"If they can make penicillin out of moldy bread, they can sure make something out of you.”
Muhammad Ali

Group Project 1 on the course web page (not blackboard). Wednesday- sit in your group row and we will have a group work day.

You will want to have a calculator handy for the remainder of this course.

Stars do not all appear the same

We now know why some stars are brighter than others.

How to make a star brighter

- Make it hotter: $L_{ap} \sim T^4$
- Make it bigger: $L_{ap} \sim R^2$
- Make it closer: $L_{ap} \sim 1/d^2$

Reconsider luminosity

Apparent Luminosity: $L_{ap} = R^2 \sigma T^4 / d^2$

From an image we measure L_{ap} and from a spectrum, we measure T. If from parallax we measure d, what else do we know?

$$\mathbf{R} = [L_{ap} d^2 / (\sigma T^4)]^{1/2}$$

And $L = L_{ap} 4\pi d^2$

Parallax is due to the motion of Earth around the Sun and gives us distances to stars.

Proper motion is a stars motion *across* the sky. (not towards or away from us)

Radial velocity uses the Doppler shift to measure a star's motion towards or away from us.

We want to know:

- How hot are stars?
- How BIG are stars (size)?
- How massive are stars?
- What are stars made of?
- How much energy do stars emit?
- Where does that energy come from?
- How far away are stars?
- Are they in motion? Yes!

Luminosity (brightness)

When we look at a star from Earth, we measure its APPARENT LUMINOSITY (BRIGHTNESS): L_{ap}

We call the TOTAL energy emitted from a star its LUMINOSITY: L

We also have a standard called ABSOLUTE LUMINOSITY: L_{abs} which is how bright a star would appear if it were at 10 parsecs (pc) from us.

Parsecs

$1pc = 3.1x10^{16}$ m

1pc = 206,667 AU

1pc = 3.26 light years (ly)

ABSOLUTE LUMINOSITY: L_{abs} which is how bright a star would appear if it were at 10 parsecs (pc) from us.

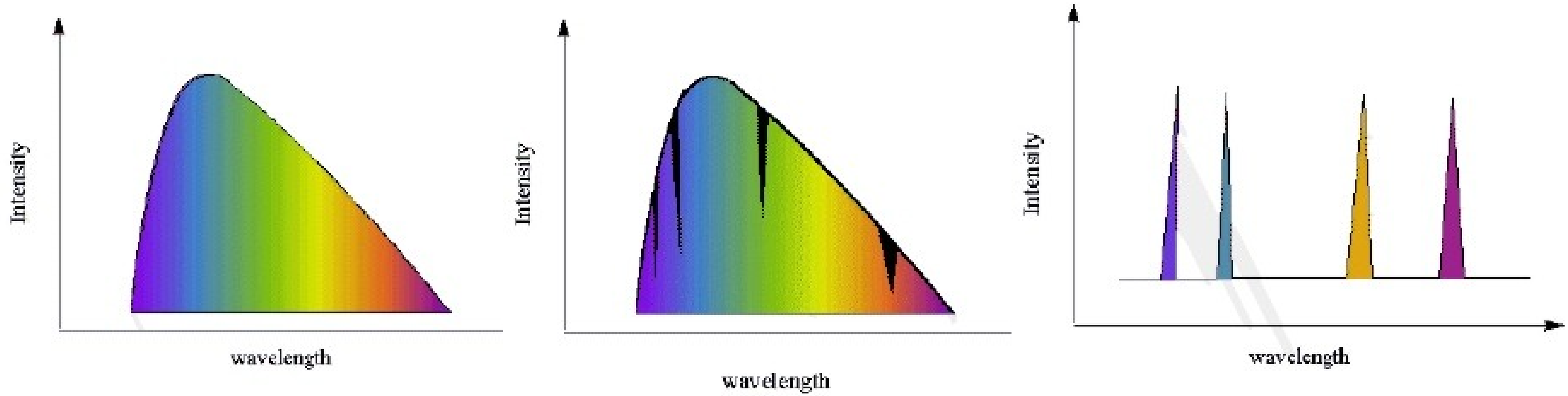
This allows us to compare brightnesses of stars independent of distance.
(Compare stars' true brightnesses.)

Reminder: $L_{ap}=R^2\sigma T^4/d^2$

Kirchoff

In the 1850s, Gustav Kirchhoff took another look at Wien's work.

He discovered 3 types of spectra

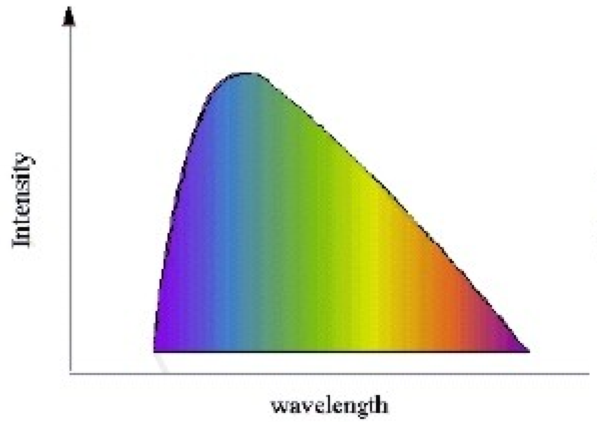


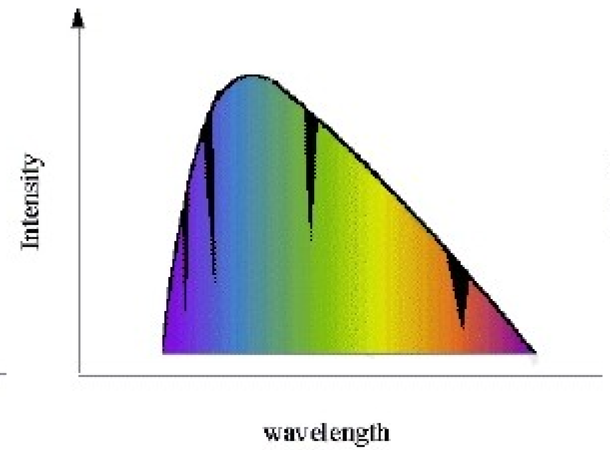
He also heated ceramics and got the spectrum on the left.

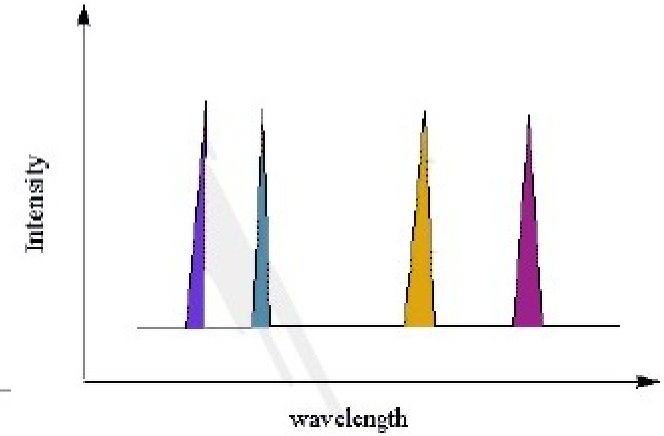
Then he put a cool gas in front of the ceramic and got the center spectrum.

