Lives of the Stars Lecture 3: What makes a star?

Presented by
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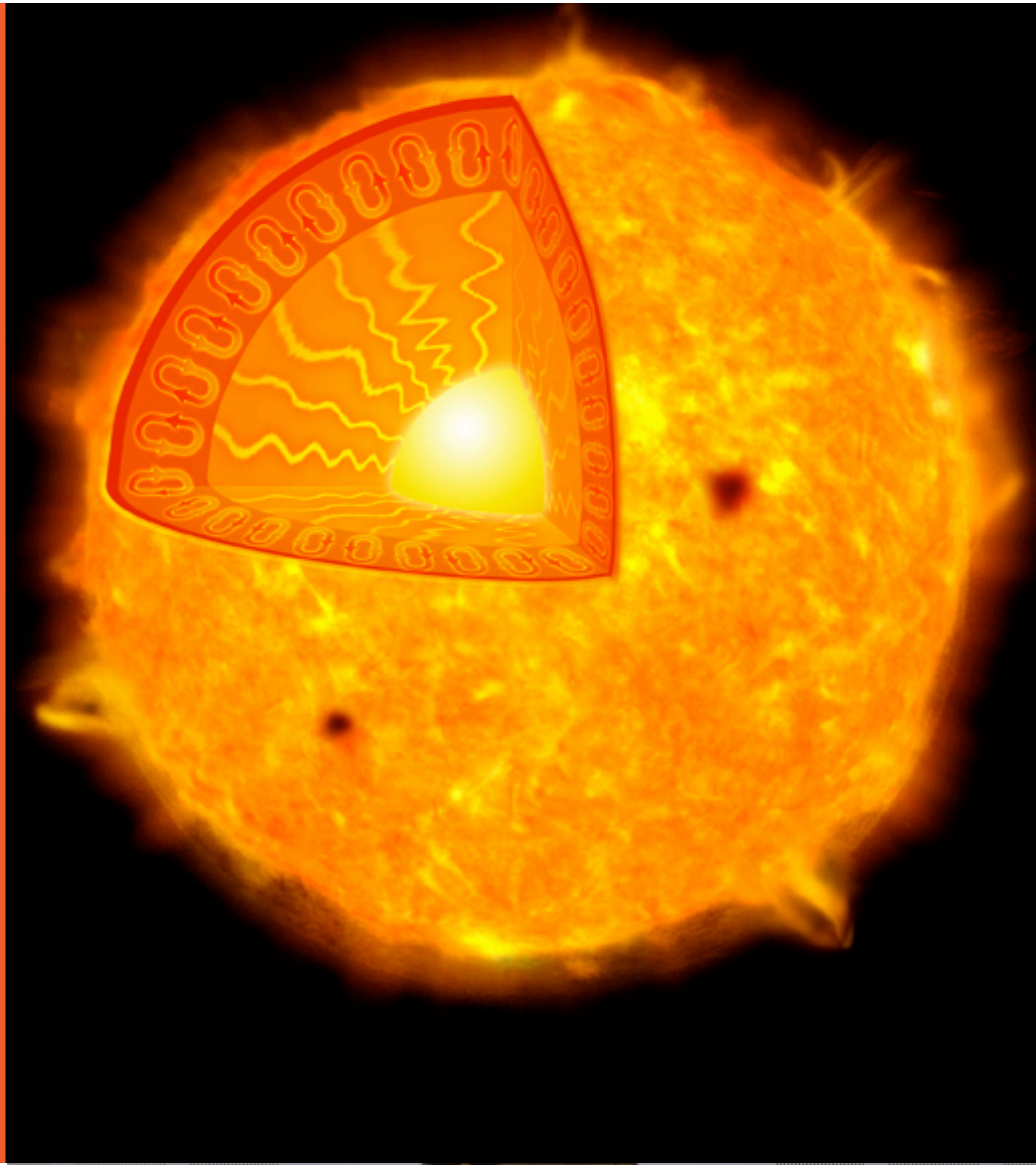
School of Physics

Spring 2016

THE UNIVERSITY OF SYDNEY



Night-viewing evening

The night-viewing evening, scheduled for Saturday 29 October, has been

CANCELLED

John will try for a future date. If you would like to be notified of this, please leave your name and email address on the sheet at the front.

Prologue

What is a star?

"… a gravitationally confined thermonuclear reactor whose composition evolves as energy is lost to radiation and neutrinos"

– Woosley, Heger and Weaver 2002

Prologue

What makes a star?

