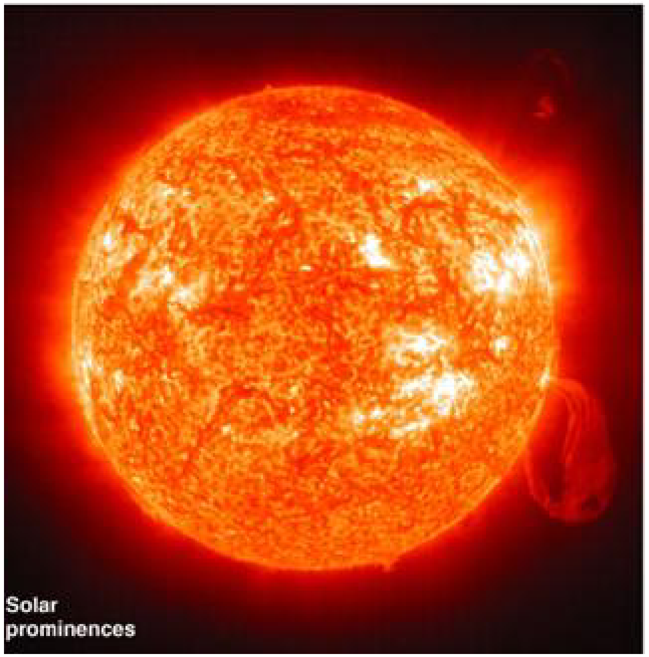
The Sun

October 21, 2002

1) H-R diagram
2) Solar Structure
3) Nuclear Fusion
4) Solar Neutrinos
5) Solar Wind/Sunspots



Review

- Blackbody radiation
- Measuring stars
  - distance
  - luminosity
    - brightness and distance
  - temperature
    - wavelength of light
  - size
    - luminosity and temperature
  - mass
    - interaction with gravity

How to Measure Velocity

- The light put out by stars contains absorption lines
  - caused by atoms in star's atmosphere absorbing certain wavelengths of light
- These lines are shifted by Doppler effect
  - if star is moving relative to us
  - can measure its velocity towards or away from us

