



ESS 200C

# The Sun

Lectures 4 and 5

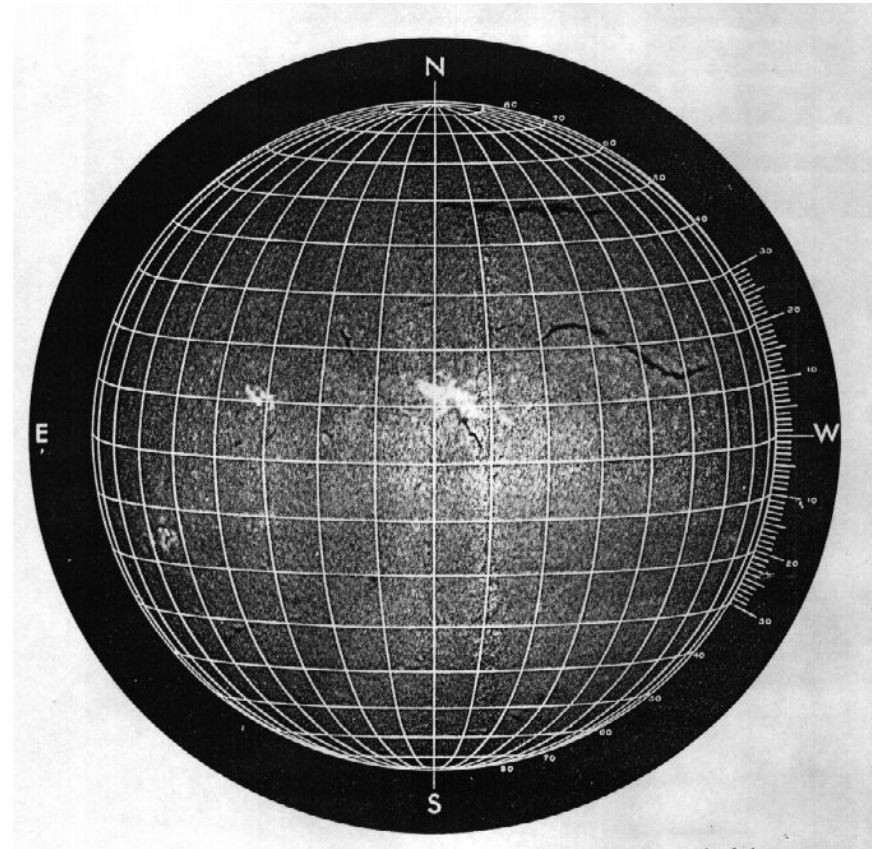
Structure of the Sun

Physical processes within the Sun

The Active Sun

# The Structure of the Sun

- The north and south poles are at opposite ends of the rotation axis.
- Because of the  $7^\circ$  tilt of the axis we are able to see the north pole for half a year and the south pole for the other half.
- West and east are reversed relative to terrestrial maps. When you view the Sun from the northern hemisphere of the Earth you must look south to see the Sun and west is to your right as in this picture.
- The image was taken in  $H\alpha$ . The bright area near central meridian is an active region. The dark line is a filament

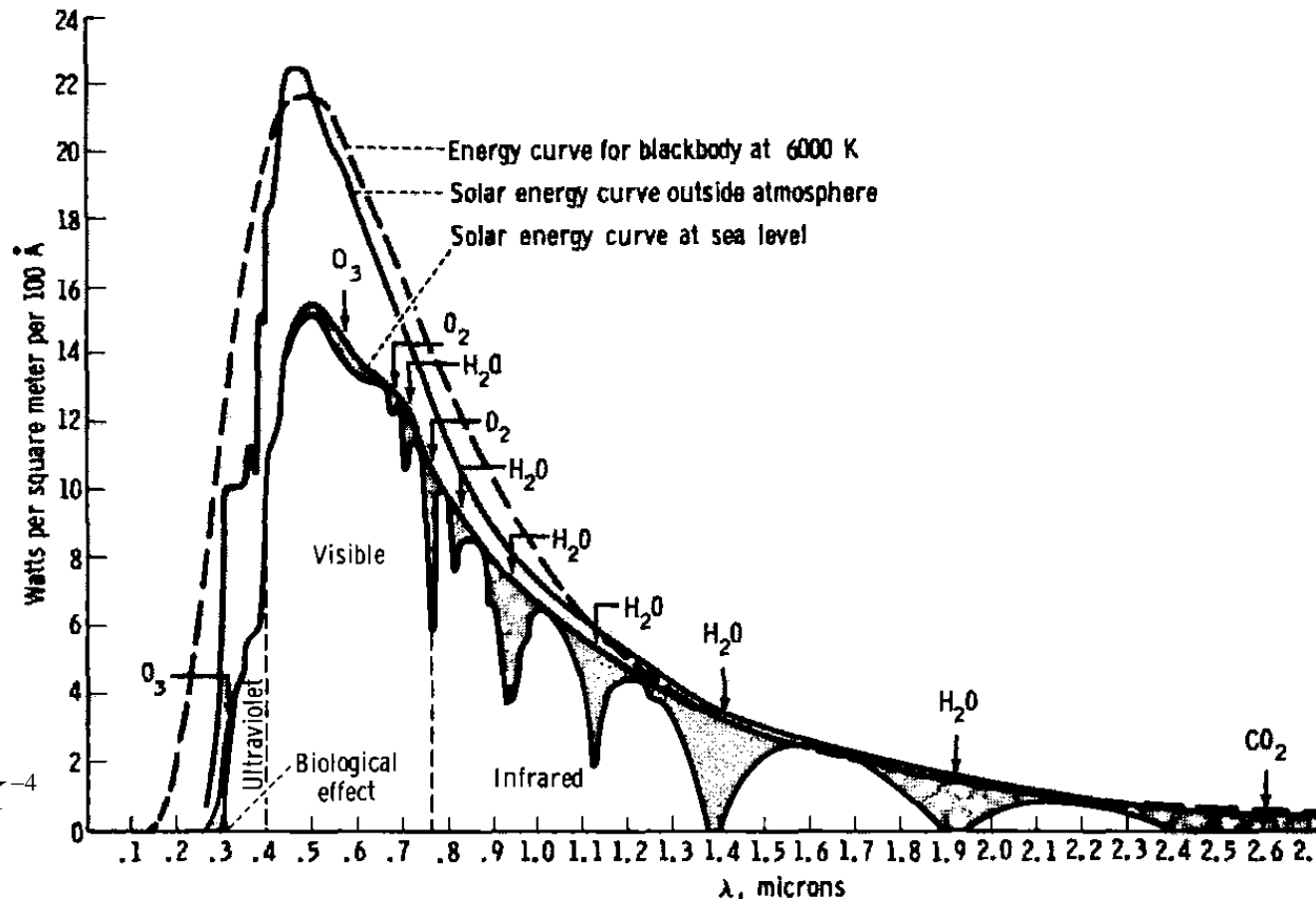


- Age =  $4.5 \times 10^9$  years
- Mass =  $1.99 \times 10^{30}$  kg.
- Radius = 696,000 km (= 696 Mm)
- Mean density =  $1.4 \times 10^3 \text{ kg m}^{-3}$  (=  $1.4 \text{ g cm}^{-3}$ )
- Mean distance from Earth (1 AU) =  $150 \times 10^6$  km (= 215 solar radii)
- Surface gravity =  $274 \text{ m s}^{-2}$
- Escape velocity at surface =  $618 \text{ km s}^{-1}$
- Radiation emitted (luminosity) =  $3.86 \times 10^{26} \text{ W}$
- Equatorial rotation period = 27 days (varies with latitude)
- Mass loss rate =  $10^9 \text{ kg s}^{-1}$
- Effective black body temperature = 5785 K
- Inclination of Sun's equator to plane of Earth's orbit =  $7^\circ$
- Composition: 90% H, 10% He, 0.1% other elements (C, N, O,...)

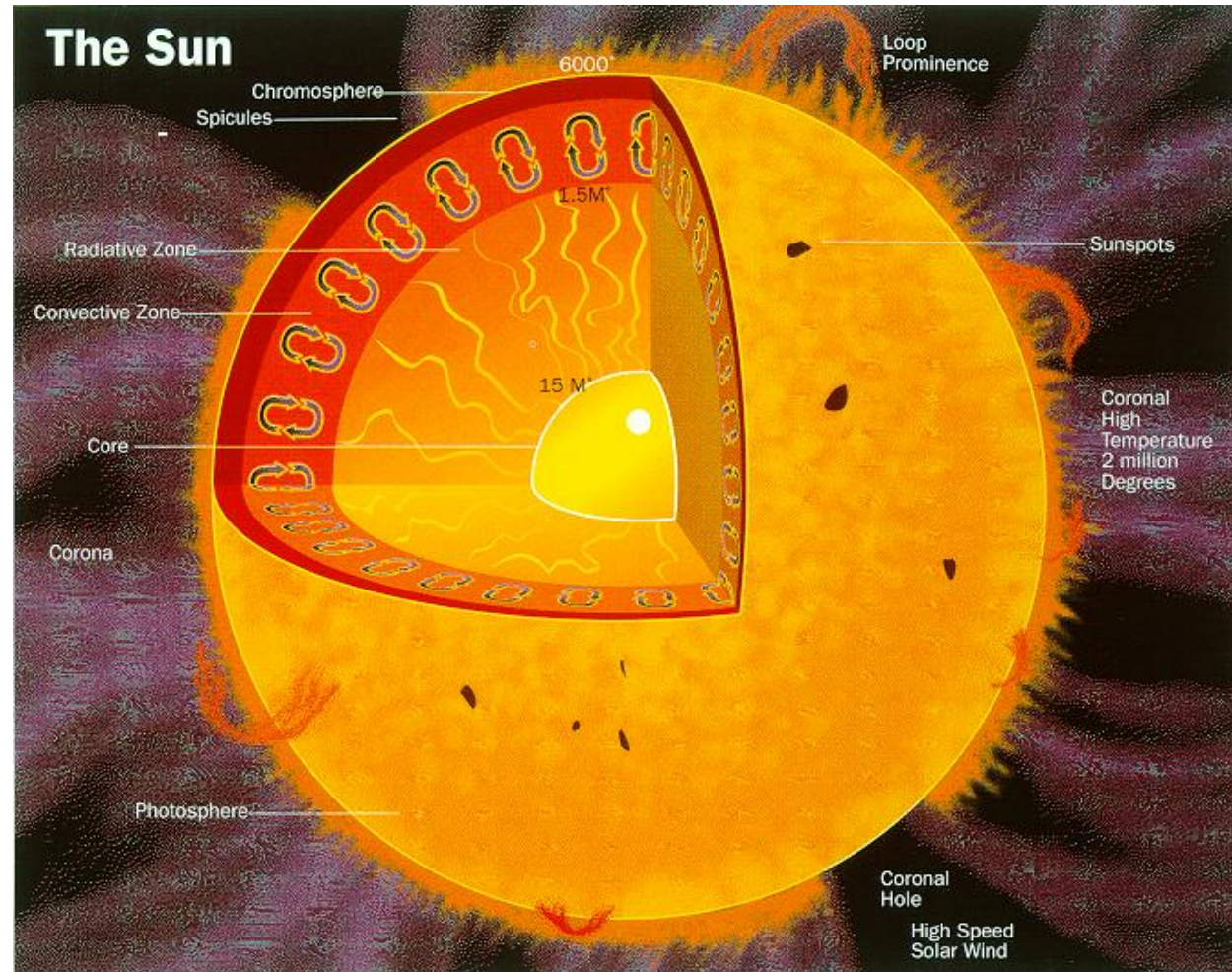
# •The Spectral Radiance of the Surface of the Sun as a Function of Wavelength

- The photosphere radiates like a black body at 6000 °K

- The Stefan-Boltzman law gives  $R = \sigma T^4$  where R is the integrated radiation, T is the black body temperature and  $\sigma = 5.67 \times 10^{-8} \text{ w m}^{-2} \text{ K}^{-4}$



- The Solar Structure
  - Core
  - Radiative Zone
  - Interface Zone
  - Convection Zone
  - Photosphere
  - Chromosphere
  - Transition Zone
  - Corona
  - Solar Wind



## •Properties of the Regions

Core - Nuclear reactions

Radiative Zone - Energy transfer by photons

Interface region - Bottom of convection zone

Convective zone - Heat transfer by fluid motion

Photosphere - Opaque to radiation from below. Emits most of the Sun's light ( $10^{23}\text{m}^{-3}$ , 4200K)

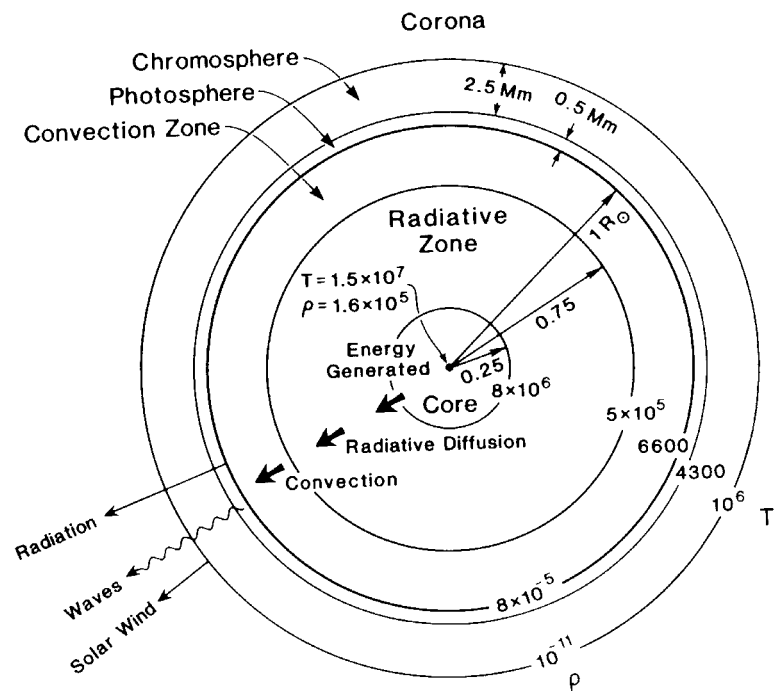
Chromosphere - Region of rapid rise in temperature ( $10^{17}\text{m}^{-3}$ , 20,000K)

Transition region - Bottom of corona

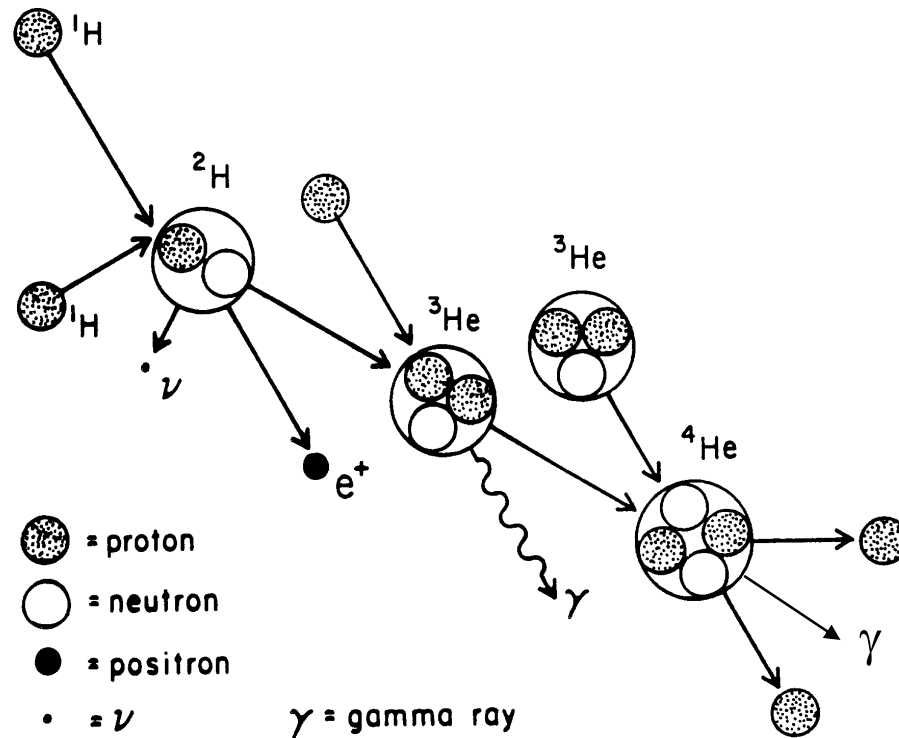
Corona - Very hot outer envelope of Sun ( $10^{15}\text{m}^{-3}$  near the Sun to  $10^7\text{m}^{-3}$  near the Earth,  $2 \times 10^6\text{K}$ )

## •Dimensions of Interior Regions

- The boundaries of the core, radiative and convective zones are roughly located at .25 and .75 solar radius
- The photosphere is about 500 km thick
- The chromosphere is about 2500 km thick



# • Nuclear Reactions in the Core



# •Details of the Nuclear Reaction

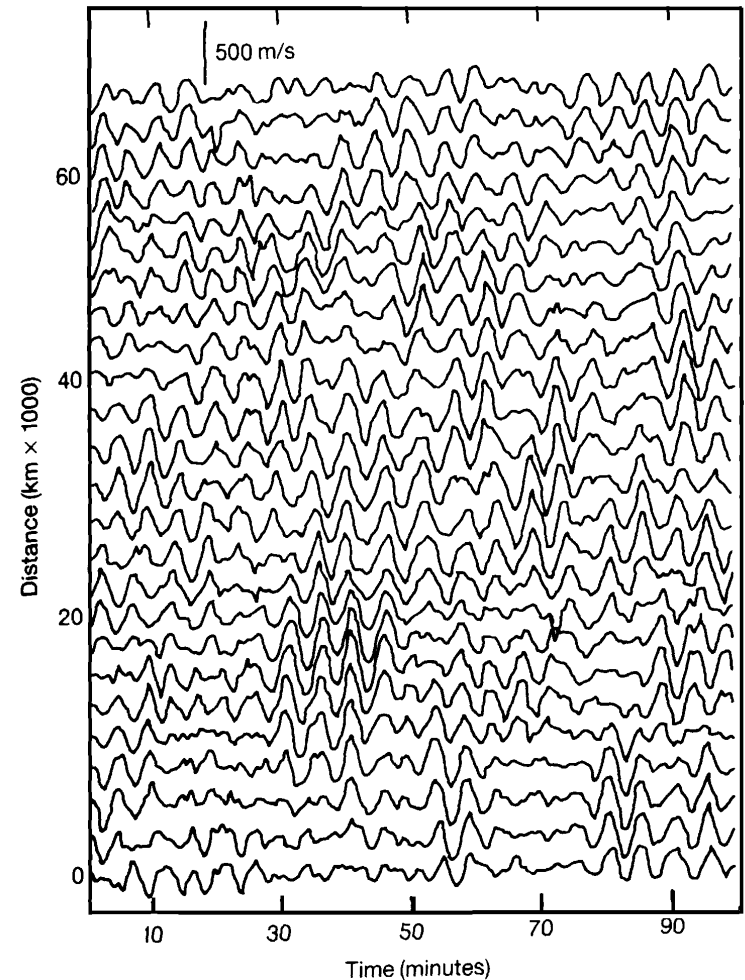
- When the temperature is above 10 million K two protons fuse to create an unstable particle that immediately decays into a deuterium nucleus, a positron, and a neutrino.
- The positron is annihilated by an electron giving off two gamma rays.
- A hydrogen atom immediately combines with the deuterium creating a  $\text{He}^3$  nucleus and a gamma ray.
- Two  $\text{He}^3$  nuclei eventually combine creating a helium nucleus (alpha particle) and two protons
- The average time for each step is quite different
  - ❑ The first step takes 14 million years
  - ❑ The second step takes about 6 seconds
  - ❑ The third step takes 1 million years
- Overall six protons interact producing one helium nucleus, two neutrinos, two positrons, five gamma rays and two protons
- Altogether 0.7% of the mass of four protons appears as energy

