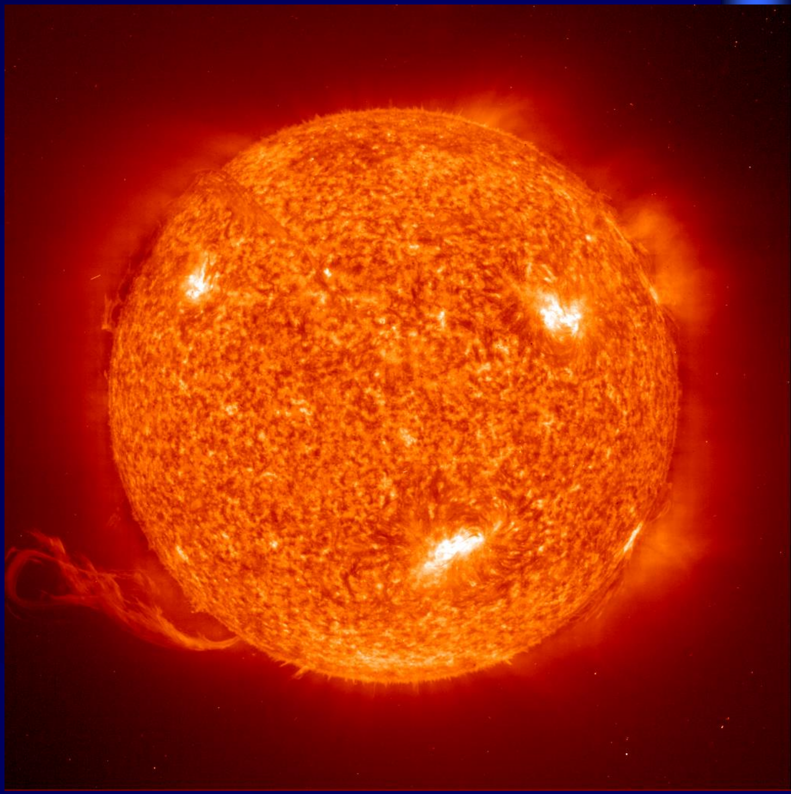
The Sun

The Sun – A typical Star

- The only star in the solar system
- Diameter: 110 × that of Earth
- Mass: 300,000 × that of Earth
- Density: 0.3 × that of Earth (comparable to the Jovians)
- Rotation period = 24.9 days (equator), 29.8 days (poles)
- Temperature of visible surface = 5800 K (about 10,000º F)
- Composition: Mostly hydrogen, 9% helium, traces of other elements



Solar Dynamics Observatory Video

How do we know the Sun's Diameter?

- Trickier than you might think
- We know only how big it **appears**
  - It appears as big as the Moon
- Need to measure how far it is away
  - Kepler's laws don't help (only relative distances)
- Use two observations of Venus transit in front of Sun
  - Modern way: bounce radio signal off of Venus

How do we know the Sun's Mass?

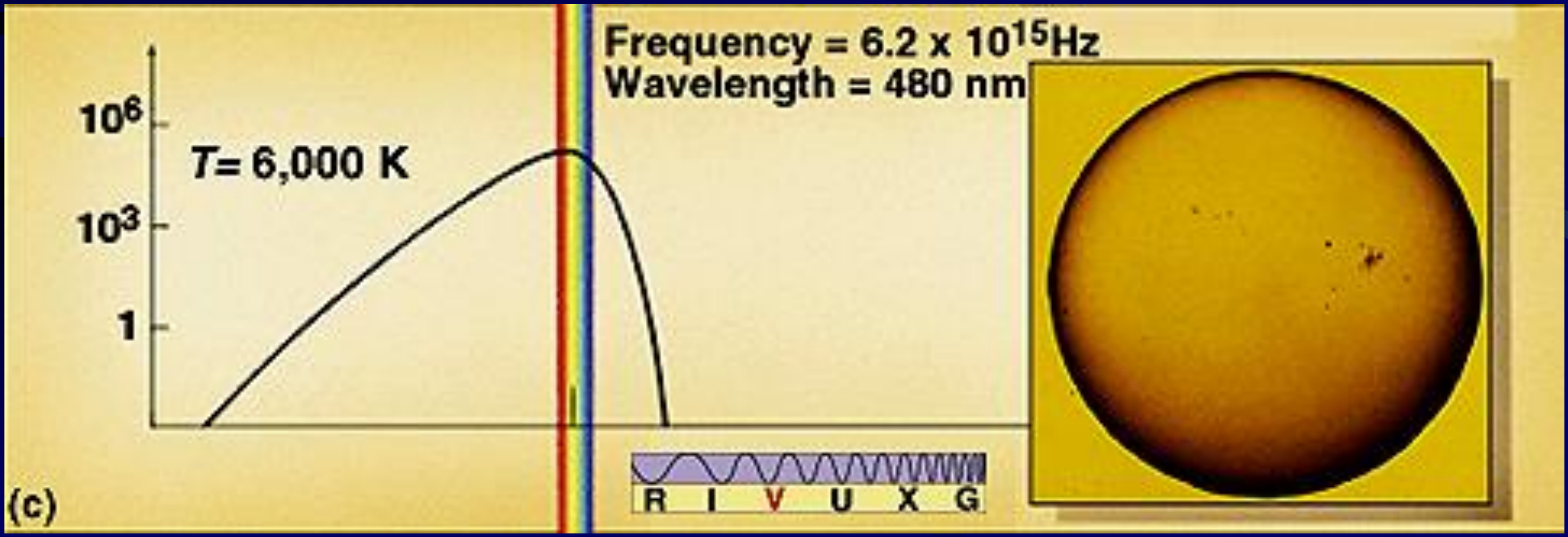
- Fairly easy calculation using Newton law of universal gravity
- Need to know distance Earth-Sun
- General idea: the faster the Earth goes around the Sun, the more gravitational pull → the more massive the Sun
- Earth takes 1 year to travel 2π (93 million miles) → Sun's Mass = 300,000 × that of Earth

How do we know the Sun's Density?

- Divide the Sun's mass by its Volume
- Volume = $4\pi/3 \times (\text{radius})^3$
- Conclusion: Since the Sun's density is so low, it must consist of very light materials

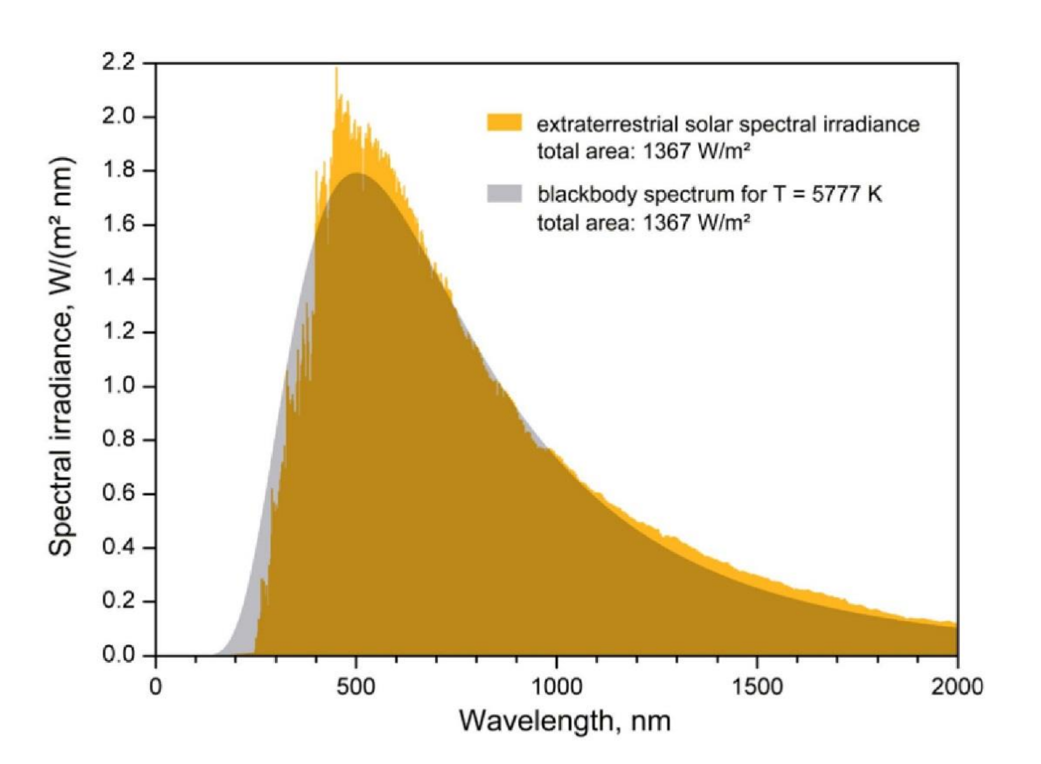
How do we know the Sun's Temperature?

