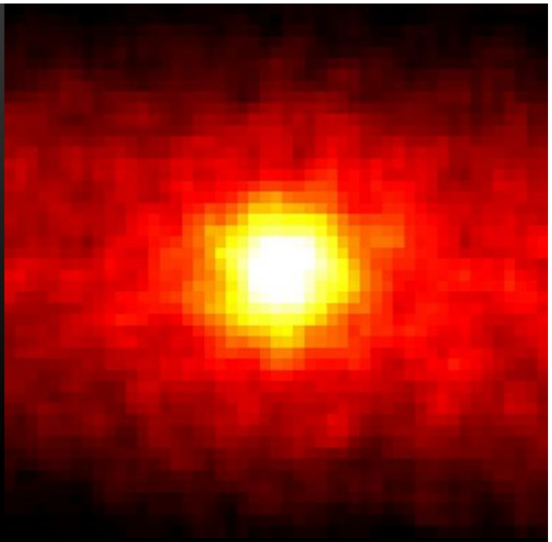
BACK TO THE PROBLEM



- We seen ν's from the sun:
  - But no one sees enough ν's to account for the amount of power the Sun produces
- Helioseismology checked that we know how the Sun is built: hot enough, dense enough
- Particle physics experiments show we know how ν are created and detected
- Maybe something happens along the way?

NEUTRINO OSCILLATIONS

- Each experiment saw a slightly different sample of ν's from the Sun
- Quantum mechanics suggests if ν's have mass, they might change "flavors" as they travel
- A different flavor of ν won't be seen
- Combine all the data, this looks like what is going on

THE ICING ON THE CAKE

- The SNO (Sudbury Neutrino Observatory) in Ontario uses “heavy water”
- Looks at the ν’s in yet another different way
- Last big piece of the puzzle
  - Saw that the sum of all neutrino flavors was correct
  - So the “missing” ones simply had changed flavors

SOLAR NEUTRINOS UNDERSTOOD

- After much research, we understand the ν's from the Sun
- They are being created as predicted with fusion
  - So we know exactly How the Sun Shines!
- Some of them change to a different sort of ν along the way
  - This accounts for the missing ν's

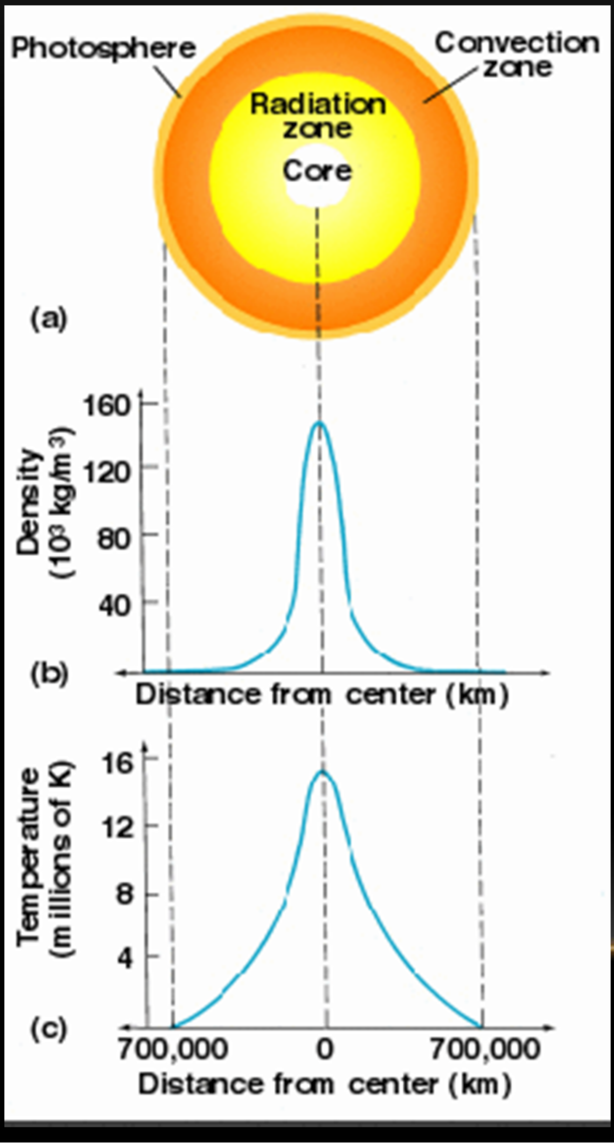
2015 NOBEL PRIZE

- The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Led the Super-K team that in 1998, saw neutrinos from cosmic rays changing (*was my postdoc research*!)

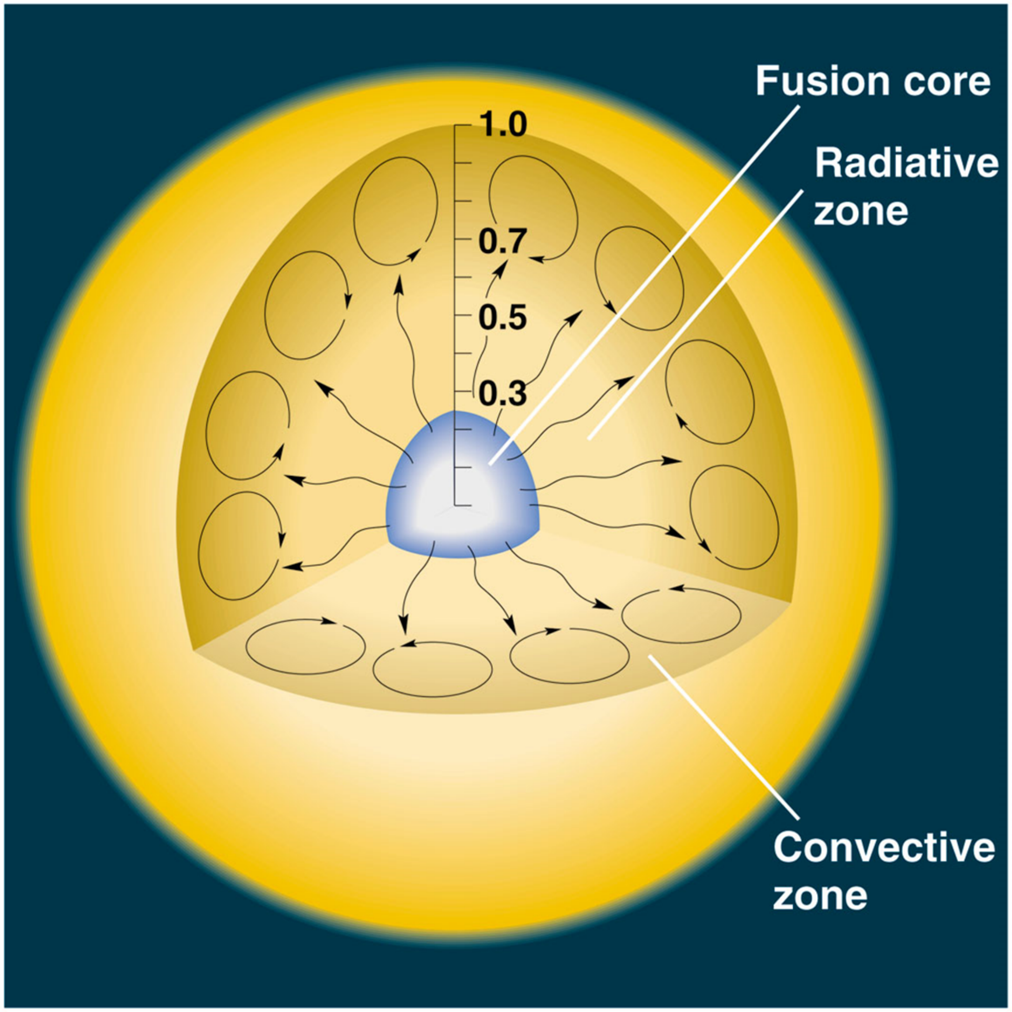
Led the SNO experiment that in 2000, saw that the "missing" neutrinos from the sun had simply changed flavors

WORKING OUT THE DETAILS



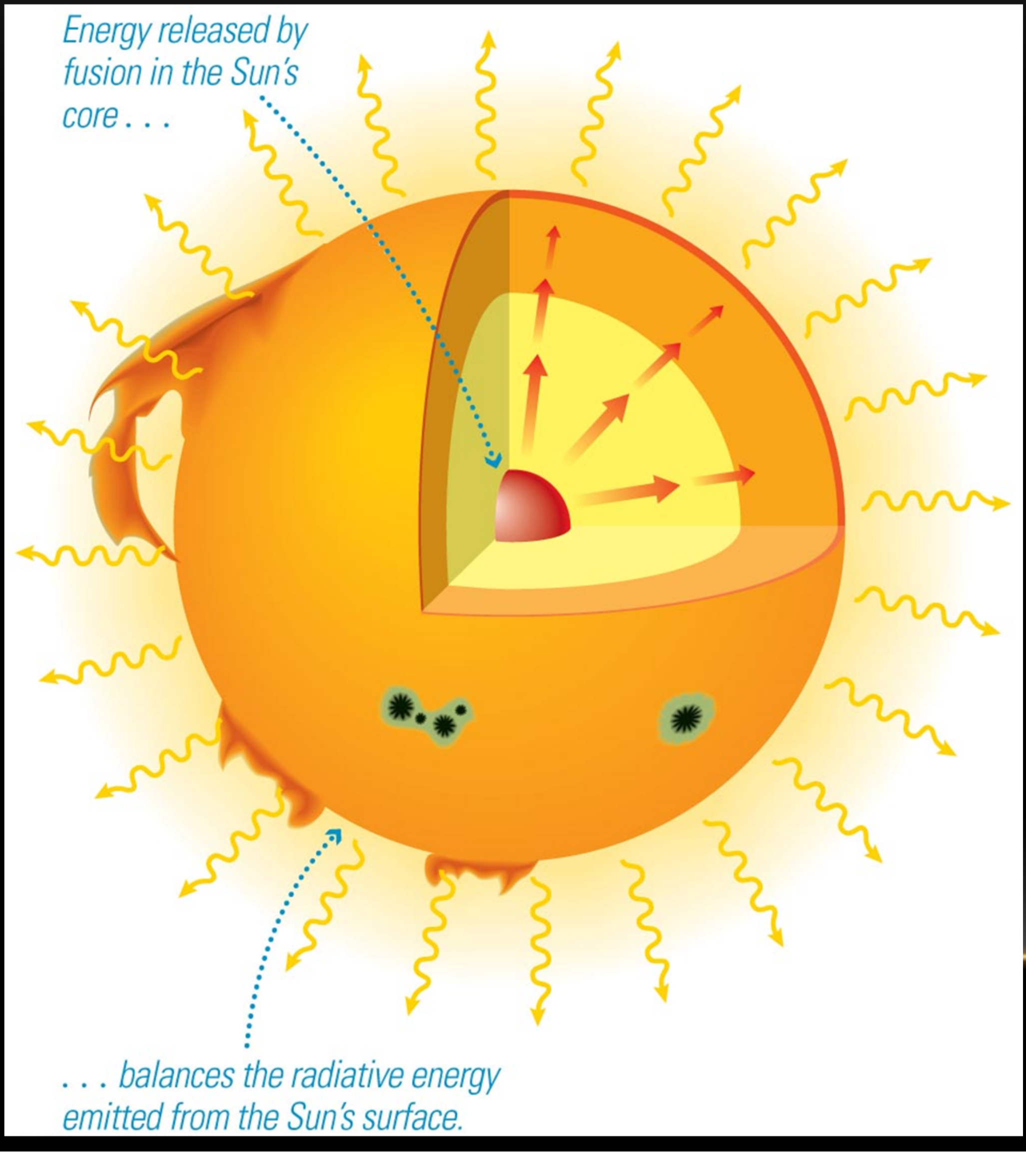
- Solve the equations of thermodynamics for hydrostatic equilibrium with gravity
- The density and temperature graphs to the left are produced