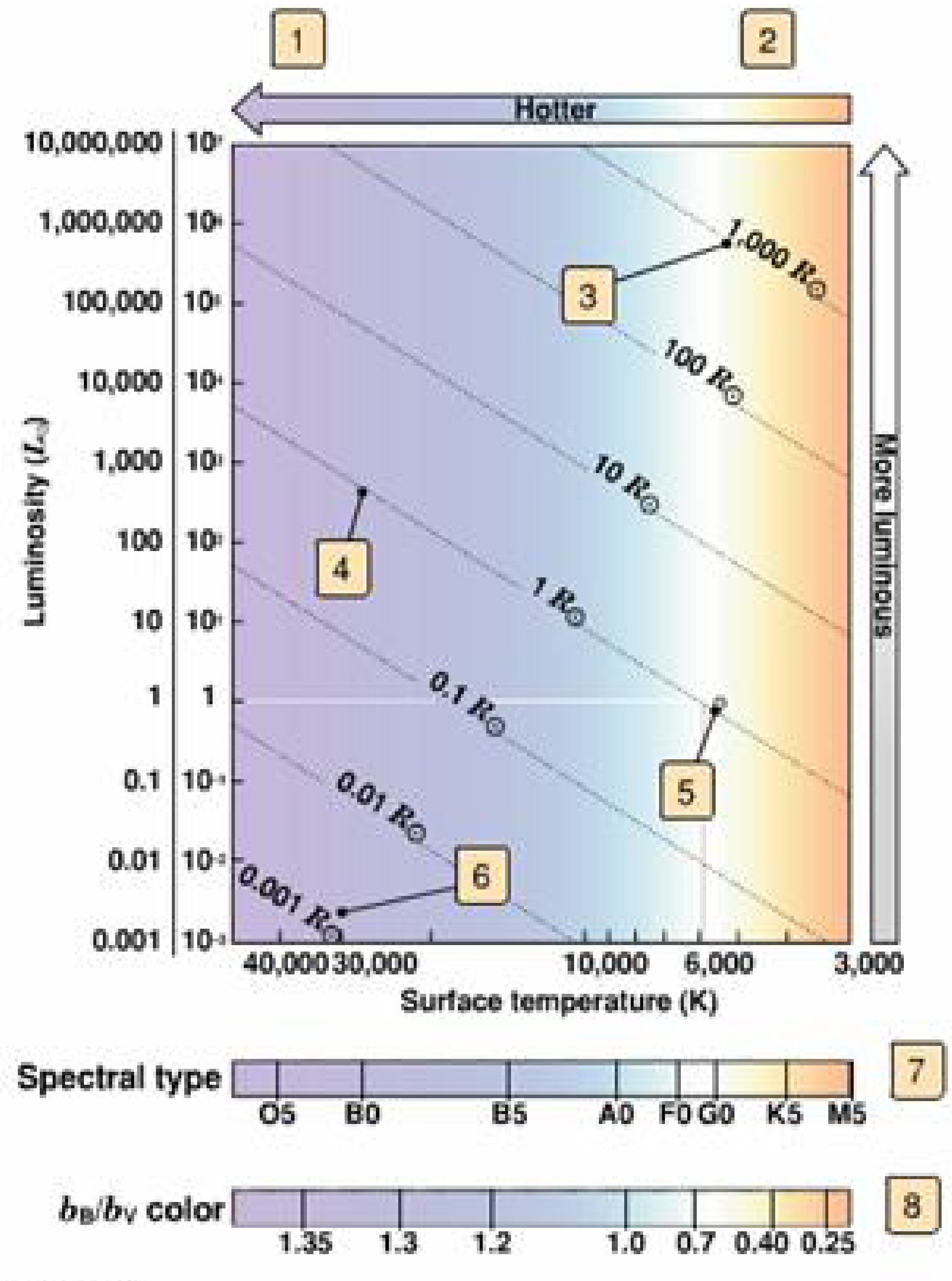
Stellar Composition

- Stars are primarily composed of hydrogen and helium
  - some other trace elements
- Here's a sampling of composition

Element	Percent by Number	Percent by Mass
Hydrogen	92.5%	74.5% .
Helium	7.4%	23.7% .
Oxygen	0.064%	0.82%
Carbon	0.039%	0.37%
Neon	0.012%	0.19%
Nitrogen	0.008%	0.09%
Iron	0.003%	0.13%