- Use the fact that the Sun is a "blackbody" radiator
- It puts out its peak energy in visible light, hence it must be about 6000 K at its surface

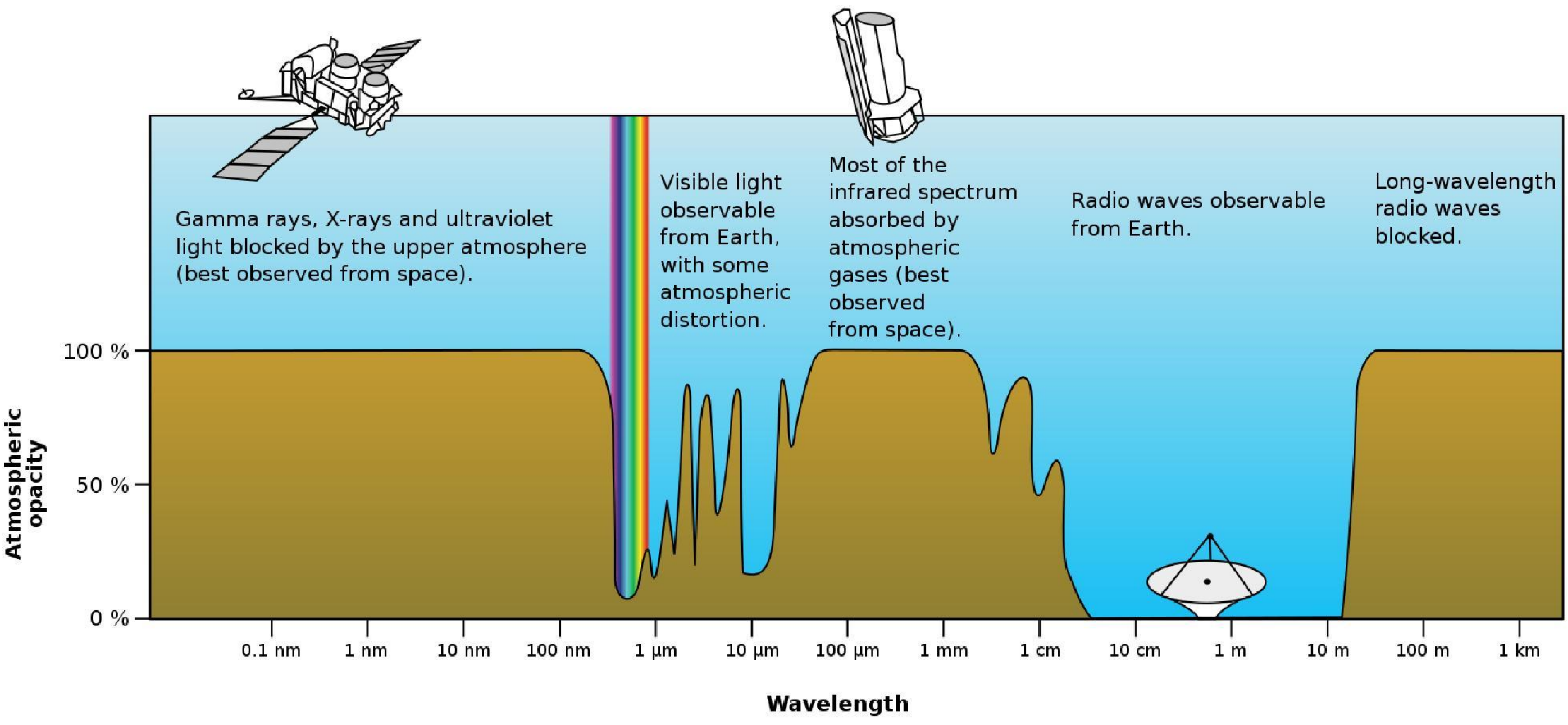


The Sun's Blackbody spectrum

- Peaks at 500nm (green)
- is more complicated than a perfect blackbody
- Still, a good approximation
- Used by J. Stefan in 1869 to calculate the temperature of the Sun for the first time!



Recall that EM waves of many wavelength cannot be observed from the Earth's surface



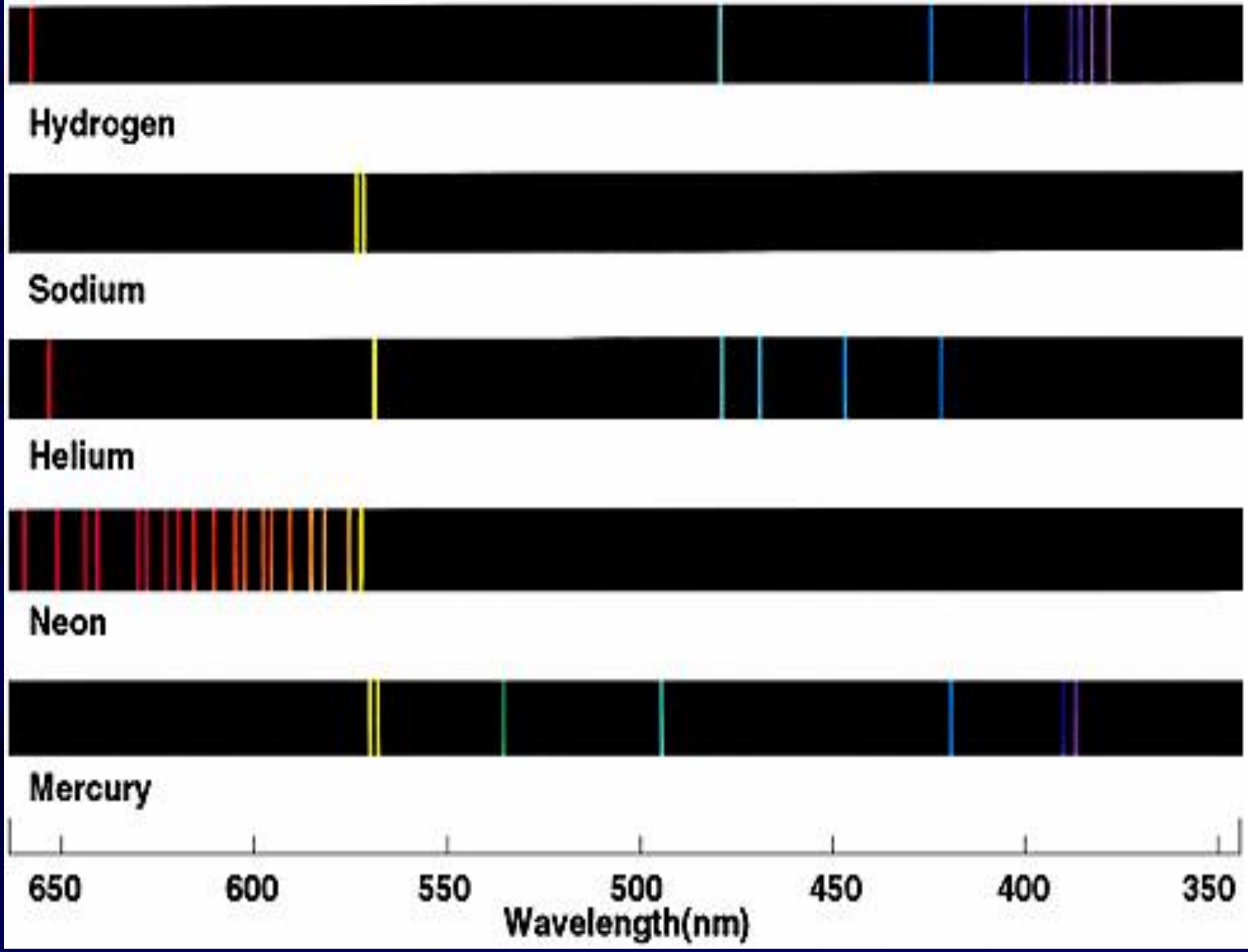
How do we know the Sun's composition?