THE SUN'S INTERIOR



- It's only hot and dense enough for fusion to occur in the inner 25% of the Sun
  - So that's where the energy comes from
- From core to 2/3 the way out is the "Radiative Zone"
- "Convective Zone" is the outer 1/3
- All hot ionized gas ("plasma")

ENERGY TRANSPORT

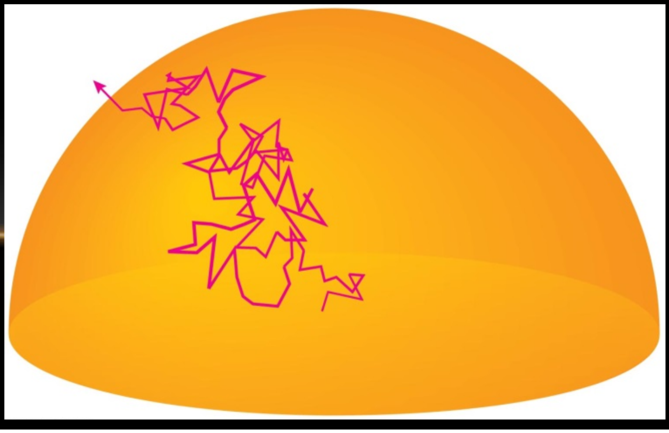


- The fusion energy gets from the core to us in several steps
- Inside the core, by *conduction*
  - Physical contact lets the heat flow
  - Touching a hot stove burns you by conduction

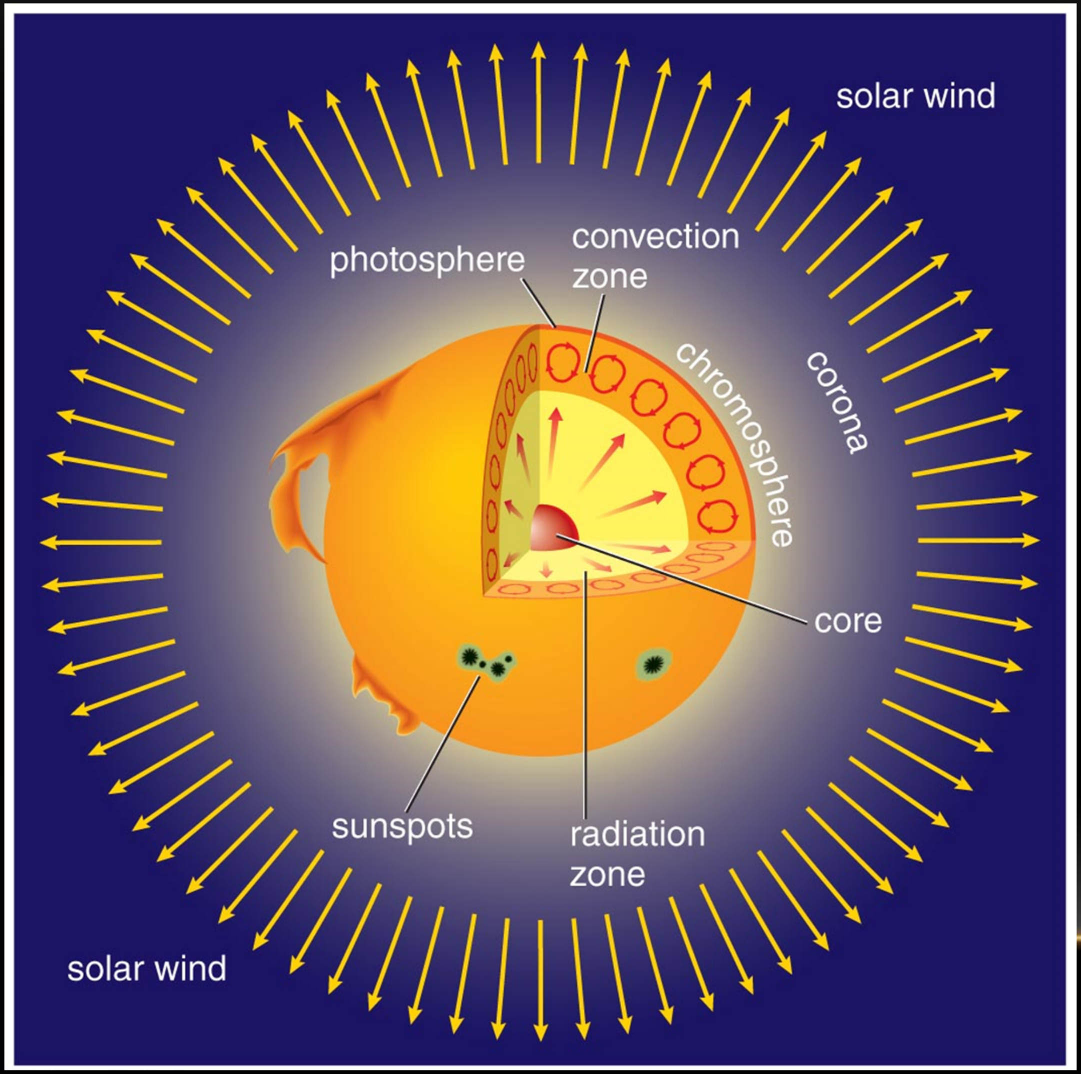
Fig.11.3

RADIATION

- Outside the core, the gas is less dense, does not conduct well
- The energy travels by radiation
  - A cat warming himself in the sun is being heated by radiation, or you under a heat lamp
- The sun is not clear – the light is absorbed and re-emitted many times in its trip through the “Radiative zone”
  - A bit of light takes ~1 million years to work its way out



RADIATION ZONE



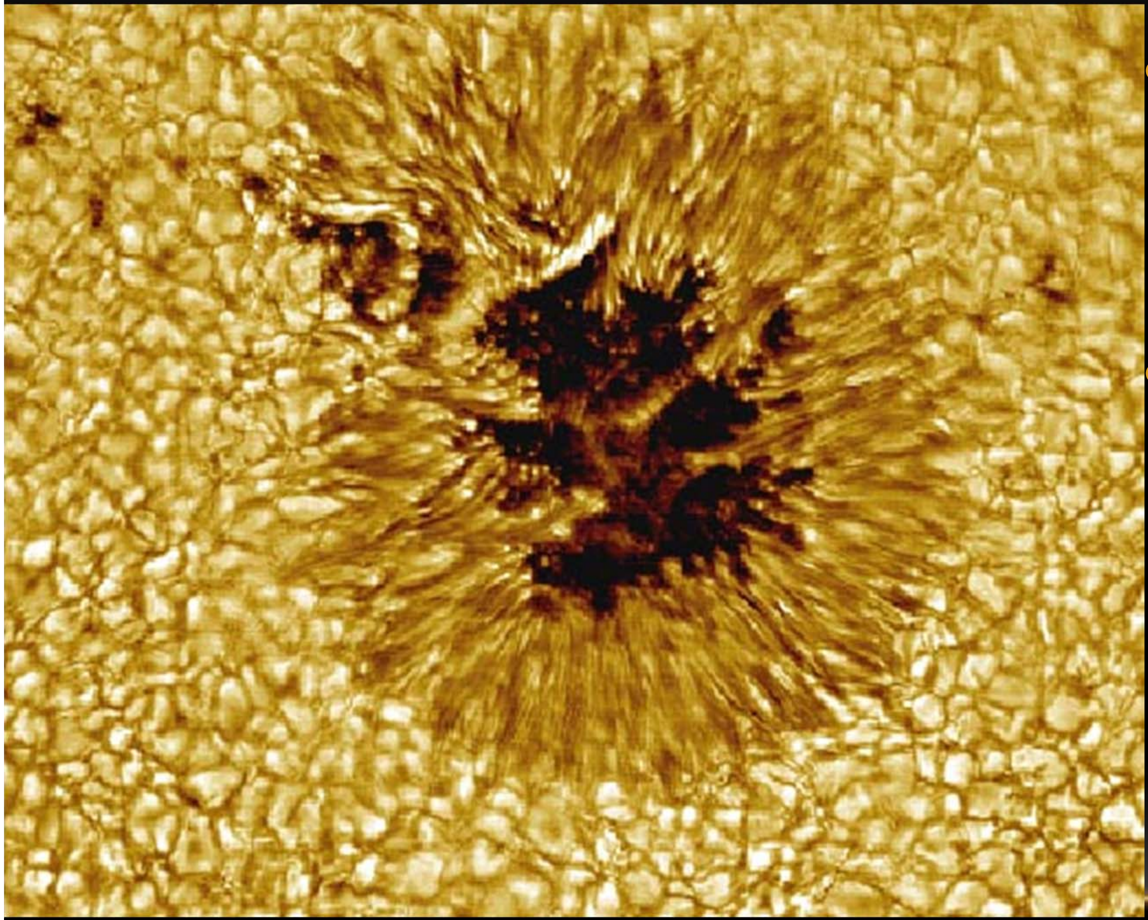
- The middle step in the diagram

Fig.11.4

CONVECTION

- Hot material physically moving carries energy by convection
- A boiling pot of water has convection
  - Hot water bubbles up from the bottom to the top
- The “convective zone” in the sun is like a great boiling pot of gas