Then he just heated the gas (with electricity) and got the spectrum on the right.

So now we have 3 types of spectra







Continuous spectra are made by objects under high pressure (like solids)

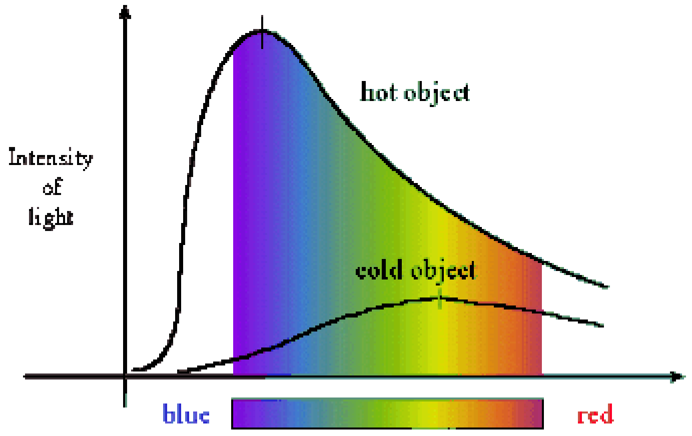
Absorption line spectra are made by cool (comparatively) low pressure gases.

Emission line spectra are made by (comparatively) hot, low pressure gases.

Quiz 7

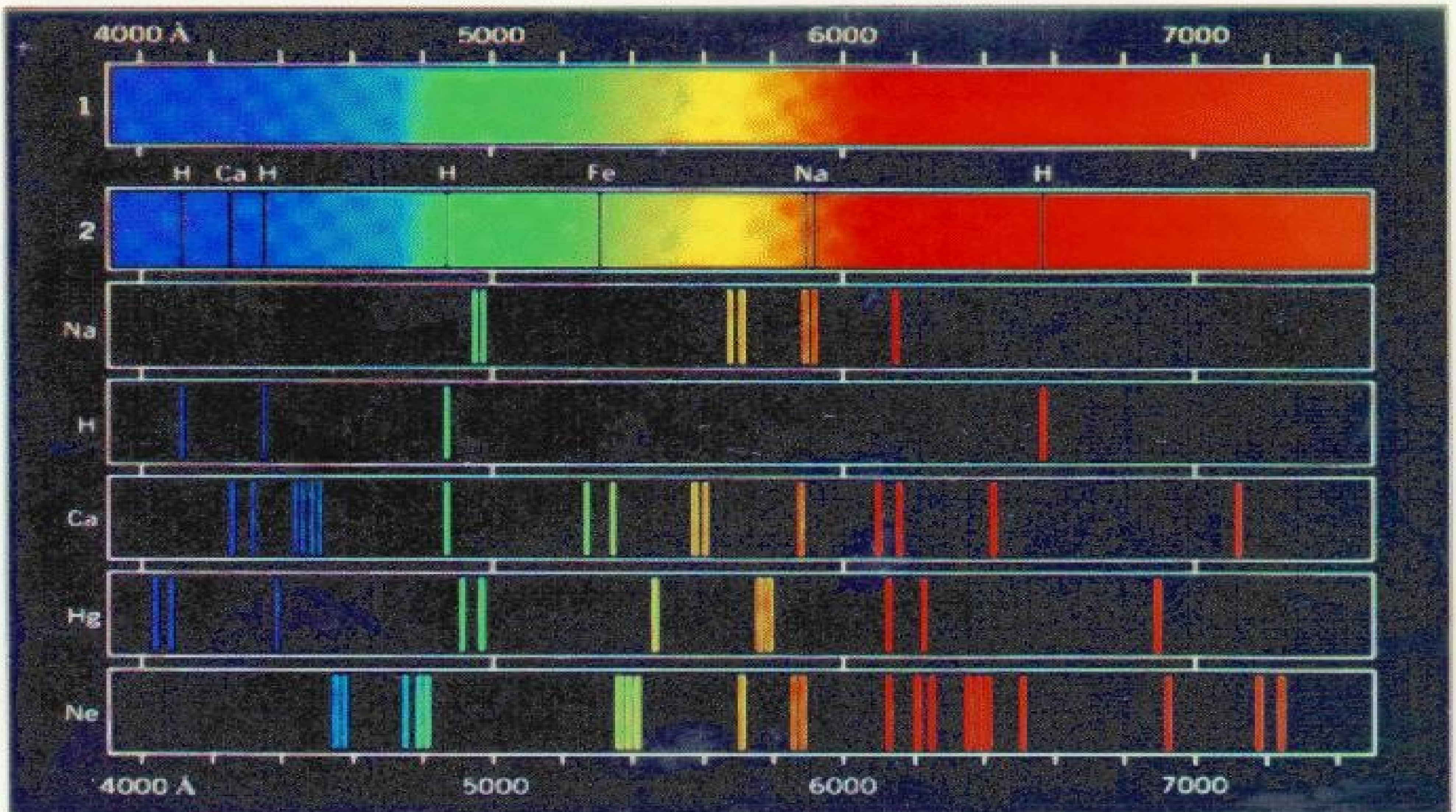
What 2 things can a continuous spectrum tell us?

A) Color and pressure
B) Composition and temperature
C) Temperature and energy (per square meter)
D) Energy and composition

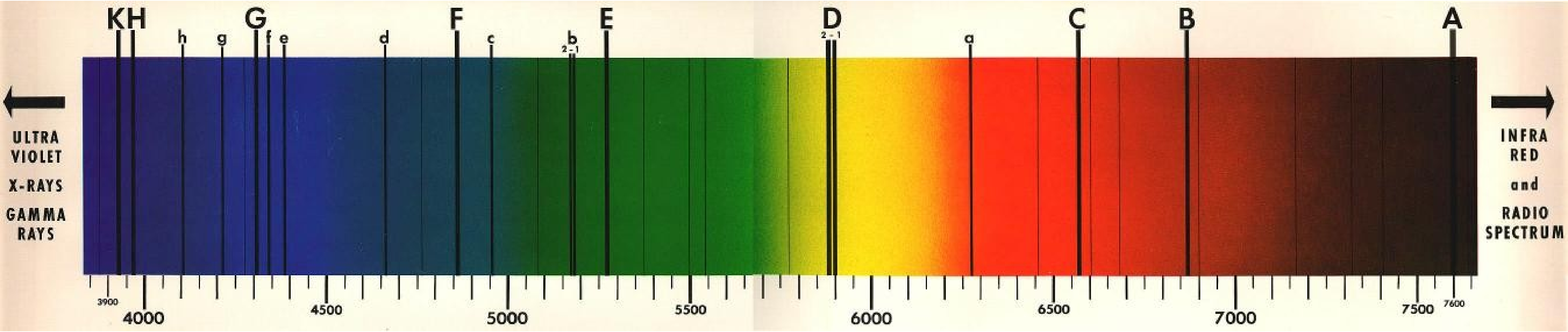


Below are the 3 kinds of spectra again.

