Astronomy 404
October 18, 2013

- Parker Wind Model
    - Assumes an isothermal corona, simplified H**S**E
    - *Why does this model fail?*

- *Dynamic* mass flow of particles from the corona, the system is not *closed*

Re-write acceleration as a velocity *flow (dv/dr)* and consider the force of gravity and pressure exerted by the gas:

$$\frac{d^2r}{dt^2} = \frac{dv}{dt} = \frac{dv}{dr}\frac{dr}{dt} = v\frac{dv}{dr}$$

$$\rho v\frac{dv}{dr} = -\frac{dP}{dr} - G\frac{M_r\rho}{r^2}$$

conservation of mass *flow* (dM = rho * dV)
dV ~ function of dr ~ v dt

$$4\pi r^2 \rho v = \text{constant}$$

→ deriv both sides

$$\frac{d(\rho v r^2)}{dr} = 0$$

Outward pressure waves via convection, F_E flux (v_s) of wave *energy (rho * v_w^2)*

- What happens if the density rapidly declines?

$$F_E = \frac{1}{2}\rho v_w^2 v_s$$

$$v_s = \sqrt{\gamma P/\rho}.$$

$$v_s = \sqrt{\frac{\gamma k T}{\mu m_H}} \propto \sqrt{T}$$

The sound speed depends on the local temperature!

What happens: density drops dramatically outside of convection zone → since v_s (T!) and the flux energy F_E stay approximately the same across the boundary, the wave amplitude creates a *shock front* which heats the chromosphere and beyond!

In the immortal words of Bill O'Reilly, *where do the magnetic fields come from? How did they get there?*

MHD == plasmas and their interactions with H-fields

- Magnetic fields are generated from *moving electric charges*, and the energy of their creation is "stored" in them-- as a pseudo potential energy
- Magnetic energy density is numerically equivalent to magnetic pressure – work is done to compress plasma, which increases density of magnetic field lines "locked" in the plasma

$$\boxed{u_m = \frac{B^2}{2\mu_0}.} \qquad \boxed{P_m = \frac{B^2}{2\mu_0}.}$$

Information can travel along magnetic field lines as transerve **Alfven waves** (think: plucking a guitar string)

Adiabatic (dQ = 0) sound speed

$$v_s = \sqrt{\frac{\gamma P_g}{\rho}}$$

Alfven Speed
Estimates the propagation speed of a wave or disturbance down a magnetic field line
Analogy: plucking a guitar string

$$v_m \sim \sqrt{\frac{P_m}{\rho}} = \frac{B}{\sqrt{2\mu_0\rho}}$$

With less hand-waving,

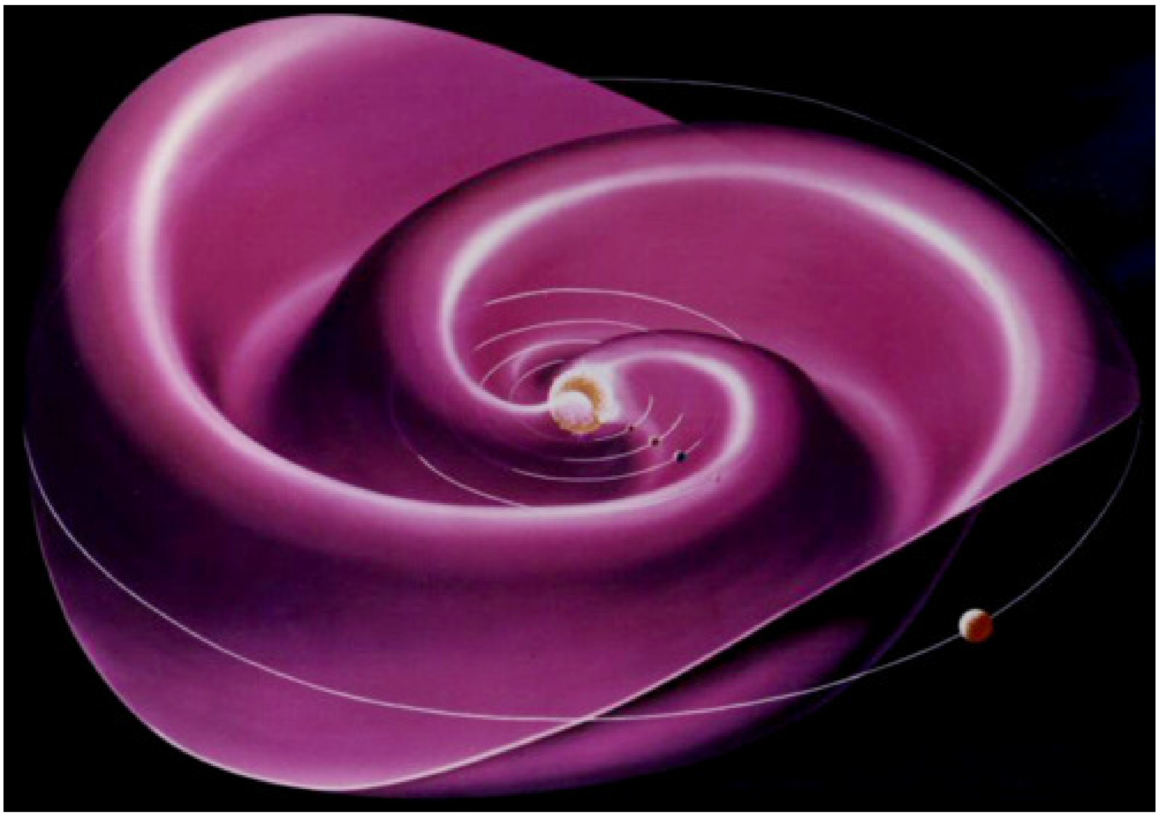
$$v_m = \frac{B}{\sqrt{\mu_0\rho}}$$

Useful to compare the Alfven speed along magnetic field lines to the plasma sound speed

“Information” travels along these lines – energy transport. What are the consequences of a varying magnetic field according to Maxwell's equations?

