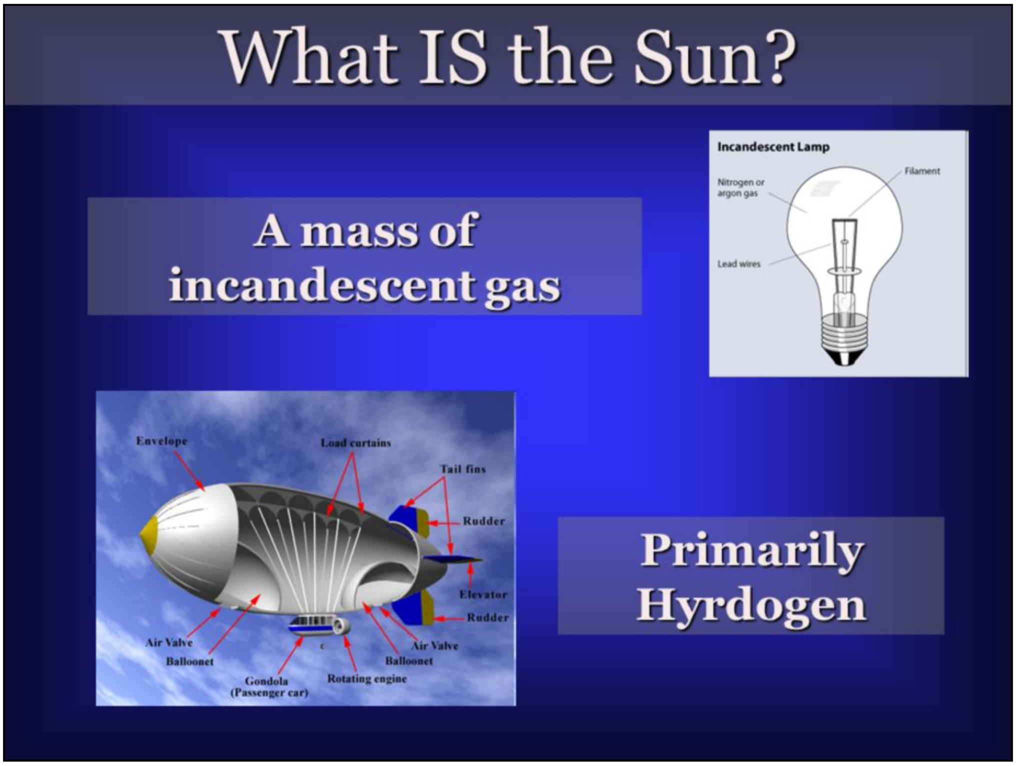
The Sun

Overview

1. What is the composition of the Sun?
   1. How do we know?
2. Why does the Sun shine?
3. What is the Sun's energy source?
   1. Chemical?
   2. Gravitational?
   3. Fusion!
4. Are we sure it's Fusion?
   1. Basic Fusion Process.
   2. Can we measure the byproducts?
5. The Solar Thermostat
   1. Why is the Sun so stable?
6. What is the structure of the Sun?



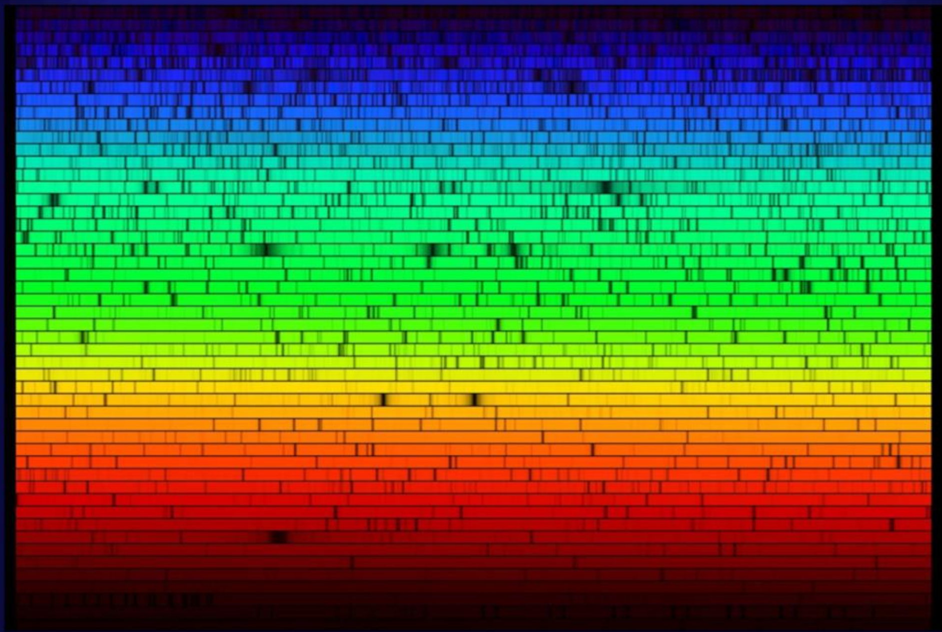
The Sun is composed *primarily* of Hydrogen.

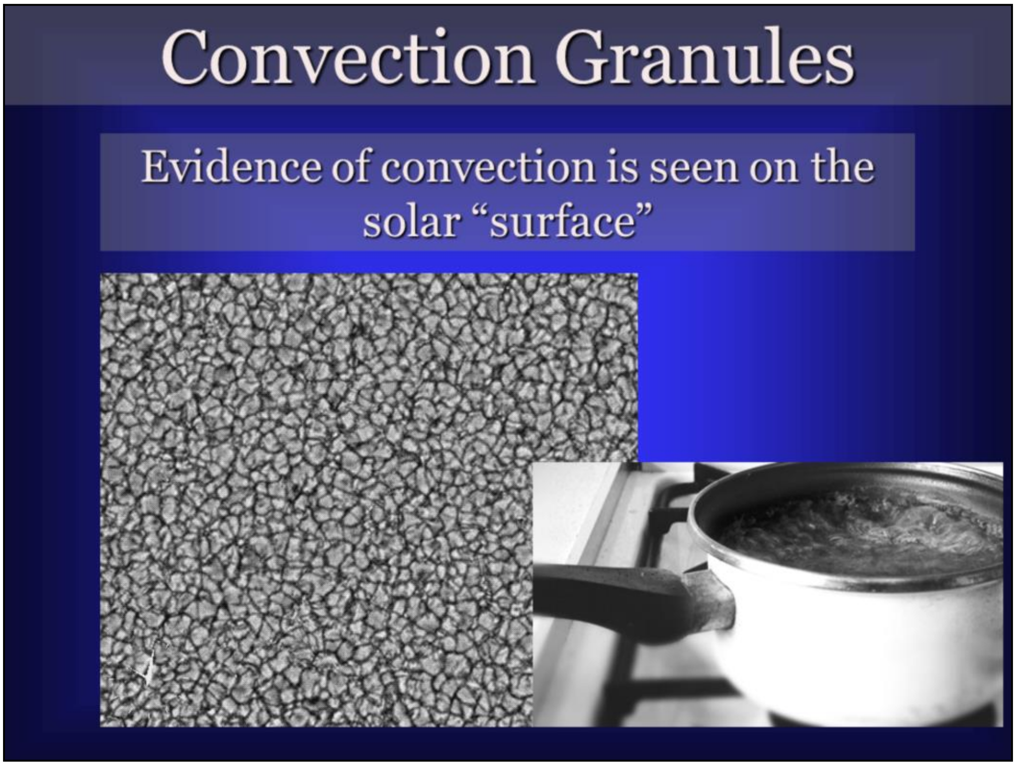
A LOT of hydrogen. It contains 98% of the mass of the solar system.