As you can see from the labels on the left, different elements produce different spectral lines.



A spectrum of our Sun:



The lines give us composition! So we can see what our Sun is made of !

Now we can get the Sun's composition.

By Mass

- 76% Hydrogen
- 22% Helium
- 0.8% Oxygen
- 0.4% Carbon
- 0.2% Neon
- 0.1% Iron and Nitrogn
- ~0.08% Silicon and Magnesium
- ~0.24% Everything else

Astronomers call this stuff "metals"

Now we can get the Sun's composition.

By Mass

- 76% Hydrogen
- 22% Helium
- 2% ‘metals’

By Number...

Now we can get the Sun's composition.

By Mass

- 76% Hydrogen
- 22% Helium
- 2% ‘metals’

By Number...

- 91.2% Hydrogen
- 8.7% Helium
- 0.1% ‘metals’

Nearly all stars....

- Are ¾ H and ¼ He with a trace (<3%) 'metals' (everything else).

We want to know:

- How hot are stars?
- How BIG are stars (size)?
- How massive are stars?
- What are stars made of?
- How much energy do stars emit?
- Where does that energy come from?
- How far away are stars?
- Are stars in motion? Yes!

Now we can ask, What provides the energy our Sun emits?

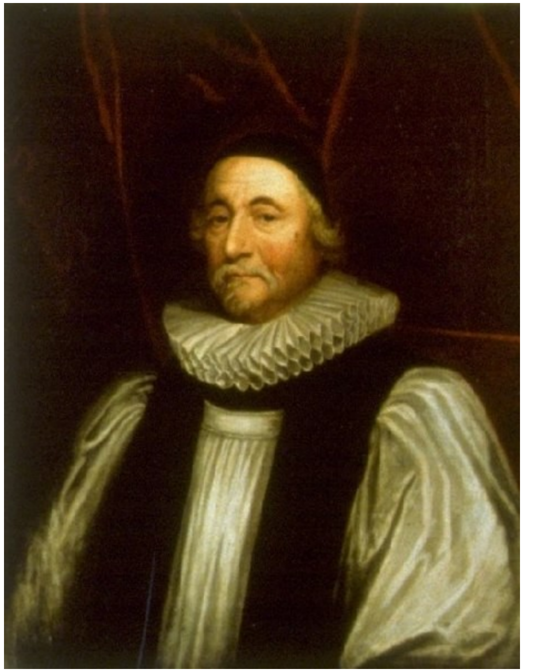
the Sun radiates $L = 3.9 \times 10^{26}$ W

How to solve the problem.

To determine the energy source of the Sun, astronomers tried to calculate the total energy emitted by the Sun in its lifetime. To do this, you simply multiply the amount of energy the Sun radiates ($L = 3.9 \times 10^{26}$W) by its age.

In the beginning....

Chemical burning is a way to generate heat.
Chemical reactions (burning) could power the Sun for ~6,000 years.
This agreed with religious dogma at the time.
Archbishop of Armagh, James Ussher, calculated the beginning of the Earth to be Saturday, Oct. 22, 4004BC



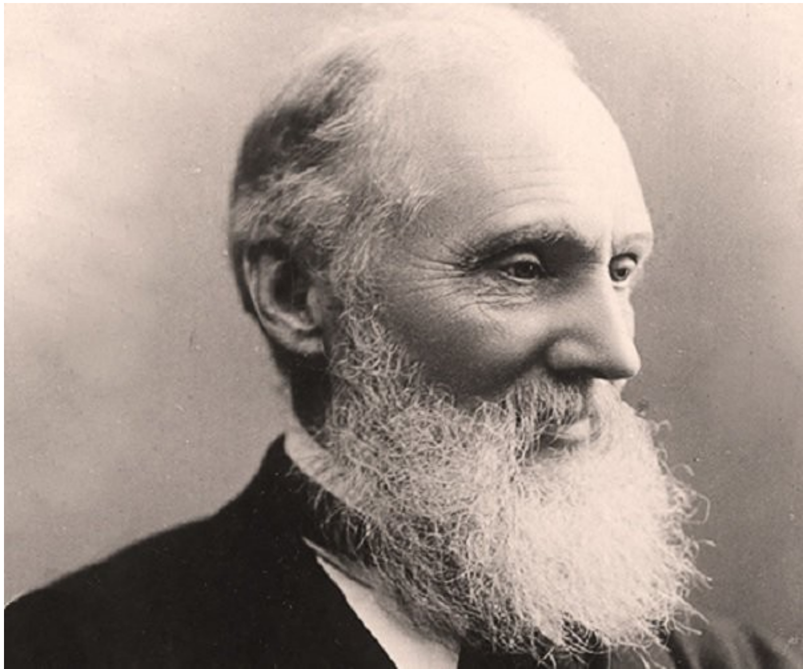
In the beginning....

What if the Sun just cooled?
In the 1700s, Count Buffon calculated the Earth’s age based just on cooling. He estimated the age at ~75,000 years. The Sun would be correspondingly older.

Another way

Back in the 1850s, Lord Kelvin thought the Sun's energy came from gravity- the Sun was converting gravitational energy to heat.

E_{grav}=GMm/R. So as R gets smaller, energy can be released. Lord Kelvin estimated the Sun could last 30 million years.