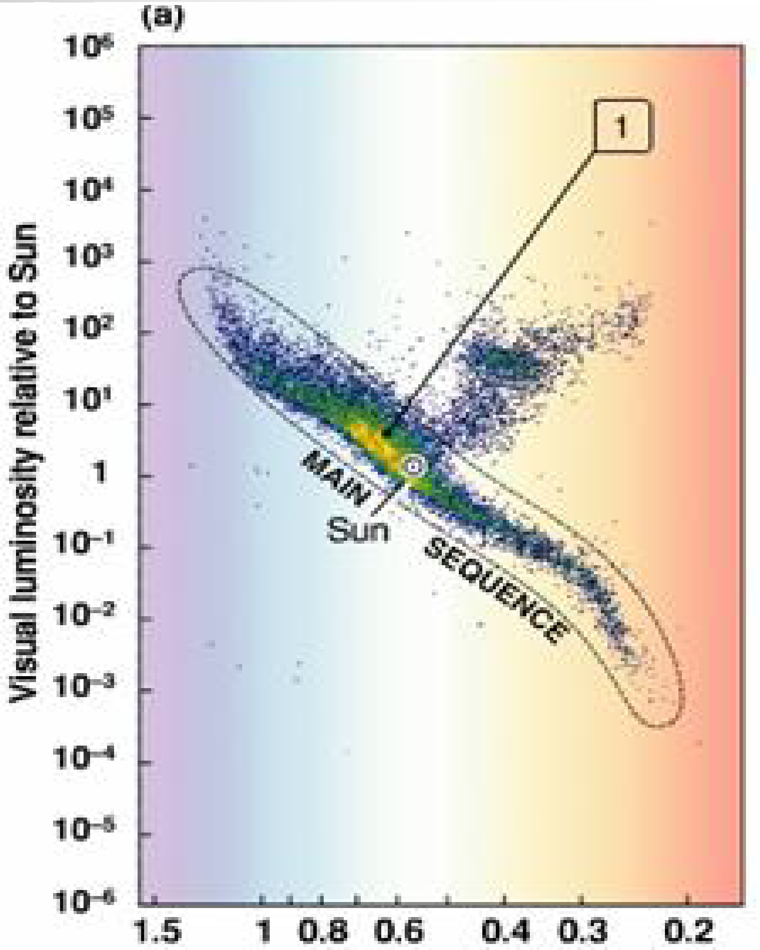
H-R Diagram

- Einar Hertzsprung
- Henry Russell
- Compiled data on stars
- Plotted luminosity vs temperature
- Astronomers consider this the most important plot

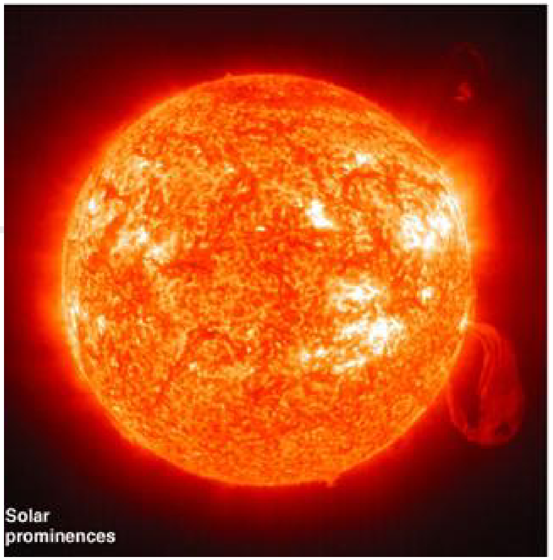


Main Sequence

- 90% of all stars are grouped together
  - Main Sequence stars
  - share similar properties
- Once you know a main sequence star's temperature, you know a lot about it
  - luminosity, distance, mass, size
- The mass of a star determines its place on the main sequence
  - and its future fate



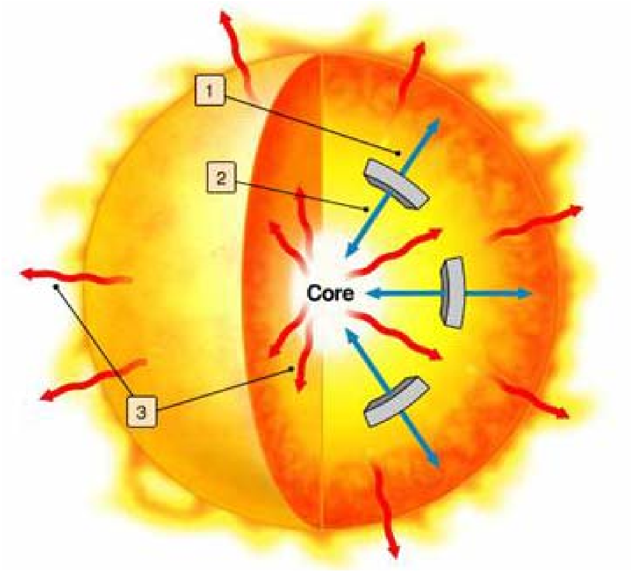
Our Sun



- Classification: G2
- Mass: 1.99×10^{30} kg
- Radius: 696,000 km
- Luminosity: 3.85×10^{26} Watts
- 99% of the mass of the Solar System
- A main sequence star

