The Magnetic Sun

Lecture Presented at the Alpbach Summer School on Space Weather: Physics, Impacts and Predictions

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Lecture Aims

- Focus on the Sun as the cause of Space Weather phenomena in the near-Earth environment ("what happens in the Sun?")
- Describe the magnetic features of the sun that are involved

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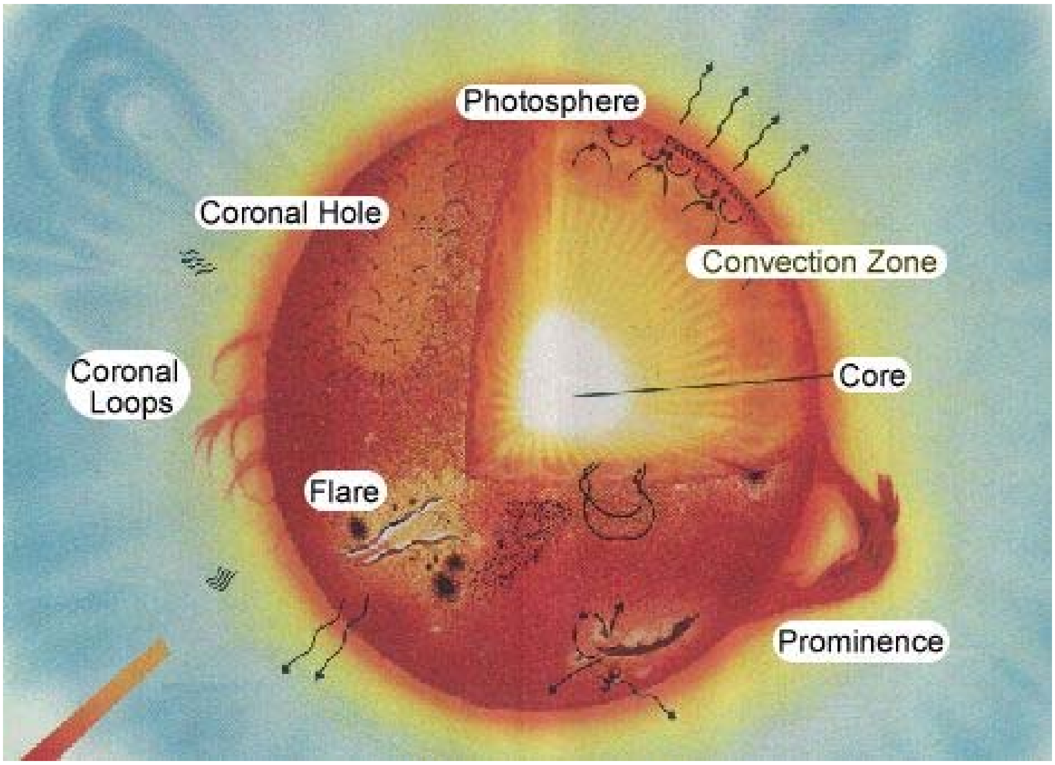
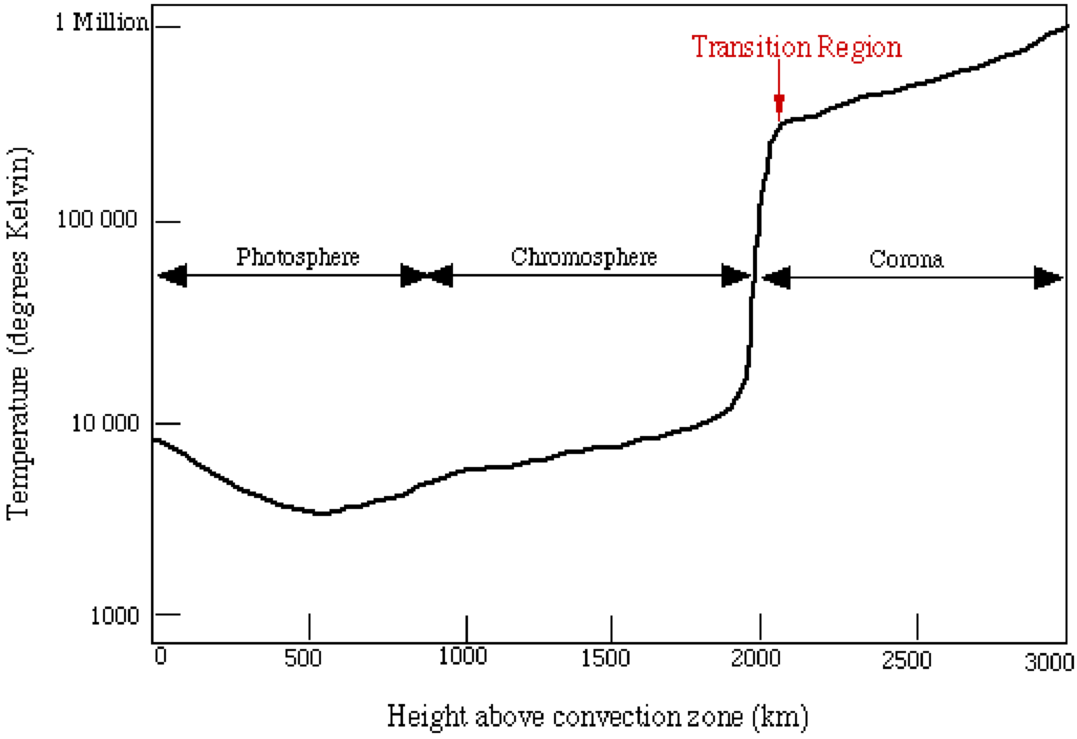
Lecture Outline

- Introduction - Sun's Structure, Magnetic Flux and Solar Activity
- Helioseismology - P-mode waves and studies of the Sun's interior
- Magnetic Flux Emergence - SOHO MDI magnetograph observations
- Solar Atmosphere - Coronal structures and Solar Wind
- Solar Flares - Standard magnetic reconnection model
- Coronal Mass Ejections (CMEs) - Signatures in the solar atmosphere
- Magnetic Helicity - Definition and role in Sun-Earth interactions
- Conclusions

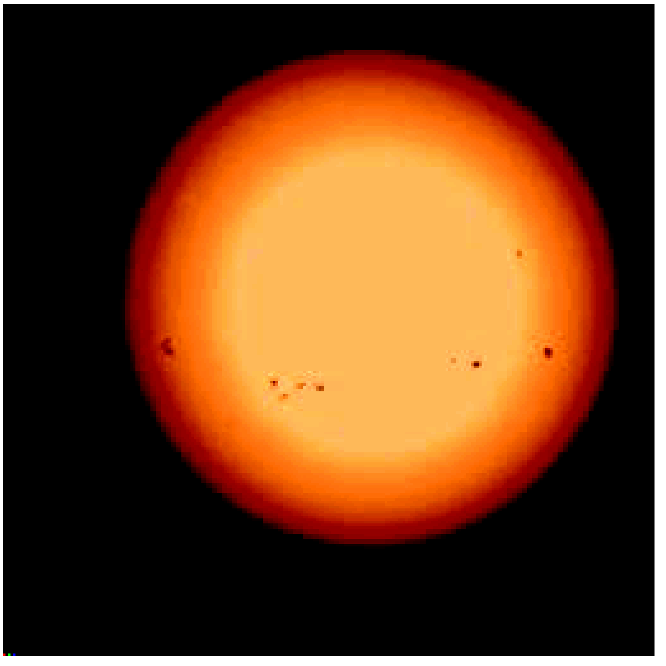
Schematic of the Sun



Temperature - Height Plot in the Solar Atmosphere



Journey through the Solar Atmosphere

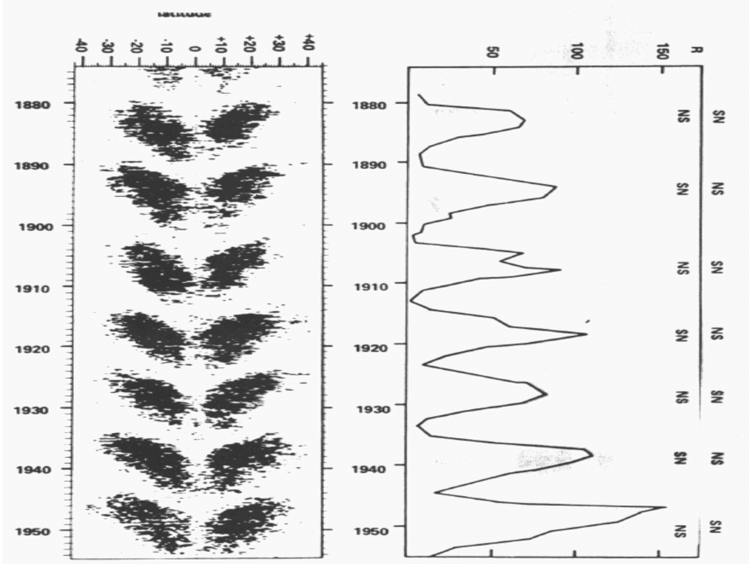


Movie Sequence

Solar Activity

- Sunspot activity shows an 11 year cycle with new spots appearing at high latitudes (<| 35°|) and gradually migrating towards the equator as the cycle progresses.
- The sunspot cycle forms half of a 22-year cycle during which the magnetic field evolves from a poloidal to a toroidal field and back to a poloidal field of opposite polarity (11 years).
- Another sunspot cycle then takes the magnetic configuration back to the starting polarity.
- The solar dynamo theory, that seeks to explain all of these observed features, is still in a qualitative state!

Butterfly Diagram and the Solar Cycle



The solar activity cycle. The smoothed Relative Sunspot Number, R, is plotted against time in years. The butterfly diagram shows the heliographic latitudes of sunspots against time. The indications NS and SN at the top specify the polarities of the active regions, with N for positive (northern) polarity and S for negative polarity. The first symbol stands for the polarity of the leading part, and the top pairs refer to the northern hemisphere.

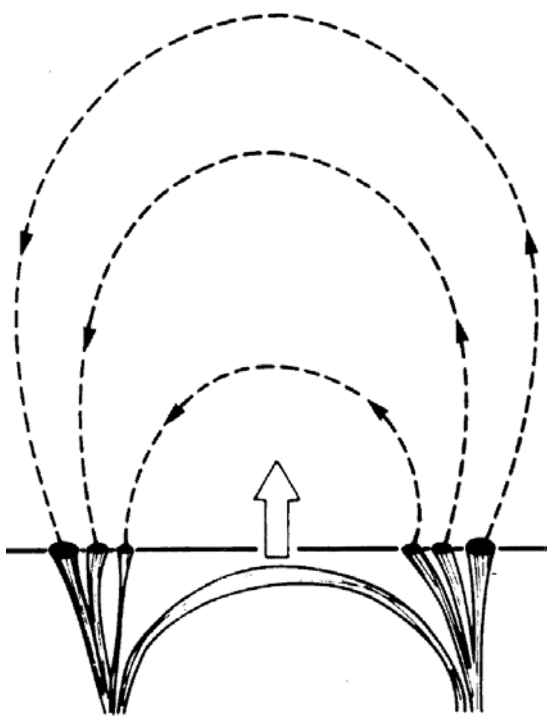
Magnetic Flux Tube Emergence from below Photosphere

If $P_{ext} = P_{int} + B^2/2\mu$, and if

$T_{ext} = T_{int}$, then

$\rho_{ext} > \rho_{int}$

Resulting magnetic buoyancy causes flux tubes to rise. This occurs when B reaches a critical value as the solar cycle evolves



$\beta = P_o/[B^2/2\mu]$ - ratio of thermal to magnetic energy where P_o is external pressure and B is field in flux tube

Below Photosphere: $\beta \gg 1$ and gas pressure dominates

Above Photosphere: $\beta \ll 1$ and magnetic pressure dominates

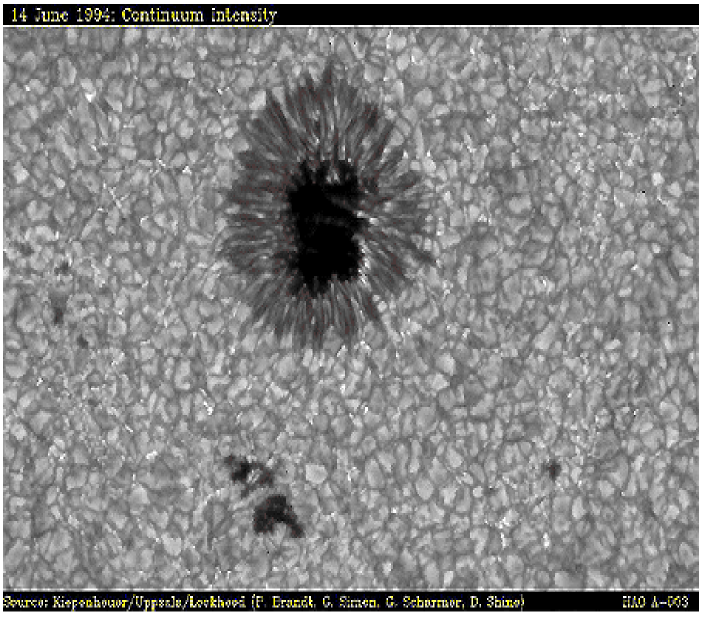
Sunspots and Pores
Visible Manifestations of Magnetic Activity

