

# Helios in Greek & Sol in Roman

- Drove his chariot across the sky to provide daylight
- Returned each night in a huge golden cup on the river Oceanus
- His son Phaeton drove the chariot one day but lost control burning Africa and turning the Ethiopians black

Japanese sun goddess Amaterasu emerges from her cave



T17.1 HELIOS & THE CHARIOT OF THE SUN



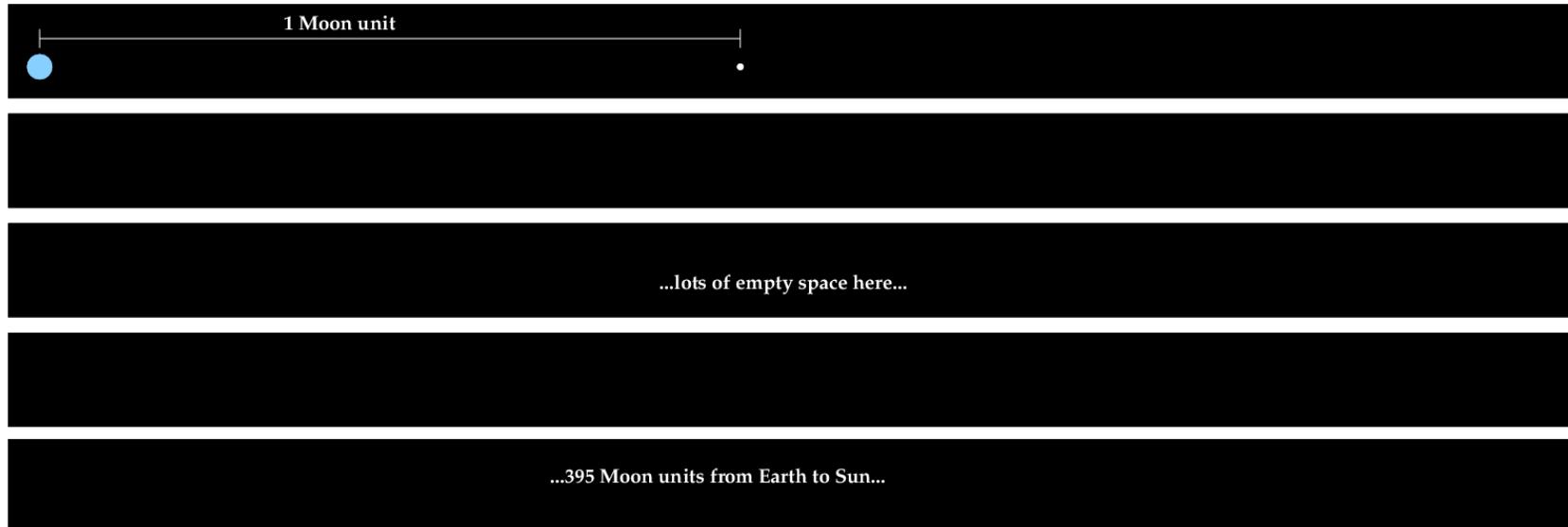
Ra and his barge



# The Sun's Distance

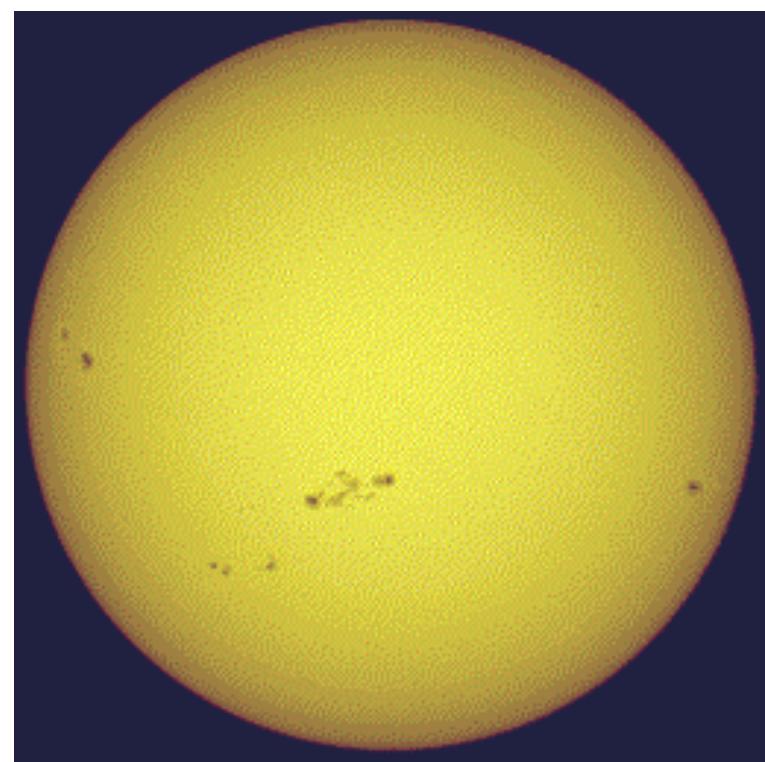
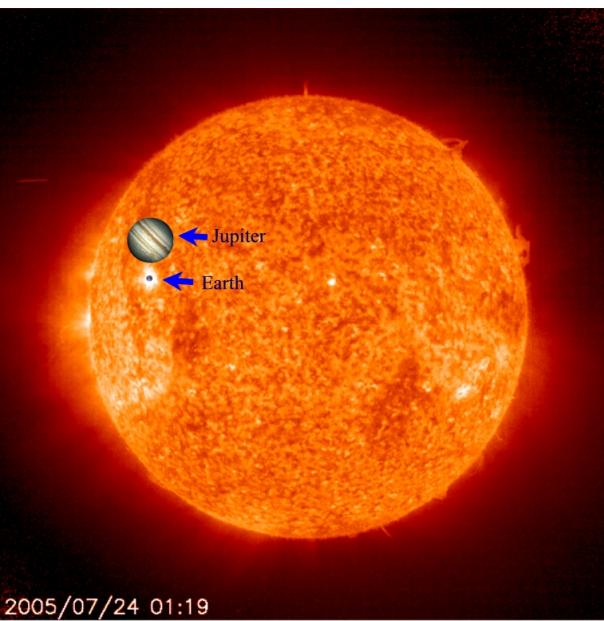


- Sun supplies light & heat making Earth habitable!
- Is it going to keep on shining? Dependably????
- All from 150million km = 170years in car = 20years in a jet



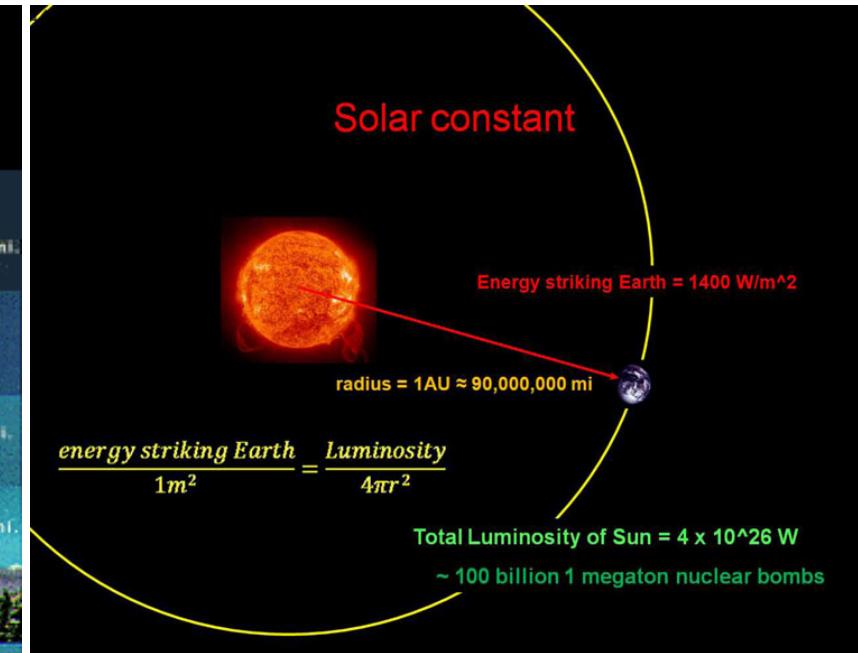
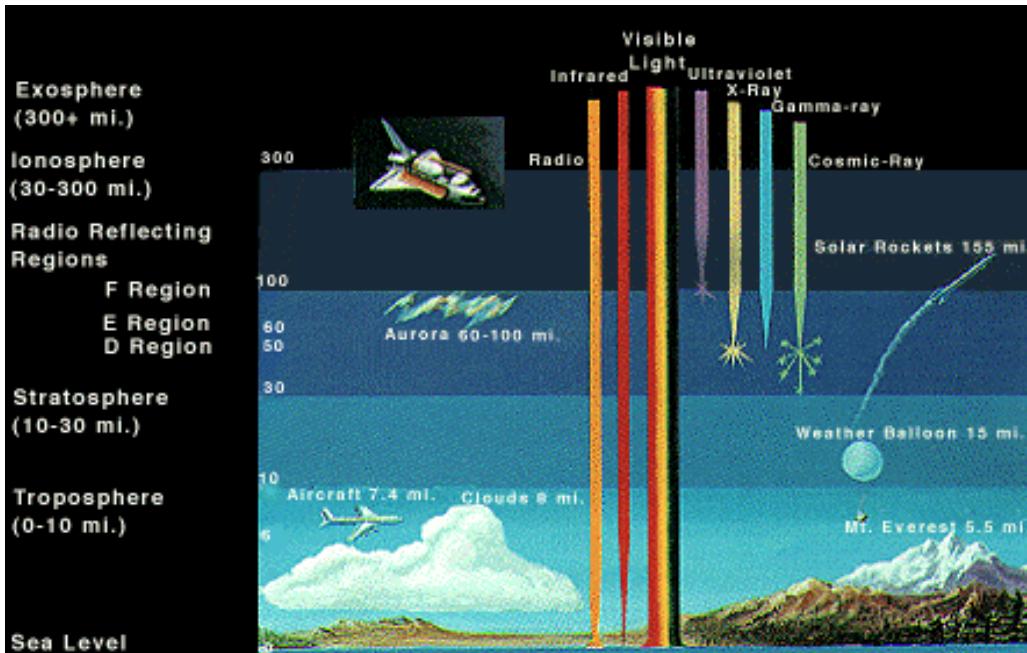
# Sun's Density

- From distance & apparent size:  
Solar radius = 100 Earth radii
- From Newton's Laws:  
Mass = 300,000 Earths
- Density=1.4gm/cc→Hydrogen



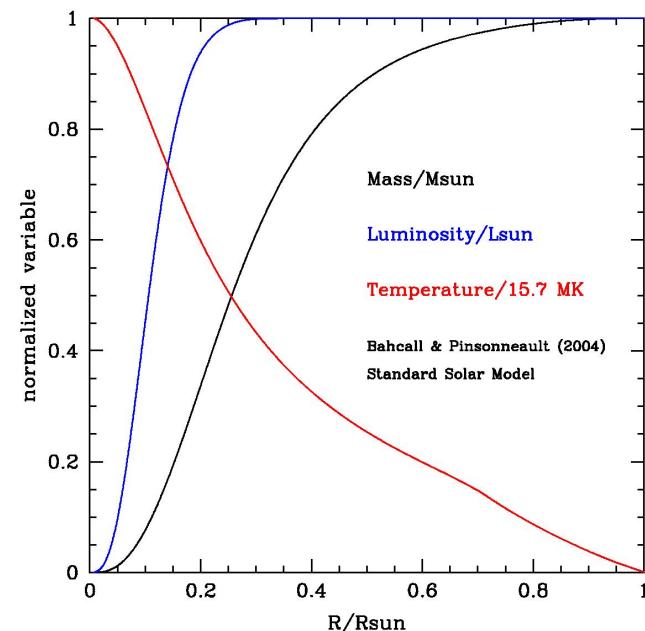
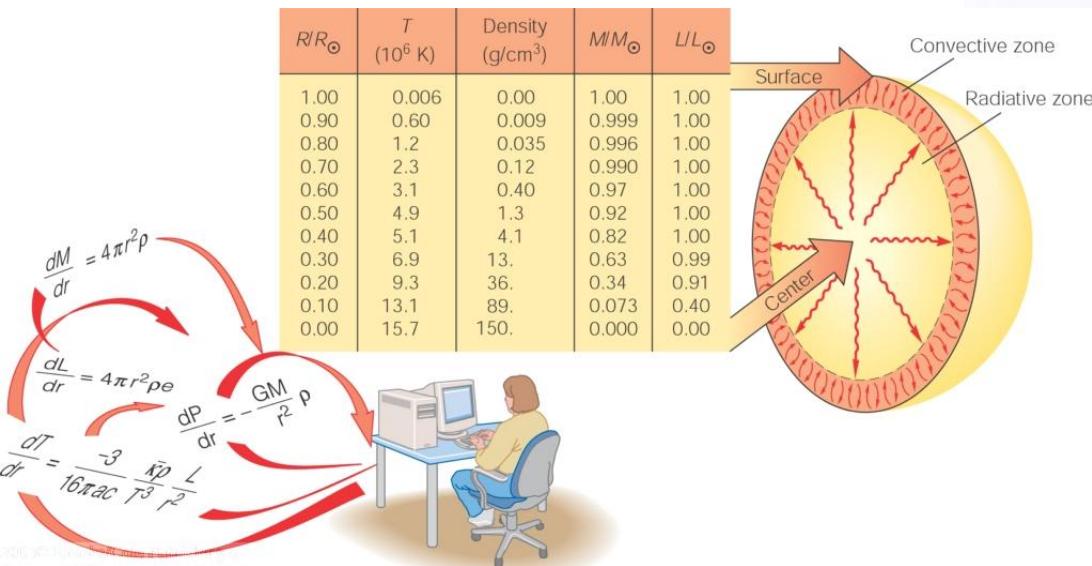
# Solar Luminosity

- Solar Constant is the amount of energy received from Sun per square meter at Earth's Distance from above atmosphere including all wavelengths
- Solar Luminosity=total energy emitted by the Sun

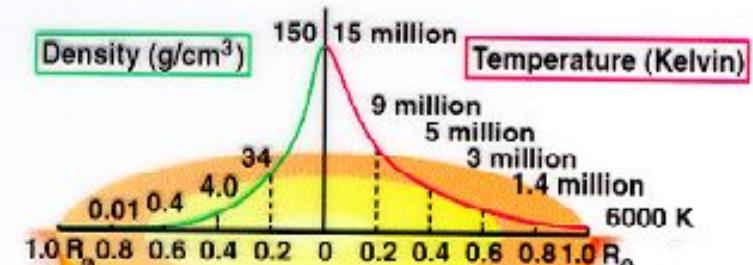


# Standard Solar Model

- Mathematical Model used to predict temperature & density (pressure) inside the sun
- Sun radiates energy- so it must be replaced from inside

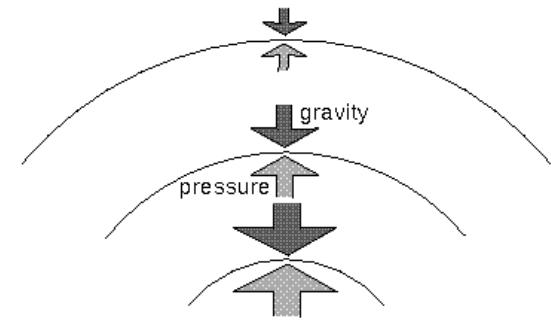
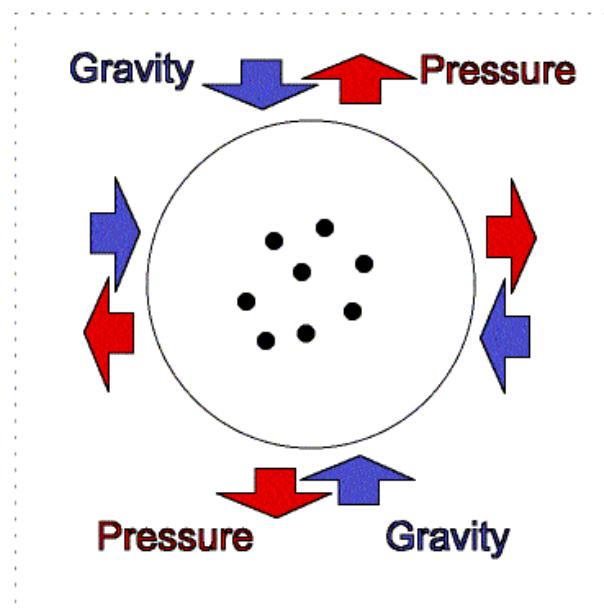
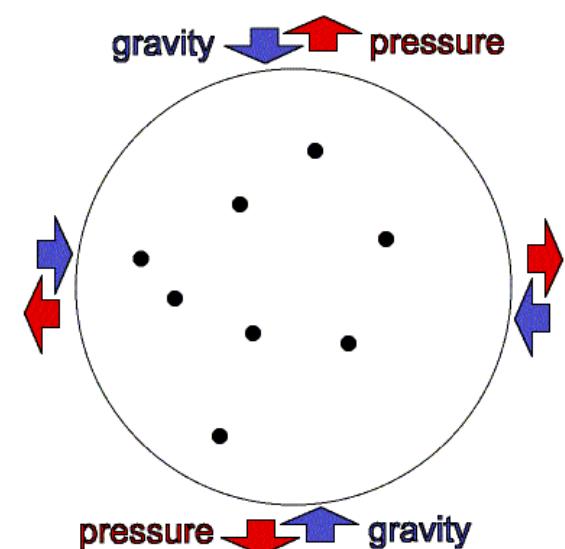


## How Temperature and Density Vary Inside the Sun



# Hydrostatic Equilibrium

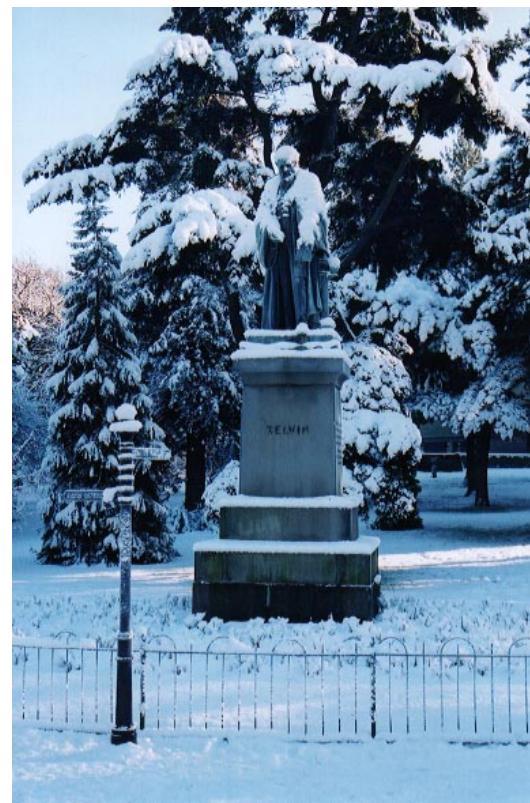
- Since the Sun is not getting bigger or smaller it must be in **Hydrostatic equilibrium**
- Gravity pulls gas together but is resisted by pressure of gas



Deeper layers have more gravity compression, so they have greater outward pressure to compensate.

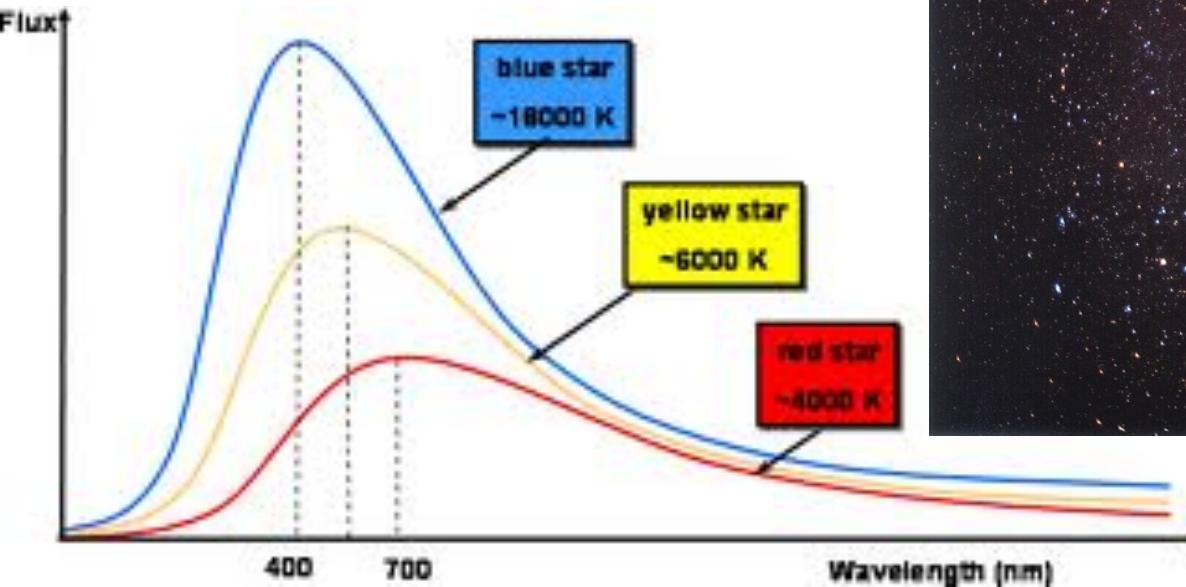
# Atoms & Heat & Temperature

- Hotter temperature; the faster the atoms move
- The amount of heat (=thermal energy) depends on temperature AND mass/number of atoms
- The atoms cease moving at **Absolute Zero** = zero **Kelvin Scale**
- Bowtie nebula  $-272^{\circ}\text{C} = 1\text{K}$



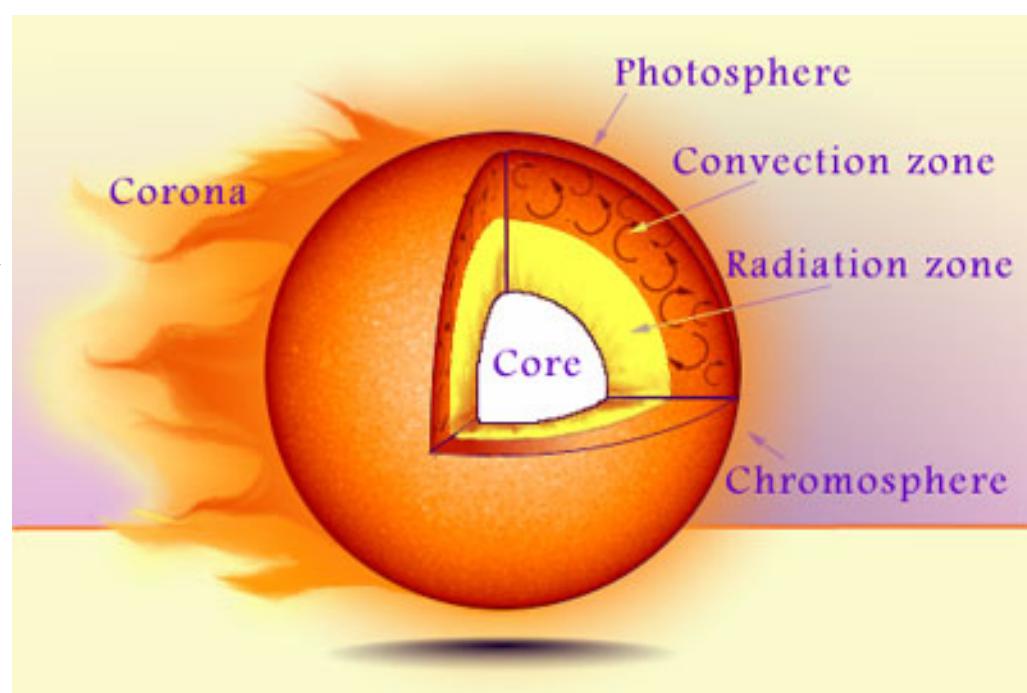
# How Hot is the Sun? Blackbody Spectra

- As the temperature goes up there are more collisions & more violent
- So more photons AND more energetic photons (=blue)
- Higher temperature shorter **wavelength of peak emission**=
- Higher temperature **bluer** color



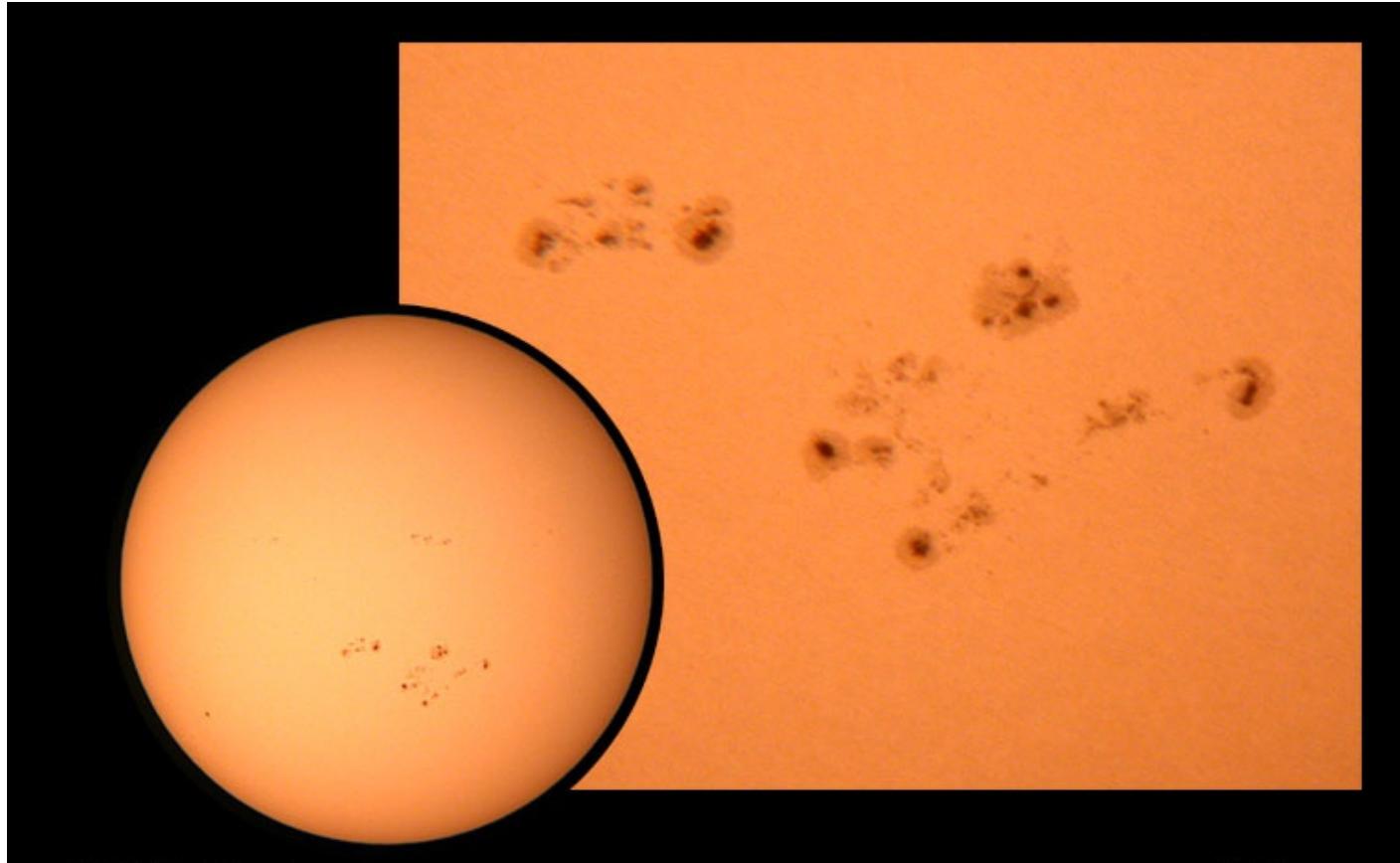
# Parts of the Sun

- Core, Radiative Zone, Convective Zone
- Photosphere, Chromosphere, Corona, Solar Wind



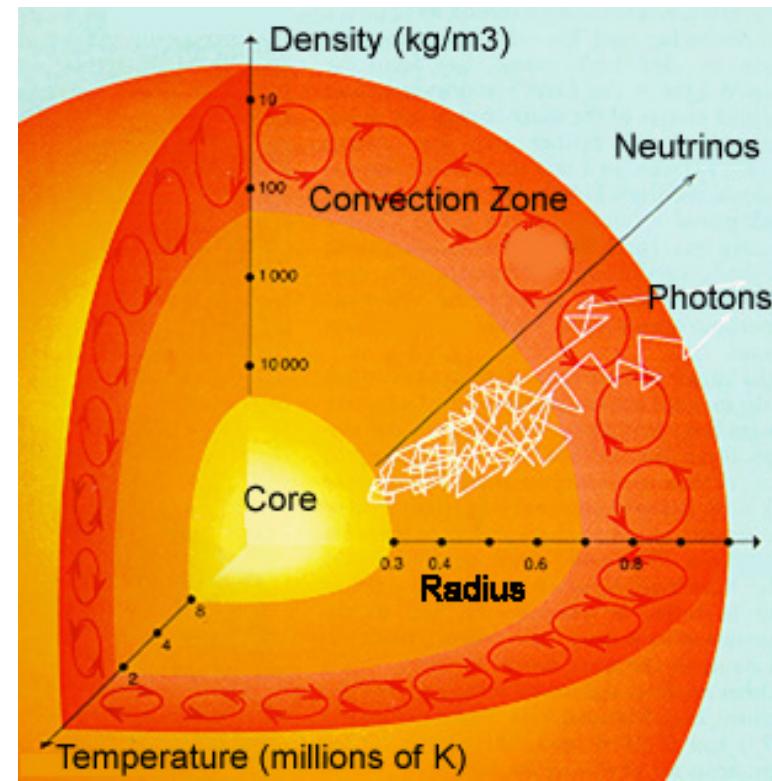
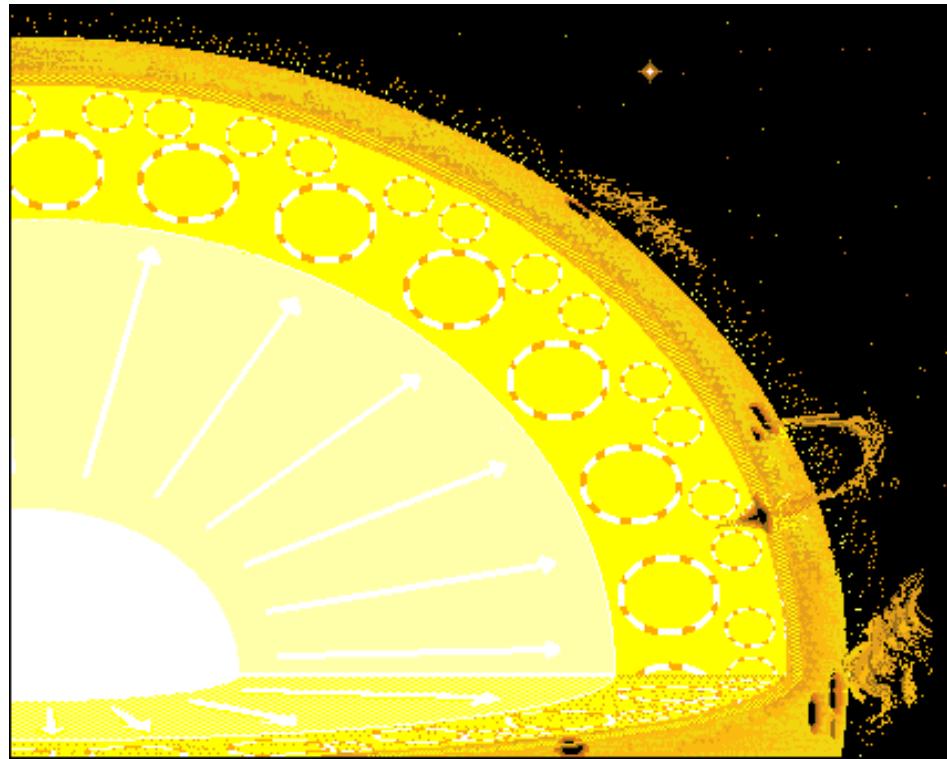
# Photosphere: Bright Surface of Sun

- Effective temperature 5780K: all elements gaseous/ionized
- Photosphere is 3400 times less dense than air on Earth
- Sunspots are cooler regions
- Photosphere radiates light/heat - interior must be hot to replace energy