- Take a spectrum of the Sun, i.e. let sunlight fall unto a prism
- Map out the dark (Fraunhofer) lines in the spectrum
- Compare with known lines ("fingerprints") of the chemical elements
- The more pronounced the lines, the more abundant the element

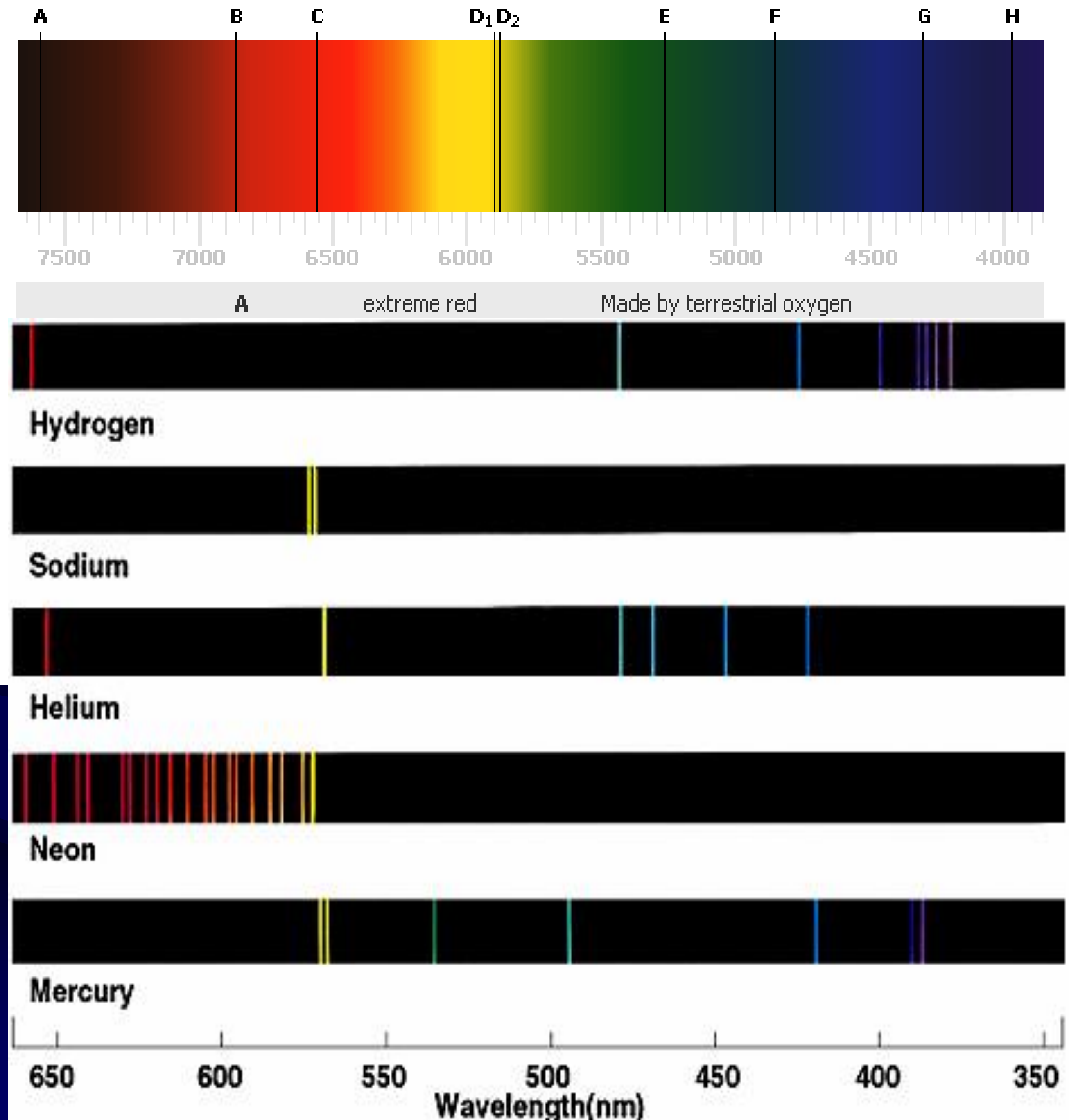
Spectral Lines – Fingerprints of the Elements

- Can use spectra to identify elements on distant objects!

- Different elements yield different emission spectra



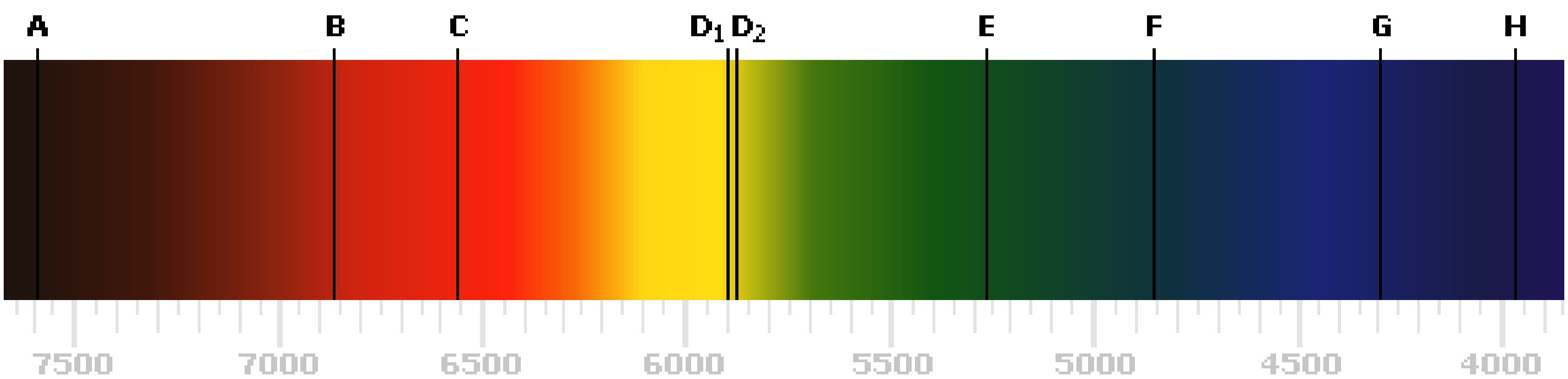
Sun →



Compare Sun’s spectrum (above) to the fingerprints of the “usual suspects” (right)