Sunspots

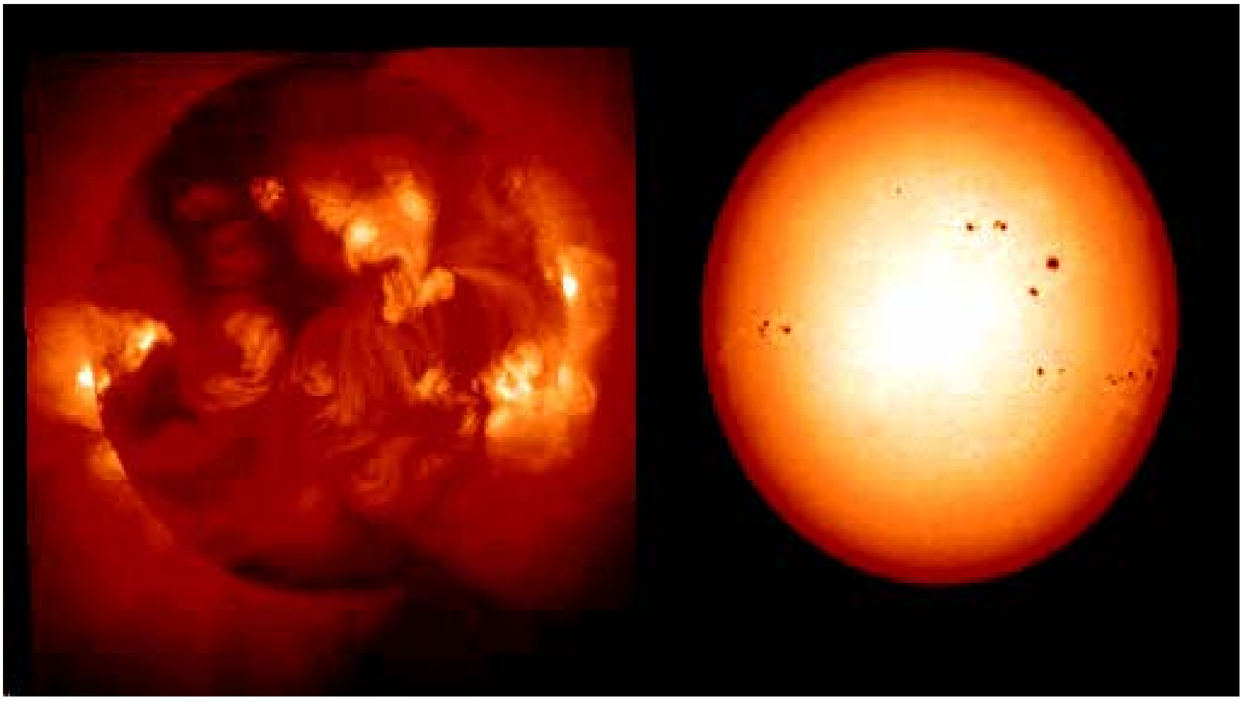
Umbra size ~ 20,000 km.
Contain strong B fields.
These inhibit convection,
hence $T_{spot} < T_{phot}$
or for
$B_{spot} \sim 0.4$ Tesla,
$T_{spot} \sim 3700$ K

Pores

Sunspots in process of formation



The Sun in X-rays and White Light



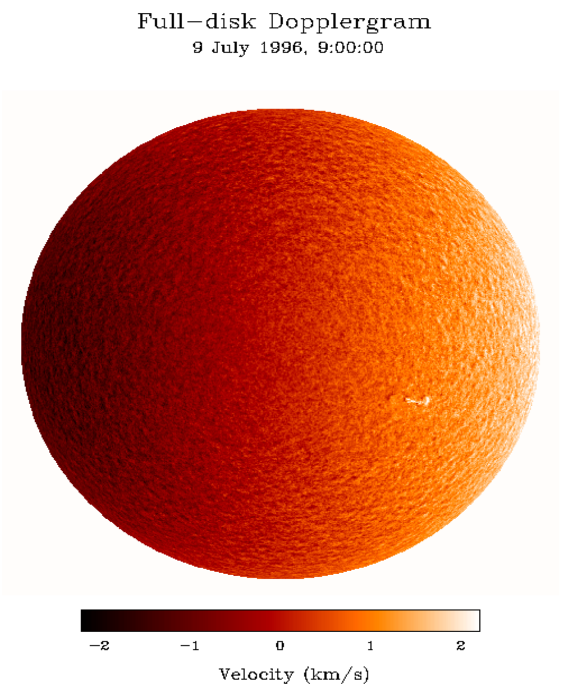
Movie Sequence

Sound or Pressure - P-mode Waves in the Solar Interior

- More than 10^6 standing-wave modes.
- Two boundaries:

- Reflection from surface of Photosphere - low density above so wave cannot propagate

- Refraction of wave in the interior due to steep T gradient [$V_s = (\gamma kT/m)^{1/2}$]

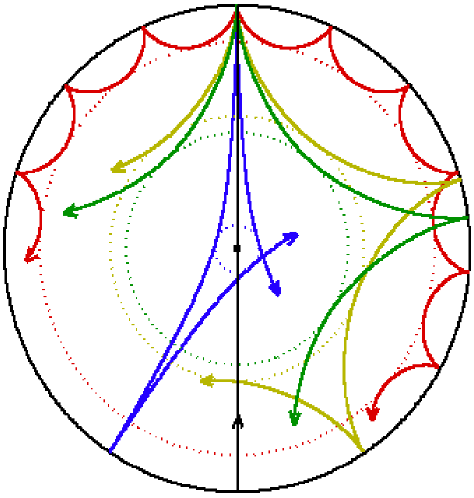


- Modes are described by spherical harmonic functions with "quantum numbers" n, l and m

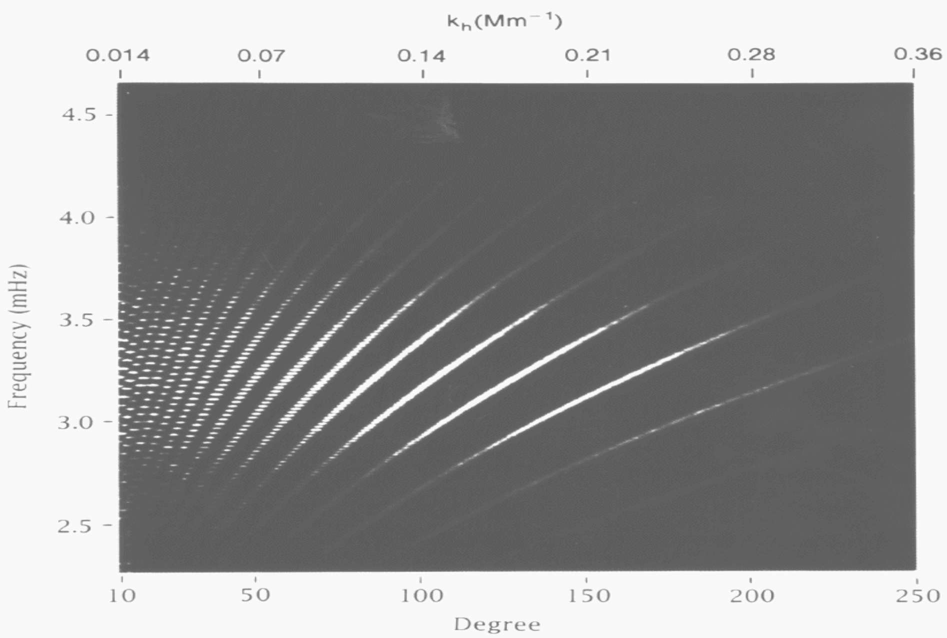
P-mode Wave Paths

Horizontal wavelength λ_h: distance around solar circumference ($2\pi R_O$) between reflections

l $= 2\pi R_O/ \lambda_h$ is called the degree of the mode
low l – deep, high l – shallow
l indicates the number of node lines on the surface. l – m is the number of latitudinal planes
n is called the order of the mode and is the number of nodes in the radial direction
m is the azimuthal number and describes the number of longitudinal nodal planes



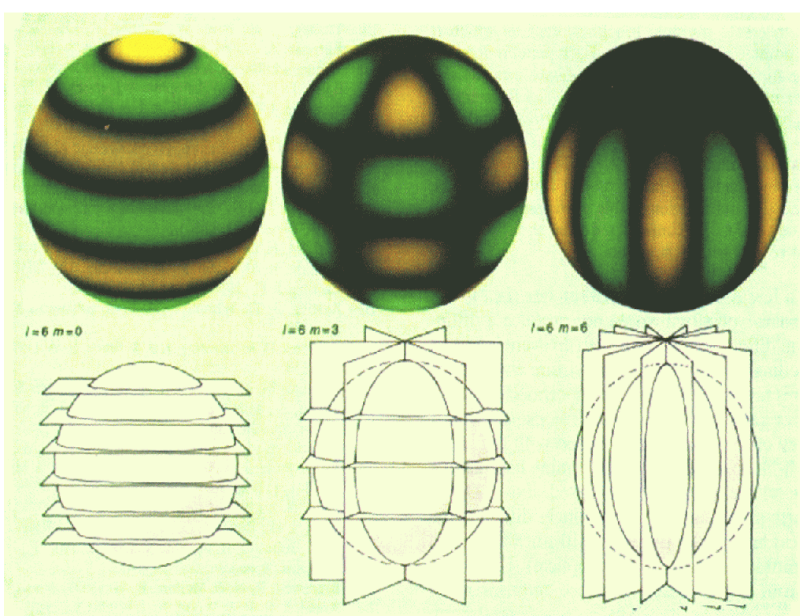
Distribution of Power among Modes



Observed distribution of oscillatory power in photospheric 5-min oscillations plotted in the plane of frequency vs. wavenumber (top scale) or degree (bottom scale) plane. Derived from South Pole observations such as those illustrated in Fig. 7-8. By permission of T. Duvall.