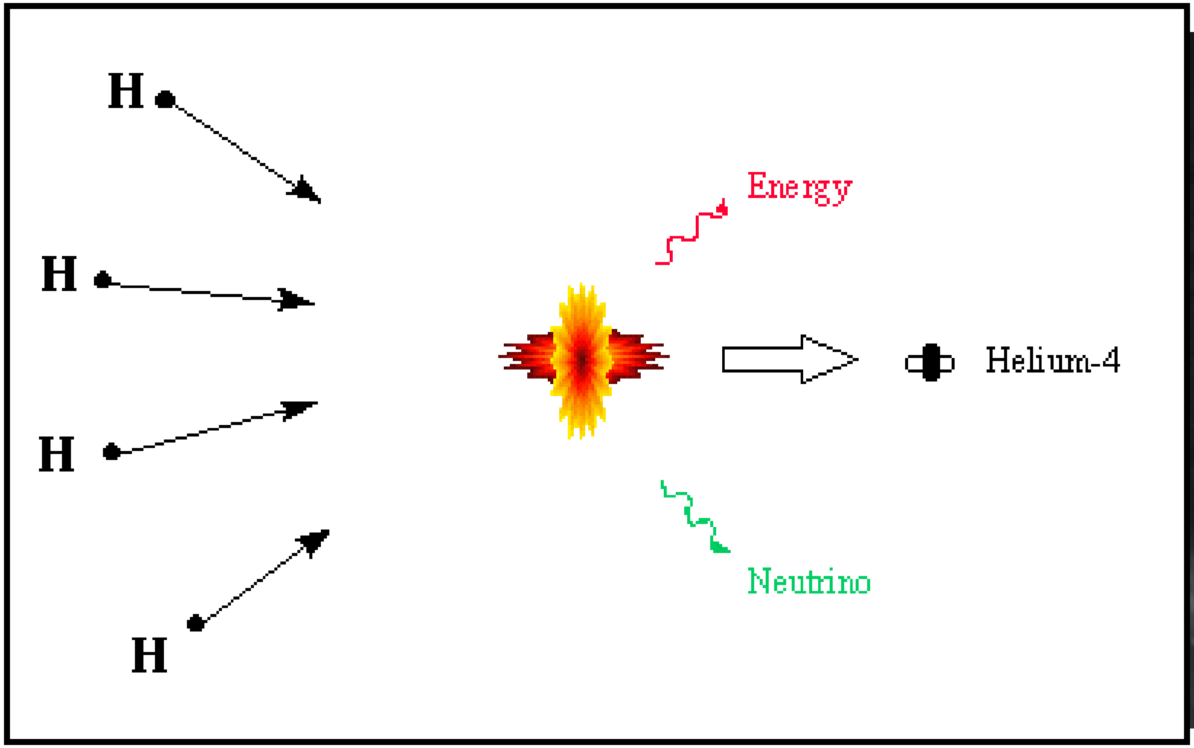
The Earth's age

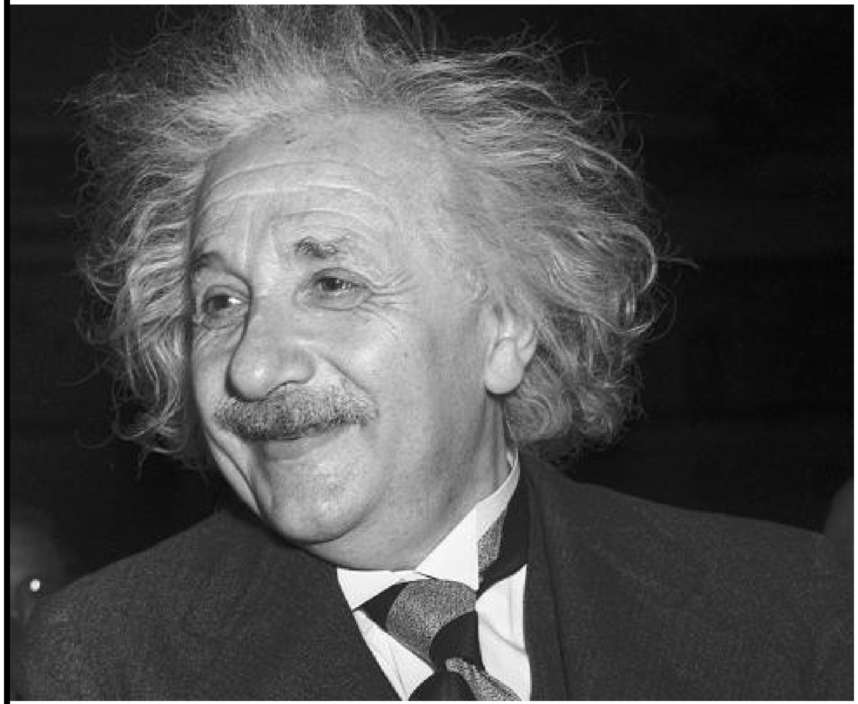
By late in the 19th century, Darwin had determined that the Earth must at least be hundreds of millions of years old.

Early in the 20th century, radiation provided a new power source and the age of atomic physics was born.

Einstein

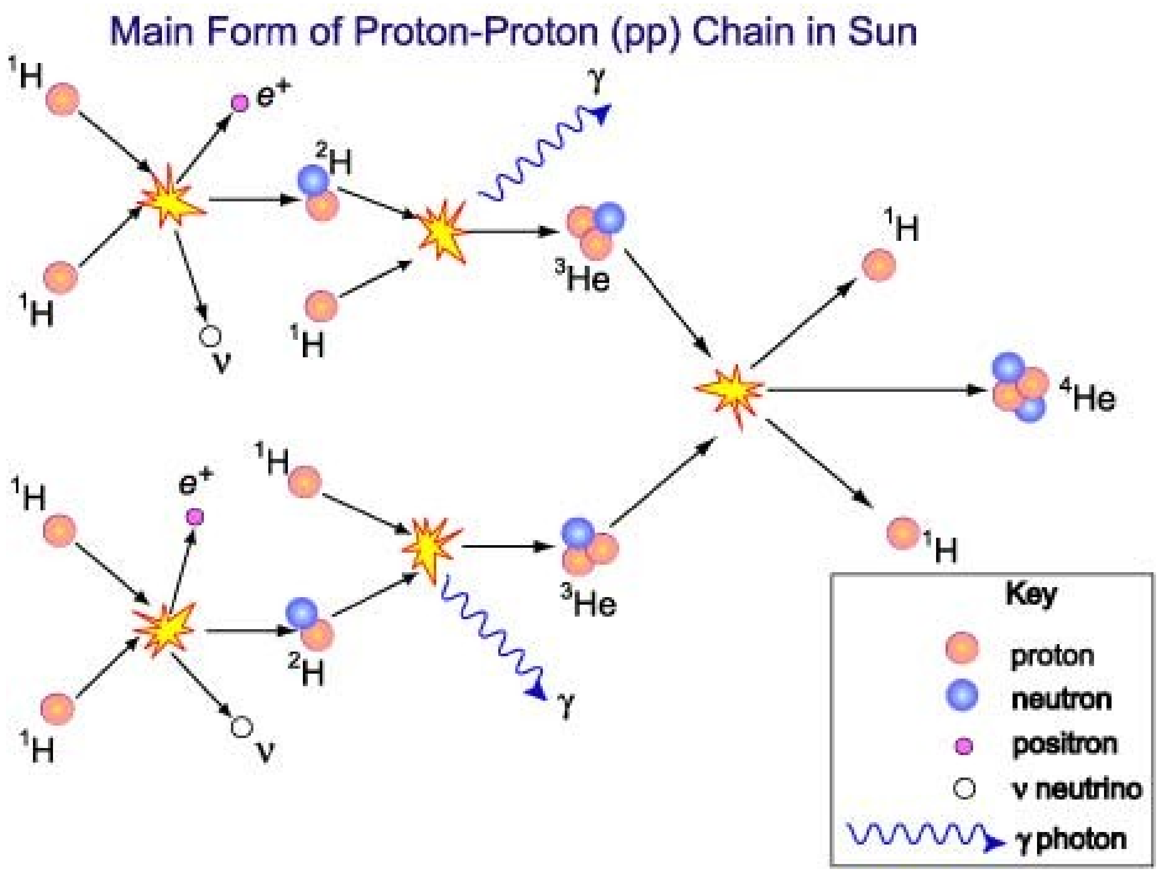
We now know that the Sun is 4.6 billion years old and converts hydrogen to helium via nuclear fusion. This releases energy based on Einstein's famous equation: $E=mc^2$. In each reaction, the Sun converts a little bit of mass into energy.





The Sun emits a million billion tons of TNT worth of energy each second.

By converting hydrogen to helium.