Hydrogen: B,F
Helium: C
Sodium: D

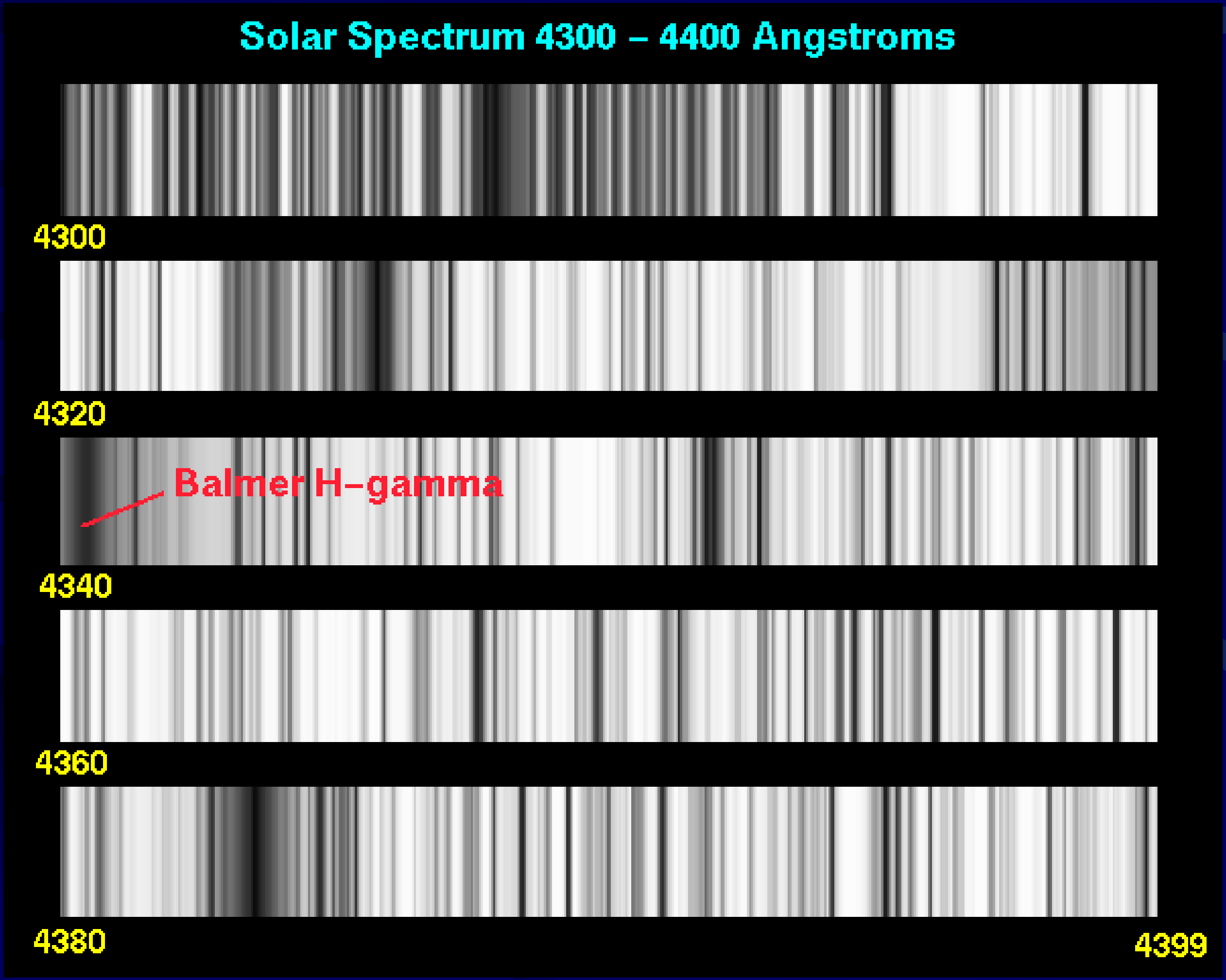
“Sun spectrum” is the sum of many elements – some Earth-based!



A	extreme red	Made by terrestrial oxygen
B	red	Made by terrestrial oxygen
C	red	Made by solar hydrogen
D_1	yellow	Made by solar sodium
D_2	yellow	Made by solar sodium
E	green	Made by solar iron
F	blue	Made by solar hydrogen
G	violet	Made by solar iron and calcium group
H	extreme violet	Made by solar calcium

The Sun's Spectrum

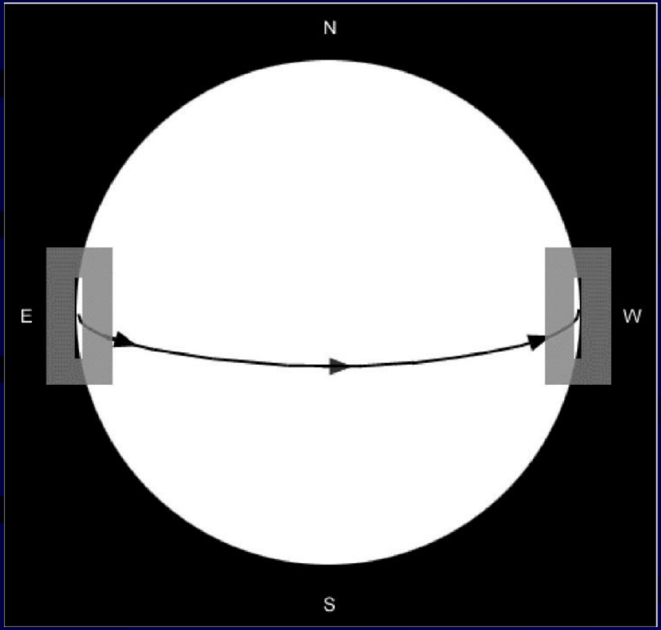
- The Balmer line is very thick → lots of Hydrogen on the Sun
- How did Helium get its name?



How do we know the Sun's rotation period?

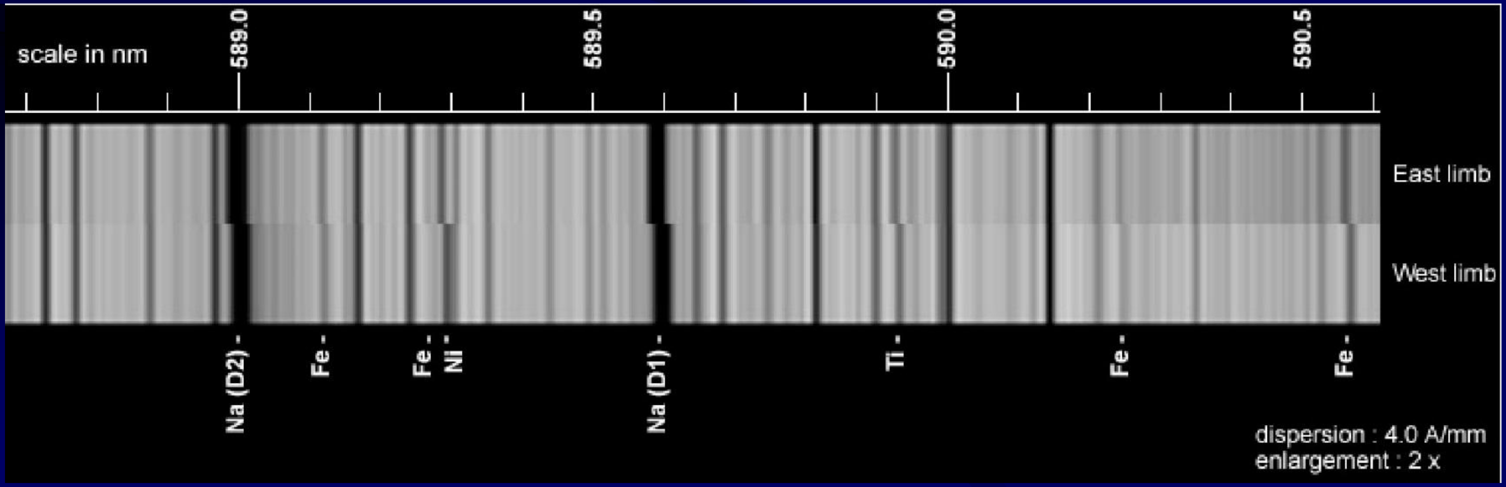
- Crude method: observe sunspots as they travel around the Sun's globe
- More accurate: measure Doppler shift of spectral lines (blueshifted when coming towards us, redshifted when receding).
  - THE BIGGER THE SHIFT, THE HIGHER THE VELOCITY

Doppler Shift applied to Sun's Rotation



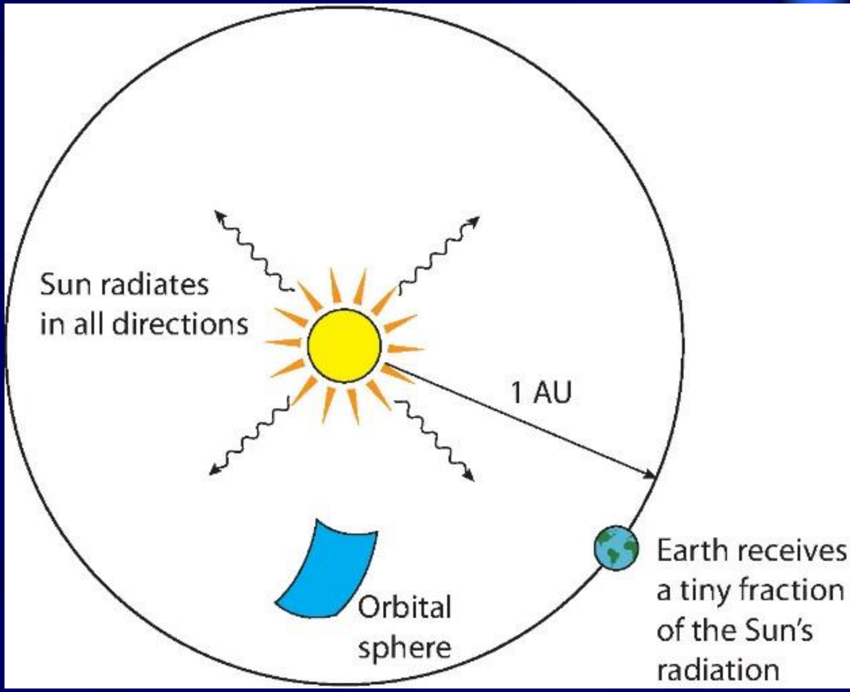
Vogel (1871): Sun rotates, so its eastern limb is coming towards us ➔ blue-shifted spectral lines