Parker Spiral → spiraling magnetic fields.

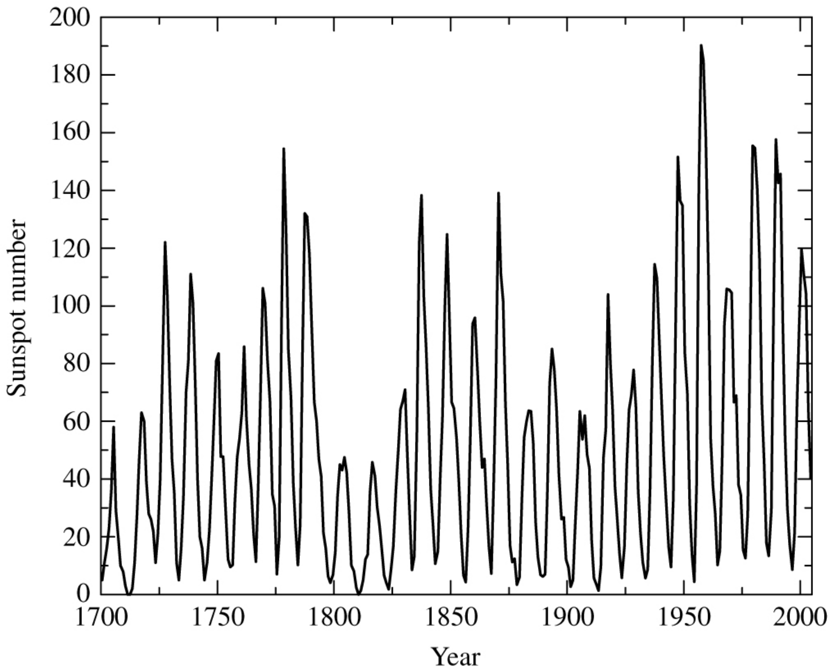
- Angular momentum is transferred *away* from the Sun
- The extended magnetic fields are caused by the ejection of *solar wind* and the Sun's rotation



How do other stars compare to our Sun?

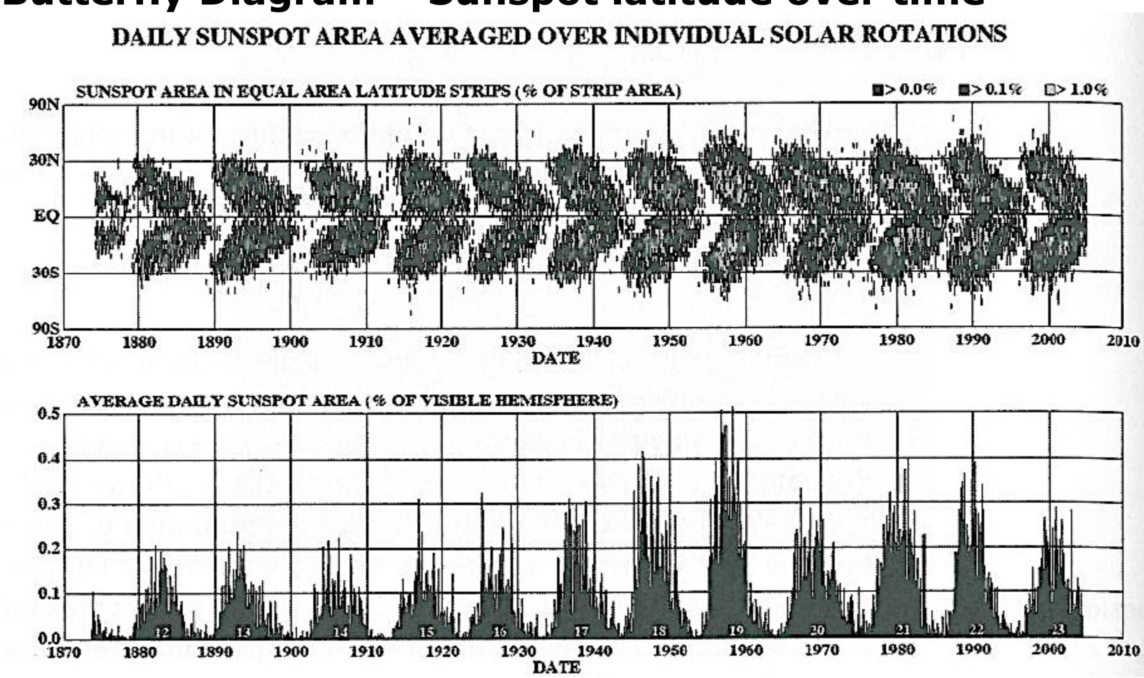
→ The field of research is even more dynamic than the stars themselves