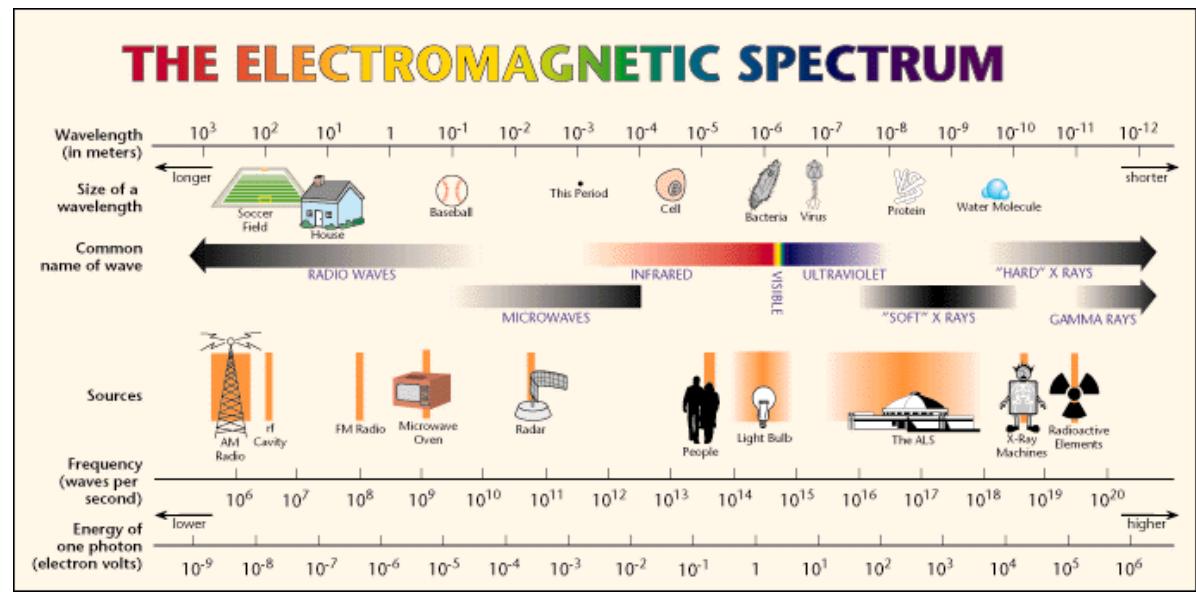
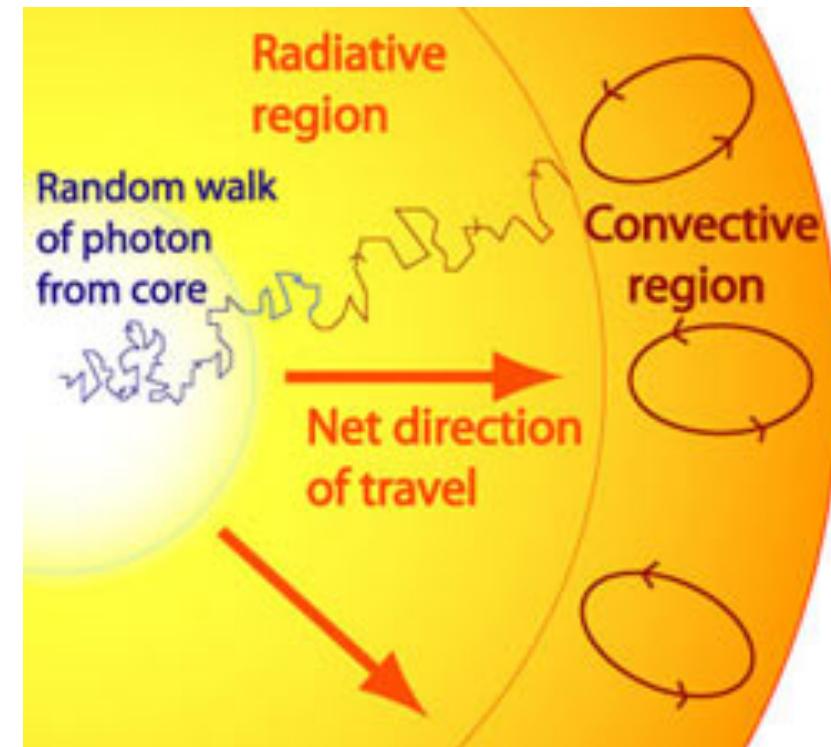
# Radiation Zone & Convection Zone

- Heat/energy produced in hot dense **core** (15 million Kelvin)
- Transported by **radiation** initially in **Radiation Zone**
- By **convection** in **Convection Zone** after 70% of Radius
- By **radiation** from Photosphere to Earth



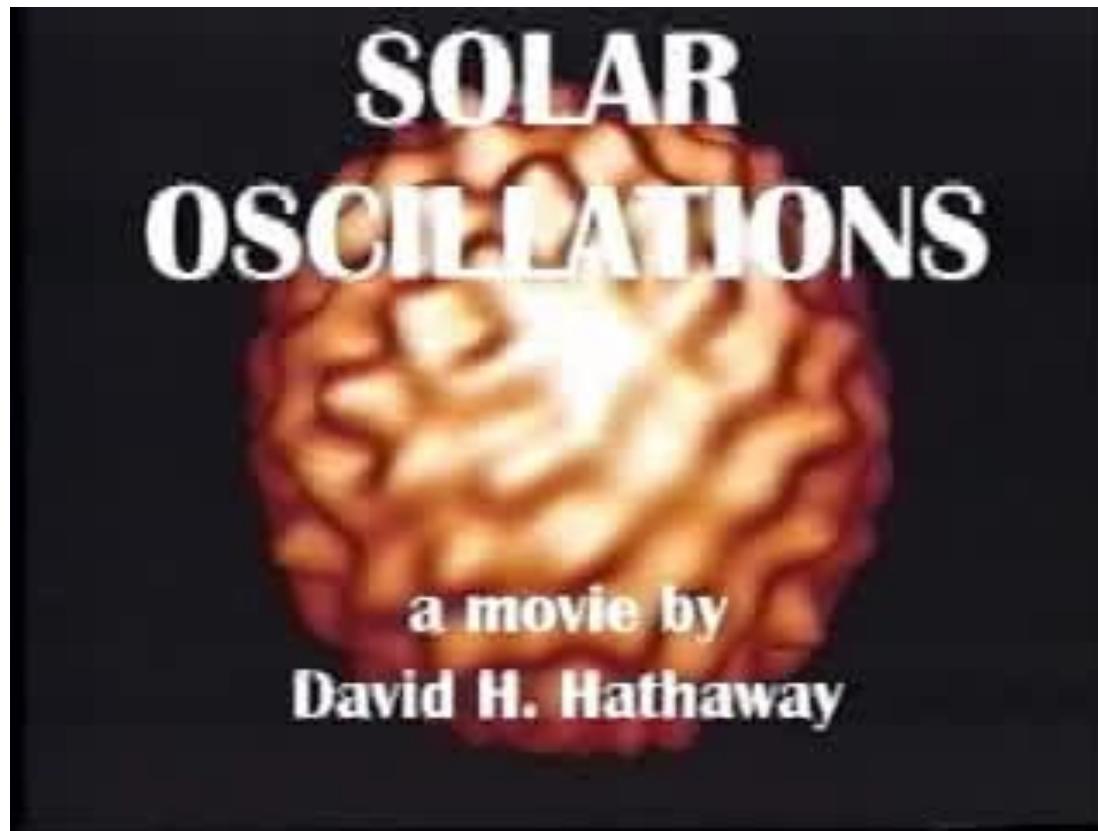
# Energy Transport

- One high energy photon is absorbed & its energy remitted as lower energy photons
- One gamma ray becomes ~1800 visible photons
- Trip to Sun's surface takes ~millions years



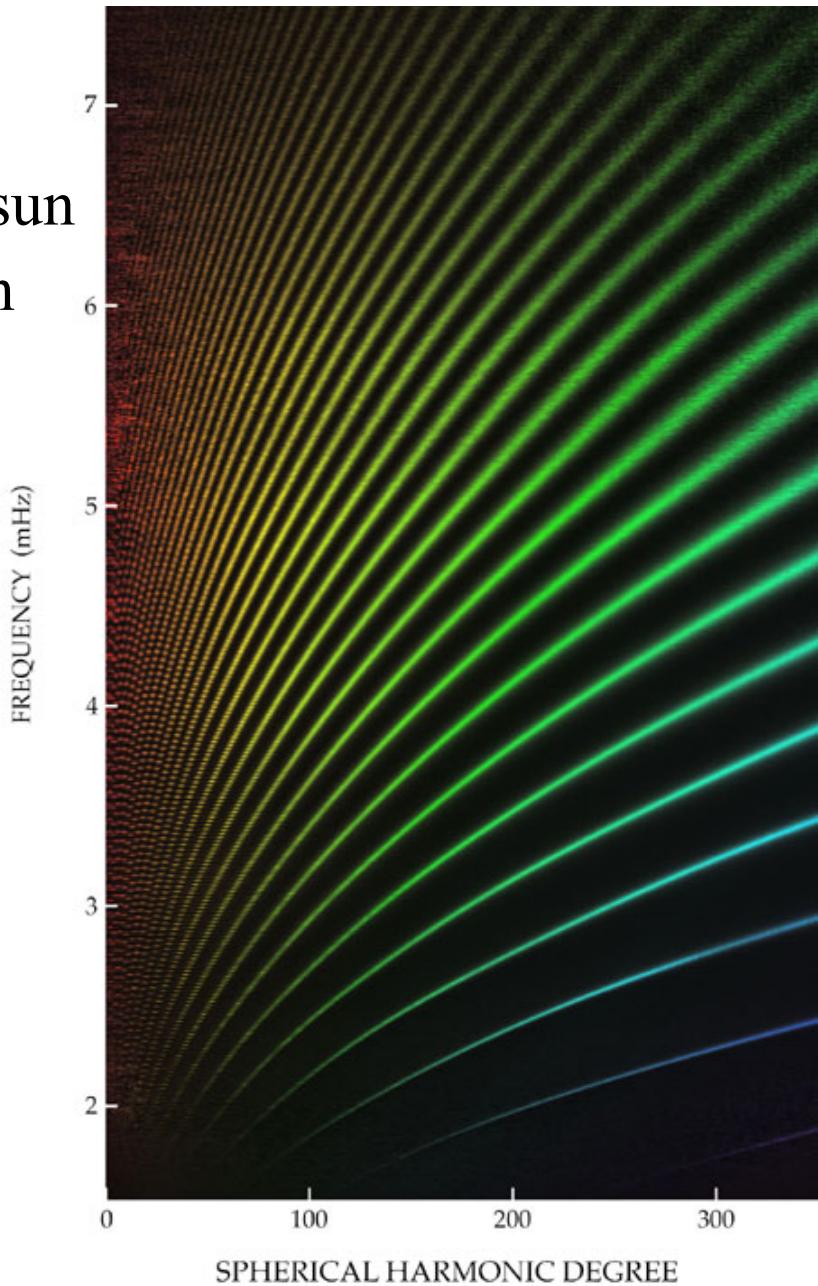
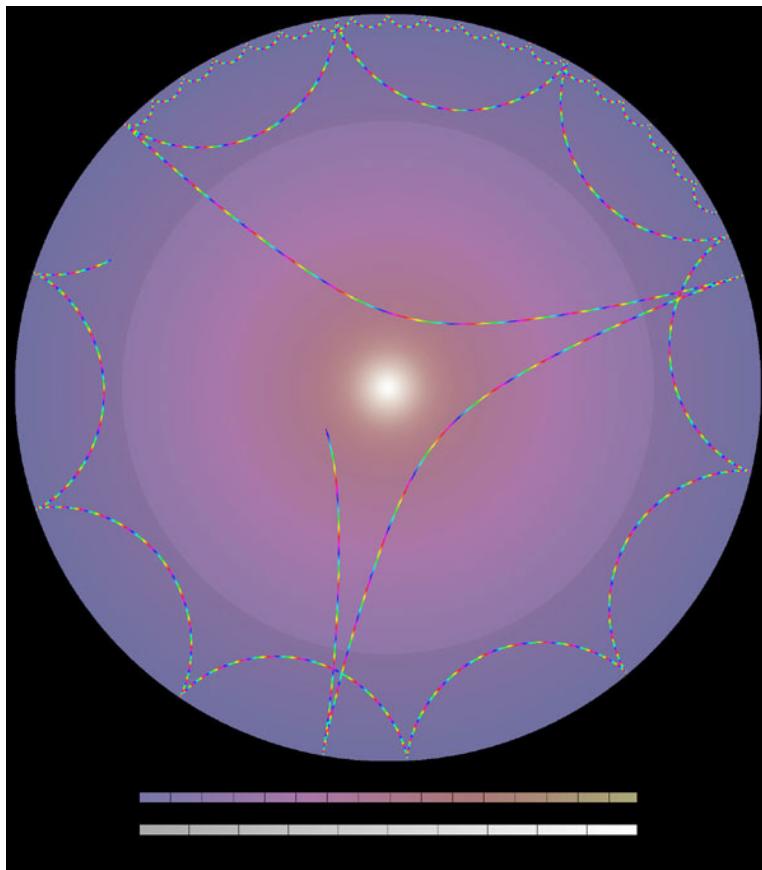
# Helioseismology

- Science: Theory makes predictions / Observations show theory correct
- Solar surface moves up and down like ocean waves
- 5 minute oscillations were first of millions of modes to be discovered



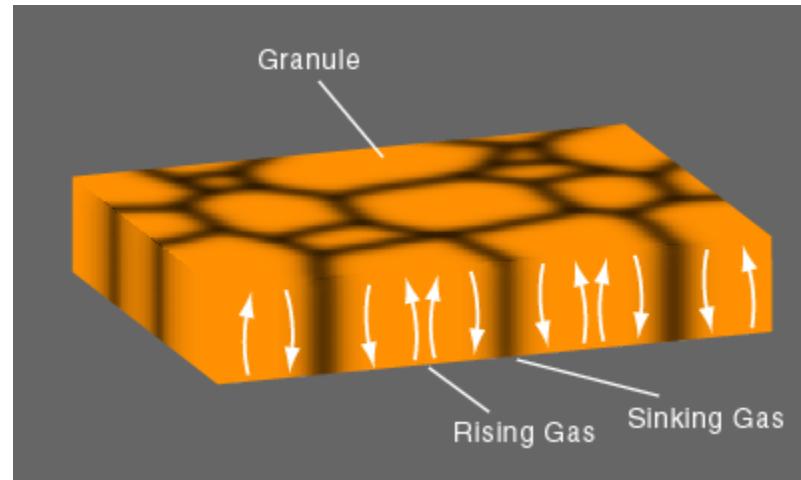
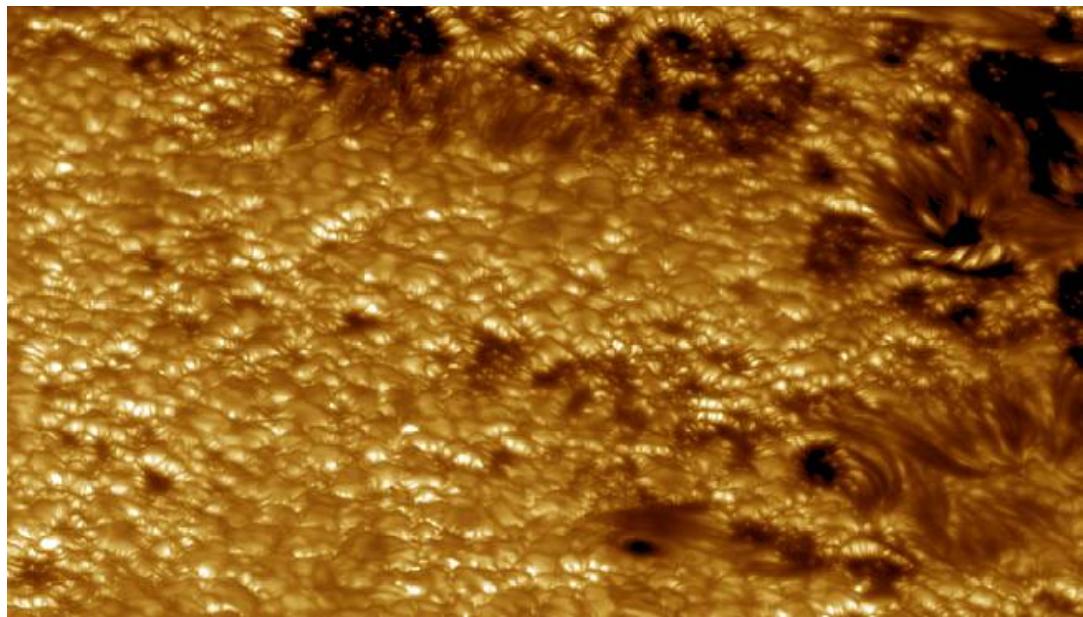
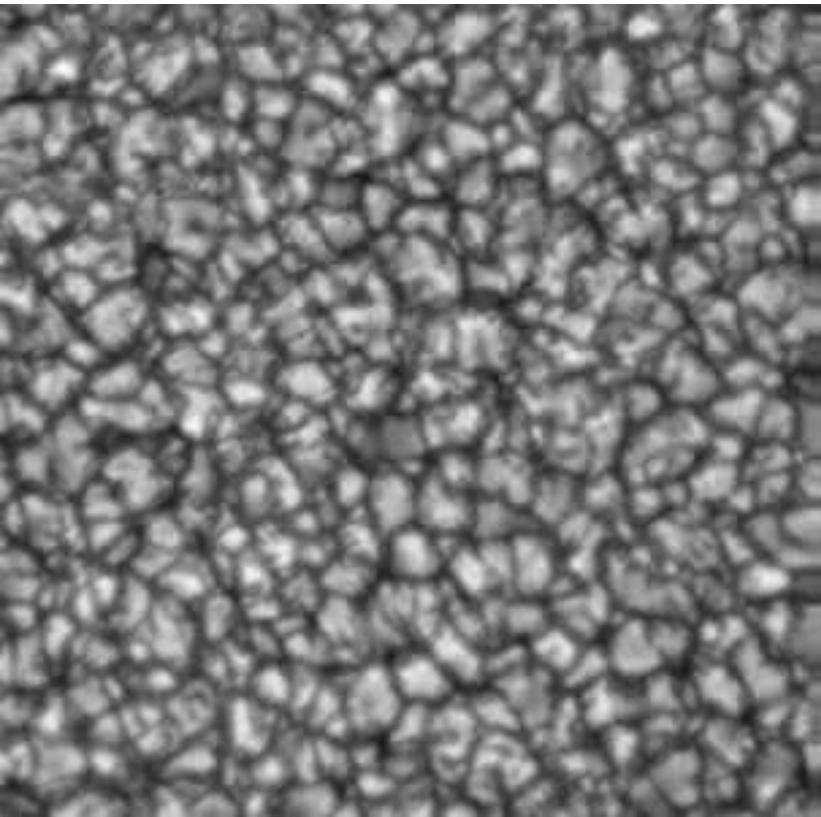
# Oscillation Modes

- Sound waves refracted back to surface
- Certain wavelengths resonate
- Longer wavelengths reach further into sun
- Gives temperature & density with depth
- Agrees with **Standard Solar Model**



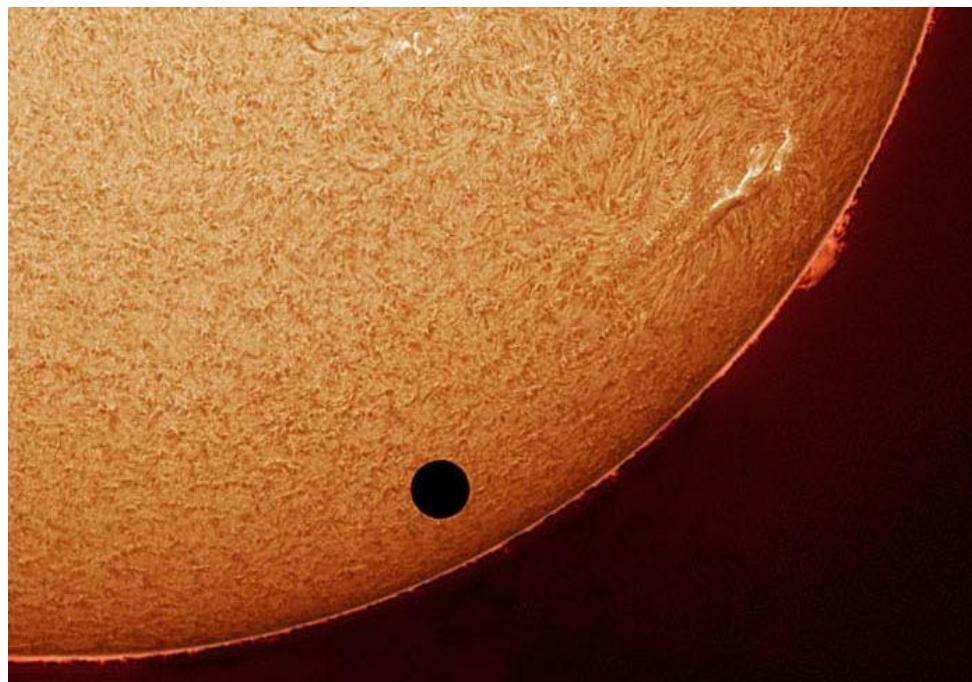
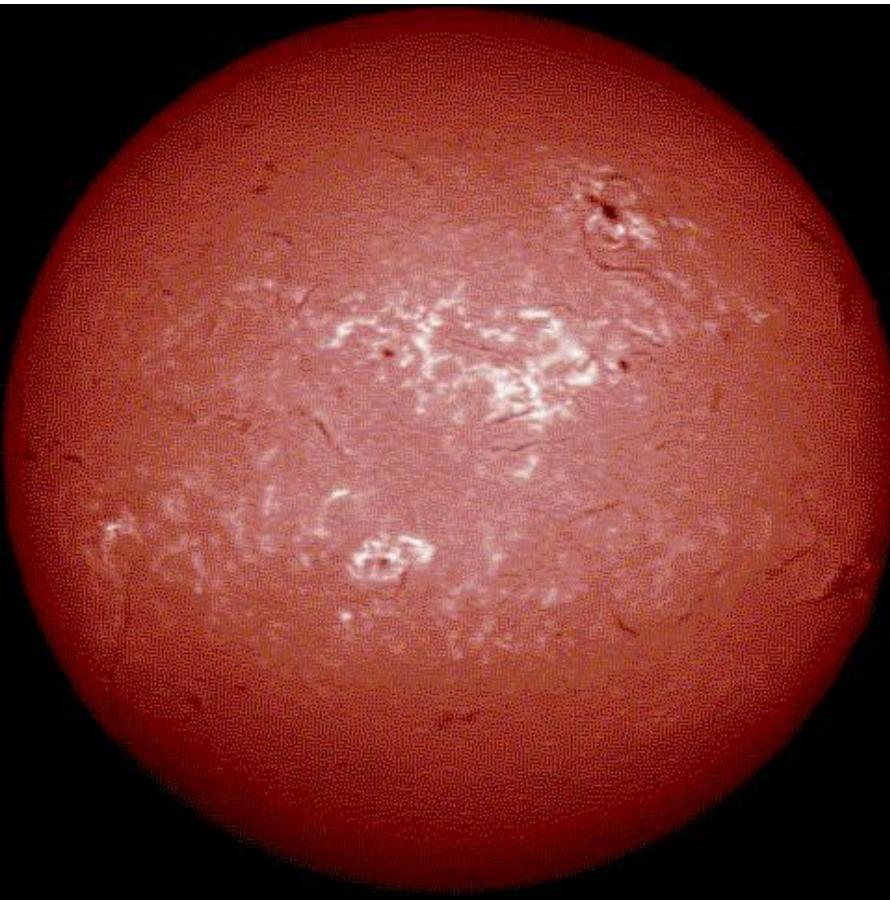
# Granulation

- Photosphere is Granulated = top of convection cells
- ~1000km =British Columbia
- Hot gas rises & cool gas sinks
- Lasts ~10 minutes



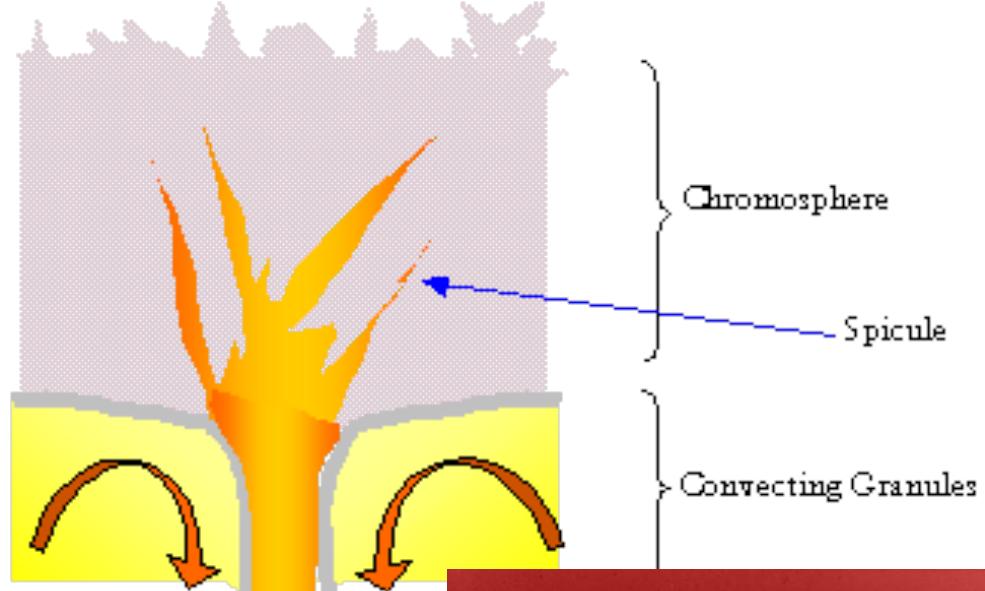
# Chromosphere

- Faint thin pink layer above Photosphere ~1000km thick
- Seen during solar eclipse or
- Hydrogen-Alpha filter

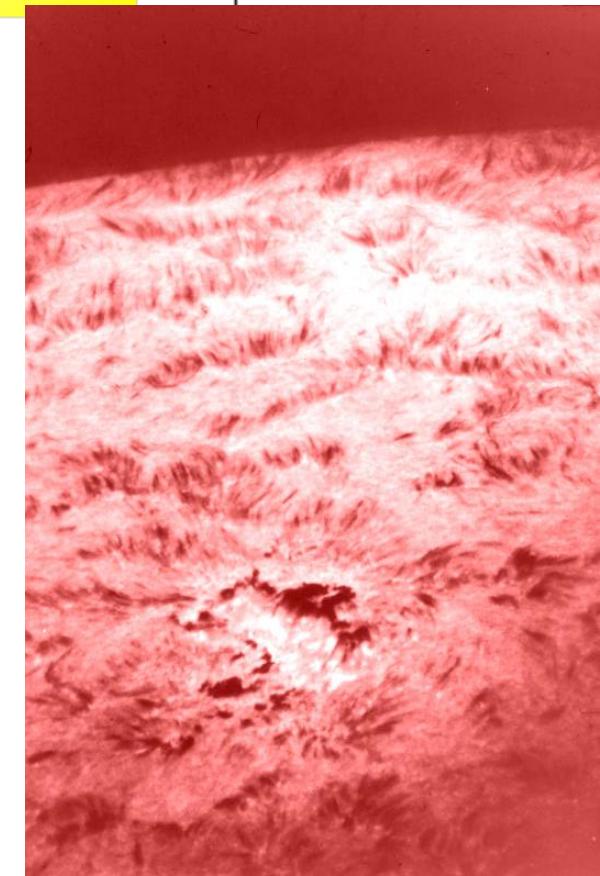
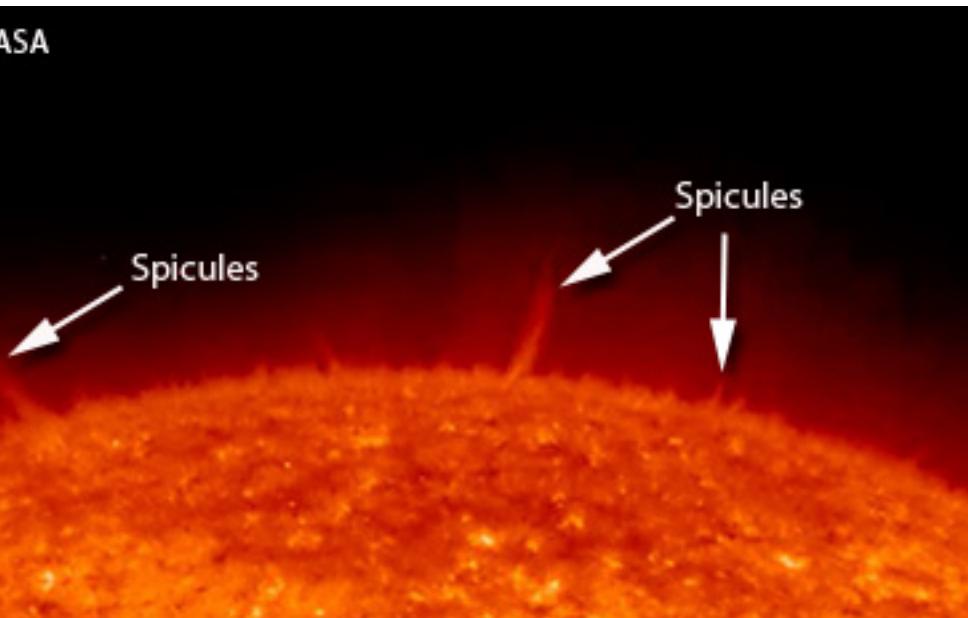


# Spicules on Limb

- Spikes of gas rise 7000km through chromosphere
- Last ~5 minutes
- Ultra-Violet Sun's limb

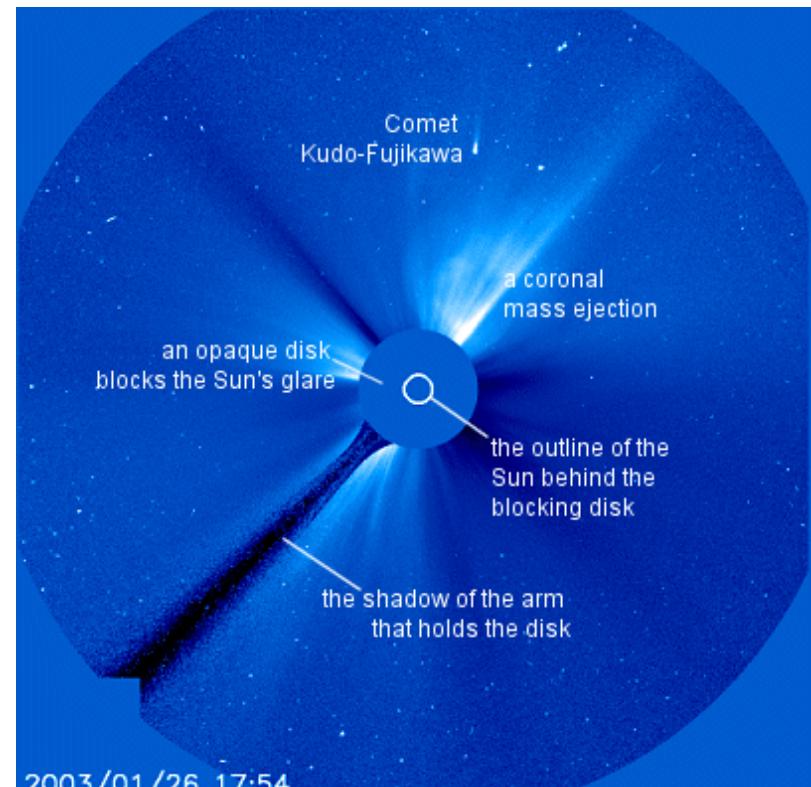
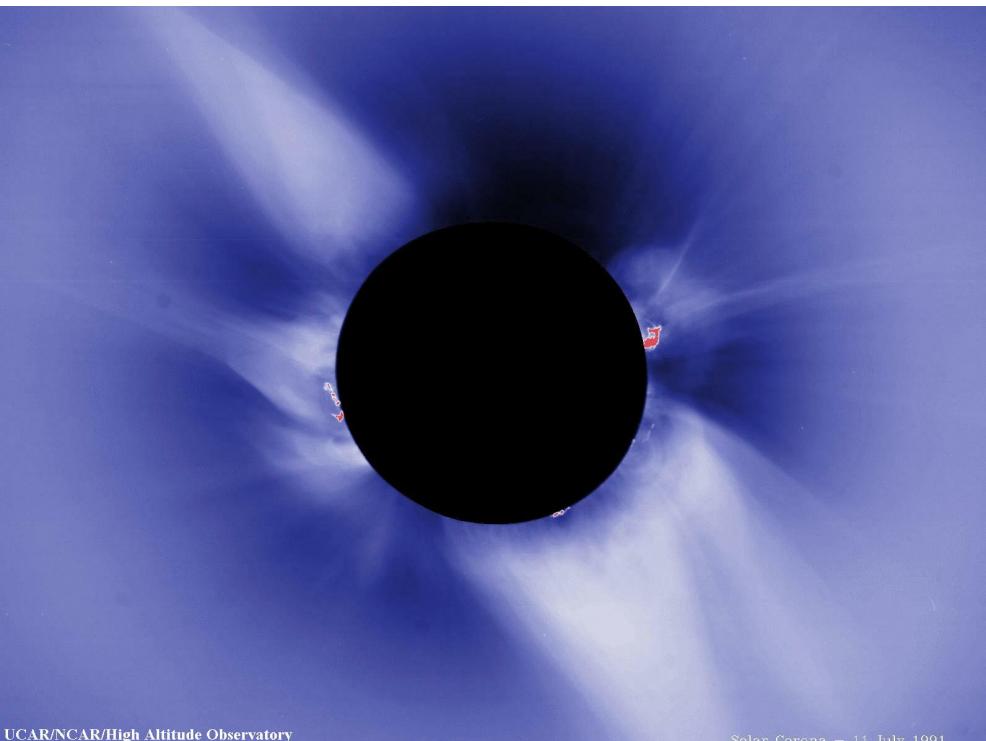