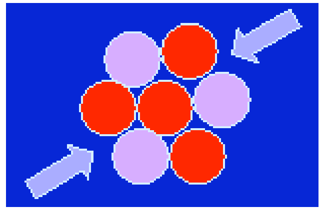
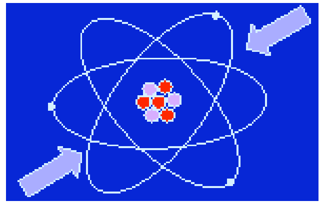
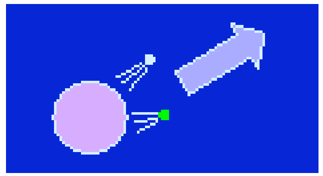
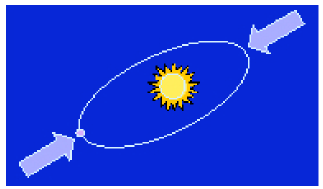
In fact, there is a simple answer to this question:

Gravity

To understand why, we need to look at the four *fundamental forces* which govern the universe.

Forces are the means by which particles in the universe interact with each other: no evidence for a fifth force has ever been found.

Every particle in the Universe reacts to at least one of these forces. Forces can be either attractive or repulsive.

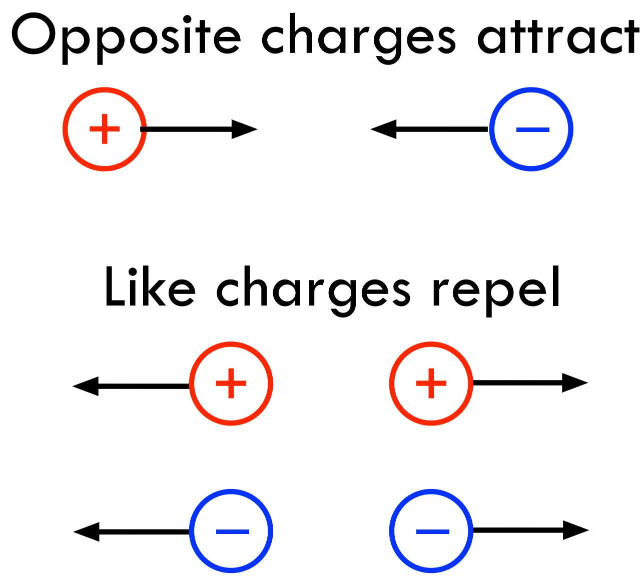
Force	*acts on*	*Strength*	*Range*	
strong nuclear	protons neutrons	1	10^{-15} m	
electromagnetic	*charged* particles: *protons, electrons*	0.007	infinite	
weak nuclear	protons, neutrons, electrons, neutrinos	10^{-5}	10^{-17} m	
gravitational	particles with *mass*: protons, neutrons, electrons	10^{-39}	infinite	

- The *strong nuclear force* is the strongest, but falls off very rapidly with distance: it only acts over the diameter of the nucleus

- The *weak nuclear force* has an even shorter range than the strong force, and governs processes like beta decay and radioactivity.

- The *electromagnetic force* governs all interactions between protons and electrons. It falls off as the square of the distance, so its range is infinite.

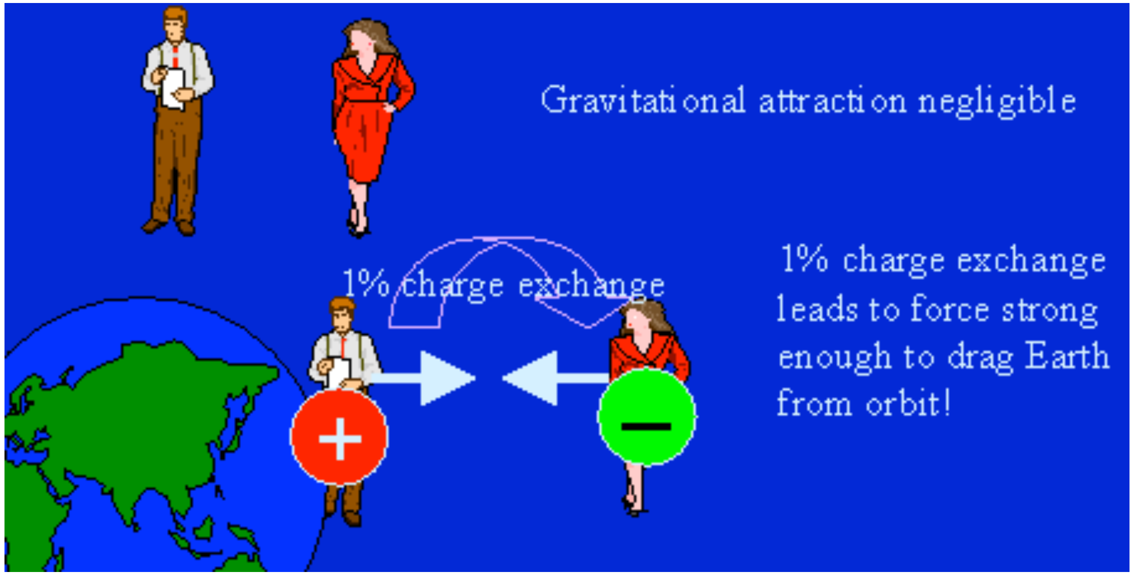
  The *direction* of the force depends on the sign of the charges.