Spherical Harmonic Mode Representations

A **B** **C**



<u>**A**</u>
l = 6, m = 0

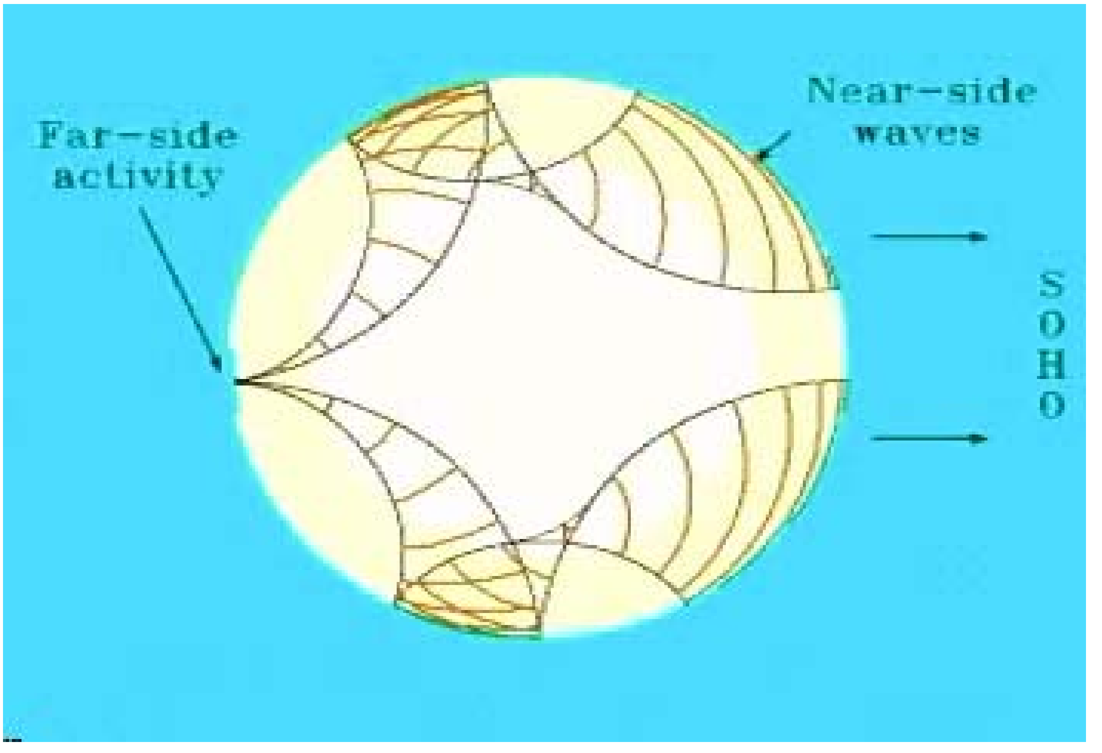
<u>**B**</u>
l = 6, m = 3

<u>**C**</u>
l = 6, m = 6

No. of latitudinal planes = l - m

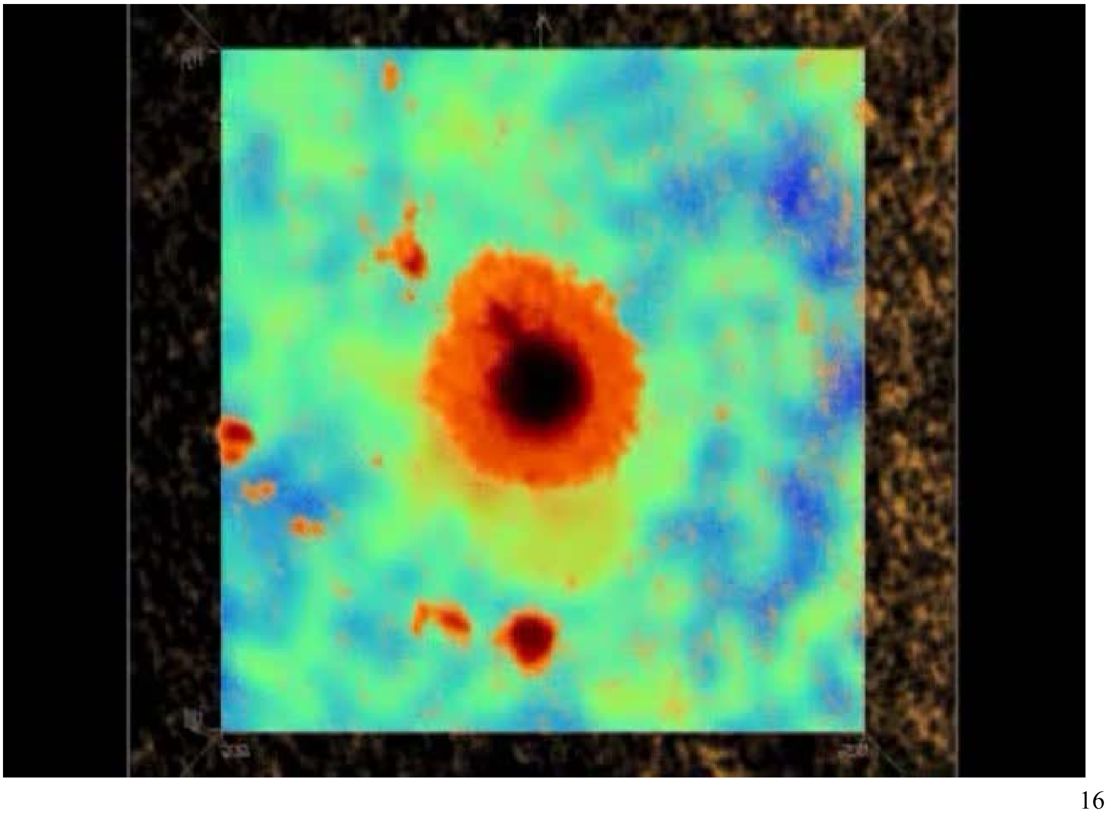
The dark regions are the nodal boundaries, the green colours denote areas moving radially outwards and the yellow colours denote areas moving radially inwards

Active Region Formation on the Far Side of the Sun



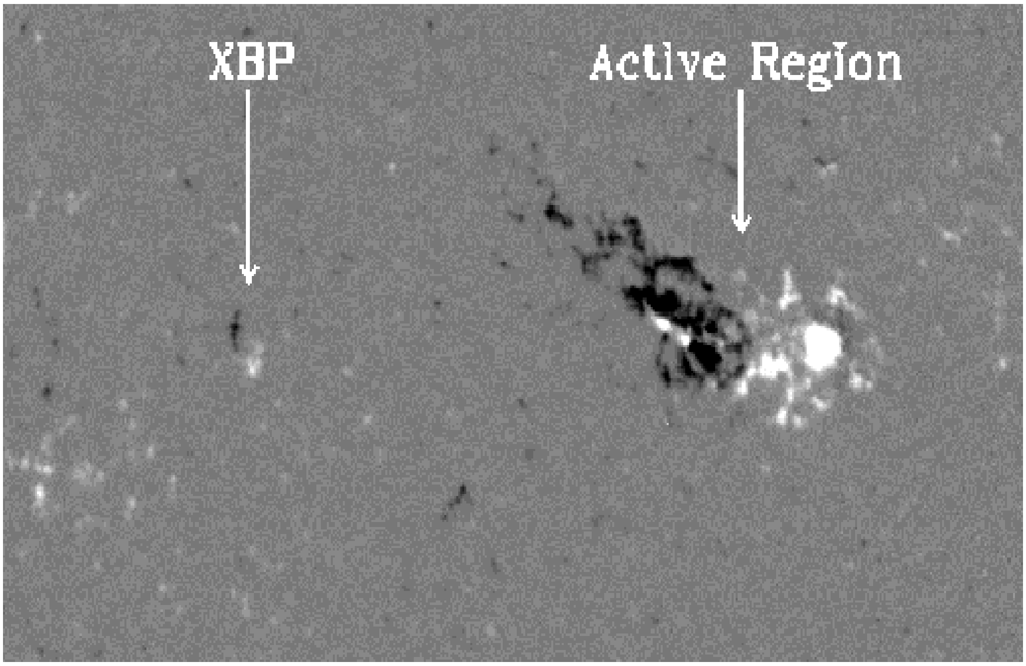
Movie Sequence

Sound Speed and Flows below an Active Region - SOHO MDI Data

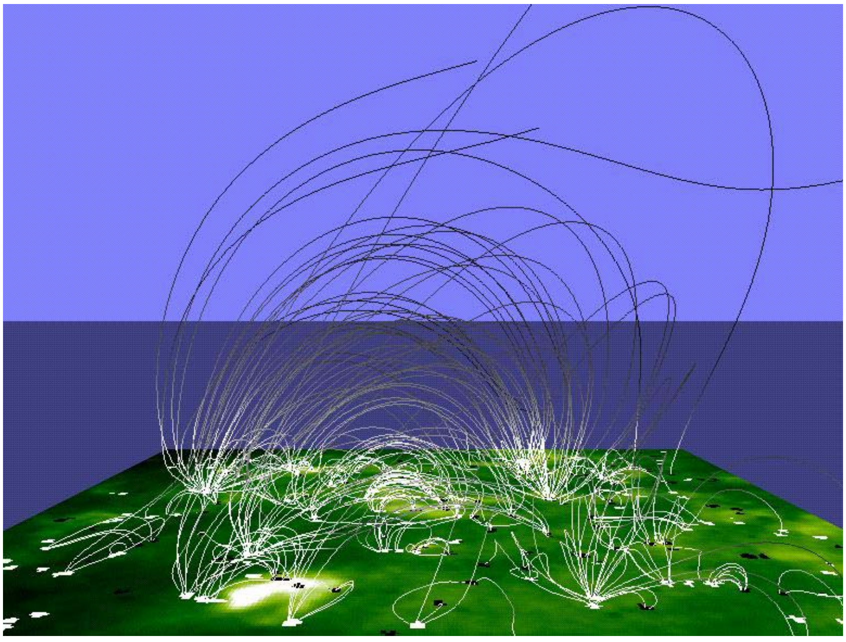


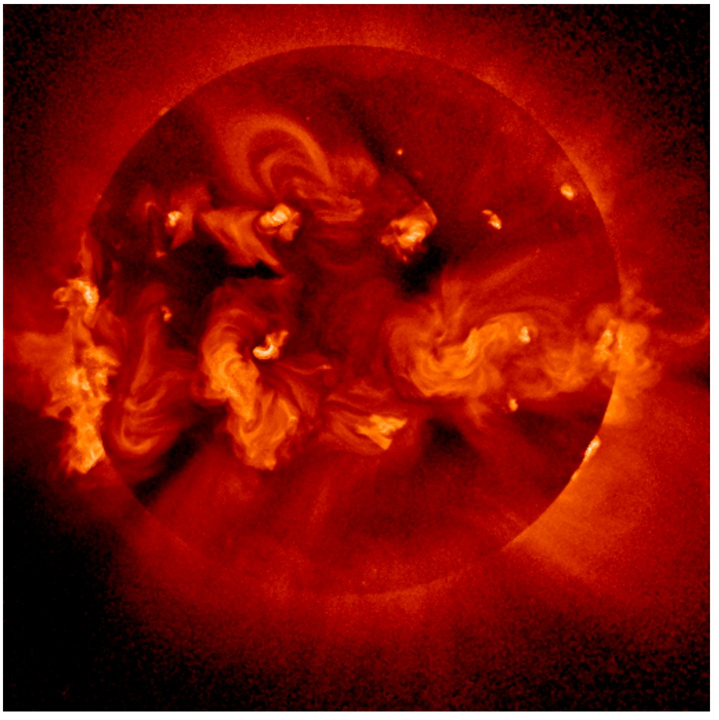
Movie Sequence

MDI Magnetogram - Bright Point and Active Region



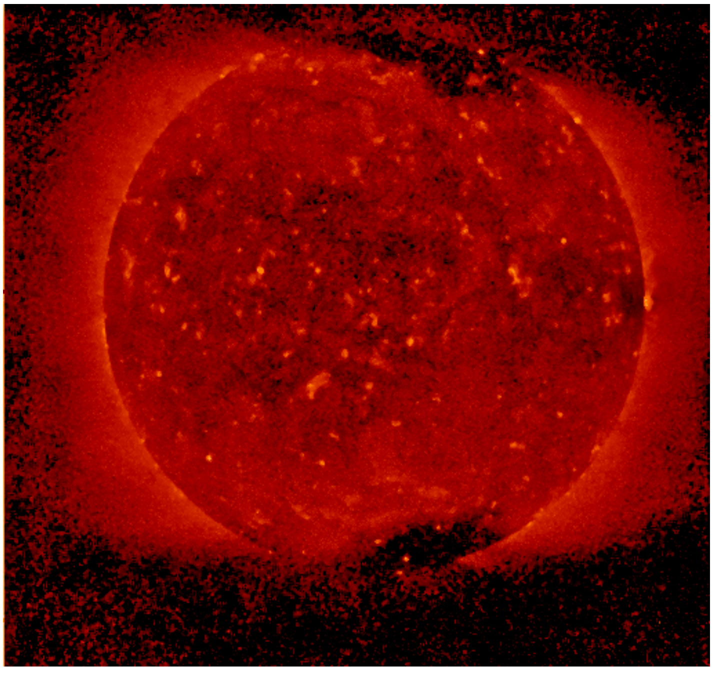
The Magnetic Carpet





Yohkoh X-ray images during Jan 92.

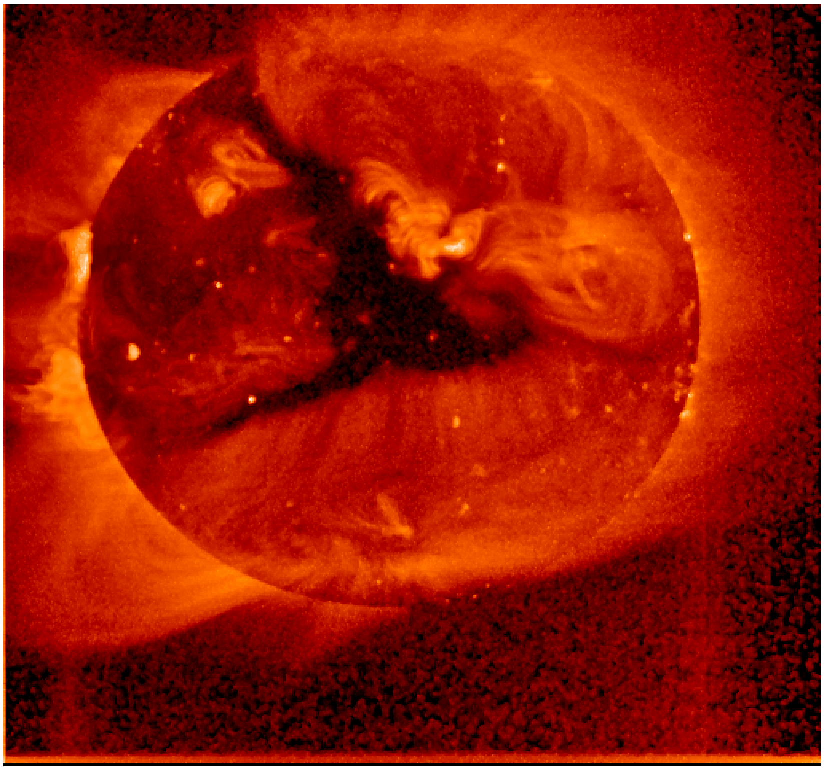
Notice the complex bright active regions.