Credit: ESA/NASA



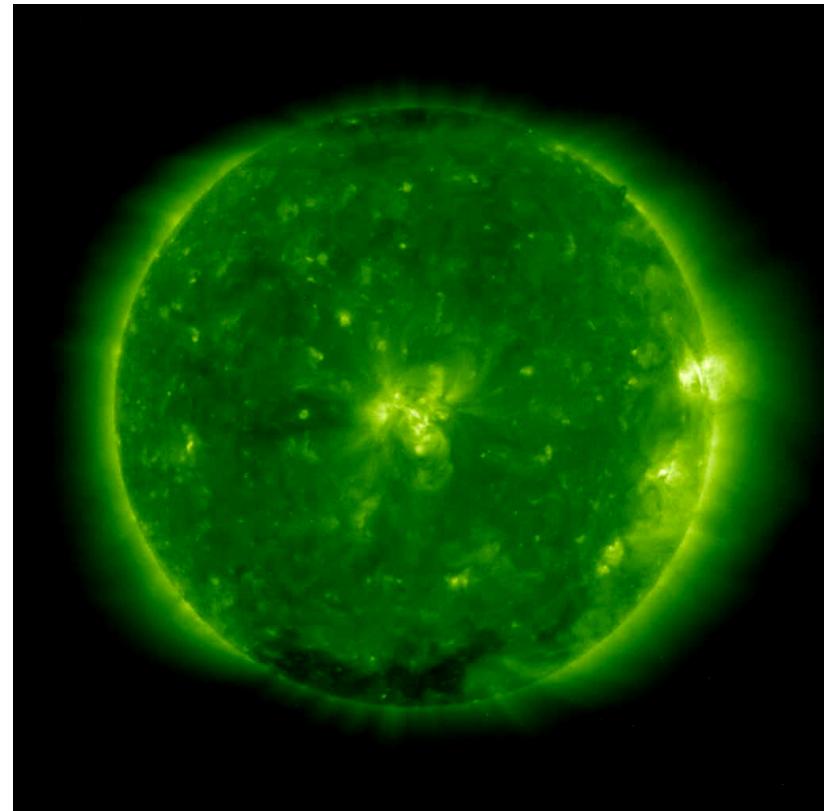
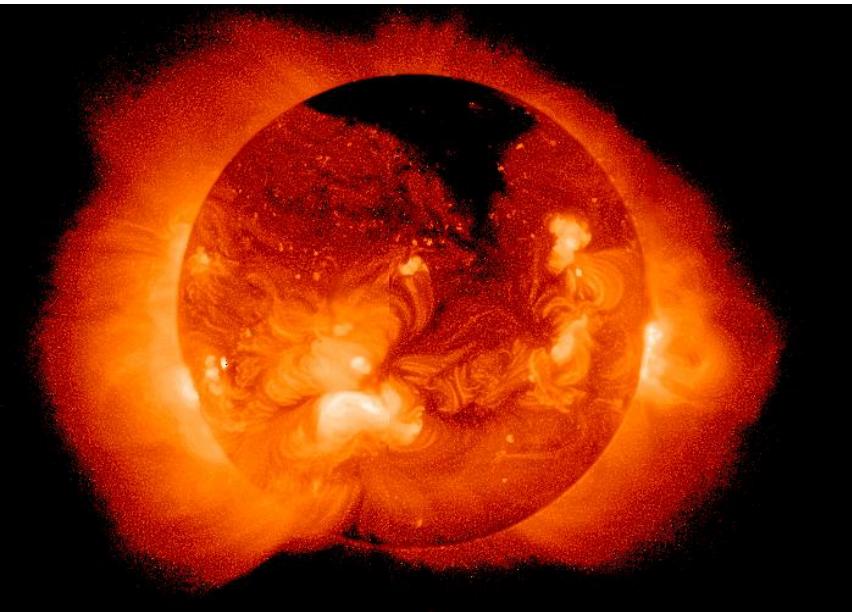
# Corona

- Pearly white corona seen during a solar eclipse or with coronagraph
- Light scattered from dust and electrons – continuum
- Spectrum taken during eclipse shows emission lines of highly ionized elements: curved=chromo & rings =corona.
- Very rarified & hot (Millions Kelvin)



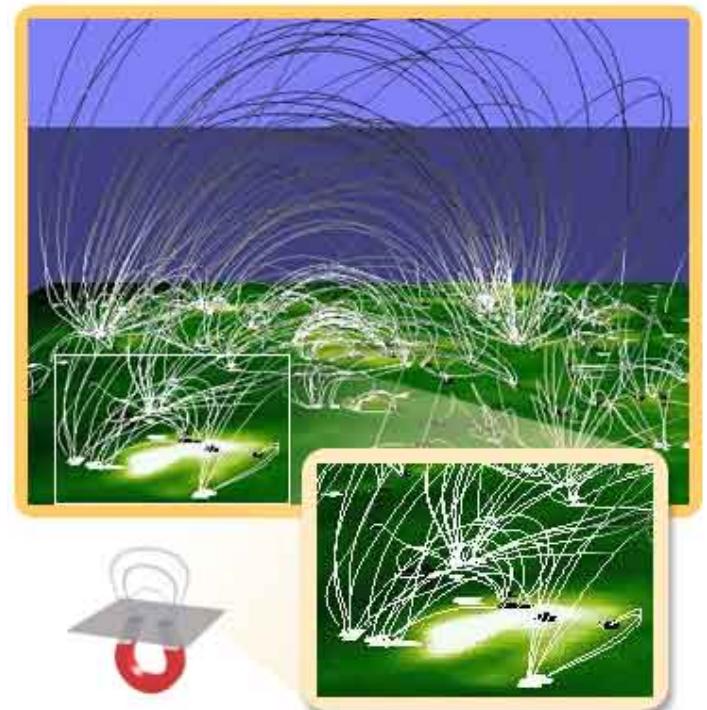
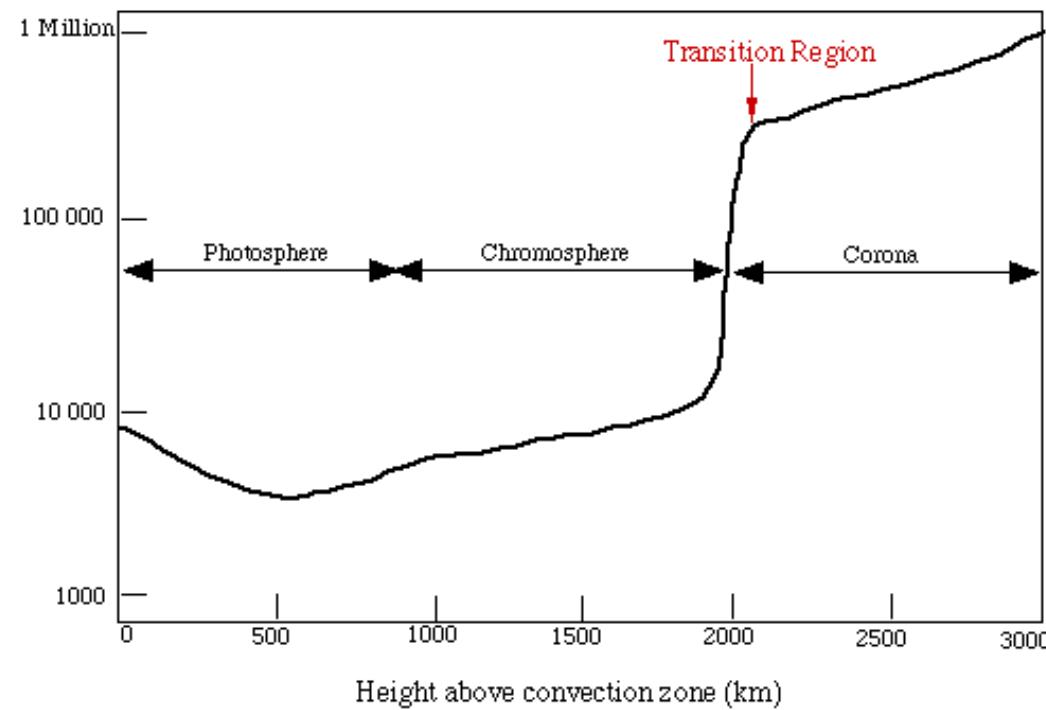
# Corona in X-rays &UV

- Photosphere relatively cool so it emits few X-rays and is dark
- Photosphere (5800 Kelvin) heats the Corona to millions Kelvin?



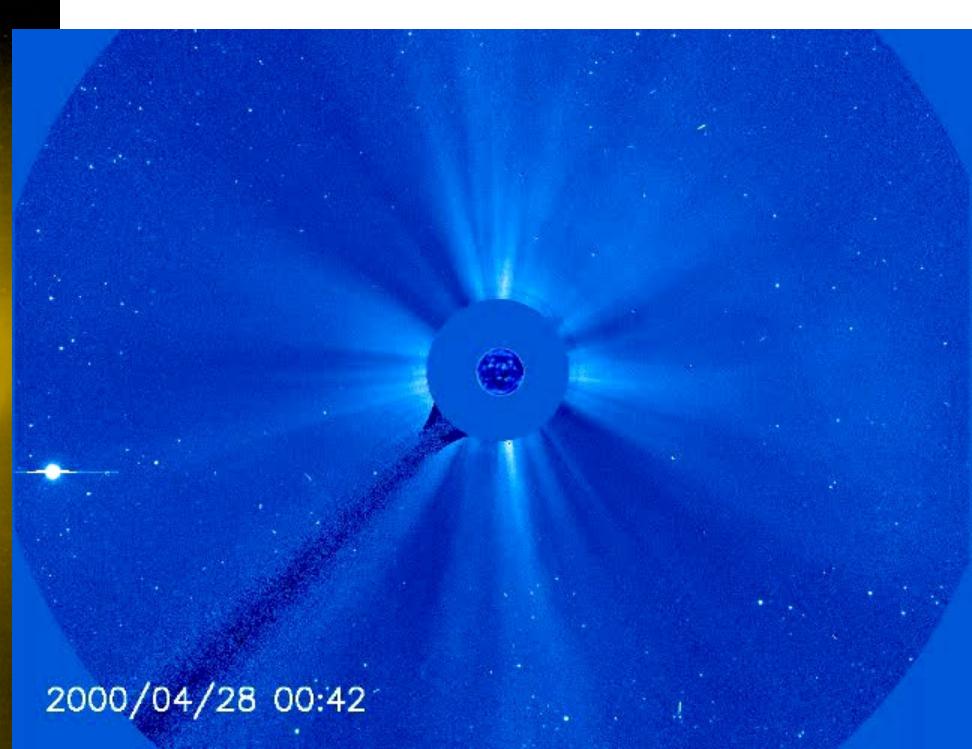
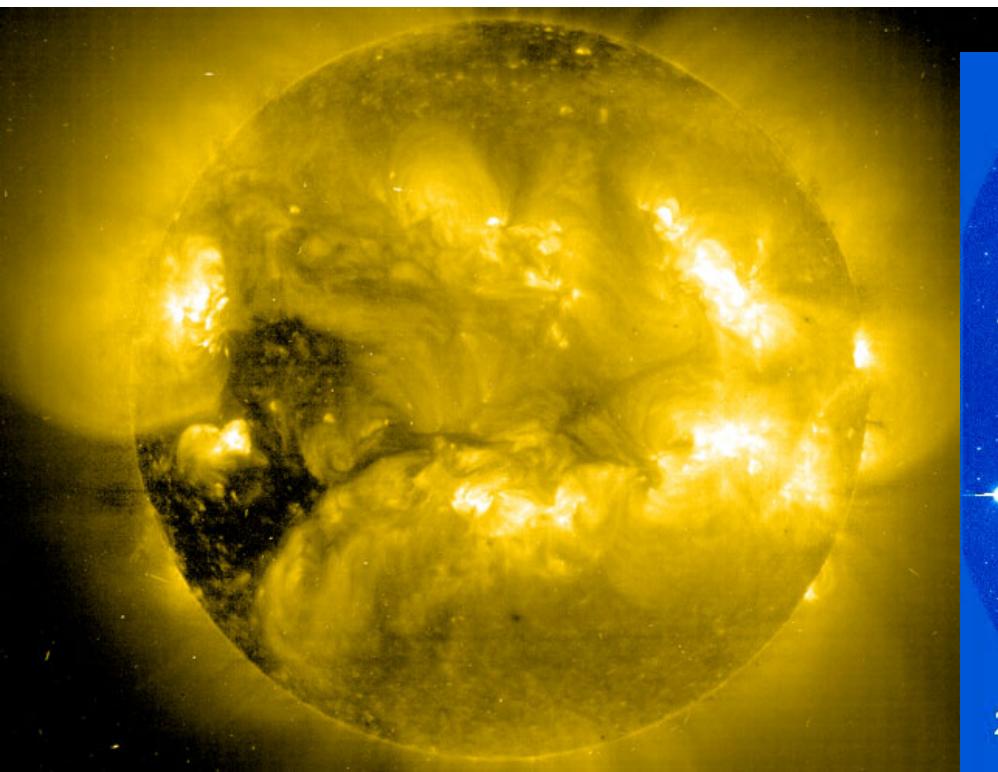
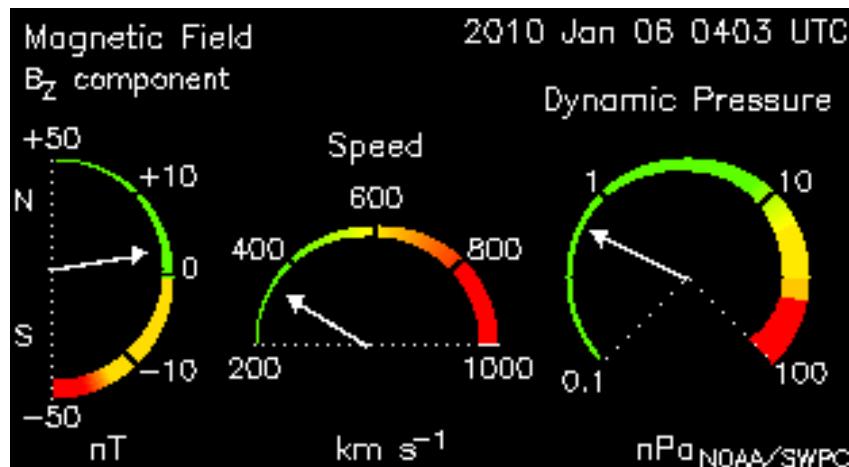
# Heating of Corona

- **Transition zone** between Chromosphere & Corona where temperature increases most quickly 10,000-1,000,000 Kelvin
- Rapid motions of Spicules or ????



# Dark Coronal Holes Emit Solar Wind

- Solar Wind speed  $\sim$ 400km/sec
- Density  $\sim$ 7 protons/cm $^3$
- Sun loses 10 million tons/year or  $10^{-14}$  solar masses

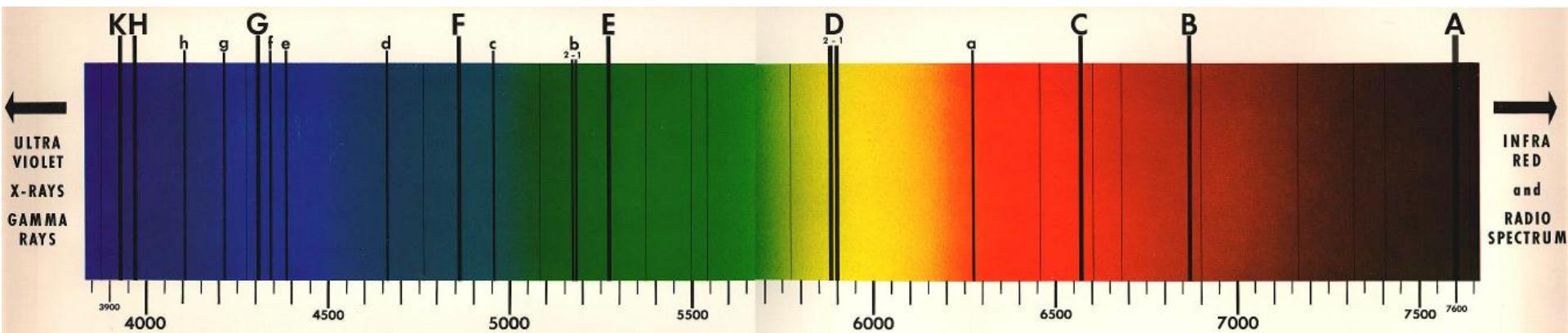


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# What is the Sun made of?



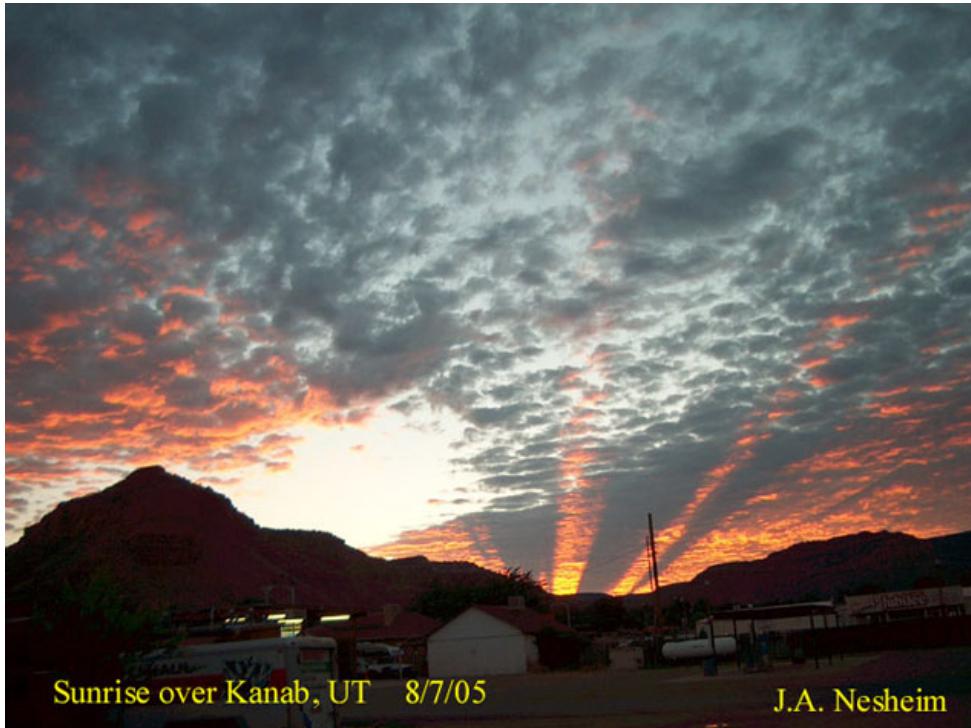
- Fraunhofer discovered dark lines in solar spectrum 1817
- D=Sodium, C&F&h=Hydrogen, H&K=Calcium
- Different elements have a different set of lines like a bar code



# Lifetime of the Sun

## How Does the Sun Generate Its Energy?

- Sun radiates  $10^{26}$  watts = Solar Luminosity
- Burning oxygen&hydrogen–18,000 years- Electromagnetic
- Gravitational potential energy – 30 million years- Gravity
- But weathering & radioactive age of rocks- billions of years

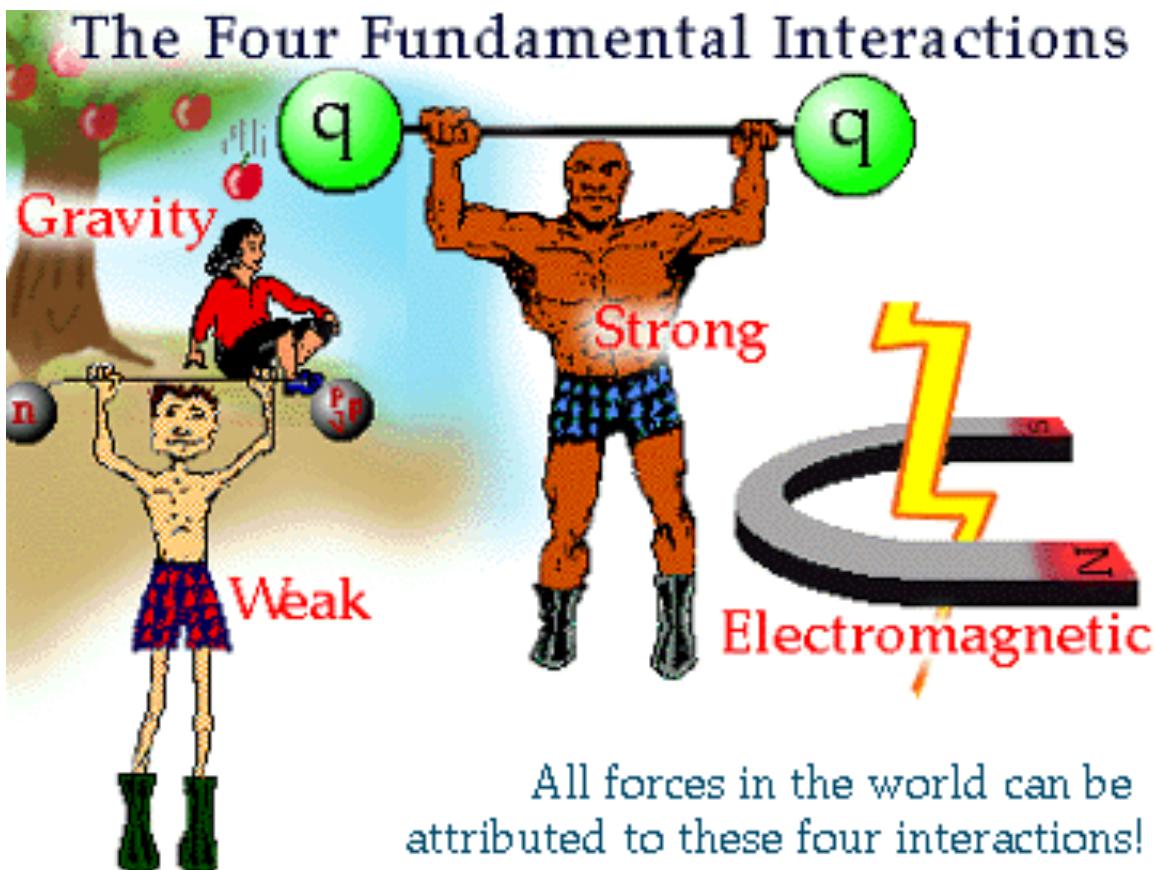


Sunrise over Kanab, UT 8/7/05

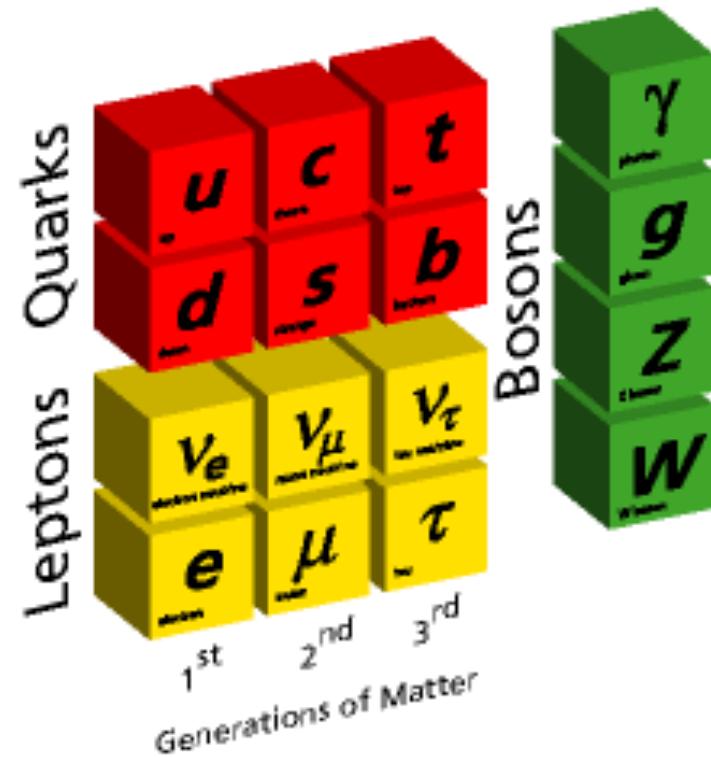
J.A. Nesheim

# Sun's Energy Source

- Nuclear (**Strong force**) is a million times the chemical (Electromagnetic force)
- Standard Model - Electromagnetic, **strong force**, **weak force**, and elementary particles, but NO gravity

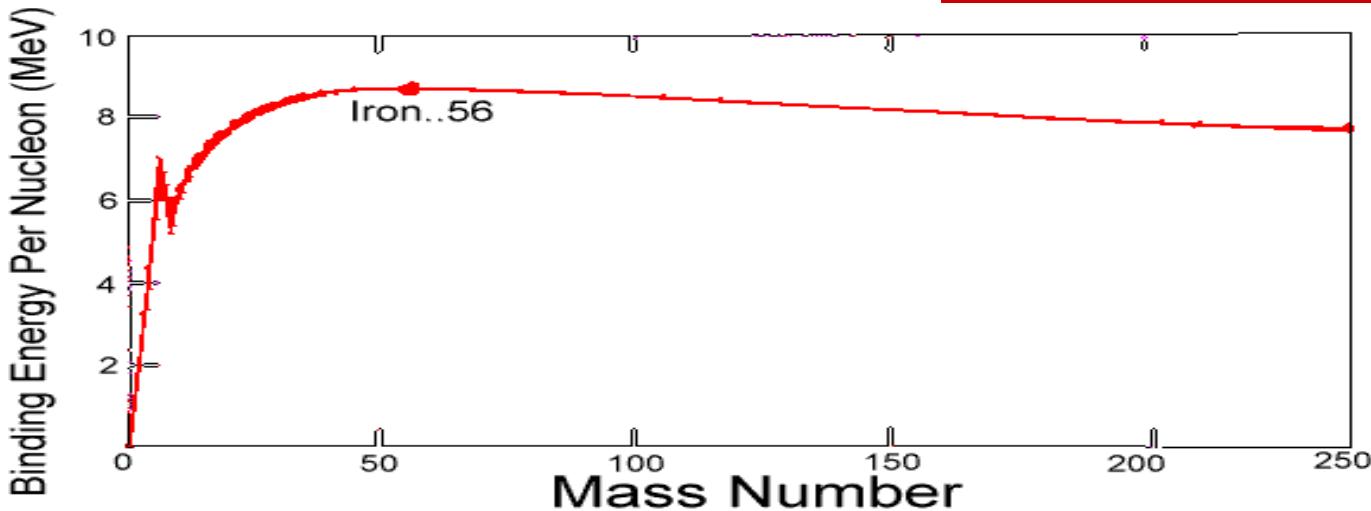
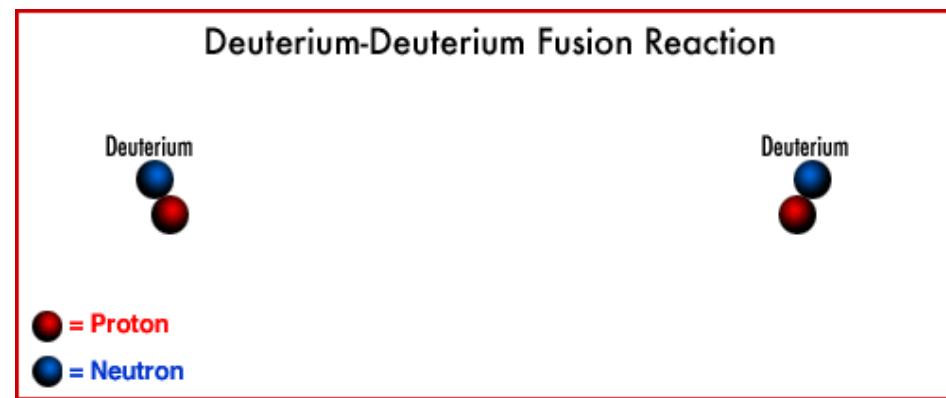
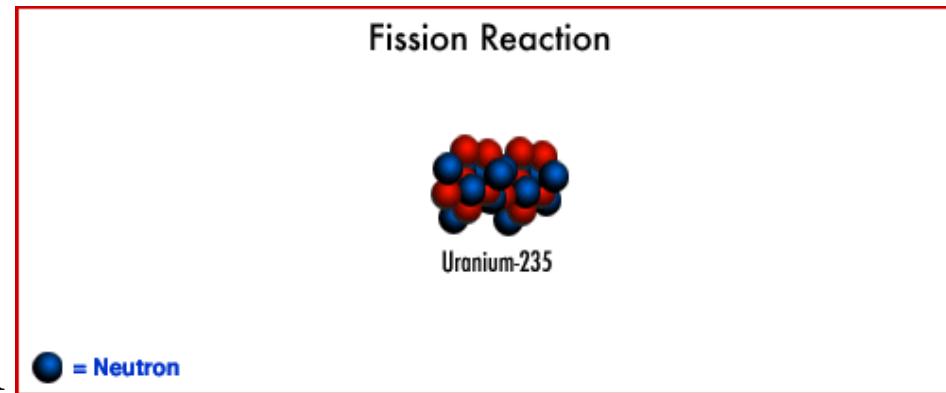


Elementary Particles



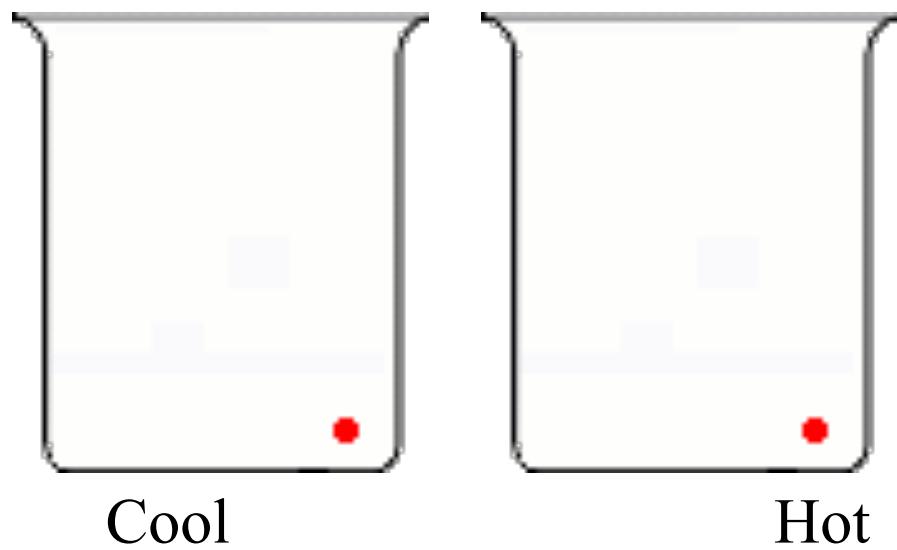
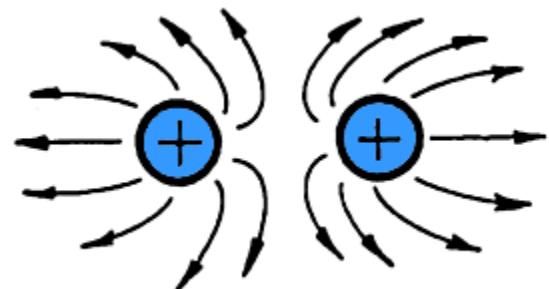
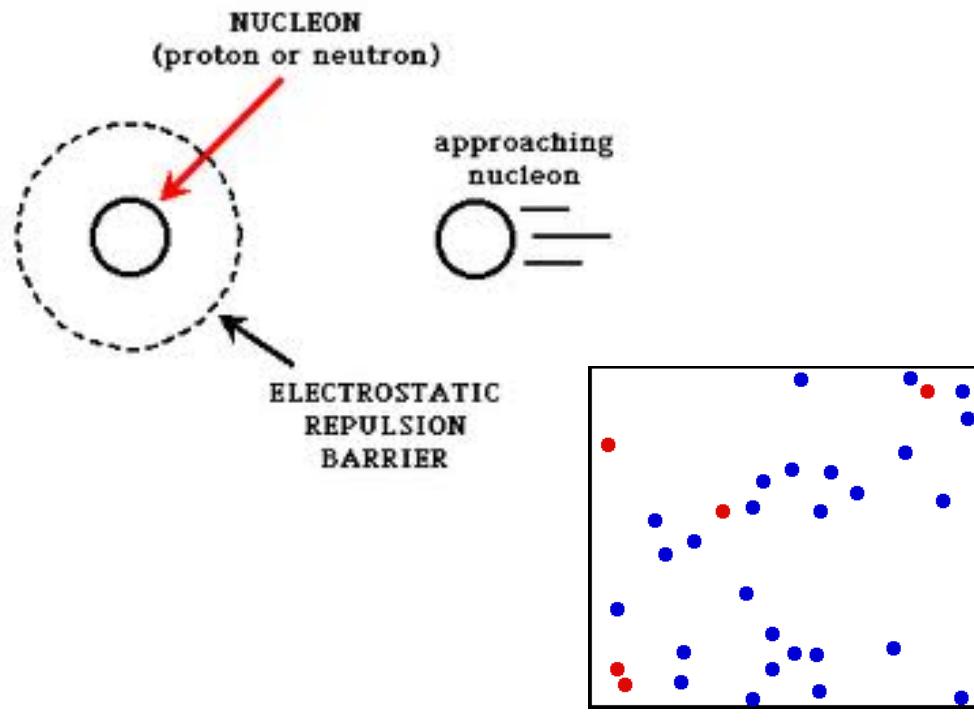
# Nuclear Fission/Fusion