- Helioseismology

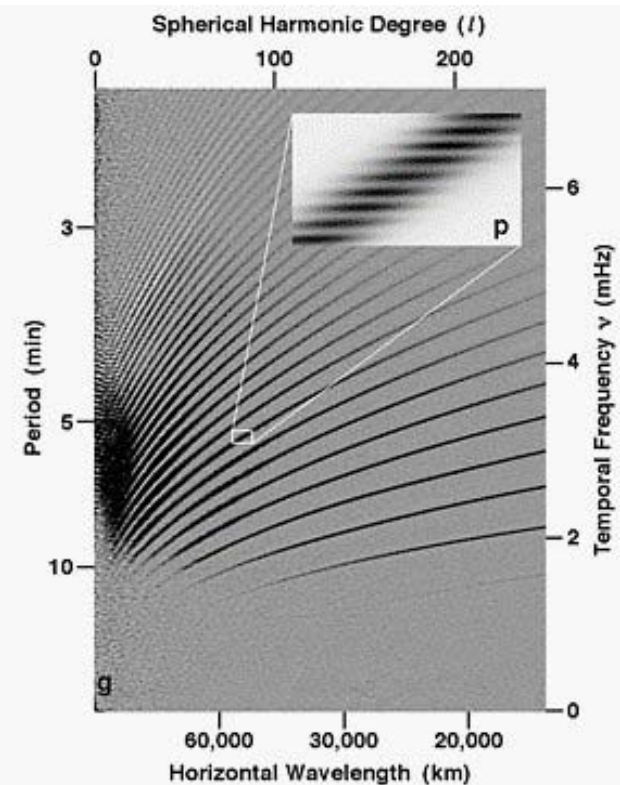
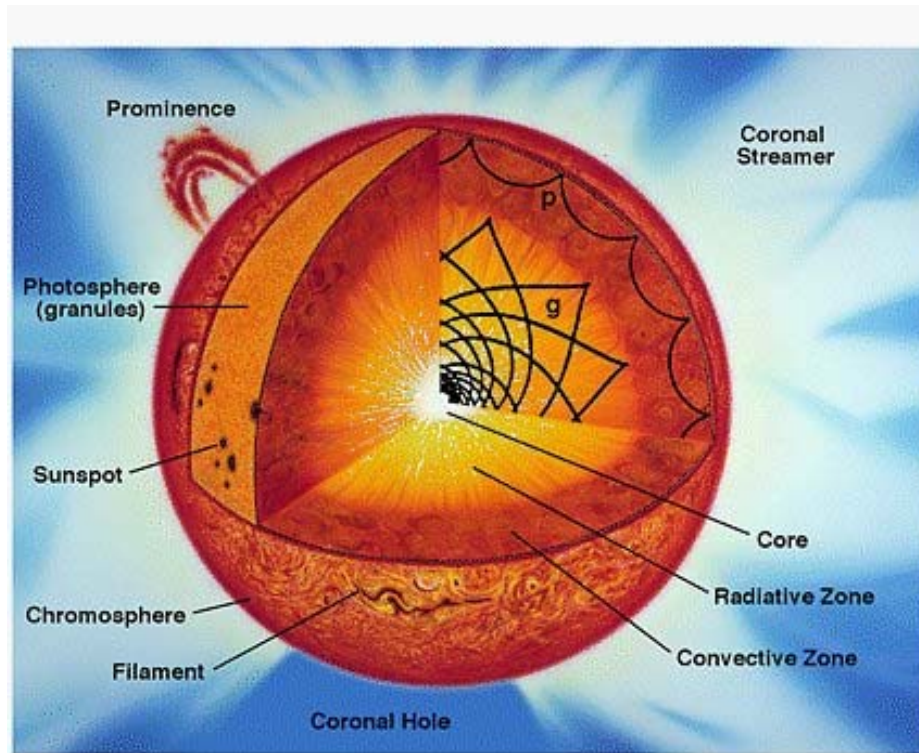
- Use Doppler shift in absorption line to monitor vertical velocity of points on Sun's surface
- Fourier transform time series to get wave frequencies
- Fourier transform spatial profiles to get wavelengths
- Different modes penetrate to different depths depending on sound velocity (temperature)
- Adjust the model to predict the observed mode structure

# • An Example of Surface Oscillations

- The Sun oscillates globally.
- Measure the Doppler shift in the center of an absorption line at points
- Translate the frequency shift into a vertical velocity ( a few cm/s)
- Plot time series of the velocity at each point.
- Fourier transform along a vertical line to get wavelength
- Fourier transform a given time series to get frequency spectra
- Sound waves trapped between the surface and a given depth depend on the order of the spherical harmonic.



# •Helioseismology



–The core rotates rigidly but the convection zone is rotating differentially (faster at the equator). This shows up at the surface (26 days at the equator and 37 days at the poles).

2 January 2006

# •The Radiative Zone

- Gamma rays emitted by the nuclear reactions travel in all directions from the core
  - There is a net flux of radiation towards the surface
  - Upward moving photons encounter atoms and ions that absorb, scatter and reradiate the energy at different wavelengths
  - The wavelength is changed by these interactions as energy is given to particles and then reemitted
  - The radius of the Sun is two light seconds, but it takes about 10 million years for a photon to reach the surface
- There are four processes that are important:
    - ❑ Bound-bound transition: Excite a bound electron to a higher state in an atom and then emit an atomic line
    - ❑ Bound-free transitions: Strip the electron from the atom leaving both with kinetic energy. The electron eventually recombines and the atom radiates the excess energy
    - ❑ Free-free transitions: Increase the energy of an electron by absorption some or all of the energy of a photon
    - ❑ Scattering: Alter the direction of propagation of a photon by interaction with an ion or electron

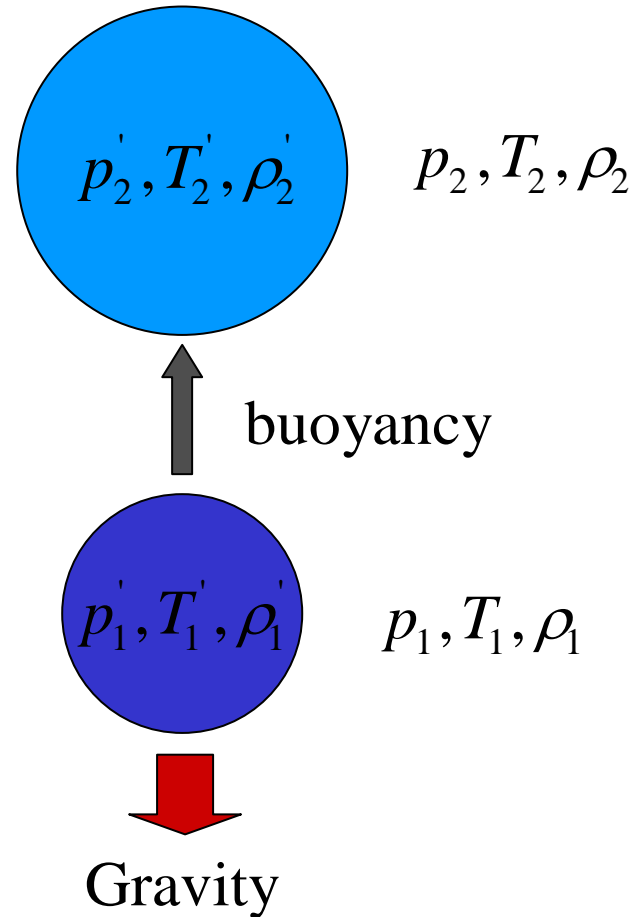
# •The Convection Zone

- Temperature in the Sun drops from 15 million degrees in the core to 4500 degrees at the top of the photosphere
- The temperature gradient allows energy to diffuse toward surface
- The surface temperature is so low that hydrogen and helium recombine to form neutral atoms
- Metals in the surface layer are still ionized at these temperatures providing free electrons
- The electrons can combine with the hydrogen atom to form a negative hydrogen ion
- These ions are easily disrupted by light of any wavelength absorbing radiation from below
- Recombination and negative ion formation make this top layer opaque
- The bottom of this layer becomes hotter trying to create a temperature gradient that will drive the radiation through
- If the gradient is steep enough it becomes more efficient to transport energy by convection (fluid motion) than by radiation

# • Convection

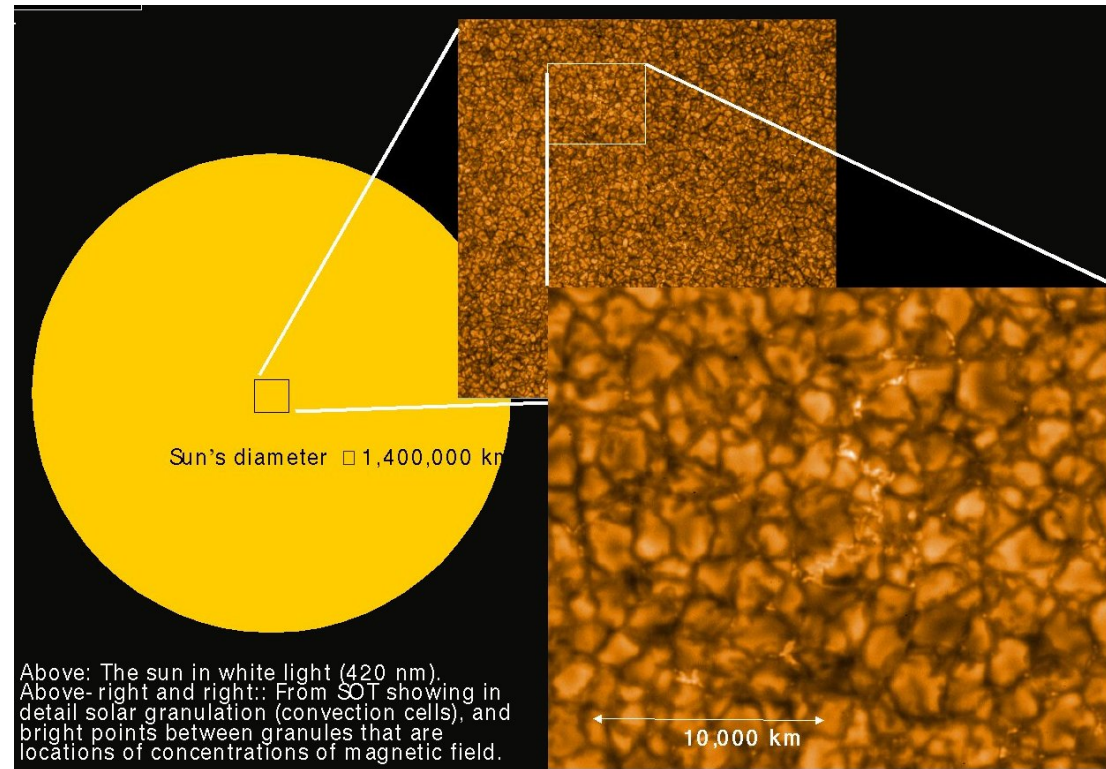
- Convection will occur if a rising fluid element becomes lighter (less dense) than its surroundings
- In this case the force of gravity on the element is weaker than the force exerted by the surrounding fluid (buoyancy)
- Assume no heat transport across the boundary of the rising element
- As the element rises it expands to maintain pressure equilibrium with its surroundings
- Expansion reduces the density and cools the interior of the element
- If the element is hotter than its surroundings it will be less dense, buoyant, and continue to rise

To photosphere



# • Photospheric Granulation

- The granulation resulting from the convection covers the photosphere
- The size of typical granulation cells is  $\sim 1000$  km and their separation is about 1400 km
- The life time of a granule is  $\sim 18$  minutes
- They are separated by intergranular lanes that are about  $400^\circ$  cooler
- Fluid rises in the center of cells, flows towards edges, and falls in the lanes with a relative velocity of  $\sim 2$  km/s

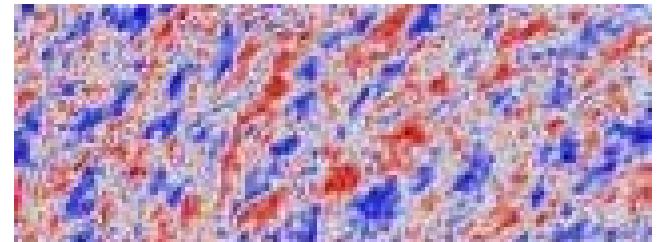
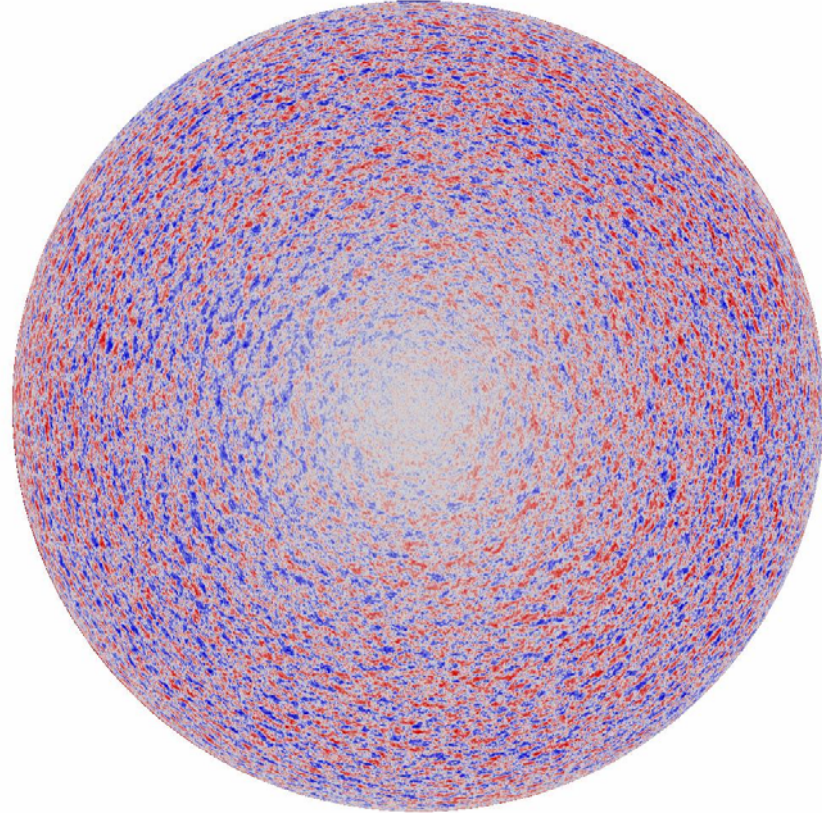


Granules and sunspot from the Hinode satellite.