It has the same abundances as the gasses in the early solar system.

98% hydrogen and helium and around 1% of all of the other stuff on the periodic table.

Absorption

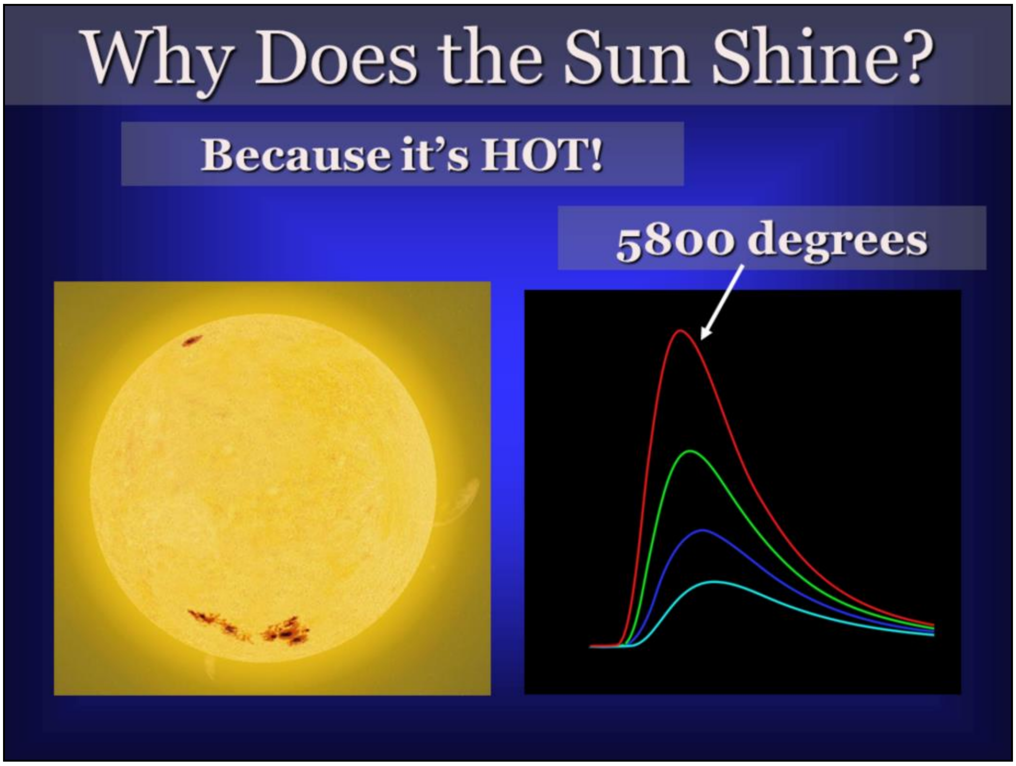




Although the surface of the Sun appears smooth evidence of the underlying convection cells can be seen.

These are called granules.

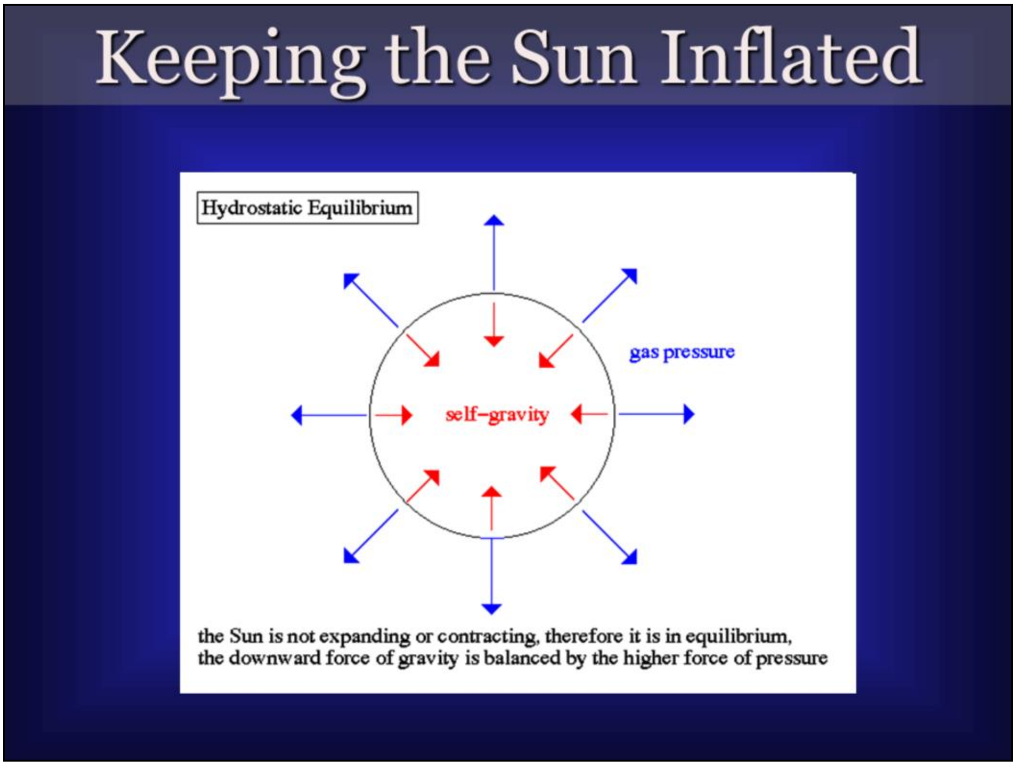
Each one of the granules is about 600 miles across.



EVERYTHING with a temperature emits light.

What's that funny plot on the right? It's called a BLACK BODY curve.

How do we get temperature from that?



The Sun is in **Hydrostatic Equilibrium**, much the same way that the atmosphere holds itself up.

BUT… it's always losing energy through radiation into space… which means it's always cooooooling off… because space is cold.

As it cools off, it should keep collapsing.

But… It doesn't continue to collapse (at least not on short time scales) so it MUST have an energy source that keeps the temperature (and thus the pressure) up.