- Fission produces energy by breaking up high mass nuclei



# Coulomb Barrier

- Protons repel each other since both have positive charge
- **Strong force** has a short range, but is much stronger
- Coulomb barrier overcome by temperature of Millions Kelvin



# Proton-Proton Chain

- Two protons -> **Deuteron/Deuterium+positron+neutrino**
- Then proton + deuteron produce Helium-3 + gamma ray
- Then two Helium-3 produce one Helium-4 + 2 protons

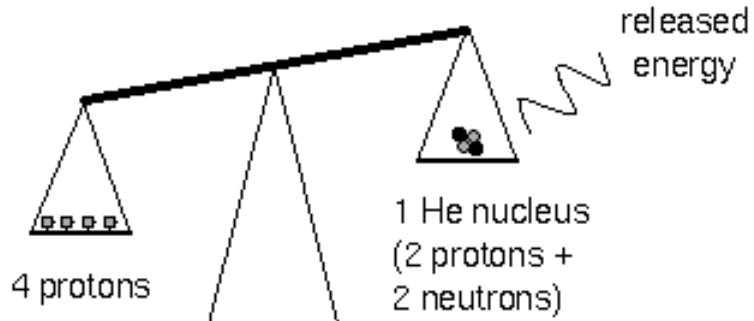
Proton-proton fusion chain process



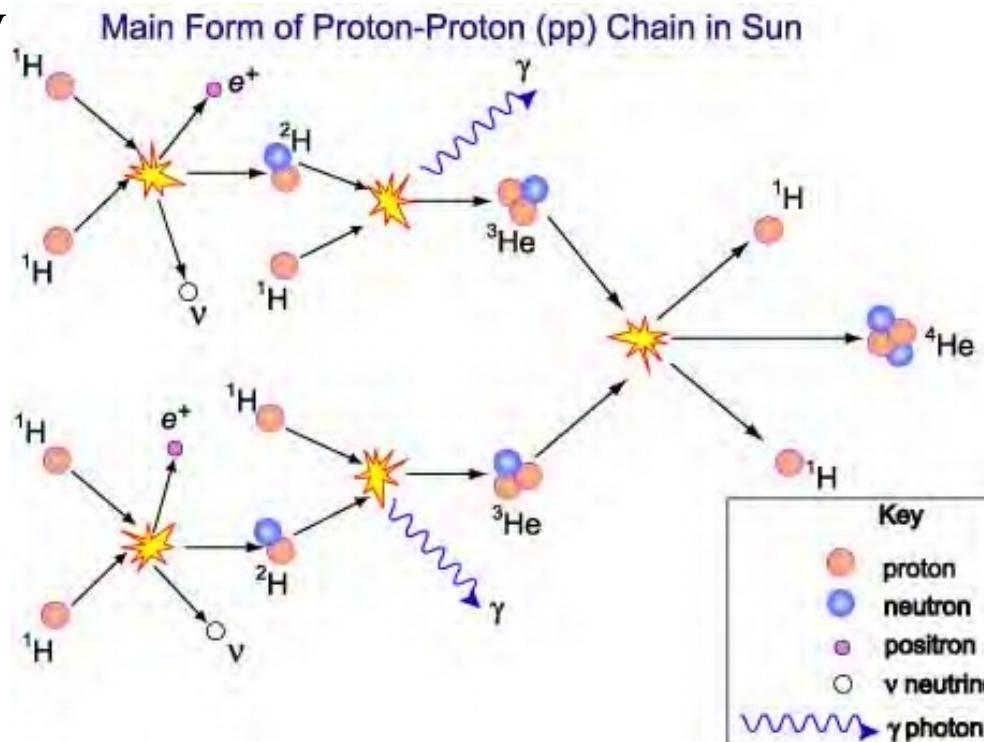
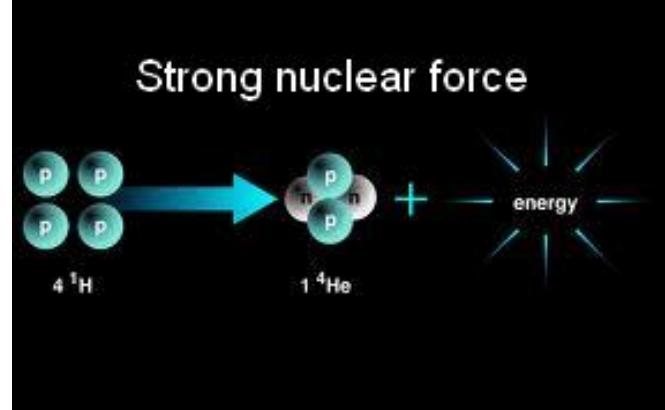
1st step: In two separate reactions, 2 protons in each reaction fuse

# Law of Conservation of Mass and Energy

- 4 protons have more mass than 1 Helium
- 0.7% of input mass ( $m$ ) becomes energy ( $E$ )
- $E=mc^2$  **Mass Energy Equivalence**
- Per second sun converts 600million tons of Hydrogen into Helium
- 4 million tons of mass to energy



Some mass is converted into energy ( $E=mc^2$ )

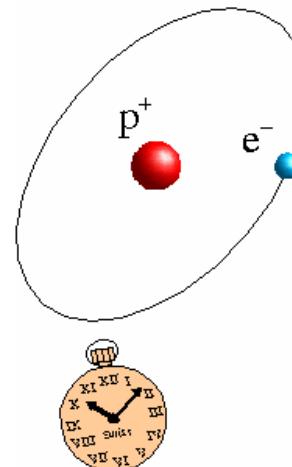


# Antimatter

- Each subatomic particle has an **antiparticle**
- Antielectron is called a **Positron**
- When a particle meets its antiparticle they annihilate
- Producing only energy = gamma rays  $E=mc^2$
- Lucky for us the universe seems to be all matter!??



Hydrogen

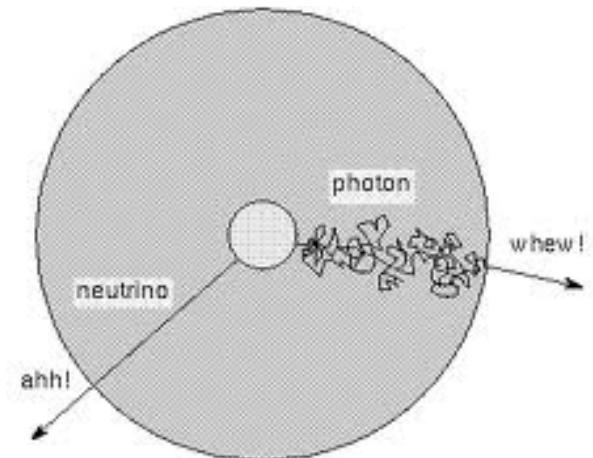


Antihydrogen



# Solar Neutrino Problem

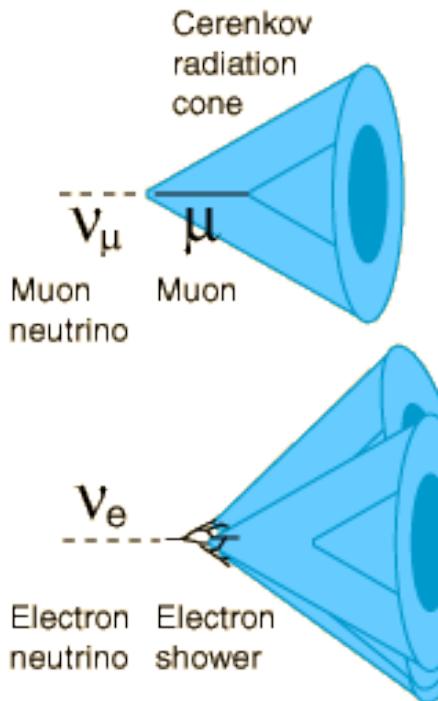
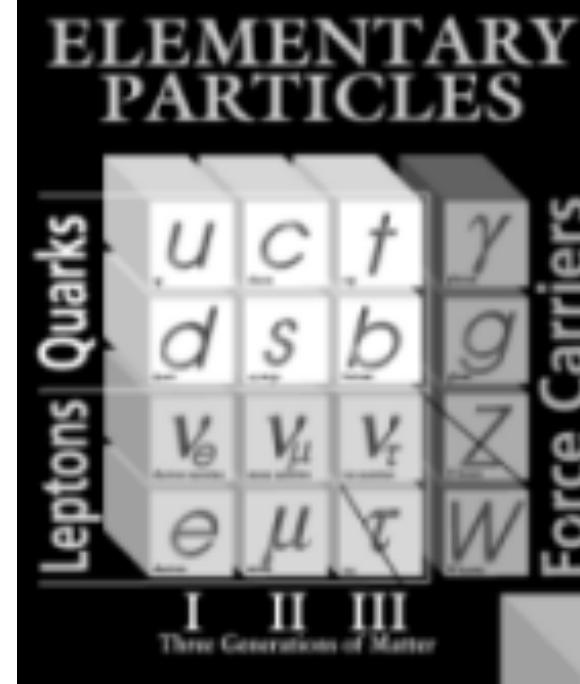
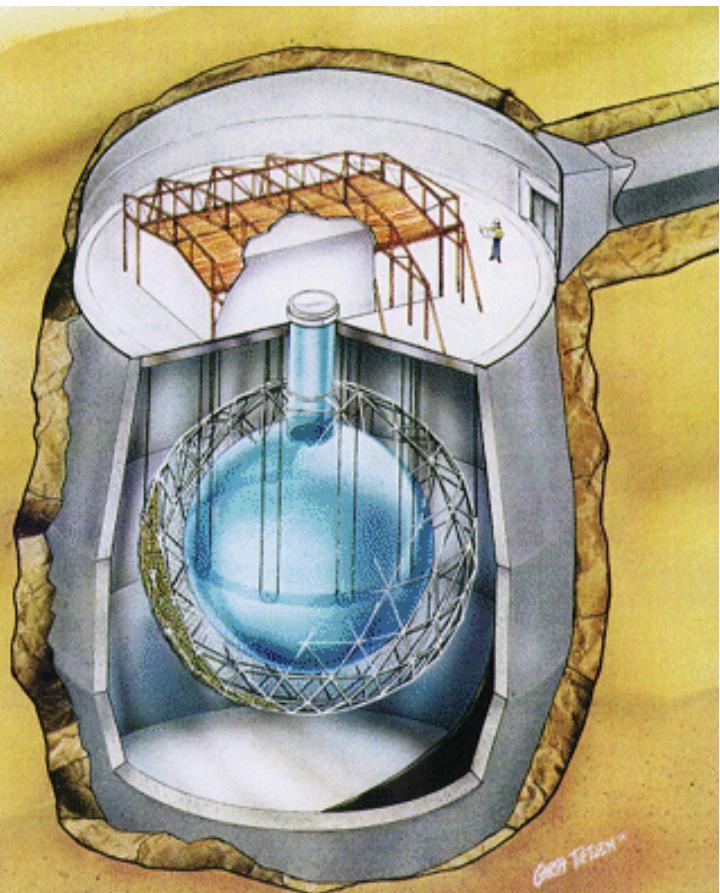
- **Neutrino** is subatomic particle associated with the Weak Force
- Average neutrino not stopped by a light year of lead
- First Neutrino detectors only found a third of the expected number
- Problem with sun?, neutrino detector?, neutrinos?
- Ray Davis won Noble Prize in 2002



Photons take tortuous paths out of the Sun's interior.  
Neutrinos pass right on through in just two seconds.

# Sudbury Solar Neutrino Observatory

- Neutrinos “oscillate” from electron to muon to tau type



The Cerenkov radiation from a muon produced by a muon neutrino event yields a well defined circular ring in the photomultiplier detector bank.

The Cerenkov radiation from the electron shower produced by an electron neutrino event produces multiple cones and therefore a diffuse ring in the detector array.

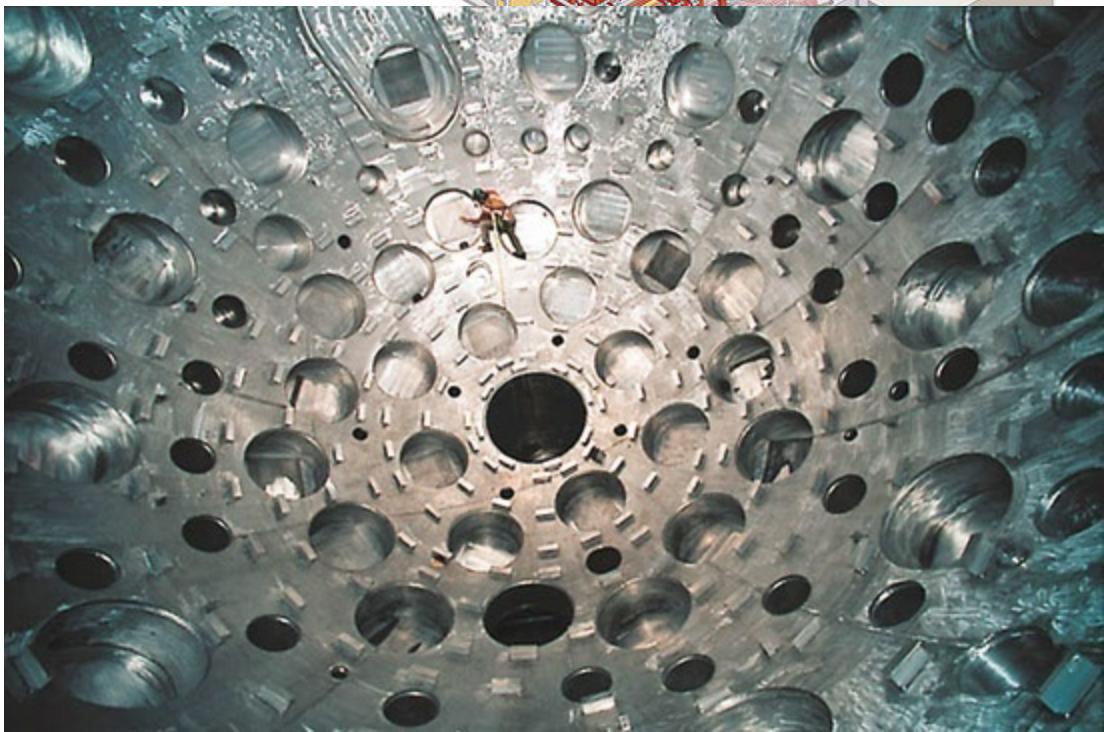
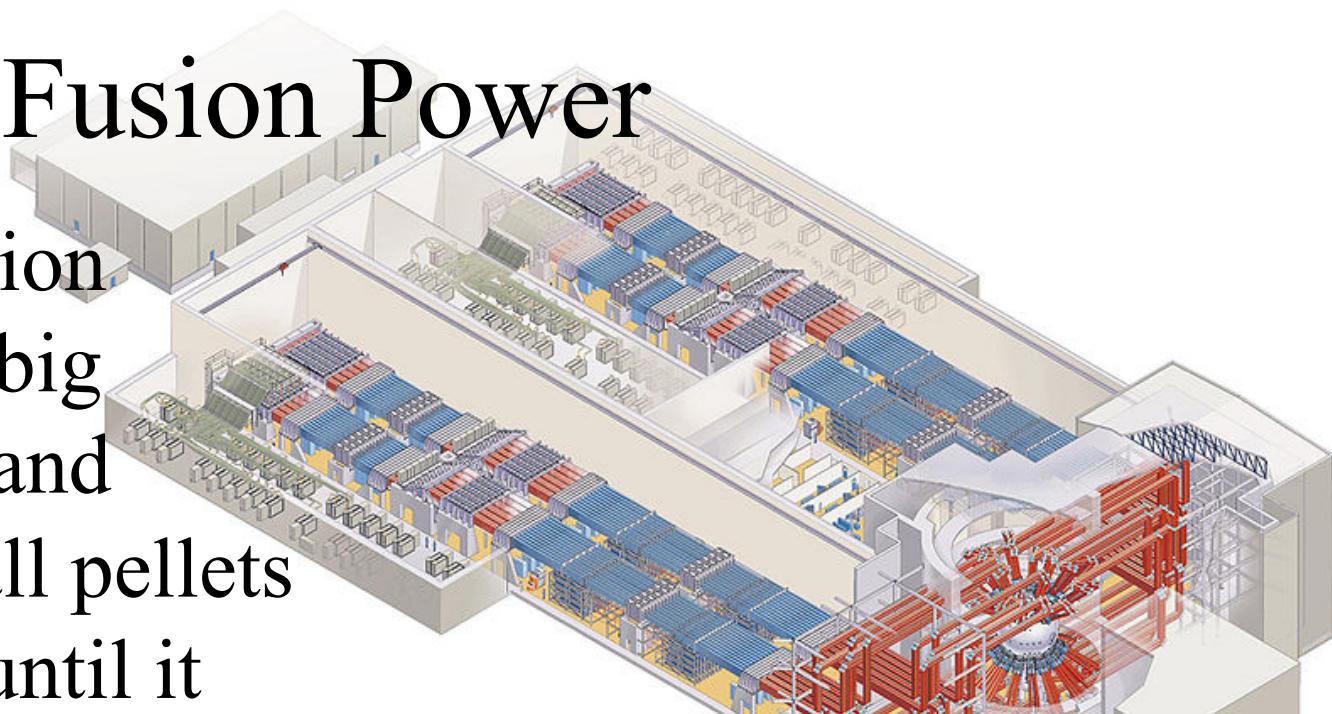
# Hydrogen Fusion Bombs

- Largest bomb USA made:  
15 Megaton Bikini Atoll =  
Castle Bravo blast 1954
- Largest Fusion Bomb =  
Tsar Bomb 50Megatons 1961



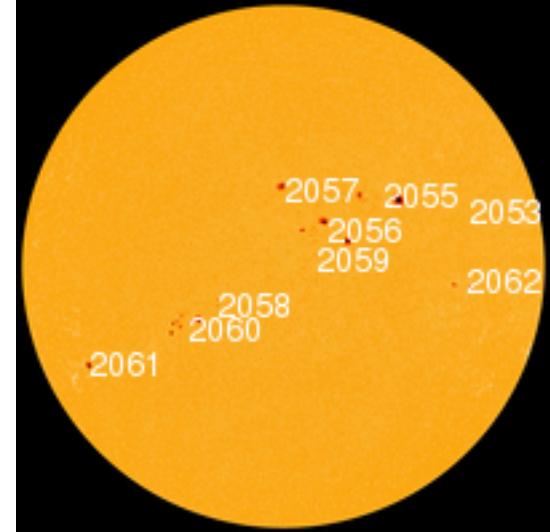
# Hydrogen Fusion Power

- National Ignition Facility uses big lasers to heat and compress small pellets of Hydrogen until it fuses, producing energy

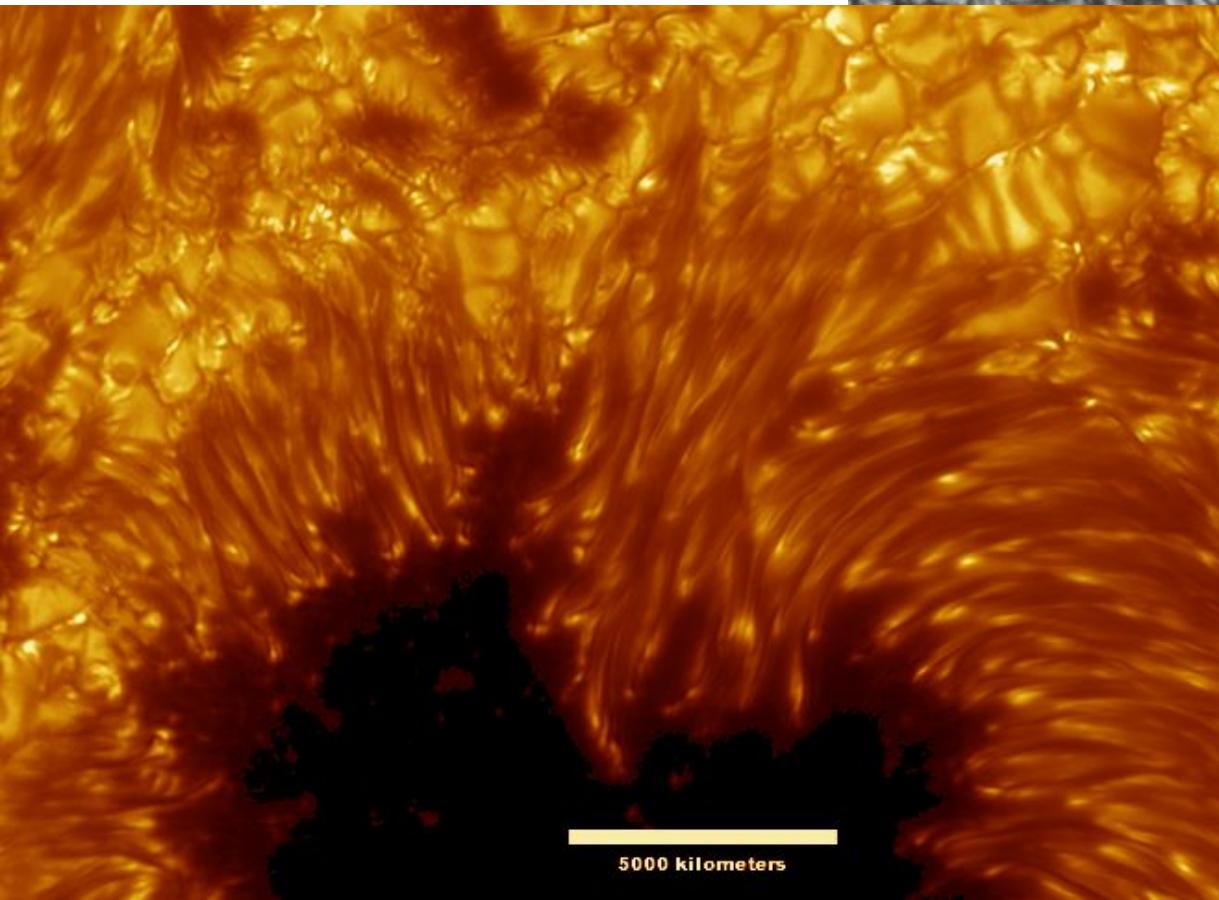


# Sunspots

- Sun rotates in a month
- Small spots last days: Big spots ~a month
- Group of spots is called an active region



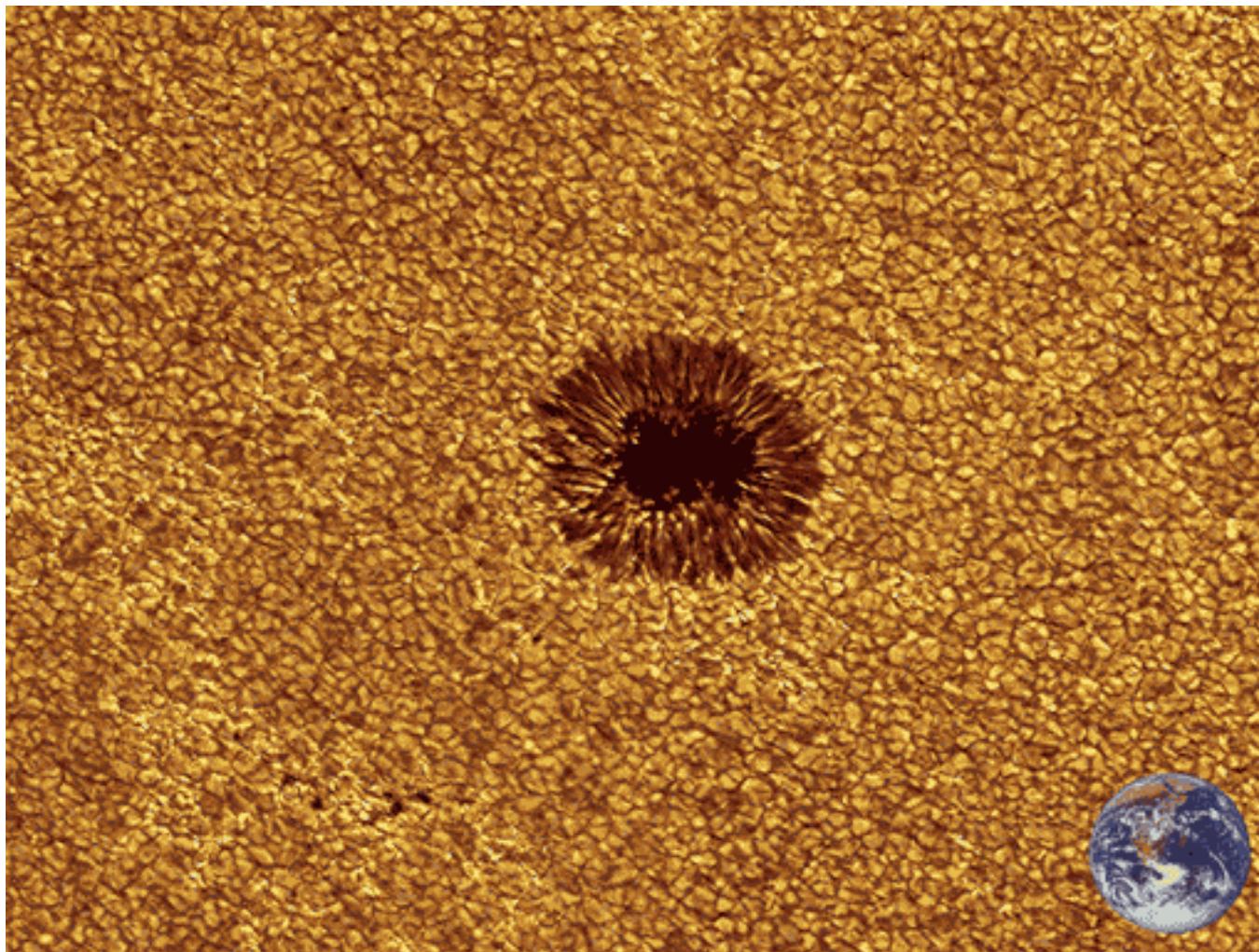
# Sunspots Are Cooler Regions



- Dark central region called **umbra**  
Temp~4500K
- Grey surrounding region is **penumbra**  
Temp~5500K

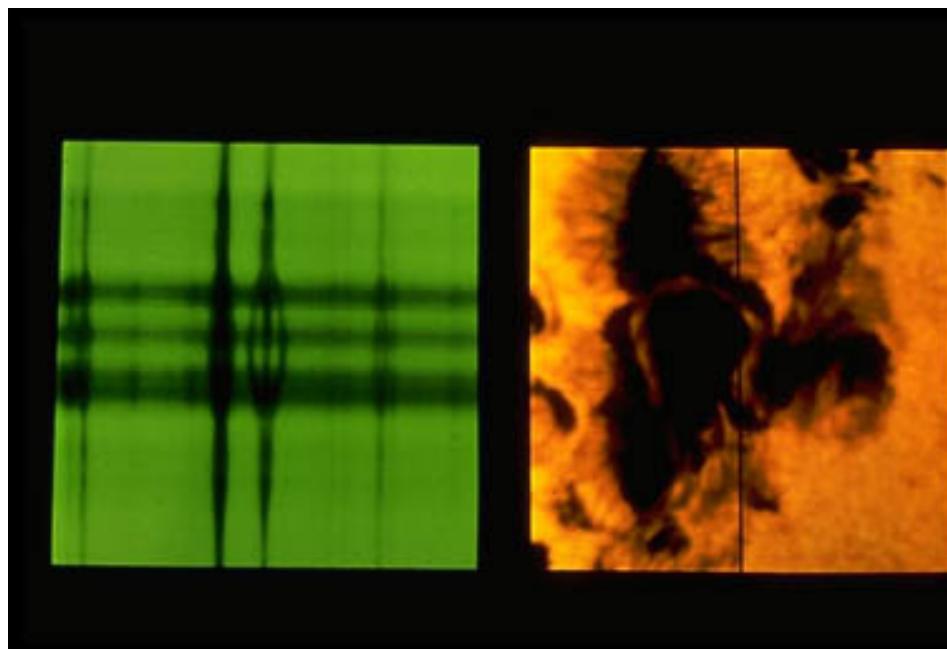
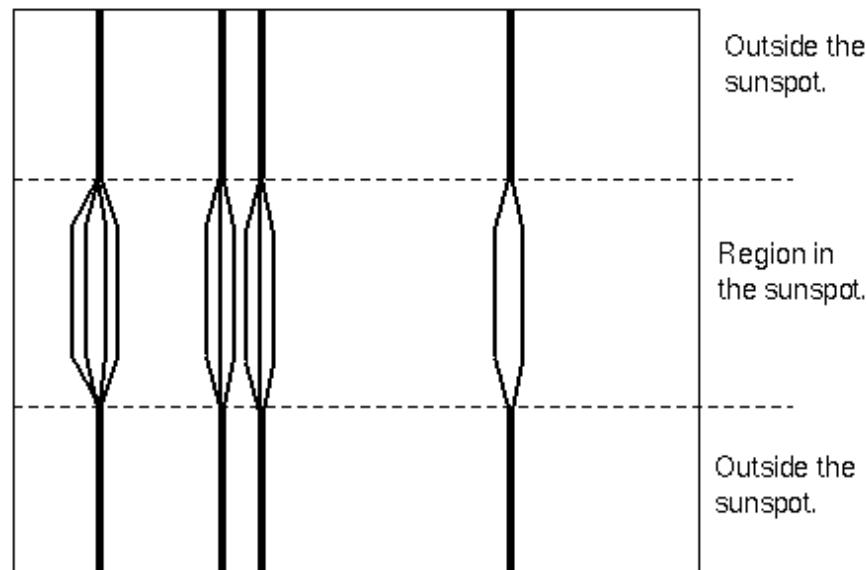
# Sunspots the Size of the Earth

- From photosphere to a few hundred kilometers to chromosphere at few thousand km.