➔ Accurate measurement of sun's rotation period



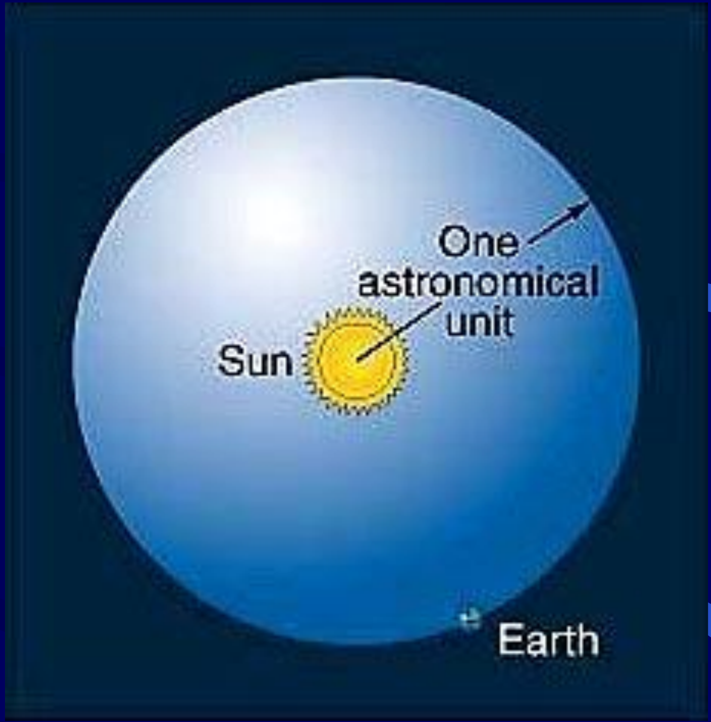
The Sun as a Blackbody radiating energy, mostly in the form of EM waves

- Solar constant: the amount of energy we receive on earth per second per area
- In 1837: 1400 W/m^2
- Scale up to area of sphere with radius 1AU
- Total power radiated by the sun:
- $P_{sun} = 3.8 \times 10^{26}$ W



How do we know how much energy the Sun produces each second?

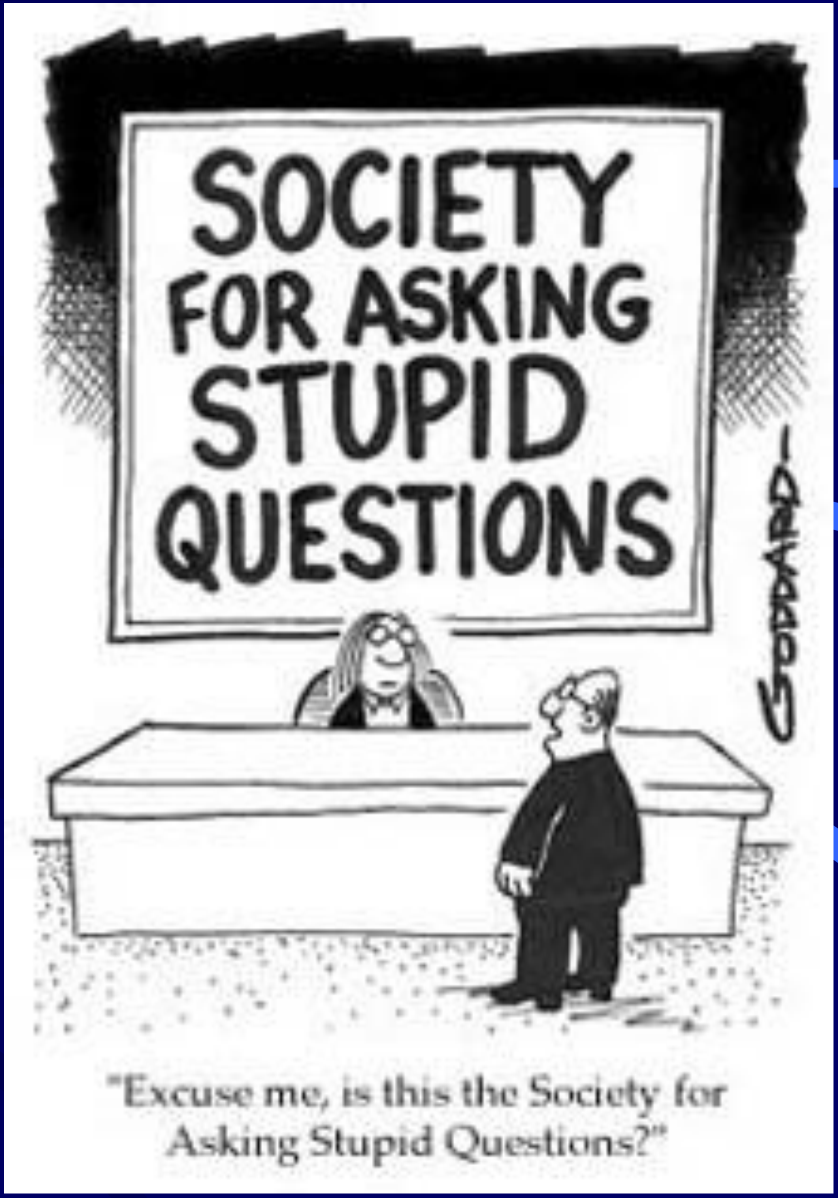
- The Sun's energy spreads out in all directions
- We can measure how much energy we receive on Earth
- At a distance of 1 A.U., each square meter receives 1400 Watts of power (the solar constant)
- Multiply by surface of sphere of radius 149.6 bill. meter (=1 A.U.) to obtain total power output of the Sun



Energy Output of the Sun

- Total power output: 4×10^{26} Watts
- The same as
  - 100 billion 1 megaton nuclear bombs per second
  - 4 trillion trillion 100 W light bulbs
  - $10 quintillion (10 billion billion) worth of energy per second @ 9¢/kWh
- The source of virtually all our energy (fossil fuels, wind, waterfalls, …)
  - Exceptions: nuclear power, geothermal

This begs the question: What are Stars?



„What Stars are we do not know, and we will never know“

Physicist Heinrich Wilhelm Dove to his Leipzig colleague Karl-Friedrich Zöllner [First(?) astrophysicist]

1859

Indeed, back then stars were …

Thermodynamic Beginnings of Star Models (c. 1850)

- Excitement about newly discovered laws of Thermodynamics (Mayer, Helmholtz)
  - Energy is conserved: $\Delta U = Q - W$

    (Change in energy content equals heat transferred minus work done)
  - Cannot be created, only transformed
- Energy Conservation is a balance sheet
- Realization that most energy on Earth is supplied by the Sun and must come from "something"

Meteoric Hypothesis

- Robert Mayer (1840s): meteors fall into the sun, replacing the energy that is being radiated away at $4\ \mathrm{x}10^{26}$J per second
- Idea: gravitational potential energy is converted to thermal energy
- Advantage: not a lot of mass needed
- Disadvantage: still earth year would decrease by seconds over time → ruled out

Contraction Hypothesis

- Helmholtz-Kelvin (really: Waterston) 1850s
- As the Sun contracts, gravitational energy is converted to thermal energy
- Assume spherical uniform sphere of known radius and mass
- Laws of physics allow radiation of half of potential energy
- Compare available energy to energy radiated each second

→ Time constant ("Age of Sun") about 20 million years

Acceptance by lack of Alternatives

- Compare to religious, geological estimates
  - Bible: 6000 years
  - Geological record: 100s of millions of years
- Doesn't make much sense, but what is the alternative?
- Plus: Authority (2 top physicists say so...)