The process begins with protons (^{1}H) and ends up with helium (^{4}He). But several other products are made along the way.

- Lithium: this is easily broken apart in the Sun.
- Berylium: Some of this remains stable and in the Sun.
- Boron: Some of this also remains in the Sun.
- ν: Neutrinos: Many of these are made. Neutrinos do not interact well with matter. They could pass through lead 1 light year thick!
  - The Sun emits $2x10^{38}$ neutrinos per second!
  - 60 billion neutrinos per square centimeter pass through the Earth (our bodies included) every second.

With all these neutrinos, we have to try to detect them!

But neutrino detectors only detect about 1/3 as many neutrinos as what should be produced by sufficient fusion to power the Sun.

With all these neutrinos, we have to try to detect them!

The solution to “the neutrino problem” is that neutrinos are changing flavor as they travel.

We want to know:

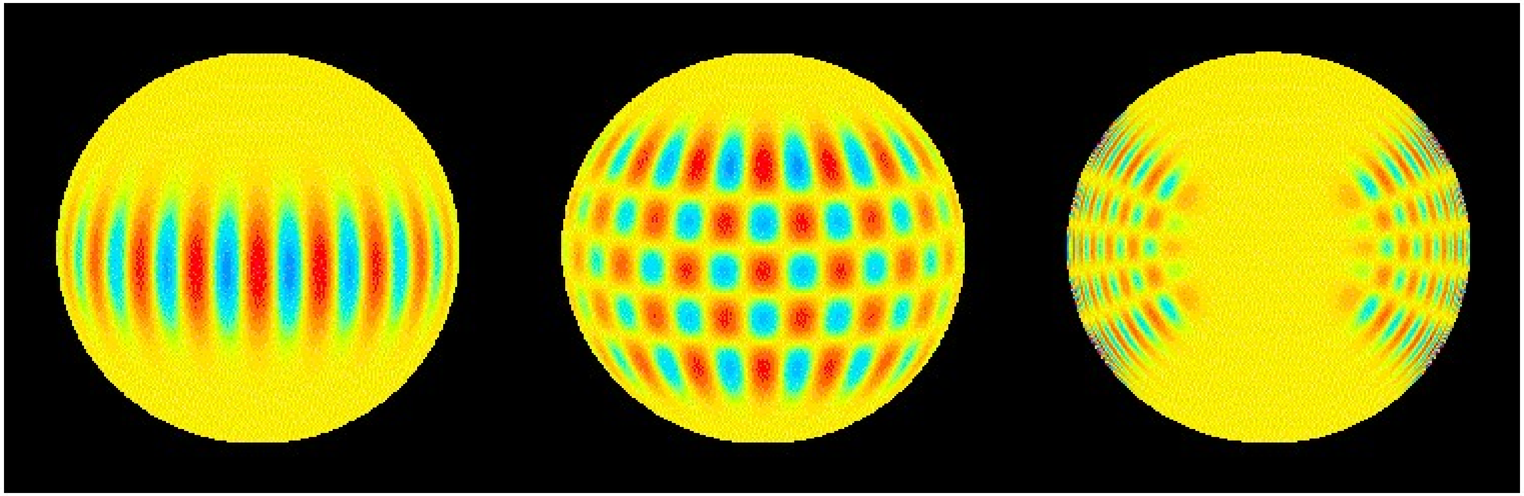
- How hot are stars? $T = 2.9\text{x}10^6/\lambda$
- How BIG are stars (size)?
- How massive are stars?
- What are stars made of? ¾ H ¼ He, few % ‘metals’
- How much energy do stars emit? Luminosity
- Where does that energy come from? Fusion $H \rightarrow He$
- How far away are stars? Parallax
- Are they in motion? Yes. Proper motion & radial velocity

How do we know what is inside our Sun? The Solar Model

The solar model is a computer/calculated model of the Sun that obeys physics as we know it. No matter what is put into the model, it must meet the following requirements:

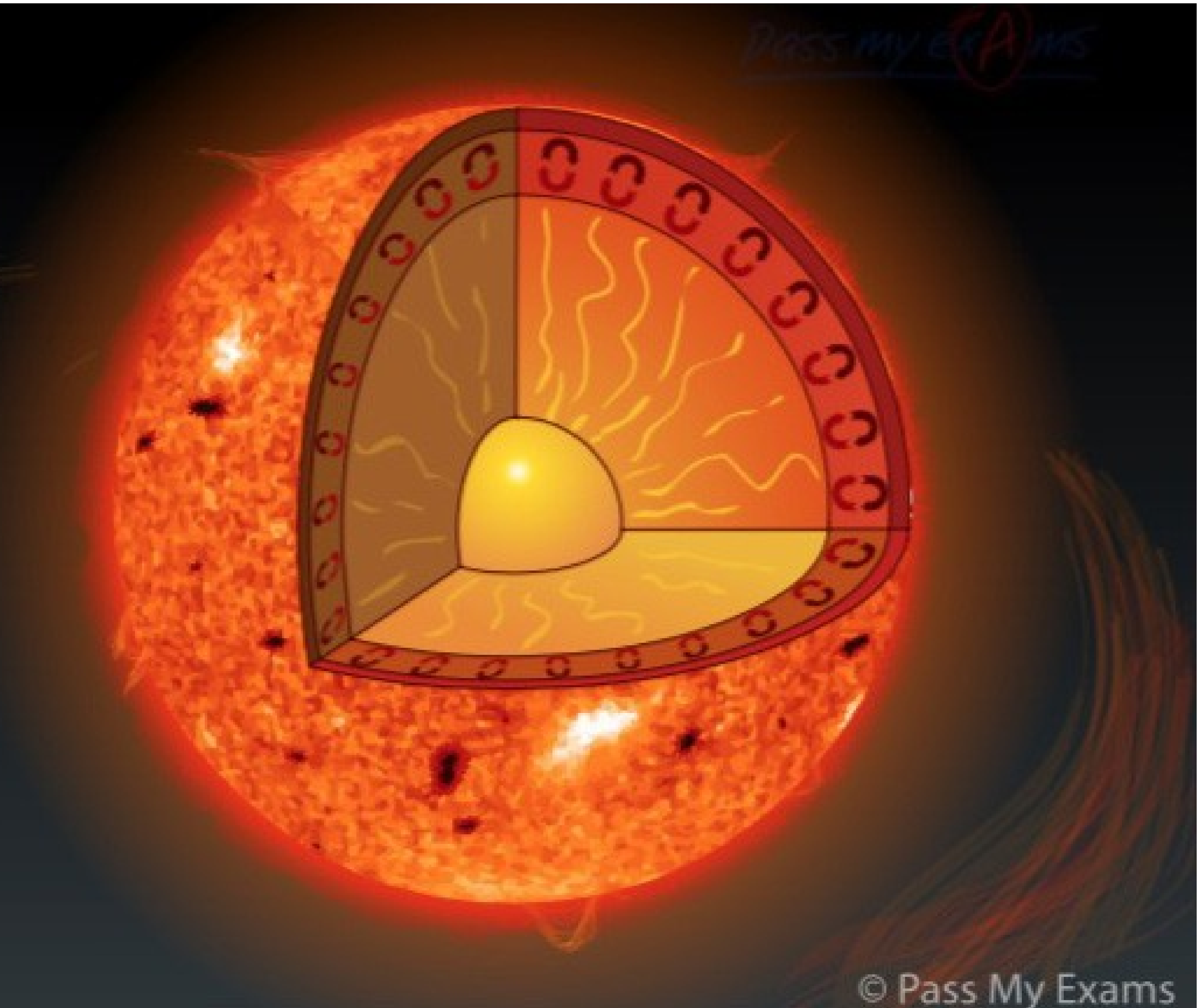
* The outside temperature and luminosity of the Sun must equal what we observe.
* The Sun's size must be what we observe it to be.
* The composition must be what we see.
* The interior must generate enough heat to support the mass above it.