- Supergranulation

- A “Dopplergram” with red showing material moving away from Earth and blue moving toward the Earth
- The motion is organized into cells called supergranulation
- Supergranulation is driven by deep-rooted convection caused by helium deionization
- Typical spatial scale is 32,000 km (5 Re) with a life time of 1-2 days
- Horizontal convection velocities are ~400 m/s (faster than a hurricane!)
- Vertical velocities in the center of cells are very low, and at edges about 100 m/s
- At the edges the magnetic field is concentrated to 1kG

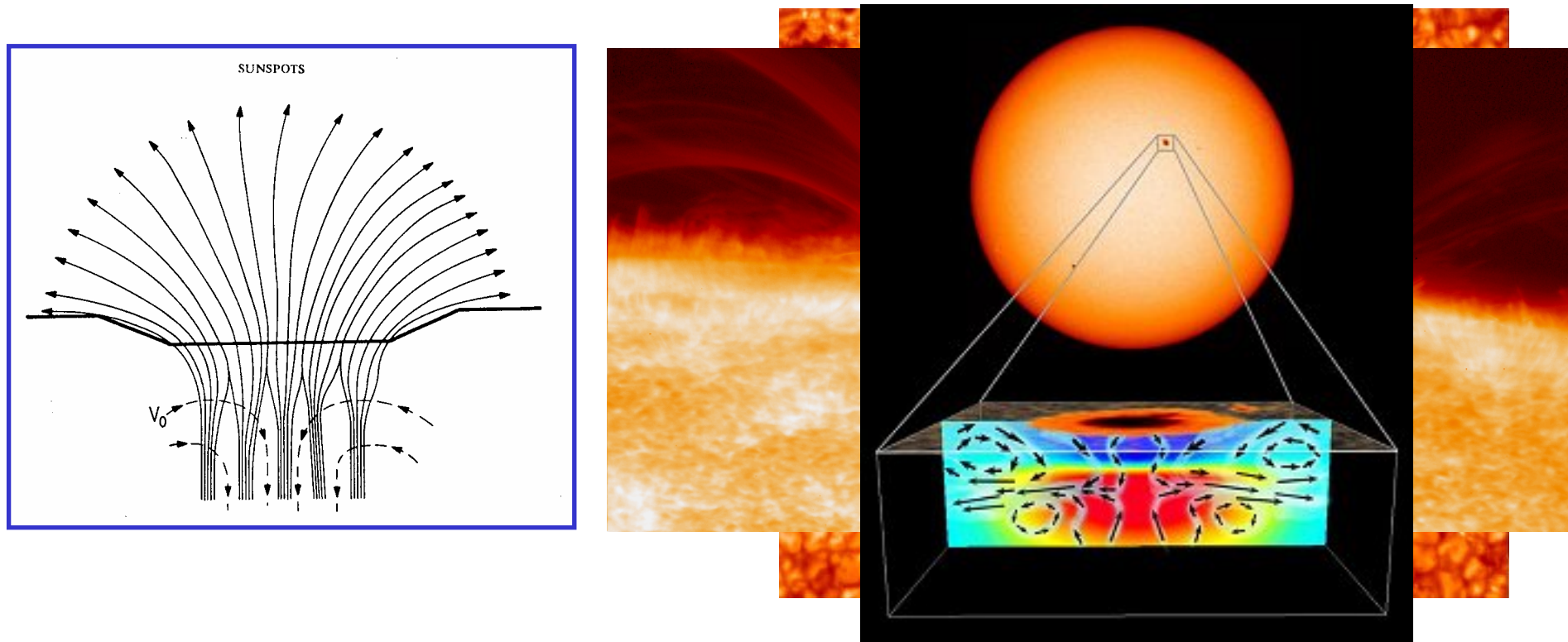
Convection Pattern 1996 June 15



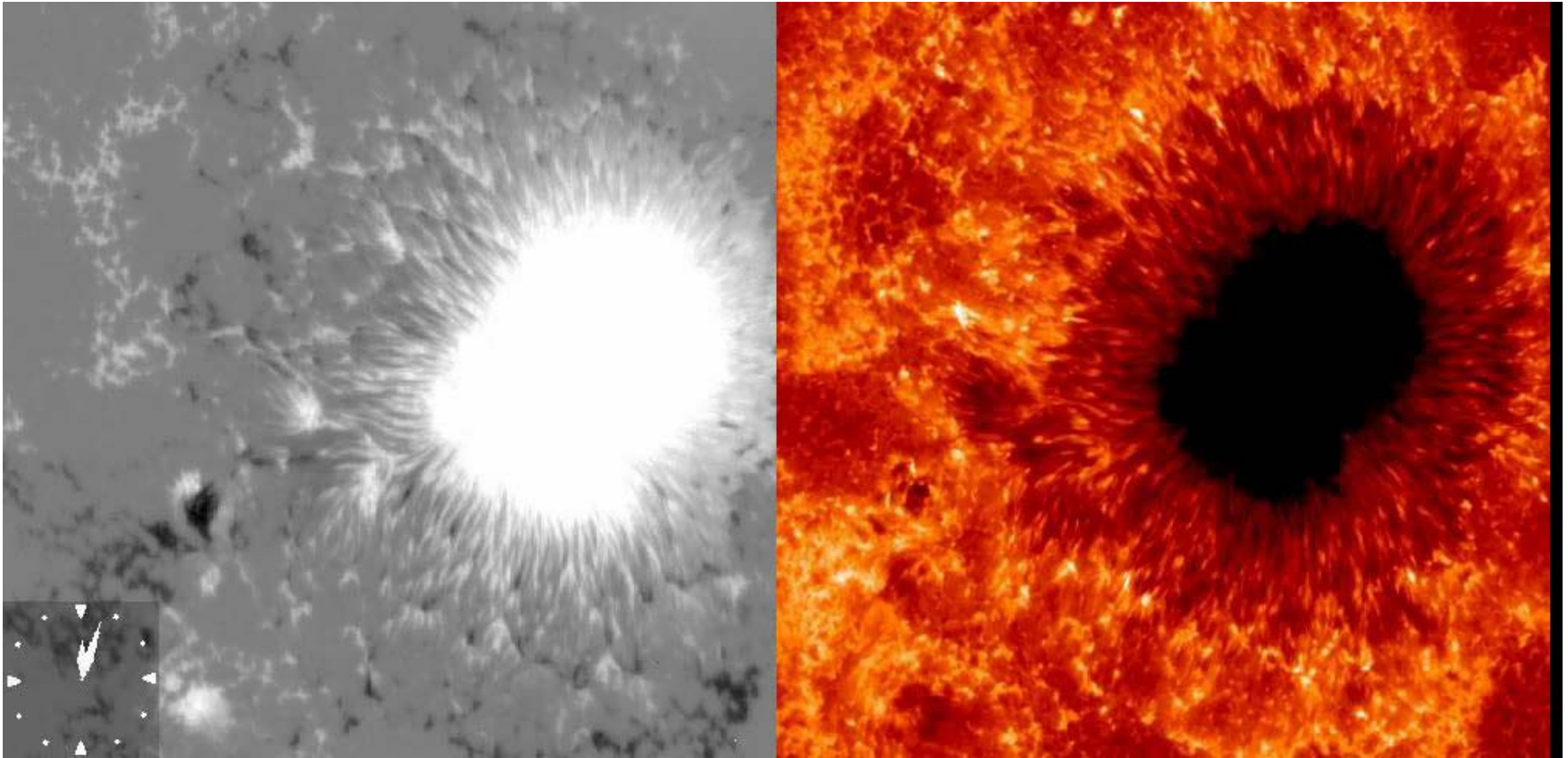
# ● Sunspots

- *Sunspots* are regions of intense magnetic field in the photosphere of the Sun. They last from 1-2 days to several weeks.
- Sunspots usually come in *pairs* of opposite polarity.
- The field is so strong in the central, dark portion (*umbra*) that it suppresses heat transfer hence appears darker than the photosphere.
- The field is weaker and more horizontal in the surrounding *penumbra*.

Images in Ca II from Hinode

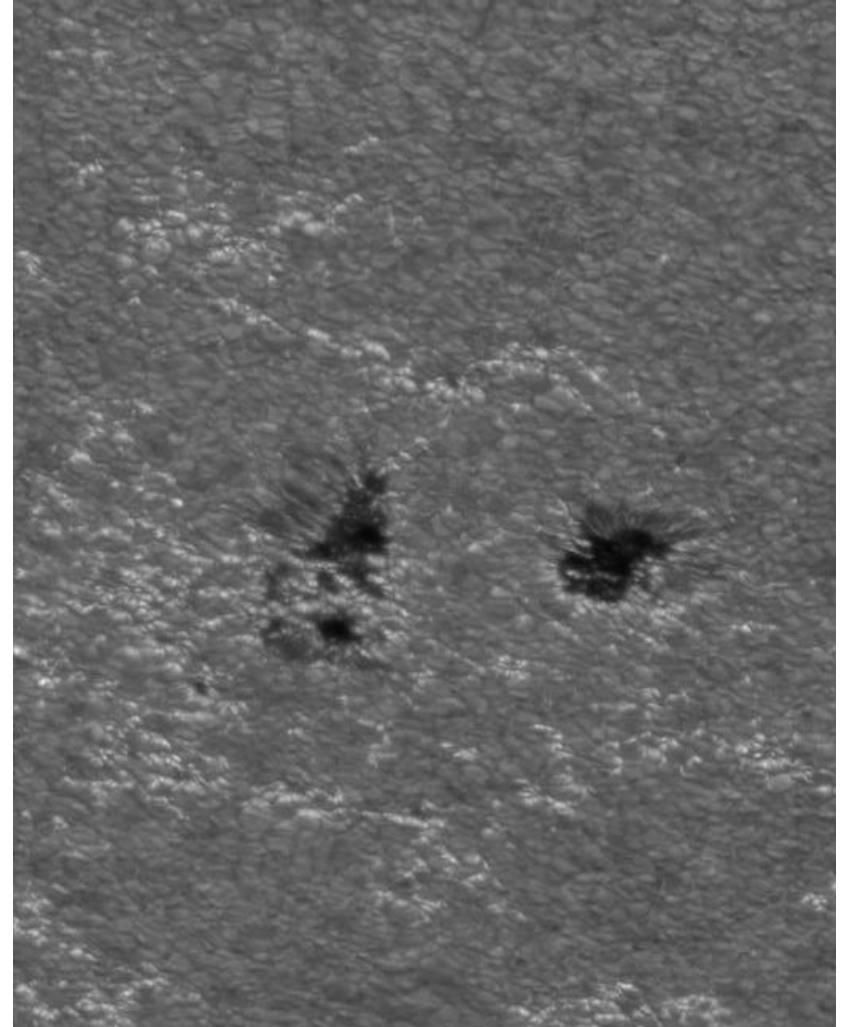


- Dynamics of sunspots
  - Magnetogram (left) and sunspot in Ca II (right)



# • Faculae

- Faculae are bright areas that are most easily seen near the limb, or edge, of the solar disk.
- These are also magnetic areas but the magnetic field is concentrated in much smaller bundles than in sunspots.
- While the sunspots tend to make the Sun look darker, the faculae make it look brighter.
- The faculae outline the boundaries of supergranule cells.



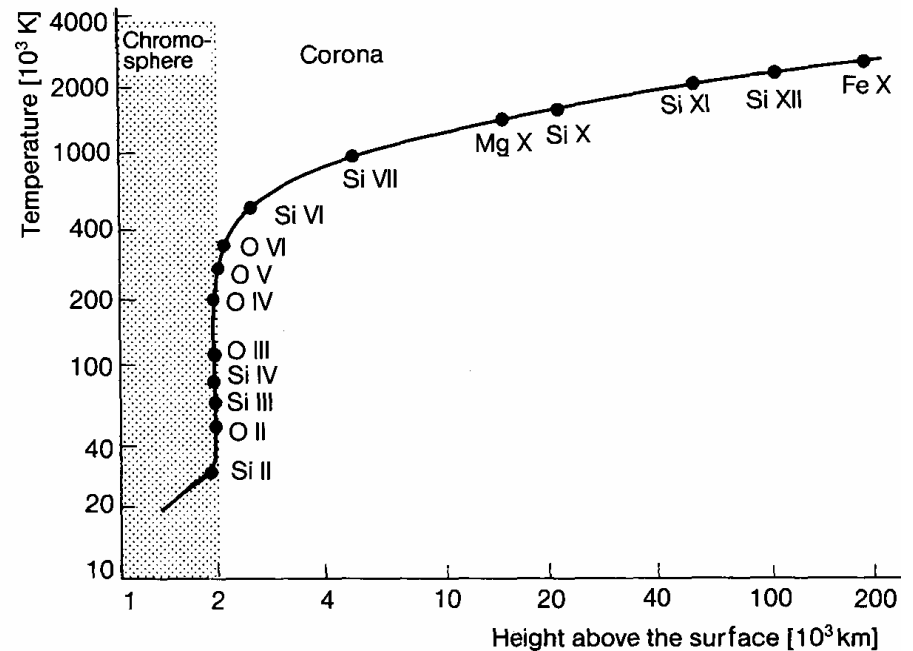
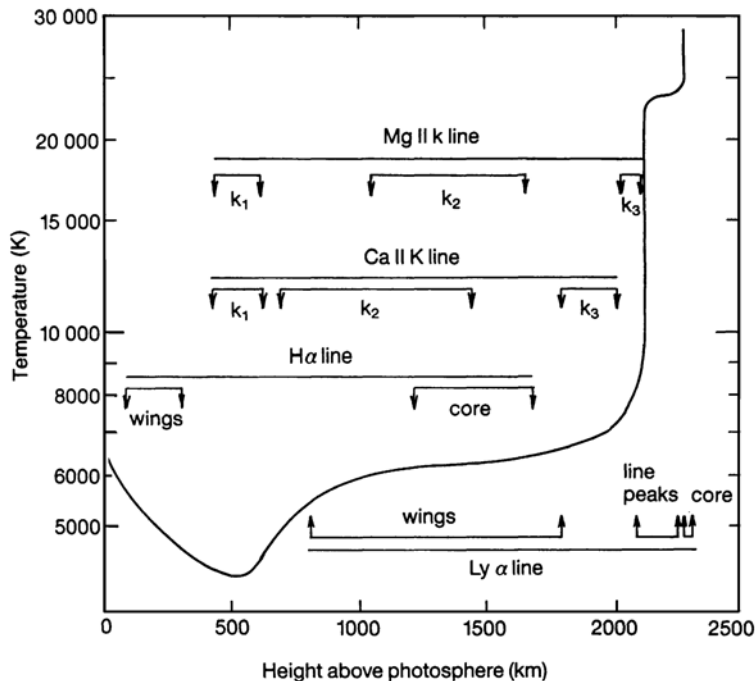
# • Probing the Chromosphere

- The Sun has *no surface* defined by a discontinuity in density
- The *apparent surface* is a region of finite thickness called the *photosphere*. This surface is the point above which the probability of a photon being absorbed by other particles is less than one while below it equals one
  - The average *temperature* of the *photosphere* is 5785 °K
  - The region immediately above the photosphere is called the *chromosphere* from the Greek word for color. During a full lunar eclipse this region is dominated by the red emission of hydrogen alpha
  - The *temperature* of the low density *corona* somewhat higher up is 2 million degrees!
  - As the temperature rises, heavier and heavier atoms loose their electrons and emit *characteristic wavelengths* of light (spectral lines)
  - These spectral lines are used to *image features* of the Sun at different heights in the solar atmosphere

# • Structure of Chromosphere

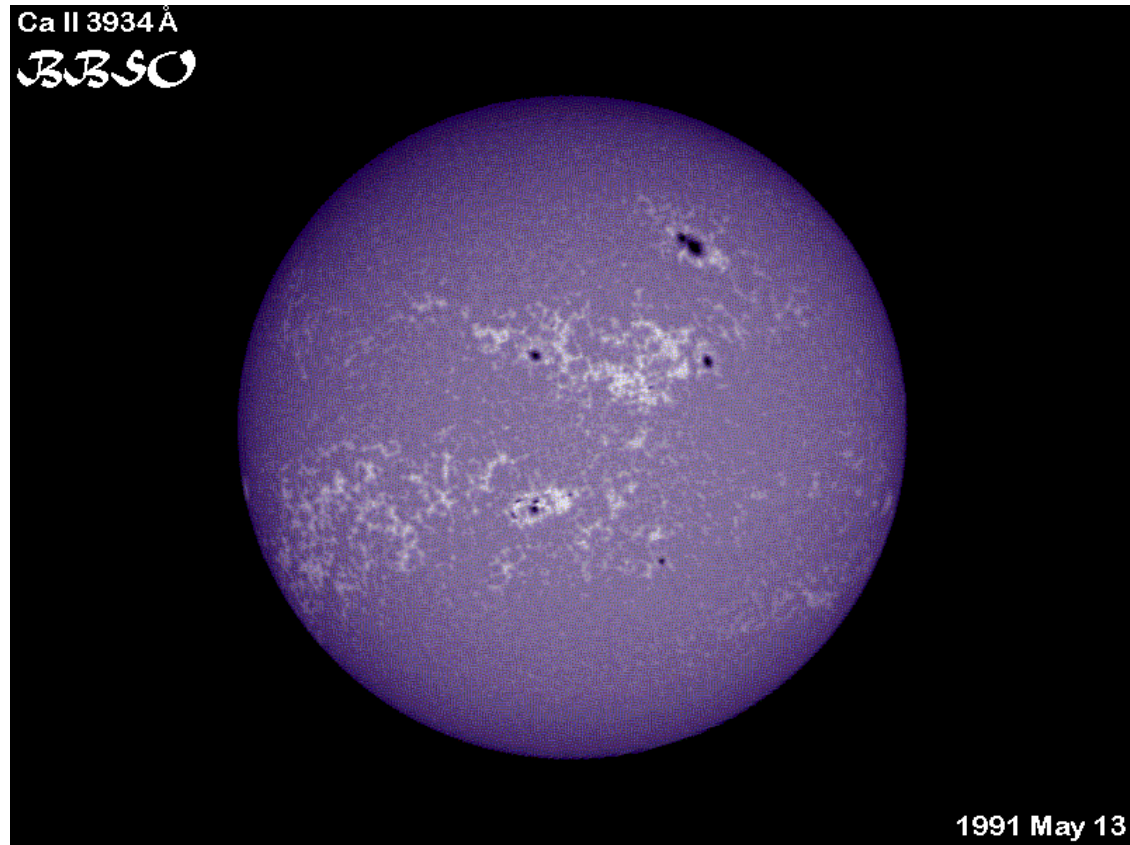
–A model temperature distribution for photosphere and chromosphere calculated by matching calculated UV spectrum to observed spectrum is shown on left

–A similar diagram for the transition region is shown on the right



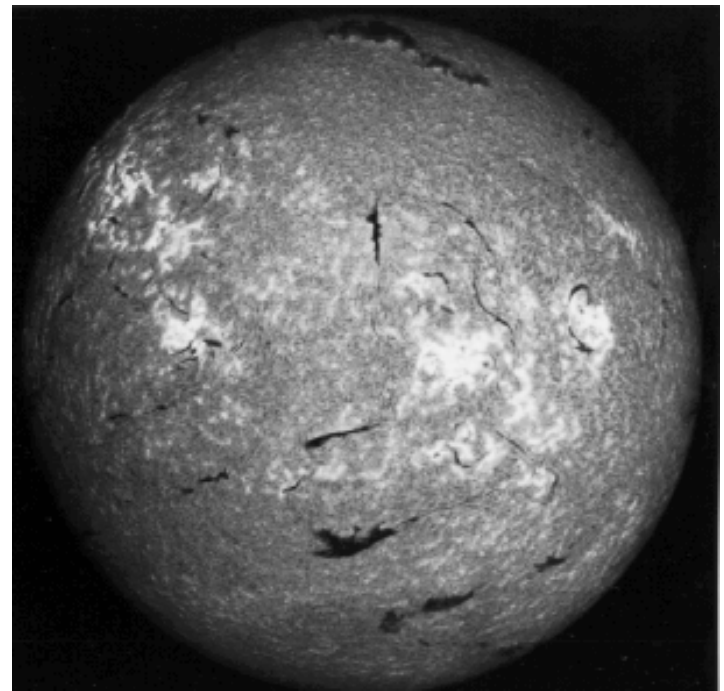
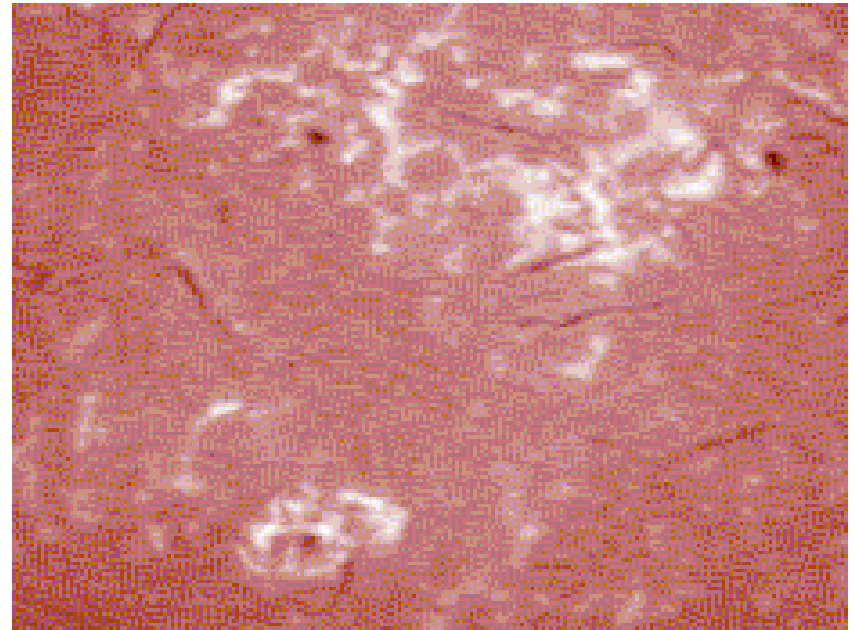
# • The Chromospheric Network

- The chromospheric network is a web-like pattern most easily seen in the emissions of the red line of hydrogen (H-alpha) and the ultraviolet line of calcium (Ca II K - from calcium atoms with one electron removed).
- The network outlines the supergranule cells and is due to the presence of bundles of magnetic field lines that are concentrated there by the fluid motions in the supergranules.



