Solar Magnetism

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Iron filings around a bar magnet  Solar corona during a total solar eclipse

Solar magnetic fields do affect our lives!
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 ultraviolet (EUV).
1844: Heinrich Schwabe discovered the 11-year sunspot cycle

The cycle has many irregularities
**Maunder minimum** 1640 – 1720
Little ice age!
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 ($\sim 10^{-3}$ 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 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


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

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
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

\[ B = B(r, \theta)e_\phi + \nabla \times [A(r, \theta)e_\phi], \]

Velocity field

\[ \Omega(r, \theta) r \sin \theta e_\phi + \mathbf{v} \]

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

The code \textit{Surya} solves these equations
Can we predict the strength of a sunspot cycle before its advent?


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

EIT 195 Å
Dec. 1996

EIT 195 Å
June 1999

Solar Minimum  Solar Maximum
Magnetic fields in the coronal loops imply currents

Can the heat generated by the currents produce the high temperature 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.
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
Eugene Newman Parker (1927 - )
My guru

Amazon India is already selling Kindle edition for less than Rs. 300/-
Helioseismology

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