# Sunspots Caused by Magnetic Field

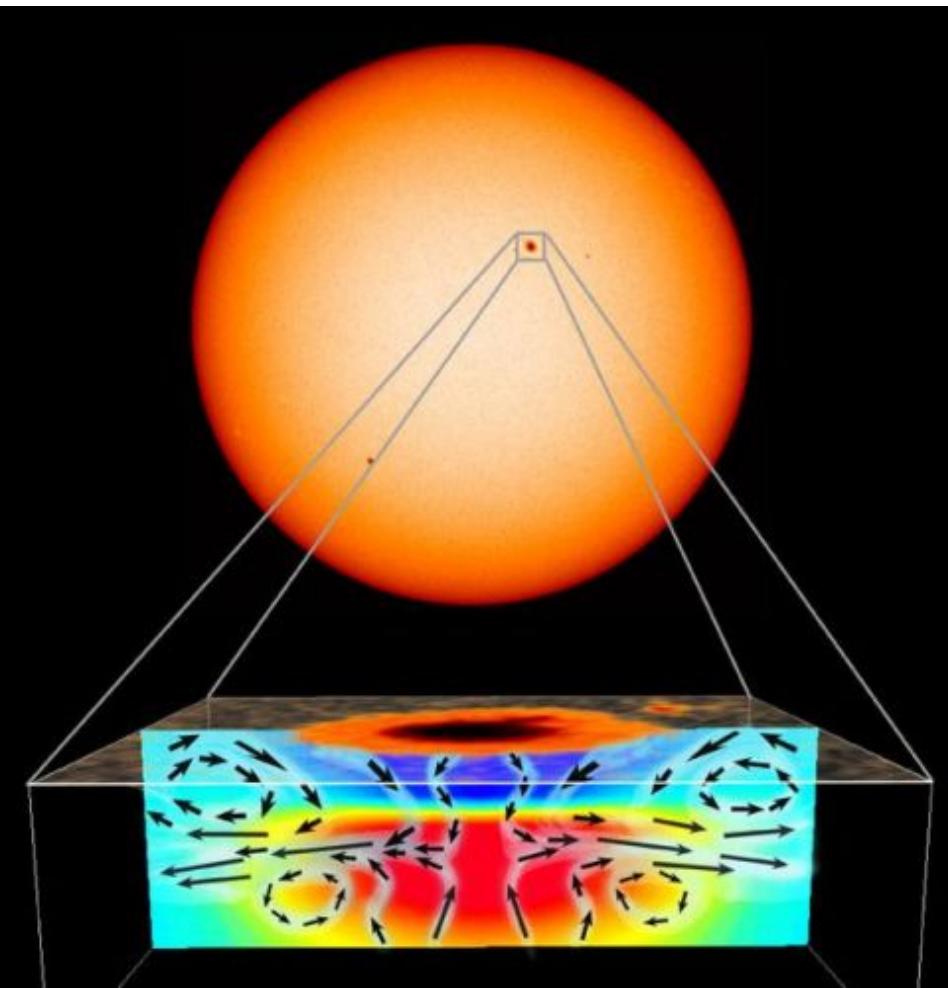
- Magnetic fields can be detected by **Zeeman effect**
- Sunspots have magnetic field 1000 times Sun's average field, which is several times Earth's magnetic field



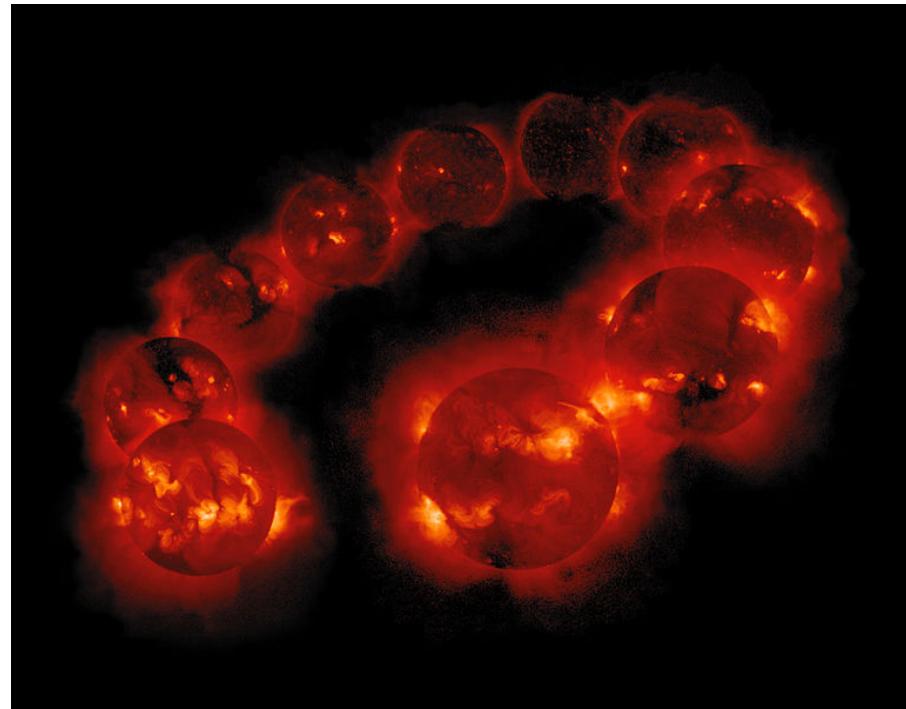
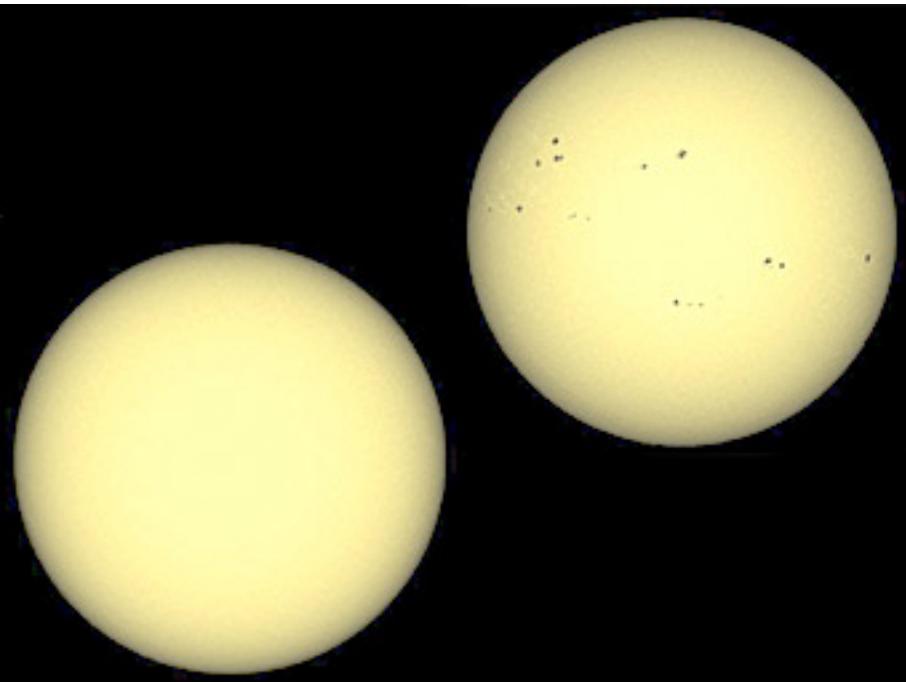
The Zeeman effect: a strong magnetic field splits the spectral lines into two or more components. The strength of the magnetic field can be measured from the amount of separation of the components. Sunspots are regions of strong magnetic fields.

# Under A Sunspot

- Spots are cooler due to deceased circulation
- Energy blocked by strong magnetic fields

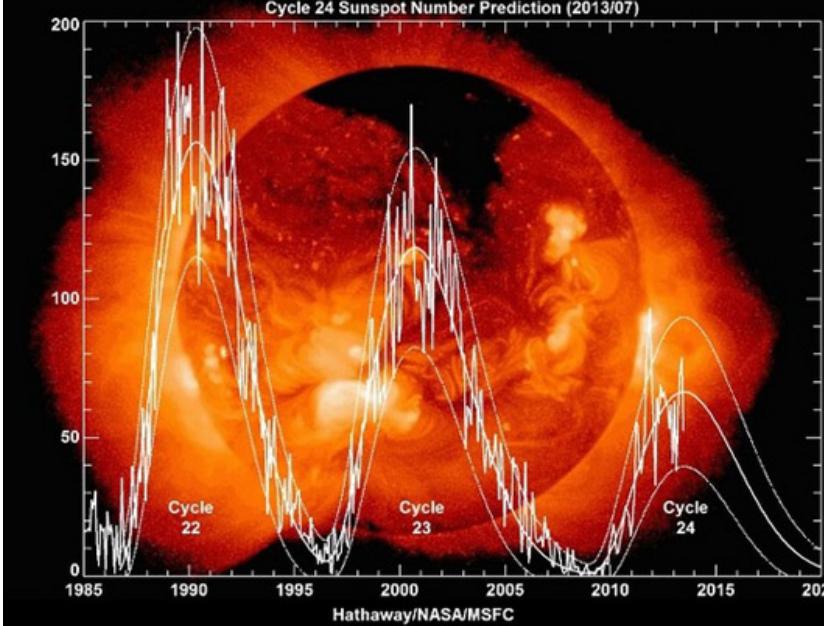


# Number of Sunspots Varies

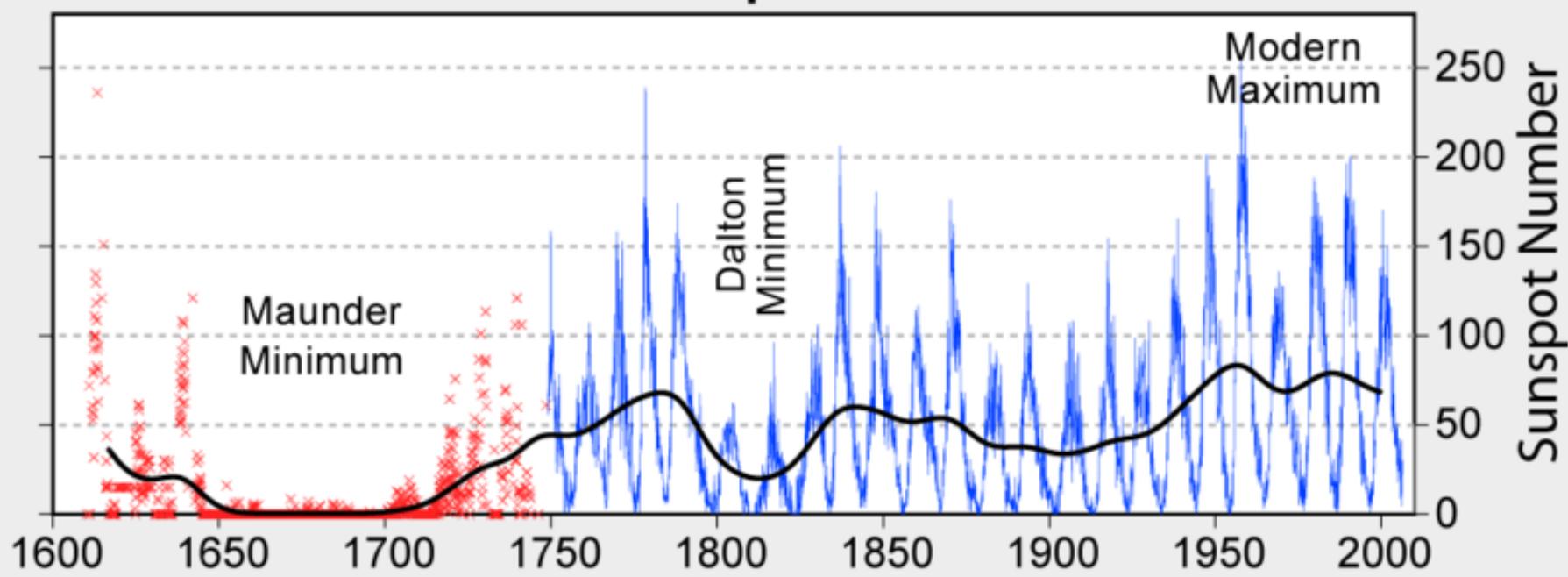


# Sunspot Cycle

- More sunspots at maximum & sometimes none at minimum
- In 1843 Schwabe discovered that the number of spots varies with 11 year cycle

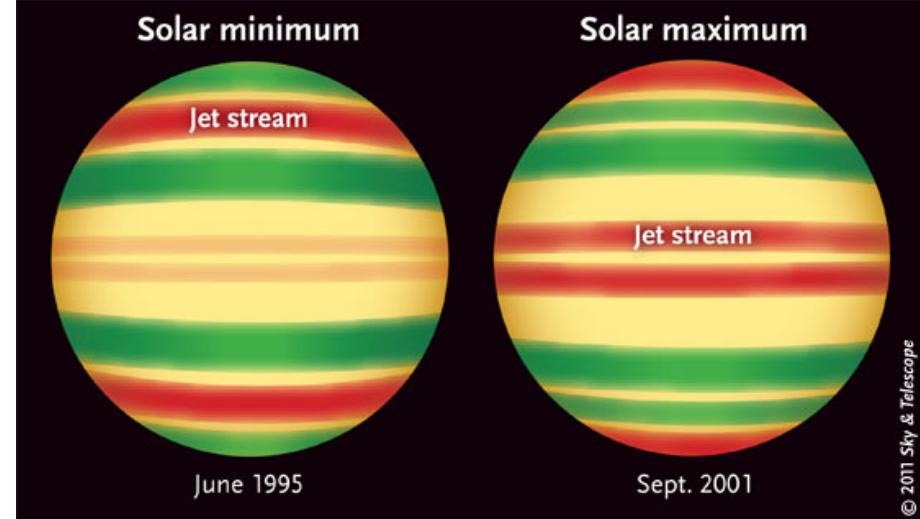


## 400 Years of Sunspot Observations

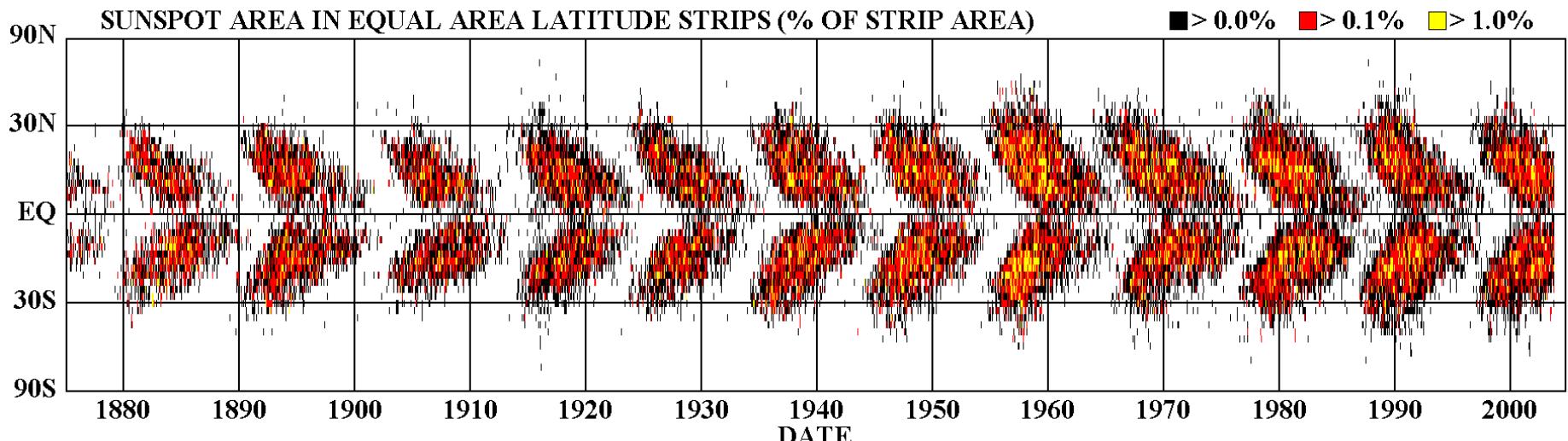


# Maunder Butterfly Diagram

- Spots first appear at  $35^\circ$  N/S
- Later spots appear closer to equator
- Spots from new cycle can overlap with old cycle



DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS

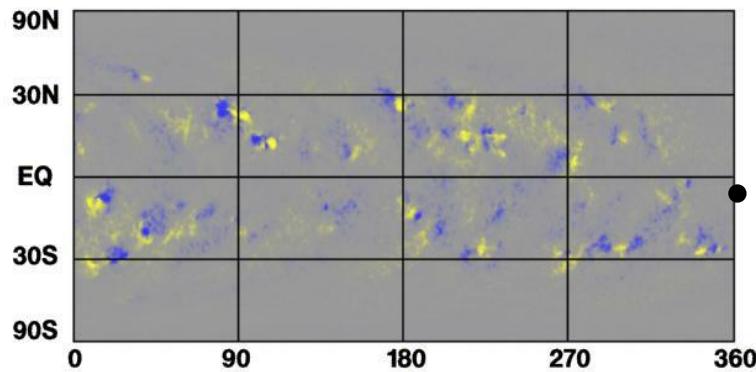


# Magnetic Polarity of Sunspots

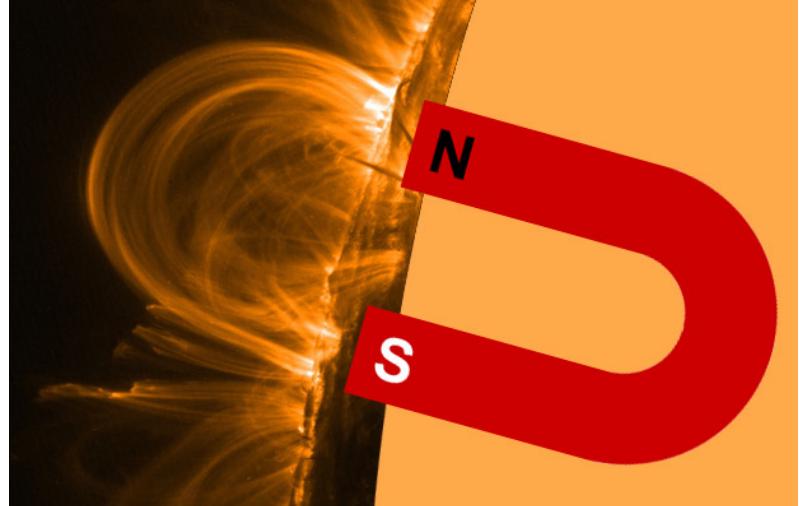
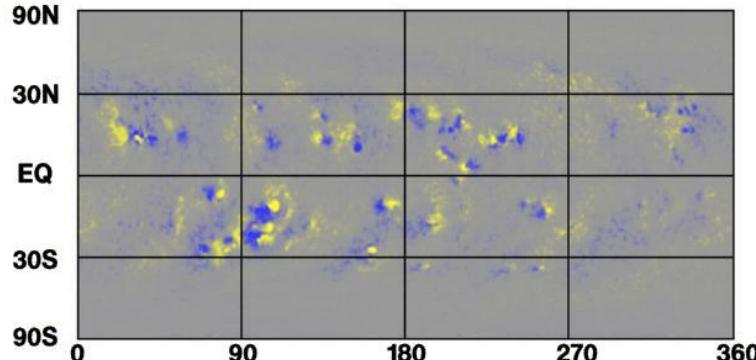
## Hale's Polarity Law:

The polarity of the leading spots in one hemisphere is opposite that of the leading spots in the other hemisphere and the polarities reverse from one cycle to the next.

Cycle 21



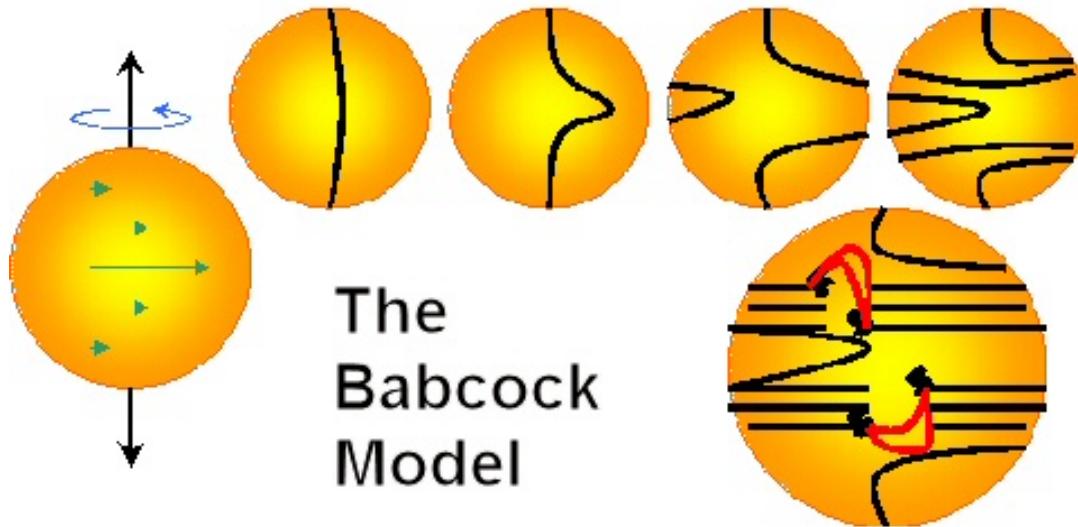
Cycle 22



- If leading spot is North pole then trailing spot will be South polarity
- Opposite polarity in other hemisphere
- Global field reverses after 11 year sunspot cycle making the **Solar Cycle 22** years long

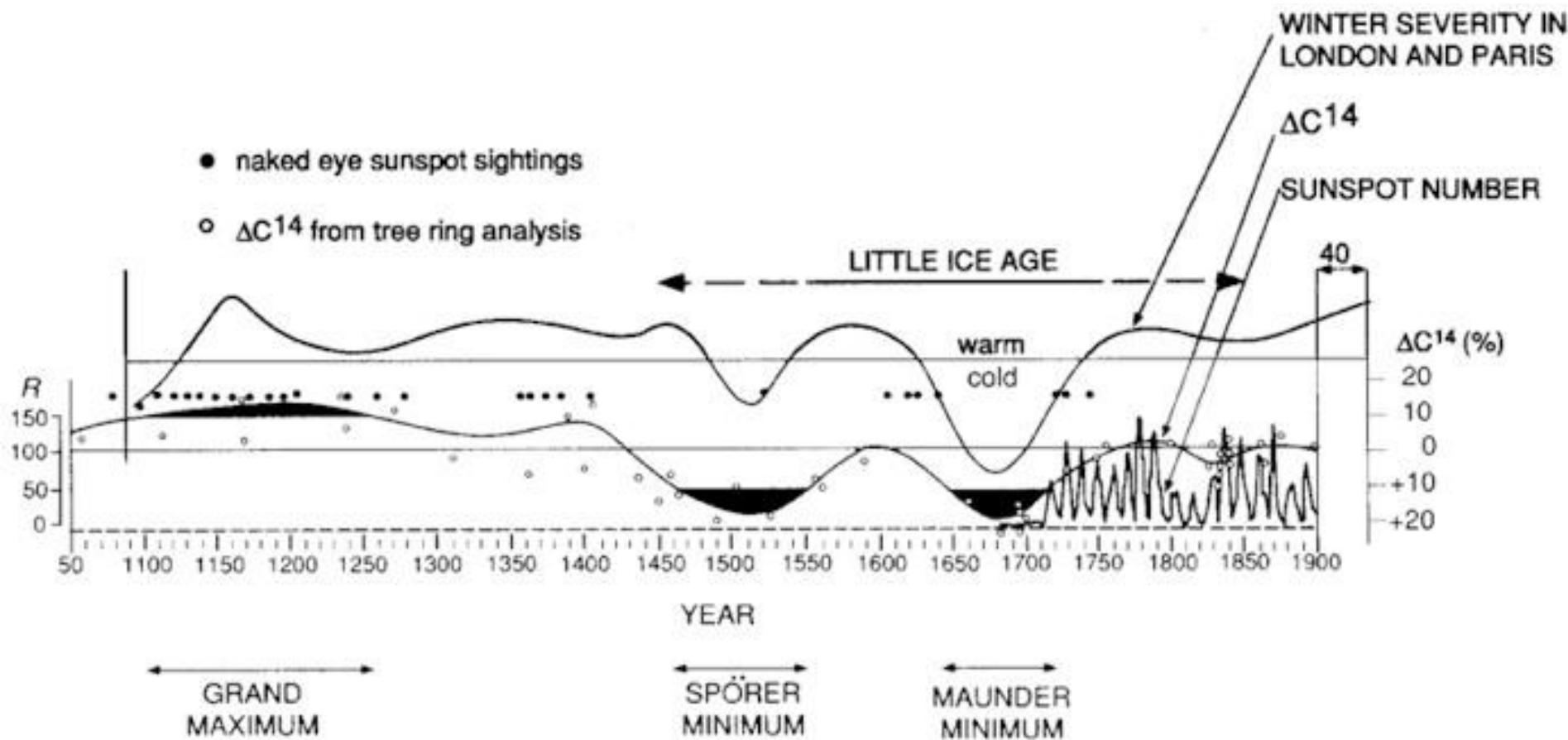
# Babcock Model

- Sun Rotates faster at equator and slower at poles = Differential rotation
- Winds up field lines, which then loop through photosphere making a pair of spots
- Spots appear closer to equator during cycle
- Overall field reverses with 22 year **Solar Cycle**



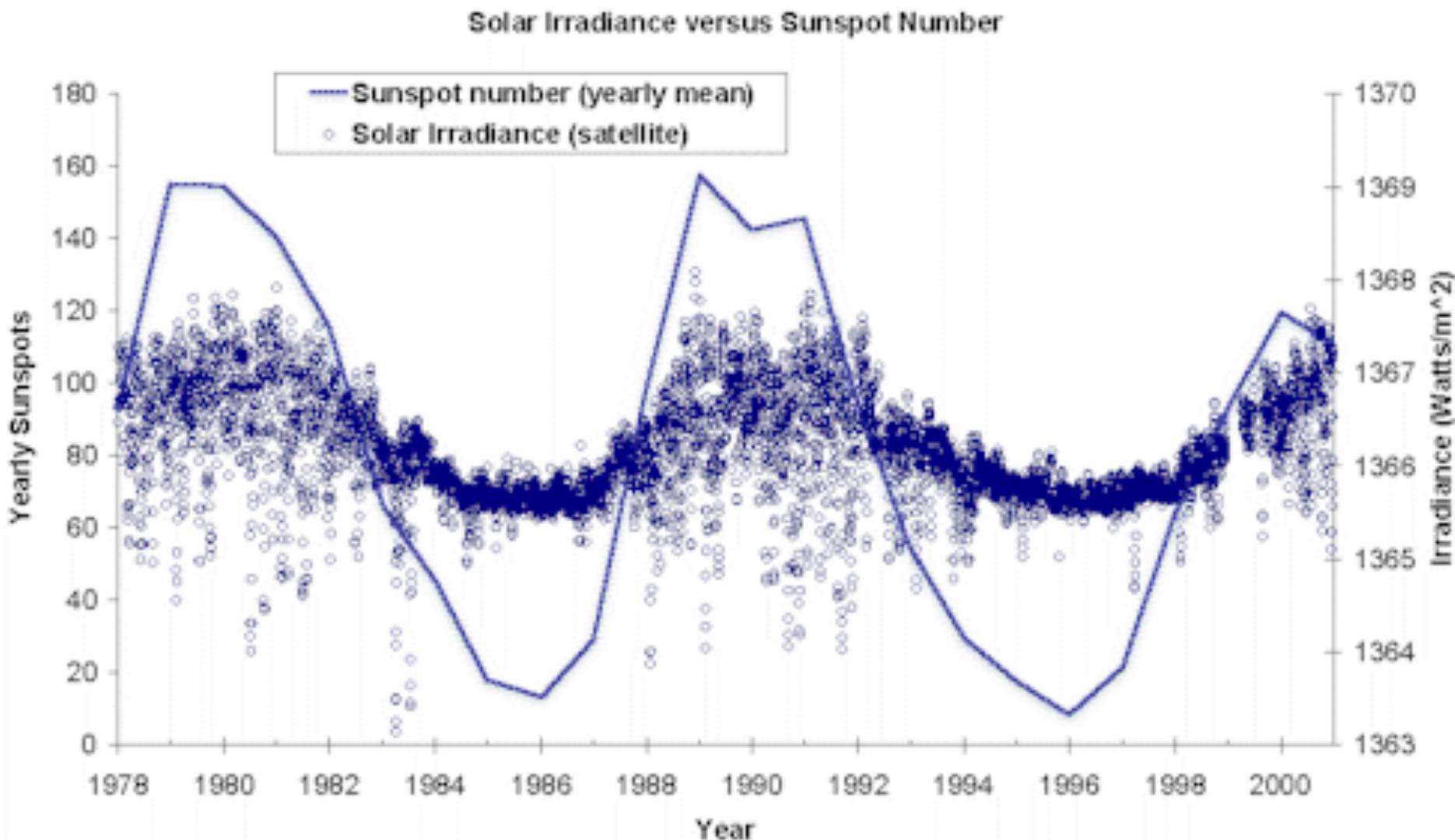
# Is the Solar Constant Constant?