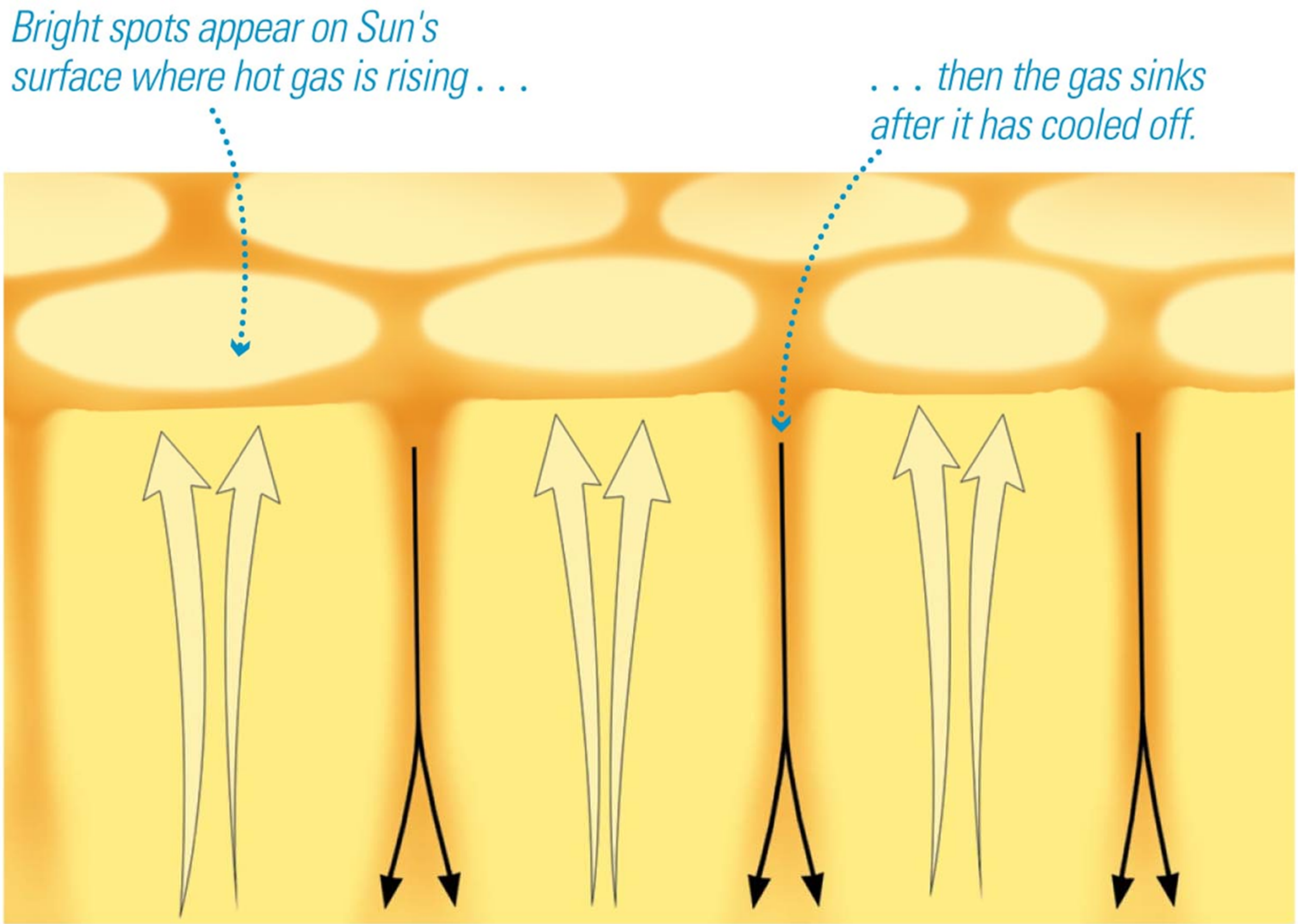
CONVECTION GRANULES



- Each “bubble” is about the size of Texas
- Here is a close up of a sunspot, with a good view of the “granules” caused by convection

Image by Vacuum Tower Telescope
NSO, NOAO

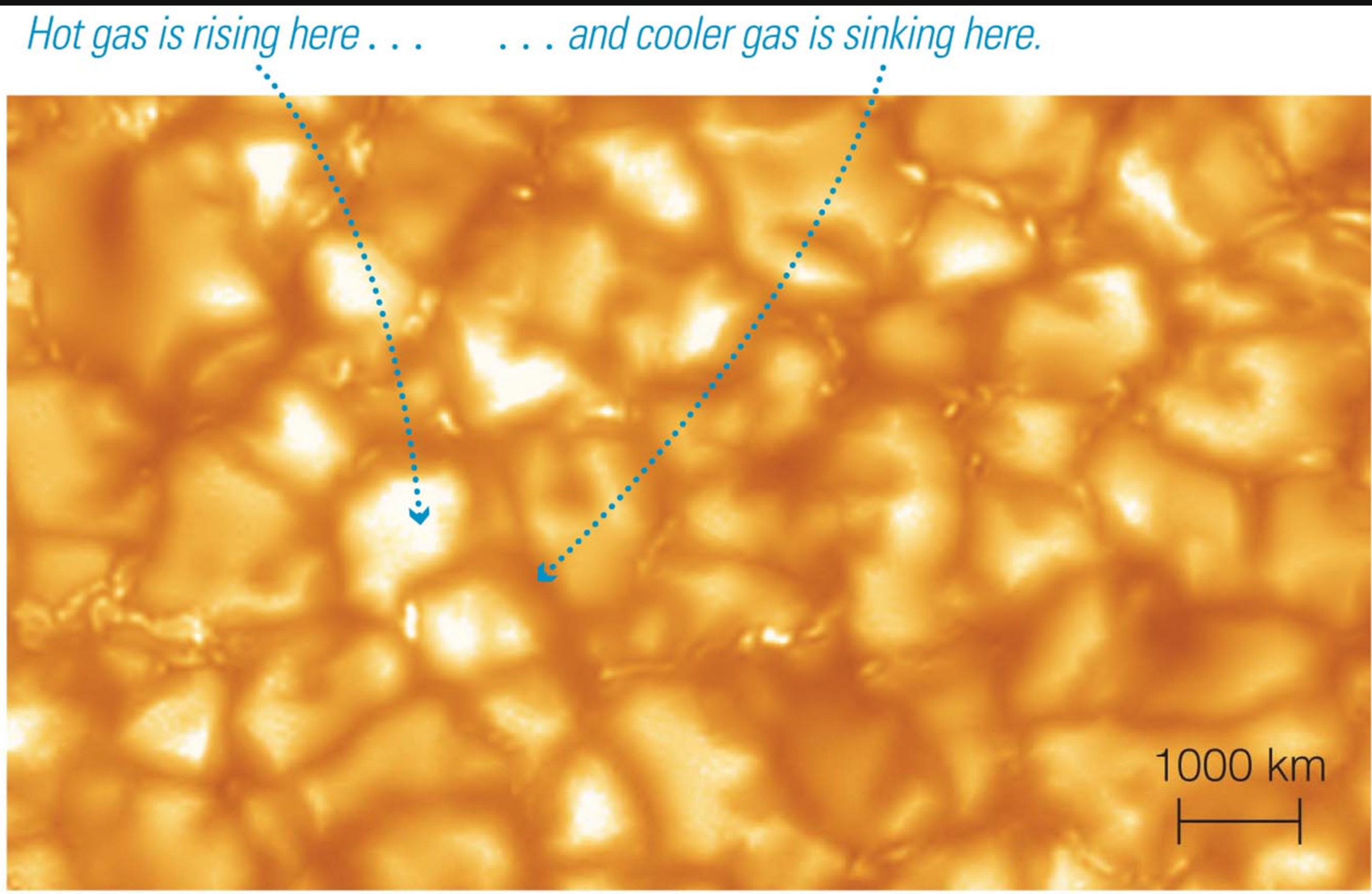
CONVECTION GRANULES



a This diagram shows convection beneath the Sun's surface: hot gas (yellow arrows) rises while cooler gas (black arrows) descends around it.

Fig.11.10a

CONVECTION GRANULES



b This photograph shows the mottled appearance of the Sun's photosphere. The bright spots correspond to the rising plumes of hot gas in the diagram in part a.

Fig.11.10b

FROM THE SUN TO US

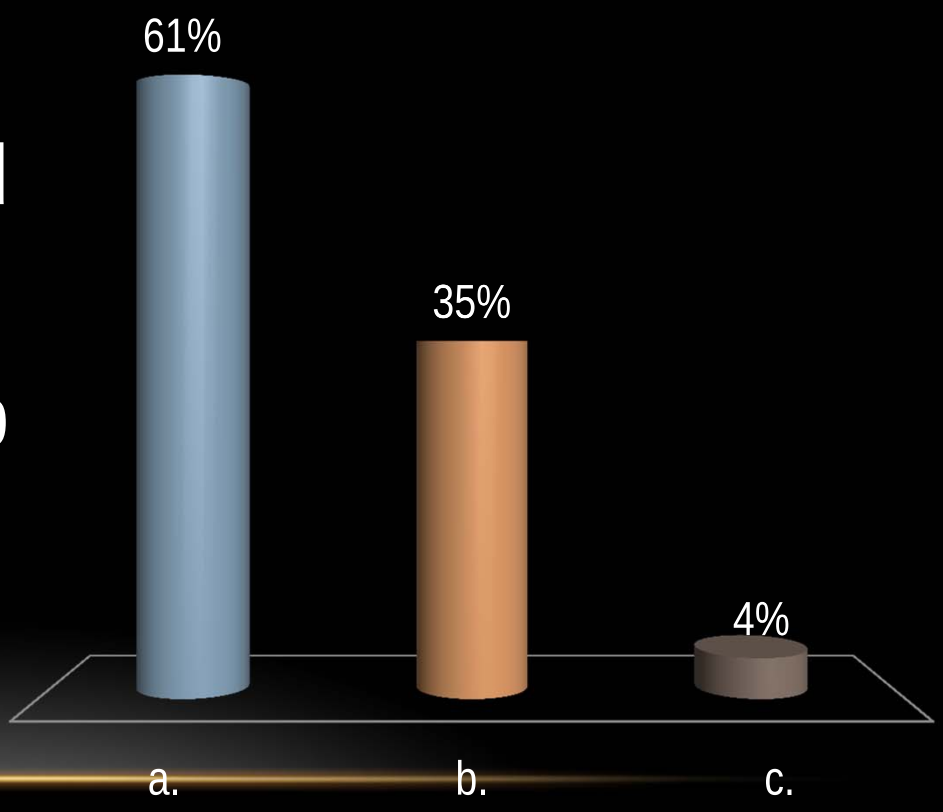
- The “surface” of the Sun we see is called the photosphere
- It’s incandescent
  - A 5780 K blackbody
- Energy travels from there to us via radiation again

WHAT WOULD HAPPEN INSIDE THE SUN IF A SLIGHT RISE IN CORE TEMPERATURE LED TO A RAPID RISE IN FUSION ENERGY?

a. The core would expand and heat up slightly.

b. The core would expand and cool. ✓

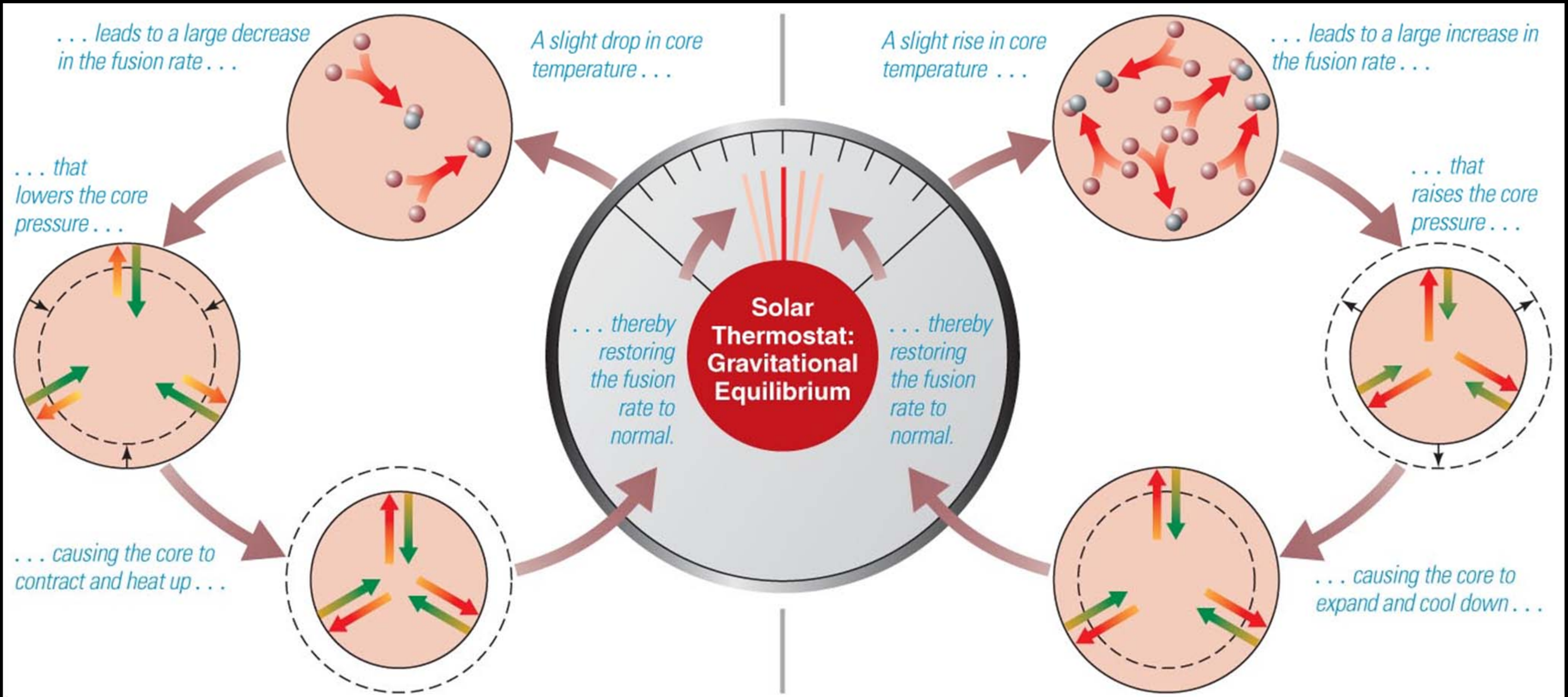
c. The Sun would blow up like a hydrogen bomb.