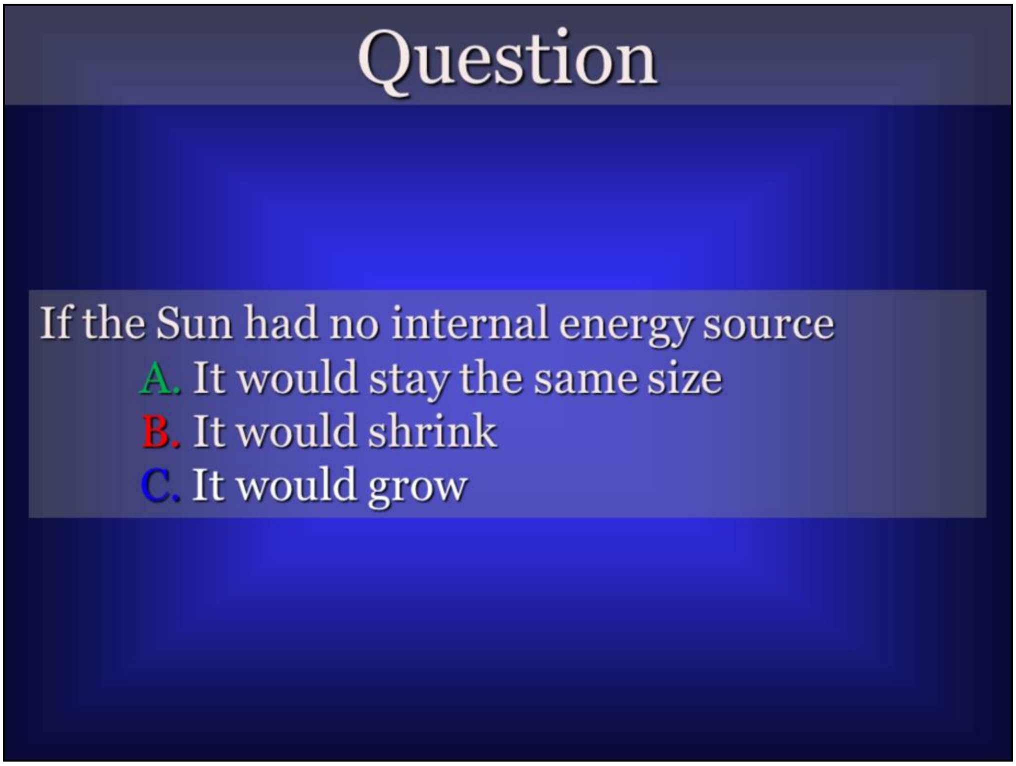
The fusion reactions keep adding energy.

The fusion reactions are also temperature sensitive… So the system auto-regulates.

If the core cools down a little… the Sun contracts a little increasing the temp and the density in the core which speeds up the reaction.

If things get too hot, the Sun expands, lowering the temperature and density in the core, slowing the reactions.

In both cases, things return to equilibrium

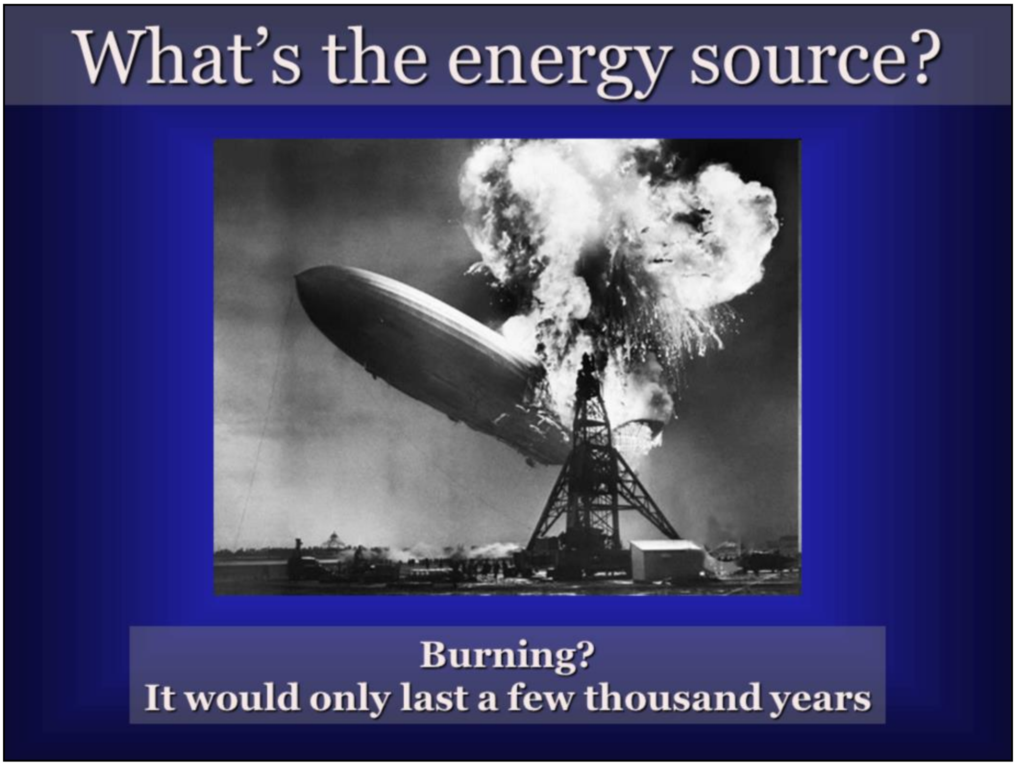


B – It would shrink.

Because:

With no heat source, the sun would cool down.

Gas pressure holds it up against gravitational collapse and as the temperature drops, the Gas Pressure will drop



“burning” is usually a way of saying “oxidation”

Hydrogen Oxide is H2O, or water.

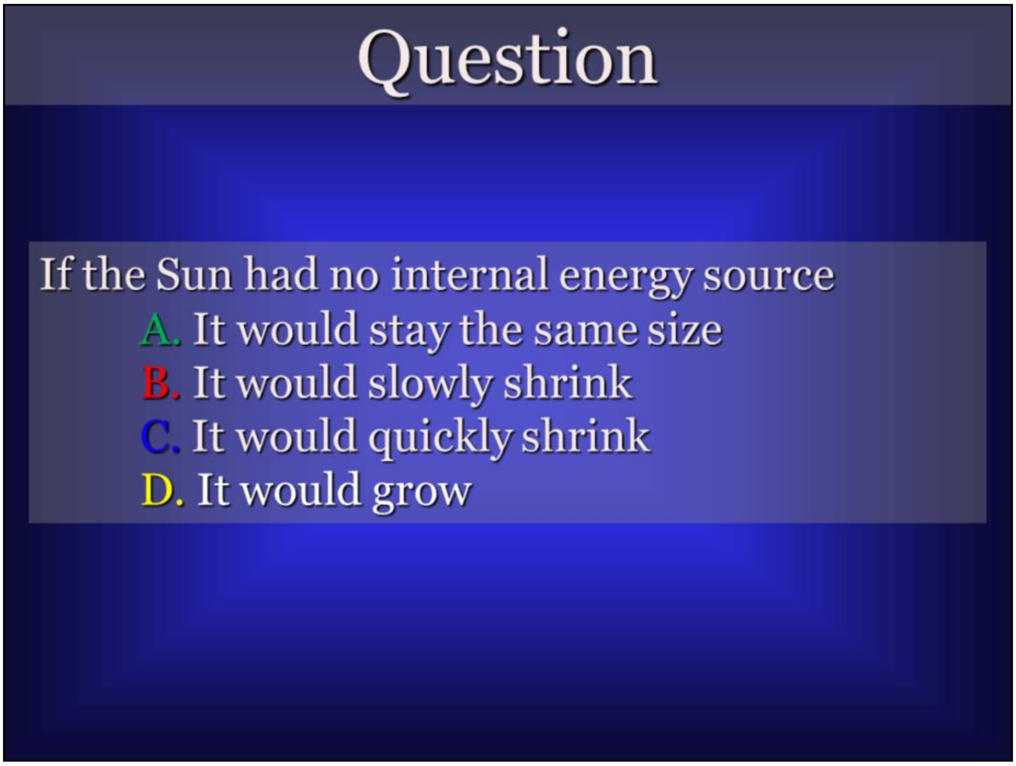
We know how much energy the Sun is throwing off.