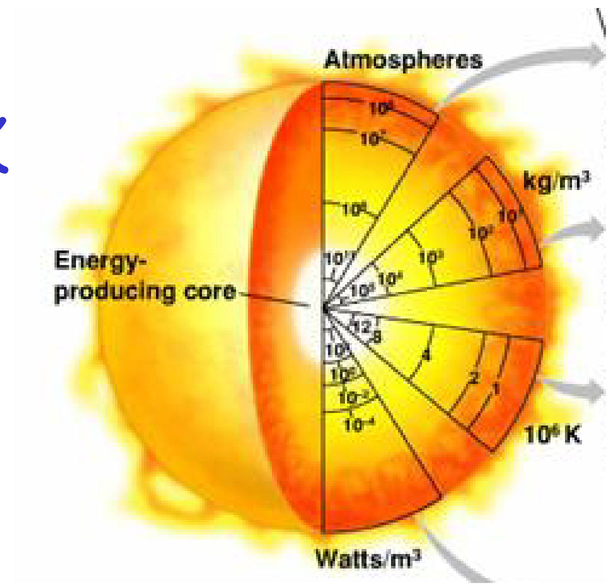
A Matter of Balance

- Equilibrium
  - a static state – everything is balanced – not changing
- Gravity
  - pulls atoms of Sun inward
- Pressure
  - pushes atoms of Sun outward
- Sun maintains constant size
  - in equilibrium
    - if gravity was stronger than pressure, the Sun would shrink
    - if pressure was stronger than gravity, the Sun would grow
- **Each point within the Sun is in equilibrium**



Solar Interior

- *As you move inward through the Sun, the pressure increases*
- Increasing pressure means increasing temperature
  - higher temperature means atoms are moving faster
  - surface temperature = 5,800 K
  - core temperature = 15,000,000 K

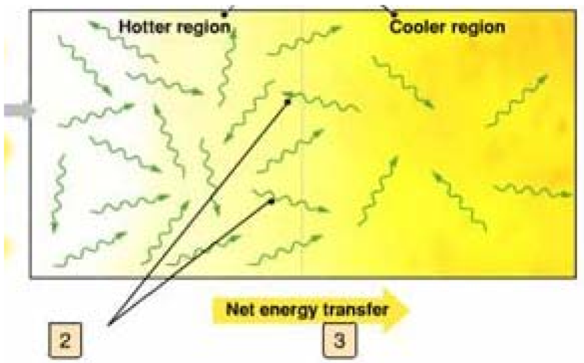


Nuclear Fusion

- The Sun is powered by nuclear fusion
  - two nuclei combining to form a single nucleus and release energy
- Hydrogen burning
  - conversion of hydrogen into helium
  - $^{1}H + ^{1}H + ^{1}H + ^{1}H \rightarrow ^{4}He$
  - four hydrogen atoms are 1.007 times the mass of one helium atom
- $E = mc^2$
  - mass = energy
  - this process converts some of the mass of the Sun into energy
  - what form of energy?

Fusion in the Sun

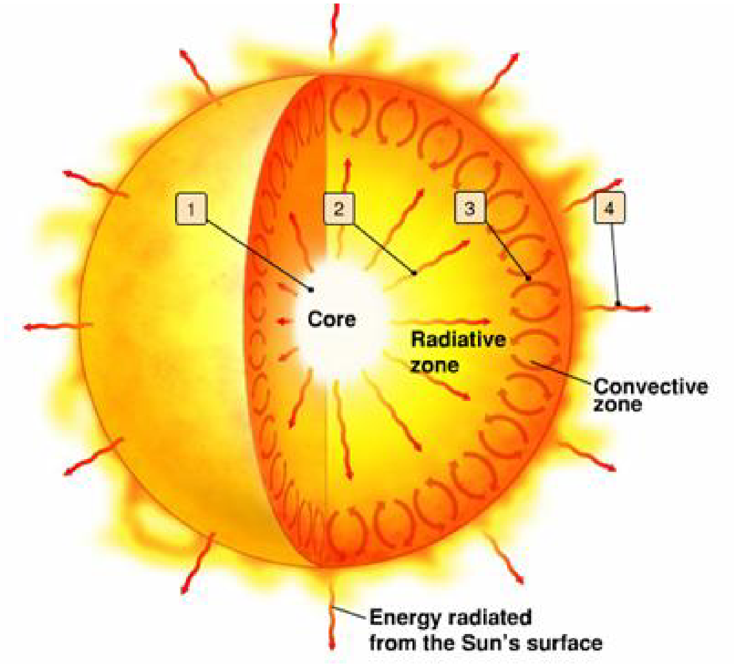
- Nuclei must get close together to fuse
  - only occurs in Sun's interior: pressure & density must be incredibly high
- Emits neutrinos and photons
  - neutrinos easily escape
  - photons collide with atoms in Sun
    - take ~100,000 years to escape the Sun