THE SOLAR THERMOSTAT

- This process is stable
  - So can last a long time

Fig.11.8



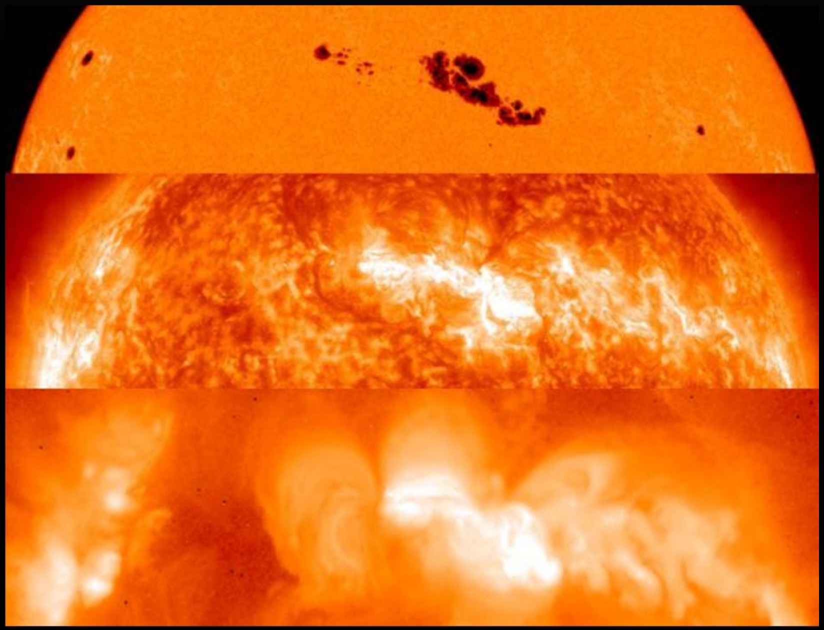
THE SUN'S ATMOSPHERE

and "surface"

THE SUN'S "ATMOSPHERE"

- "Interior" and "Atmosphere" rather foggy concepts when the whole thing is a ball of gas
- The dividing line is:
  - Interior – stuff we can't see directly
  - Atmosphere – stuff we can see directly with visible light

THE SUN'S "ATMOSPHERE"

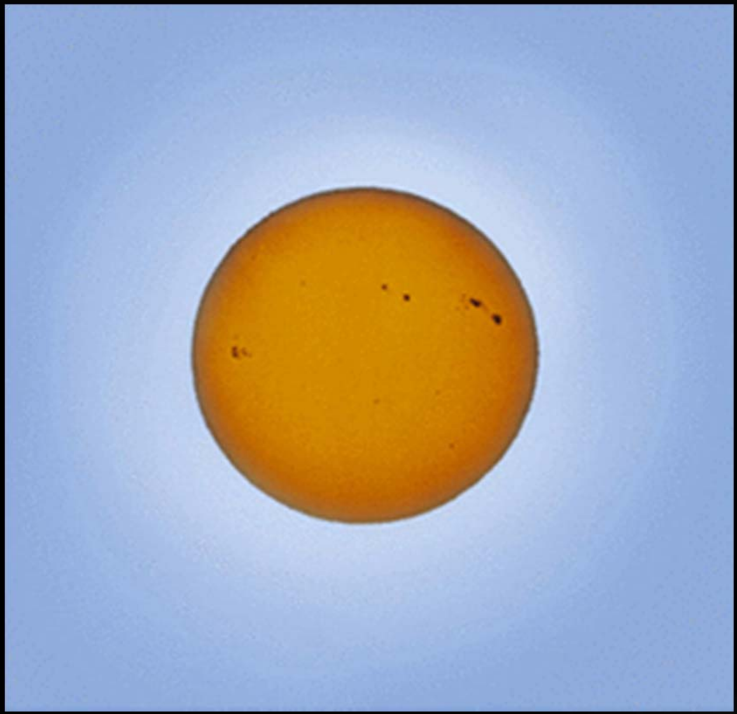


The same view from SOHO and Yohkoh in 3 different wavelengths of light

- We will discuss three regions:
  1. Photosphere
     – Visible light
  2. Chromosphere
     – UV + emission lines
  3. Corona
     – X-ray

PLAY

PHOTOSPHERE



- “light sphere”
- The incandescent surface we see as the Sun’s disk
- Simply the place in the big ball of gas where it’s not transparent anymore
- So why so sharp?
- Thin! Only 500 km thick

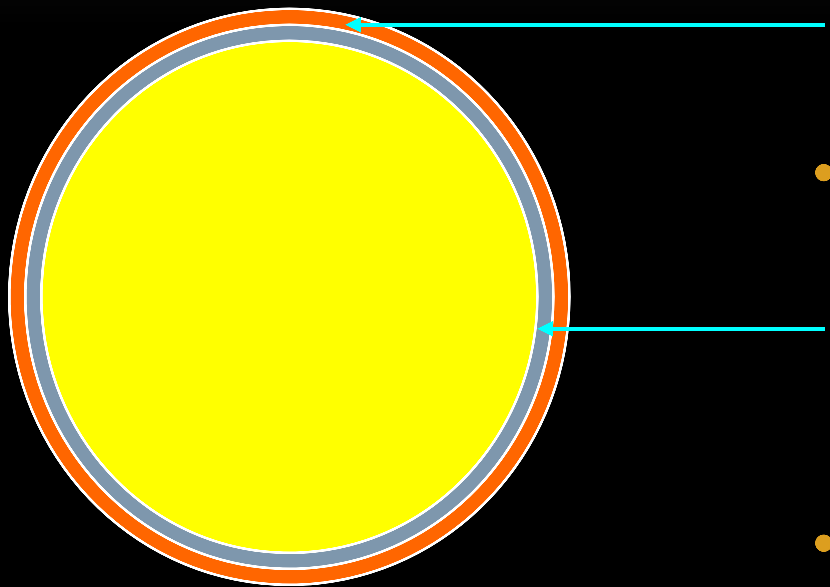
PHOTOSPHERE

- Temperature
  - Deepest part – 6500 K
  - Top part – 4400 K
  - Average 5780 K
- Density
  - Only 5/10,000 ths of the air in this room!
- But gravity is 28 g's, so pressure is
  - 1% of an atmosphere

LIMB DARKENING

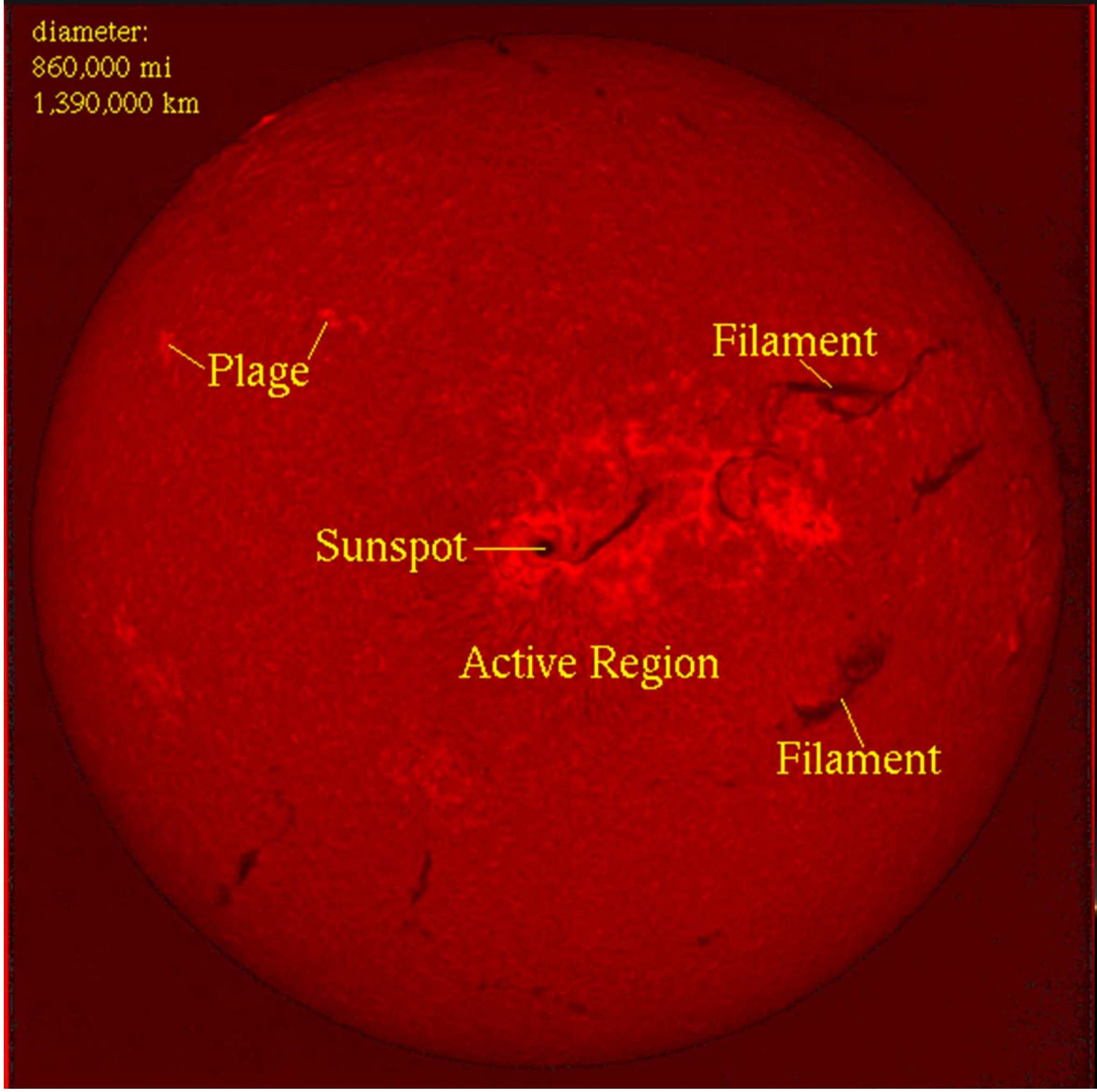
- The "limb" is the edge of the Sun's (or Moon's) disk
- The Sun's limb is darker than the middle!
- Why?