Yohkoh X-ray images during Apr 96.

Fewer active regions, and the smaller X-ray bright points are now obvious.

Varied and Continuous Nature of Coronal X-ray Activity

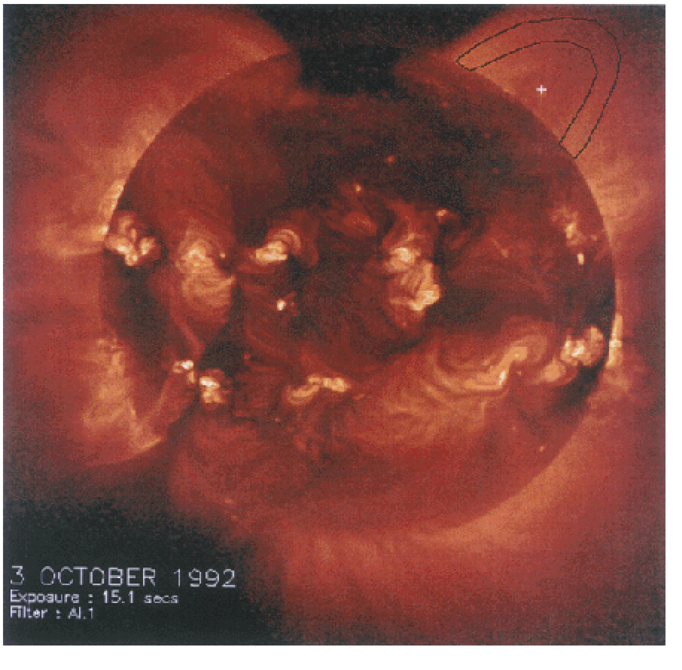


Sequence of Yohkoh Images April, 1994

Movie Sequence

Origin of the Solar Wind

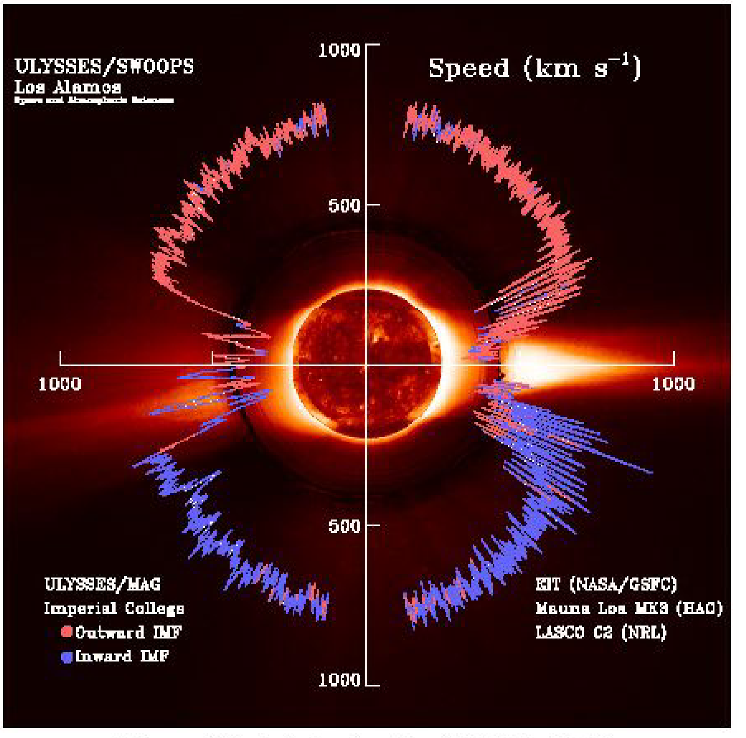
Skylab and near-earth plasma spacecraft in 1973 showed that Solar Wind velocity was correlated with Coronal Hole area.
However a range of wind velocities ~ 300 to 800 Km/s is observed.



Solar Wind Velocity Observations from Ulysses

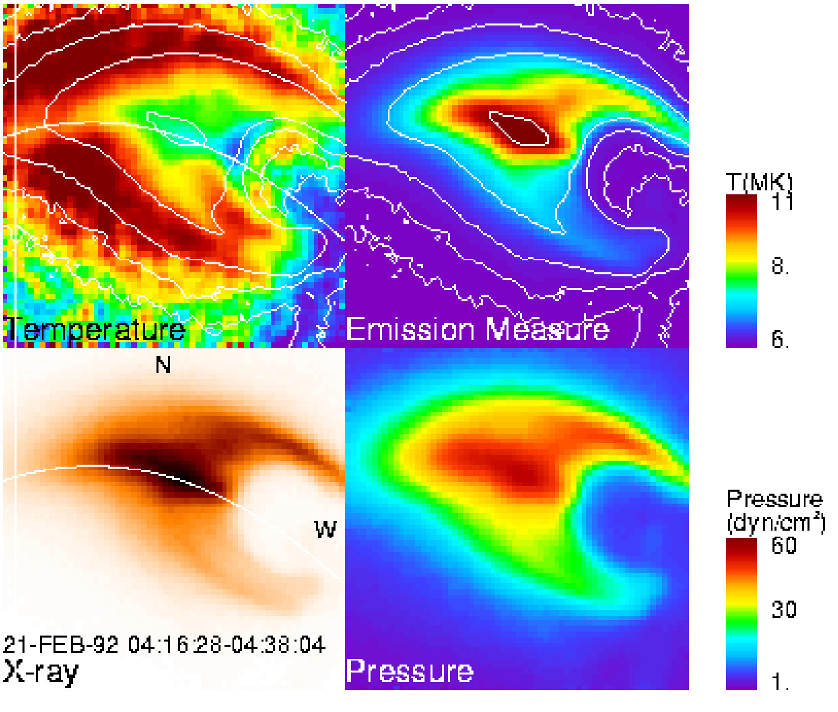
Higher velocity - high latitude origin: Coronal Holes

Lower velocity - low latitude origin: Streamers



McComas, D.J., et al., Geophys. Res. Lett., 25, 1-4, 1998

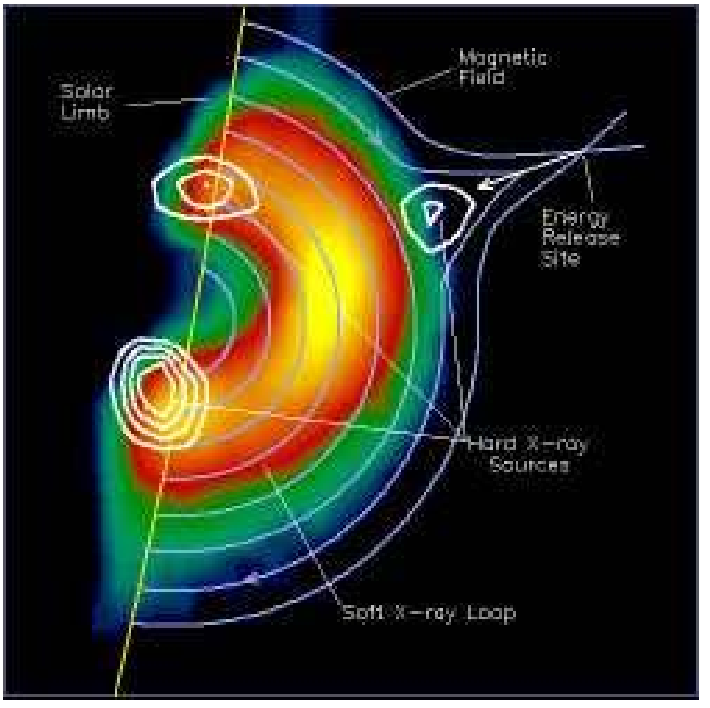
Large Flare Observed by Yohkoh



Temperature found to be higher outside the loops.

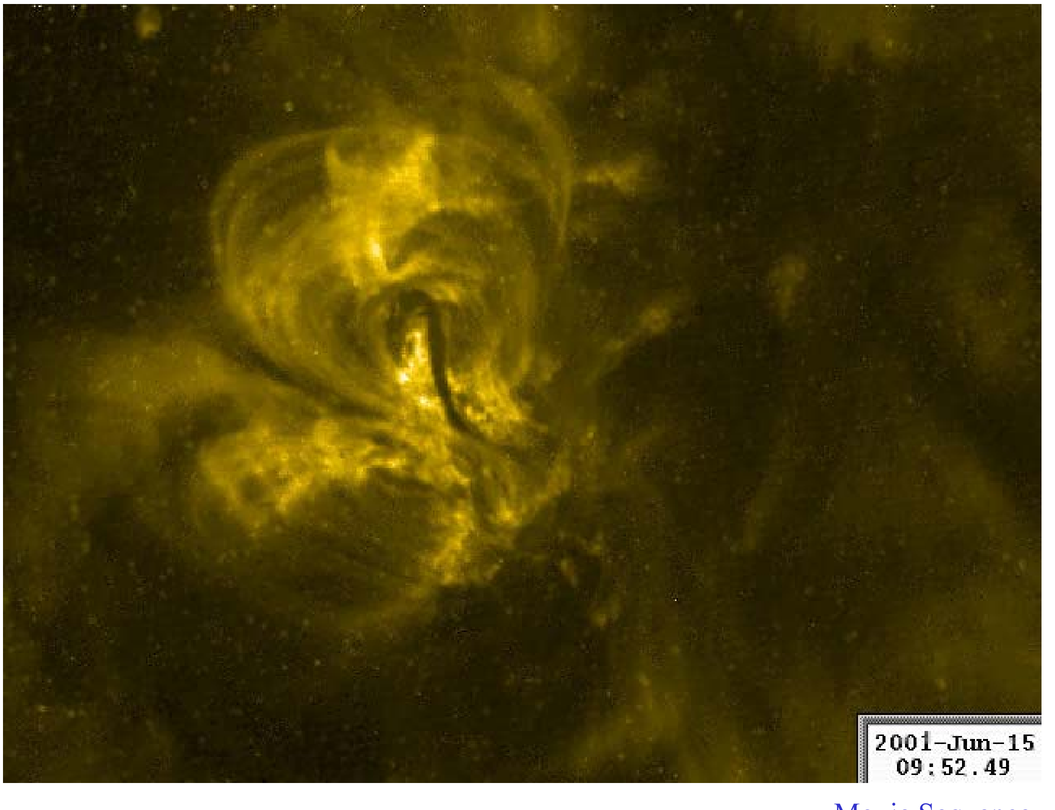
Tsuneta 1996

Yohkoh Observation of a Compact Flare with Loop-top Hard X-ray Source (Masuda et al, 1995, Nature)



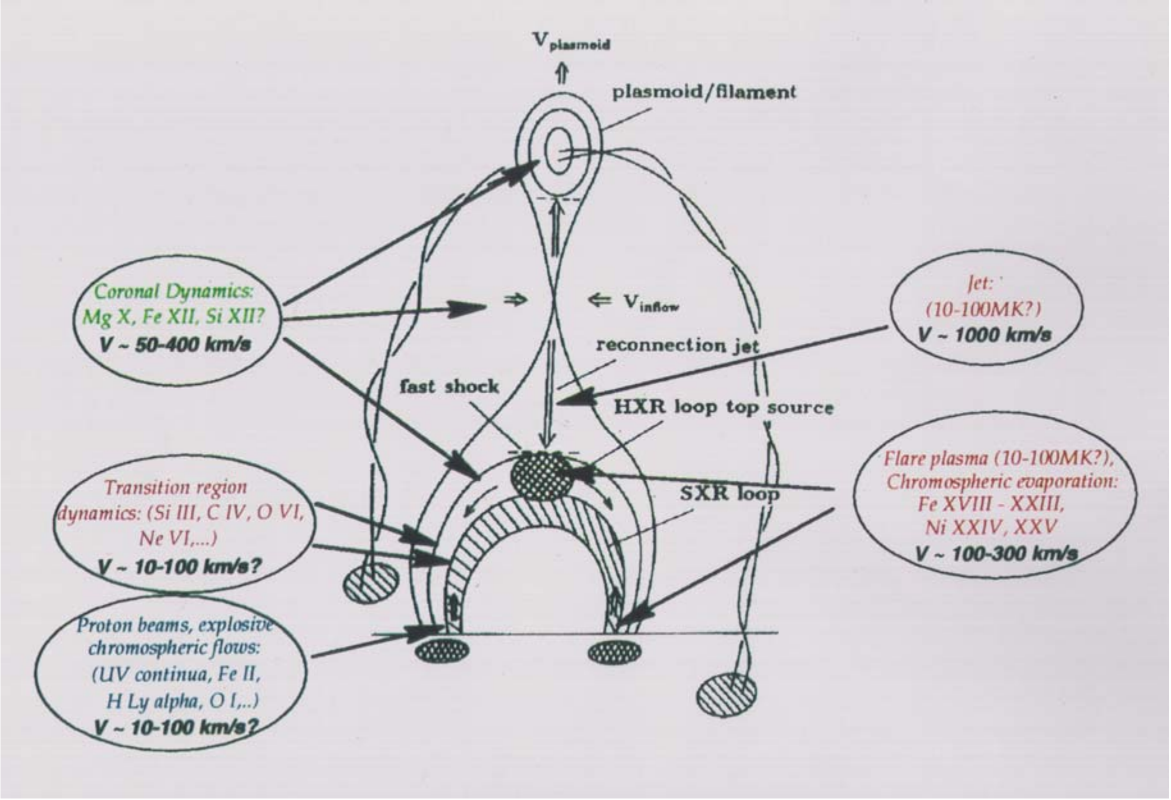
Hard X-ray contours (HXT, 33 - 53 keV) and soft X-ray image (SXT, 0.2 - 4.0 keV)