THE SOLAR CYCLE: Observational Evidence

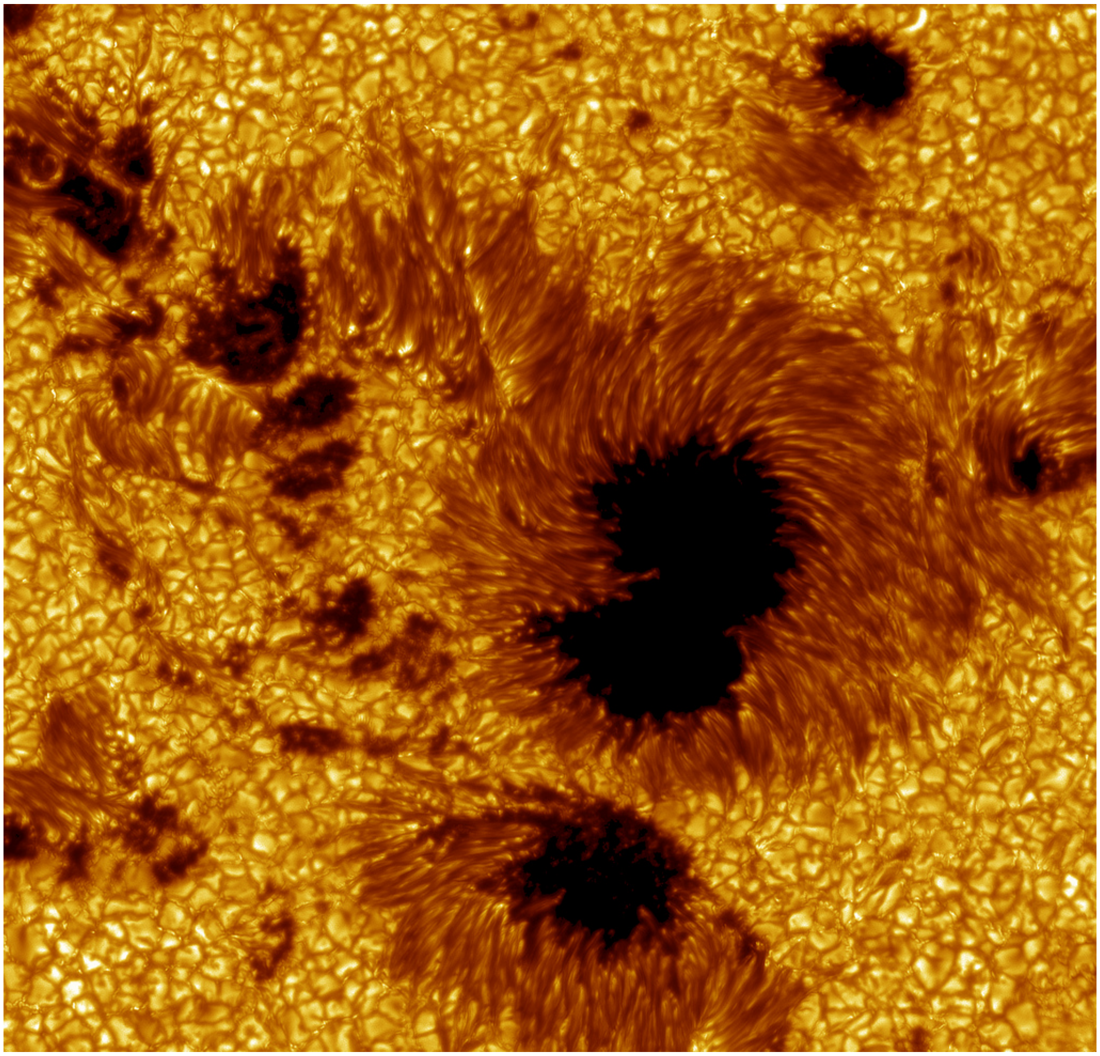


Number of sunspots between 1700 and 2005 showing the 11-yr periodicity, with large amplitude variations occurring over hundreds of years

Butterfly Diagram – Sunspot latitude over time



% of Sun covered by sunspots over time

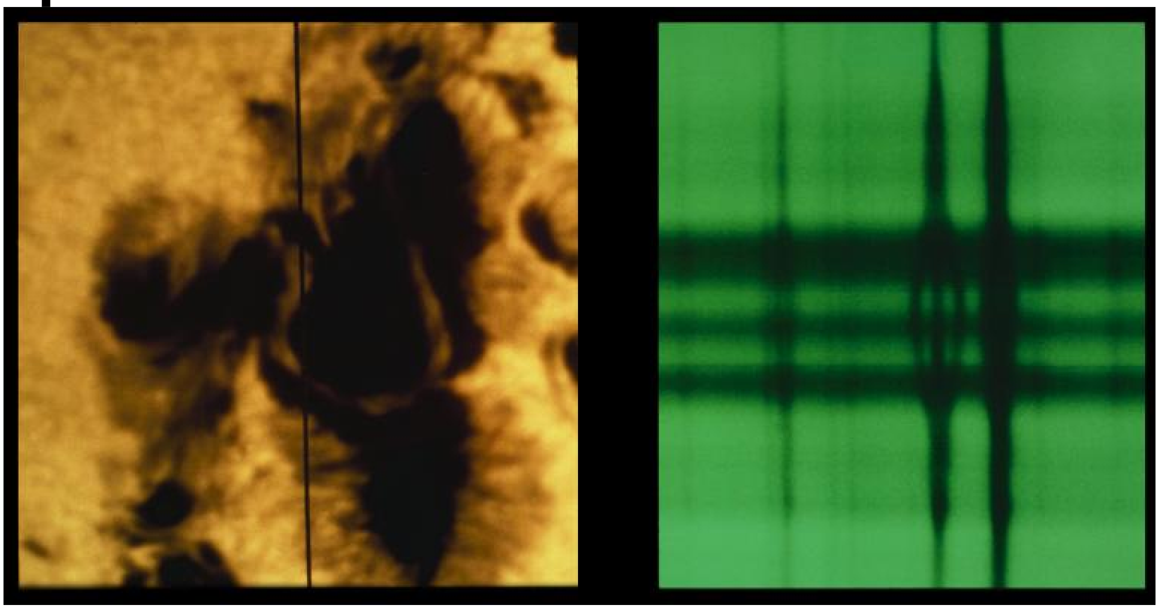


A typical sunspot group

- Umbra – can be 3x Earth sized
- Filamentary penumbra

How do we know sunspots are indicative of magnetic fields? How do we measure their direction and strength?