- *Gravity* acts on all particles with mass. Like the electromagnetic force, it falls off as the square of the distance, so its range is infinite.

  However, unlike the electromagnetic force, there is no repelling component: there is no "negative mass". Gravity *always* attracts.

The EM force is incomparably stronger than the gravitational force. If you put a person in orbit and left 1% of their electrons behind, the EM force would be strong enough to affect the orbit of the Earth!



So why do we rarely have to worry about the EM force in astronomy?

The Earth contains about 10^{51} protons, but it also contains about 10^{51} electrons. This means that the overall electric charge on the Earth is quite close to zero.

The gravitational field of the Earth, however, is 10^{51} times that of a single proton: the fields of *each and every particle* that makes up the Earth all add up to make the overall gravitational field of the Earth.

That is why the gravitational force is so important in the universe. All the other forces are essentially only local, whereas the gravitational force is both *long-range* and only *attractive*.

This is why gravity eventually wins.

Stars

Let's see how these facts about gravity affect the behaviour of stars.

A star consists of about 2×10^{30} kg of gas, mostly hydrogen and helium.

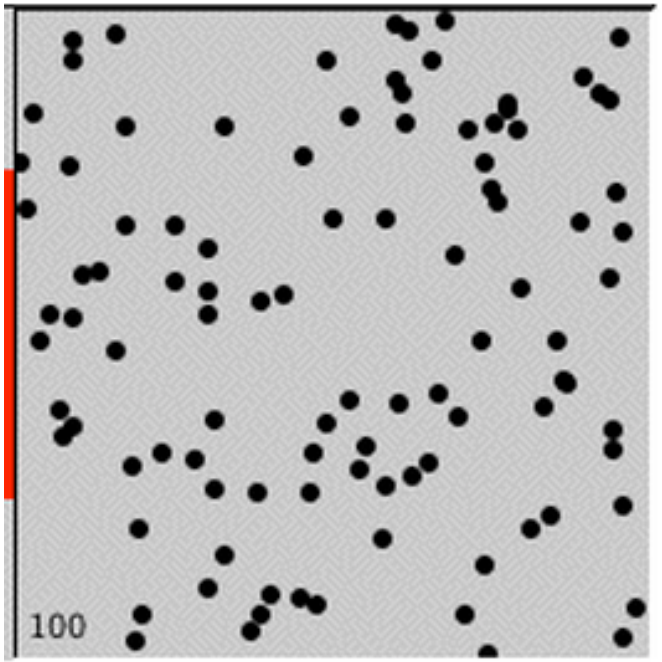
If each of those atoms is attracting each of the others, what is stopping the gas collapsing in on itself?

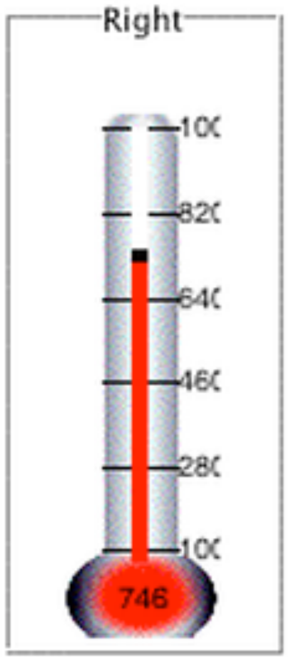
Something must be *resisting* the collapse.