Observational evidence too!



Just like the Earth, the Sun vibrates. It is possible to detect these vibrations and infer the interior conditions. These vibrations cause velocity (Doppler) changes as well as brightness changes.

The Sun's structure



Core, radiative zone, convective zone, and Photosphere. (Summary slide coming)

Core

- Is ¼ the size of the Sun
- Contains 50% of the mass
- **Generates 99% of the energy**
- 15 million degrees K.
- Pressure: 250 billion times Earth's air pressure
- Density: 158 g/cc
- Yet elements exist as gases- ionized gases, so the electrons are free.

Radiative Zone

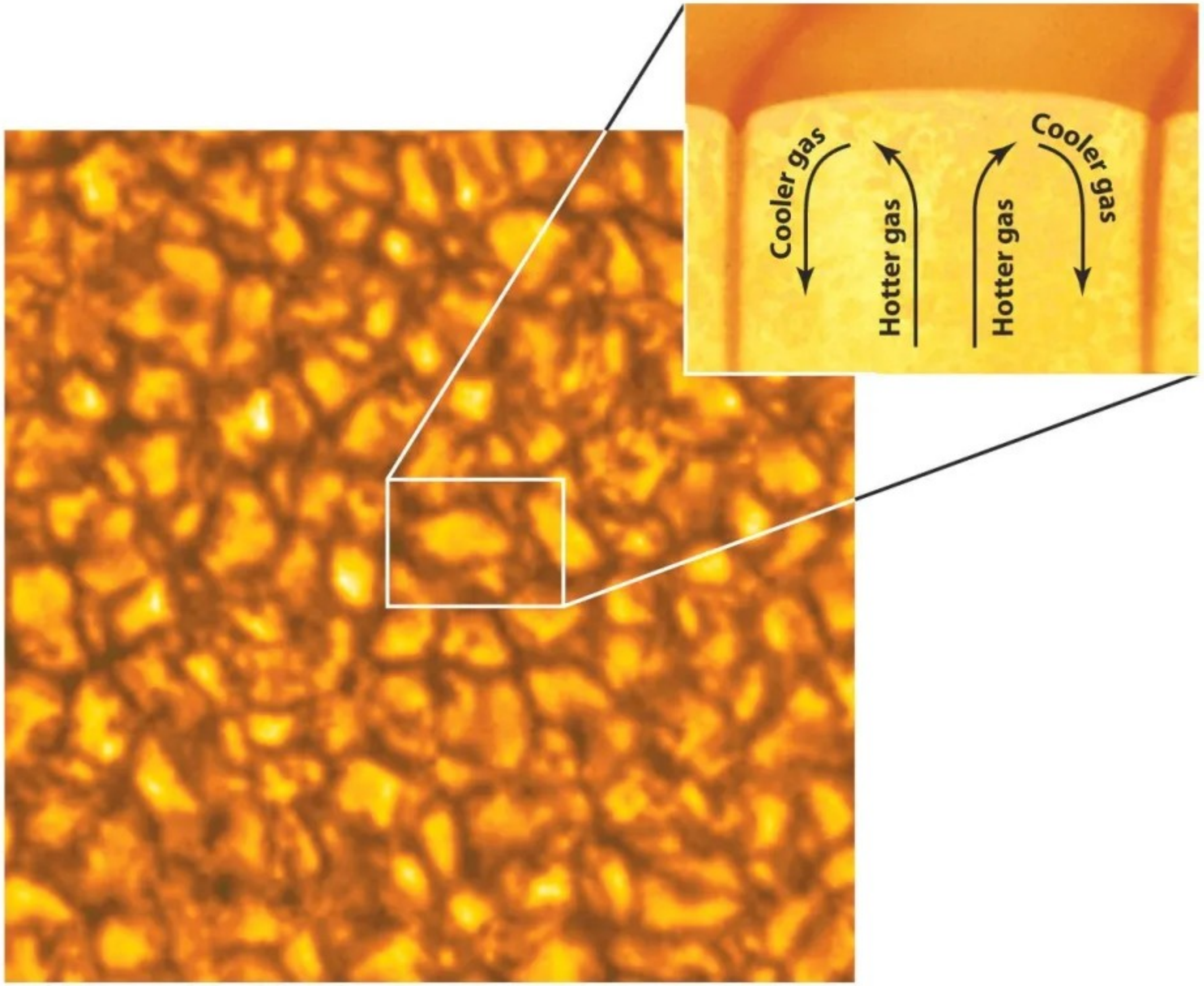
- **Transports energy away from the core as light.**
- Photons are absorbed and re-emitted as particles take some of the energy to support the mass above.