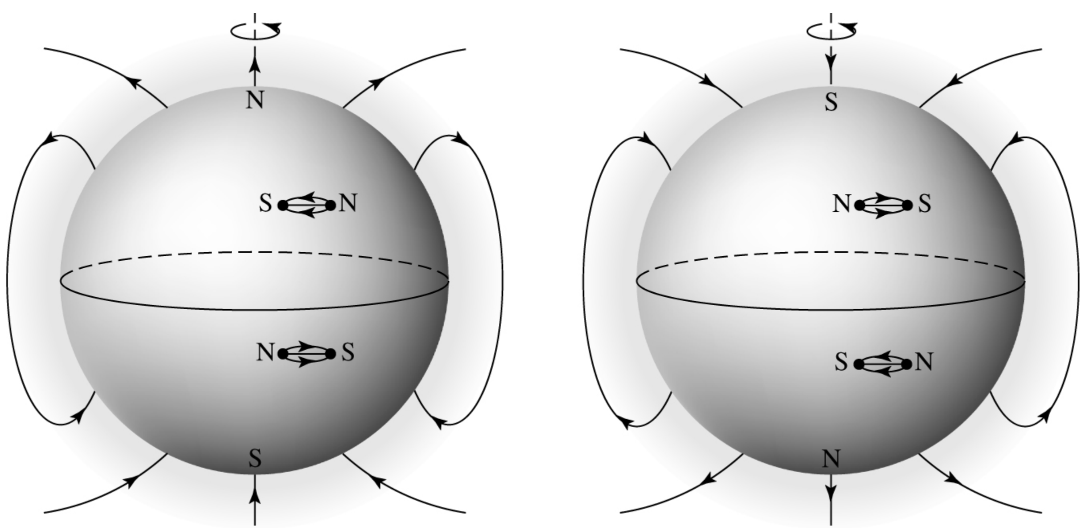
Spectral line SPLITTING – ZEEMAN EFFECT



Left: sunspot with corresponding spectroscopic slit
Right: spectra

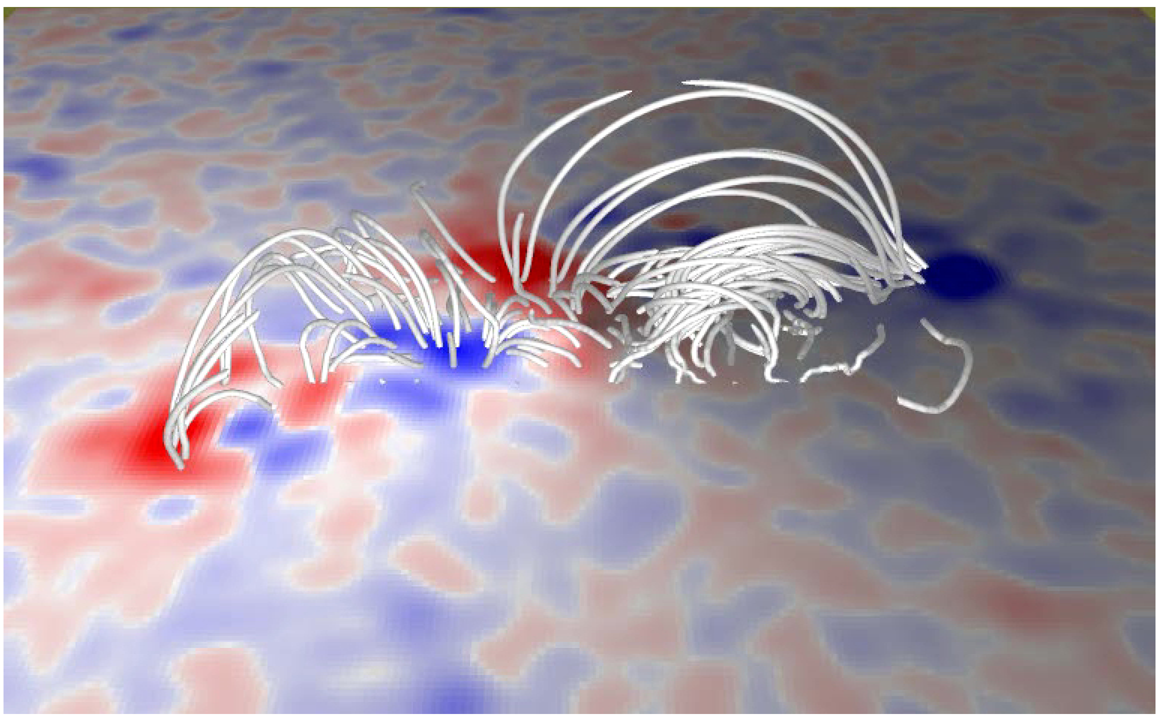
Do the characteristics of sunspots vary across the solar surface?