The gas itself is what resists the collapse. As the outer layers press down on the gas in the interior, the *pressure* increases: the individual atoms are squeezed together.

The gas is made of individual particles, and the behaviour we observe of gases at large scale (*macroscopic* quantities) relate to the small-scale behaviour of these particles (*microscopic* quantities).

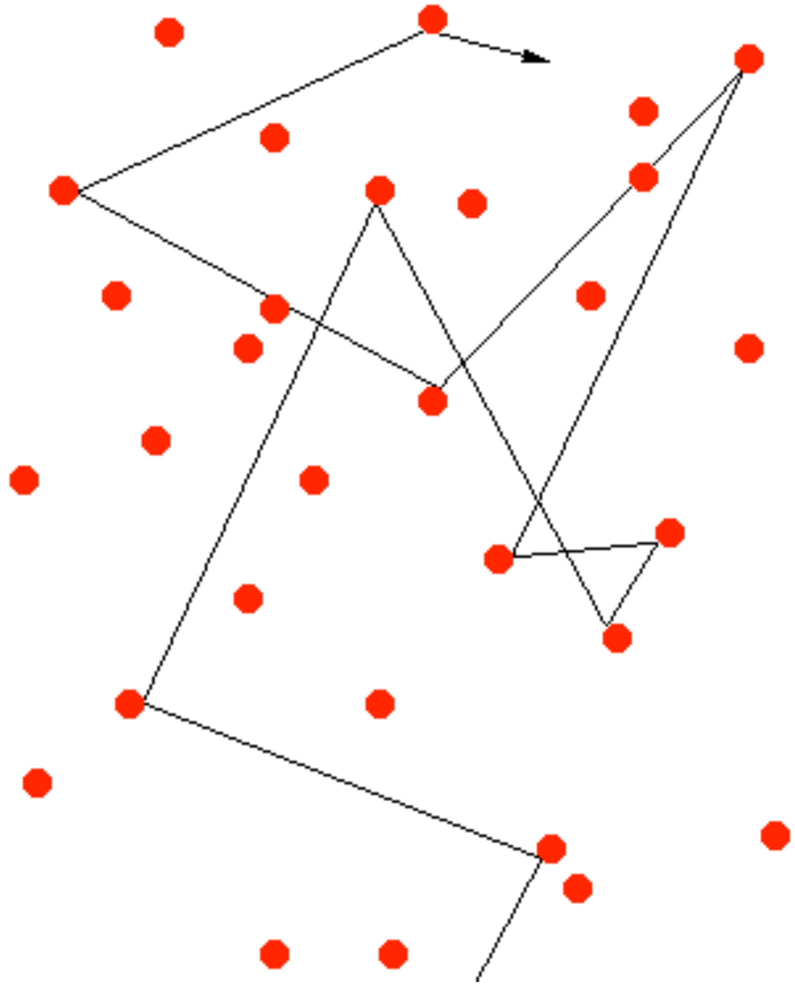
Gases are made up of tiny particles moving in straight lines and bouncing off each other – the *kinetic theory of gases*.





High *temperature* means particles are moving faster (more kinetic energy); high *pressure* is the transfer of kinetic energy from particles hitting the sides of the container

In air at 0° C, the molecules are typically travelling at 400 m/s, though they have a spread of speeds from almost zero up to 1200 m/s. However, they never get very far: on average, a particle only travels $2\text{x}10^{-5}$ cm before colliding with another molecule, so on average each molecule makes five billion collisions per second!



Everything we know about the behaviour of gases follows from this simple model.

This behaviour summarised in the ideal gas law:

$$PV = nRT$$

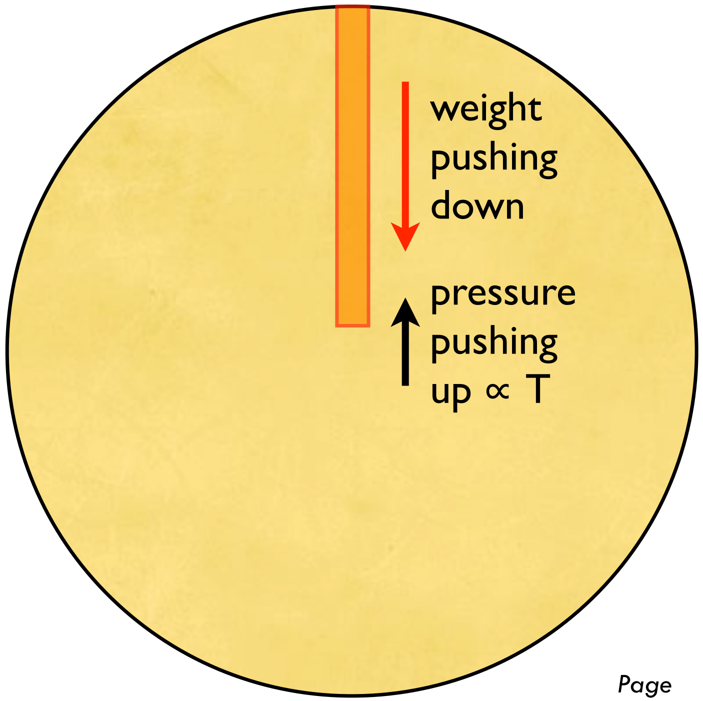
as *P goes up*: V goes down, T up, density up

as *V goes down*: P goes up, T up, density up

as *T goes up*: P goes up, V up, density down

So: gravity is squeezing the gas in the star. This increases the pressure, and also increases the temperature of the gas at the centre.

In fact, we can work out very roughly what the temperature in the middle of the star is, by working out what pressure is required to counterbalance gravity. A very rough estimate shows that the temperature must be about 20,000,000 K.



Let's leave this for a moment, and consider another interesting fact about stars: they are shining, i.e. losing energy.

Stars must be producing energy, since they can keep this up for billions of years.

Where do they get this energy from?

Chemical energy? ⇒ *only enough for a million years*

Gravitational energy? ⇒ *only enough for 100 million years*

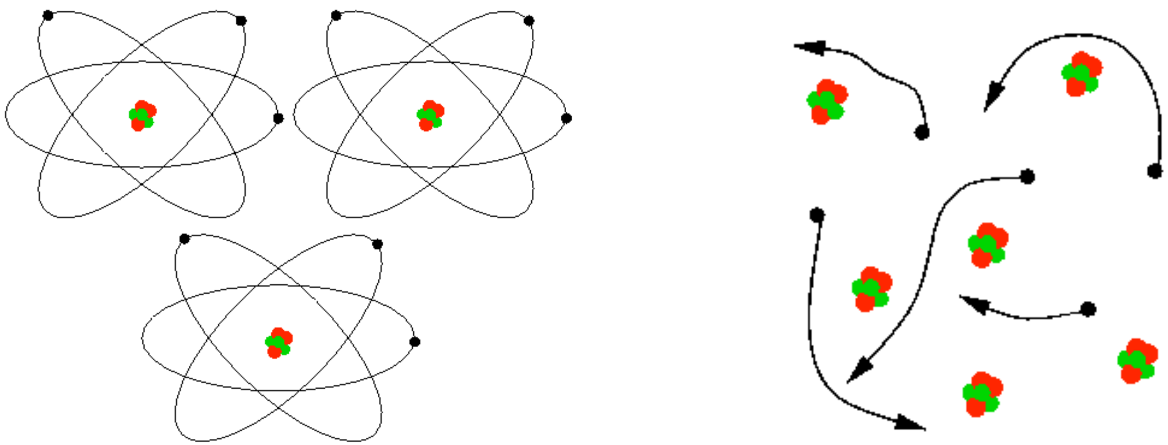
Since we have good evidence that the Solar System is at least 4 billion years old, we need another source.

The only possible source of energy which could keep the Sun burning for billions of years is nuclear energy: somehow, the Sun is converting a tiny fraction of its mass into energy according to Einstein's relationship