LIMB DARKENING



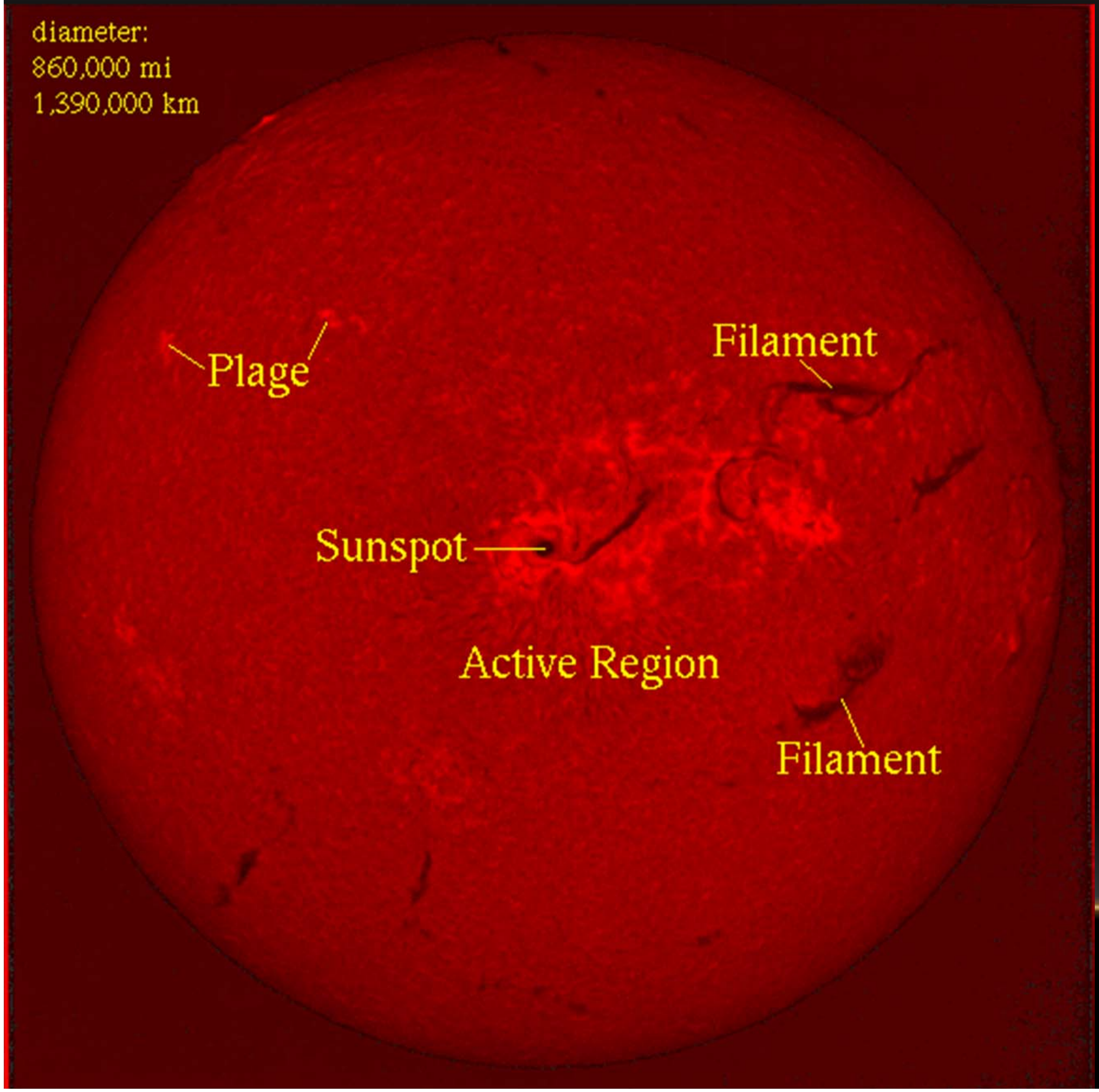
- We can see through some few hundred km of photosphere
- Near the limb, the layer we see is closer to the surface
  - Cooler (4400 K)
  - Less bright
- Looking straight in, we see a deeper layer
  - Hotter (6500 K)
  - Brighter

CHROMOSPHERE



- "Color Sphere"
- 2000 km thick, above photosphere
  - Transparent
  - ~10,000 K
- Causes the absorption lines in the solar spectra
- Which also means it re-emits the light
- This image is in Hα

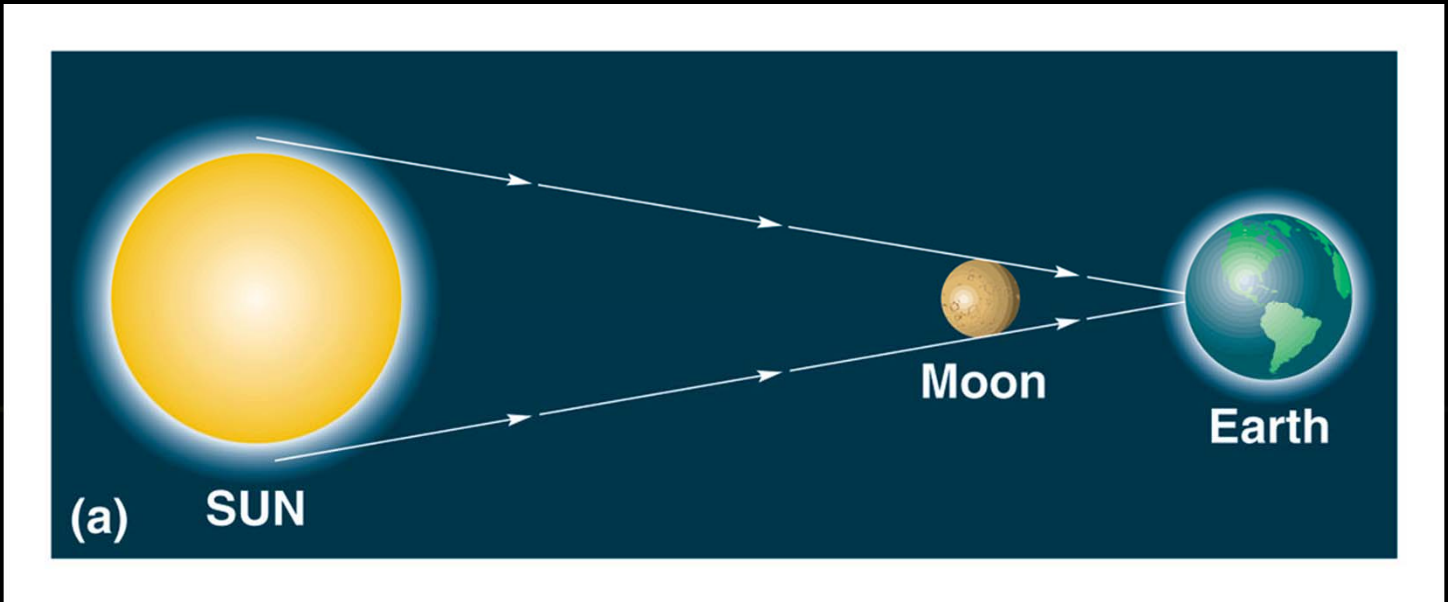
CHROMOSPHERE



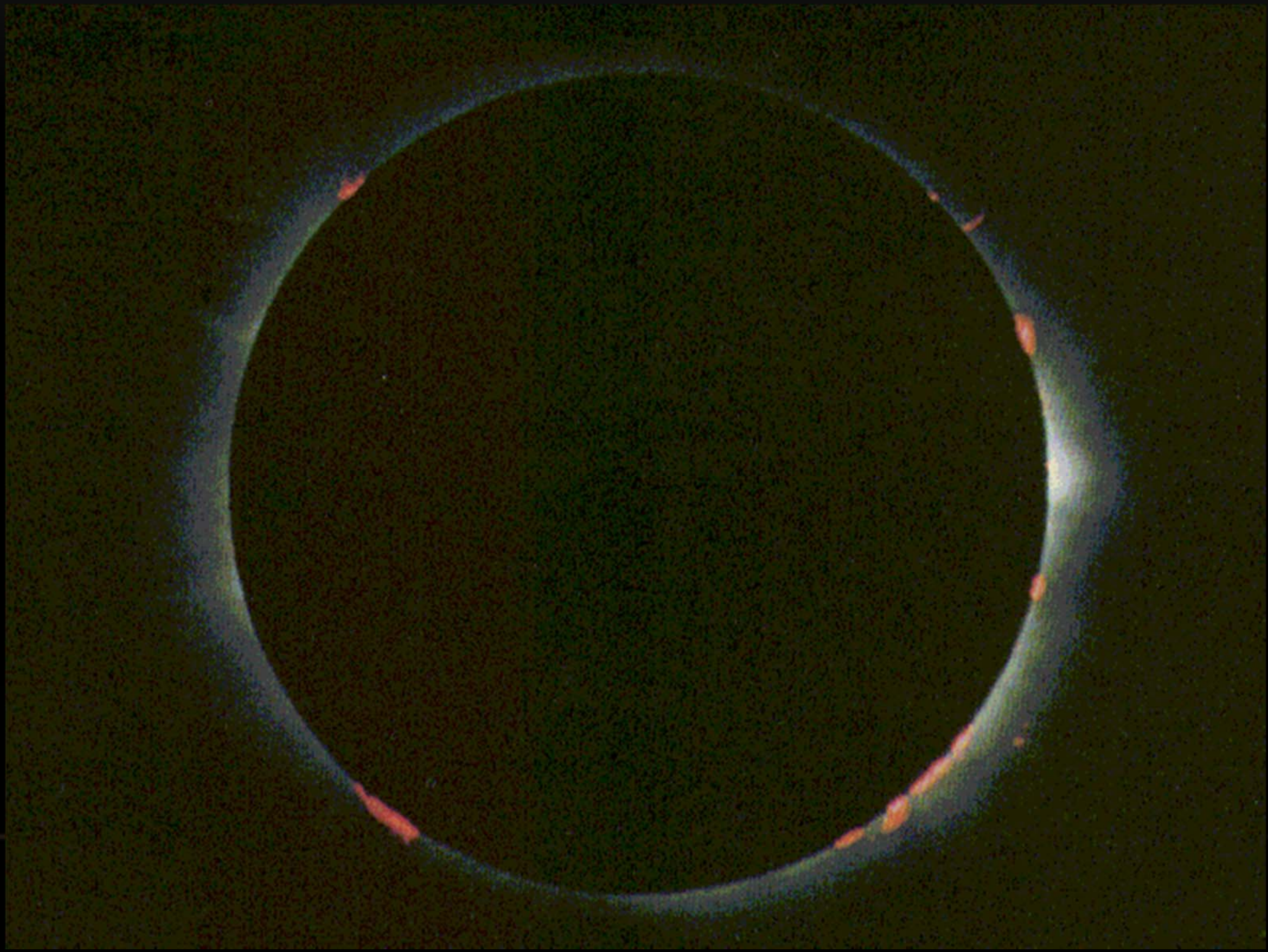
- “Plage” is a bright area
- “Filament” a dark area
  - A “prominence” seen on the disk not the limb
- Sunspots and active regions still visible (more later)

CHROMOSPHERE DISCOVERY

- Before narrow-band optical filters, eclipses were only way to see solar atmosphere
- Moon blocks out photosphere
- See Chromosphere around edges
- Can us a “coronagraph” to make an artificial eclipse



CHROMOSPHERE IN AN ECLIPSE

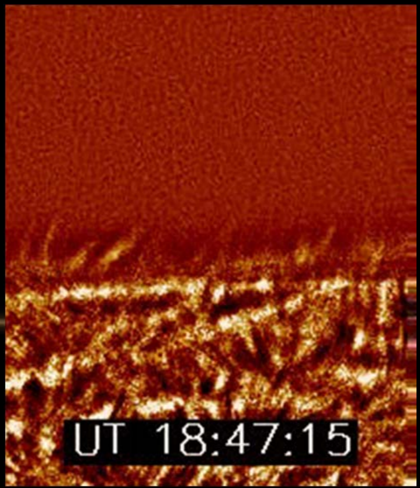


SPICULES

- Small "flame"-like jets in chromosphere
- Shoot up 6-10,000 km
- Last 10-20 minutes

Dark features in right of image are spicules, jets of gas moving toward the camera at about 30,000 mph (13.4 kps). In upper left are small sunspots and large magnetic loops connecting the sunspots. The brighter areas are strong areas of magnetism called "plage" regions, usually organized in small flux tubes. The photo measures 40,000 miles (64,370 km) across.