Convective zone

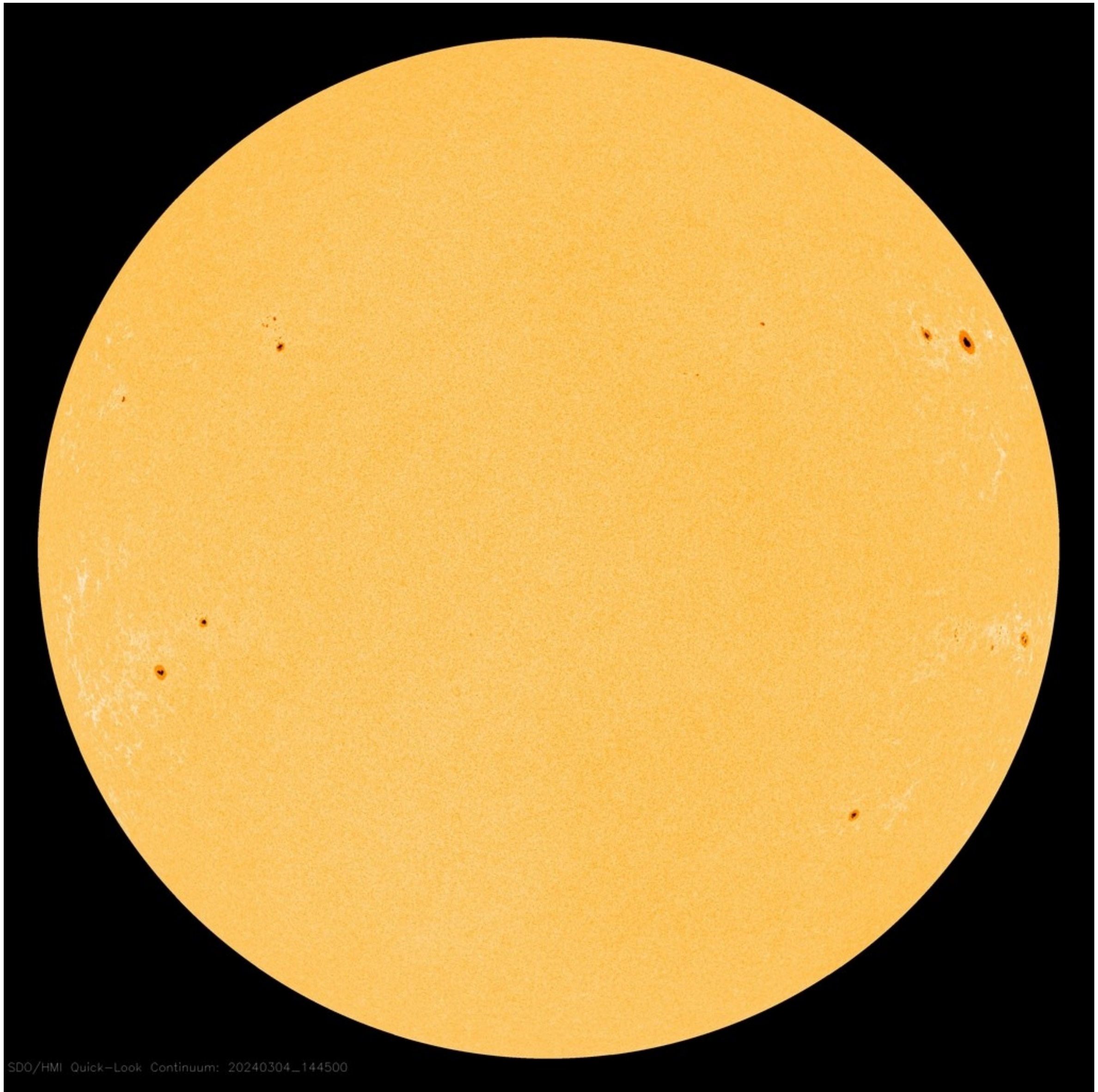
- The outer portion of the Sun
- Hot portions rise, release their heat, and sink to get more heat. Thus, **energy is *transported* to the surface**, not through light, but **with matter.**
- Of course some energy is transported as light. It is not dark anywhere inside the Sun.

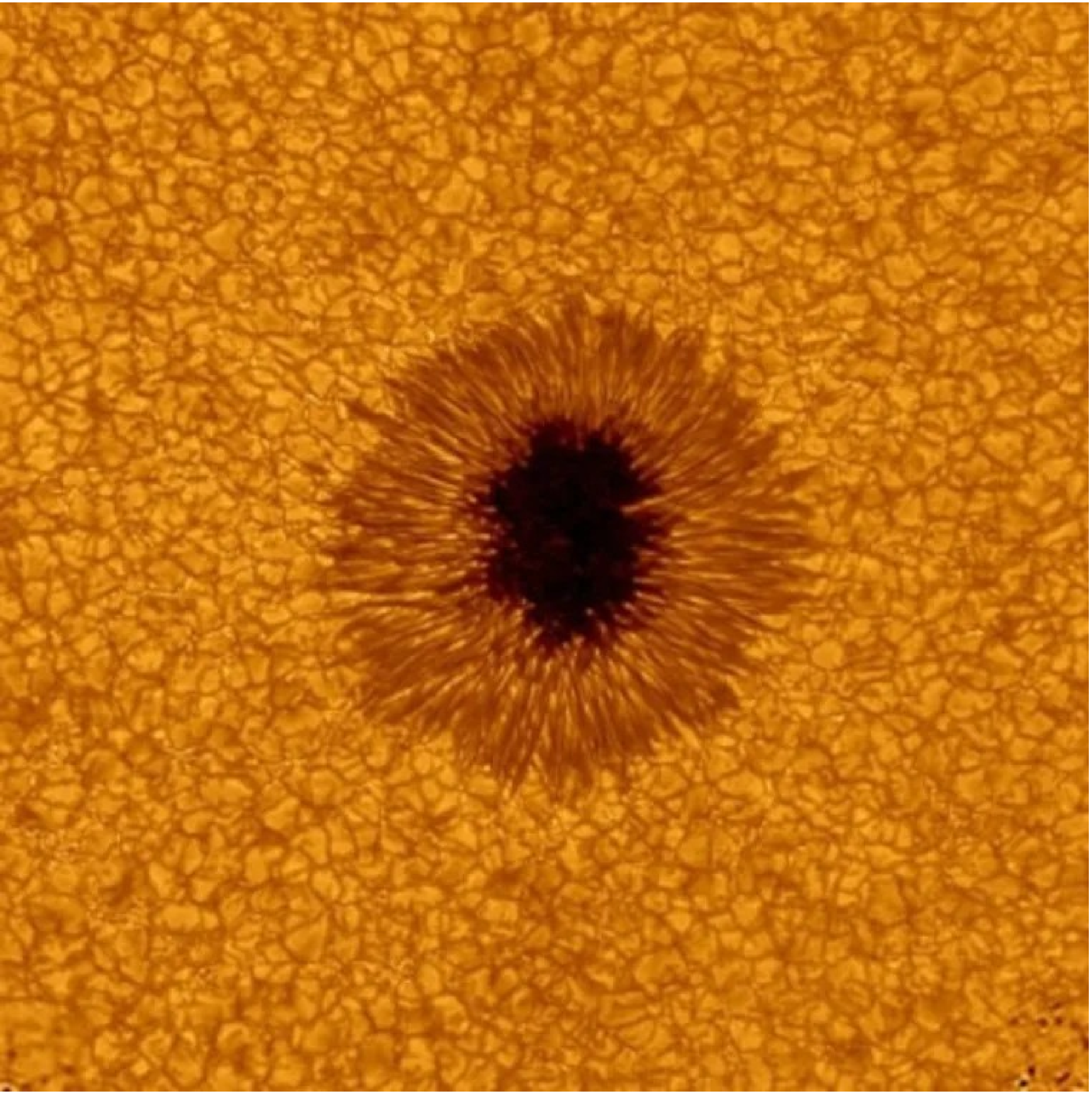
Photosphere

- This is the **visible surface of the Sun**
- Temperature is 5700 K
- The light we see leaves from here as photons are free to escape from the Sun.
- Has sunspots- regions of cooler material held in place by magnetic fields.



And now, a feature we see on the Sun's surface.