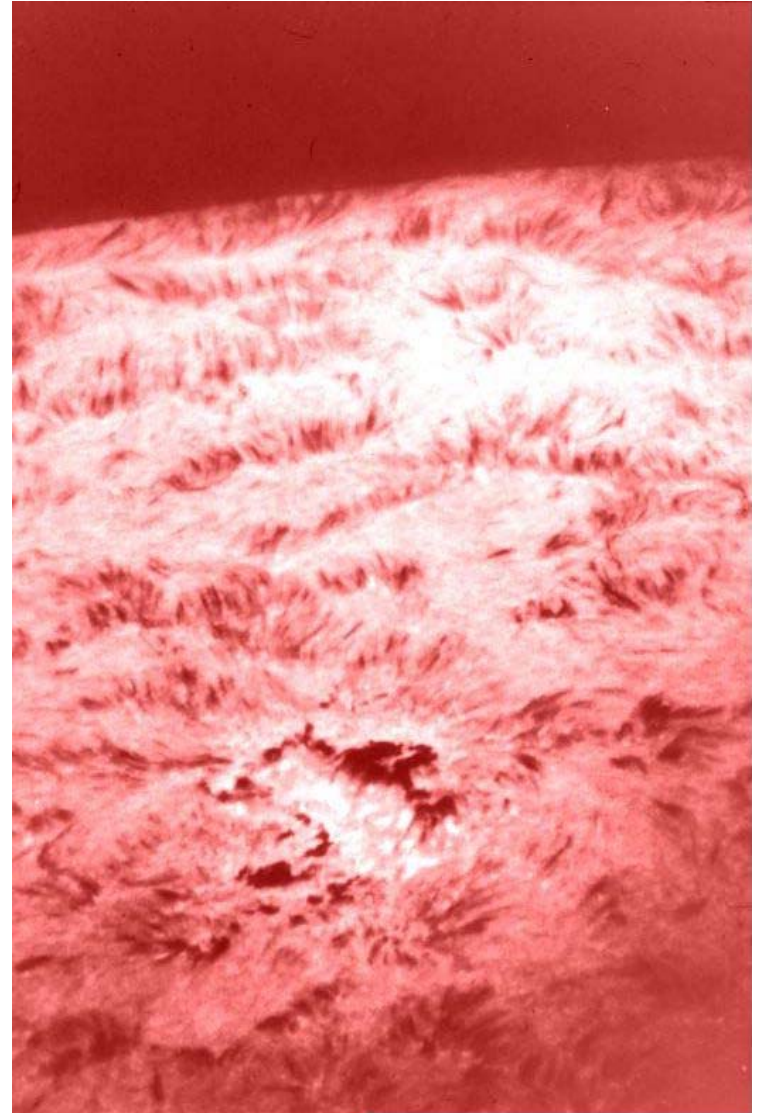
# • Plages and Filaments

- *Plage*, the French word for beach, are bright patches surrounding sunspots that are best seen in the red light of hydrogen (H-alpha). Plage are also associated with concentrations of magnetic fields and form a part of the network of bright emissions that characterize the chromosphere.
- *Filaments* are dark, thread-like features seen in H-alpha. These are dense, somewhat cooler, clouds of material that are suspended above the solar surface by loops of magnetic field.

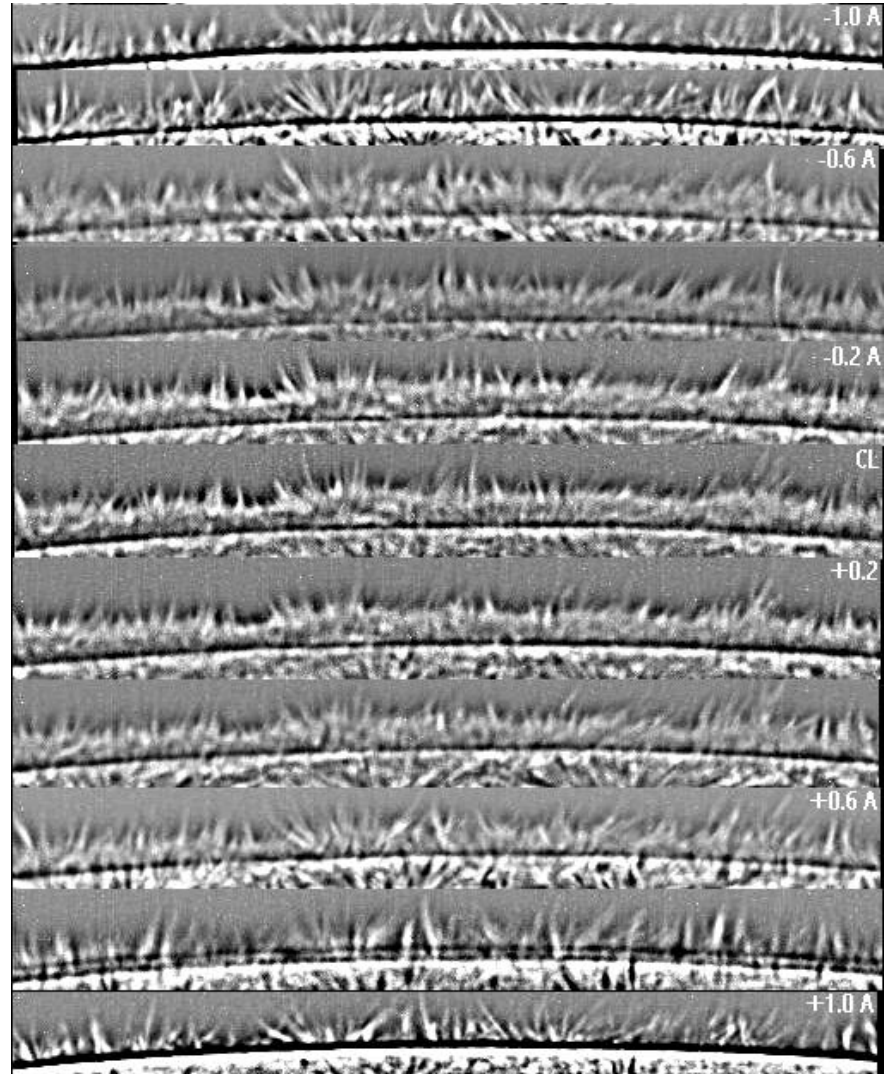


# • Spicules

- The spicules outline the supergranulation cells in the chromosphere
- There are typically about 30 spicules per cell at any one time
- The cause of spicules is not known. One suggested model is resonance between the plasma motion along field lines and granular and supergranular buffeting of the sides of flux tubes
- Spicules are jets of plasma with life times of 5-10 minutes, heights of 10,000km, diameters of 500-1000km and speeds of 20-30 km/s
- They originate in the photosphere and pass through the chromosphere into the corona.

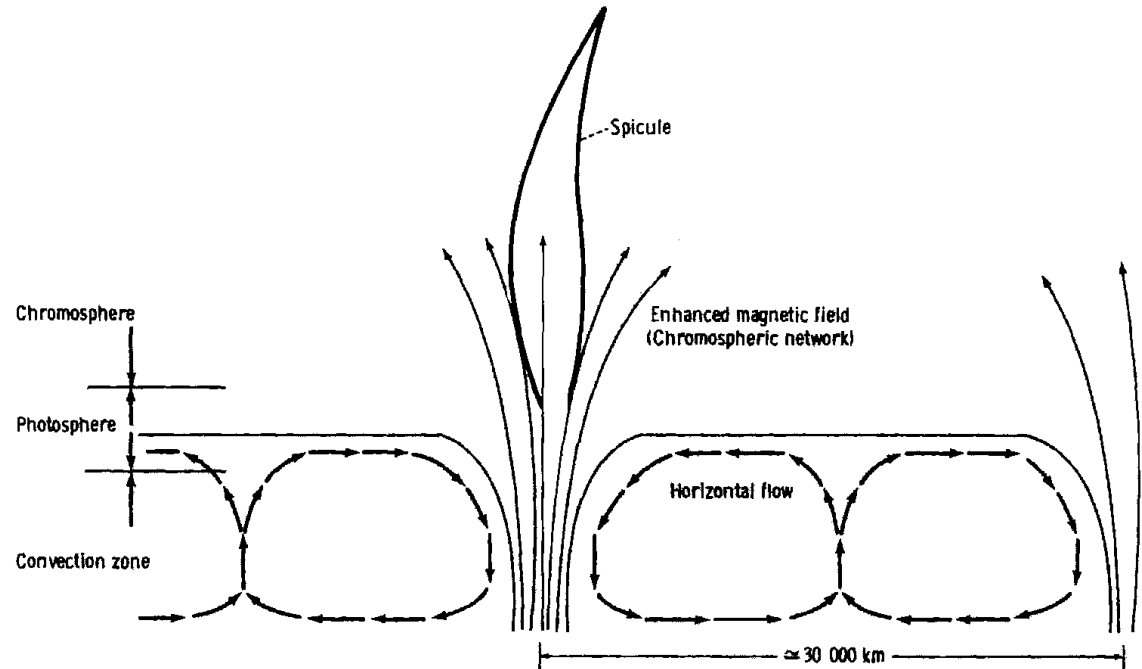


- The Structure of Spicules
  - Spicules are best observed on the limb of the Sun.
  - Note the field aligned structure.



- Relationship between spicules and convection

- Convection at the top of supergranule cells carries magnetic field to edges of cells
- Concentrated vertical field lines at the edges of the cells provide an avenue for plasma to flow through the chromosphere to the corona



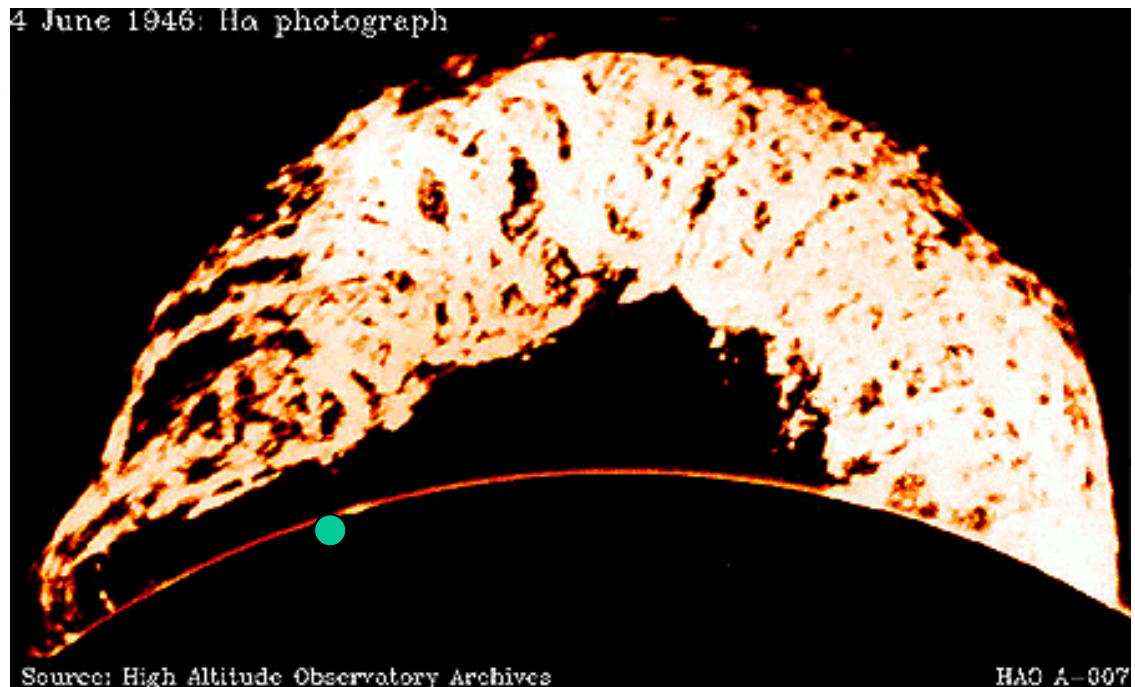
# • Prominences

- *Prominences* are dense relatively cool clouds of material suspended above the surface of the Sun by loops of magnetic field. (Density  $10^{16}$ - $10^{17} \text{ m}^{-3}$ , temperature 5,000-8,000K)
- Prominences and filaments are actually the same things except that prominences are seen projecting out above the limb, or edge, of the Sun.
- Both filaments and prominences can remain in a quiet or quiescent state for months. However, as the magnetic loops that support them slowly change, filaments and prominences can erupt and rise off of the Sun over the course of a few minutes or hours.

Eruption of June 4,  
1946 with blue  
Earth for scale

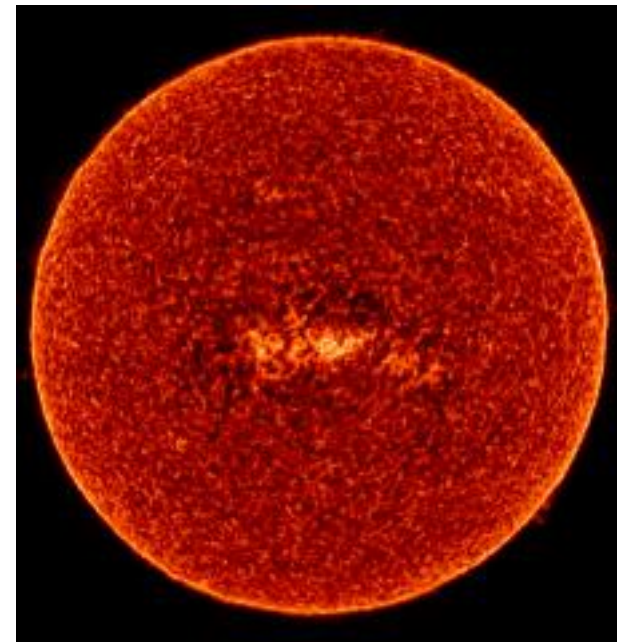
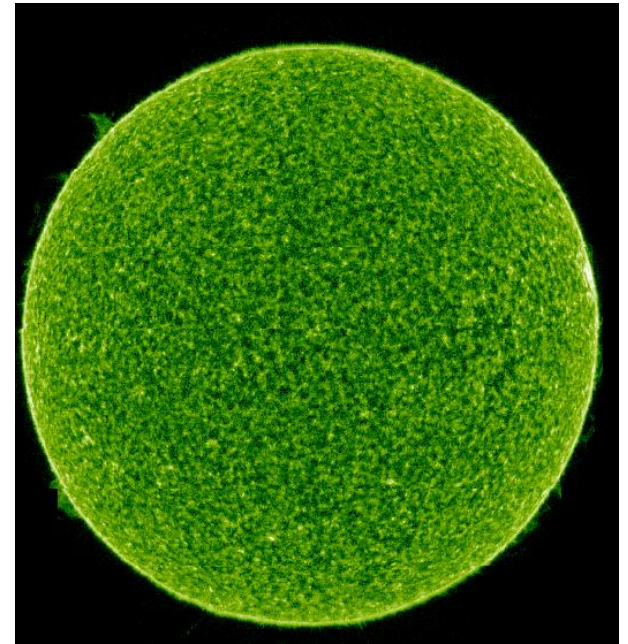
Eruption speed ~  
200 km/s

Prominence would  
cross the US in 15  
seconds



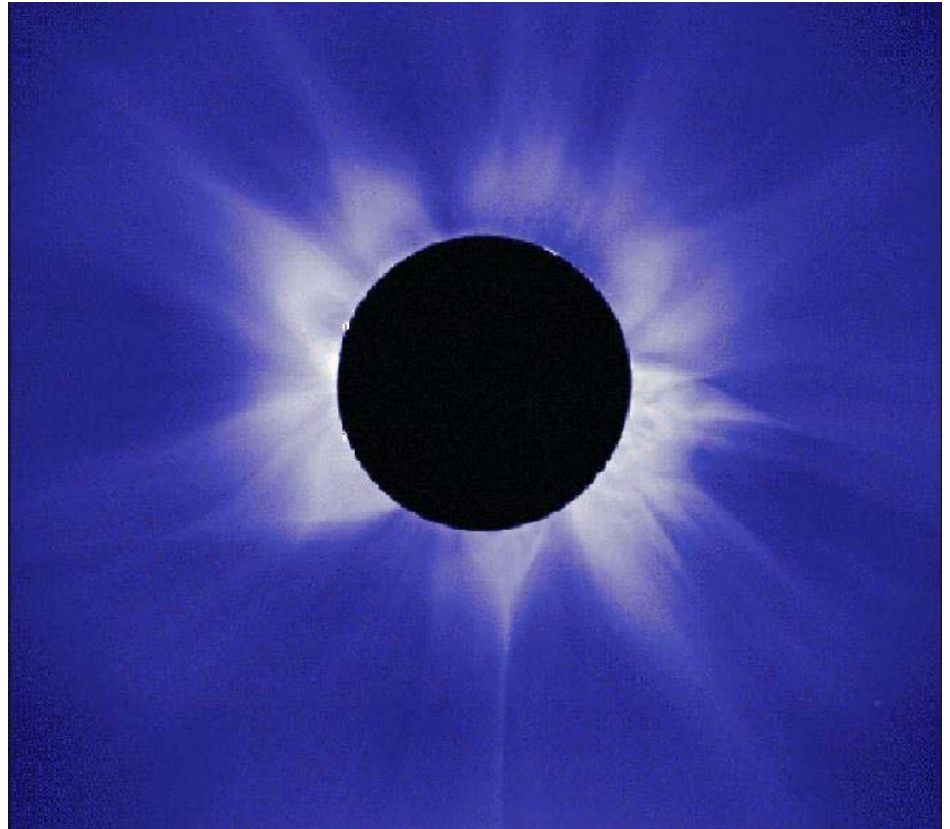
## • The Transition Region

- The thin region between the chromosphere and the corona
- Heat flows down from the corona and fully ionizes hydrogen so instead it is observed with triply ionized heavy ions
- Carbon IV (green) at 100K C and Silicon VI (red) at 200K C (from the SUMER instrument on SOHO)