Complex Flare with Outflow observed by TRACE

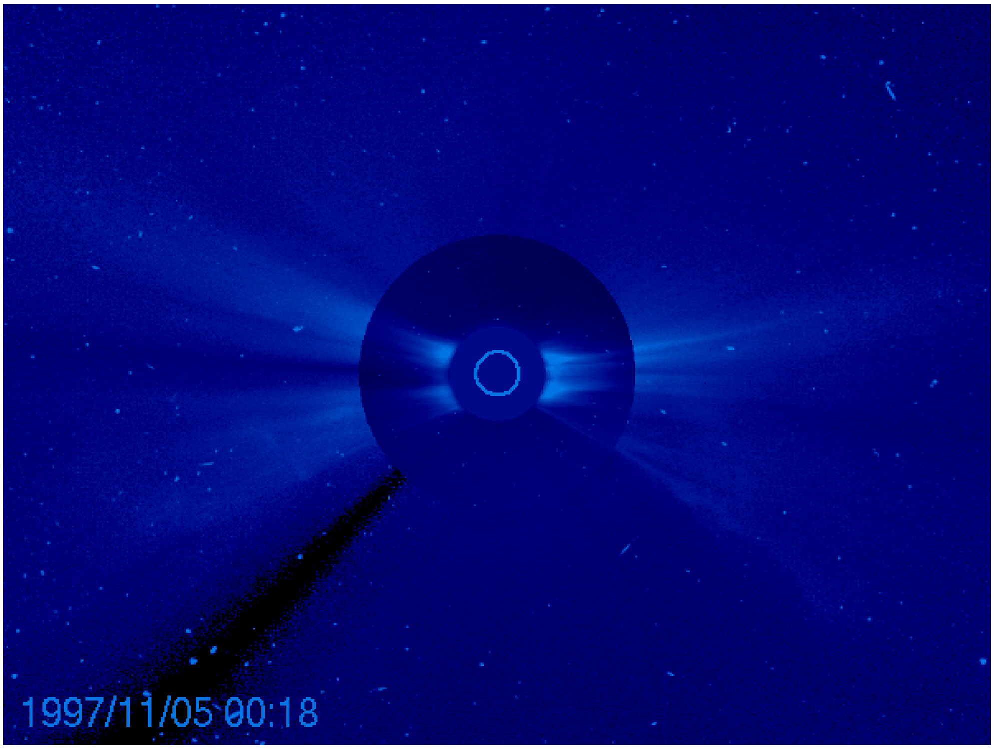


Movie Sequence

Flare Model developed by Shibata et al.

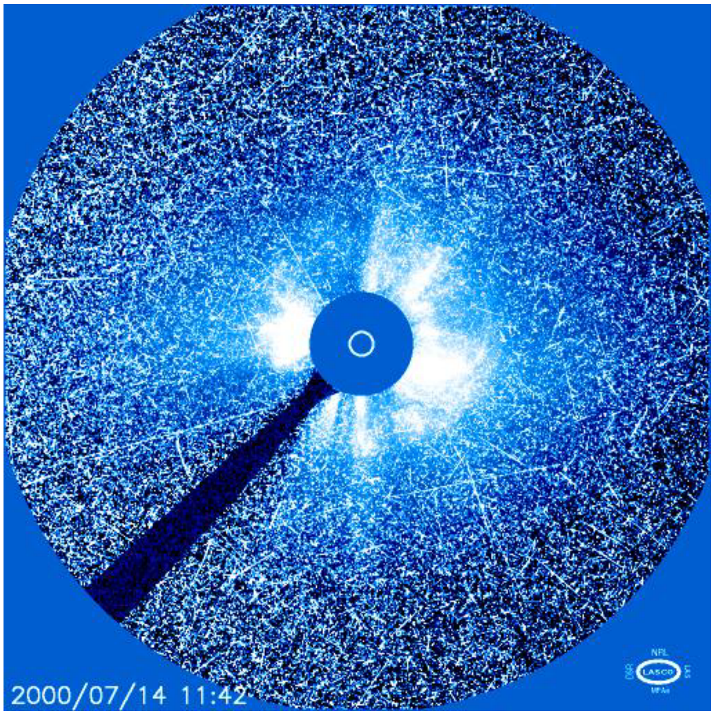


CME Observed by LASCO on SOHO

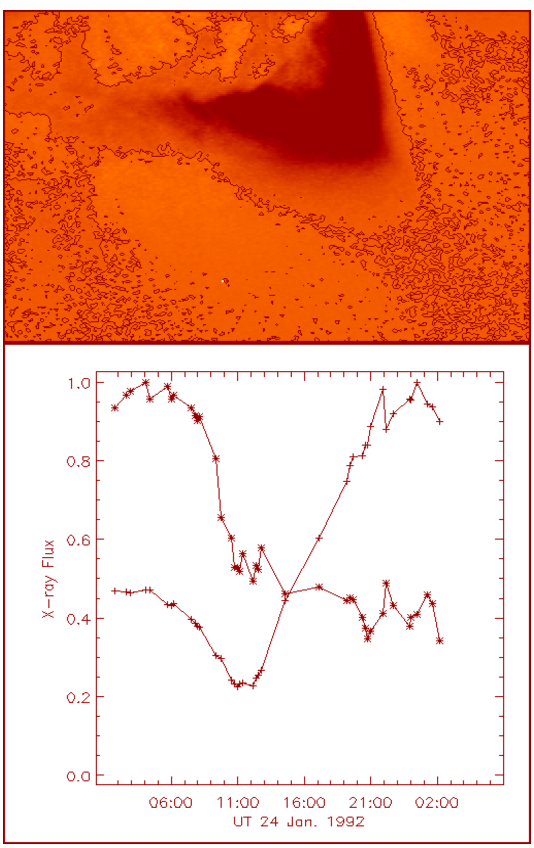


Movie Sequence

Halo CME Directed towards Earth

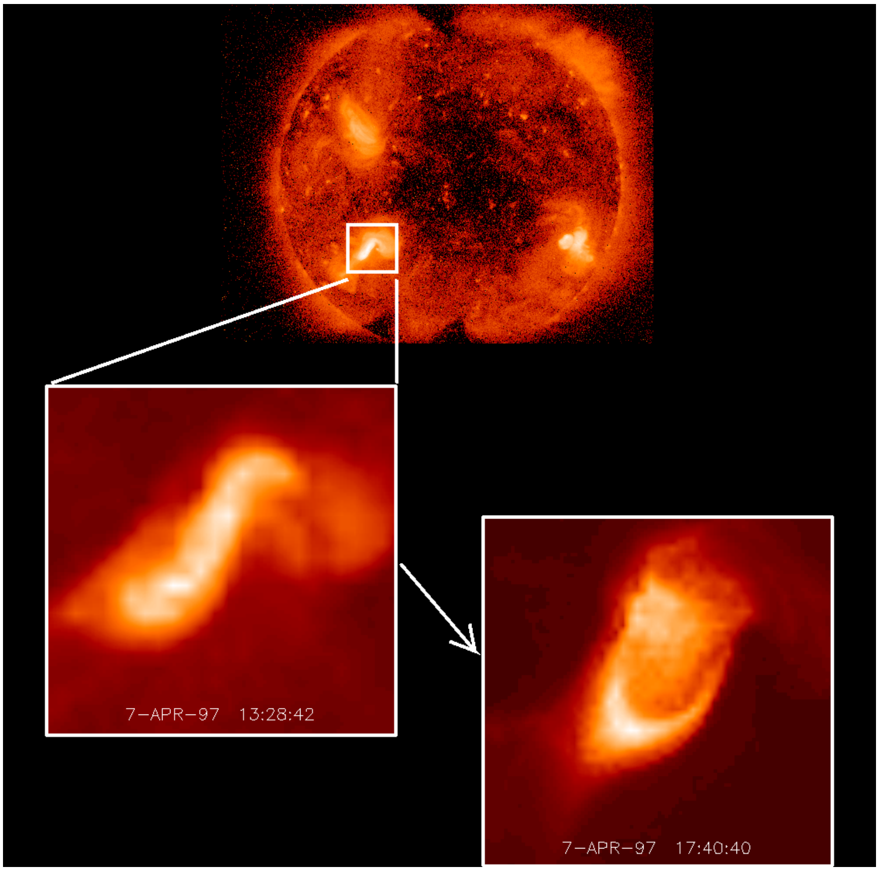


Coronal X-ray Dimming as a CME Launch Signature



Coronal depletion (X-ray Dimming) during a streamer reformation.

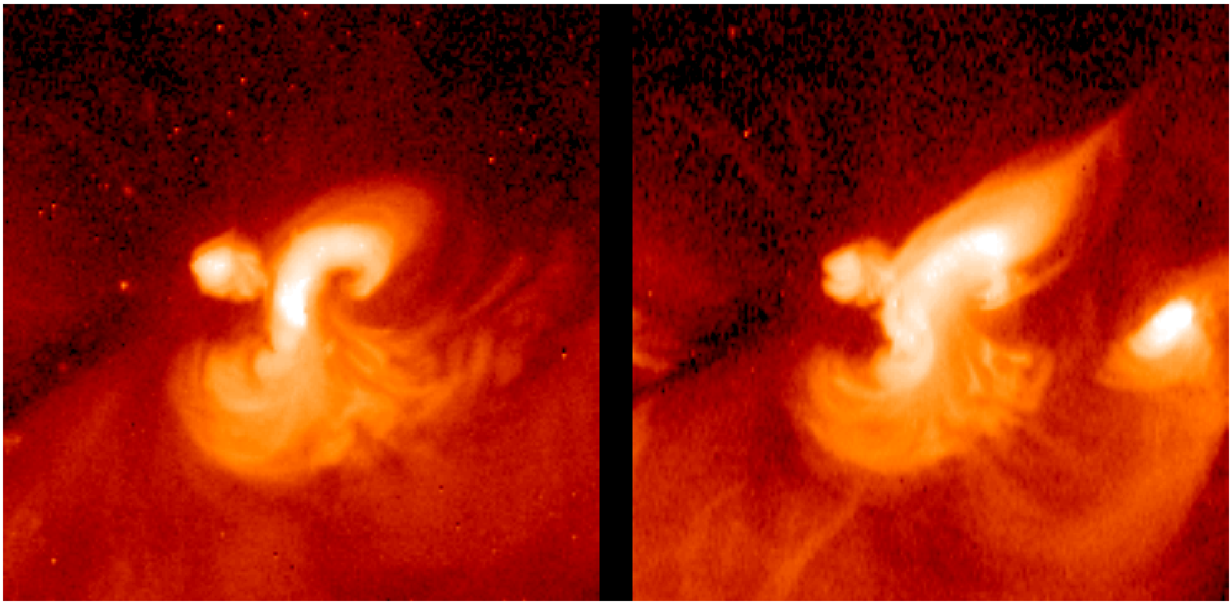
Hiei et al (1993), *Hudson* (1996)



Sigmoids-predictions of CMEs?