The meteorological Star (Lane, Ritter, Emden)

- Outsiders to the rescue!
- Meteorological Star Model:
  - Stars are balls of gas: gas pressure against gravity
  - Modeled after convective equilibrium of Earth's atmosphere (Kelvin 1850s)
- Lane 1870: stars can be stable even though gravity works to contract them
- Ritter 1880: yes, and many different ways of achieving stability are available
- Emden 1907: Gaskugeln – a summative book

What we want from a Star Model (I)

- Density in all parts of the star: $\rho(r)$
- Temperature in all parts of the star: T(r)
- Pressure in all parts of the star: P(r)

(Usually a spherical star is assumed, so *r* is the radial variable (distance to center))

Main Idea: Hydrostatic Equilibrium

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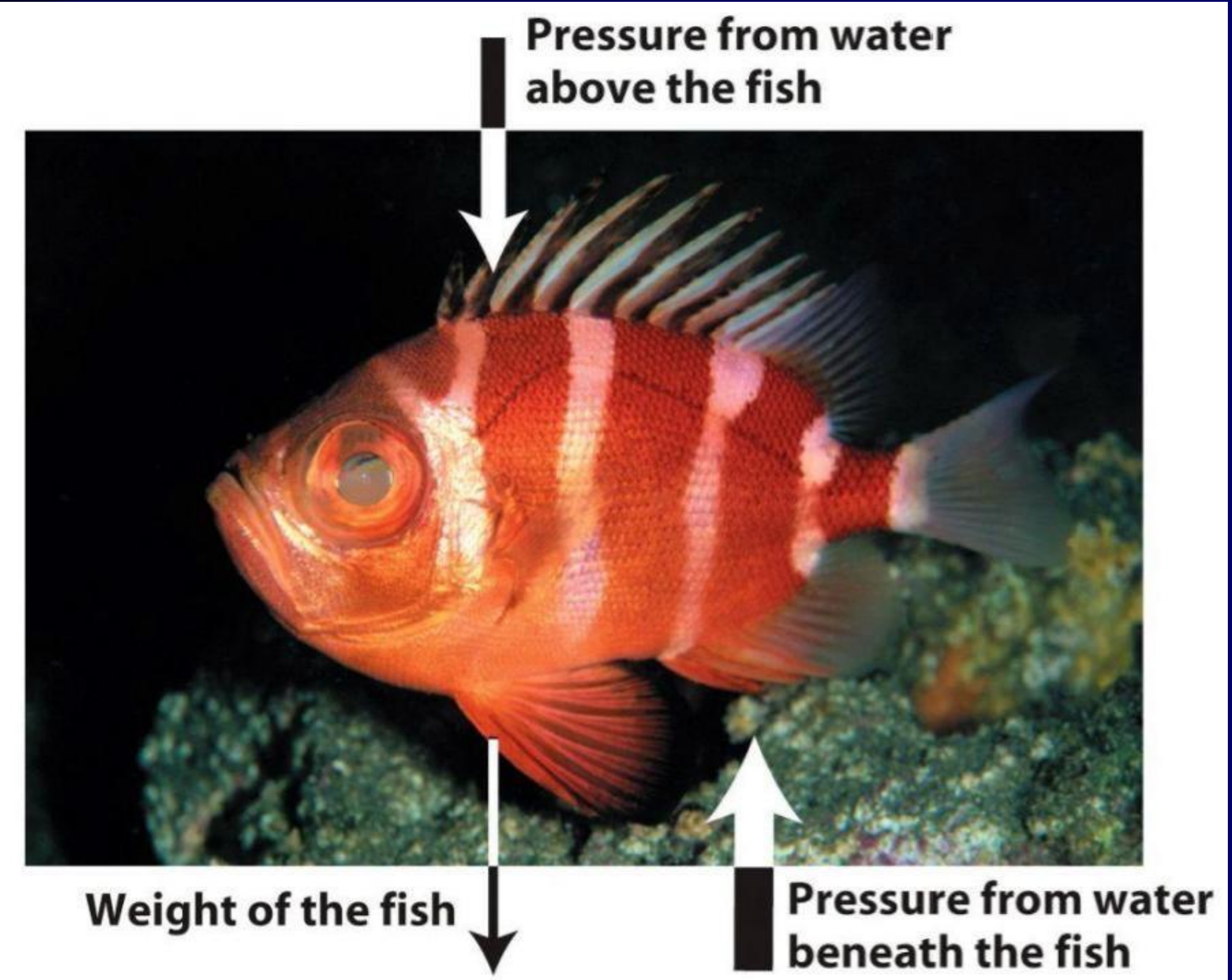
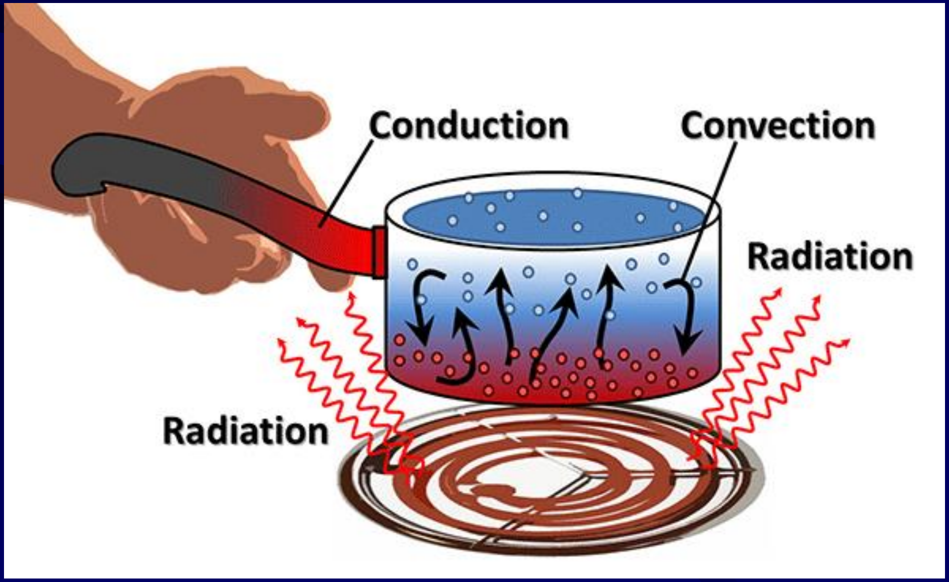


A fish floating in water is in hydrostatic equilibrium, so forces balance

Three Mechanisms of Energy Transfer

- In stars: either convection or radiation
- Criterion: if temperature gradient is too steep (superadiabatic) then radiation dominates



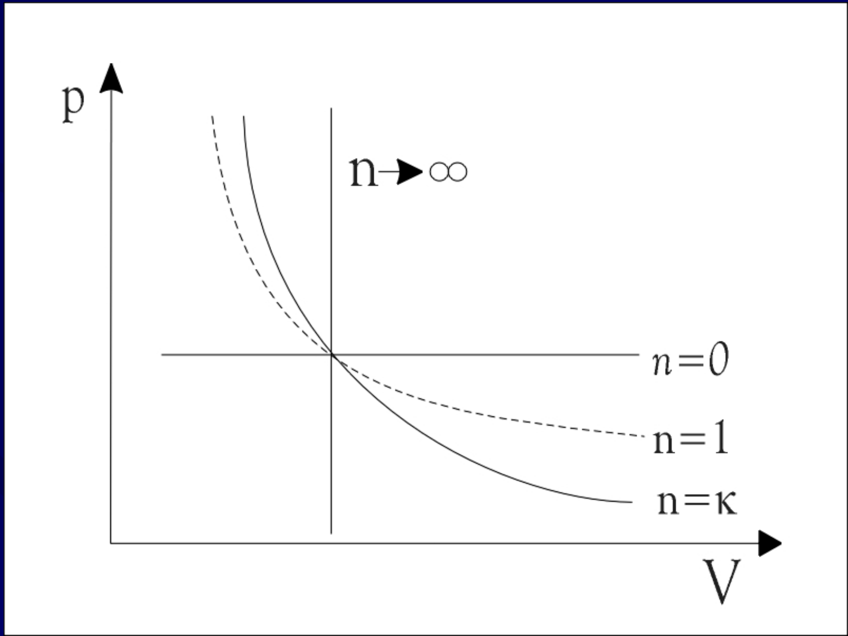
The Emden Equation

- There is a relation between pressure P and density ρ; both depend on the distance to the center of the gas ball
- There is an equation encoding how the gas ball "works"; here: adiabatic convection
- Put it all together to arrive at a differential equation for the density of the star matter as a function of the distance from the star's center