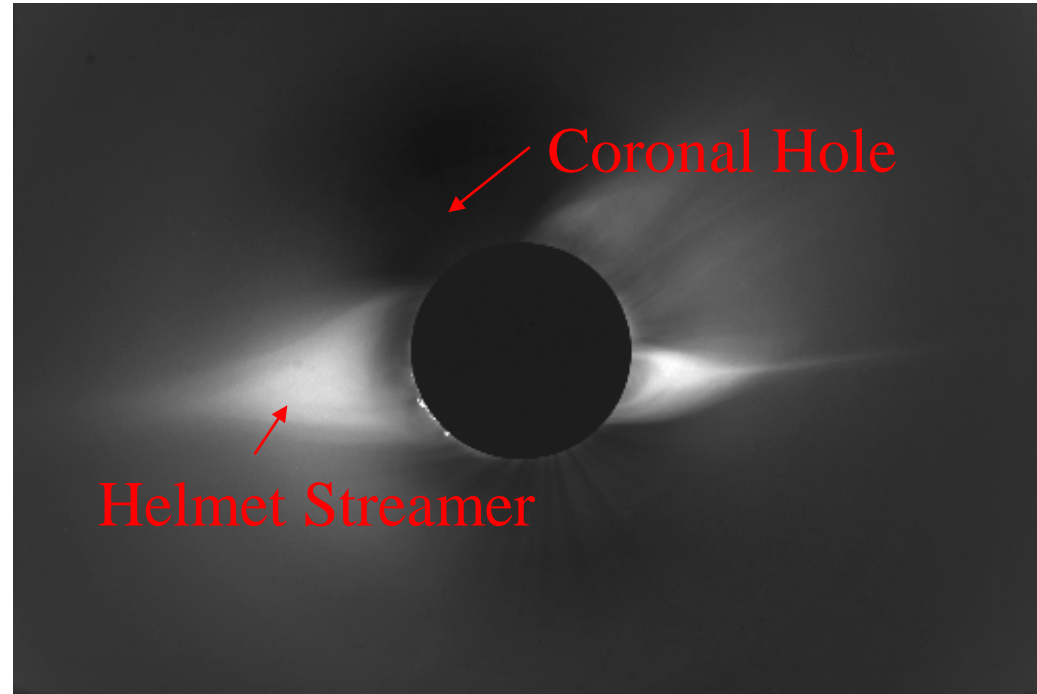
# •The Corona

- During a lunar *eclipse* the moon blocks the image of the Sun almost exactly!
- This image is in white light.
- Radial filters, most dense at the center and decreasing outward, capture the glow of the *corona*
- Magnetic field lines organize the corona into denser regions called *helmet streamers*



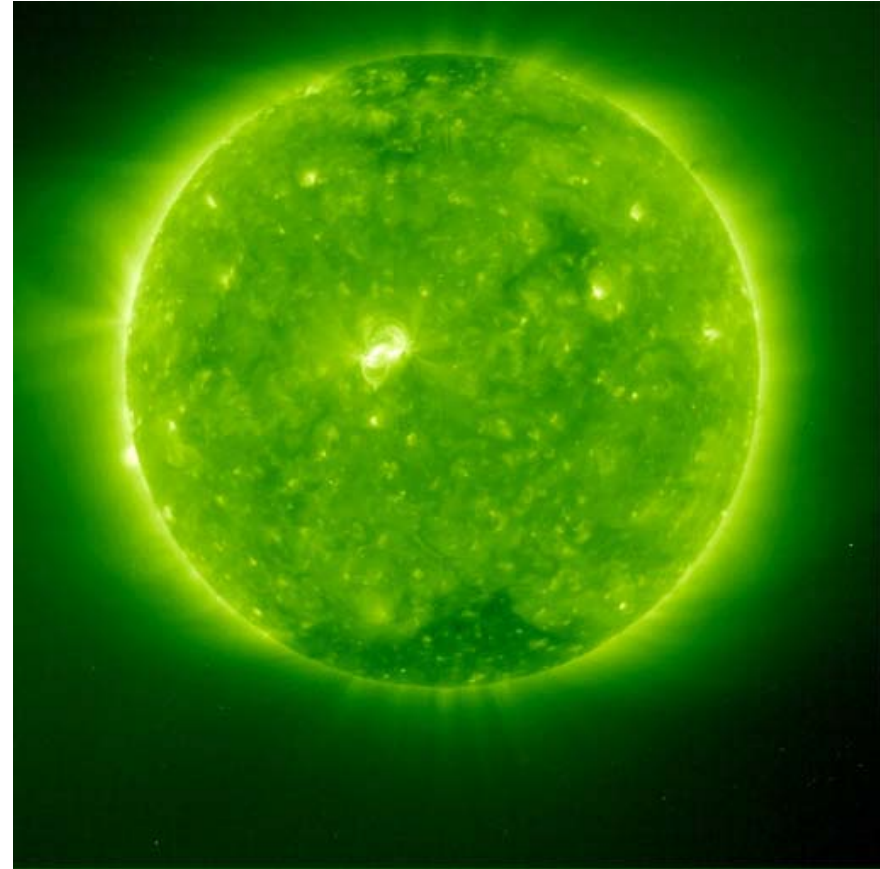
# • The Corona

- A black and white photo of the Sun near minimum of the *solar cycle*
- Note *coronal holes* above the poles
- A very large *helmet streamer* straddles the equator on the east limb
- Prominences can be seen on the southeast limb
- A smaller helmet streamer is in the southern hemisphere on the east limb, note the loops at its base



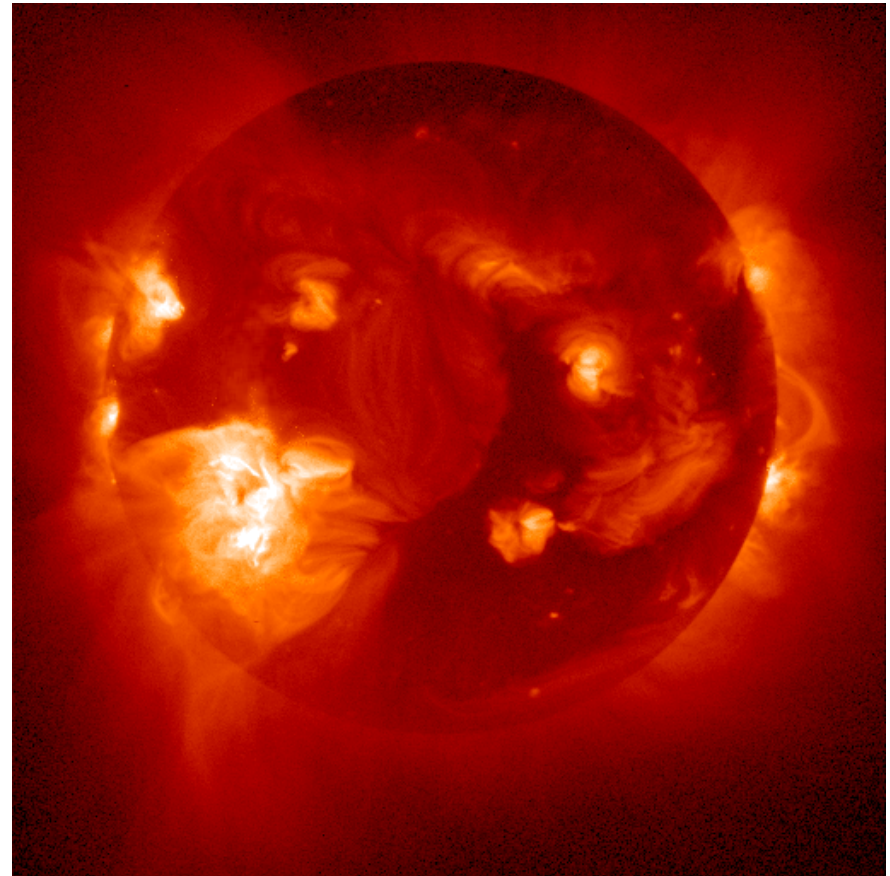
# • The Corona

- This image of  $1,500,000^{\circ}\text{C}$  gas in the Sun's thin, outer atmosphere (corona) was taken March 13, 1996 by the Extreme Ultraviolet Imaging Telescope onboard the Solar and Heliospheric Observatory (SOHO) spacecraft.
- Every feature in the image traces magnetic field structures.
- Note the plumes and coronal holes located at the poles

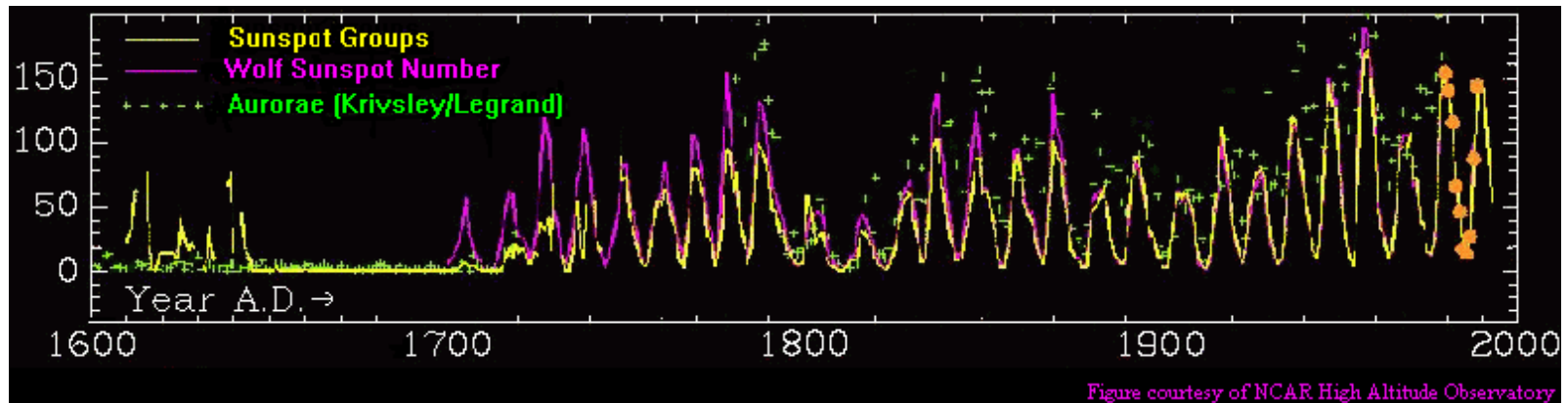


# • X-ray Observations

- X-ray observations of the Sun's corona by the YOHKOH satellite
- High intensity soft x-rays are emitted from broad diffuse regions above *active regions* on the photosphere
- Dark regions are called *coronal holes*
- Coronal holes are almost always present *above the poles*
- Coronal holes that cross the equator are sources of *high-speed solar wind* that reaches the Earth



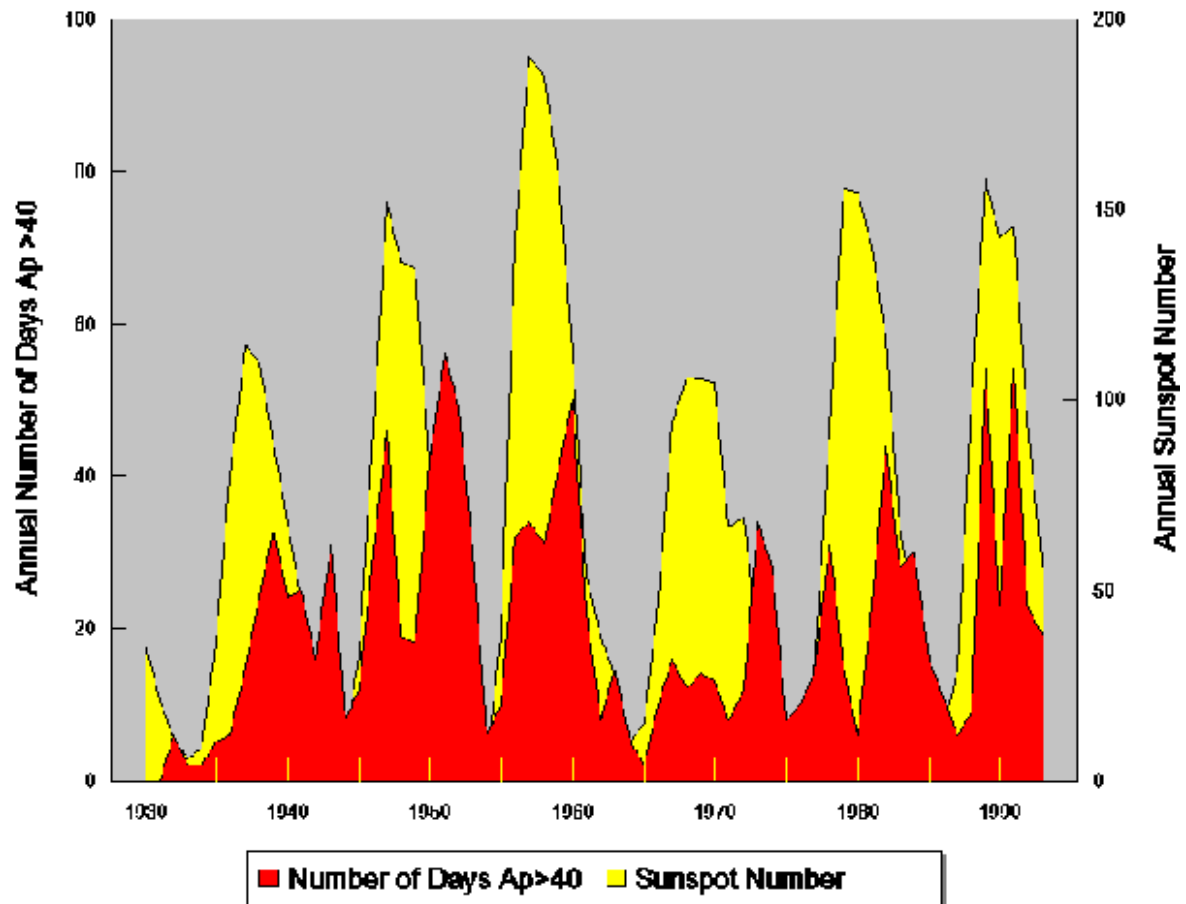
## • The Eleven Year Solar Cycle



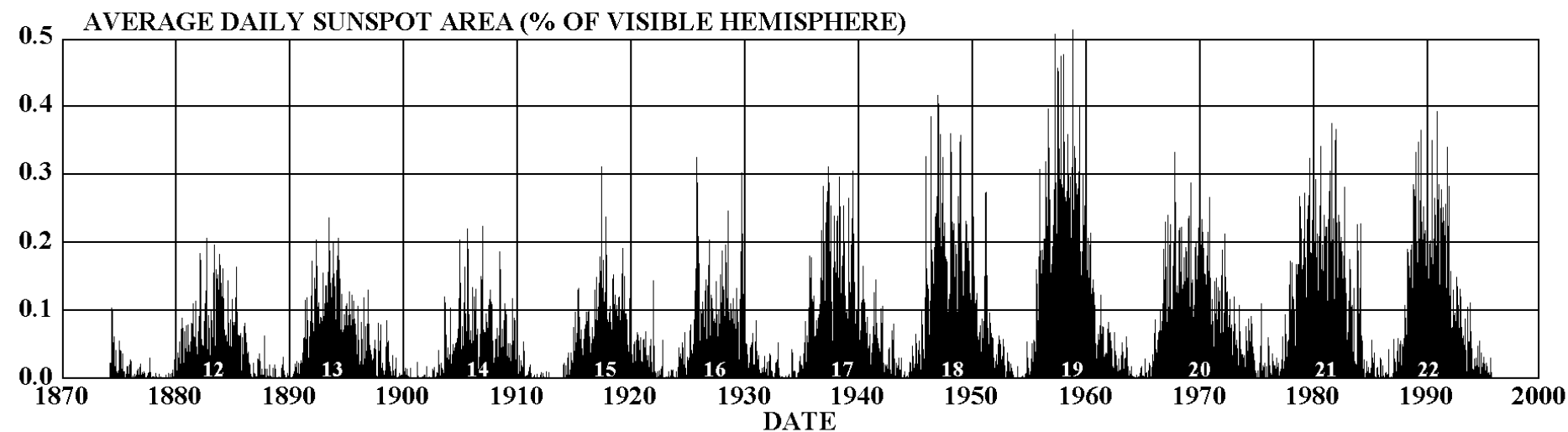
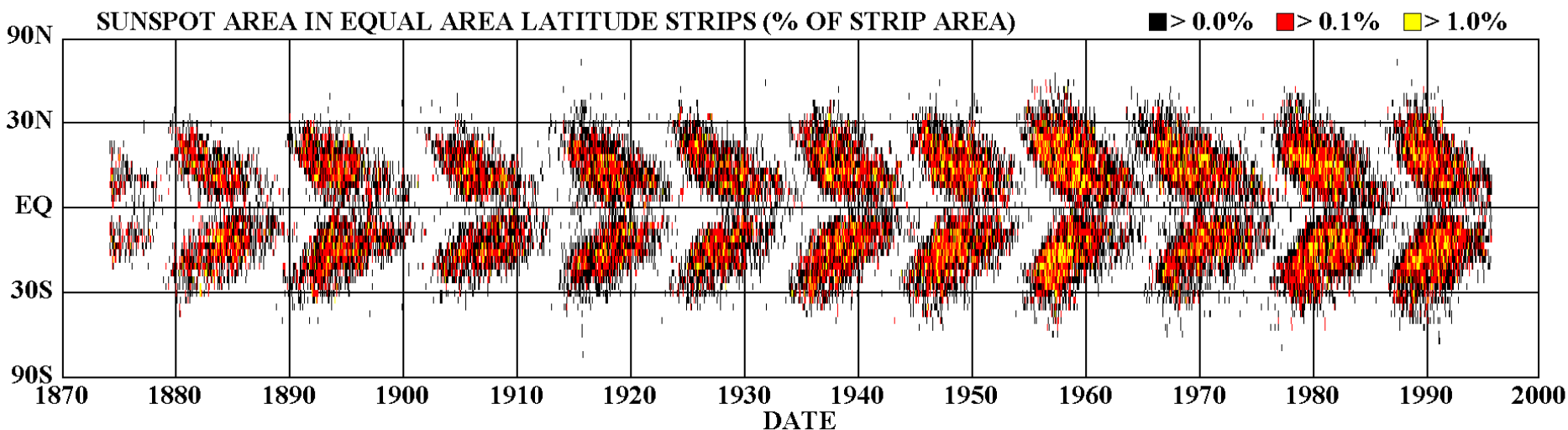
- On the average the number of sunspots peaks every 11 years
- The observation of aurora (northern and southern lights) is highly correlated with the sunspot cycle
- During the Maunder minimum of the sunspot cycle (<1700) no sunspots and no aurora were reported. This period was also called the “little ice age”