We know how much energy a typical chemical reaction gives off.

Based on it’s mass,

If the sun were combusting (or having some other chemical reaction) it would only burn for a few thousand years.

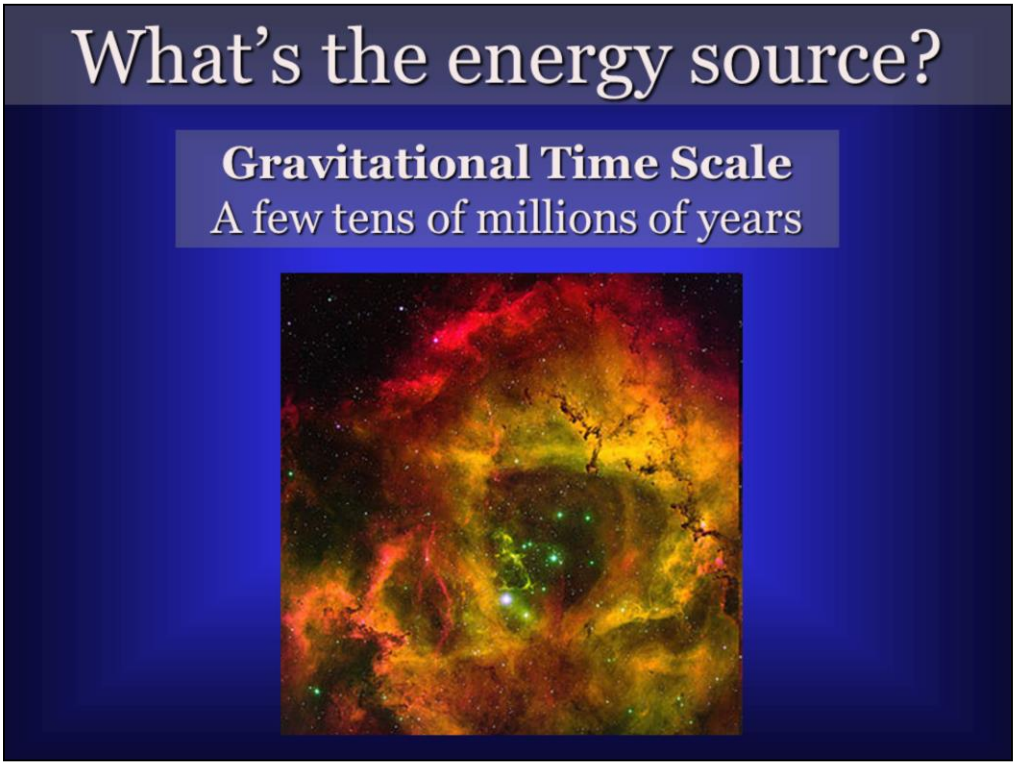
We have good reason to believe that the Sun has been around longer than a few thousand years.



B – It would SLOWLY shrink.

As opposed to quickly shrinking, as in a free fall collapse.

As it collapses, it will heat up a little bit which will increase the internal gas pressure slowing the collapse.



As the cloud collapses, the potential energy is transferred into kinetic energy.

The Sun is very dense, and since it has a temperature (from the kinetic energy gained from the collapse), it radiates like a black body.

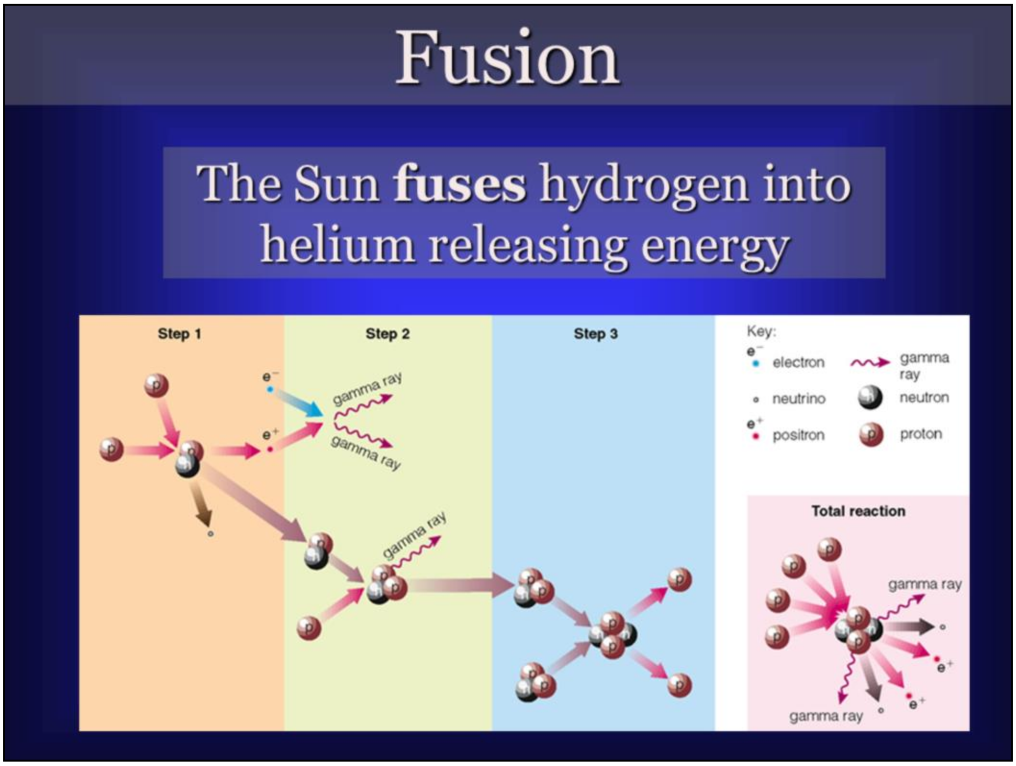
But! Only the surface can radiate… It takes the energy a loooooong time to get out.

So… the Sun should be sloooowly shrinking. We don't observe the Sun shrinking.

Additionally If the sun were releasing gravitational potential energy as heat, it would last a few tens of millions of years.

Geological evidence suggests that the Earth (and rocks from space) are several billion years old

So it's not likely powered by grav. Potential



The Sun is fusing hydrogen nuclei into helium nuclei in its core.

A Hydrogen nucleus is composed of a single proton.

A Helium nucleus is composed of two protons and two neutrons.

In order to fuse protons, the electrostatic force must be overcome, which requires very high pressures and temperatures.

Like those found in the center of the Sun

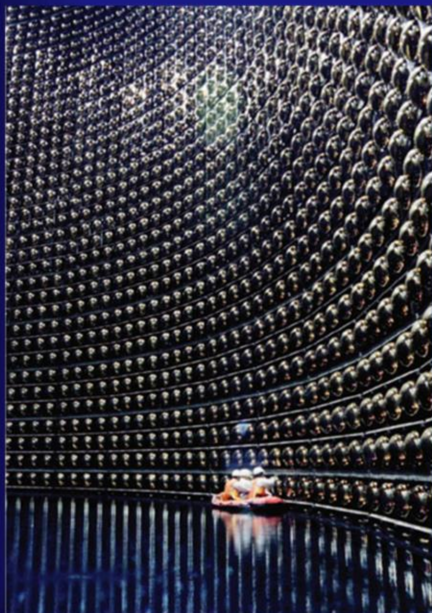
> The temperature at the center of the Sun is 12 million degrees Kelvin
>
> The central pressure is 270 billion atmospheres.