➔ The Emden Equation

Gaskugeln: Stars as Gas Balls

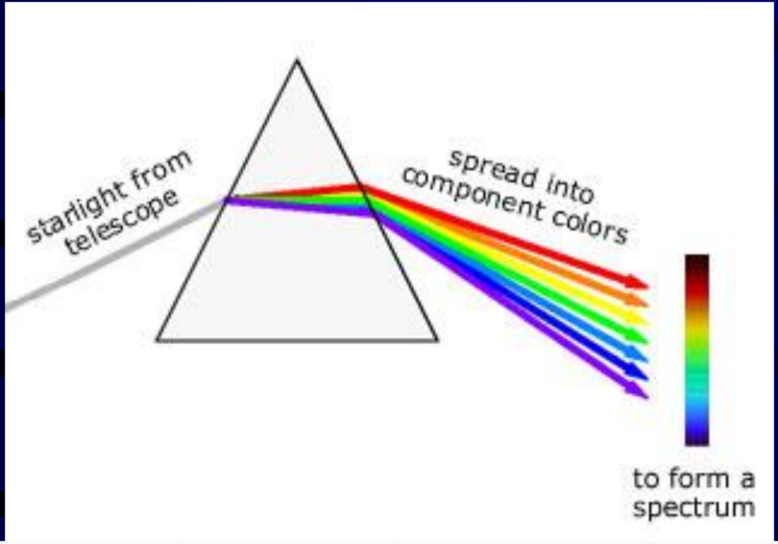
- Stars: Self-gravitating gas balls with a general, polytropic relation (index *n*) between their density and pressure: $P = K\rho^{1+1/n}$
- Temperature inversely proportional to radius
  - Hottest at center
  - Contracting → heat up
  - Expanding → cool down
- Densest at center

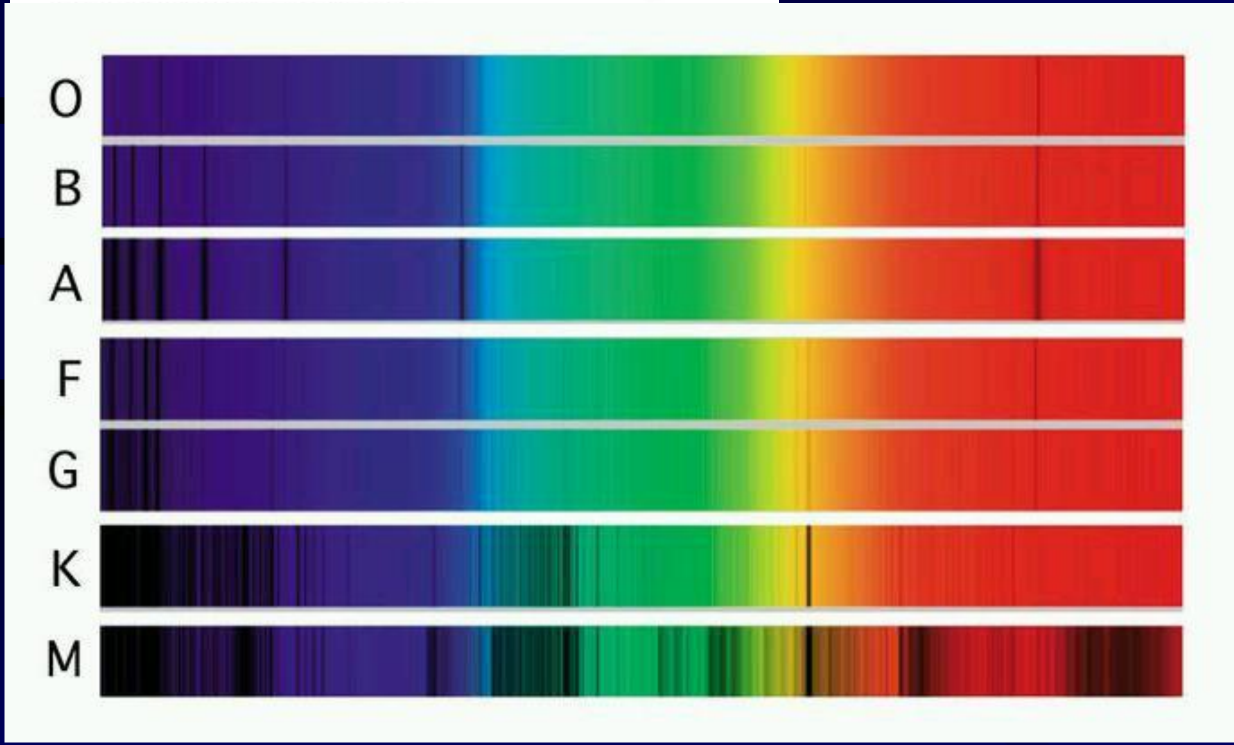


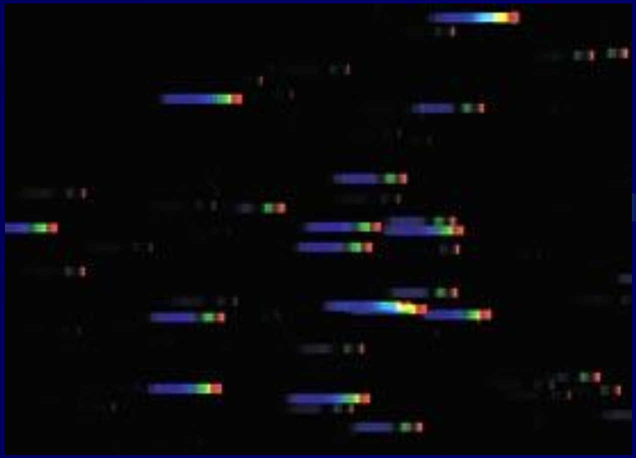
This is all THEORY! What do we OBSERVE?

- Stellar Spectra:
  - mass produced at Harvard after 1880
  - Classified by “computers” (Maury, Cannon) →spectral classes
- Distances to stars: parallax, proper motion
- Masses from binary stars (Kepler motion)
- Brightness plus distance yields Luminosity
- Sizes of a few (Michelson)

Stellar Spectra: Dark Lines in front of a continuous "rainbow"