- Heat transfer
  - conduction – atoms bumping into each other
  - radiation – emission of light
  - convection – atoms "rising" towards the exterior
- Radiation is the main source of heat/energy transfer from the interior of the Sun

Solar Interior (Part II)

- Core
  - central area where fusion occurs
- Radiation zone
  - outside of core where heat transferred by radiation
- Convection zone
  - next layer where heat transferred by convection



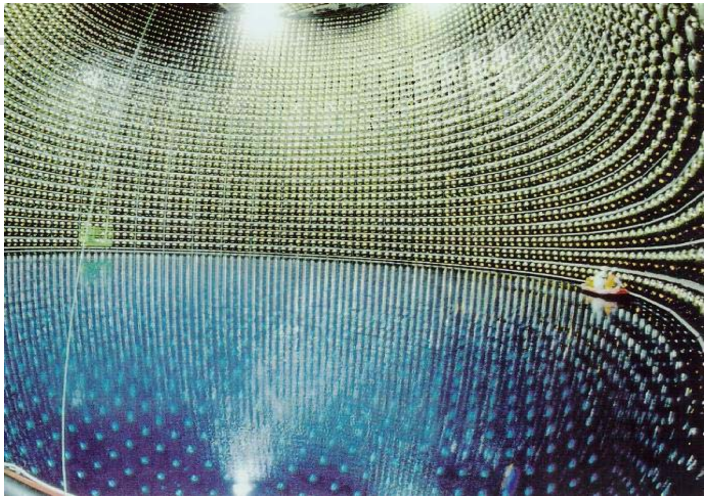
Neutrinos from the Sun

- Neutrinos are very elusive particles
  - very rarely interact with matter
  - escape the Sun's interior easily
  - pass through the Earth easily
  - pass through you easily
    - ~4×10^{14} neutrinos pass through you each second
- We can use neutrinos to study the Sun
  - need a massive detector
  - need to take data for a long time

Nobel Prize in Physics - 2002

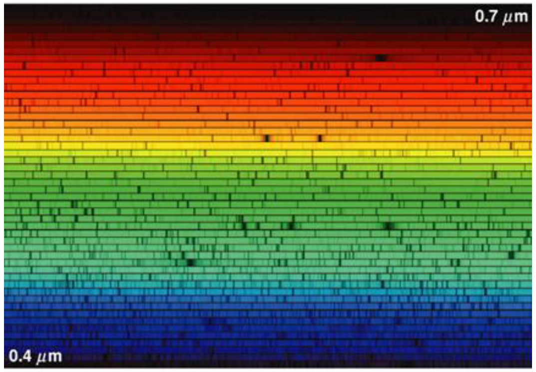
- Ray Davis, Masatoshi Koshiba, and Riccardo Giacconi
  - neutrino astrophysics
- Ray Davis measured the neutrinos from the Sun (1960's-1980's)
  - found only 1/3 the expected neutrinos
  - solar model wrong?
    - withstood many, many tests
  - neutrino model wrong
    - something happening to neutrinos?