Courtesy of John McConnell, FRAS
(Image courtesy: Royal Swedish Academy of Sciences).



SOLAR PROMINENCES

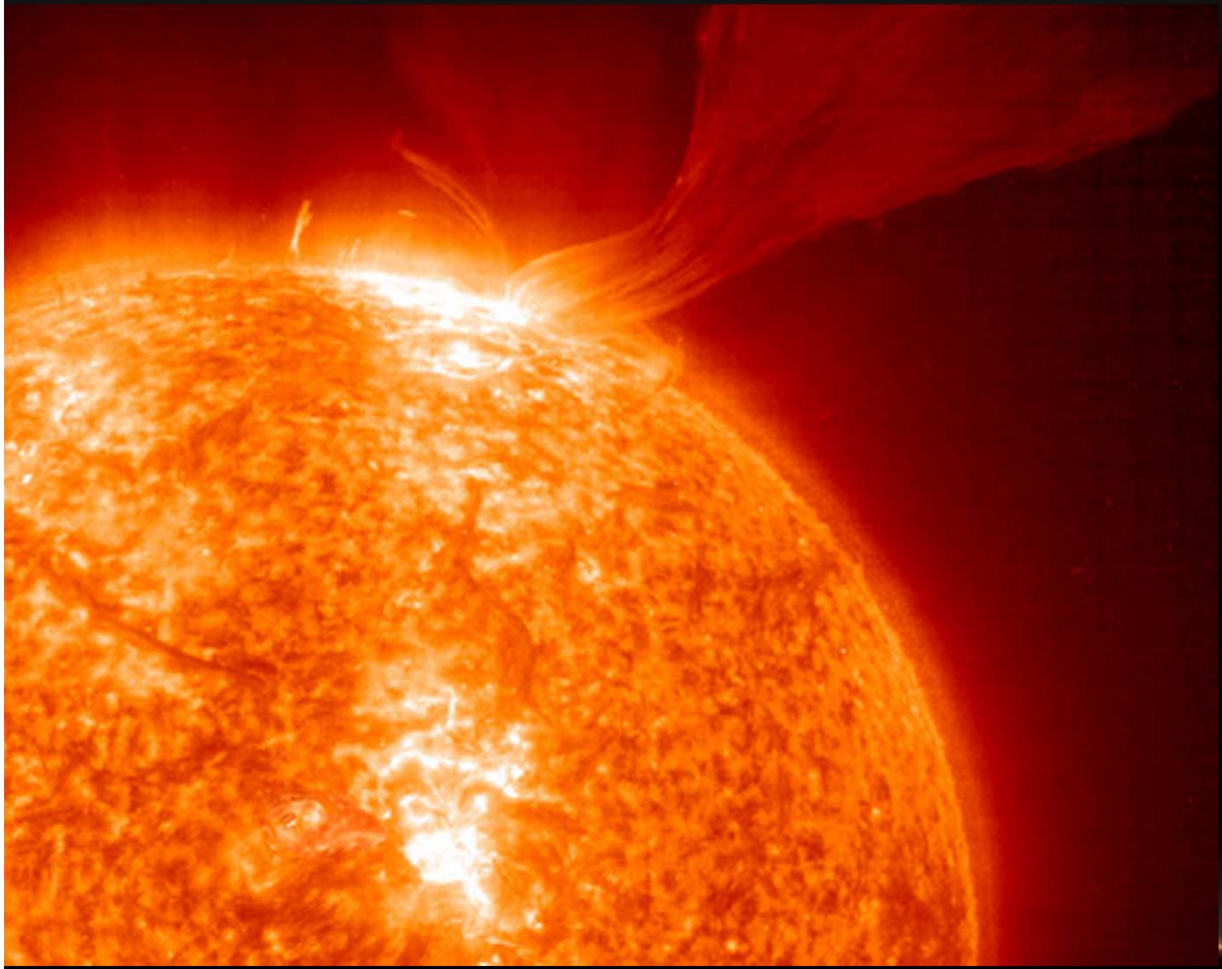


Image from SOHO

- Eruptions of material through chromosphere into corona
- Last hours to days
- Huge! But not the hugest (Solar Flares, later)
- Related to magnetic field
  - Exact mechanism still being worked out

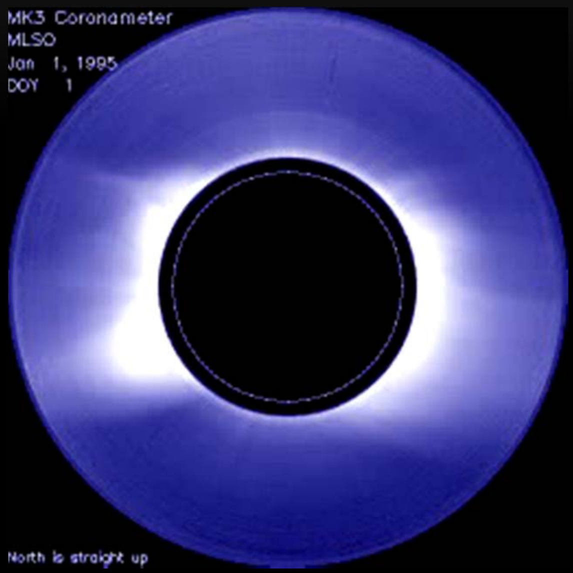
SOLAR PROMINENCES

- SOHO movie to left

TRANSITION REGION

- ~300 km thick region between chromosphere and corona
- Temperature climbs rapidly to millions of degrees K (the corona) in this region
- Why so hot?
  - Details not fully modeled, but helium is being ionized (phase transition) and magnetic fields start to dominate
- Ok, so why isn't this Really Bright? (σT^4)
  - Very tenuous – not much gas there to be glowing
  - It is, however, very visible in X-rays

CORONA



9 months coronagraph Movie HAO

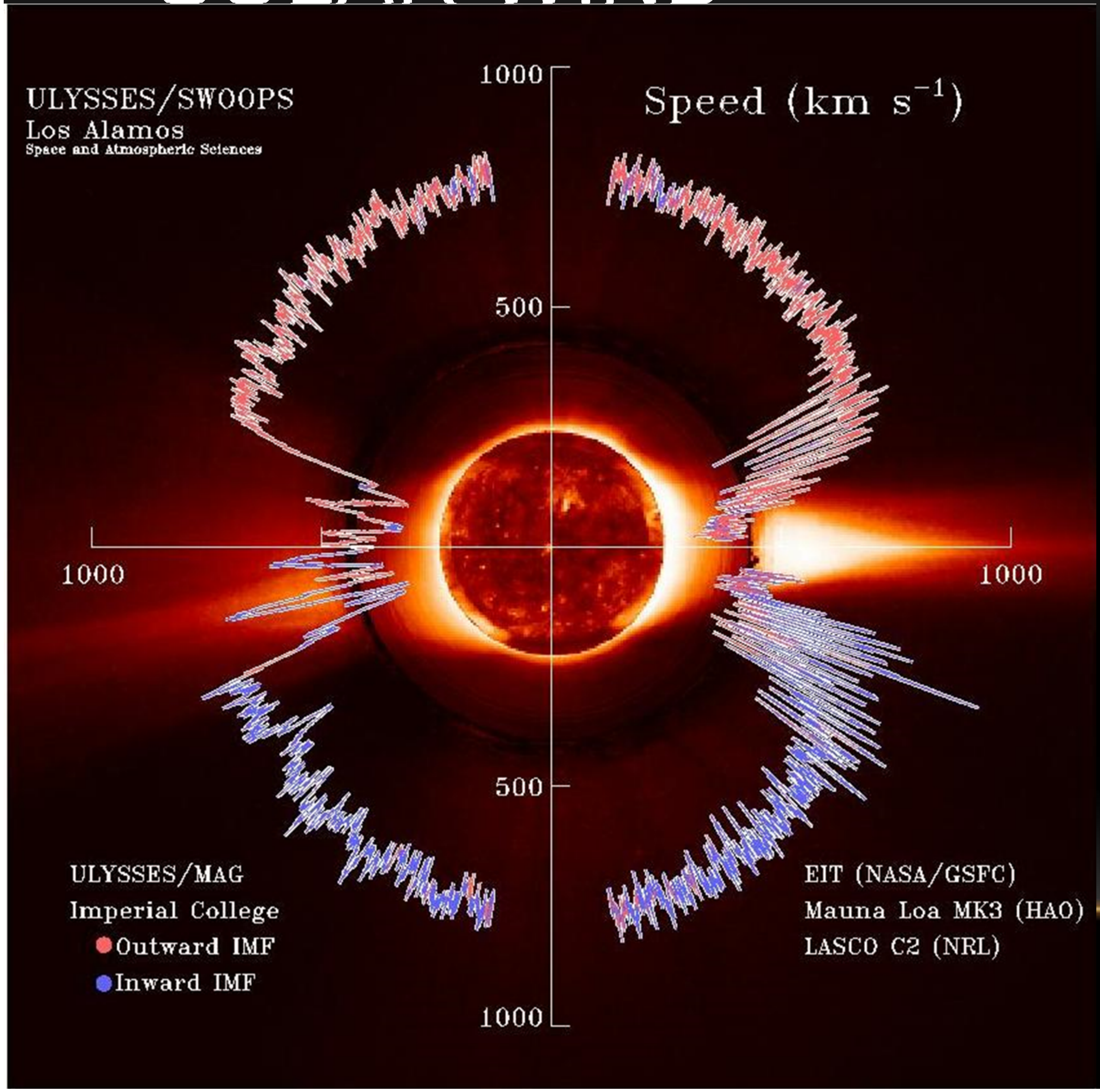
1 year movie in X-ray from Yohkoh

- The most-visible thing in an eclipse
- Very hot – millions of degrees
- Quite large
- But very tenuous
  - 1 trillionth the density of this room's air

ECLIPSE WITH EARTHSHINE!