- Lack of sunspots: 1645-1715 called **Maunder Minimum**
- Coincides with Little Ice Age

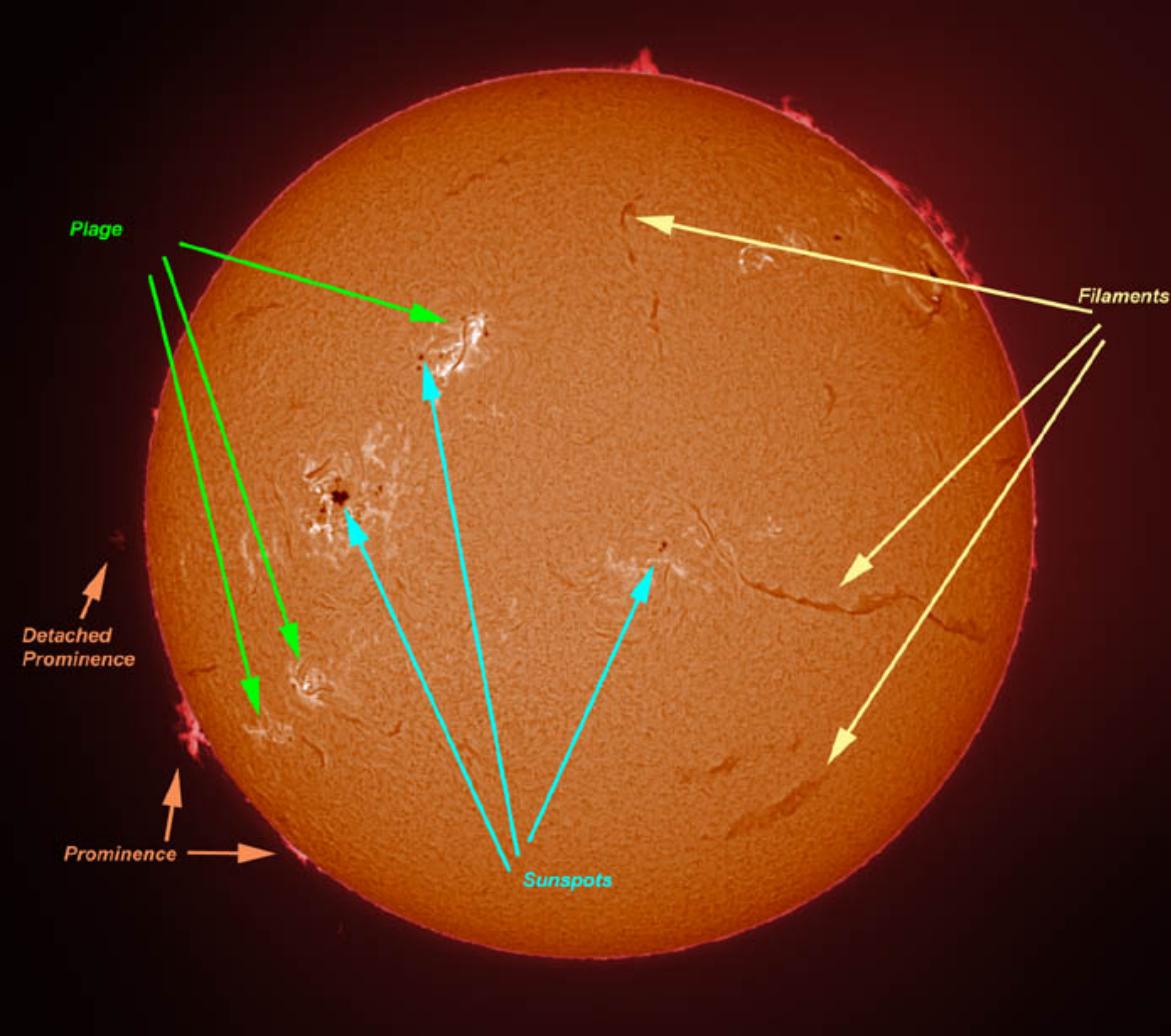


# Solar ‘Constant’ / Sunspot Number

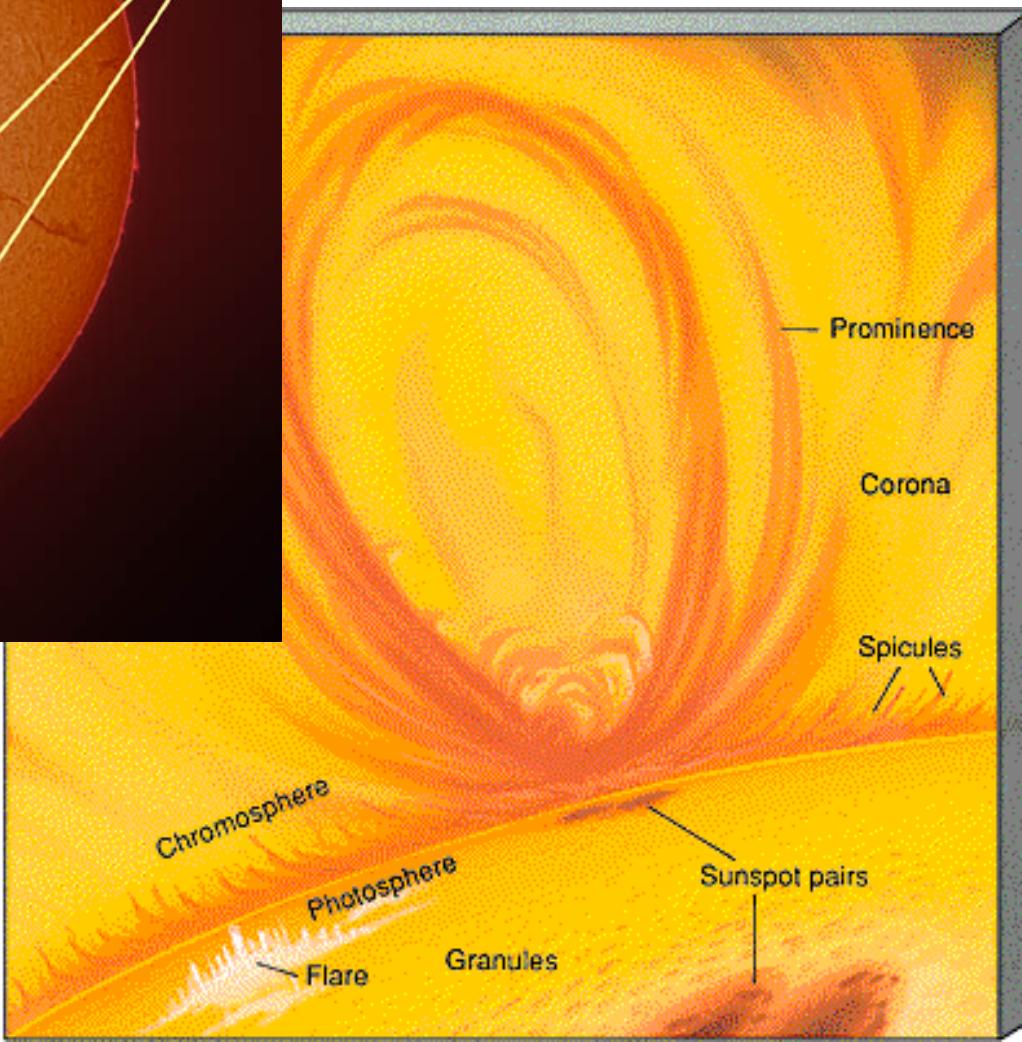
- Change of ~3% in solar constant would start an ice age



# The Active Sun

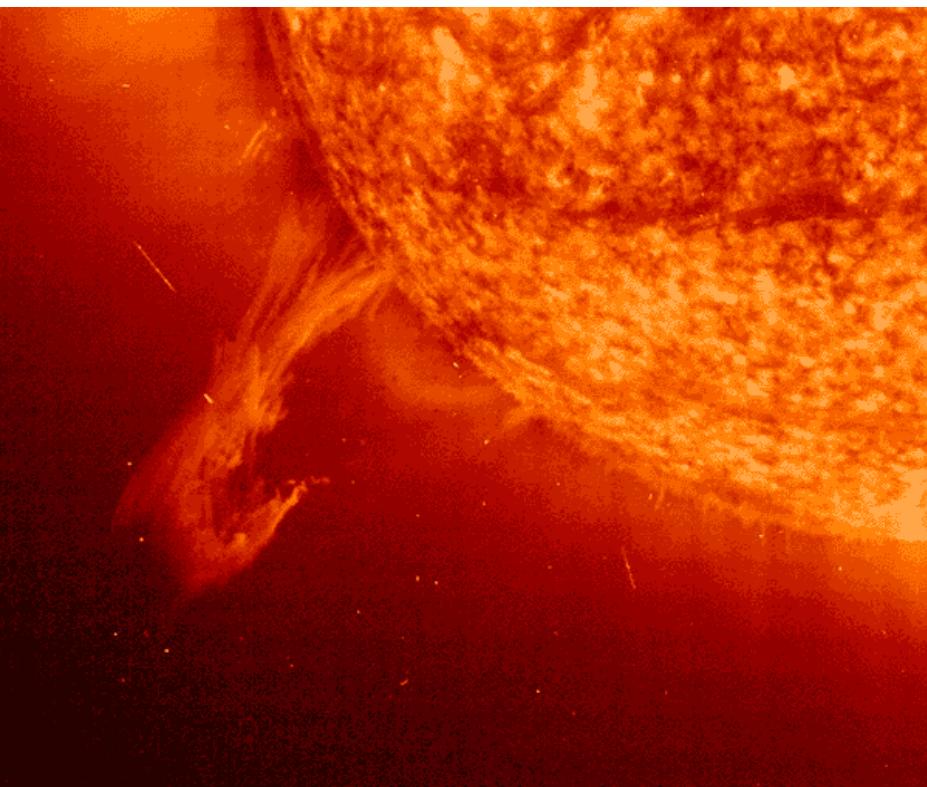


- Active regions: sunspots, prominences, flares, coronal mass ejections



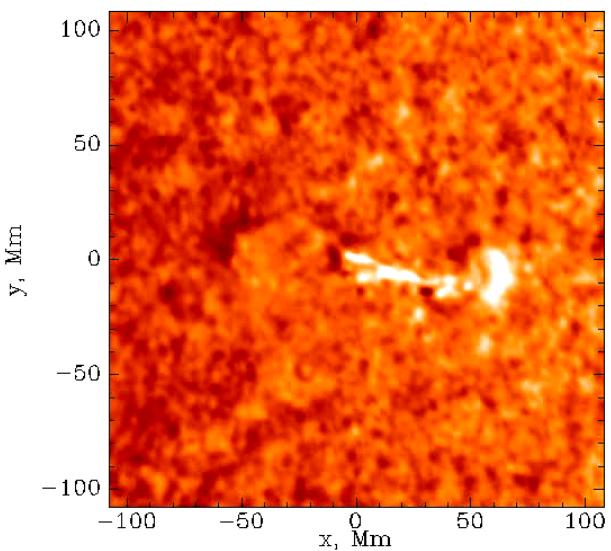
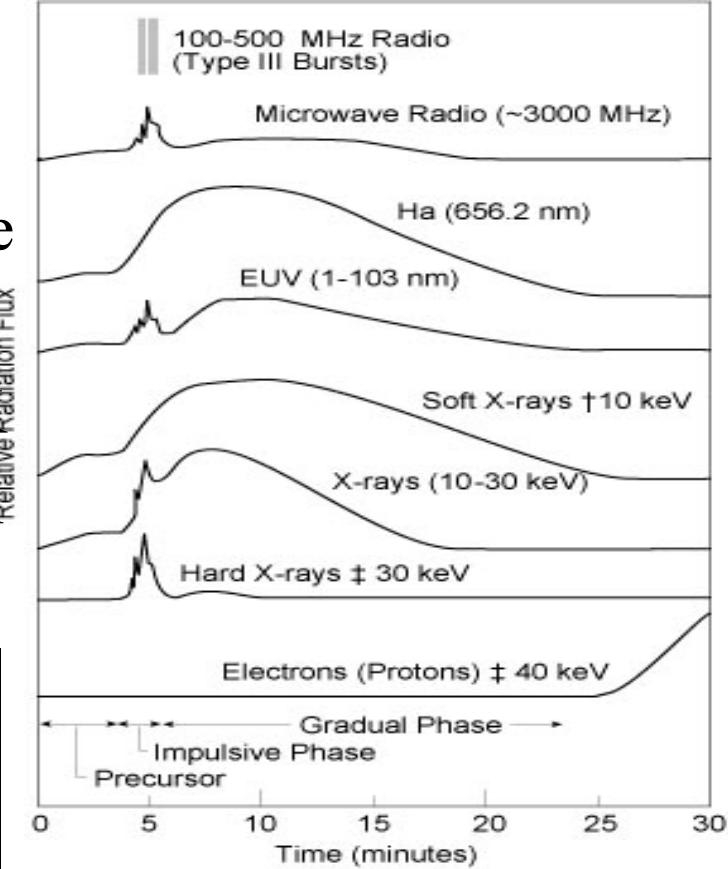
# Prominences

- Magnetically confined gas
- Quiescent prominence can last weeks
- Active prominence changes in hours



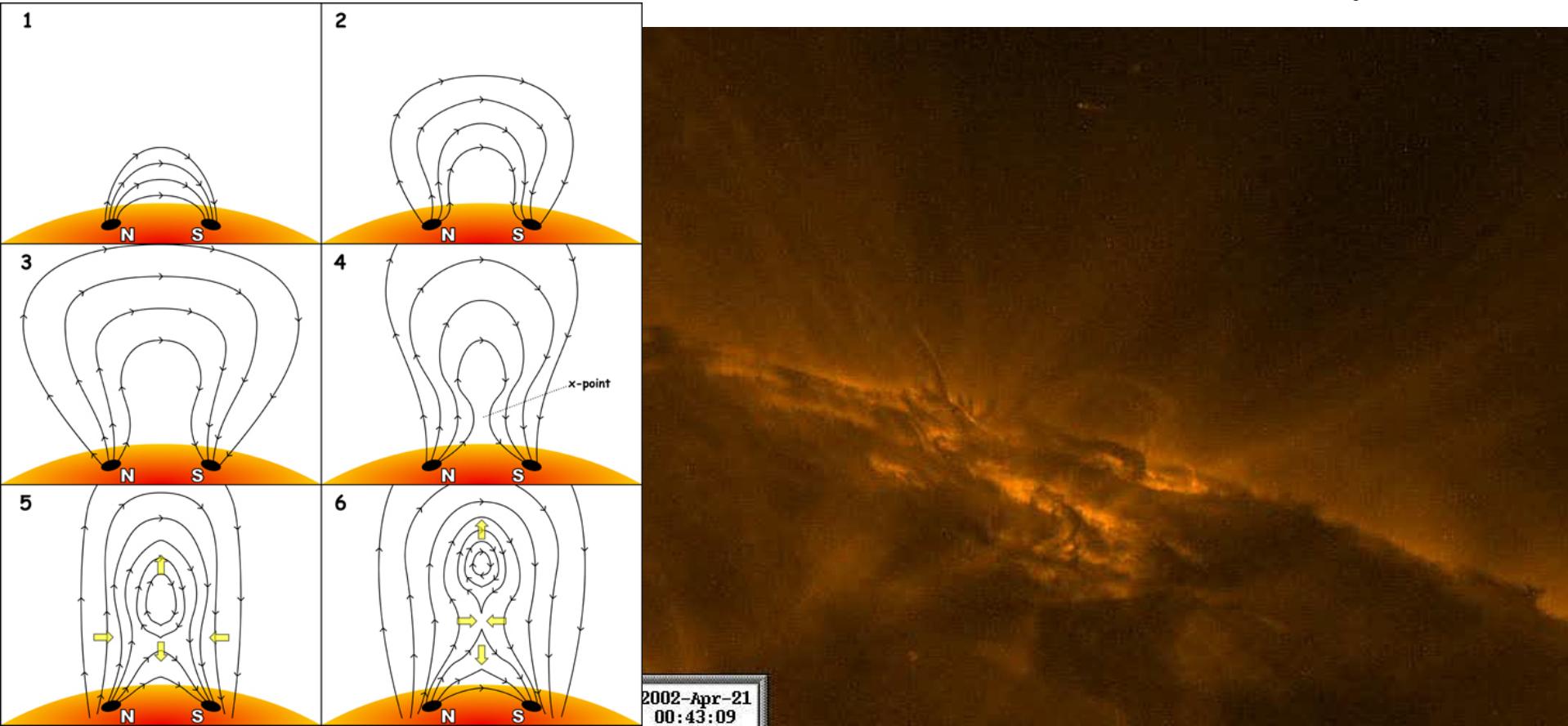
# Solar Flares

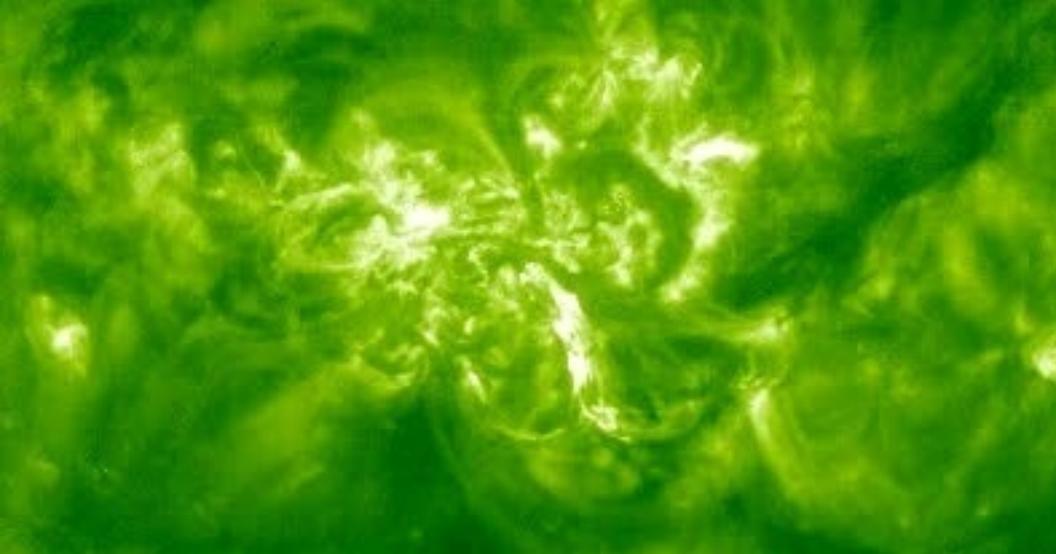
- Explosions in active region on sun's surface
- Seen in Visible, Radio, UV & X-Rays
- Flares reach temperatures of 100 million K
- Biggest seen in 1859 – equivalent to billion megaton nuclear bomb = 10% of sun



# Close Up of Flare in X-Rays

- Magnetic field line reconnection events cause flares
- Particles go up/out and downward ones heat surface
- Surface heated to millions Kelvin -emits X-rays



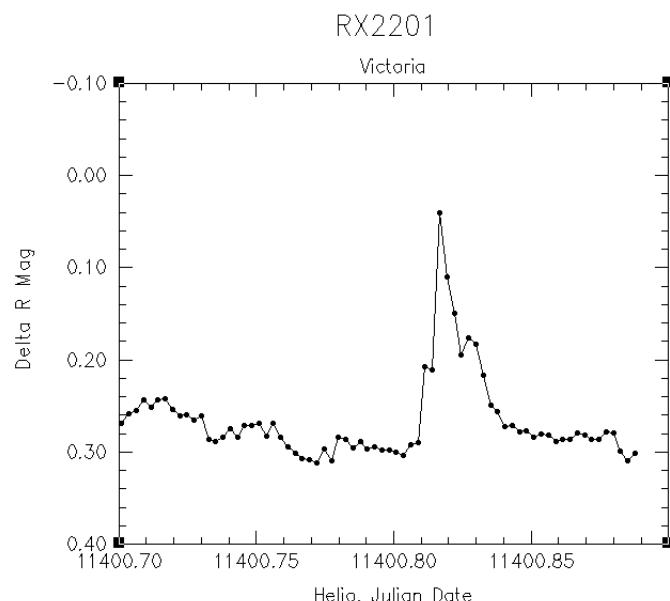
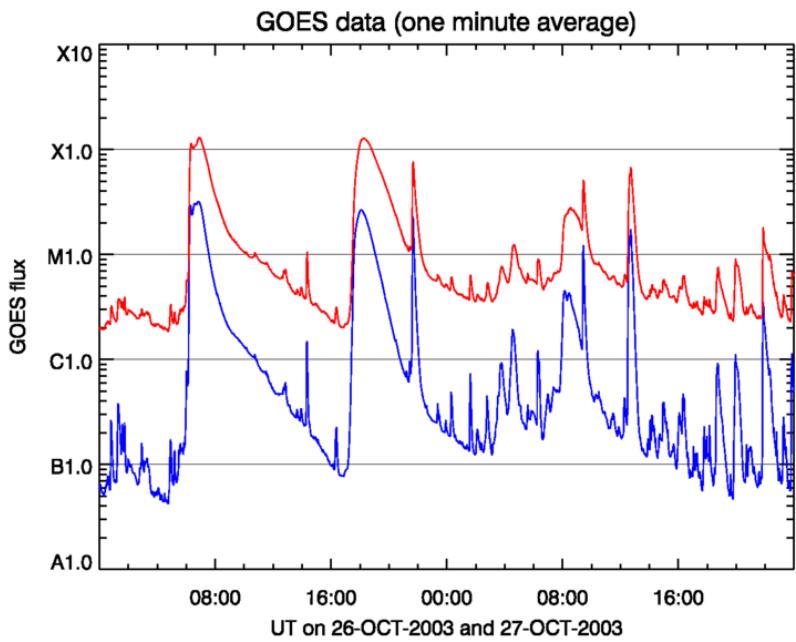


# 3<sup>rd</sup> Largest Solar Flare in X-rays

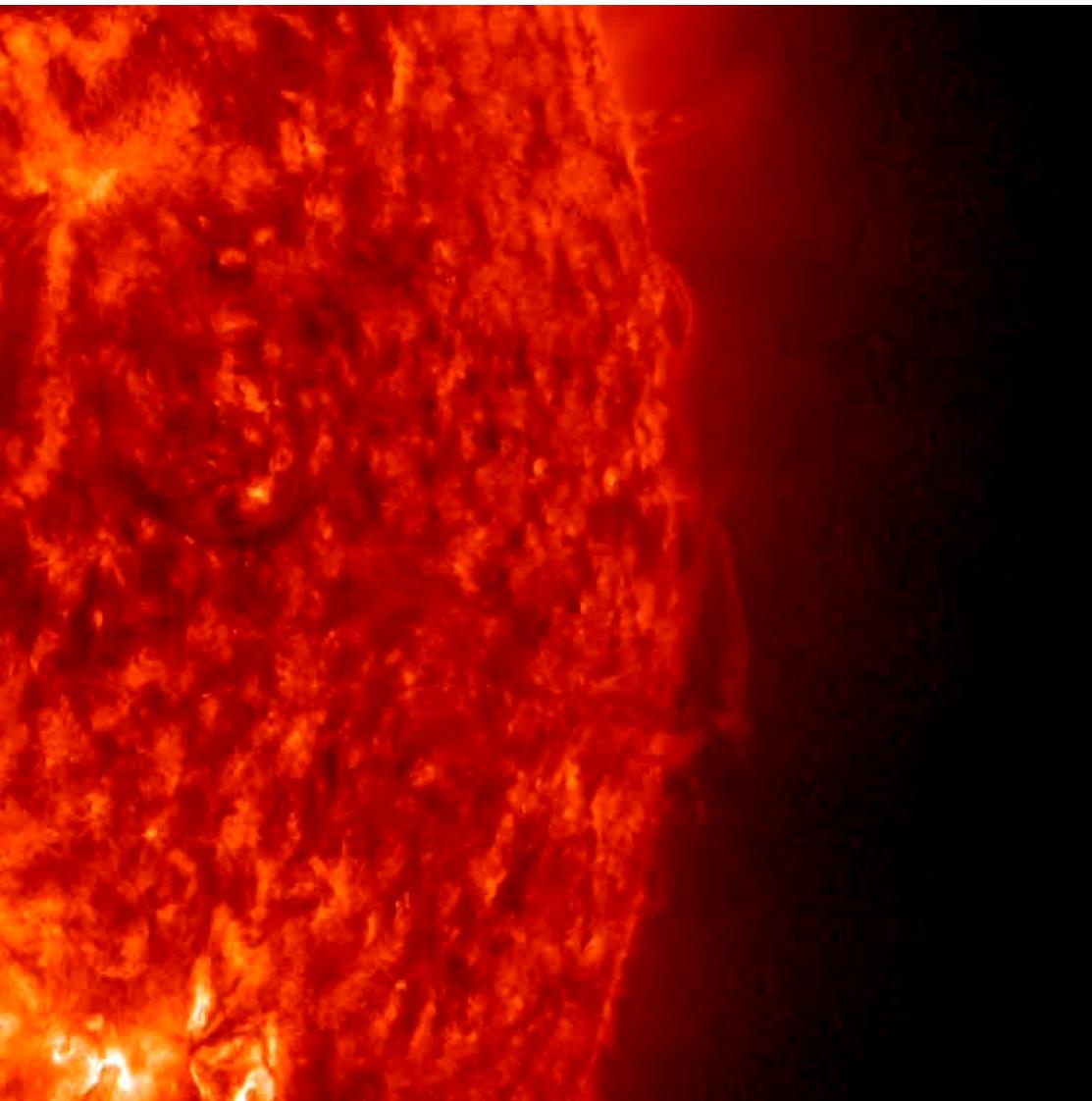
- 28 Oct 2003
  - Jupiter sized group in white light
  - Visible to naked eye but
  - More Radio and X-Ray than the rest of the sun
  - Equivalent to millions of volcanic eruptions
- 

# Same Flare

- **Coronal Mass Ejection**
- Noise caused by protons ejected at near speed of light
- X-rays seen by GOES satellite shows duration of flares can be seconds to hours
- Flares seen on other stars



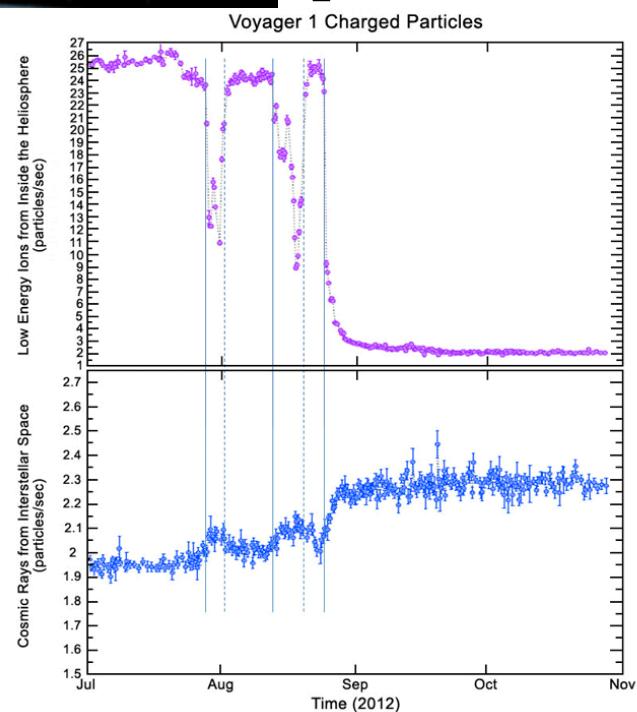
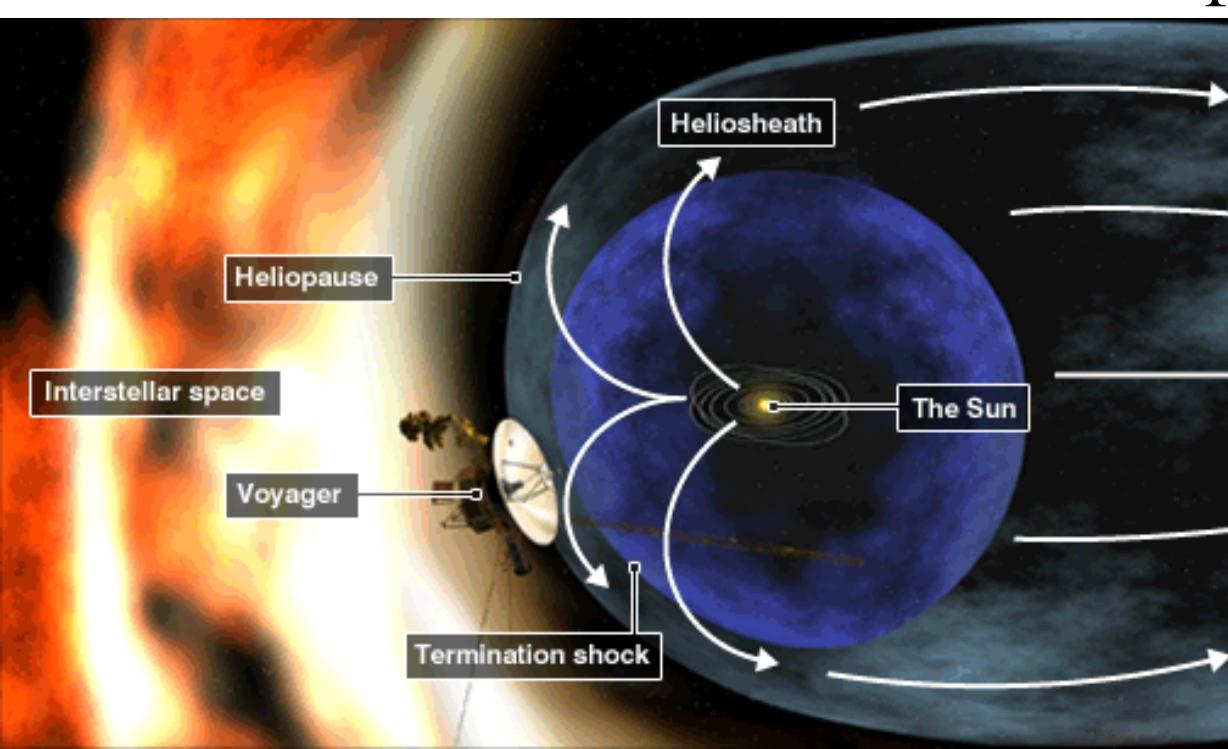
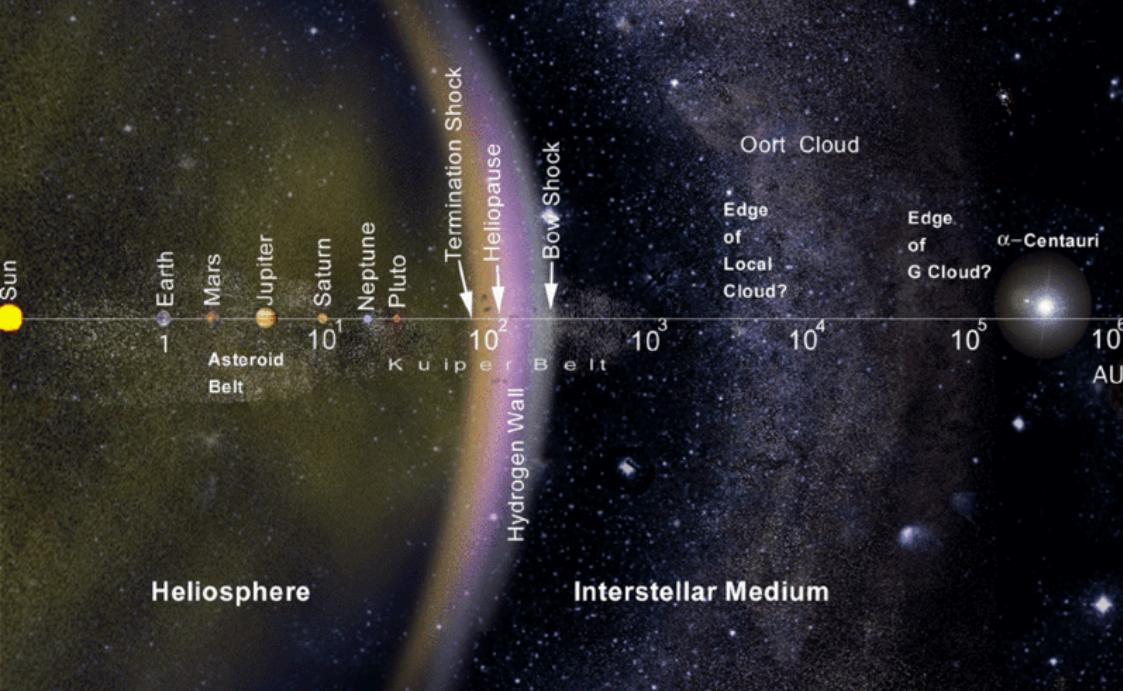
# Flare 02Jan12 Launches Coronal Mass Ejection =CME



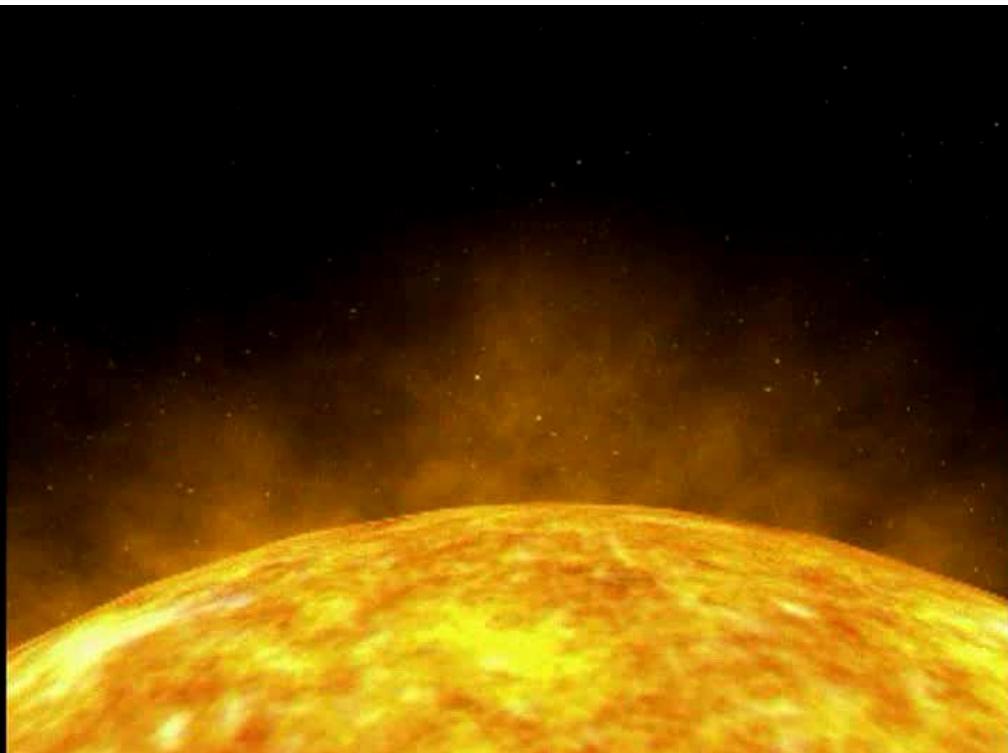
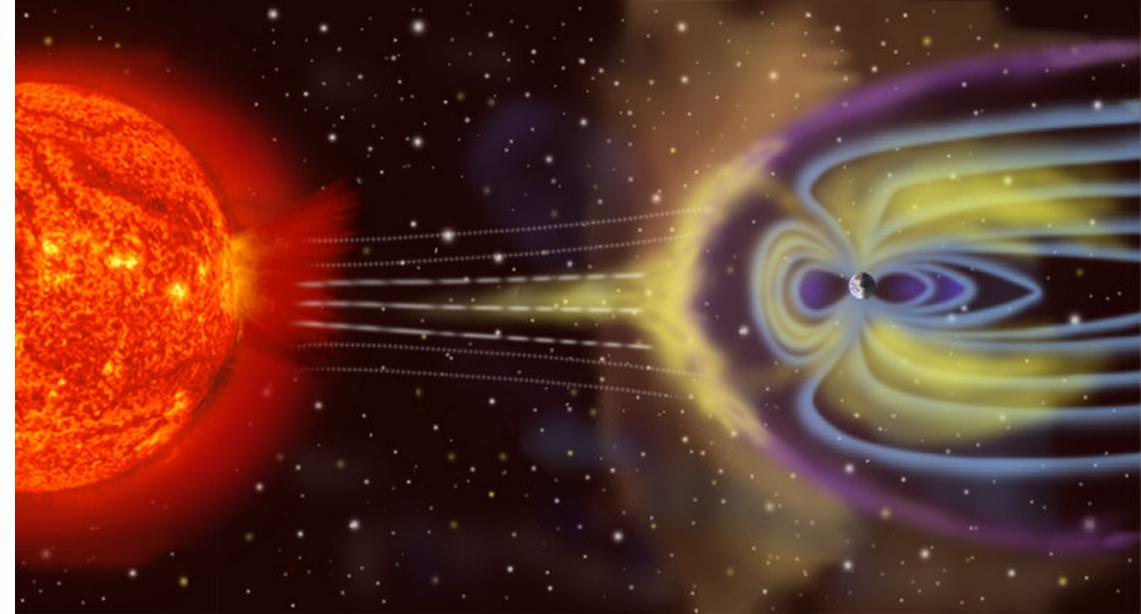
- Flares/CME's are hazardous to astronauts on ISS, Moon or Mars missions
- CMEs disrupt radio communications
- CMEs fry satellites
- CMEs overload electric power grids