Once the protons get close enough together, the strong nuclear force takes over.

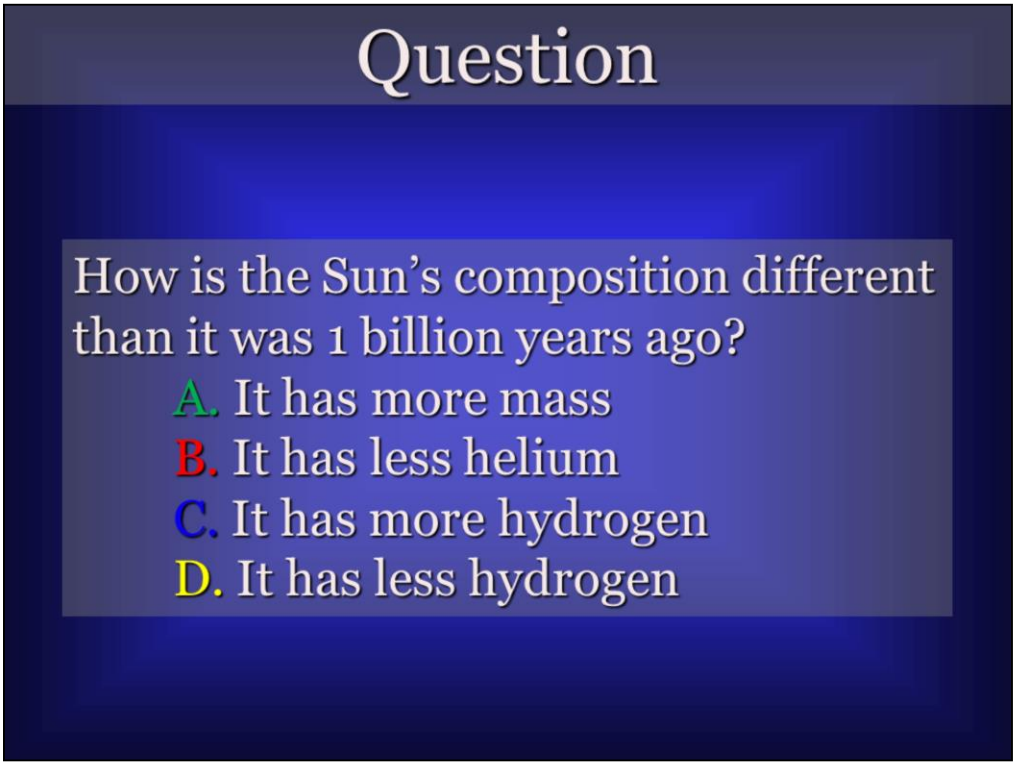
We get energy from this reaction via Einstein's equation: $E=mc^2$

> 1 helium nucleus is slightly lighter than 4 hydrogen nuclei.
>
> The extra mass was converted into energy

How do We Know?



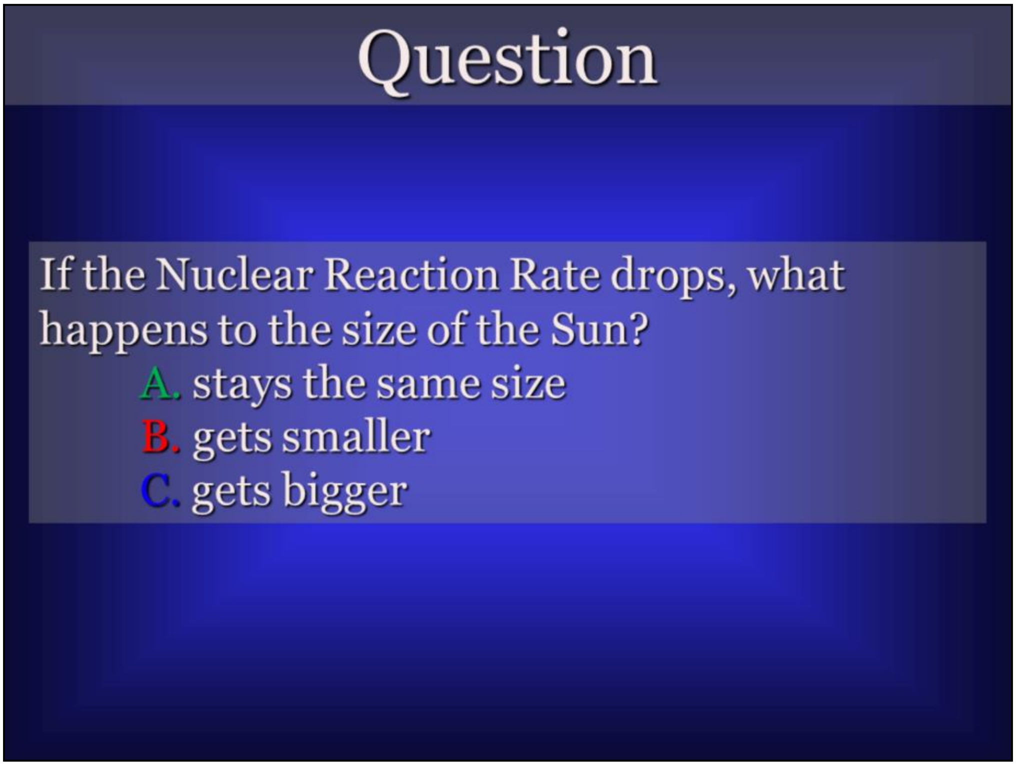
Detecting Neutrinos



D: It as less Hydrogen

Fusion is the act of combining Hydrogen nuclei to create Helium Nuclei

So, over its lifetime, the Sun will use up Hydrogen and produce Helium



B- Gets smaller

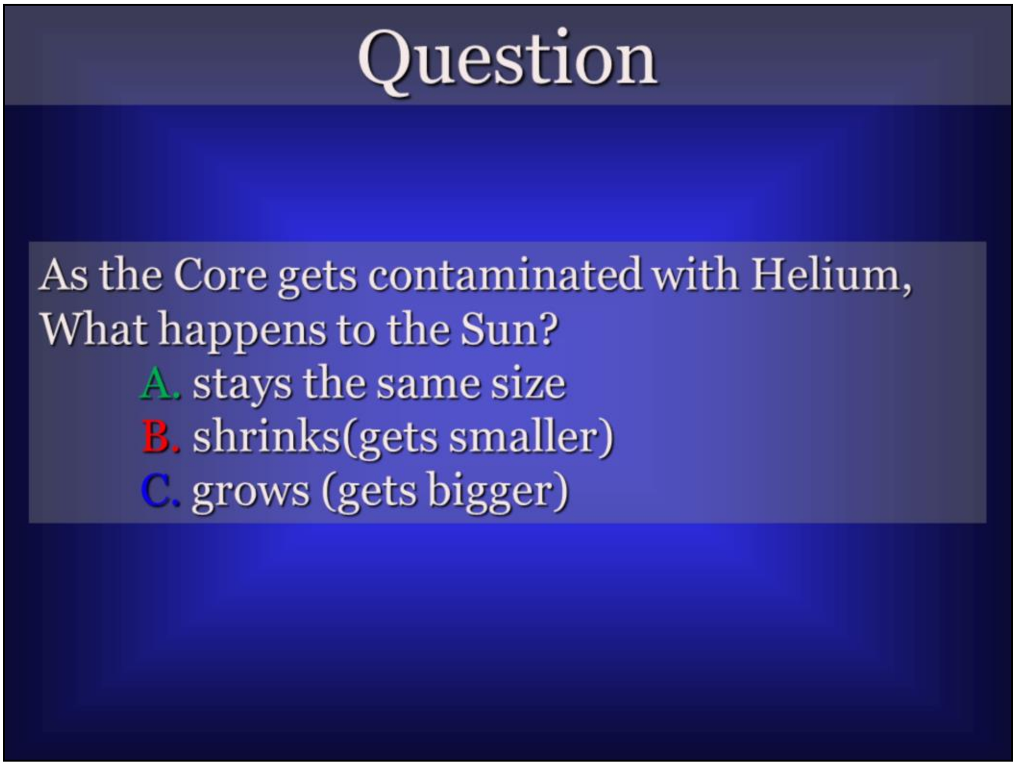
If the reaction rate drops, the Sun will cool off slightly.
This will cause the internal pressure to drop allowing the Sun to shrink.