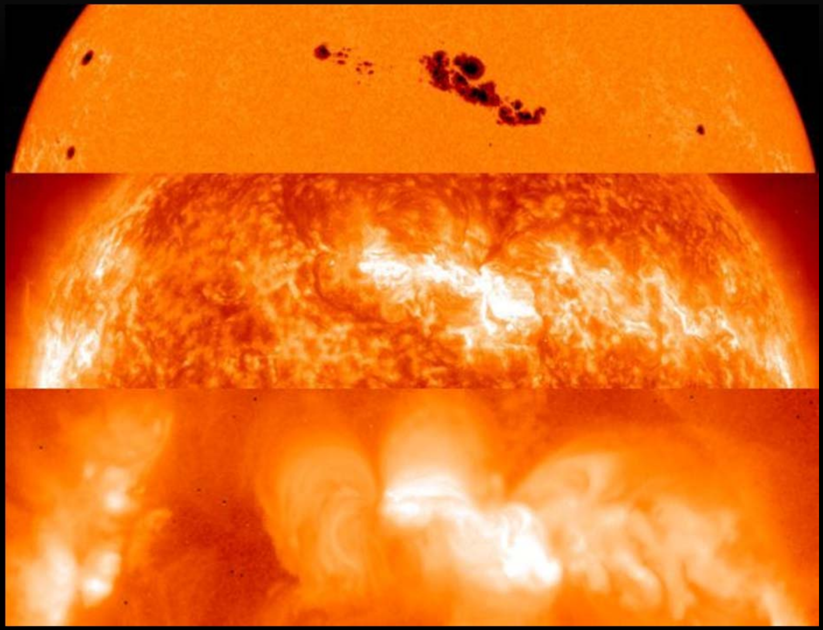
Photo by Fred Espenak of June 21, 2001 eclipse in Zambia

SOLAR WIND



- The corona extends out, boils off to form the Solar Wind
- Flares, Coronal Mass Ejections kick great piles of matter into the wind
- Coronal Holes
  - Backwards aurora
  - Particles follow magnetic field lines outwards

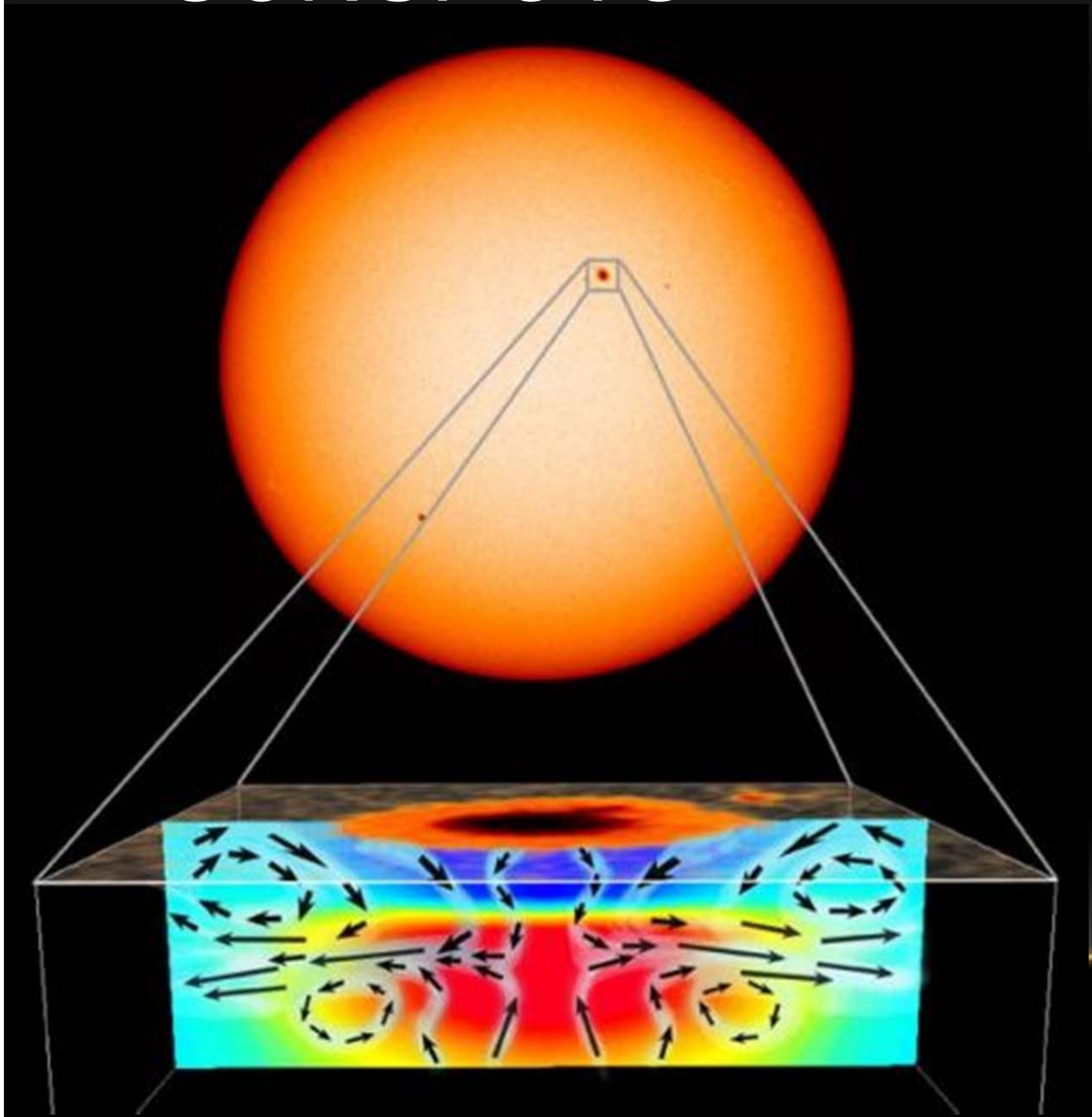
SUNSPOTS



The same view from SOHO and Yohkoh in 3 different wavelengths of light

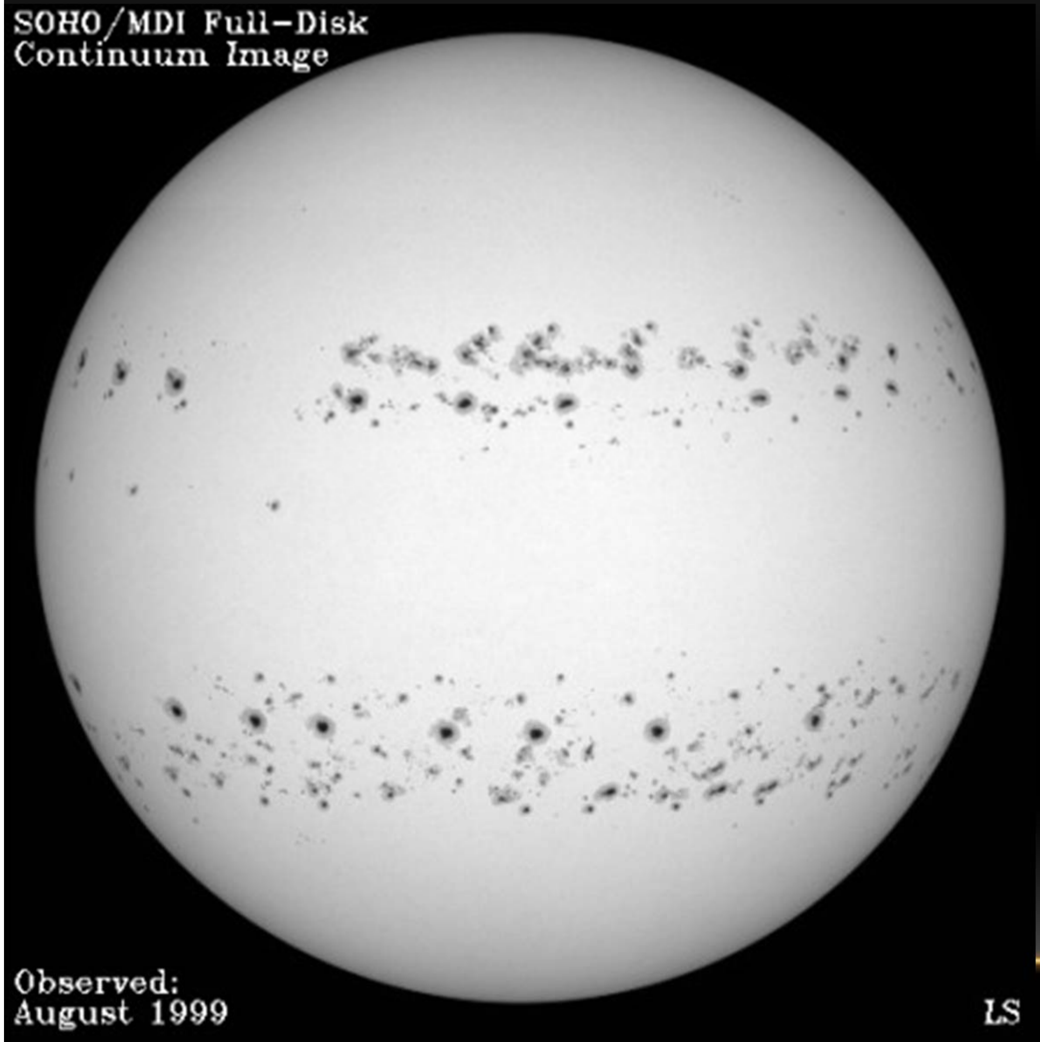
- Dark regions on the photosphere
- Match with bright regions in the chromosphere
- And active regions in the corona
- Associated with activity like prominences and flares
- About as big as planets

SUNSPOTS



- Last for a solar rotation or so
  - ~weeks to a month
- Are darker because they are cooler
  - ~1500 K cooler!
- Often in pairs
- Have strong magnetic fields
  - 1000x that of the surroundings
- Sustained by a strong undertow

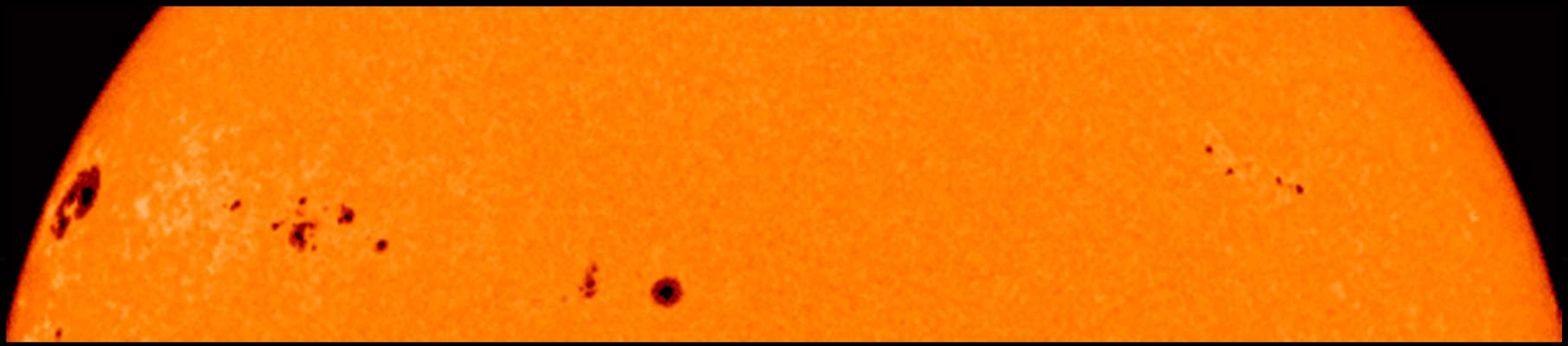
SOLAR ROTATION



- Daily images of two sunspot groups (superimposed)
- Shows rotation of Sun
- Shows changes in the active regions