Super-Kamiokande and SNO

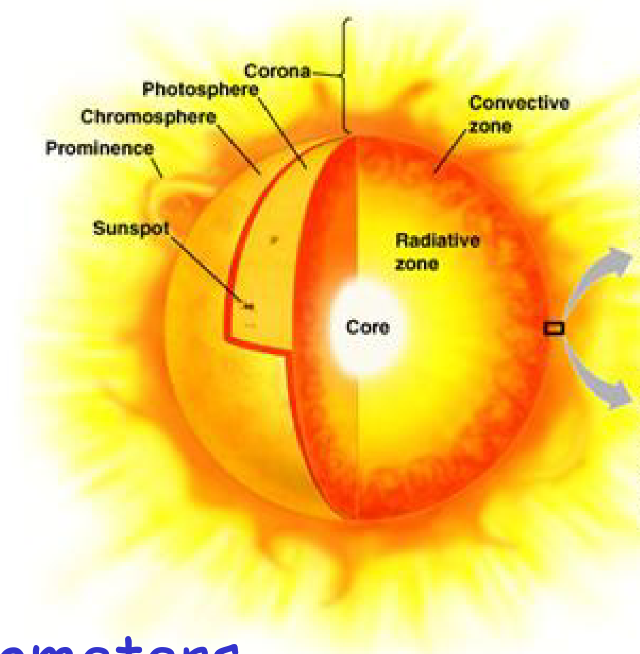


- Super-Kamiokande
  - Japanese experiment to measure solar neutrinos
  - confirmed 1/3 neutrinos
  - used 11,000 phototubes in a tank of 50,000 tons of ultrapure water
  - took first pictures of Sun with neutrinos
- SNO - Sudbury Neutrino Observatory
  - found that solar neutrinos were changing on their way to Earth
  - all the neutrinos were there - solar model correct

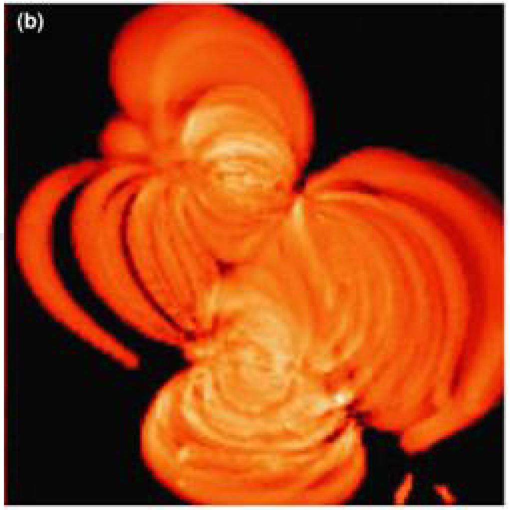
Solar Surface and Atmosphere



- Solar "surface" - photosphere
  - 500 km thick
- Atmosphere
  - absorbs some photons – creates absorption lines in light from Sun
- Chromosphere
  - above the photosphere
  - about 100 km thick
- Corona
  - above the chromosphere
  - very hot – 1,000,000 K
  - very large – extends millions of kilometers