# Solar Wind

- Solar wind stopped by interstellar medium
- Voyager 1 passed thru heliopause Oct2012
- More cosmic rays & fewer solar particles



# Flares/CME's Affect Earth's Magnetosphere



- Solar flares, coronal mass ejections & solar wind
- Compresses sunward magnetic field, extending magnetosphere tail
- Induces electrical currents causing aurora

# Aurora Movie by Andre Clay in Alaska



# Which of the following is NOT correct?

- a. The visible surface of the Sun (Photosphere) is gaseous like the tops of clouds
- b. The Sun's energy comes from fusion of Hydrogen into Helium
- c. Despite the Sun's huge output of energy it has lasted for billions of years
- d. Flares and coronal mass ejections can cause power outages and aurora
- e. All of the above are correct

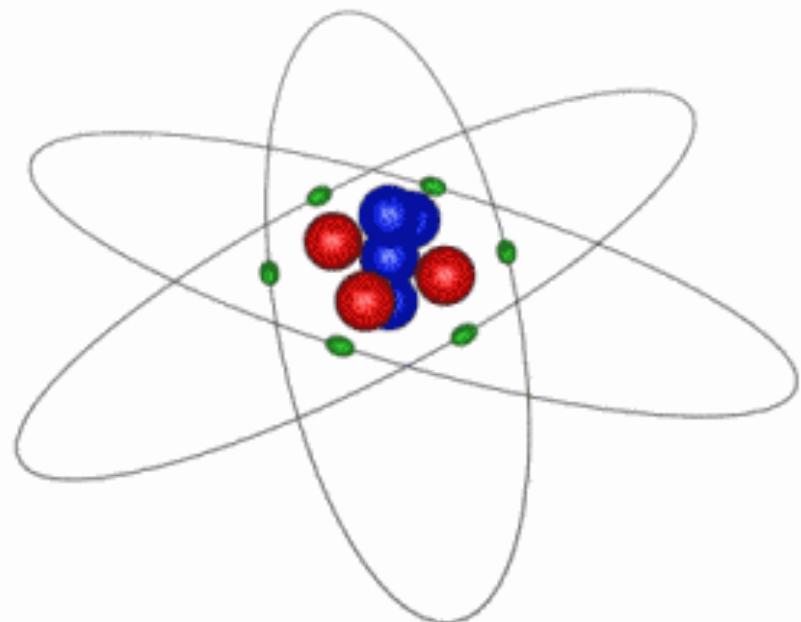
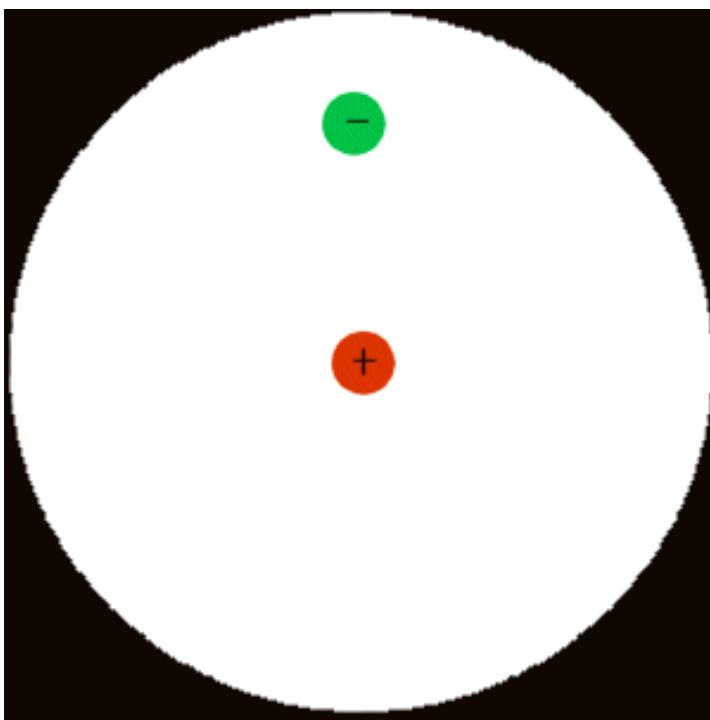




# Niels Bohr's Atom

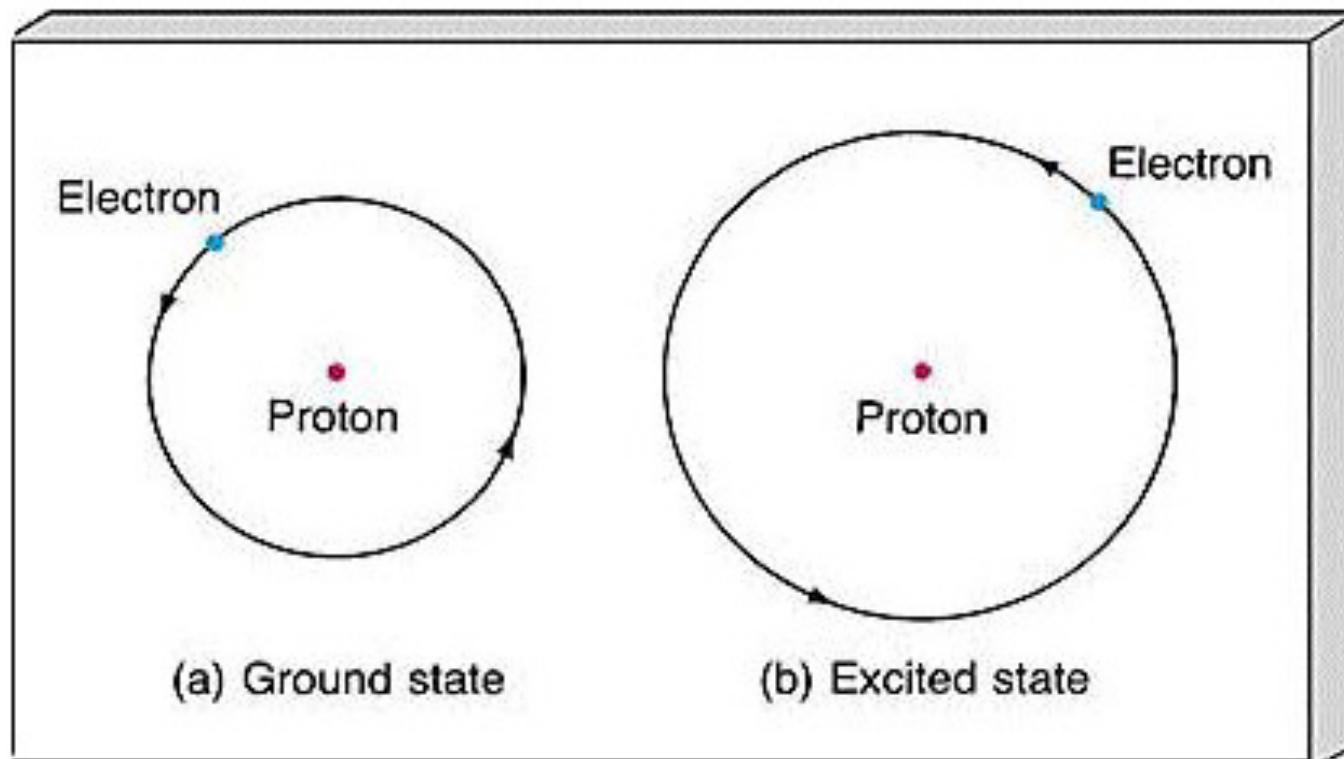


- Tiny positive nucleus contains most of mass
- “Orbited” by negatively charged electron(s)
- Different elements: different number of protons = electrons
- Different **isotopes** have number of neutrons

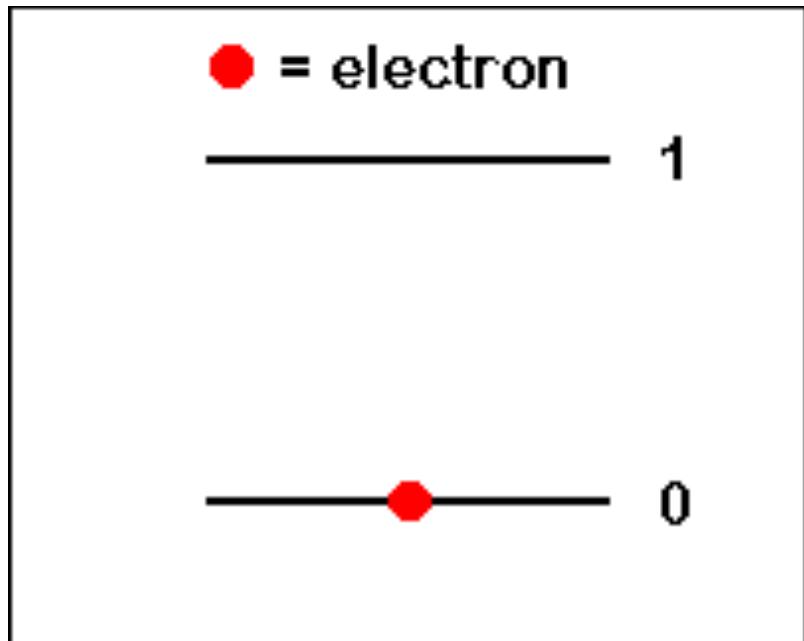


# Quantum Mechanics

- Energy is **quantized** so only certain **orbitals/energies** allowed (just like stairs, piano keys, bookshelf)
- Electron can be in lowest energy (=**ground state**) or raised to higher energy (=**excited state**)



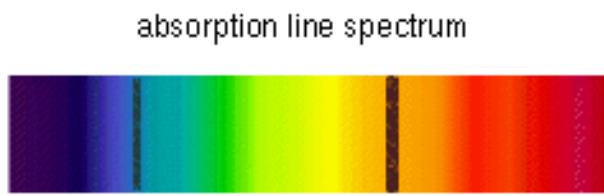
# Photon Emission/Absorption



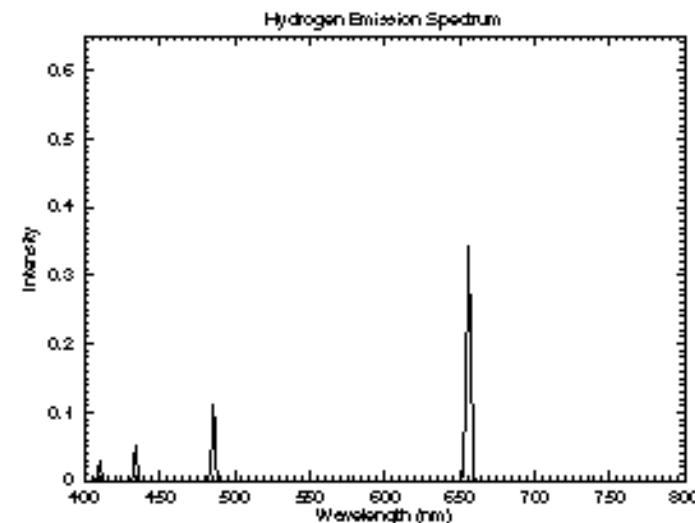
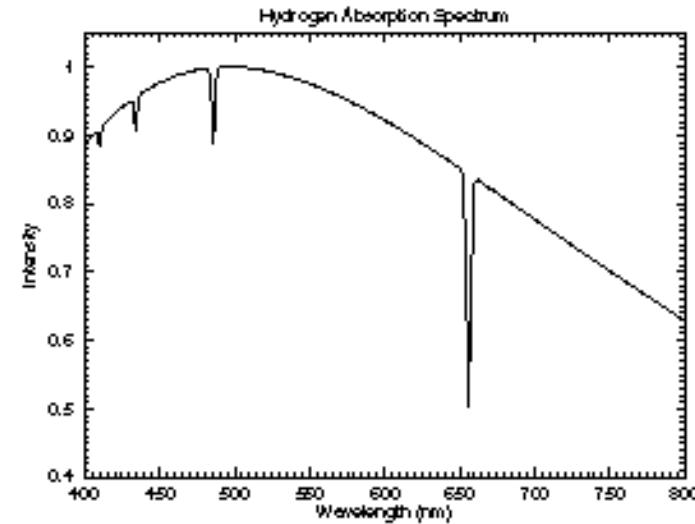
- The electron jumps to a higher **energy level** when a photon is absorbed = absorption
- **Excited state**
- The electron jumps to a lower energy when it emits a photon = emission
- **Ground state**

# Emission Matches Absorption Spectrum

- Energy difference between states determines color of photon



emission line spectrum

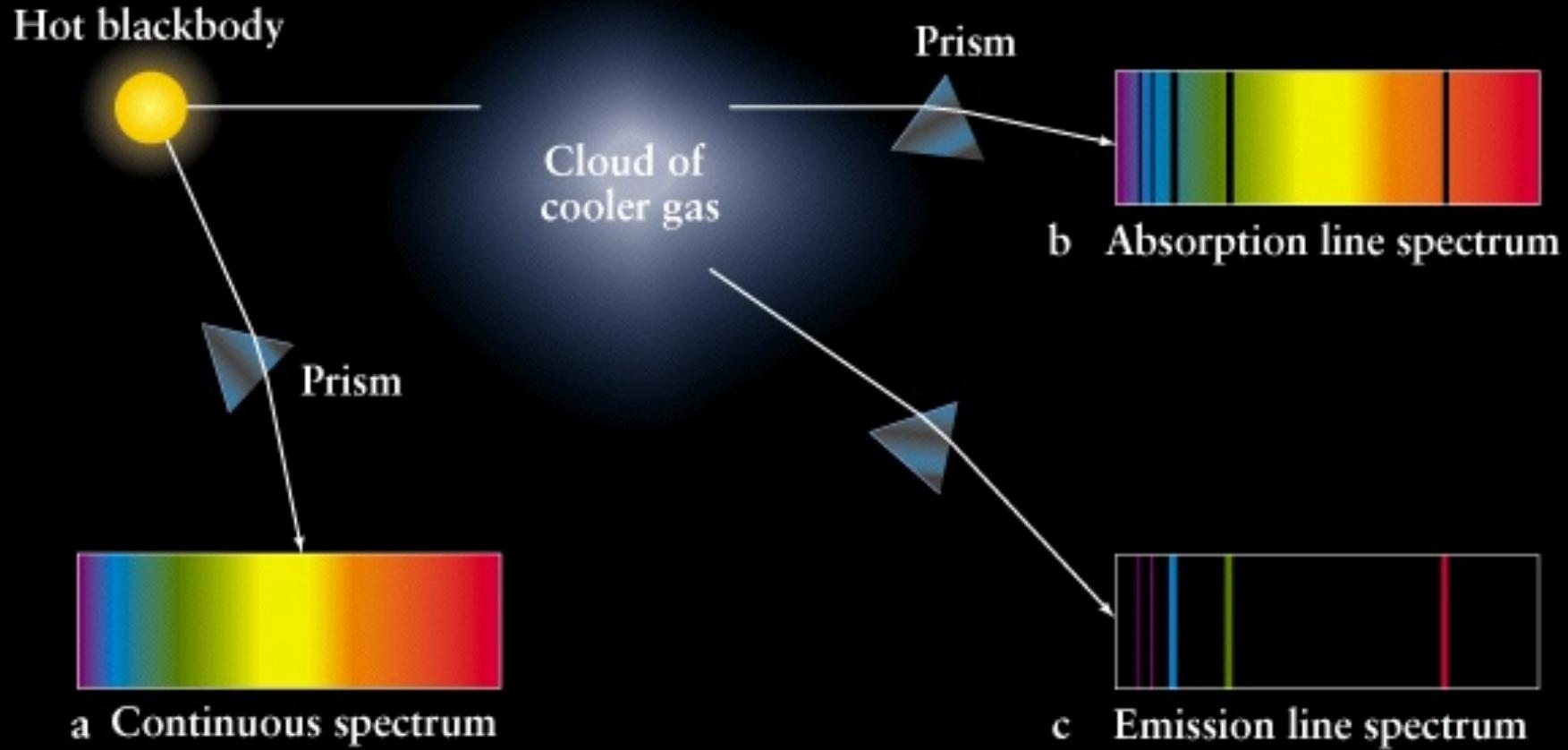


Two ways of showing the same spectra: on the **left** are pictures of the dispersed light and on the **right** are plots of the intensity vs. wavelength. Notice that the pattern of spectral lines in the absorption and emission line spectra are the **same** since the gas is the same.



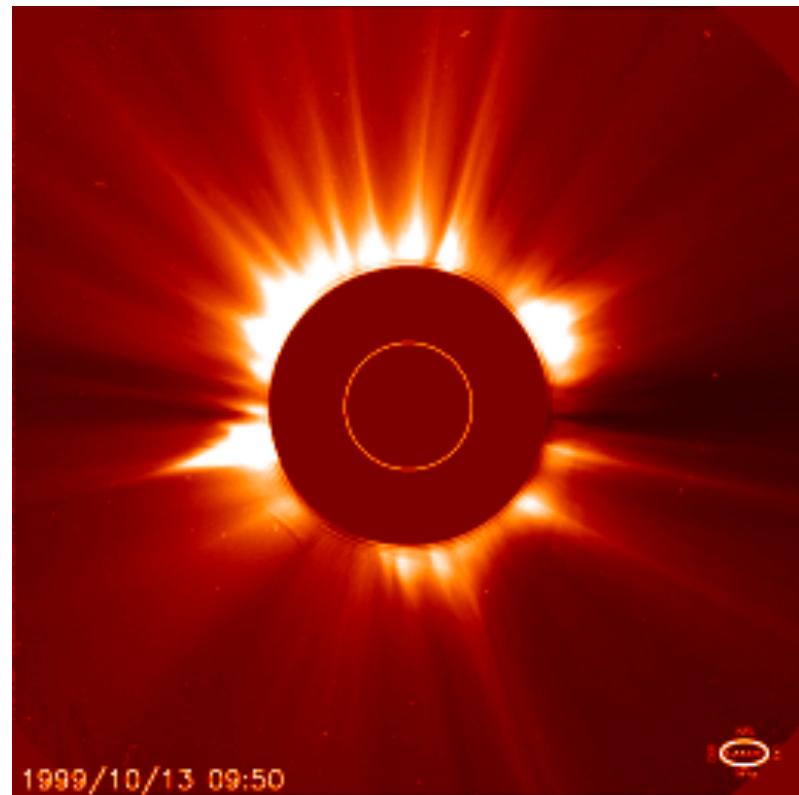
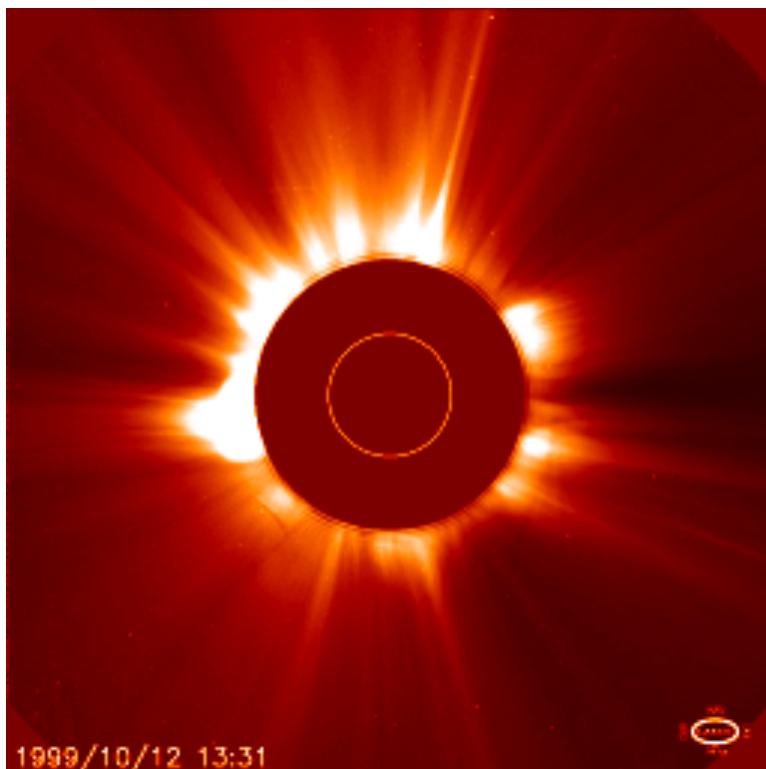
# Kirchhoff's Laws 1861

- **Continuous** – solid, liquid or dense gas will radiate at all wavelengths
- **Emission** - a low density gas will emit light at specific wavelengths
- **Absorption** - results from a continuous spectrum passing through a low density gas resulting in dark spectral lines

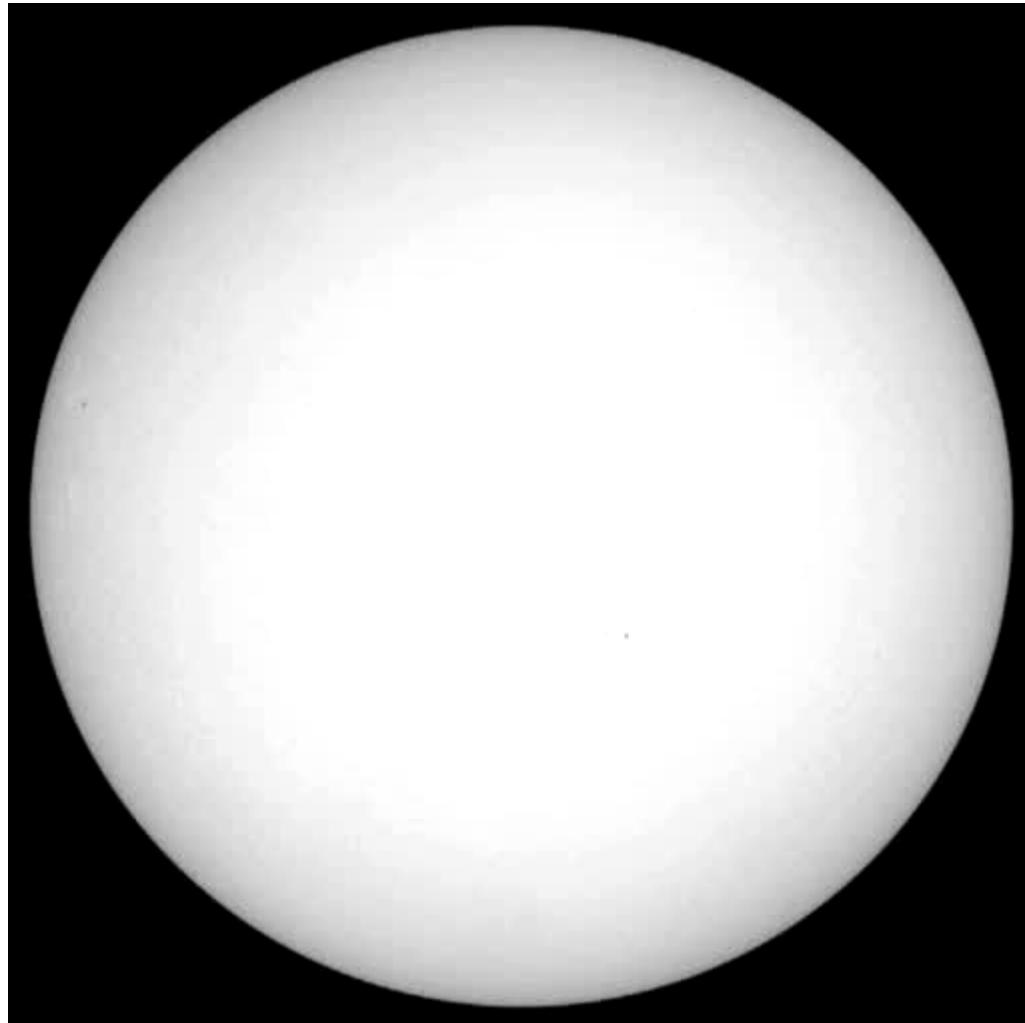


# Coronal Mass Ejections

- Ejection of material from Corona by flares or prominences
- ~400km/sec= a few days to Earth; much bigger than Earth
- Huge amount of energy – 100 billion tons of matter

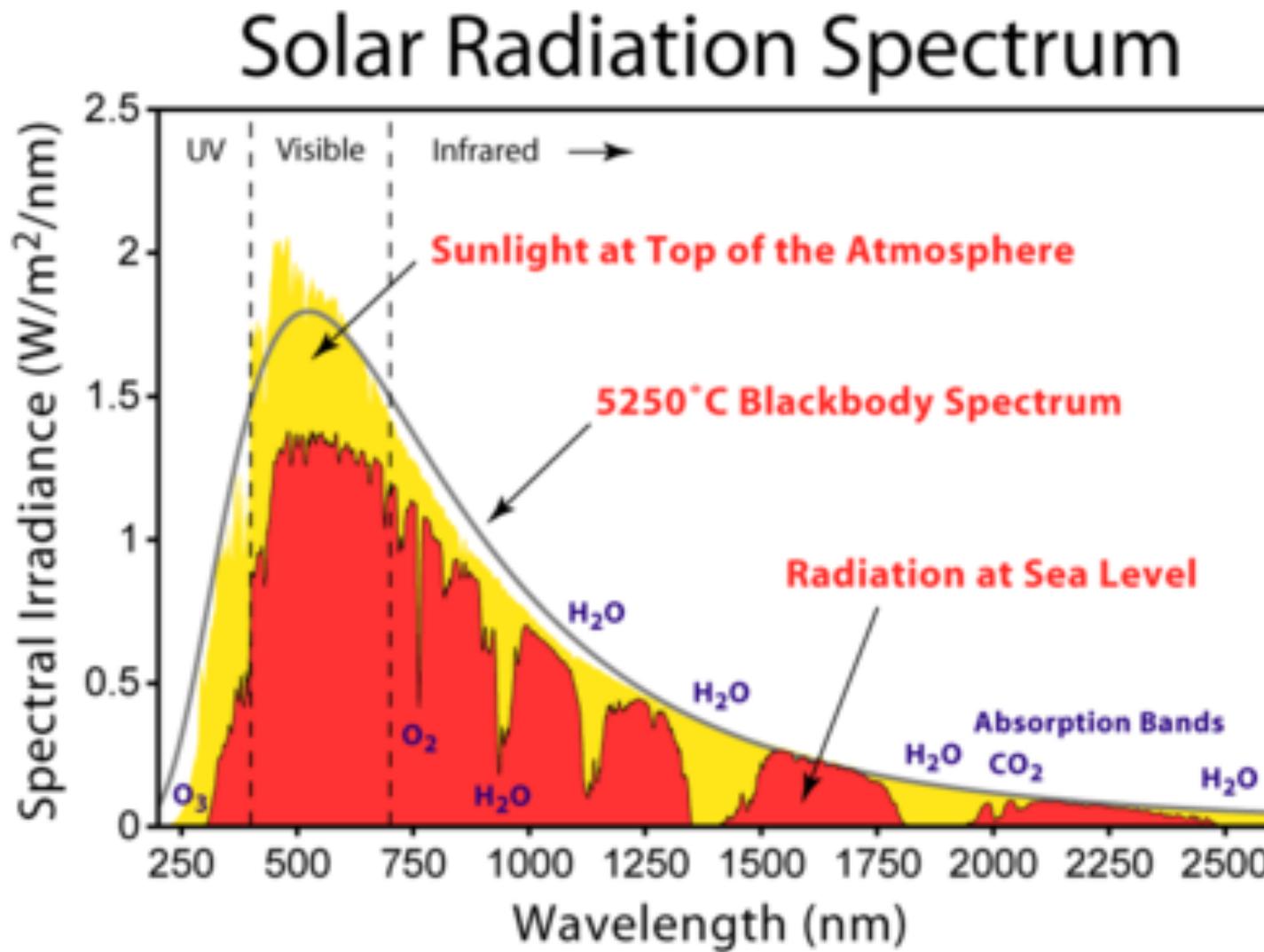


# The Sun in Many Colors

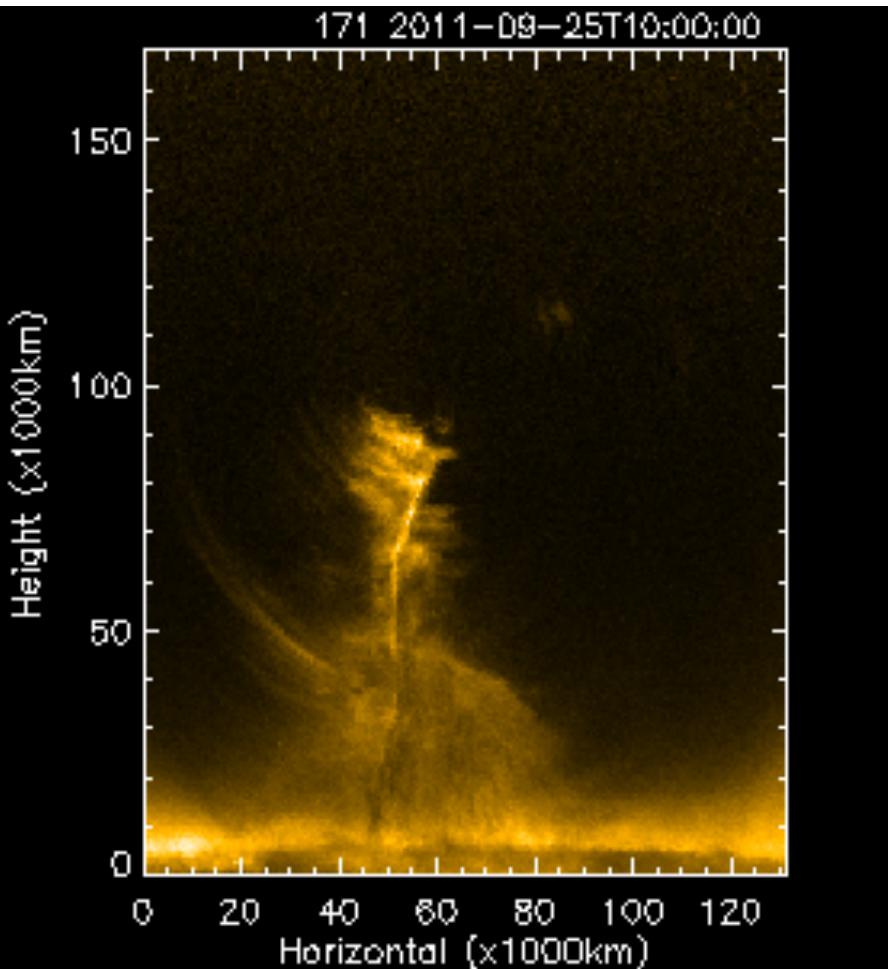


# Solar Luminosity “Constant”

- Solar irradiance more easily measured from above atmosphere
- A change of ~3% would start an ice age