The Reaction Rate

Depends On

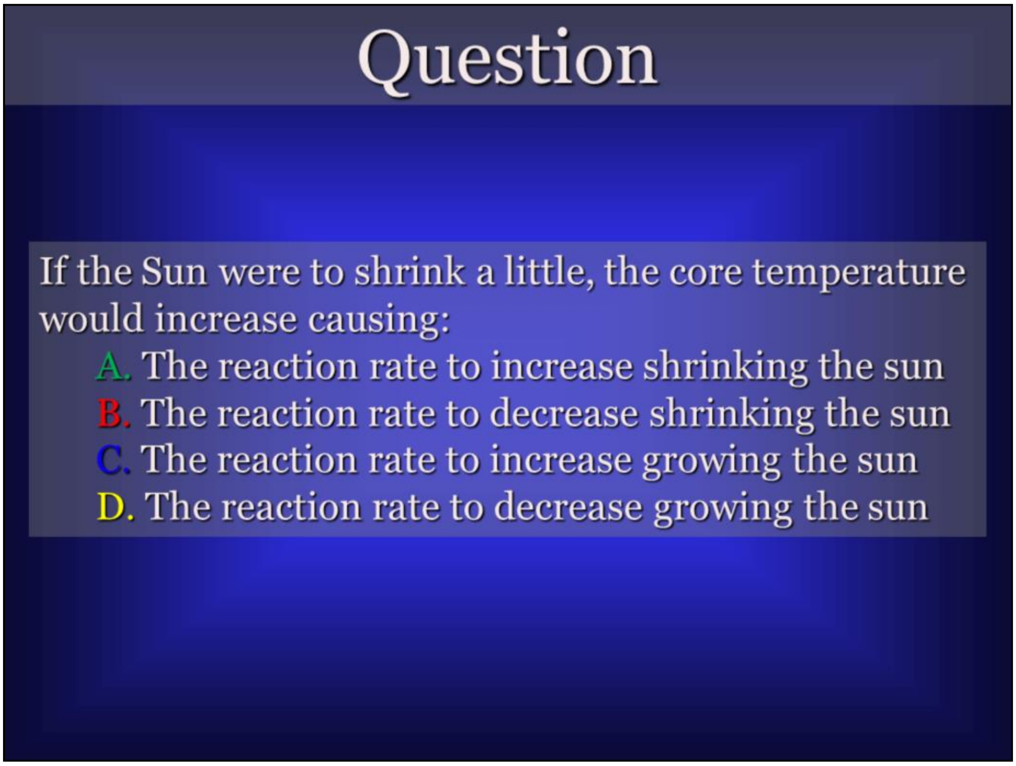
Composition:
Hydrogen to “Other Stuff” ratio. Less hydrogen, lower reaction rate

Temperature:
Hotter = Higher reaction rate



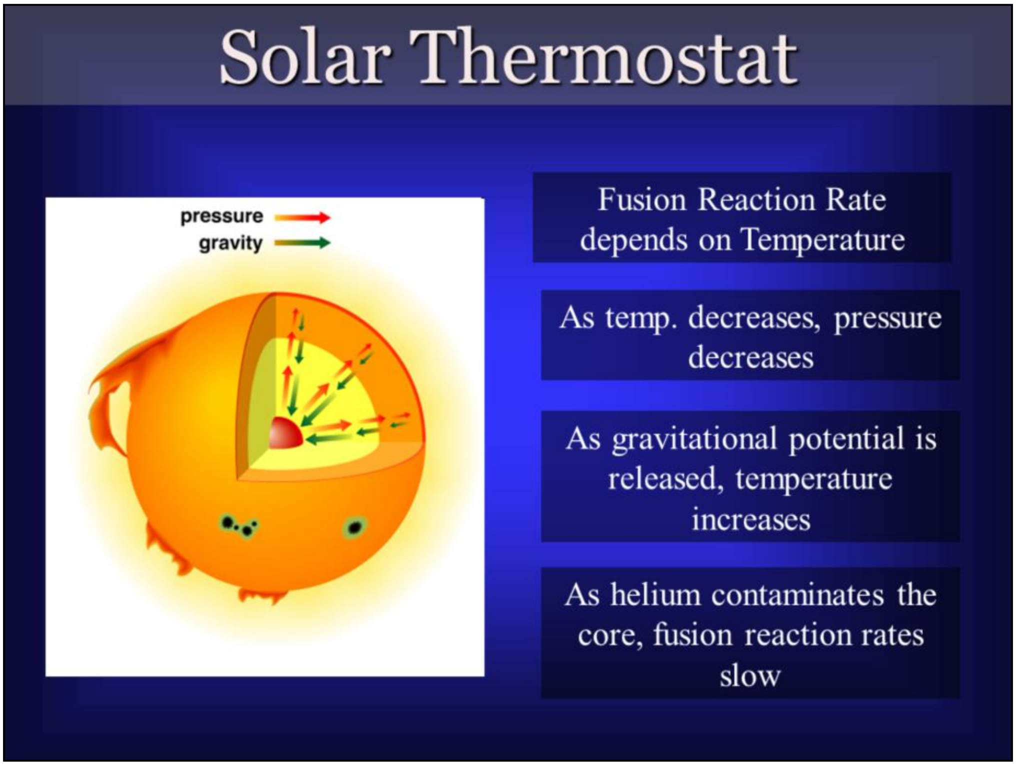
B – Shrinks

As the core gets contaminated with Helium, the reaction rate drops.
When the reaction rate drops, the Sun cools down slightly.
The drop in temperature causes the Sun to shrink slightly



C.

This entire process is known as the Solar Thermostat. It's why the Sun is so stable.



As Helium contaminates the core of the star, the hydrogen reaction rate slows.

This causes the Sun to cool, which causes the pressure to drop.

When the pressure drops, gravity causes the star to collapse slightly.

This slight compression (release of grav. Potential energy) causes the temperature to increase slightly.

The increased temperature increases the reaction rate in the core.

The star returns to equilibrium.

If the core cools down a little… the Sun contracts a little increasing the temp and the density in the core which speeds up the reaction.