Polarization of light: direction of B-field

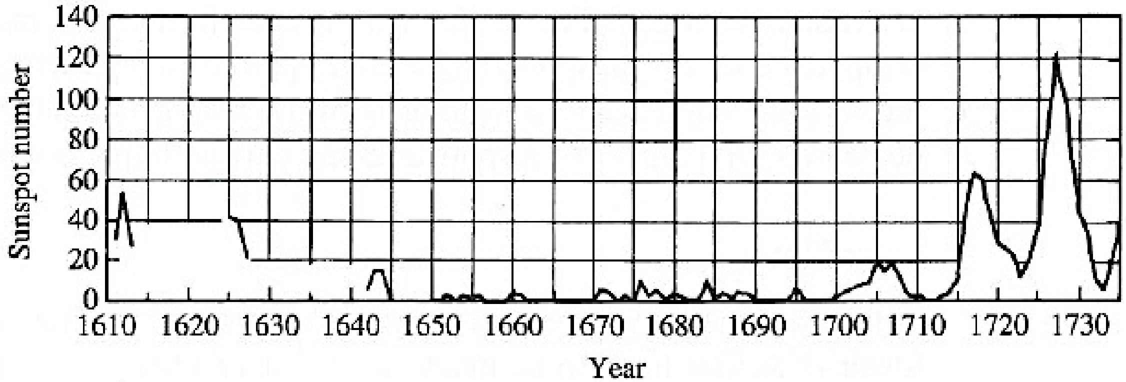


- Sunspot polarity coincides with overall solar polarity, and they cycle together through a full 22 years

- A leading sunspot in the geographical northern hemisphere will share that hemisphere's polarity
- Sunspot pairs are similar to
- Magnetic fields inhibit convective motions to the surface, reducing the shock front that would heat the photosphere
    - Decreases solar luminosity by as much as 0.1%
    - 0.1% of the solar luminosity is still 10^23 W and is measurable in temperature fluctuations of the Earth
    - Despite this, they prevent convective gas bubbles from sinking in sunspots

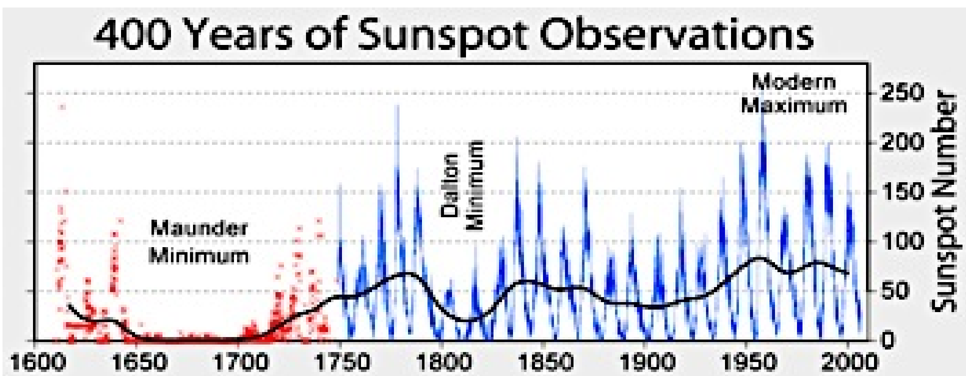


http://www.nasa.gov/mission_pages/sdo/news/sdo-year3.html



11- and 22- year cycles are thought to be *local* maxima and minima. Periodicity of sunspot activity found over centuries!

- Evidence on Earth via atmospheric radioactive carbon
- The magnetic field of sunspots reduces the outward energy flux from the Sun, reducing the # of cosmic rays



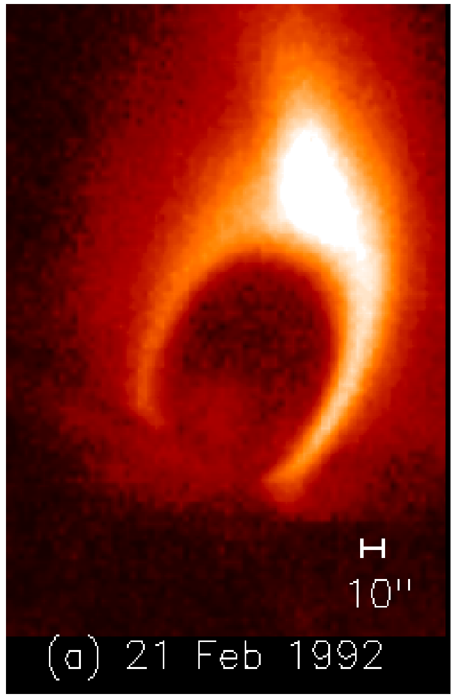
Red team: what other causes for this trend might there be?