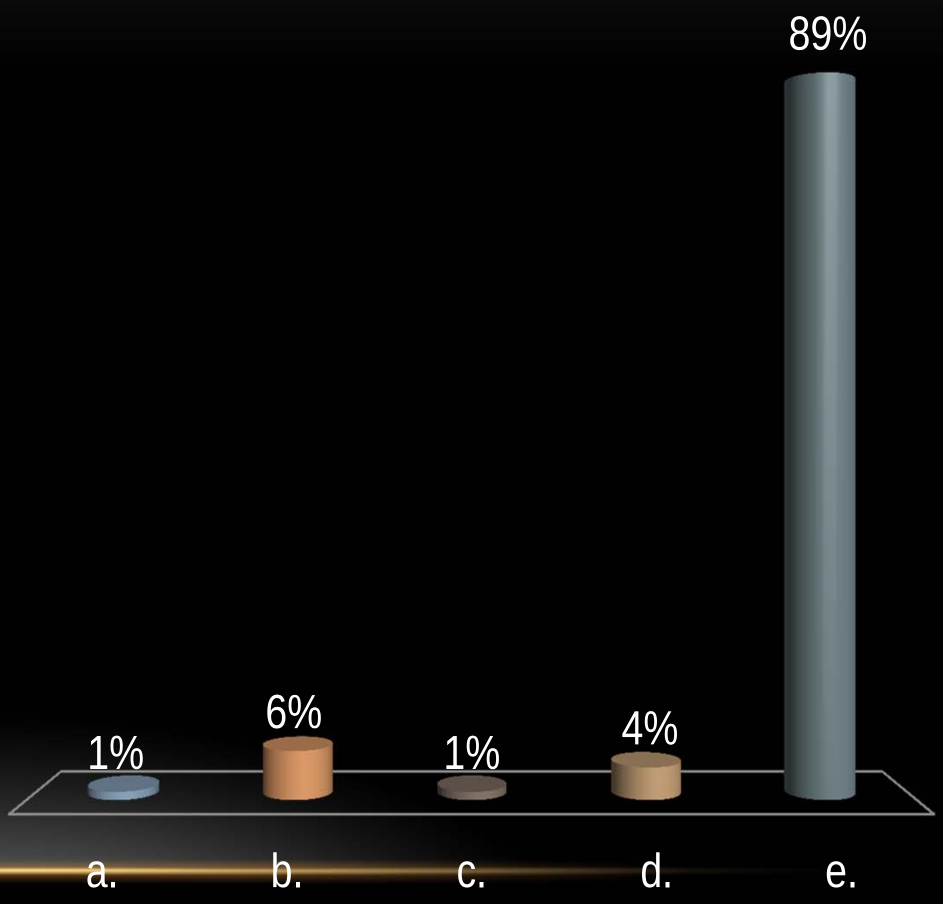
SUNSPOTS IN ACTION

- A series of pictures of AR 9393
  - 27 March to 2 April 2001
  - Composite of many photos from MDI, SOHO, ESA, NASA
  - Cuts loose with one the biggest Solar flare ever right after this movie stops

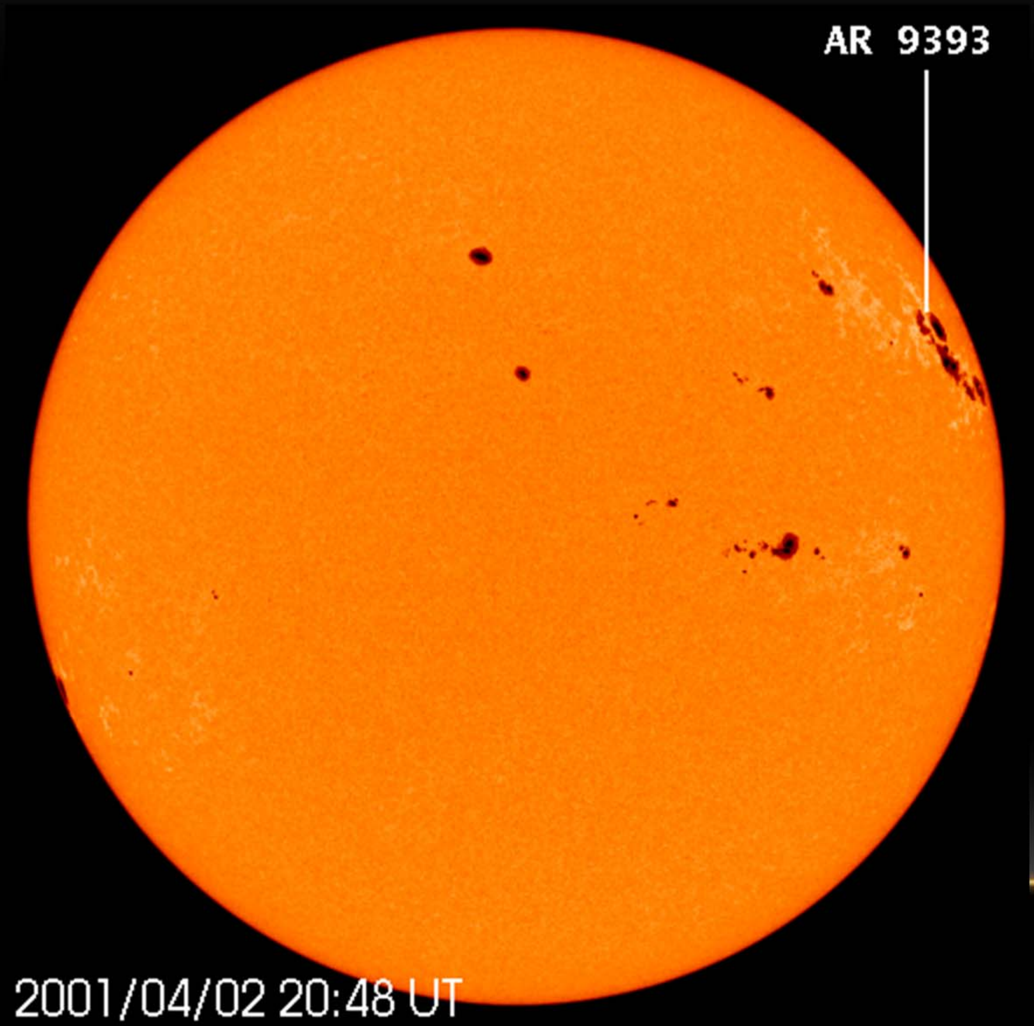


HOW DOES SOLAR ACTIVITY AFFECT EARTH?

a. It can make beautiful aurorae.
b. It can cause geomagnetic storms.
c. It can occasionally harm satellites.
d. It can sometimes disrupt electrical power.
e. All of the above. ✓

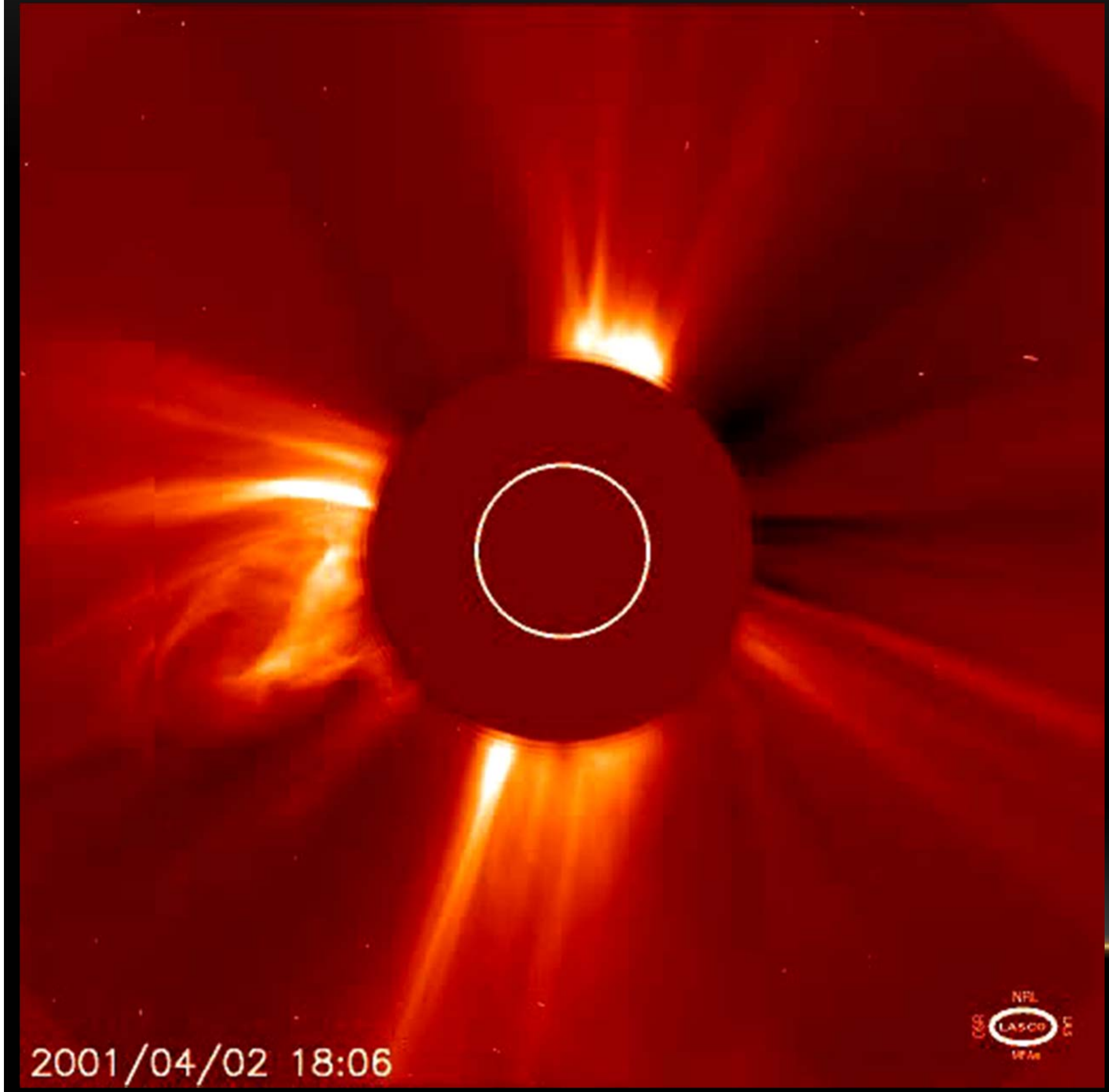


CORONAL MASS EJECTION



- Big “Coronal Mass Ejection” at 7.2 million km/hr
- Great blob of Sun stuff kicked out into the solar wind by magnet loop
- Luckily away from Earth, a smaller one toasted Quebec’s power grid in 1989

CORONAL MASS EJECTION



- Big "Coronal Mass Ejection" at 7.2 million km/hr
- Great blob of Sun stuff kicked out into the solar wind by magnet loop
- Luckily away from Earth, a smaller one toasted Quebec's power grid in 1989