# • Sunspot Number and Magnetic Activity

- Sunspot number (yellow) and the number of magnetically disturbed days (red) are highly correlated
- Magnetic activity tends to peak twice in each cycle
- Note large  $A_p$  peaks on decay from solar maximum



- Daily Sunspot Number Averaged over Individual Solar Rotations

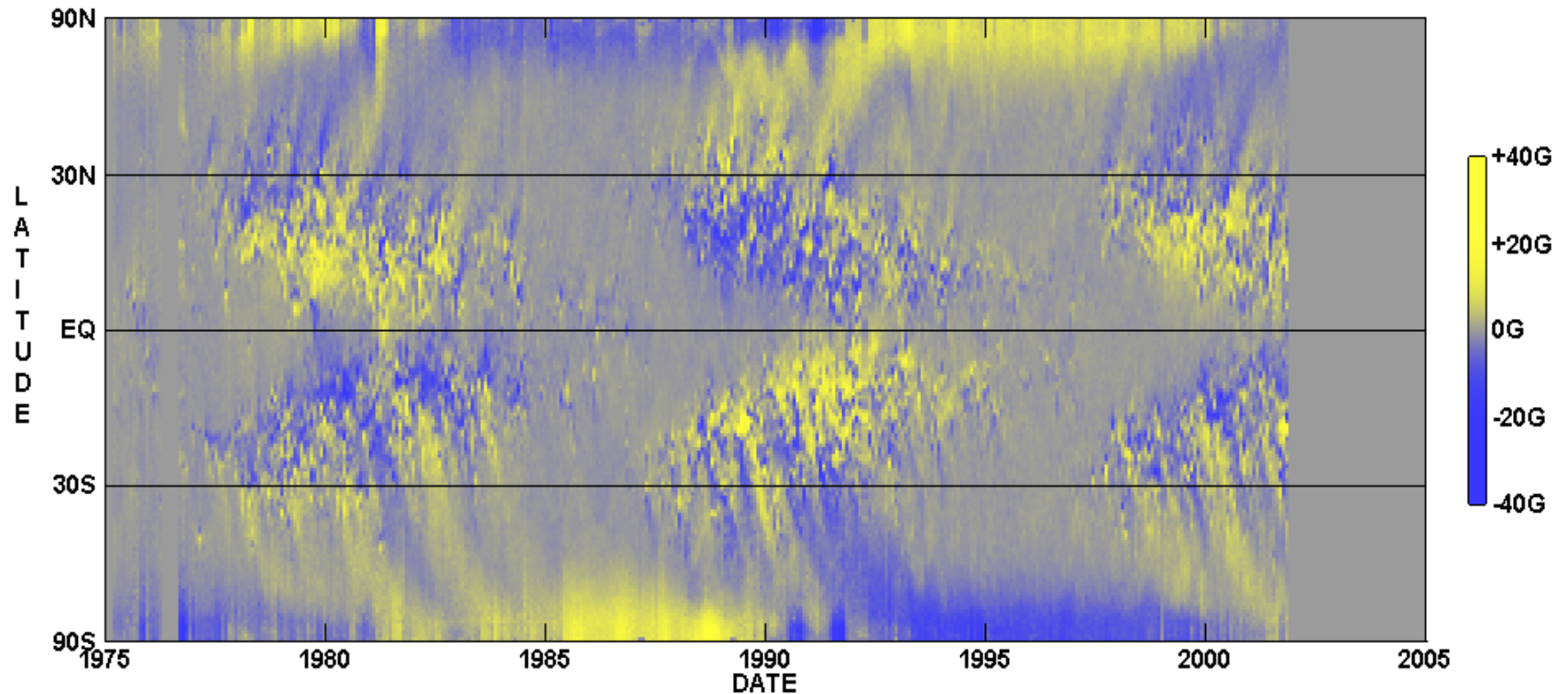


# • The Solar Cycle

- Sunspots start at relatively high latitudes and move towards the equator.
- During the solar cycle the latitude of emergence moves towards the equator.
- The magnetic polarity of the Sun reverses during the 11 year solar cycle so that it takes time (22 years) for the Sun's magnetic field to get back to its original state.
- Sunspots frequently are observed in bipolar groups with the leading spot (in the direction of apparent motion) having the same polarity as the hemisphere it appeared in while the following spot has the opposite polarity. The bipolar groups in opposite hemispheres have opposite magnetic orientation and this orientation reverses in each new solar cycle.

# •The Sun's Magnetic Field

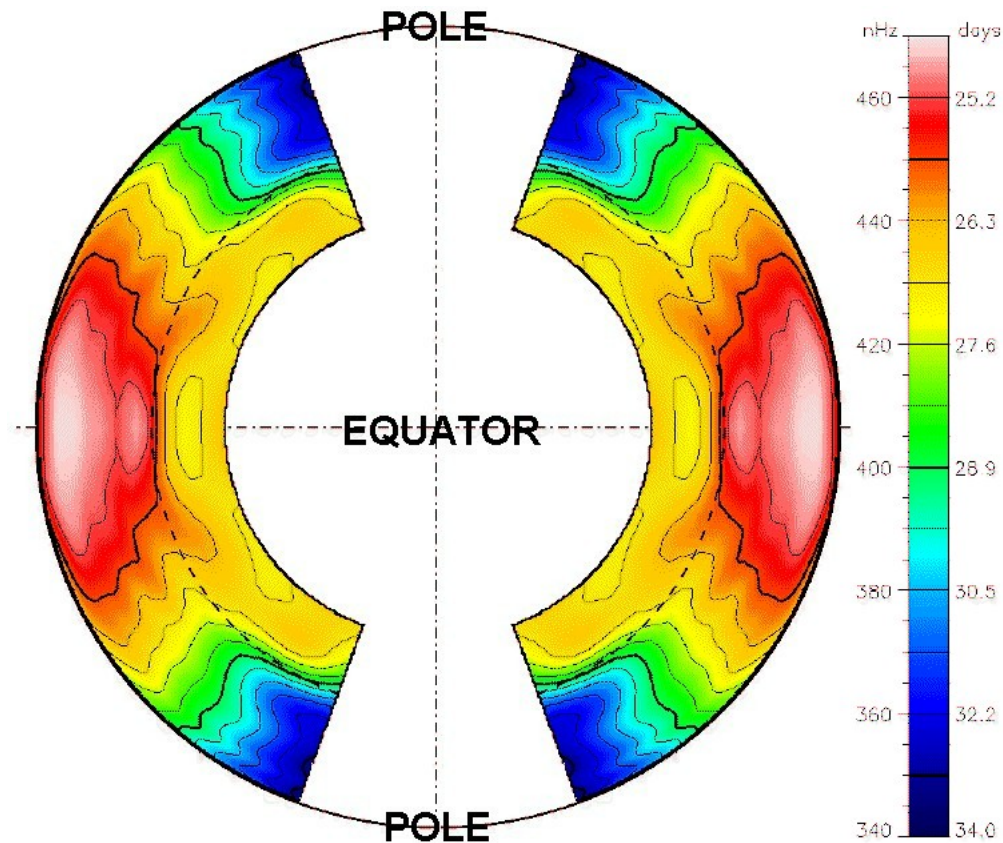
LONGITUDINALLY AVERAGED MAGNETIC FIELD



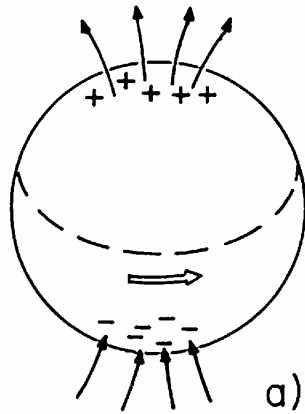
- Each vertical stripe represents the average over a solar rotation of the magnetic field observed at a specific latitude.
- Note opposite polarities in the north and south hemisphere and the reversal of sign of the field between solar cycles (Hale's law of sunspot polarities)
- At the beginning of a cycle the polar field has the opposite sign from trailing spots

- The equator rotates faster than the poles

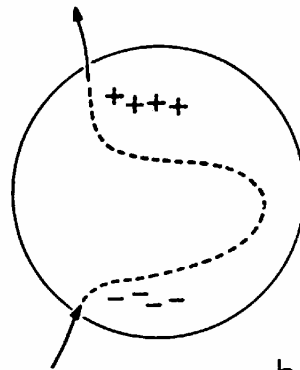
- Helioseismology enables one to determine temperature, density, composition, and motion of the interior of the sun
- The average rate of rotation with radius and latitude is shown here
- Red indicates fast rotation at the equator and blue shows the slow rotation at the poles
- The interior below the convection zone appears to rotate as a solid body



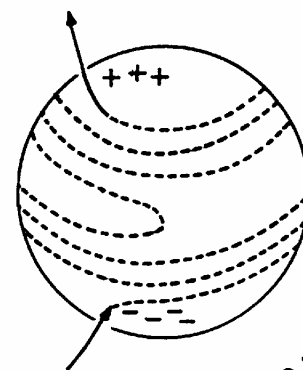
- The Solar Cycle



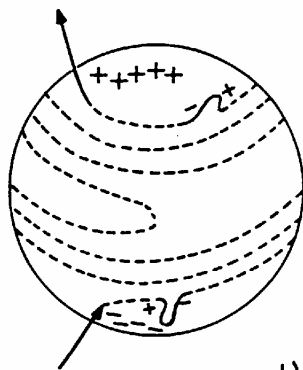
a)



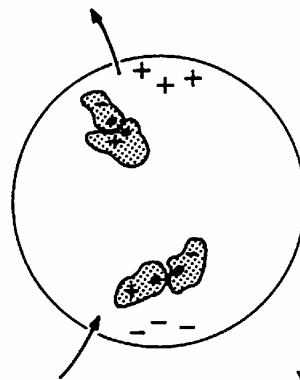
b)



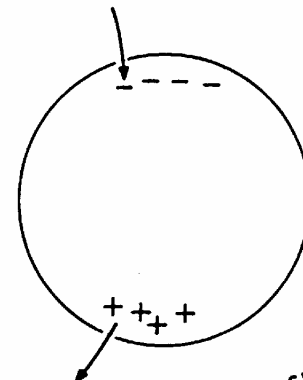
c)



d)



e)



f)

# • The Solar Cycle

- During solar minimum the magnetic field is poloidal.
- As the Sun rotates the equatorial portion of the field lines in the Sun are pulled ahead of the polar portions and wrapped around the Sun forming a toroidal field.
- Velocity shears in the convection zone cause the field to wrap into flux ropes. (The field is frozen into the flow -  $\vec{v} = \vec{E} \times \vec{B} / B^2$ )
- The field in the flux ropes becomes strong and buoyant (  $p + B^2 / 2\mu_0 = p_0$  )
- When the tube breaks through the surface it creates a pair of sunspots from which the field expands as a small dipole.
- The polarity of the dipole is determined by the direction of the toroidal field.
- The preceding spot will have the same polarity as the polar field for that hemisphere.

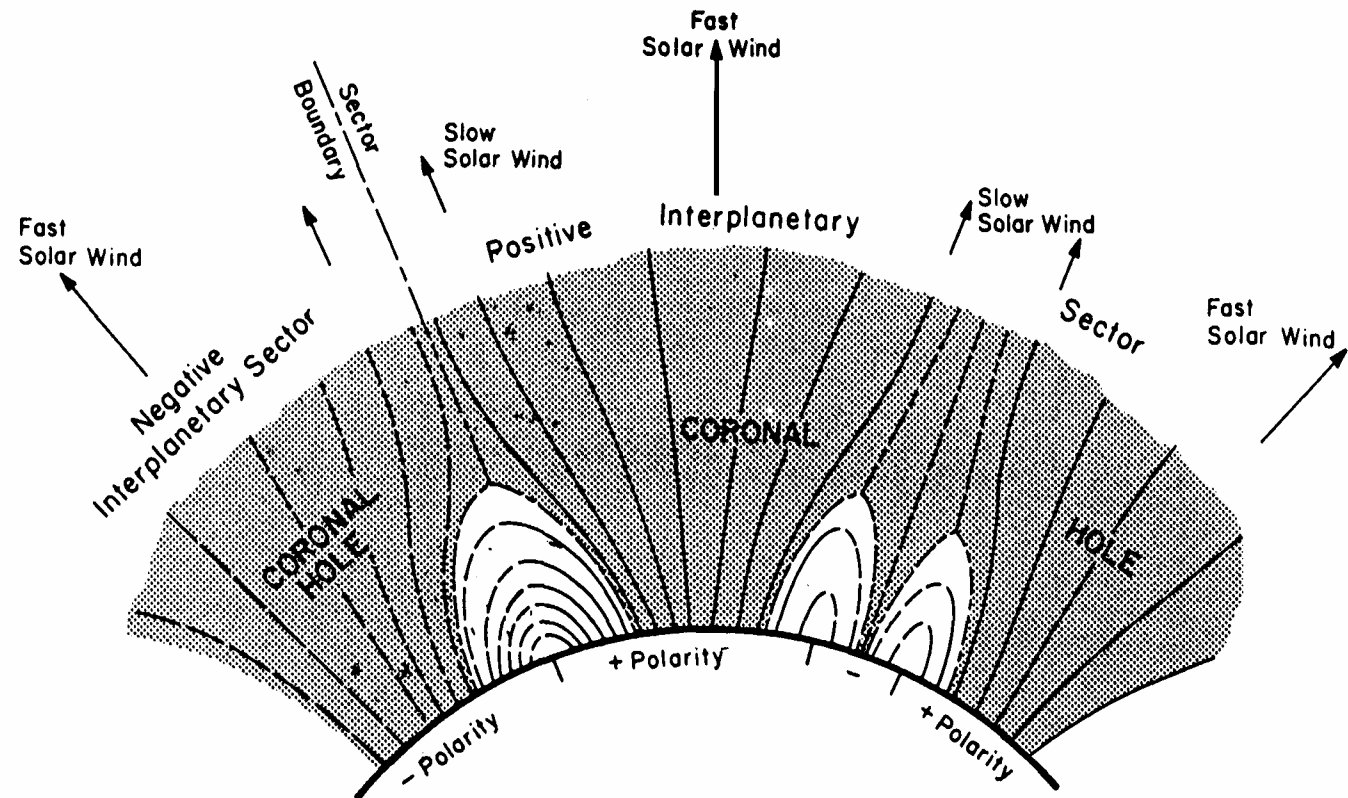
# • The Solar Cycle

- The latitude of the first appearance of sunspots depends on the differential rotation and magnetic field strength.
- When the first sunspots emerge at high latitudes the magnetic pressure is reduced. The process then moves to lower latitudes leading to motion toward the equator.
- The preceding spots from the two hemispheres merge (reconnect).
- The trailing spots merge with the polar field.
- Close to sunspot maximum the polar fields reverse as the field from the trailing spots dominate.
- Near minimum the field returns to a dipole-like field with the poles reversed.
- The last step of this process is poorly understood. In an alternate model as an element of toroidal flux rises it is twisted by Coriolis forces so as to create a new poloidal field of the opposite sense.

# • Helmet Streamers and Unipolar Regions

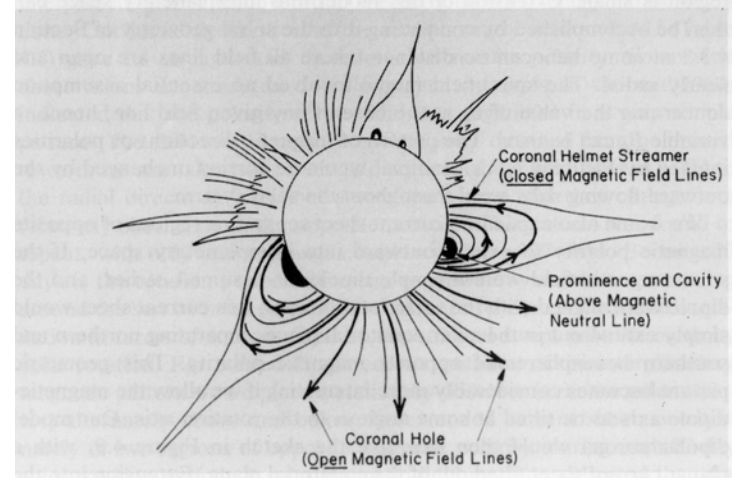
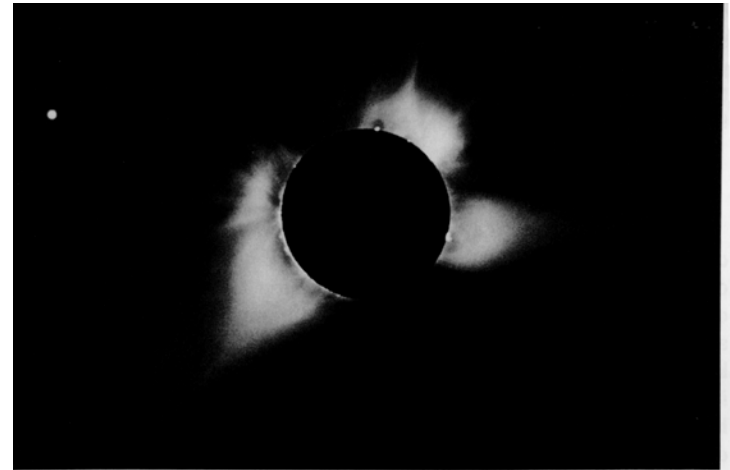
- Evolution of active regions produces large regions of unipolar magnetic field
- Coronal arcades connect the regions with loops of magnetic field
- The field from the interior of the unipolar region is nearly radial creating a coronal hole that provides a source of high speed solar wind
- Above the arcade the fields from the two adjacent regions become antiparallel separated by a current sheet. This is a helmet streamer

- ❑ Sectors are regions in the solar wind with the radial component of the magnetic field in a single direction
- ❑ They are separated by current sheets called sector boundaries