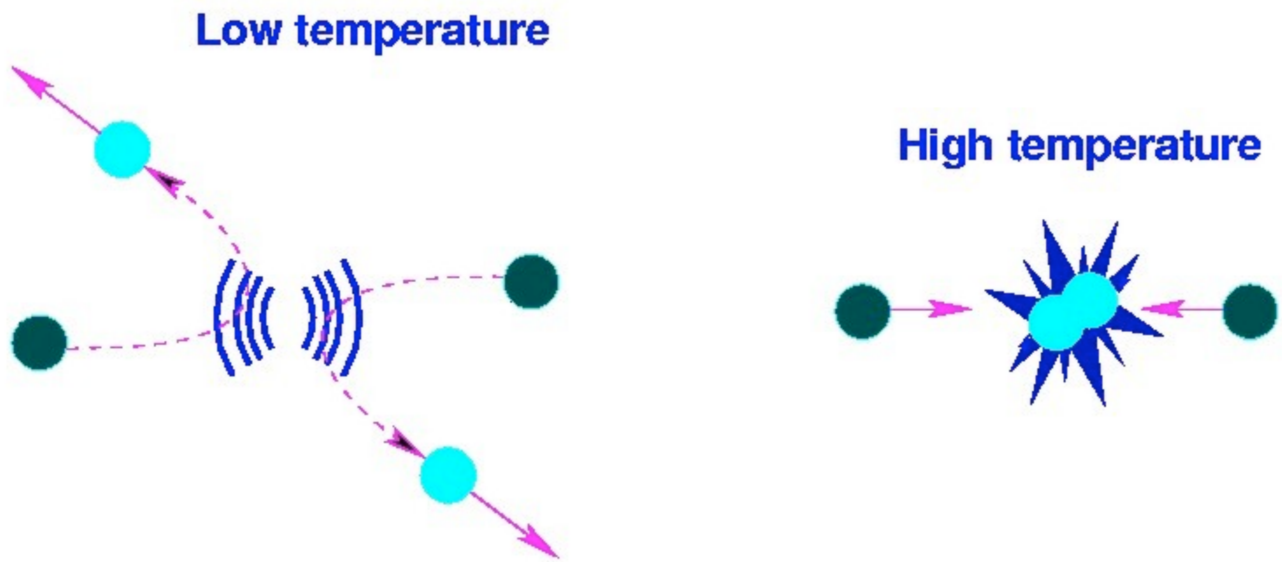
$$E = mc^2$$

Since stars are largely hydrogen, they provide this energy by the simplest method: fusing four hydrogen atoms together to form helium.

At the enormous temperatures the star's core, ordinary materials cannot exist as solids or liquids. Instead, the atoms are all completely ionised, so the bare nuclei of the atoms are moving freely through a sea of electrons: the star's interior is a *plasma*, the fourth state of matter.



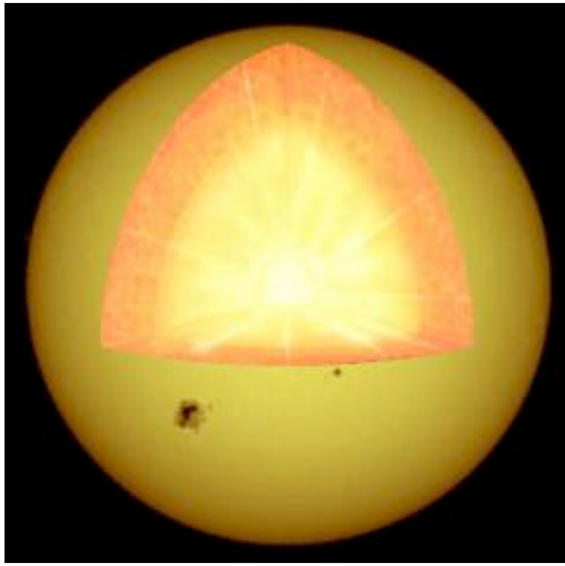
Freed from their repelling electrons, the nuclei can now approach much closer to each other until, at high enough temperatures, they can overcome the electromagnetic repulsion and get close enough for the strong nuclear force to fuse them together.



The nuclei get their speed from the random motion of the gas, so fusion only occurs when the temperature is high enough.

The temperature threshold for fusion to occur is about ten million degrees.

One consequence is that fusion only takes place in the cores of stars, where the temperature is highest. Most of the star is not in fact generating energy. This is also, of course, why fusion is not taking place in the core of the Earth (temperature 6000K) or of Jupiter (temperature 20,000 K).