Phenomenon Associated with Sunspots

PLAGES (pläzh) – bright H-alpha emission regions preceding a sunspot occurrence

SOLAR FLARES are eruptive events

- H-alpha seen as emission
- Large bursts of cosmic rays
- Occur in sunspot groups

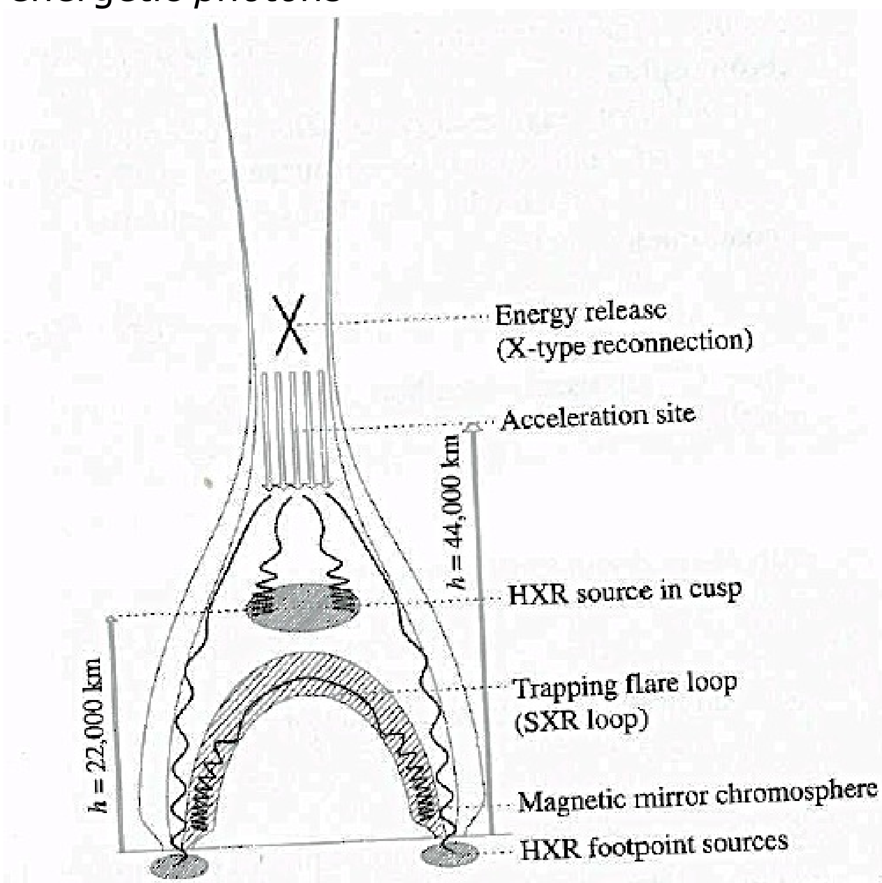


Soft X-ray image of a solar flare.
(Yohkoh Soft X-ray Telescope)

What causes a solar flare?

Magnetic Reconnection

- http://upload.wikimedia.org/wikipedia/commons/2/24/Reconnection.gif
- Magnetic field lines from different sources “reconnect” in a different configuration
- Maxwell's equations: electric resistivity in plasma opposes change to the magnetic field
- This can release thermal and, mechanical energy, and can accelerate particles
    - In the case of a solar flare, it is energy released via energetic *photons*



Spallation Reactions – (think “expellation”): the breaking of heavier nuclei into lighter via accelerated particles that are being *expelled* from solar flares

- Produce hard x- and gamma rays

1. De-excitation of Carbon

$$^{1}_{1}H + ^{16}_{8}O \rightarrow ^{12}_{6}C^{*} + ^{4}_{2}He + ^{1}_{1}H$$

$$^{12}_{6}C^{*} \rightarrow ^{12}_{6}C + \gamma$$

Photon energy 4.438 MeV

2. De-excitation of oxygen

$$^{1}_{1}H + ^{20}_{10}Ne \rightarrow ^{16}_{8}O^{*} + ^{4}_{2}He + ^{1}_{1}H$$

$$^{16}_{8}O^{*} \rightarrow ^{16}_{8}O + \gamma$$

Photon energy 6.129 MeV

3. Electron-positron annihilation

$$e^{-} + e^{+} \rightarrow \gamma + \gamma$$

4. Deuterium Production

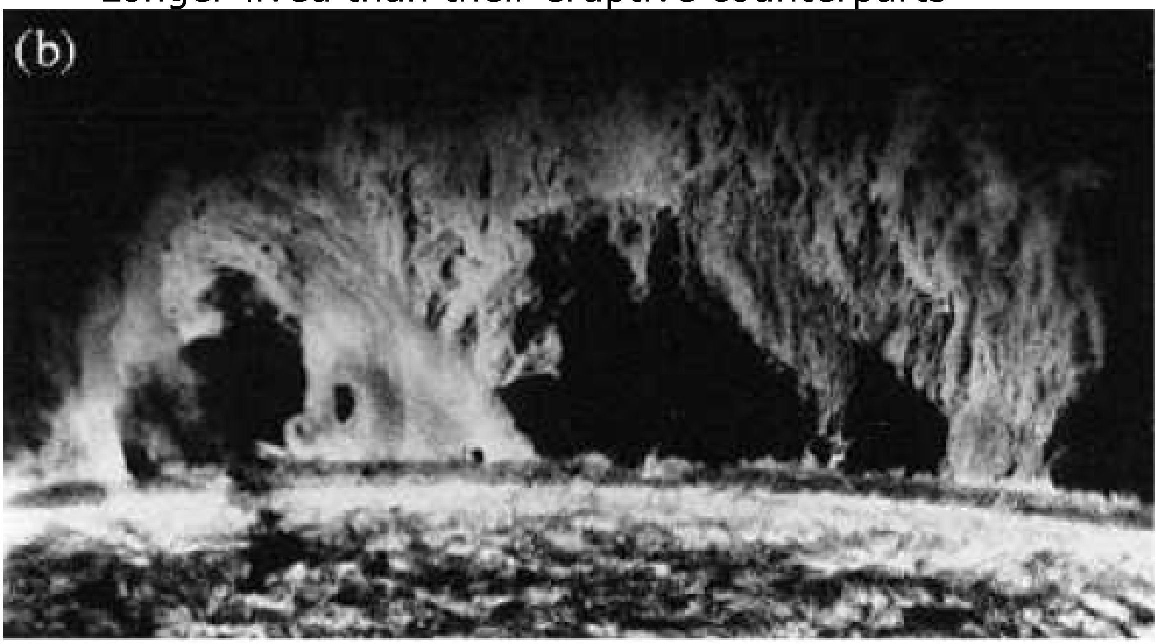
$$^{1}_{1}H + n \rightarrow ^{2}_{1}H^{*} \rightarrow ^{2}_{1}H + \gamma$$