Sterling & Hudson (1997)

Further Sigmoidal Structure Example



Sigmoid seen in the corona before (left, 8 June, 1998, 15:19 UT) and after, (right, 9 June, 1998, 16:15 UT) eruption. Note the post-eruption cusp structure

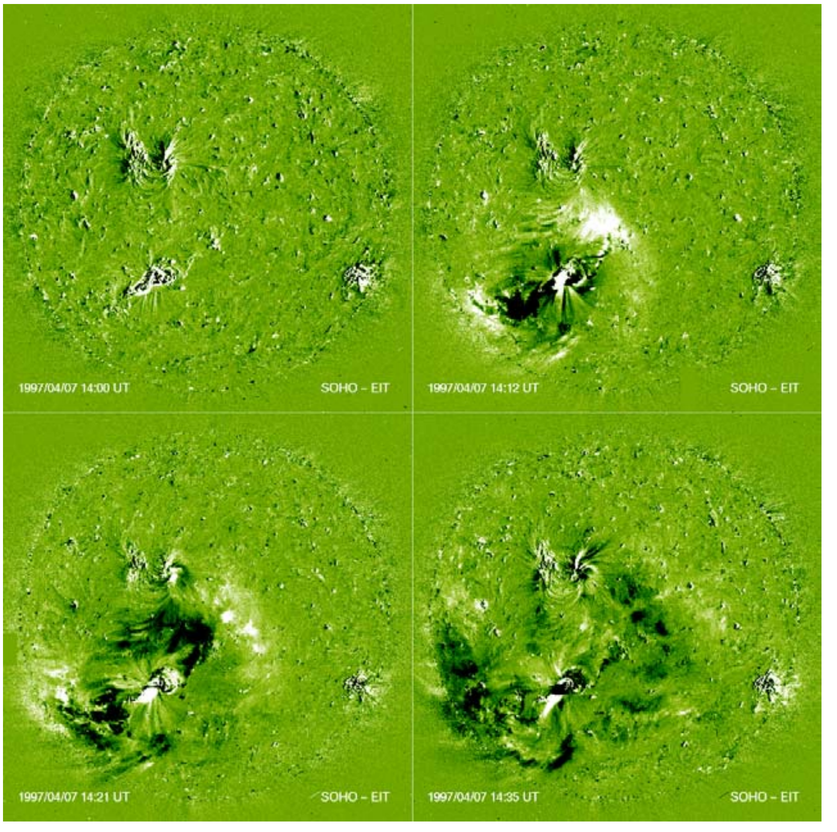
Coronal Waves Detected by SOHO EIT – Fe XII, $T_e \sim 1.2$ MK

Often associated with CMEs

Related to Photospheric Moreton Waves?

Fast mode MHD wave (Uchida, 1974)?

Possible CME triggers?



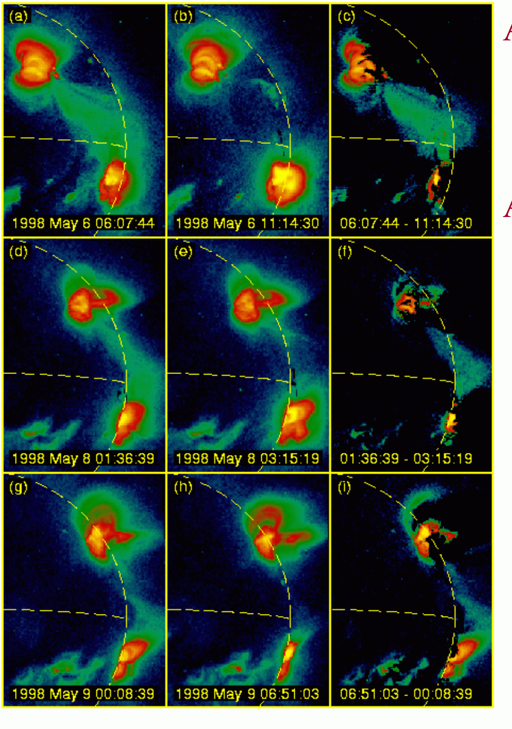
CMEs and Homologous Disappearances of Transequatorial Loops

Sequence of three transequatorial loop disappearances observed (1998, May 6 -10) with Yohkoh SXT by **Khan and Hudson (GRL, 2000)**

Each disappearance closely associated with a major flare and a CME

X-ray loop masses ~ 10^{15} g - similar to those of CMEs

Evidence that waves from the flare region (AR 8210) play a role in the disappearances



AR 8214

AR 8210

Magnetic Helicity

- Magnetic Helicity is a globally conserved quantity:
  - Convection zone → Corona → Interplanetary Medium

- Helicity $\mathbf{H} = \int_V \mathbf{A.B}\, \mathbf{dV}$ where A is the vector potential with $\mathbf{B} = \nabla \mathbf{x} \mathbf{A}$

- Requirement for V to be arbitrarily large posed a problem until:
  - Berger and Field (1984) defined *relative magnetic helicity* by subtracting the helicity of a reference field, B_0 which has the same distribution as the normal component, B_n on the boundary surface of V or

$$H_r = \int_V A.BdV - \int_V A_0.B_0 dV$$

where H_r is gauge invariant and is not dependent on the extension of B and B_0 outside V

Production and Removal of Magnetic Helicity

1. Coronal Helicity is given by

$$H_r = 2\alpha \sum_{n_x=1}^{N_x} \sum_{n_y=1}^{N_y} \frac{\left| B^2_{n_x,n_y} \right|}{l(k_x^2 + k_y^2)}$$

where B is the Fourier amplitude of the harmonic (n_x,n_y), $k_x = 2\pi n_x/L$, $k_y = 2\pi n_y/L$, $l = (k^2_x + k^2_y - \alpha^2)^{1/2}$ and L represents the horizontal extent of the computational box

The size and complexity of the AR require a large number of harmonics or $n_x = n_y = 256$

Production and Removal of Magnetic Helicity

2. Helicity generated by Differential Rotation has two terms or:

$$\Delta H_r(t) = \Delta H_r(t)\Big|_{twist} + \Delta H_r(t)\Big|_{writhe}$$

where *twist* relates to the rotation of each magnetic polarity and *writhe* involves the relative rotation of positive and negative polarities. However the *writhe* term has always the opposite sign from the *twist* term for solar differential rotation

Helicity generation is affected by:

- Latitude of the AR
- Degree of magnetic field dispersion
- Tilt of the bipole

Production and Removal of Magnetic Helicity

3. Helicity in Ejected Magnetic Clouds

Magnetic clouds are twisted flux tubes expanding as they move out from the Sun in a CME so we assume a one-to-one association. Following Berger (1999), the relative helicity per unit length for a twisted flux tube is of the form

$$\frac{dH_r}{dz} \sim 0.7\, B_{axial}^2\, R^3$$

where B_{axial} is the cloud axial field and R the cloud radius.
Following Lepping et al. (1990), $B_{axial} \sim 2.10^{-4}$ G and $R \sim 2.10^{12}$ cm
For L ~ 0.5 AU (assumes disconnection from Sun, DeVore, 2000),
$H_r \sim 20.10^{41} Mx^2$/cloud or per CME
For L ~ 2 AU (assumes connection to Sun, Richardson, 1997)
$H_r \sim 80.10^{41} Mx^2$/cloud or per CME

Source of Magnetic Helicity Shed by CMEs

- Demoulin, Mandrini, Van Driel-Gesztelyi et al. (2001) studied the Helicity budget of AR 7978 for 7 rotations from July-1996

- Procedure:
  - Extrapolate (LFF) photospheric field (MDI) into corona/derive α
  - Compute coronal AR helicity for each rotation
  - Calculate helicity due to differential rotation
  - Identify all AR 7978 CMEs and from average magnetic cloud properties, estimate the helicity shed by the CMEs
  - Compare the three helicity values to check if differential rotation could be the helicity source

- For the field extrapolation, $\nabla \times B = \alpha B$ so:
  - Compute field as f(α) and match structures with observed loops
  - Repeat for different values of α to find best global fit

Magnetic Field Extrapolations

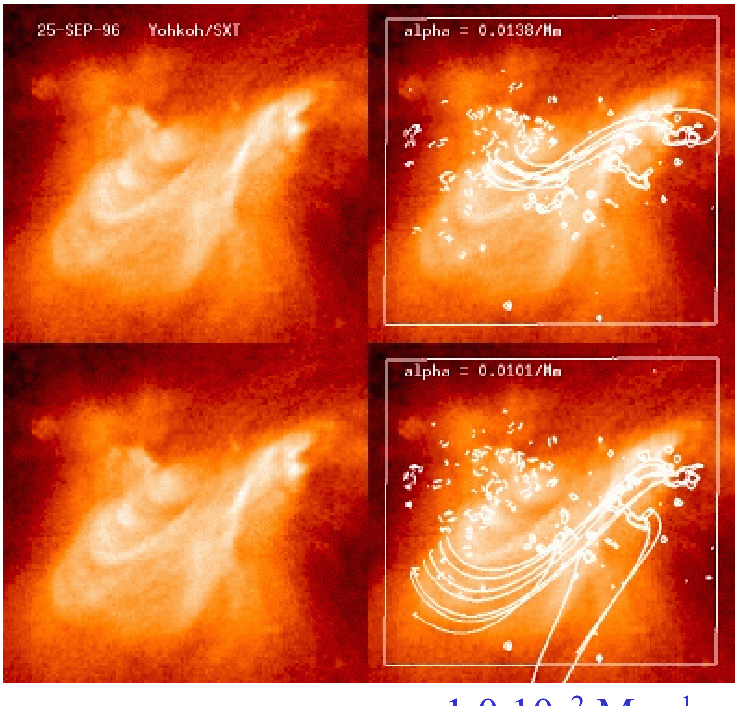
Parameter α determined by iteration

Coronal field is computed for a given α and a match sought between field lines and SXT loops

Repeated for a range of α values to find the best one for a global fit

N-S shear gradient usually requires two α values

$\alpha = 1.4.10^{-2}$ Mm^{-1}



$\alpha = 1.0.10^{-2}$ Mm^{-1}

Evolution of AR 7987

Flares and CMEs in AR 7978 | Helicity Budget of AR 7978

Rot. no.	Date of CMP	Flares X	Flares M	Flares C	Flares B	CMEs	Coronal (10^{42} Mx^2)	Diff. Rot. (10^{42} Mx^2)	Mag. Clouds (10^{42} Mx^2)
1	7-July-1996	1	2	14	16	8	-	2	[16, 74]
2	3-Aug-1996	-	-	1	17	5	[5, 11]	3	[10, 40]
3	30-Aug-1996	-	-	-	2	1	[17, 23]	3	[2, 8]
4	25-Sep-1996	-	-	-	-	7	[9, 12]	1	[14, 56]
5	23-Oct-1996	-	-	-	1	3	[4, 6]	0.8	[6, 24]
6	18-Nov-1996	-	-	-	-	4	4	0.3	[8, 16]

- Differential rotation fails to provide sufficient helicity for either the coronal field (by x 2 – x 6) or the CMEs (by x 5 – x 20)
- Ejected helicity is equivalent to that of a flux tube with the same flux as AR 7978 and having between 0.6 and 2.4 turns
- Estimating coronal helicity may allow us to recognize CME launch sites but magnetic cloud helicity has significant uncertainties

CME Launch and Interaction with Earth

From observation of flux emergence and solar magnetic structures, seek to predict for CMEs:

- launch site

- launch time

- magnetic cloud structure and B direction

Movie Sequence

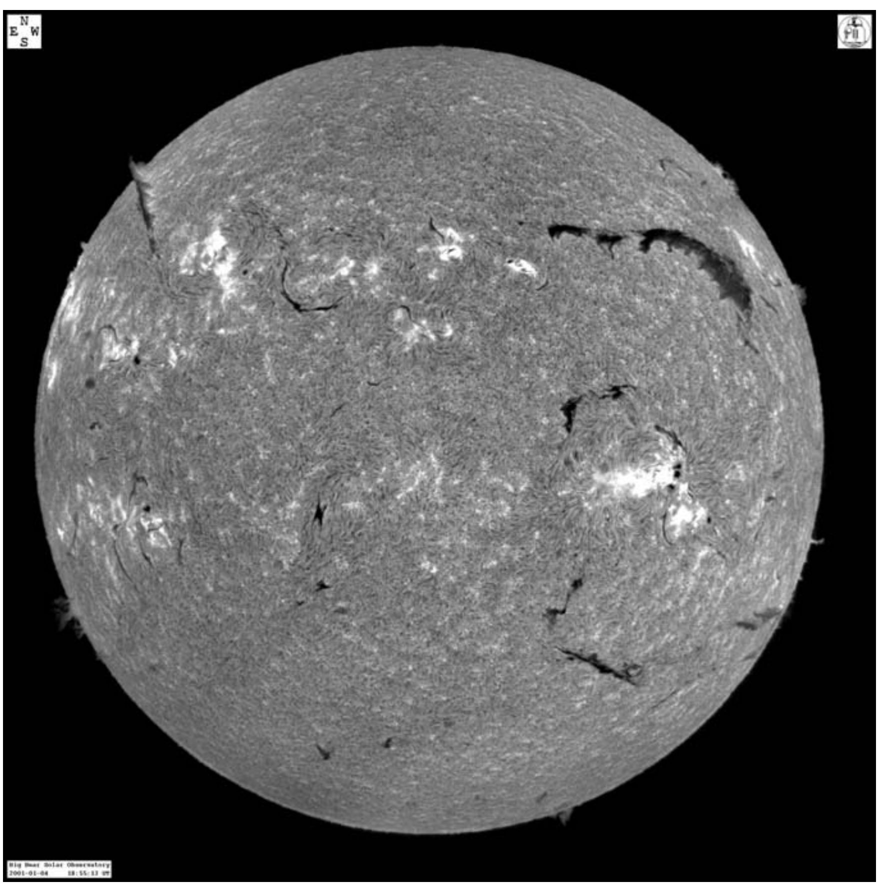
CONCLUSIONS

- Solar activity and the related Space Weather impacts on Earth are due to the emergence of magnetic flux from the convection zone
- Magnetic activity exhibits an eleven (22) year cycle and causes many features in the sun's atmosphere – e.g. sunspots, plasma loops, flares, CMEs
- Helioseismology allows the systematic study of plasma flows in the convection zone and eventually of the formation of magnetic features below the photosphere
- Observers are finding phenomena in the Corona that are related to the launch of CMEs
- Magnetic Helicity is a useful parameter that is allowing the emergence and ejection of magnetic flux to be described quantitatively – it may help CME forecasts