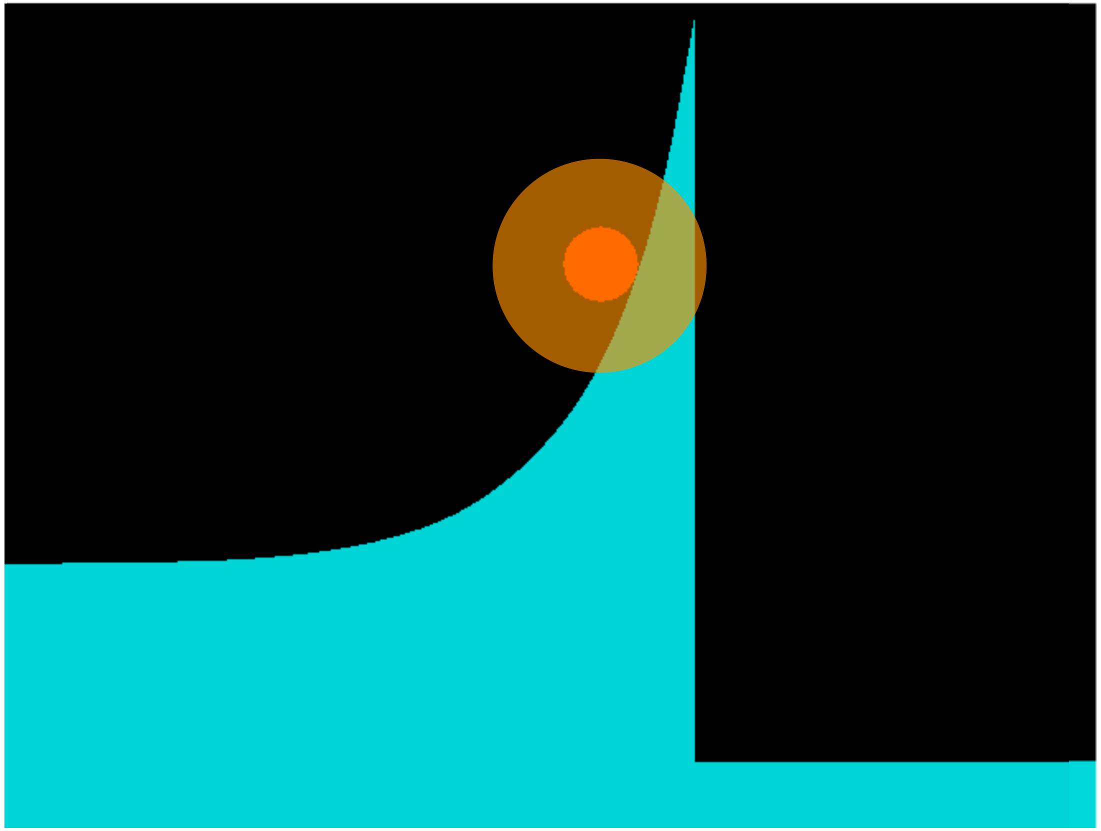


Aside:

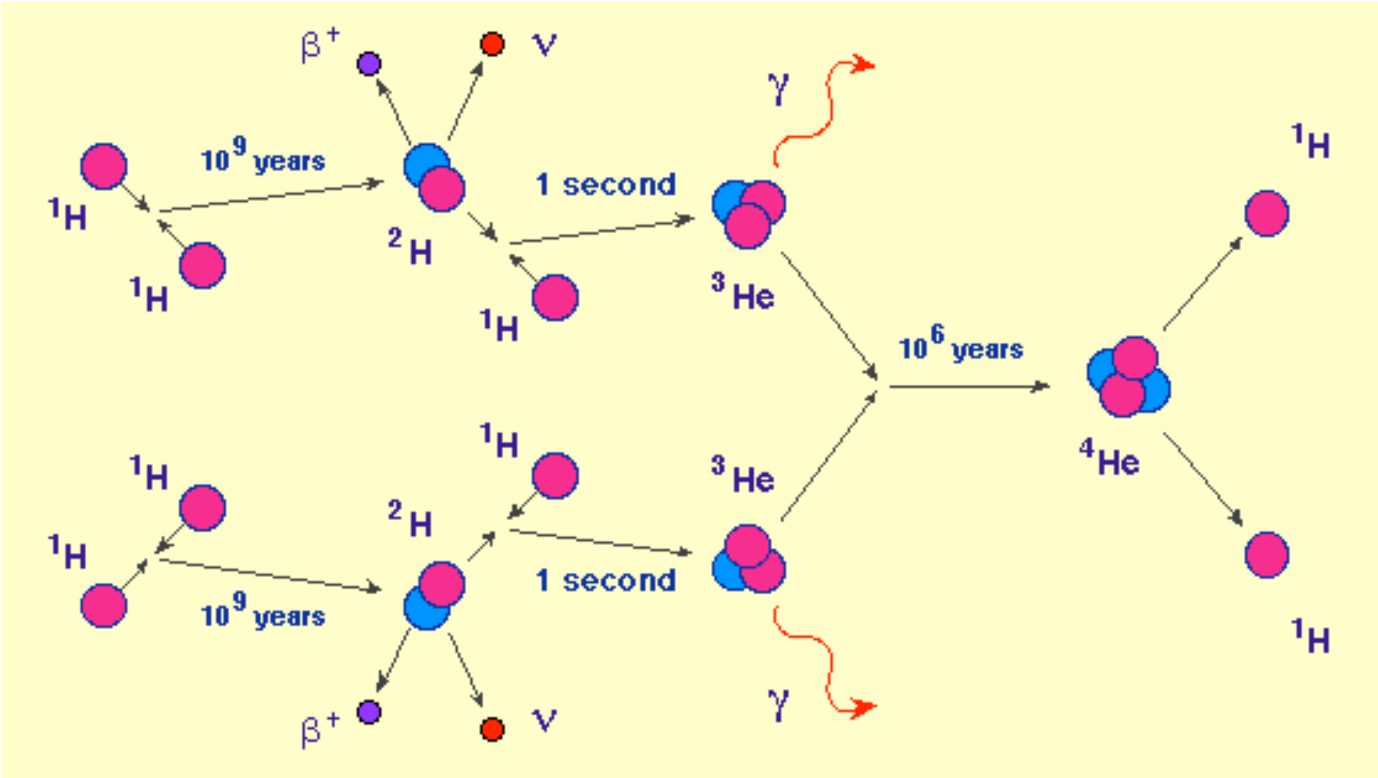
In fact, the required temperature should be even higher than ten million degrees, except for the quantum mechanical effect called *quantum tunnelling*. Because each particle also behaves as a wave, there is a small probability that it can *tunnel through* the barrier even when it doesn't have enough energy to go over.