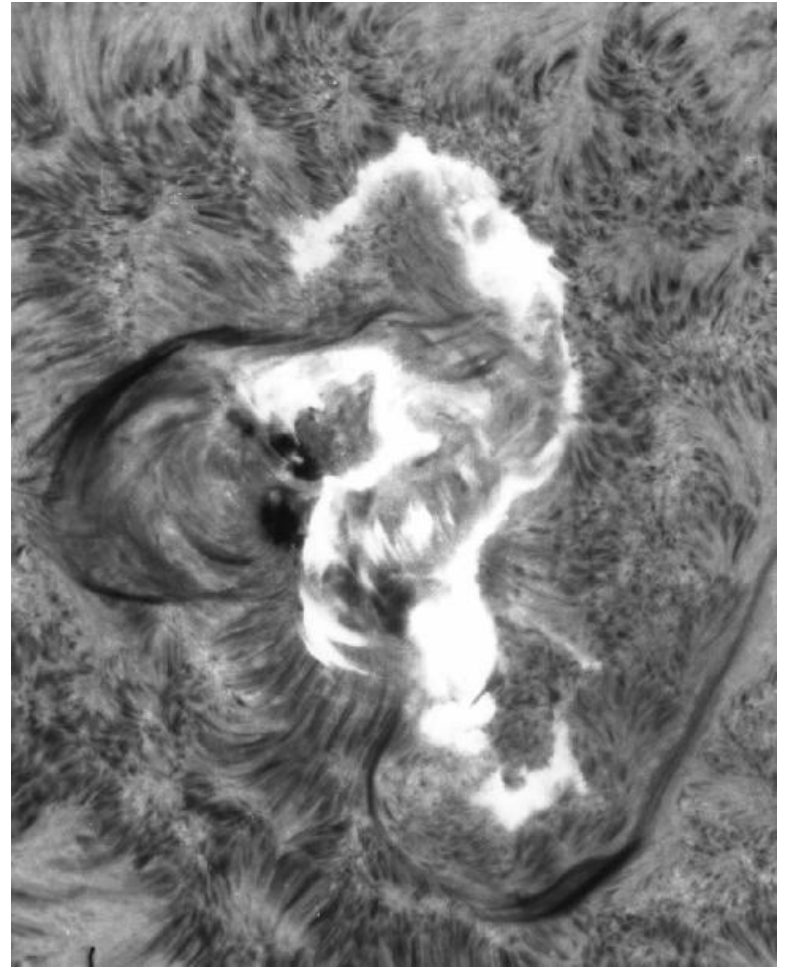
# • Helmet Streamers and Coronal Arches

- Electrons are trapped on the closed field lines of Helmet Streamers making them bright features.
- Large field line arcades provide a magnetic field that is too strong to be pulled outward by thermal expansion until some distance above the surface. They become the base of helmet streamers.
- Open fields from the interior of unipolar regions provide an easy route for the corona to expand outward as high speed solar wind thus creating a coronal hole.
- Helmet streamers are confined to the streamer belt associated with active regions.



# • Solar Flares

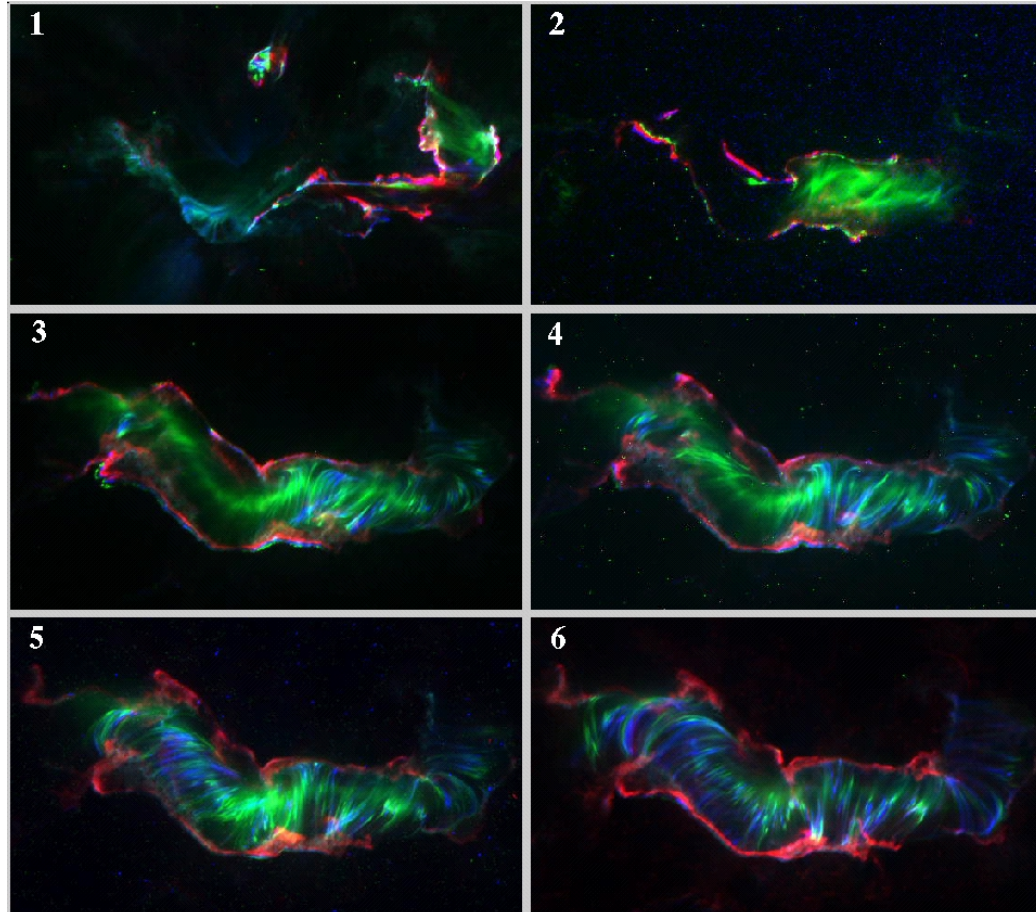
- A solar flare is a sudden eruption of energy on the Sun's surface.
- Flares are important. Even though they do not make any noticeable change in the brightness of the Sun, they can have an effect on our lives here on Earth.
- While flares only last a couple of minutes, large flares on the Sun throw out sudden bursts of high energy radiation which can disrupt and even damage communications systems on Earth.



# •Two-Ribbon Flare

[Click for Movie](#)

- A major solar flare produced an arcade resembling a slinky
- TRACE observations of this flare in three colors: the red image shows the ultraviolet continuum, characteristic of cool, dense gas; the blue image shows the  $171\text{\AA}$  pass band, characteristic of material  $\sim 1$  million degrees; the green channel shows material  $>$  than  $\sim 1.5$  million degrees up to  $\sim 10$  million degrees.



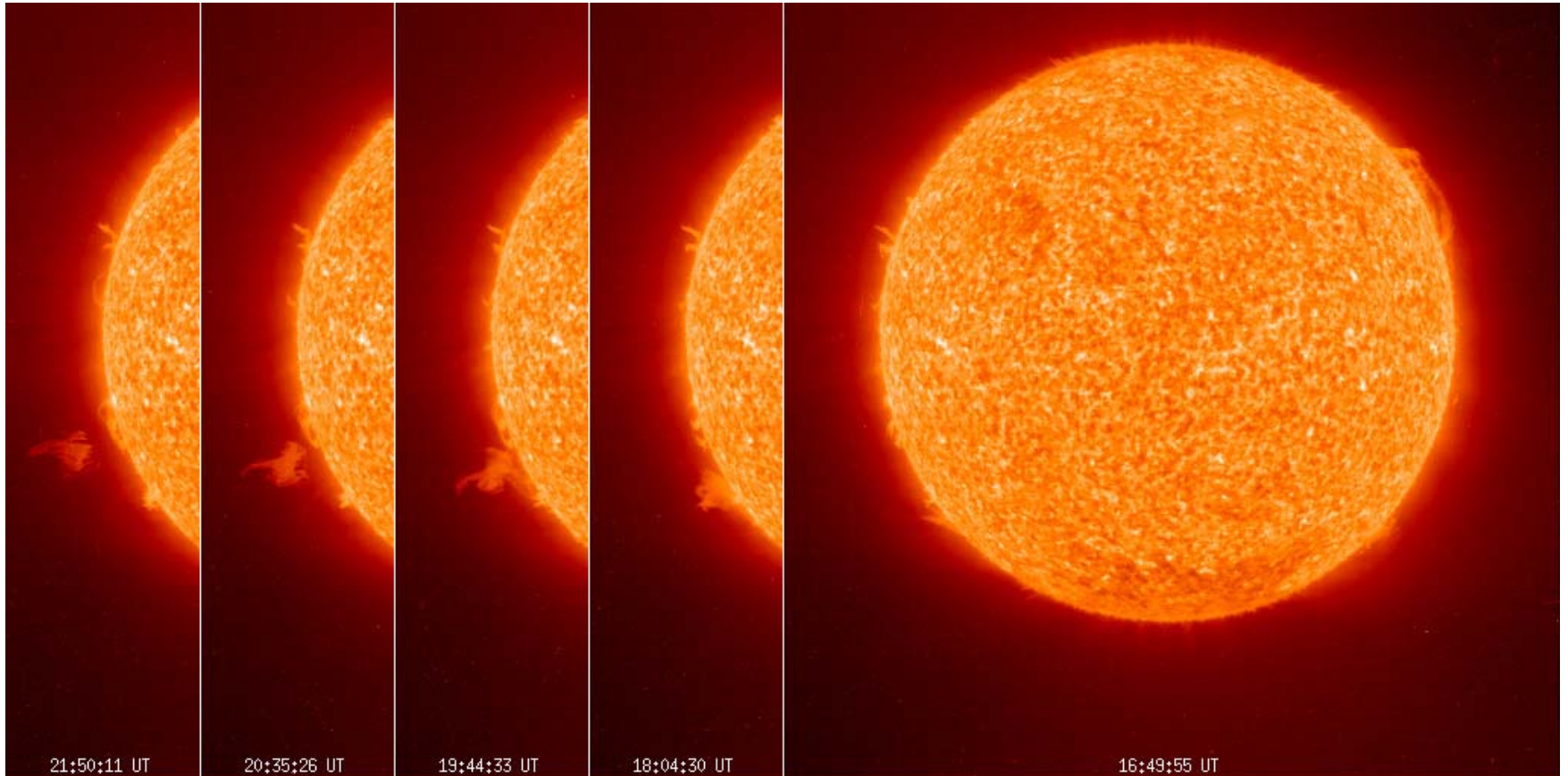
# • The Quiet Prominence

- Prominences can last for 6-10 solar rotations
- The temperature of a prominence is about 100 times colder than the surrounding corona
- The density is about 100 times larger
- Material condenses at the top of prominences and falls to lower elevations
- We see prominences in  $H\alpha$  emission lines on the limb and in absorption lines against the disk (filaments)



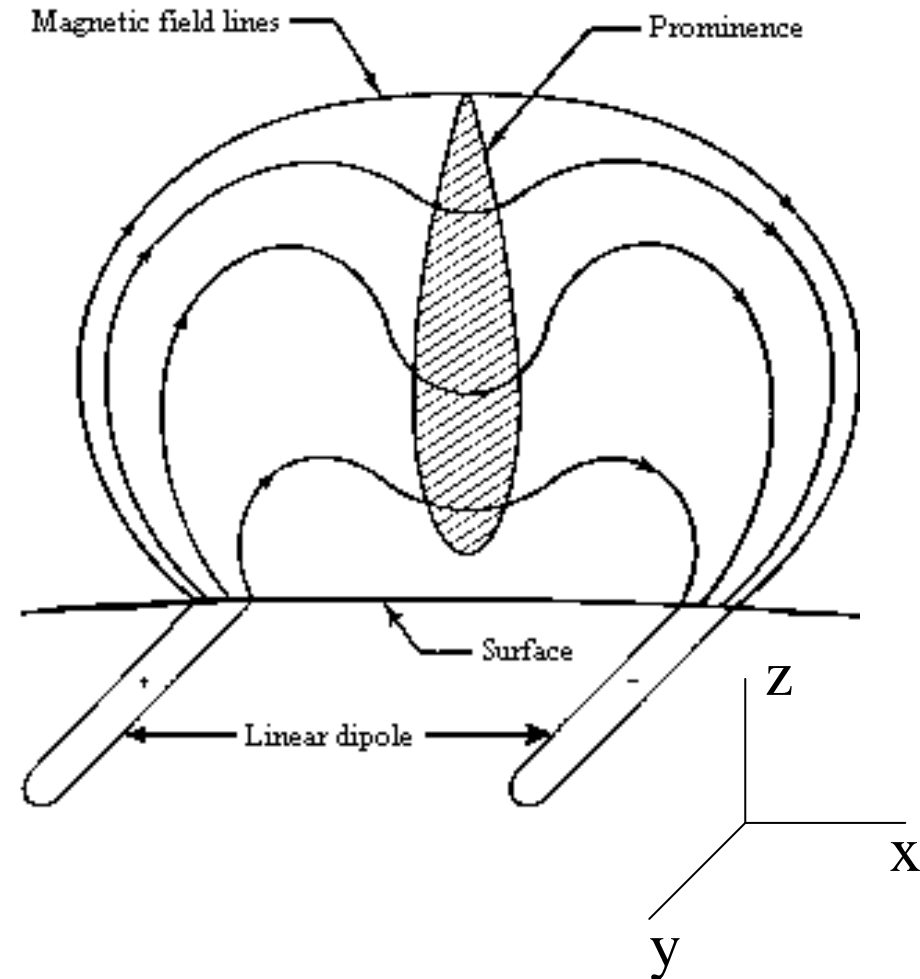
- Eruption of a Prominence

- The Sun in ultraviolet light taken by the Solar and Heliospheric Observatory (SOHO) spacecraft on February 11, 1996



# • A model of a prominence

- A long arcade is formed by the contact between two unipolar regions of opposite polarity
- The long tunnel formed by the loops of field provide a support for the material of a prominence
- An electric current flows along the axis of the arcade (through the prominence).
- The magnetic field of this current distorts the field providing a configuration that holds the prominence up against gravity



$$p + \frac{B^2}{2\mu_0} = \text{const.}$$

$$\rho g = \frac{dB_z}{dx} \frac{B_x}{\mu_0}$$

$$\rho = p/RT$$

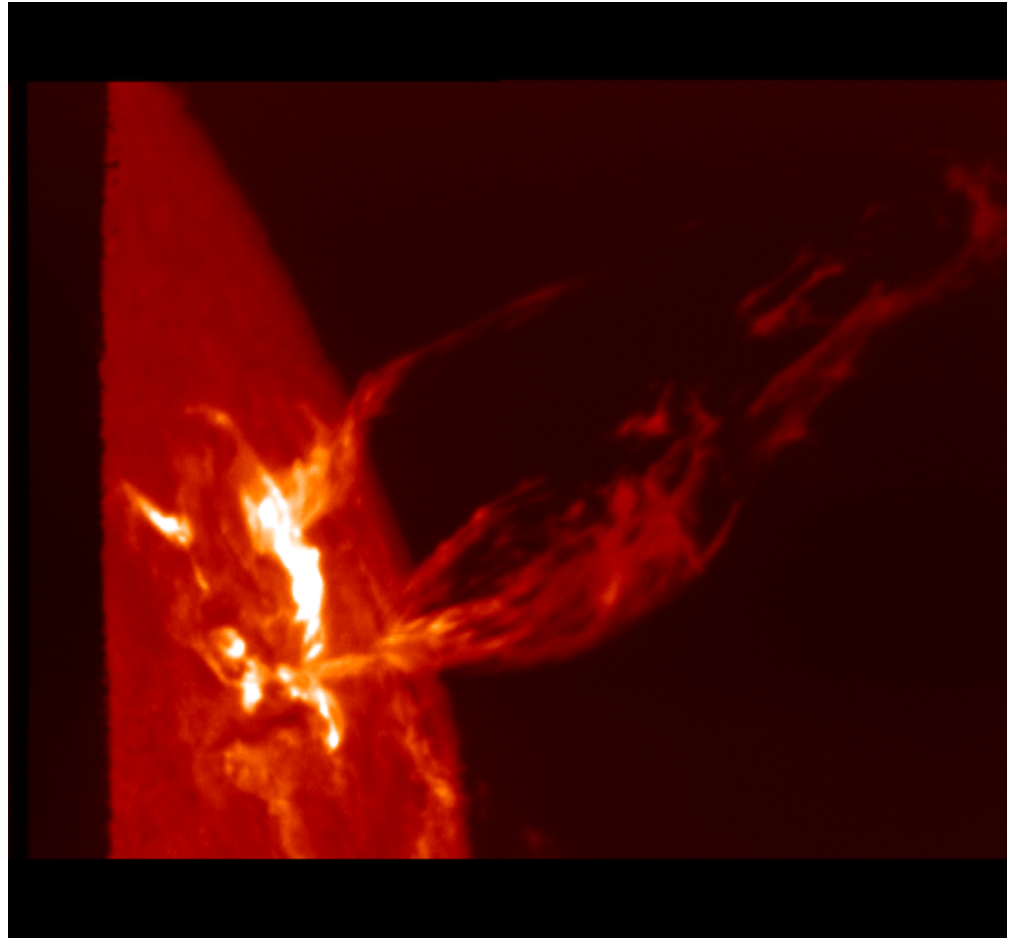
R is the gas constant  $R = N_A k = 8.3144$

The solution has the form

$$B_z = B_0 \tanh \frac{x}{l}, p = \frac{B_0^2}{2\mu_0} \text{sech}^2 \frac{x}{l}$$

The width is  $l = \frac{2B_x H}{B_0}$  where  $H \equiv \frac{RT}{g}$

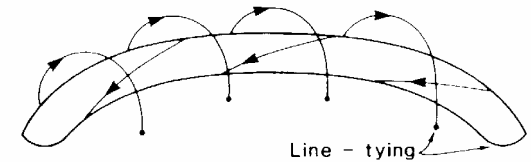
- Solar Flares, Prominence Eruptions and CMEs
  - Solar flares are often seen in conjunction with CMEs
  - CMEs are the main cause of magnetic storms on Earth
  - Since many storms follow solar flares many people believed that flares were the cause of storms but this is no longer the case.