END OF LECTURE

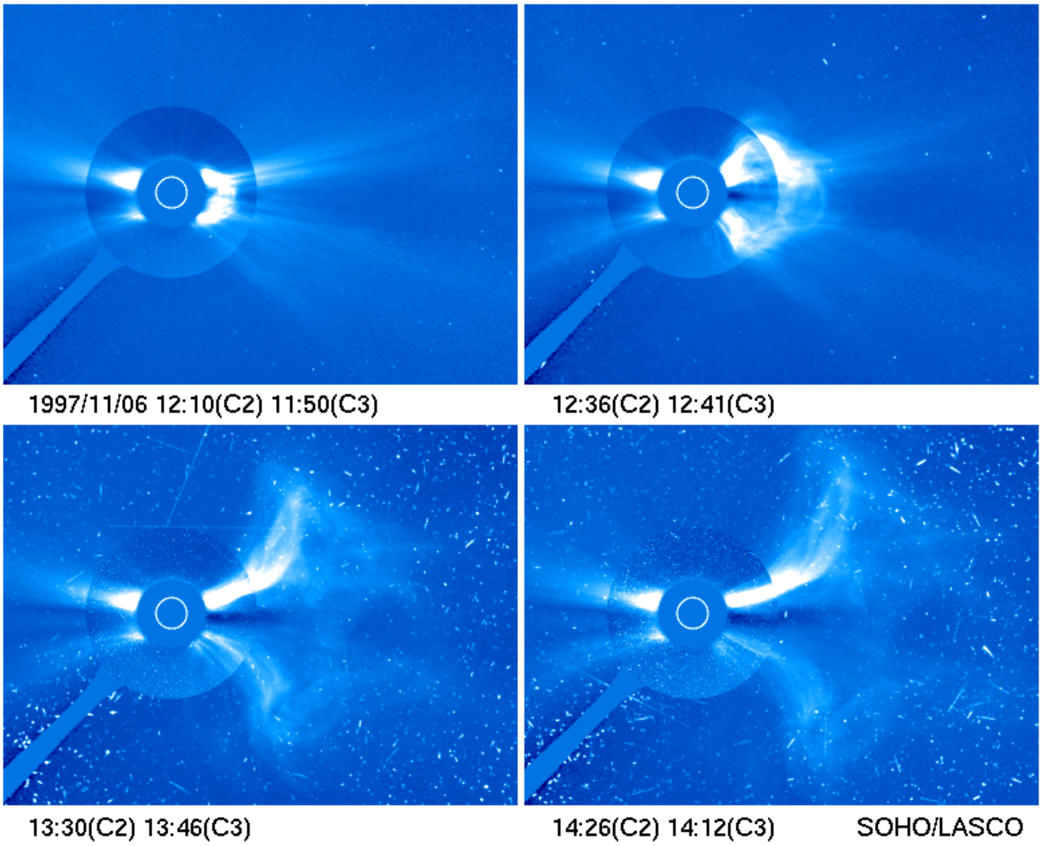
Sun Basics

- Sun is 5 billion years old - a G2 V star
- Earth distance is $1.5.\ 10^8$ km (1 Astronomical Unit)
- Energy source is by fusion of H to He
- $T_{core} \sim 15.\ 10^6$ K, $T_{surface} = 5778$ K,
- Energy is transported by radiation and convection
- Mass = $2.\ 10^{30}$ kg, Radius = $7.\ 10^5$ km,
- Density ~ $1.4.\ 10^3$ kg/m^3, Luminosity ~ $4.\ 10^{23}$ kW
- Rotation period ~ 26 - 36 days (differential with latitude)
- Extended outer atmosphere with T ~ 1- 3. 10^6 K but up to 50. 10^6 K for solar flare plasma
- Mass outflow (Solar Wind; v ~ 300 - 800 km/s)



Jan 4 2001 - image in Hα - filaments are clearly seen.

Four Images of a CME Observed by LASCO on SOHO



Solar p-mode Waves

- For spherical symmetry, sound wave modes are established in a central **gravitational** potential well
- Situation analogous to that of electron in an electrostatic well; the modes are the allowed eigenfunctions in the Solar gravitational potential well
- Gas density oscillates in space (r, θ, φ) and time (t) hence

$\rho = \rho'_{n,,l}\ (r)\ \ Y_{l,m}\ (\theta, \varphi)\ \exp\ (-i\ \omega\ t)$

- Radial density structure is a standing wave in r with n nodes along the path where

$Y_{l,m}\ (\theta, \varphi) = P_l^{\ m}\ (\text{Cos}\ \theta)\ \exp\ (i\ m\ \varphi)$ and

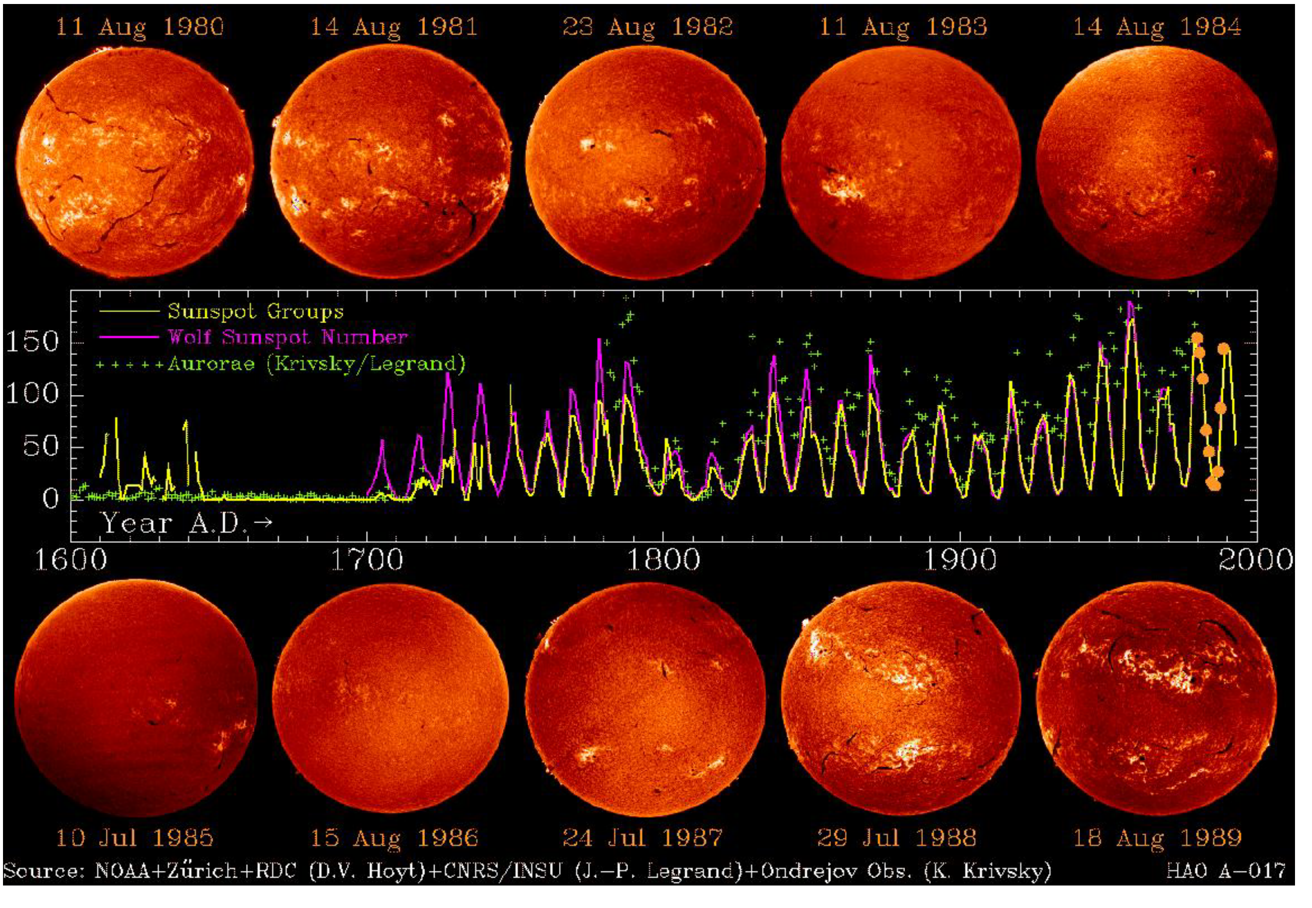
$P_l^{\ m}\ (x) = (-1)^m\ (1 - x^2)^{m/2}\ d^m/dx^m\ P_l\ (x)$ - Legendre polynomial

Solar p-mode Waves

- Order **n** defines the number of nodes in the radial function
- Degree **l** = 0, 1, 2, - - - (n-1) gives the number of surface nodal lines where

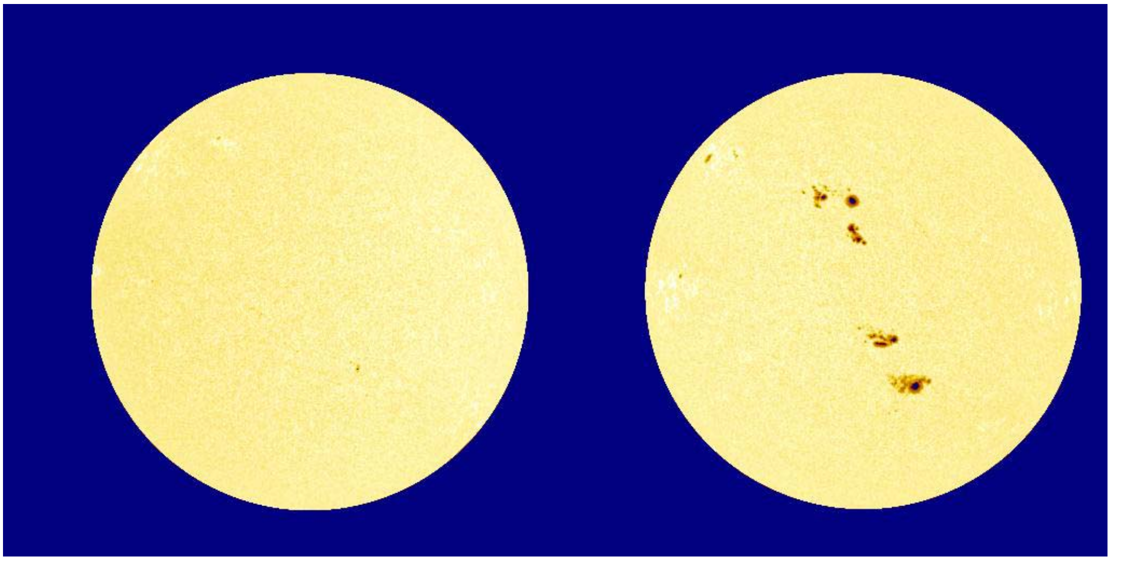
$$l = 2\pi R_O/\lambda_h \text{ and } k_h = 2\pi/\lambda_h = [l(l+1)]^{1/2}/R_O$$

- The azimuthal order of the mode |**m**| < l represents the number of surface nodal lines perpendicular to the equator
- In the absence of rotation, modes of different m all have the same frequency i.e. they are degenerate
- In the presence of rotation, modes of same n but different m are split into 2l + 1 frequency components due to their differing spatial ocsillations relative to the Sun's rotation

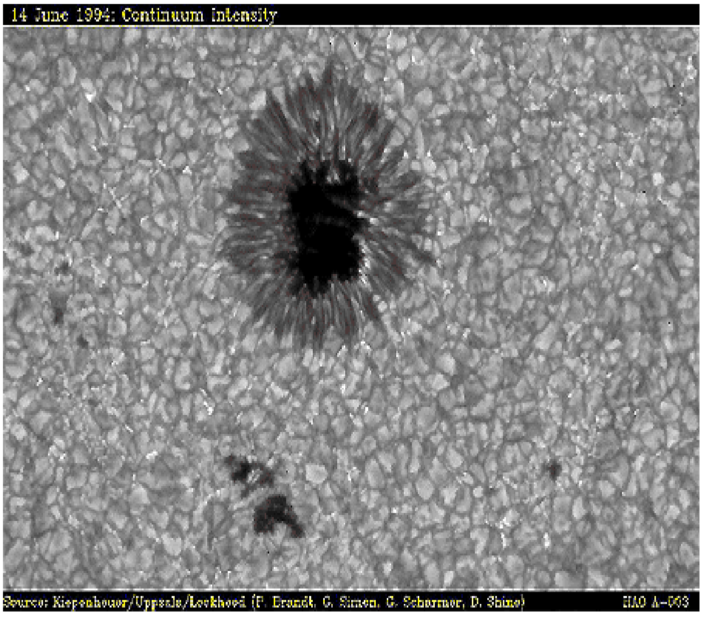


Shorter term changes

These images were taken 14 days apart (5 May 2000 and 19 May 2000)