Photon energy 2.223 MeV

Solar Promenences – quiescent or eruptive

Material hangs out along magnetic field lines within the corona in a quiescent prominence

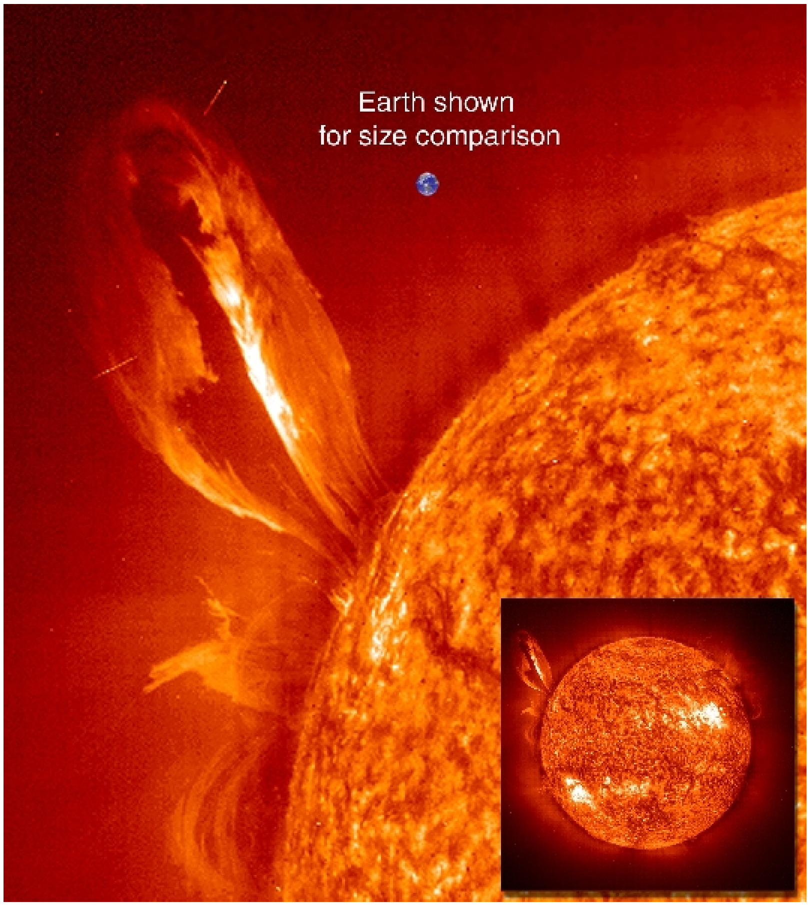
- Gas condenses and cools, causing it to fall back towards the chromosphere
- This cooler gas is a source of emission, particularly H-alpha
- Longer-lived than their eruptive counterparts



H-alpha image of a quiescent hedgerow prominence (Courtesy of Big Bear Solar Observatory)

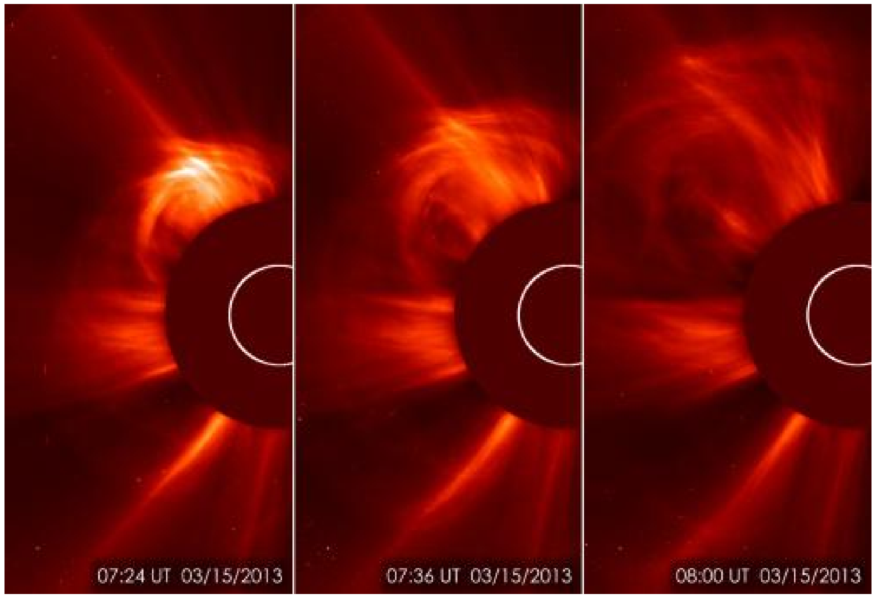
Eruptive prominences

- Related to questionable magnetic field stability
- Prominence dramatically lifts away from the Sun, a la solar flares → except gas is ejected, not EM