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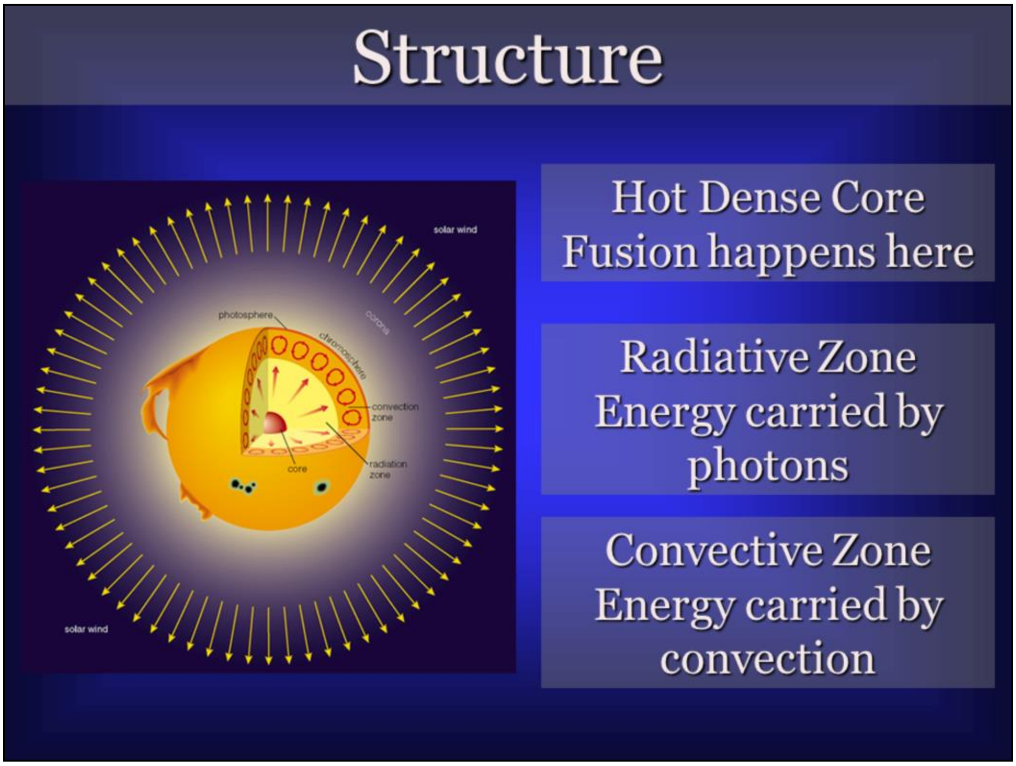


Fusion is ONLY happening in the **core** of the Sun. Only about 10 percent of the Sun's mass will be converted to Helium.

Surrounding the core is a RADIATIVE zone.

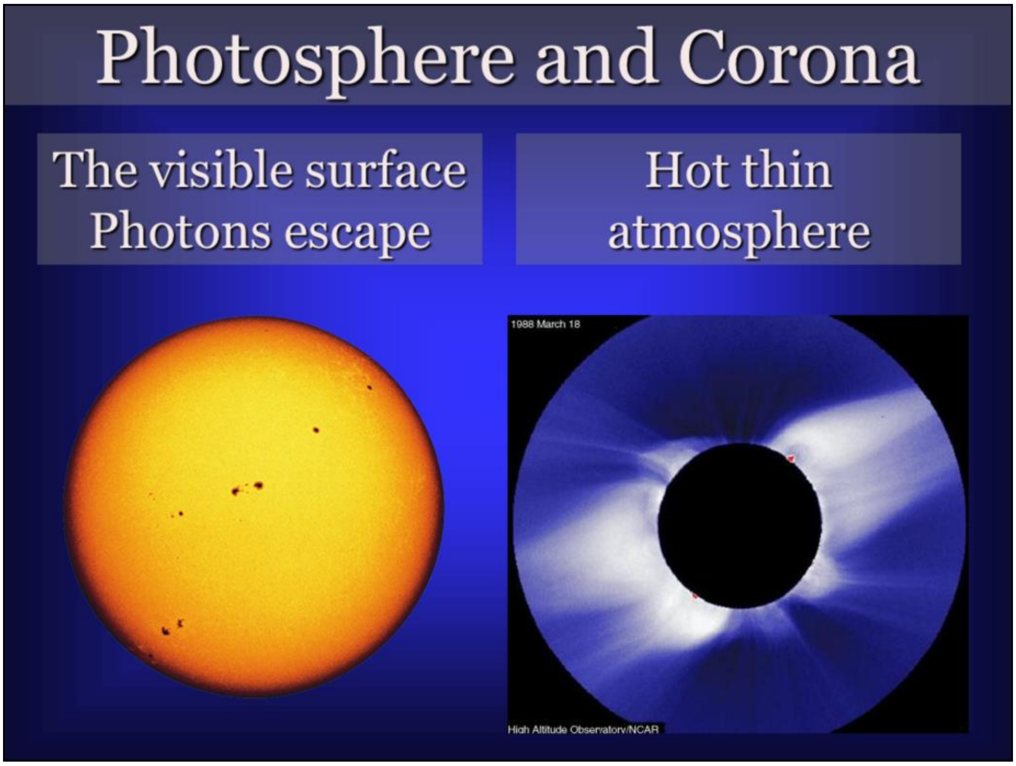
The core and the radiative zones aren't good at absorbing photons so the photons randomly bouncing around slowly working their way out.

It will take a photon about a million years to get all the way out.

The convective zone very is good at absorbing photons.

The photons created in the core are absorbed in the radiative zone and heat the gas in this region.

Convection carries the energy out in this region.



The photosphere is the ‘surface’ of the sun. The radius of the photosphere is 696,000 km

It’s the place where photons finally ‘escape’ into space.

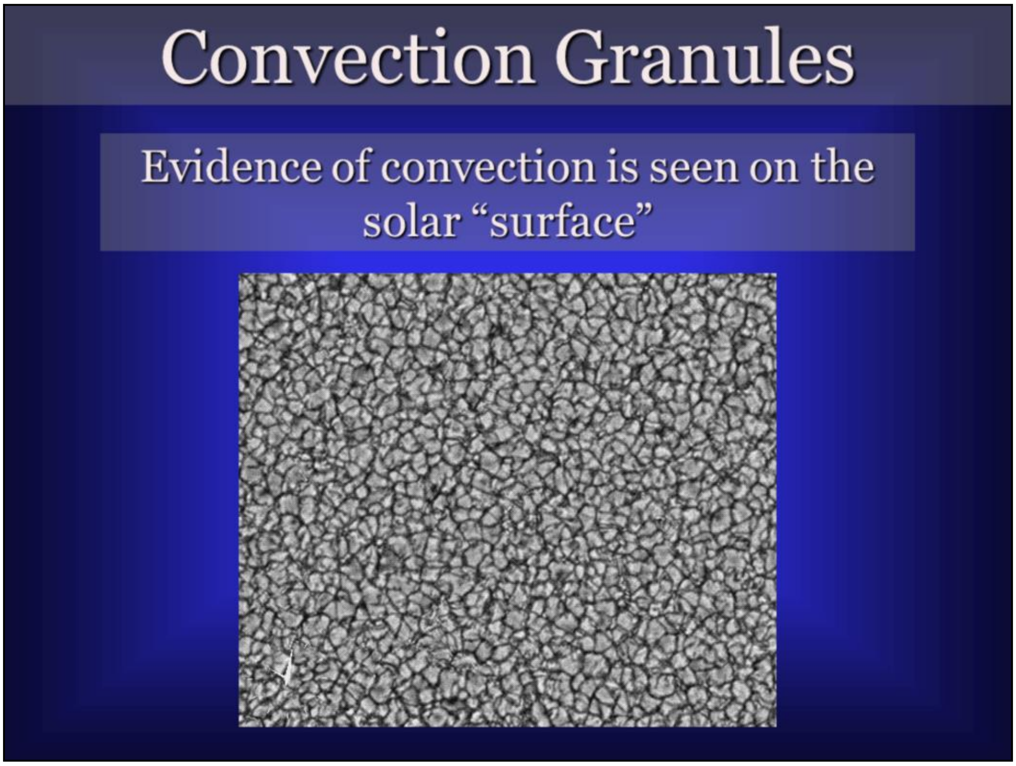
Temperature at the photosphere is 5,800 degrees Kelvin.