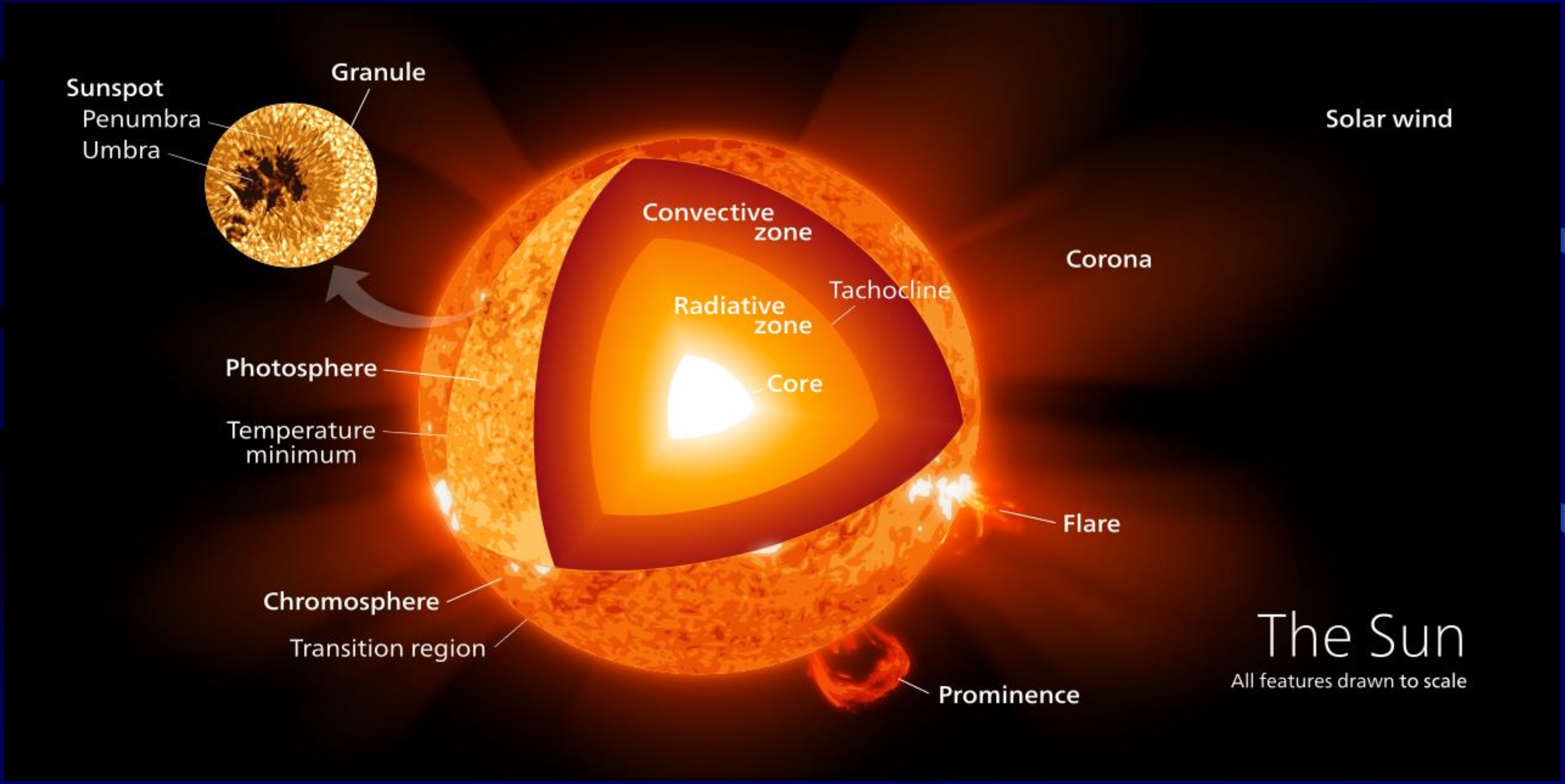
Hyades star cluster seen through an objective prism

Initially classified by strength of H lines: ABCDE...

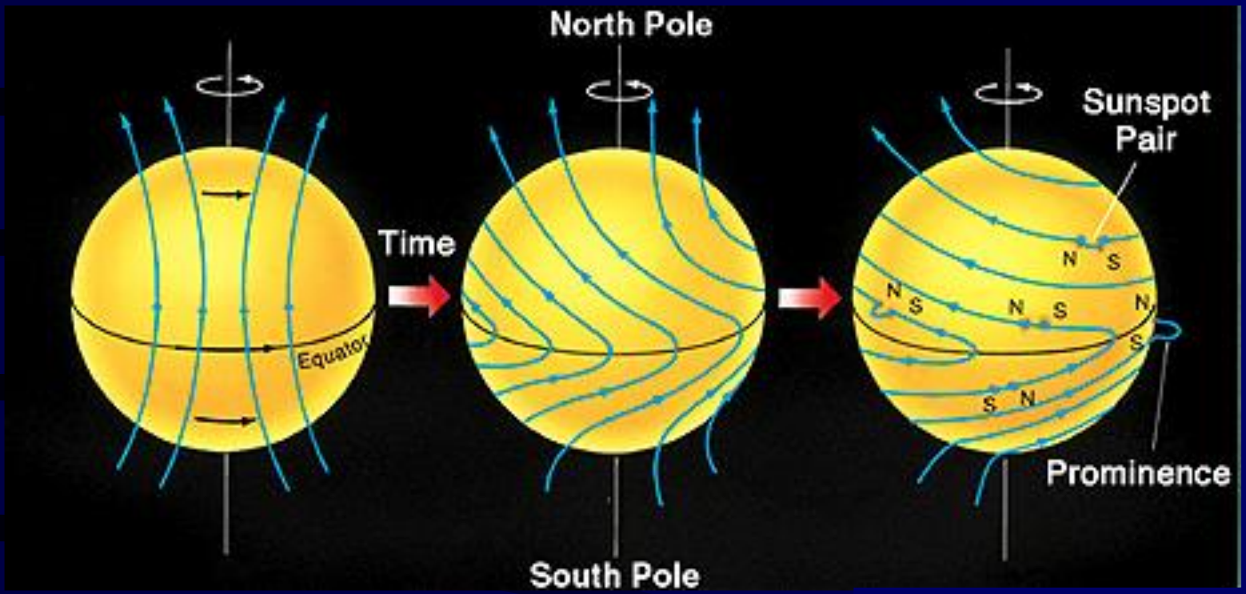
To be continued…

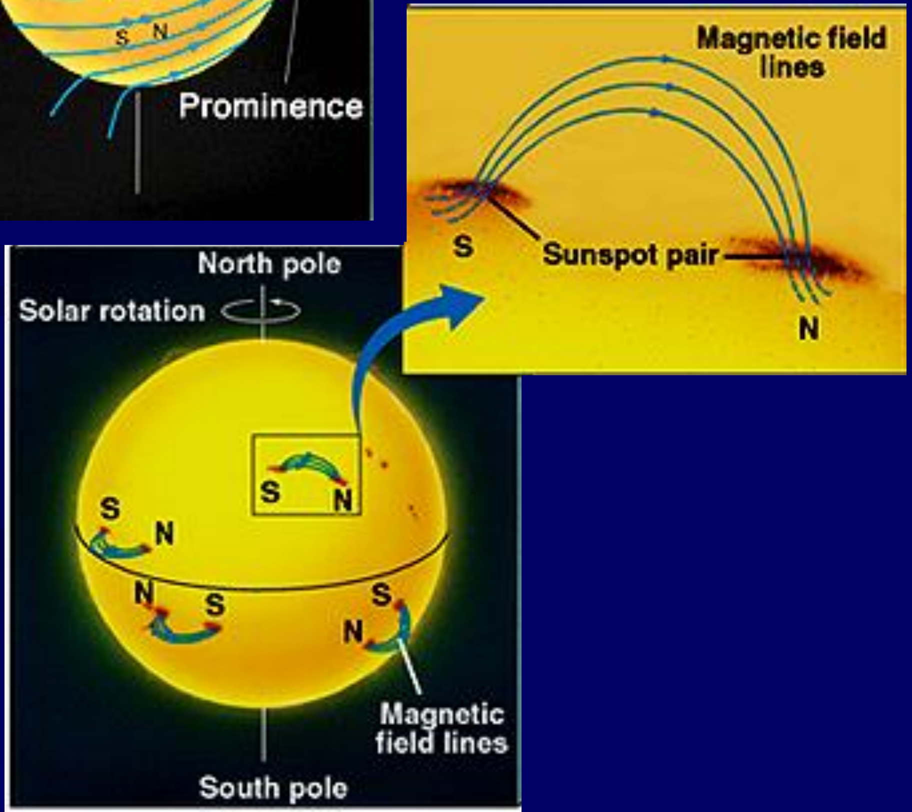
- For now, let’s OBSERVE the sun
  - Radiation Zone and Convection Zone
  - Chromosphere
  - Photosphere
  - Corona
  - Sunspots
  - Solar Cycle
  - Flares & Prominences

Focus on the Sun's outward appearance



Sunspots and Magnetism





- Magnetic field lines are stretched by the Sun's rotation
- Pairs may be caused by kinks in the magnetic field