Coronal Mass Ejections

- Ejecta of up to 10^13 kg at 10^2-10^3 km/s
- Harder to observe than their flare and prominent neighbors, and are likely associated with eruptive prominences
- 1-3.5 events/day
- “Magnetic Bubble” post magnetic reconnection



Coconal mass ejection captured by ESA/NASA's Solar and Heliospheric Observatory (SOHO) on March 15, 2013

Magnetic Dynamo Theory

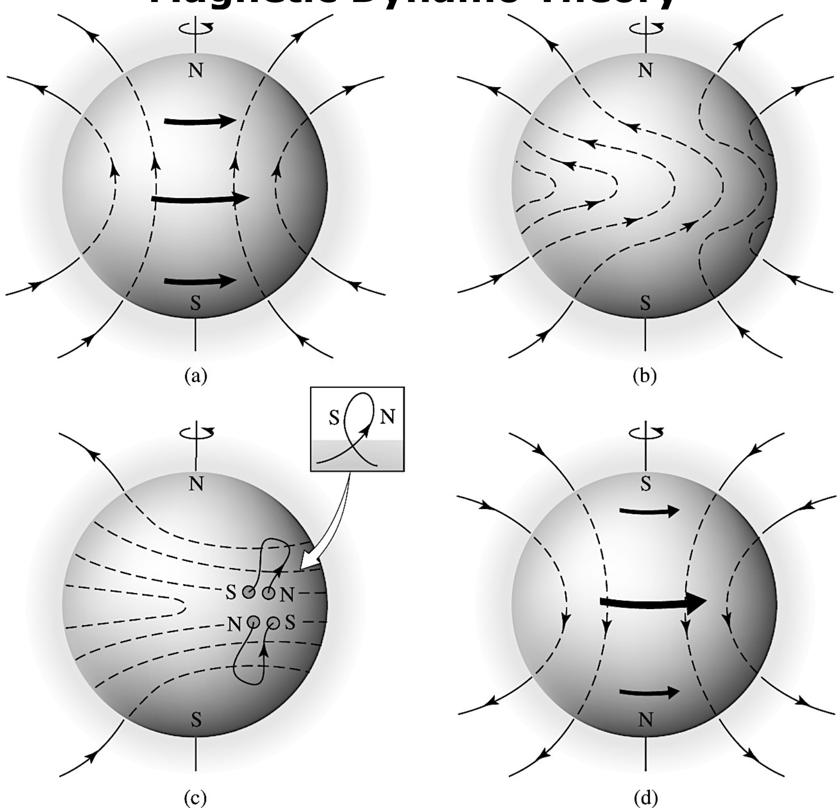


Fig. 11.38 Magnetic dynamo model of the solar cycle.

- As a result of frozen in magnetic fields, the sun's differential rotation warps the field lines to the nice poloidal – aka dipole – configuration to toroidal, where the lines wrap around the Sun
- The lines are twisted and strengthened within the convective zone... think F = v x B – what happens?
- Magnetic pressure buoyancy forces the "ropes" to the surface → sunspot groups
- Opposing polarity in opposing hemispheres – the ropes are effectiviely nullified towards the equator despite intuition that they are numerous there. This reverses the solar polarity!

Extrasolar Magnetism

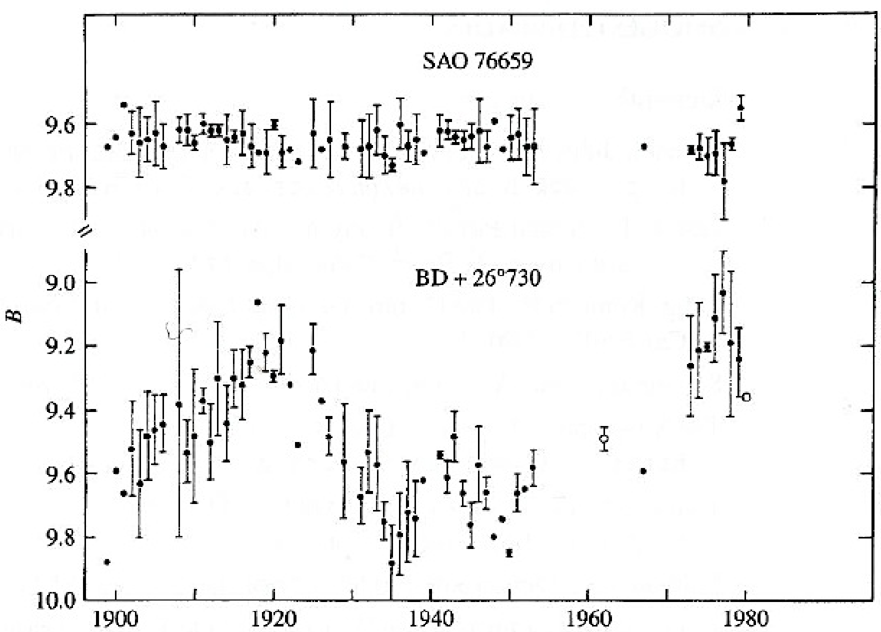


FIGURE 11.39 The light curve of BD + 26°730, a BY Dra star. SAO 76659 is a nearby reference star. (Figure from Hartmann et al., *Ap. J.*, *249*, 662, 1981.)

Flare stars: late type stars with brightness fluctuations (10^23 W matters more to these guys)

Starspots: certain stellar types exhibit long-term variations in stellar surface activity

- RS Canum Venaticorum
- BY Draconis