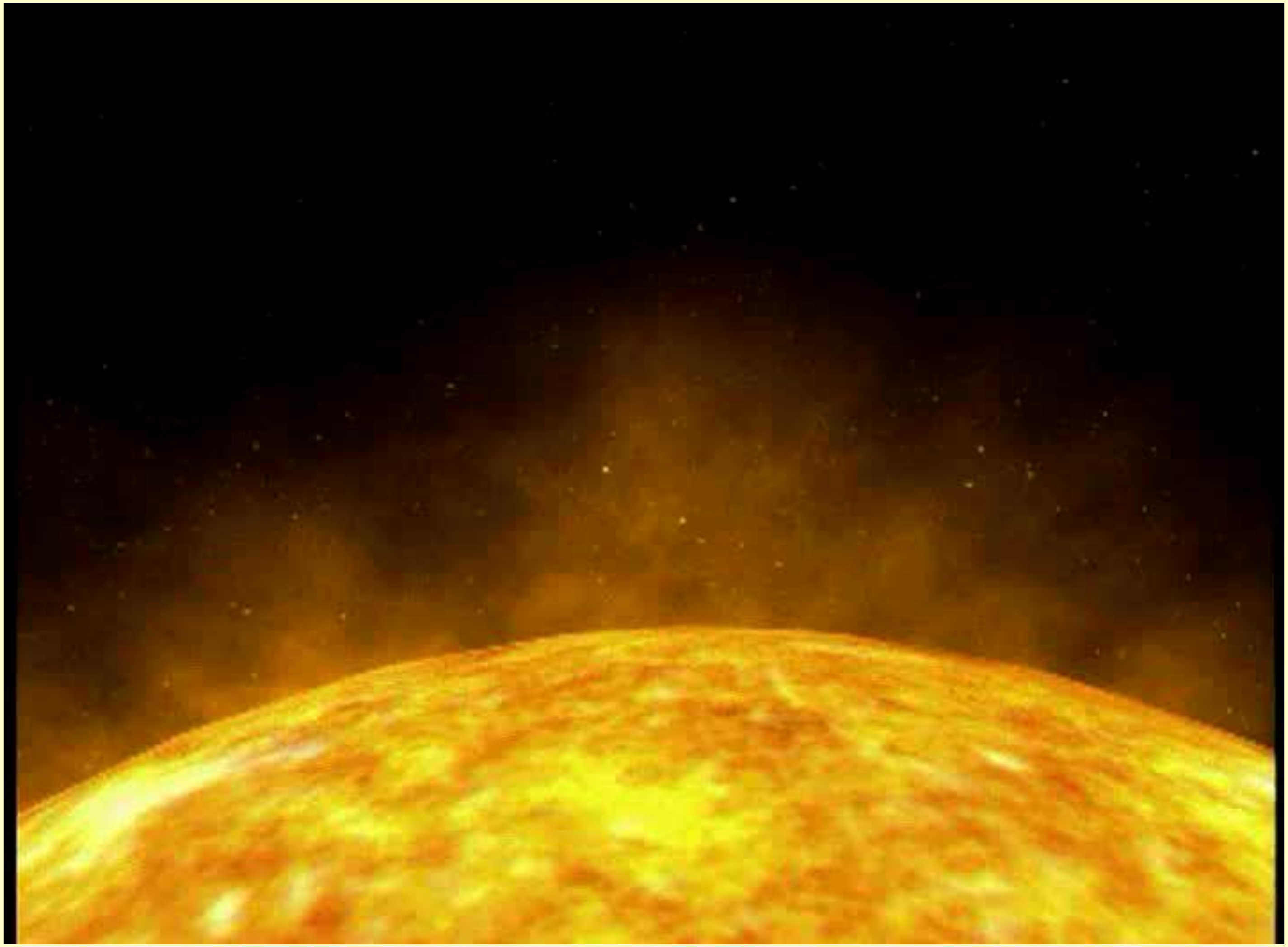
Parker 1958 – Sun's gravitational field is unable to keep the hot corona confined => a plasma outflow, the **solar wind**

Discovered by space missions within 3 – 4 years!

Solar disturbances may be carried with the solar wind, taking 3 – 4 days to reach the earth

The solar wind impinges on the Earth's magnetosphere, making it lop-sided

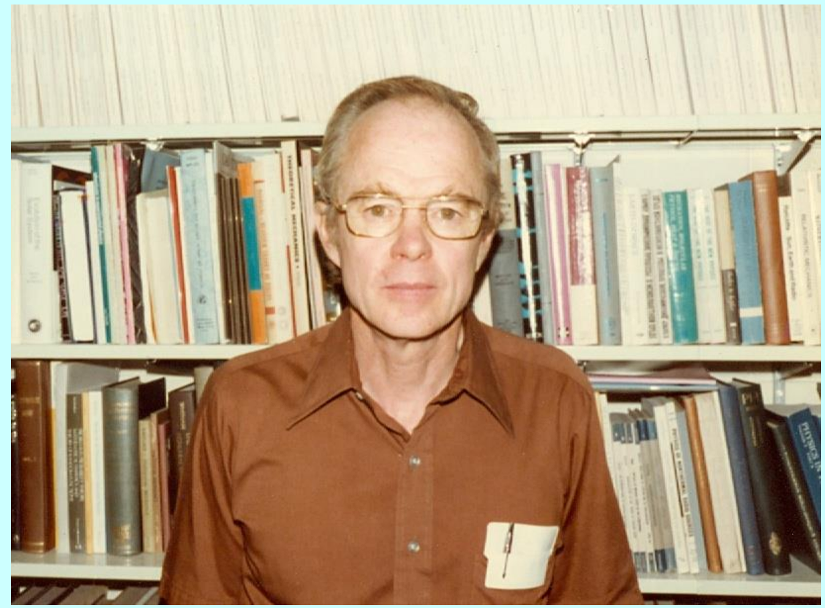




Caution: This movie is based on computer animations and not on actual observations

Dynamo process $\xrightarrow[\text{Magnetic fields}]{\text{Produces}}$ Magnetic buoyancy $\xrightarrow[\text{Sunspots}]{\text{Produces}}$ Currents in loops $\xrightarrow[\text{Hot corona}]{\text{Produces}}$ Solar wind

Eugene Newman
Parker (1927 -)
My guru



Laboratory for Astrophysics and Space Research, University of Chicago

Much of the credit for my small scientific achievements should go to my students

- Sydney D'Silva
- Mausumi Dikpati
- Dibyendu Nandy
- Piyali Chatterjee
- Jie Jiang
- Bidya Binay Karak
- Gopal Hazra

Faraday's law of electromagnetic induction – Changing magnetic flux induces current in a circuit
Lenz's law – Induced current opposes the change of magnetic flux
Magnetic flux cannot change through a circuit if resistance is zero!!

$$-\frac{d\Phi_{\mathrm{ext}}}{dt} = L\frac{dI}{dt} + RI,$$

From which

$$-\frac{d}{dt}(\Phi_{\mathrm{ext}} + LI) = RI.$$

If $R = 0$, then

$$\Phi_{\mathrm{ext}} + LI = \text{constant}.$$

MHD analogue was discovered by Alfven (1942)

Helioseimology

Leighton, Noyes & Simon 1962 – discovered solar oscillations

Deubner 1974 – recognized them as normal modes

Angular velocity distribution in the solar interior could be found by analyzing these oscillations

Strong differential rotation at the bottom of convection zone