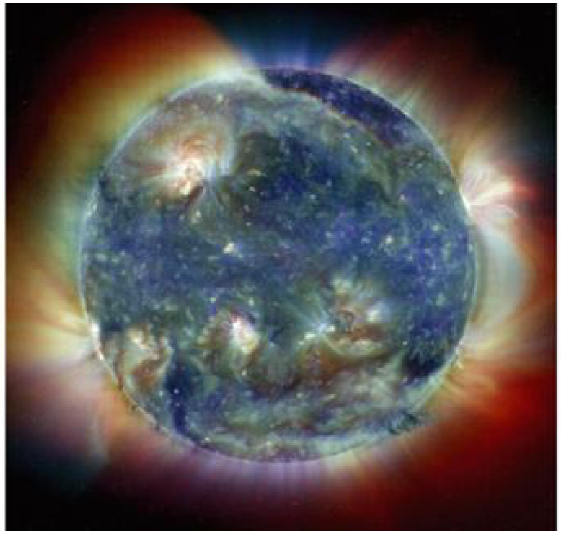


Solar Magnetic Fields

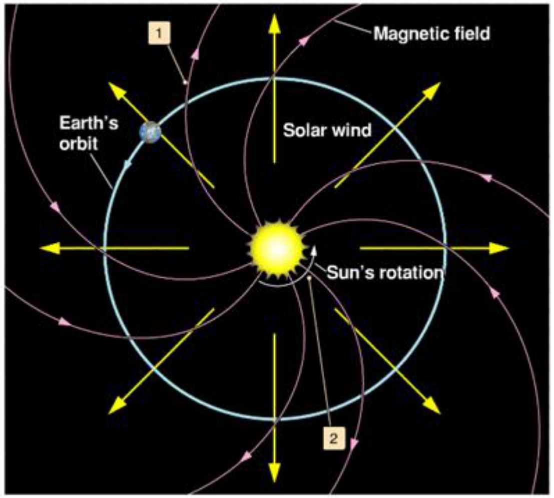


- The Sun's magnetic field is very complicated
- It has magnetic "tubes" through which particles travel
  - like a water hose
  - each end of the tube is connected to the Sun's surface
- Coronal holes
  - where magnetic field points outward and particles escape
- Magnetic field is constantly changing
  - partially due to Sun's rotation
  - occasionally flips direction

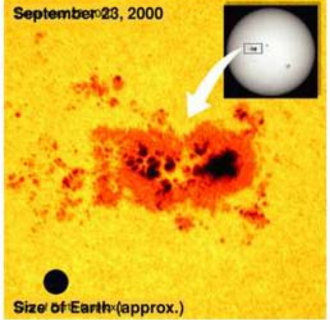
Solar Wind



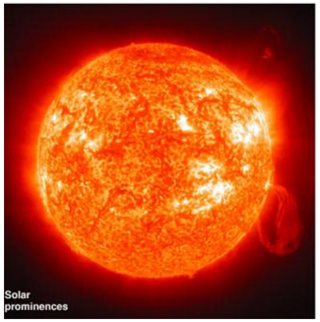
- Particles escape the Sun through coronal holes
  - travel outward from the Sun
  - responsible for comet's tail and for blowing away primary atmospheres of inner planets
  - pushes interstellar dust out of the Solar System
- Solar wind changes as Sun rotates
- Effects Earth
  - satellites
  - Aurora Borealis



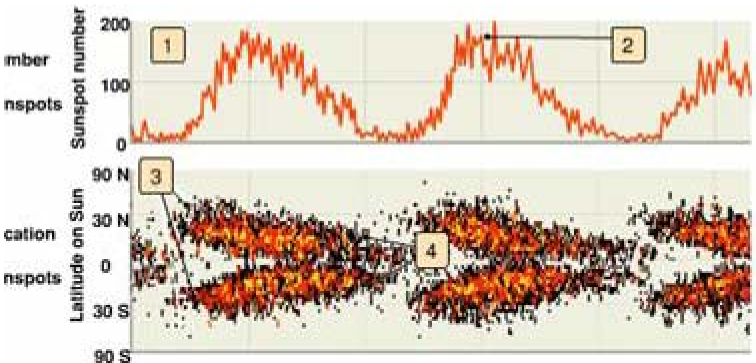
Sunspots



- Sunspots are cooler parts of the solar surface
  - most visible solar "structure"



- Caused by magnetic field loops
  - found in pairs
  - shift around with field



- Sunspot cycle
  - Sunspots follow an 11-year period
    - magnetic field changes over 11 years and then flips over

Variations in the Sunspot Cycle

- The sunspot cycle varies
  - sometimes more intense than others
  - some long periods with almost no sunspots
    - Maunder minimum – 1645-1715
    - cooler than normal in Europe