# Solar tornado

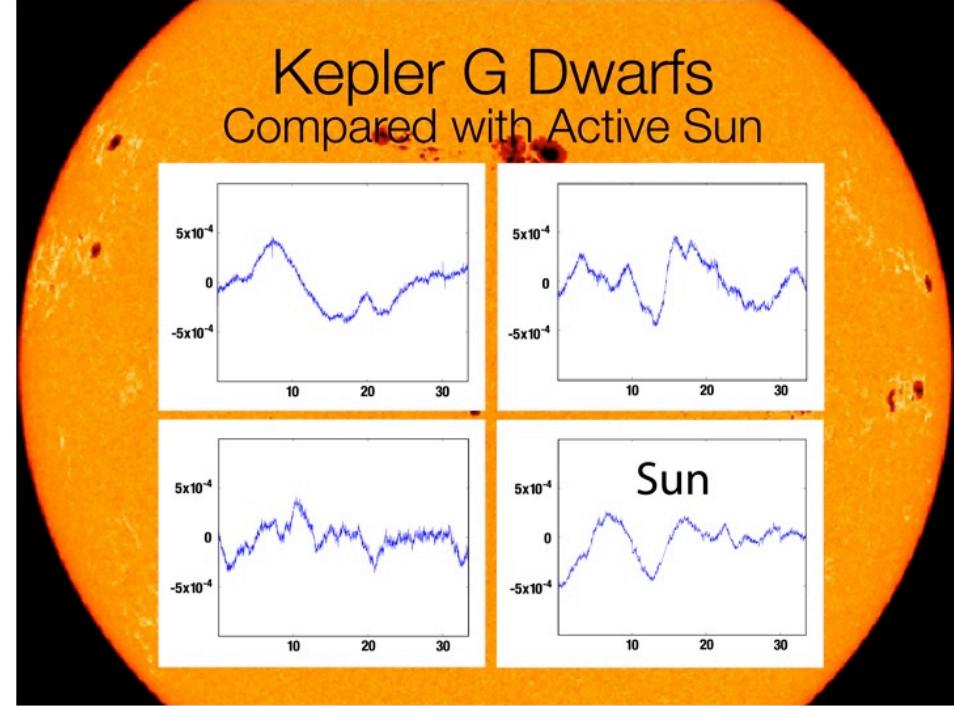
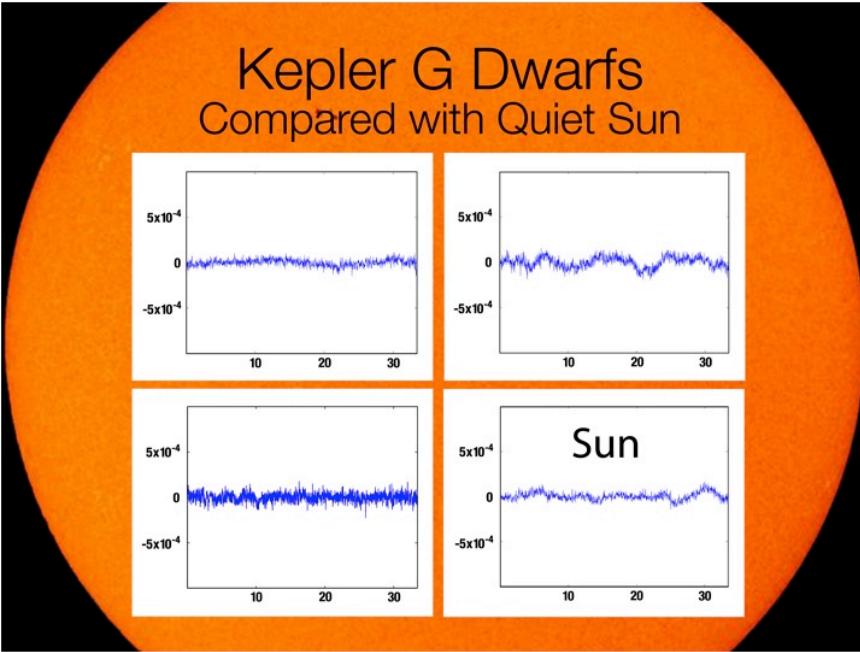
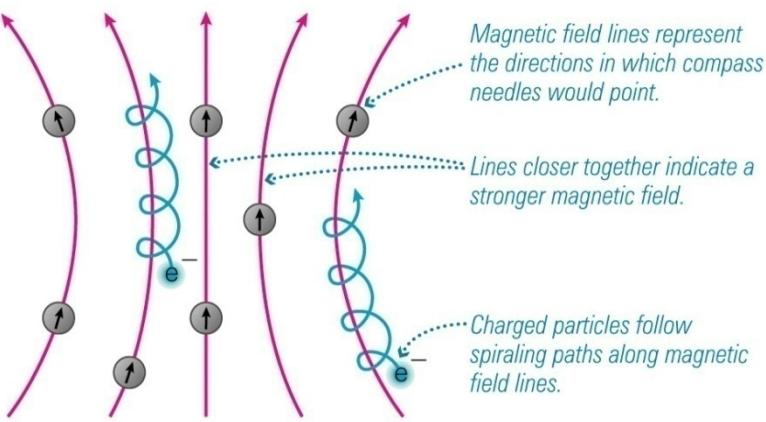


- Velocities of 200,000km/hr
- Size of 5 Earths
- Temperatures of 50,000K – 2 million K

# Sun-Earth-Aurora Connection

- Aurora forms oval surrounding magnetic pole
- Big storm → big oval



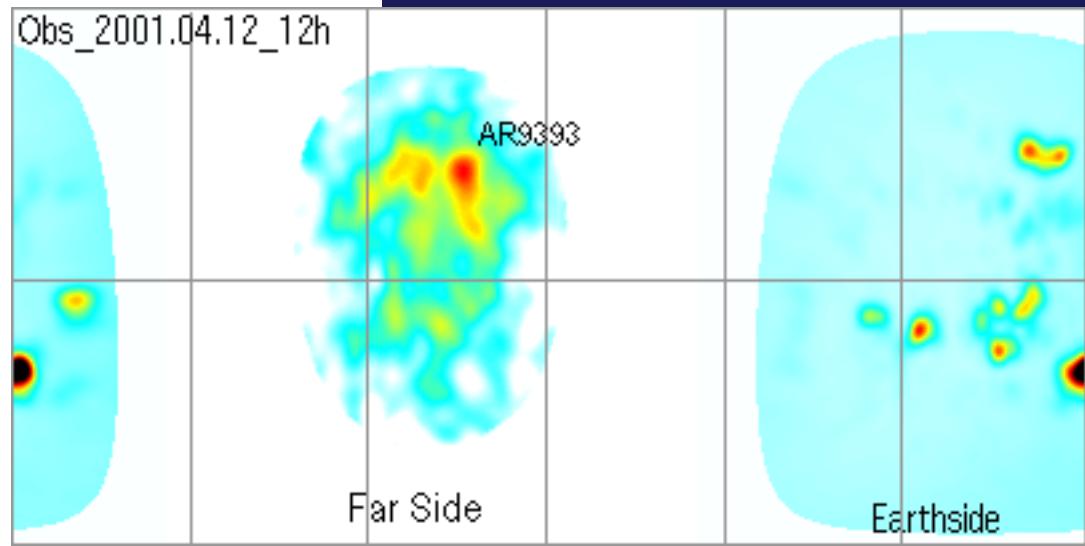
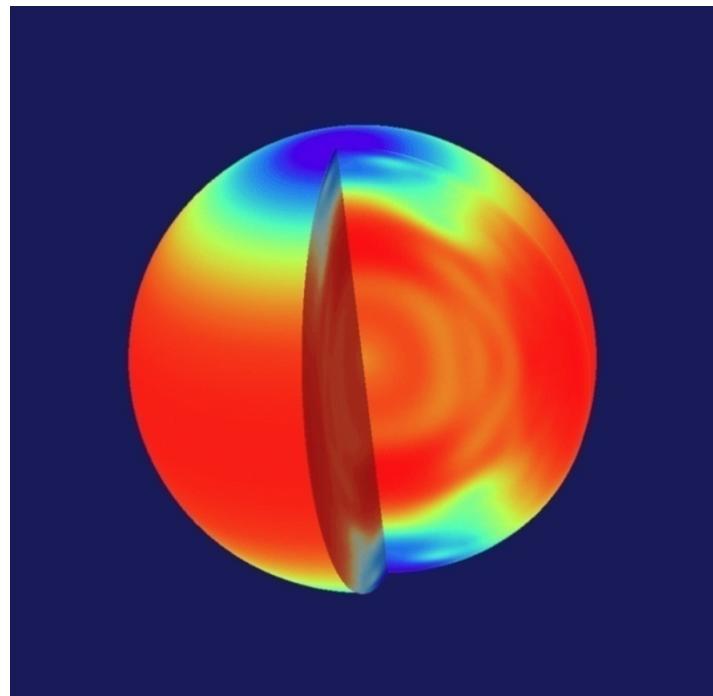


# Fusion: Proton-Proton Chain

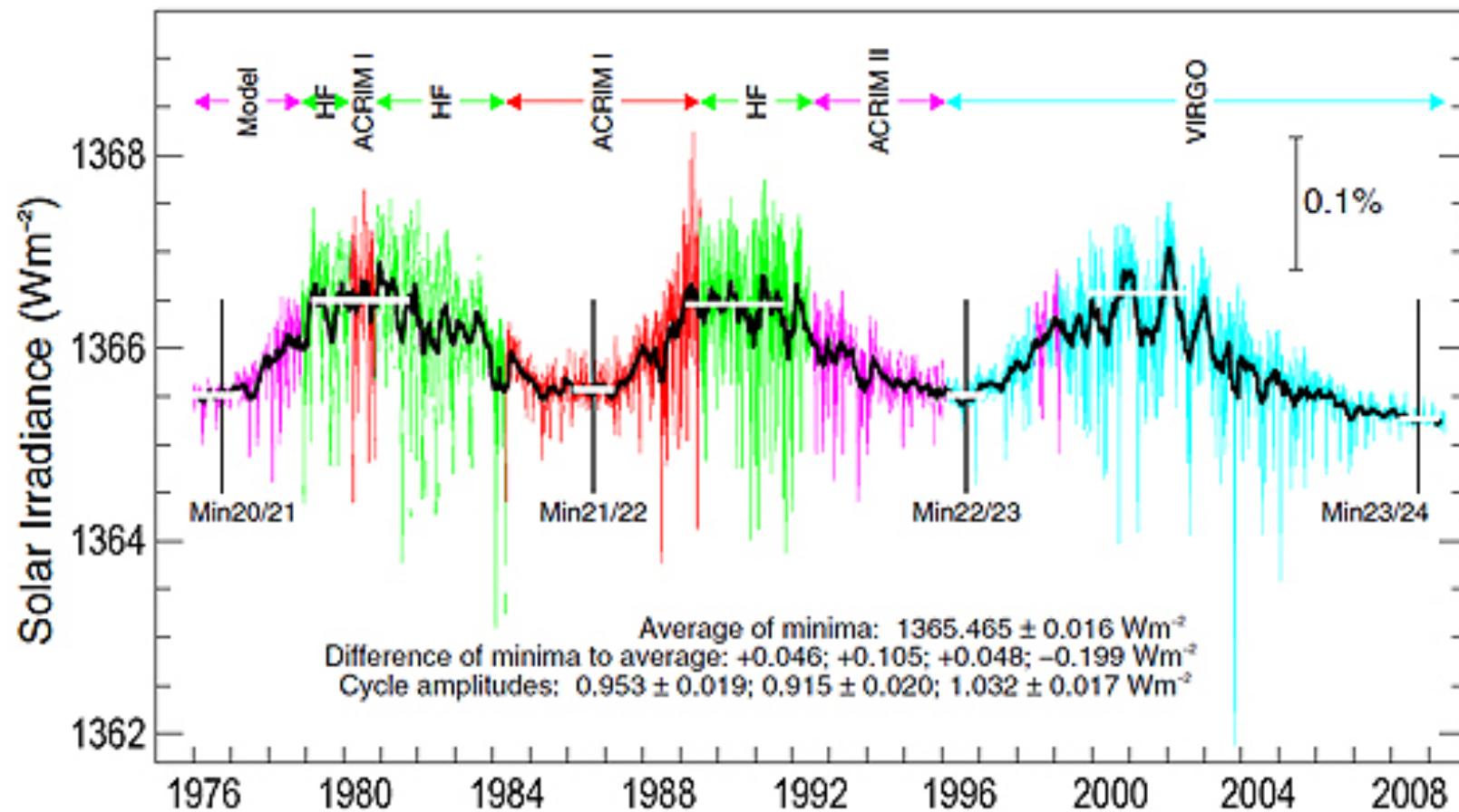
- Two **protons** make a deuterium ejecting a ***positron*** and a **neutrino**
- A proton and a deuterium make a Helium 3 and a **gamma ray**
- Two Helium 3's make a Helium nucleus and release two protons

# Differential Rotation

- Red fastest – Blue slowest
- Left side shows rotation period ~25 days at equator and ~40 days at poles
- Right side shows differential rotation persists a third of the way to the interior
- Spots on back of Sun

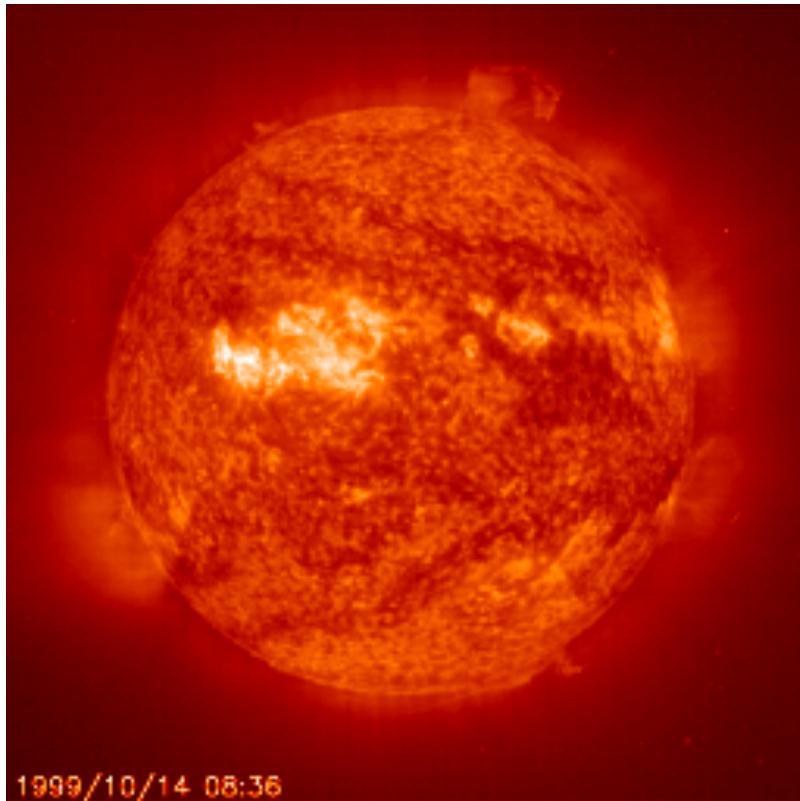


# Brightness of Sun / Solar Cycle

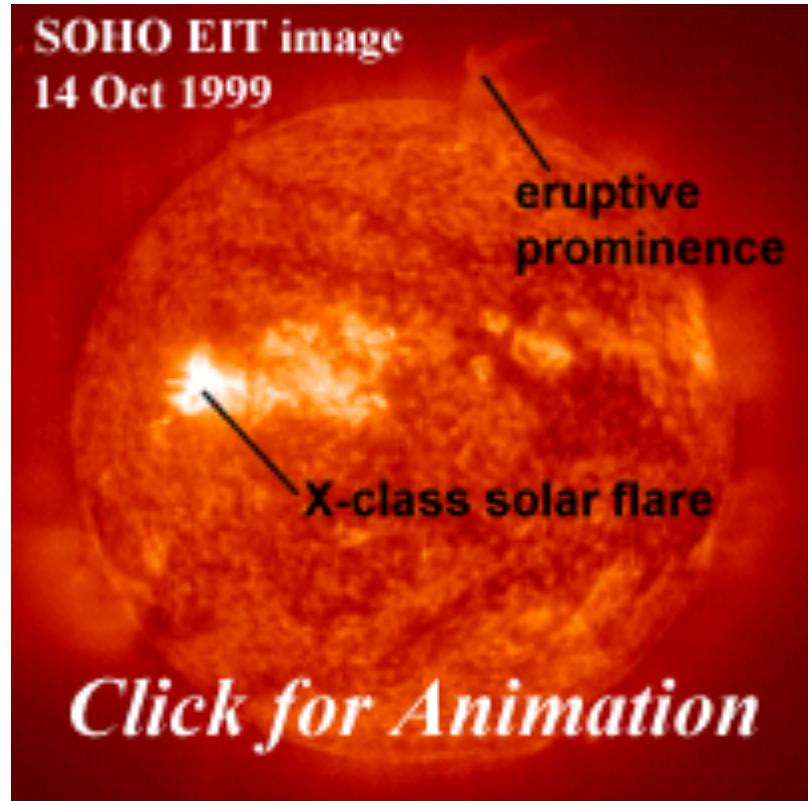


# Flare and Eruptive Prominence

- Flares hazardous to astronauts on Moon or Mars missions
- Flares disrupt radio communications & electric power grids



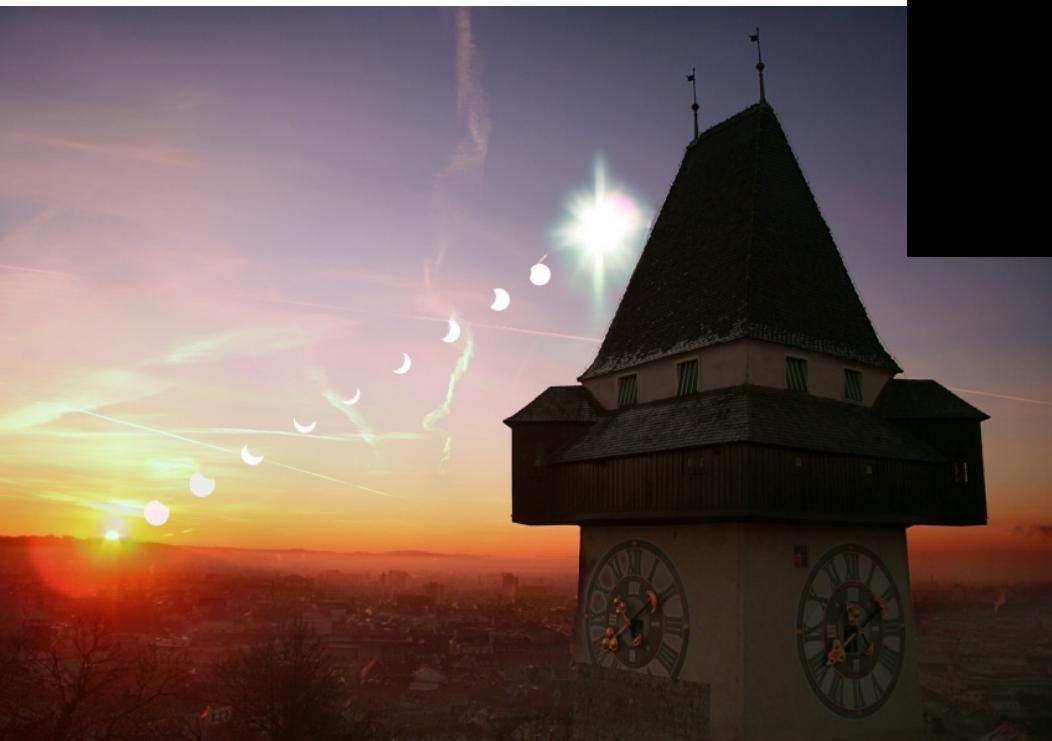
1999/10/14 08:36



*Click for Animation*

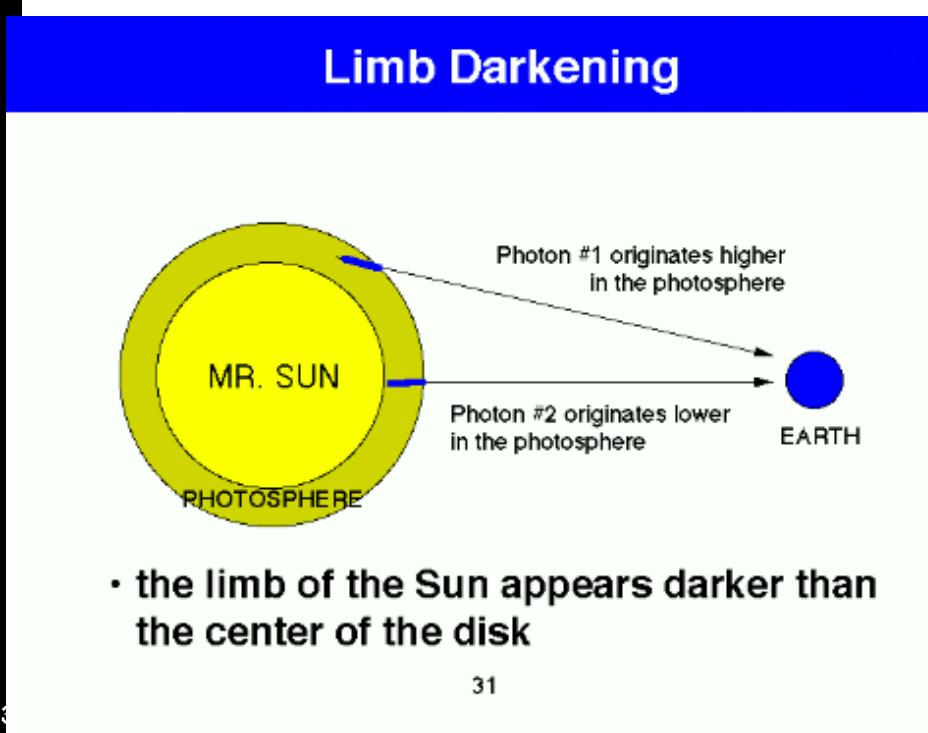
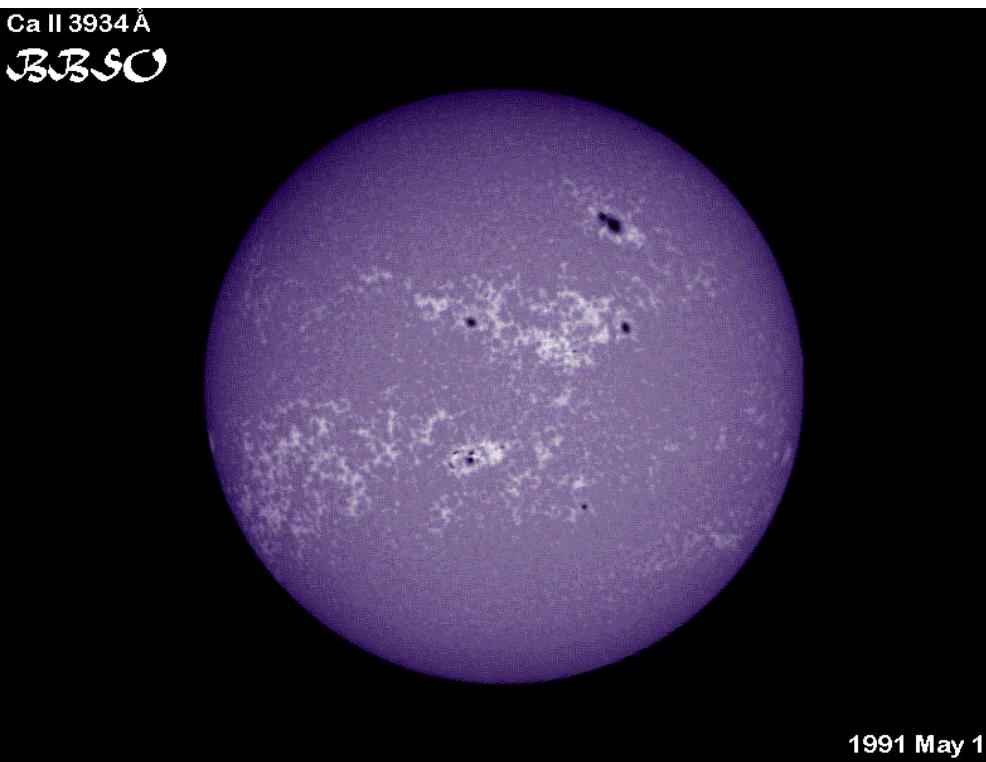
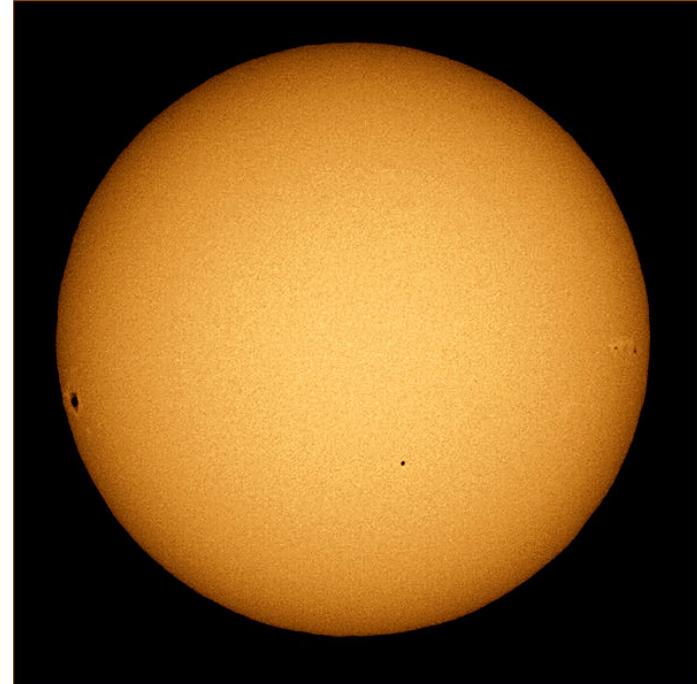
# Eclipses

- Lunar Eclipse on Solstice
- Solar Eclipse Tuesday
- 4 Partial Solar Eclipses
- 2 Lunar Eclipses in 2011



# Limb Darkening

- Edge of sun (limb) appears fainter than the center
- Shows Photosphere is like a fog ~400km thick



# Atmospheric Transmission

Exosphere  
(300+ mi.)

Ionosphere  
(30-300 mi.)

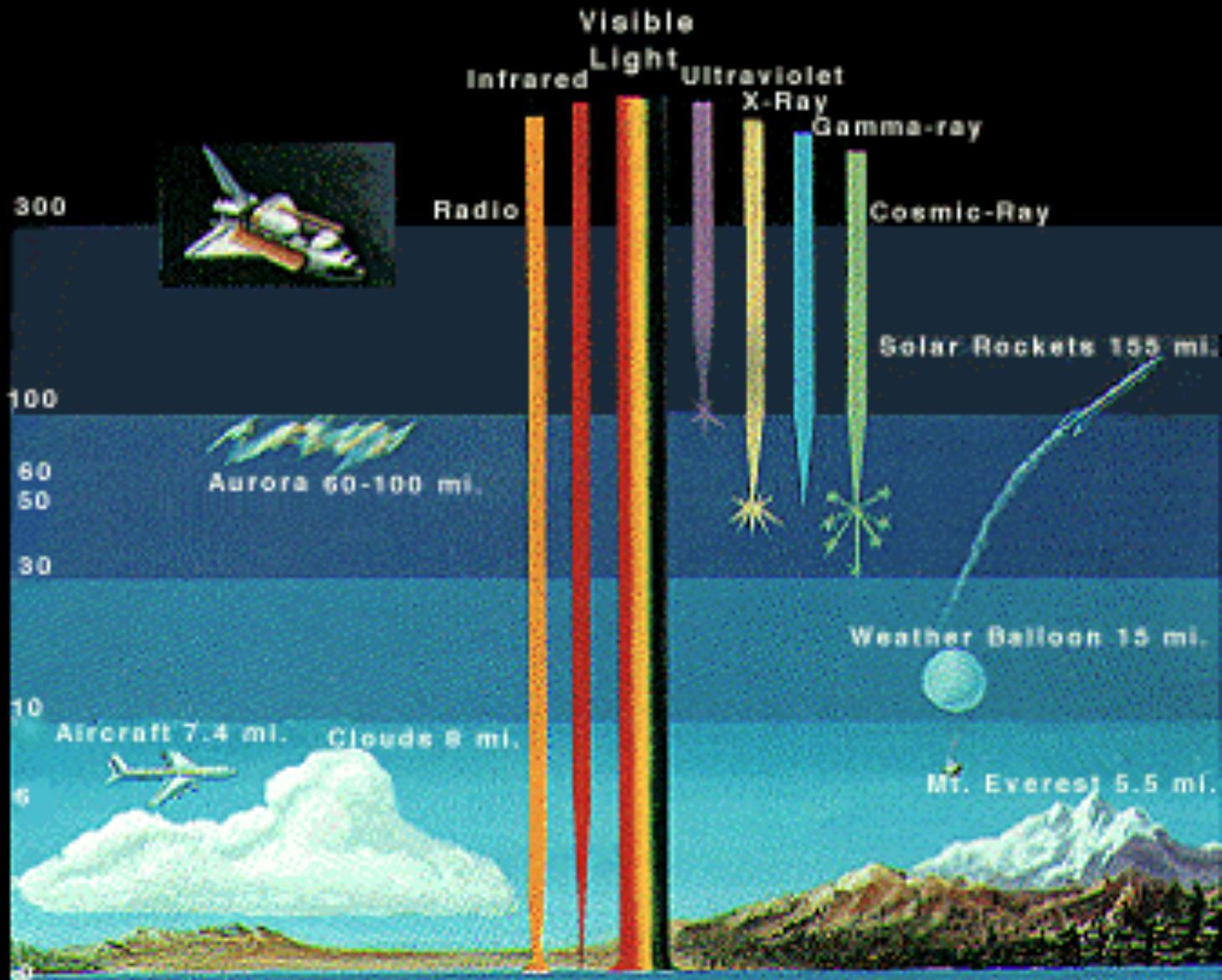
Radio Reflecting  
Regions

F Region  
E Region  
D Region

Stratosphere  
(10-30 mi.)

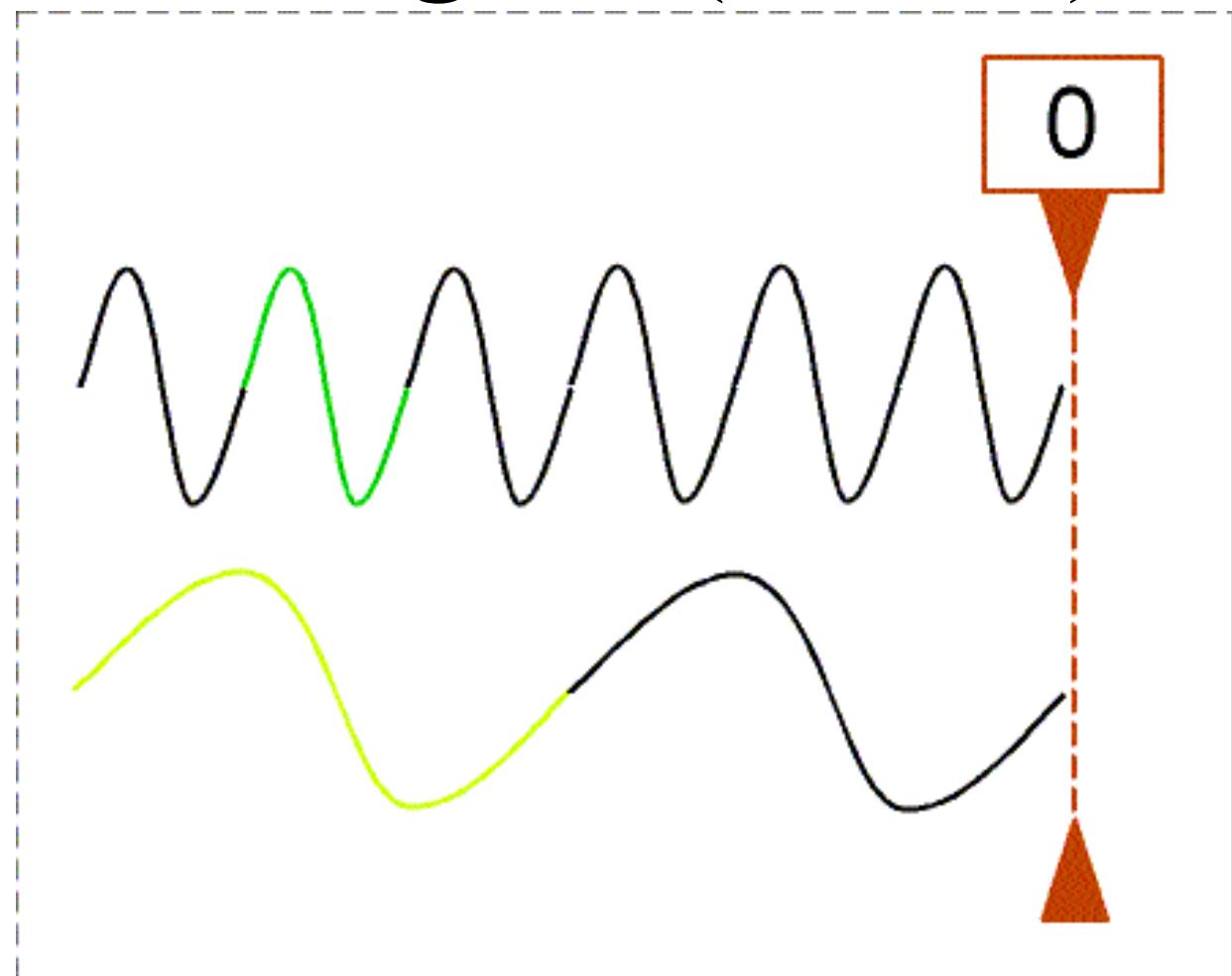
Troposphere  
(0-10 mi.)

Sea Level



# Light Waves Have a Frequency $f$ , Period $P$ , Wavelength $\lambda$ (lambda)

- **Frequency** counts number of waves
- Frequency = 3 cycles/sec or 3 Hertz
- Has 1/3 sec. **period**
- Period of 1 second
- Frequency of 1 cycle/sec= 1 Hertz
- Has three times wavelength  $\lambda$



# Stationary Source

- Speed of waves equals the wavelength  $\lambda$  times the frequency  $f$
- $C = \lambda f$



# Moving Source

- Wavelengths in direction of motion are compressed
- Wavelengths when source is moving away from observer are stretched
- Speed of source determines how much stretching



# Doppler Effect

- $V_r / C = (\lambda - \lambda_o) / \lambda_o = \Delta \lambda / \lambda_o$
- If the source is receding (moving away) then it is a **redshift**
- If the source is approaching then the light is blueshifted