The black body peaks in the green.

The Corona is a very low density, very hot gas, about 1 million degrees.

The heating mechanism is poorly understood. Leading hypothesis is that energy is transported outward by magnetic fields.

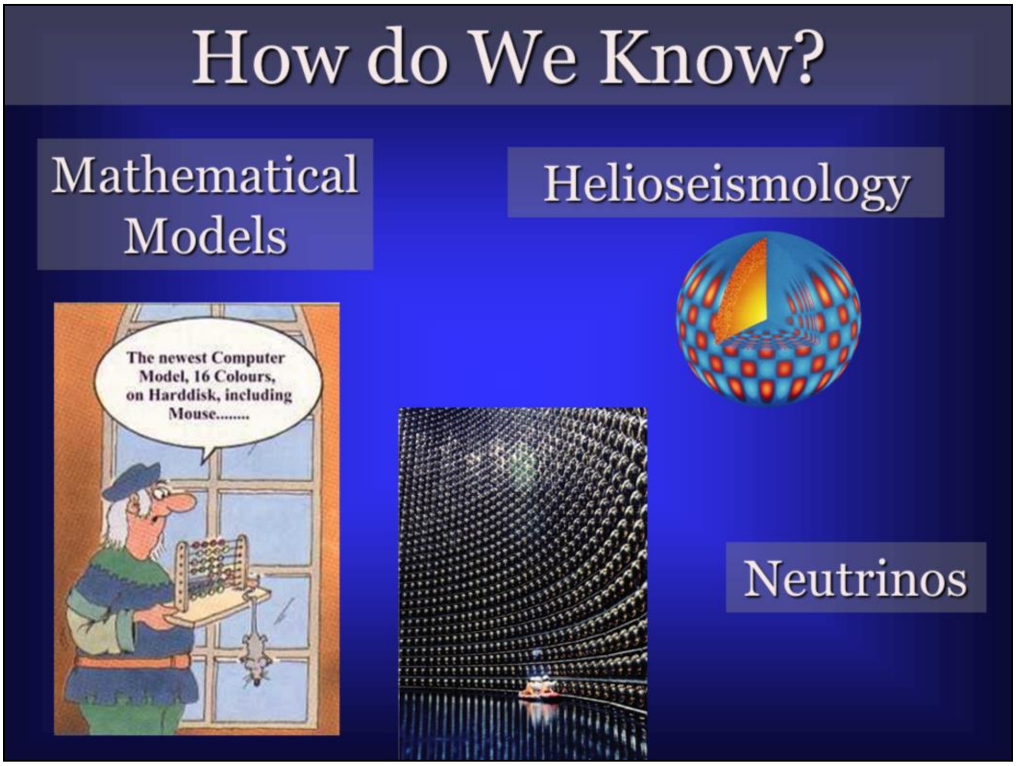
It contains relatively little heat due to low densities.



Although the surface of the Sun appears smooth evidence of the underlying convection cells can be seen.

These are called granules.

Each one of the granules is about 600 miles across.



By mixing together in a computational model:

The composition of the Sun,

The mass of the Sun,

Basic physics (hydrostatic equilibrium, radiation pressure, etc..),

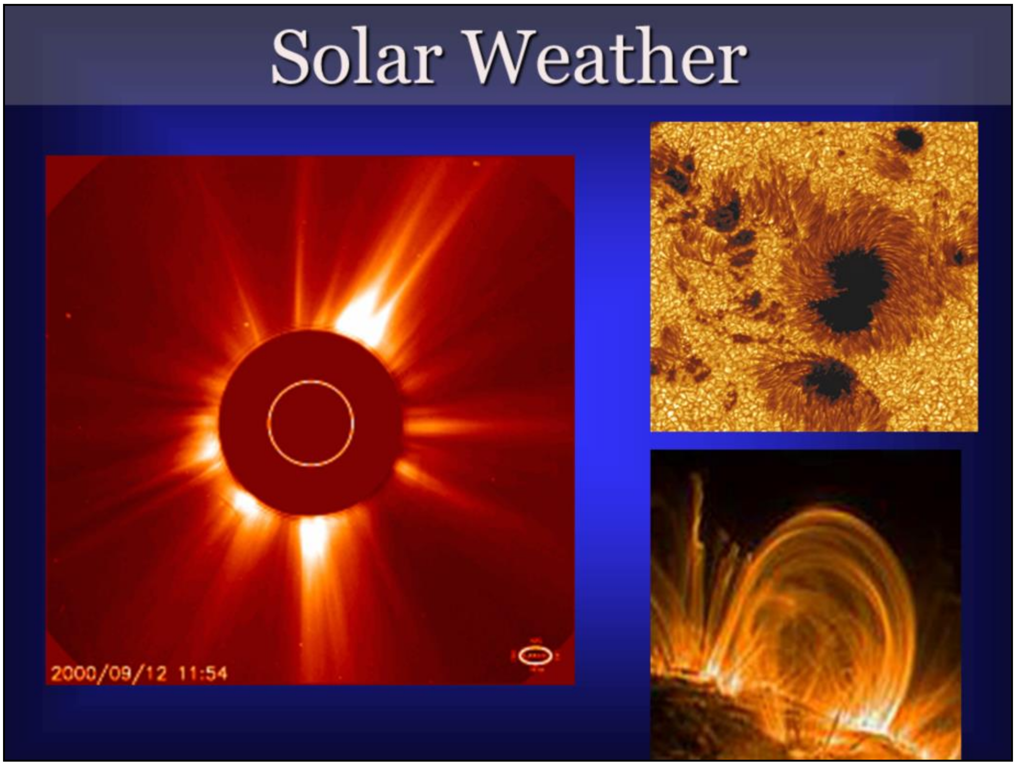
What we know from the laboratory about fusion

We get out correct luminosity and size of the Sun. This is good!

Similar to determining the structure of the Earth through seismology, we watch the vibrations of the Sun and determine its internal structure.

Results from helioseismology agree well with computer models.

By counting the neutrinos from the Sun, we verify what we know about the fusion reactions going on.



Sunspots are cool places on the photosphere.

They are associated with places where strong magnetic fields are emanating.

Magnetic fields have a loop structure exiting the photosphere and reentering it at another point.

These loops are associated with solar prominances.

When they break, CME (coronal mass ejections occur)

CMEs are the cause of the Aurora

Pretty Pictures