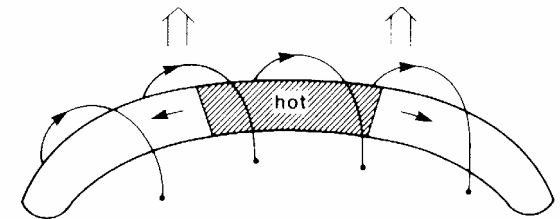
# • Prominence Eruption and Magnetic Reconnection

- The prominence begins with the formation of a long arcade of field line loops
- A current flows along the top of the arcade producing a flux rope configuration
- The two sides of the arcade are sheared by flow in the photosphere enhancing the current and further twisting the field
- The prominence rises as the feet move further apart and the overlying field becomes weaker
- At some point the field lines that overly the top of the prominence begin to reconnect adding more loops to the flux rope and releasing it to expand

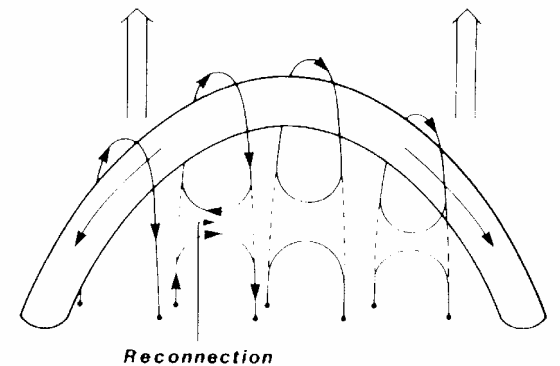
(i) Equilibrium



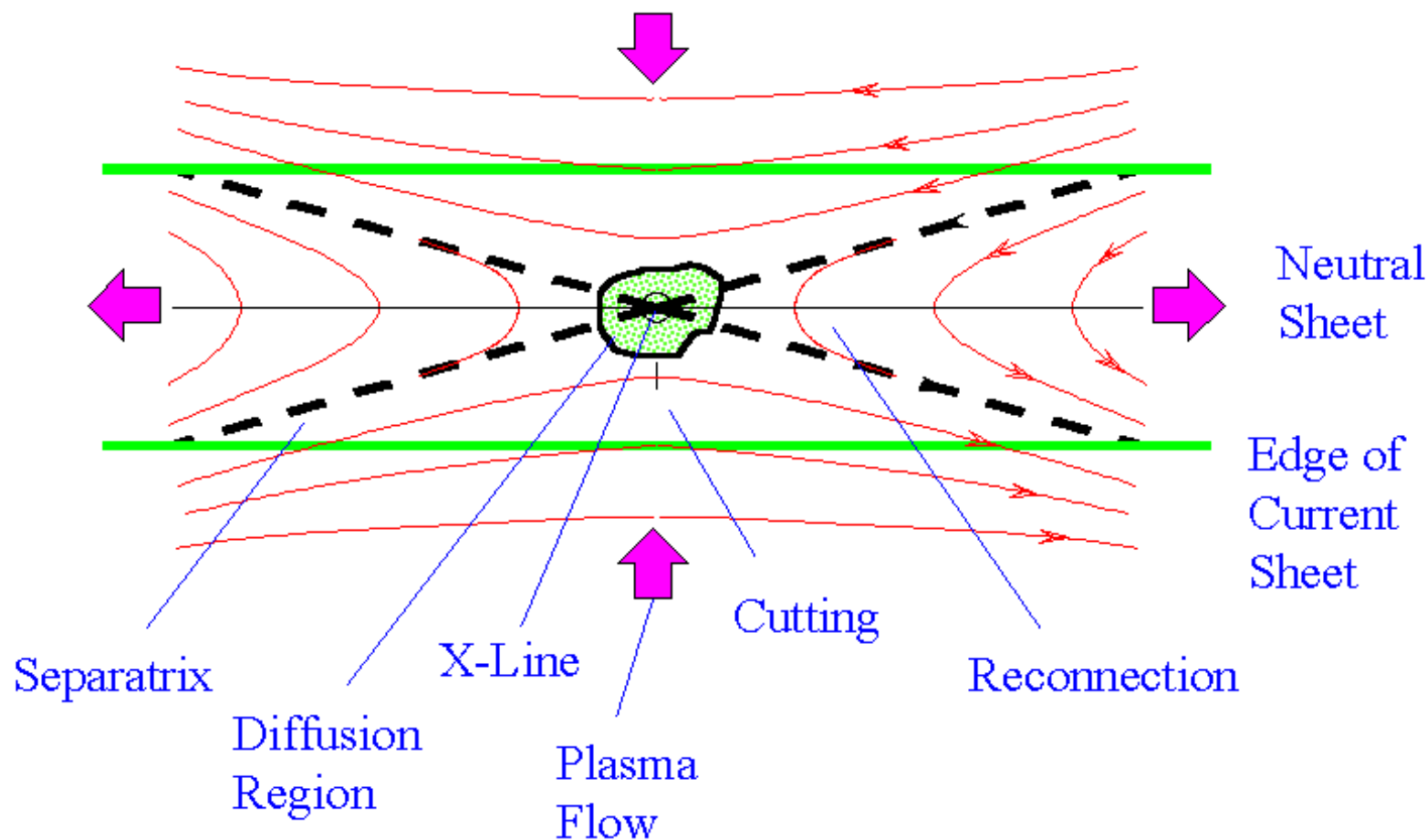
(ii) Slow Rise



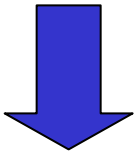
(iii) Fast Eruption Upwards



# GEOMETRY OF AN X-LINE



- Coronal mass ejections



White Light



14 Apr 1980 04:48



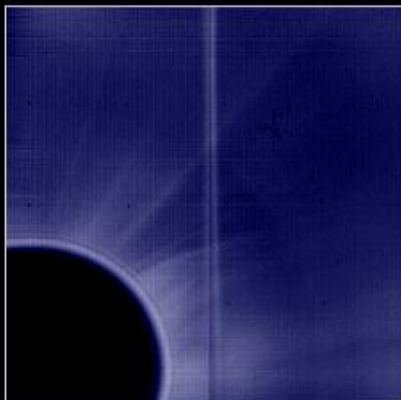
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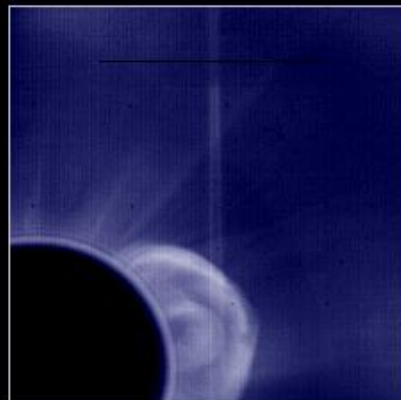
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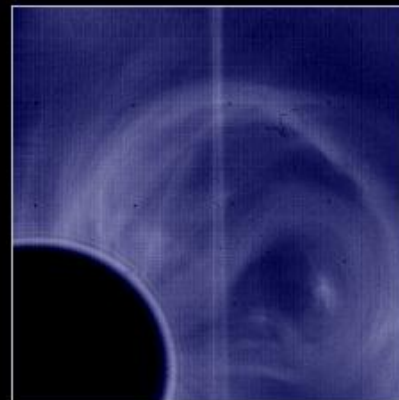
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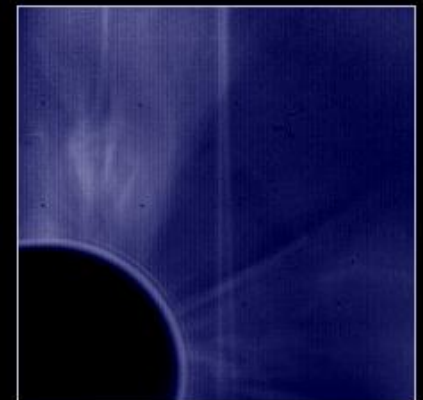
24 Oct 1989 15:23



24 Oct 1989 18:09



24 Oct 1989 18:25



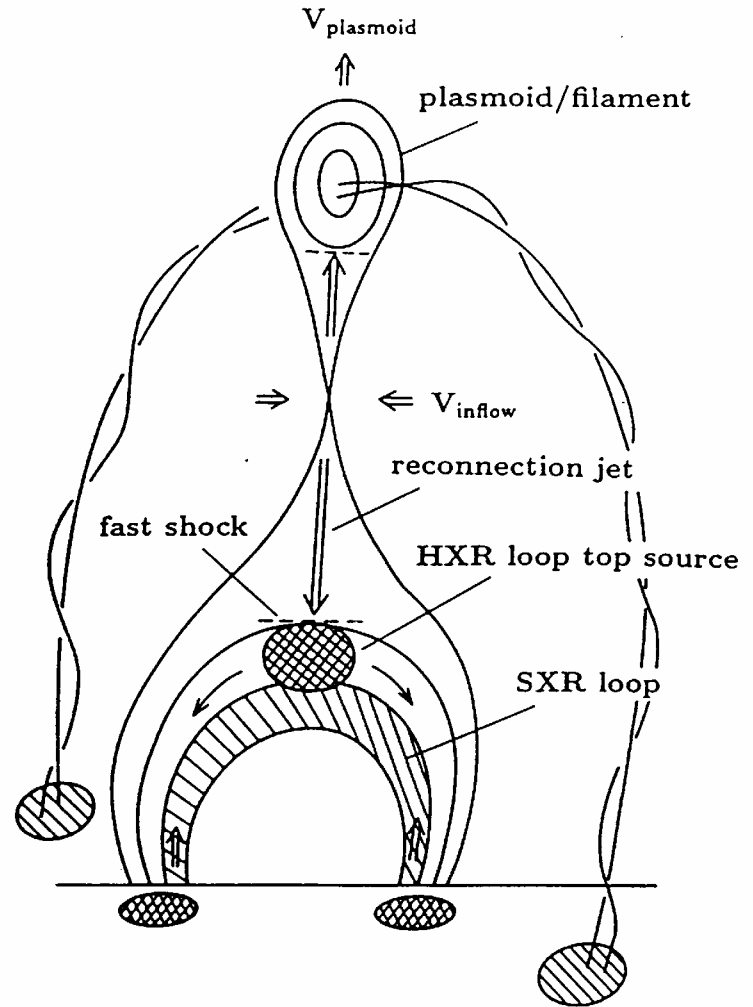
24 Oct 1989 19:15

- Coronal Mass Ejections

- During coronal mass ejections (or CMEs) large amounts of mass ( $10^{15}$  to  $10^{16}$  g) are ejected from the Sun into the interplanetary medium.
- CMEs are not caused by solar flares.
- CMEs are associated with eruptive prominences, radio bursts etc.
- Many CMEs are associated with long-duration X-ray events.

# • X-ray Sources in Flares and CMEs

- The twisted lines represent the field through a prominence
- The loops represent a coronal arcade
- The prominence is erupting because reconnection has released the constraining field and is pushing the prominence upward
- Particles accelerated by reconnection hit the top of the arcade and generate hard x-rays there and at the feet of the arcade field lines



- CMEs in the Solar Wind

- Once the CME leaves the Sun it expands as it travels towards the Earth becoming longer and thicker in cross section

- The magnetic field inside the flux rope is helical. It is nearly straight lines in the center and tight spirals on the outer surface

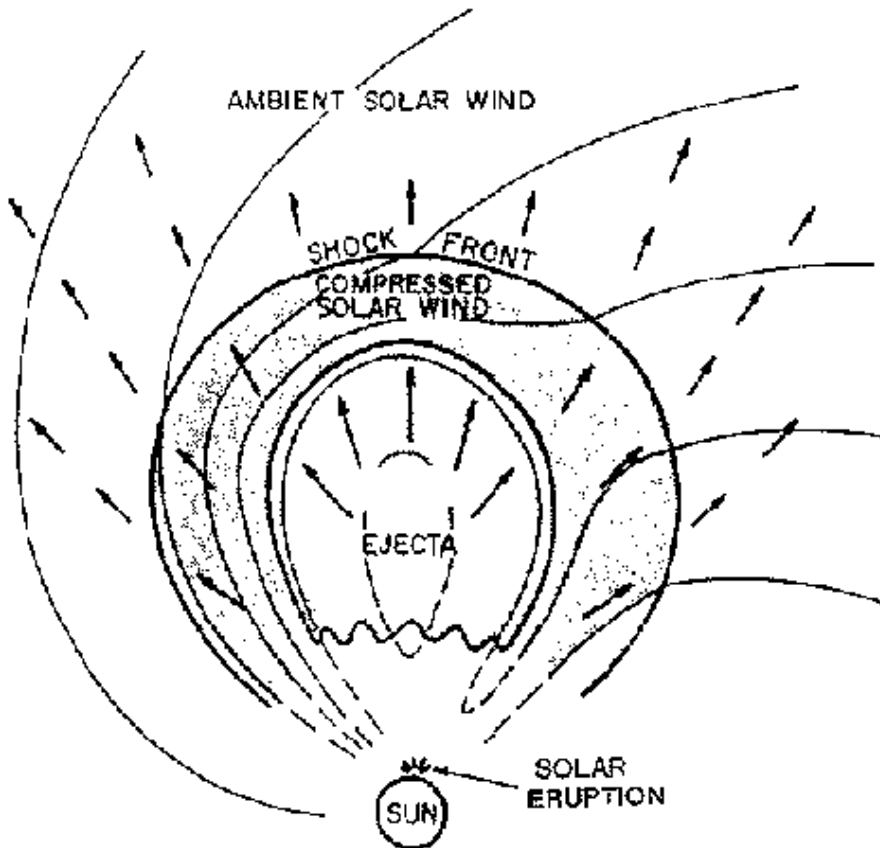
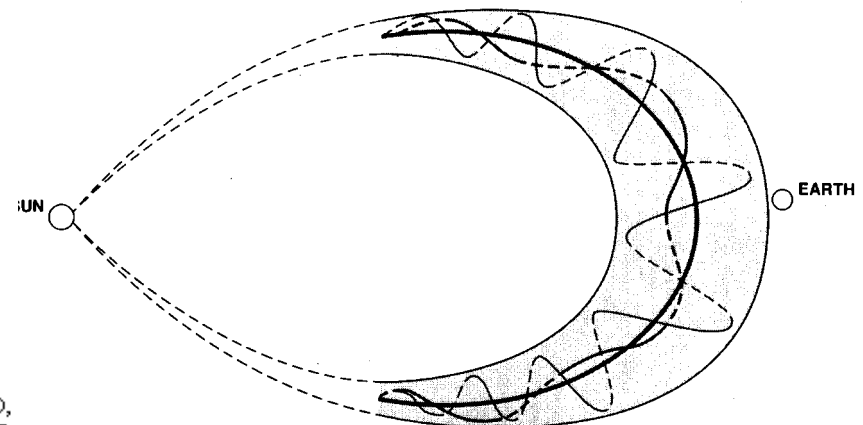


Figure adapted from Hundhausen, p. 395, in SOLAR WIND, eds. C.P. Sonett, P.J. Coleman Jr., and J.M. Wilcox, NASA SP-308, Washington DC



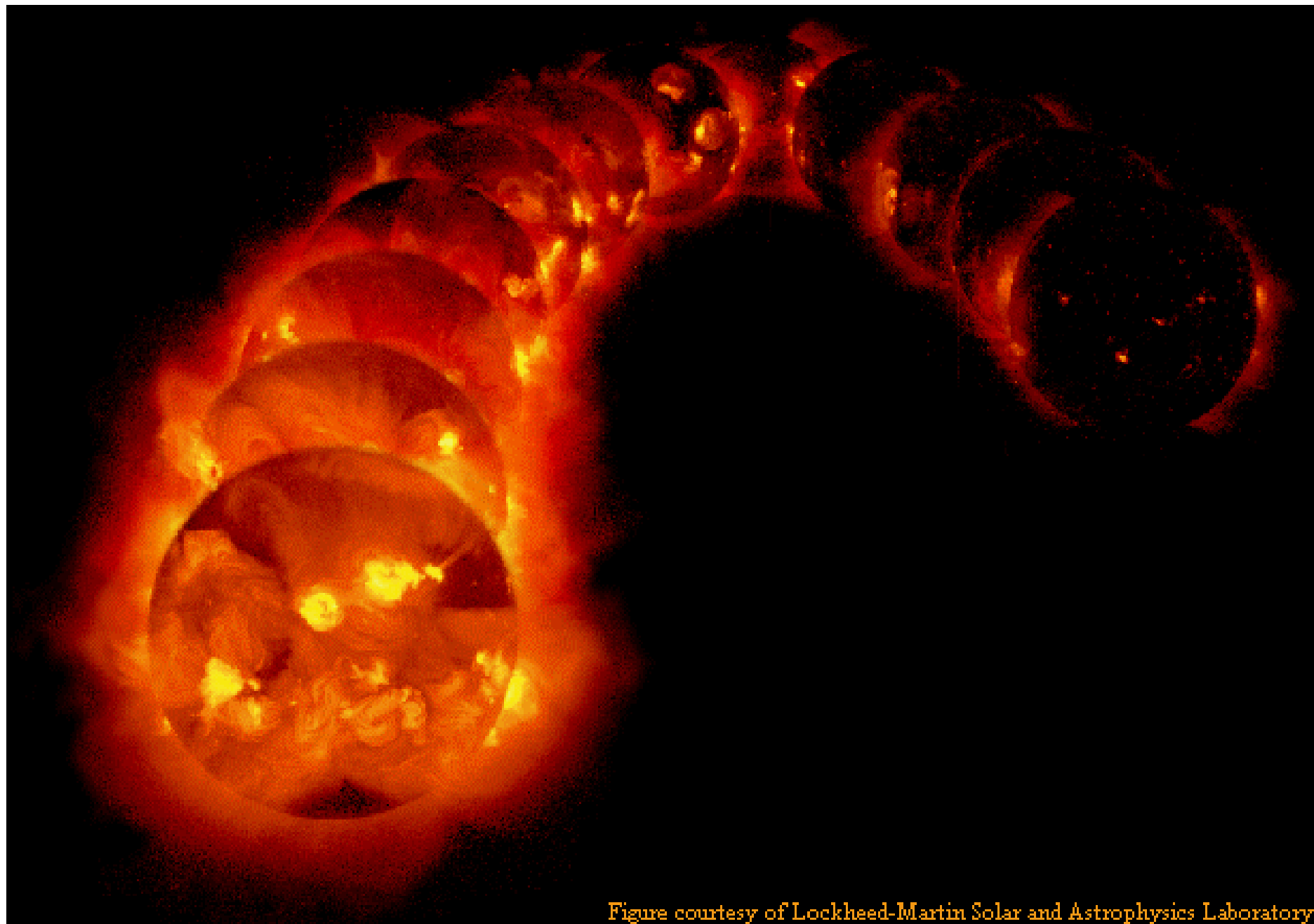


Figure courtesy of Lockheed-Martin Solar and Astrophysics Laboratory