Granulation and Sunspots



<u>Granulation</u>

Cores - radiation from up-flowing gas

Dark lanes - downflowing cool gas

Cell dimensions ~ 1100km

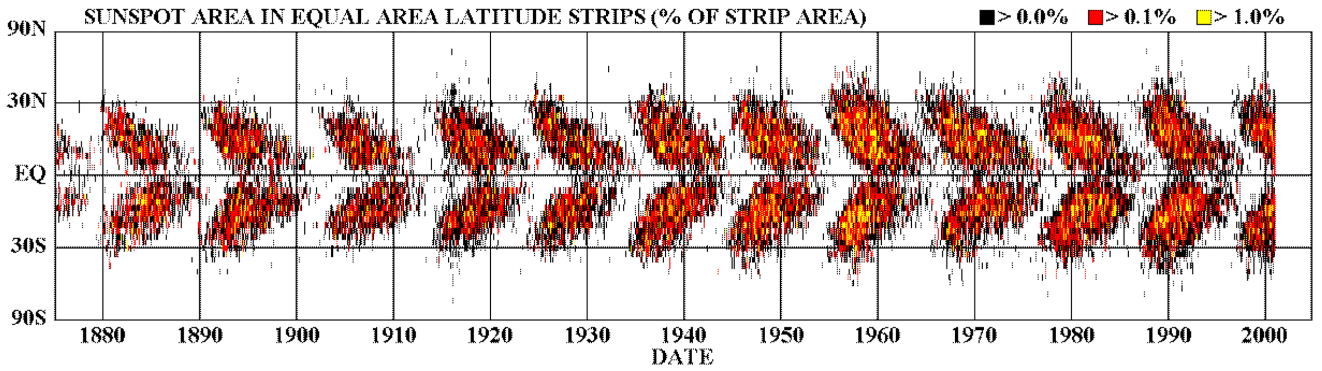
<u>Sunspots</u>

Contain strong B fields

These inhibit convection

Hence $T_{spot} < T_{phot}$ or for $B_{spot} \sim 0.4$ Tesla, $T_{spot} \sim 3700$ K. Size of Umbra ~ 20,000 km

The Butterfly Diagram



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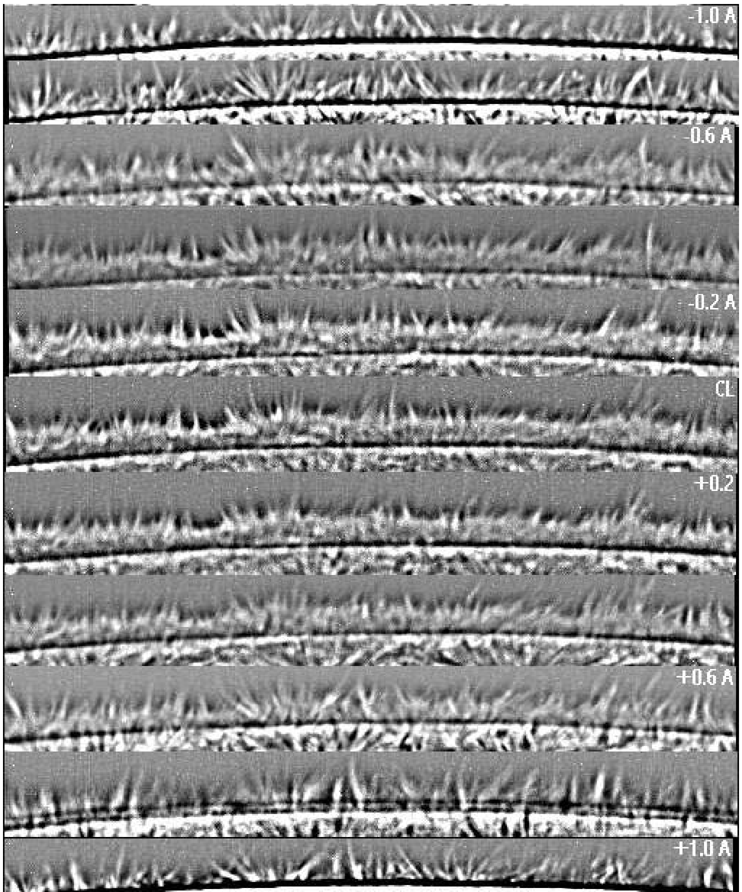
Spicules

Spicules - small jets of gas seen in Hα

They delineate the boundaries of the **Chromospheric Network**

Network cells are ~ 20,000 km in size



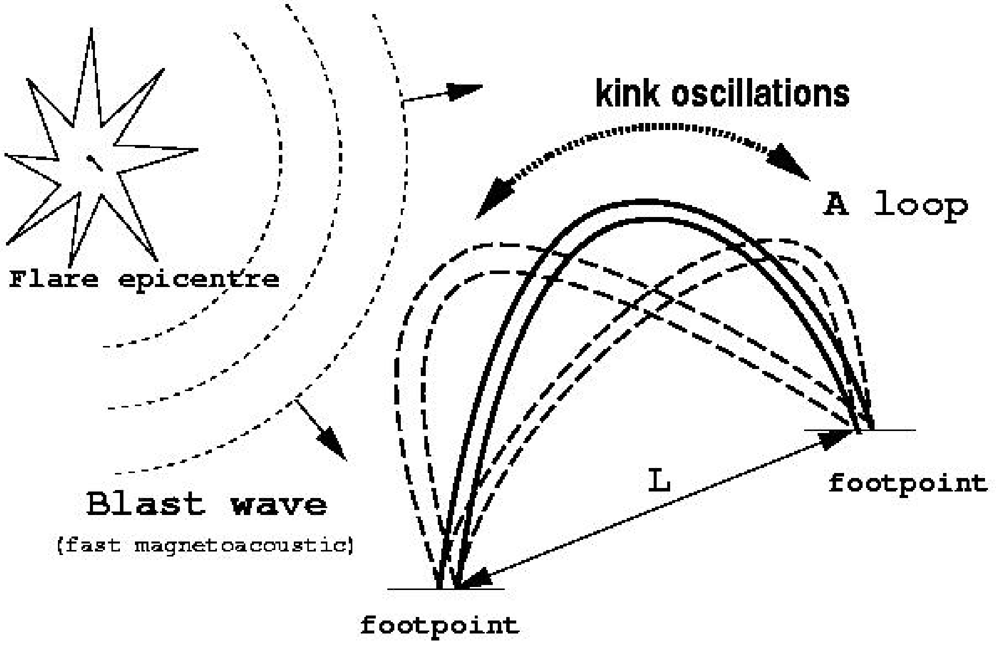
Spicules

Spicules - small jets of gas seen in Hα

They delineate the boundaries of the **Chromospheric Network**

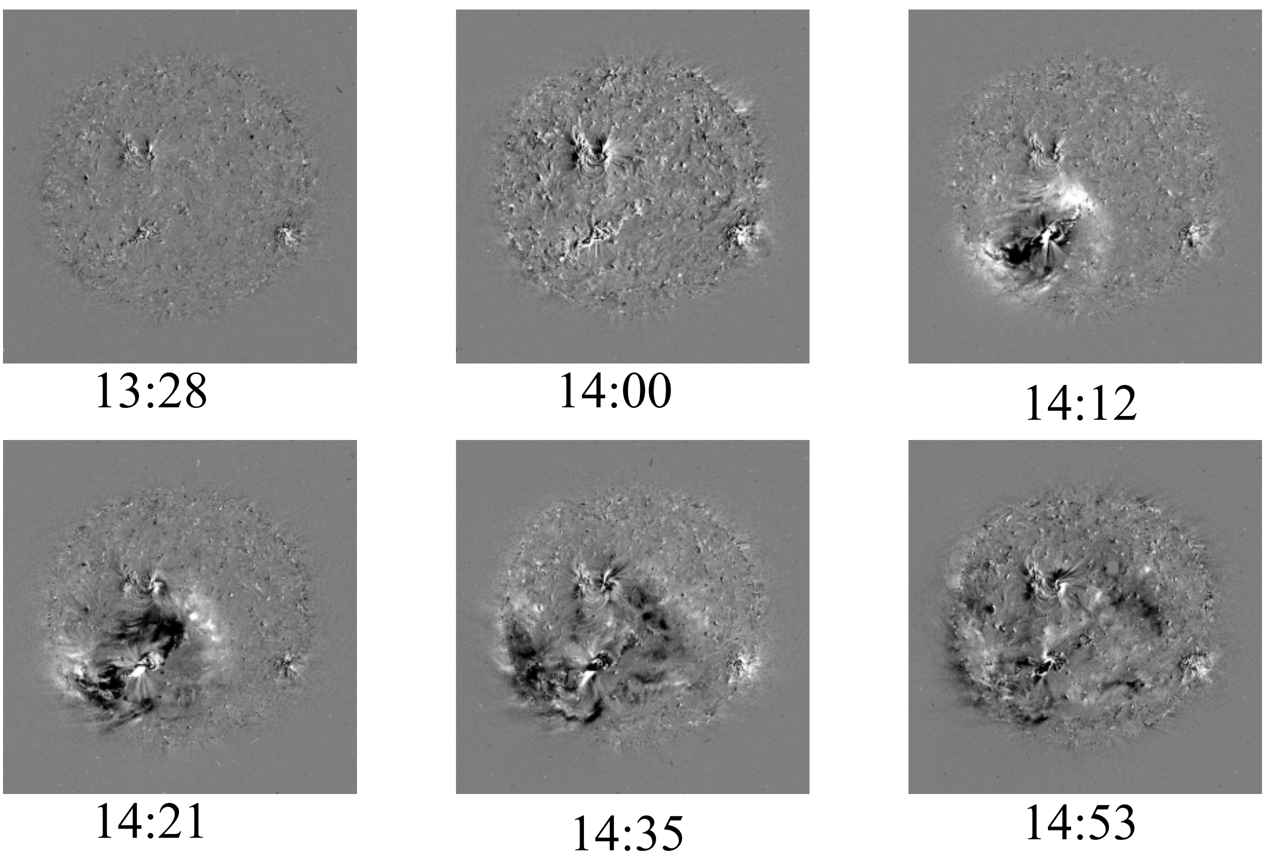
Network cells are ~ 20,000 km in size

Oscillating loops



Coronal Mass Ejections

- Large outbursts of material detected by Coronagraphs
- Approx. 10^{15} gm is lost from the Sun in a CME
- Depletion of Corona - seen as X-ray dimming, used to determine location and time of the CME launch
- Sigmoidal structures are 68% more likely to erupt
- Other CME indicators are being sought to enable prediction
- CMEs - and Flares, both result from destabilisation of the Coronal Magnetic field



Coronal Wave observed with SOHO EIT

CONCLUSIONS

- Solar activity and the related Space Weather impacts on Earth are due to the emergence of magnetic flux from the convection zone
- Magnetic activity exhibits an eleven year cycle and causes many features in the sun's atmosphere – e.g. sunspots, plasma loops, flares, CMEs
- Helioseismology will allow the systematic study of plasma flows in the convection zone and eventually of the formation of magnetic features below the photosphere
- Observers are finding phenomena in the Corona that may be related to the launch of CMEs
- Magnetic Helicity is a useful parameter that is allowing the emergence and ejection of magnetic flux to be described quantitatively – it may help CME forecasts

Solar Wind and Comet Hale-Bopp

Biermann (1957) proposed Solar Wind on the basis of seeing <u>two</u> comet tails:

1. <u>Diffuse</u> tail due to Radiation Pressure

2. <u>Collimated</u> tail due to plasma outflow - Solar Wind

Magnetic Helicity

- Magnetic Helicity is a globally conserved quantity:
  - Convection zone → Corona → Interplanetary Medium

- Helicity $\mathbf{H} = \int_V \mathbf{A.B}\, \mathbf{dV}$ where A is the vector potential with $\mathbf{B} = \nabla \mathbf{x} \mathbf{A}$

- Requirement for V to be arbitrarily large posed a problem until:
  - Berger and Field (1984) defined *relative magnetic helicity* or
  - $$H_r = \int_V A.B dV - \int_V A_0.B_0 dV$$
  - where H_r is gauge invariant and is independent of B and B_0 outside V