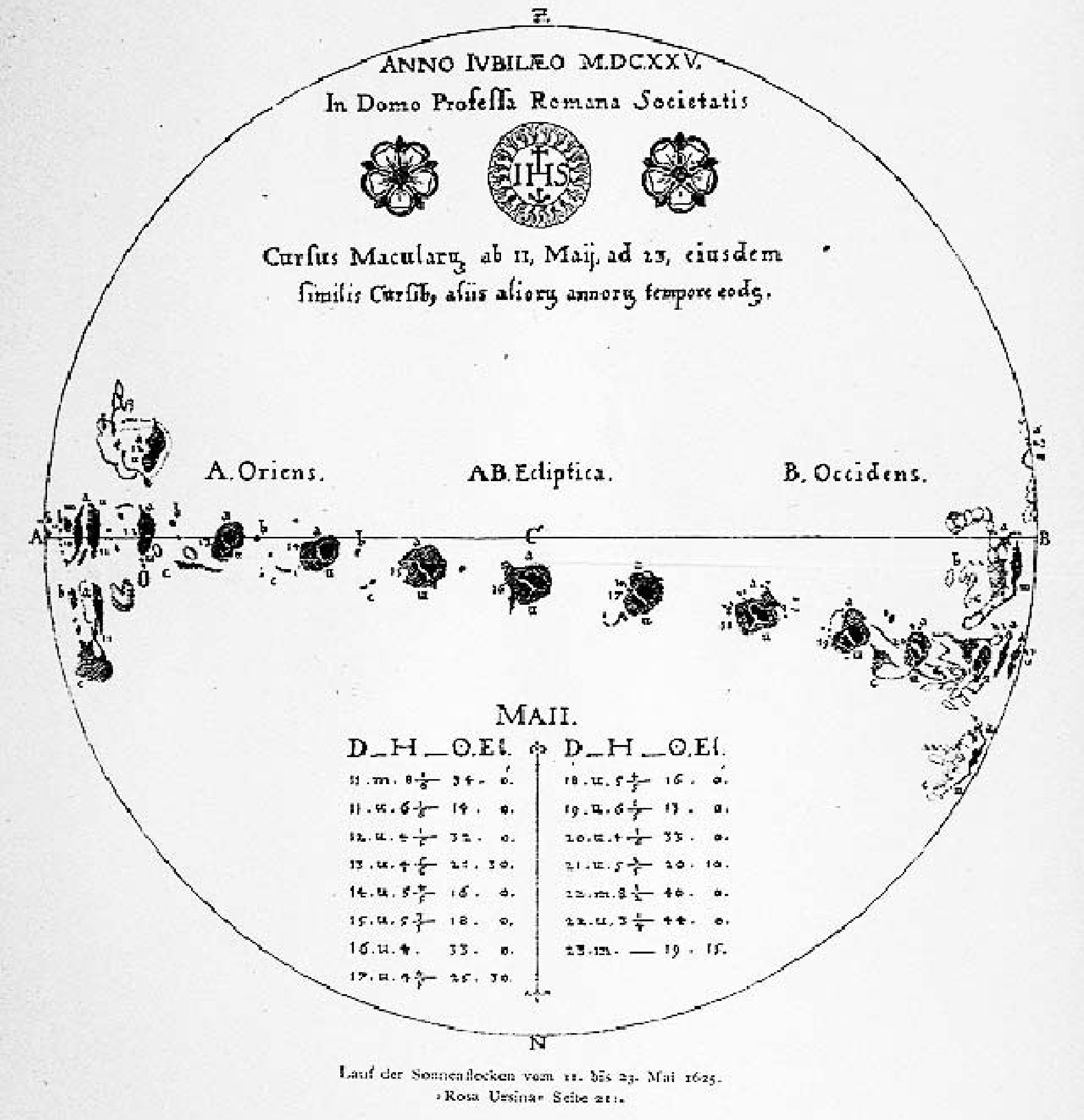




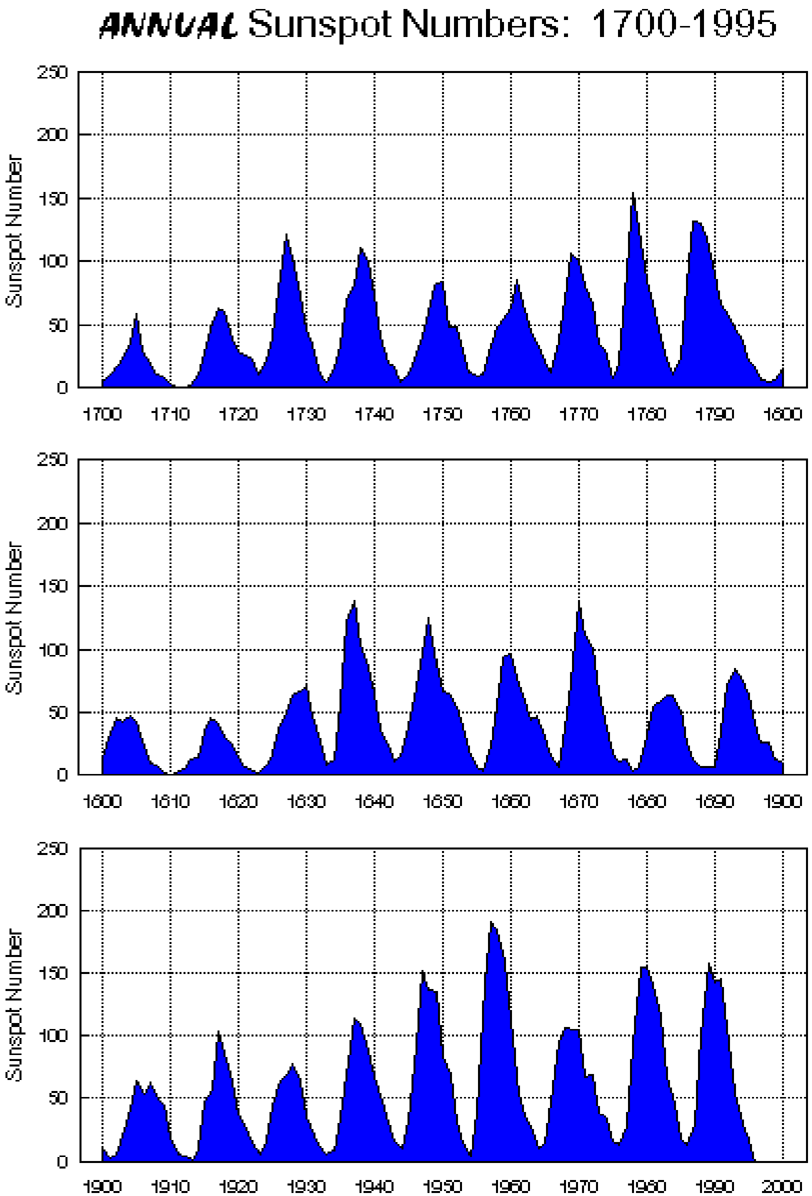
Sunspots

Sunspots only appear dark against the bright surface of the Sun, they are really over 3,700 K!

Galileo watched sunspots and determined that the Sun **spins about once every 4 weeks.**



Sunspots are regions of cooler material, held in place by strong magnetic fields.



However, they are not permanent features. Their number varies in a regular way. This is known as the solar cycle.

The Sun's magnetic field causes the solar cycle. Roughly every 11 years, the solar magnetic field switches polarity, that is the north magnetic pole becomes the south magnetic pole.