Classically, if the proton does not have enough energy to overcome the barrier of the electromagnetic repulsion, it will be reflected.

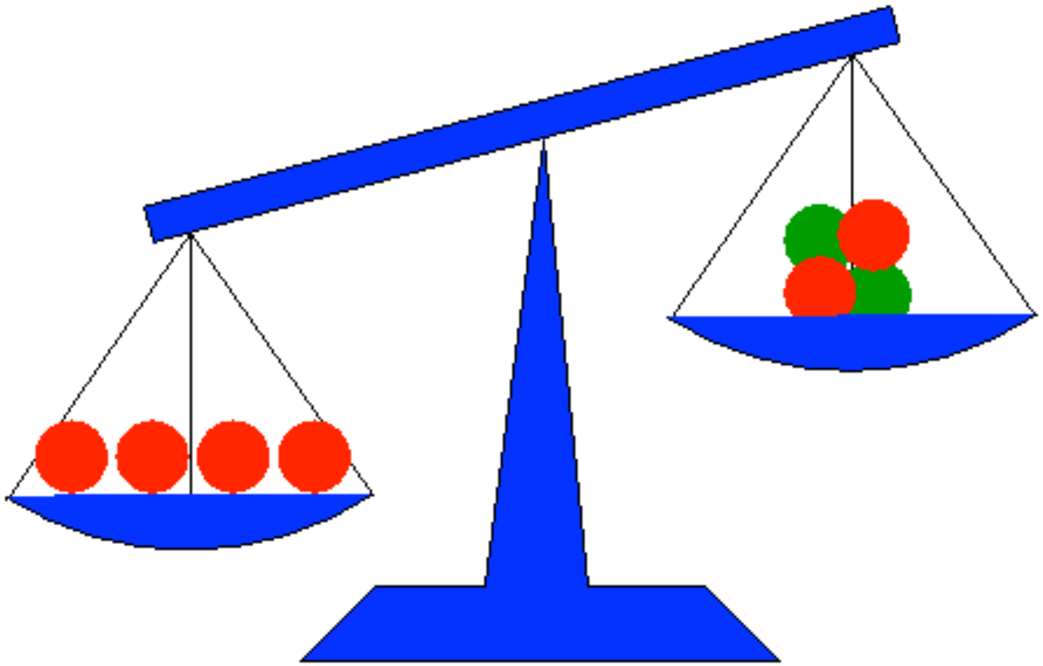
A quantum particle, on the other hand, has a finite probability of tunnelling through the barrier.



The reaction forming helium from hydrogen actually takes four hydrogen atoms, and takes place in several steps.



One helium atom weighs slightly less than four hydrogen atoms: 0.7% less. This missing mass is converted into energy, and is what powers the star. (This is the *binding energy* we discussed last week).



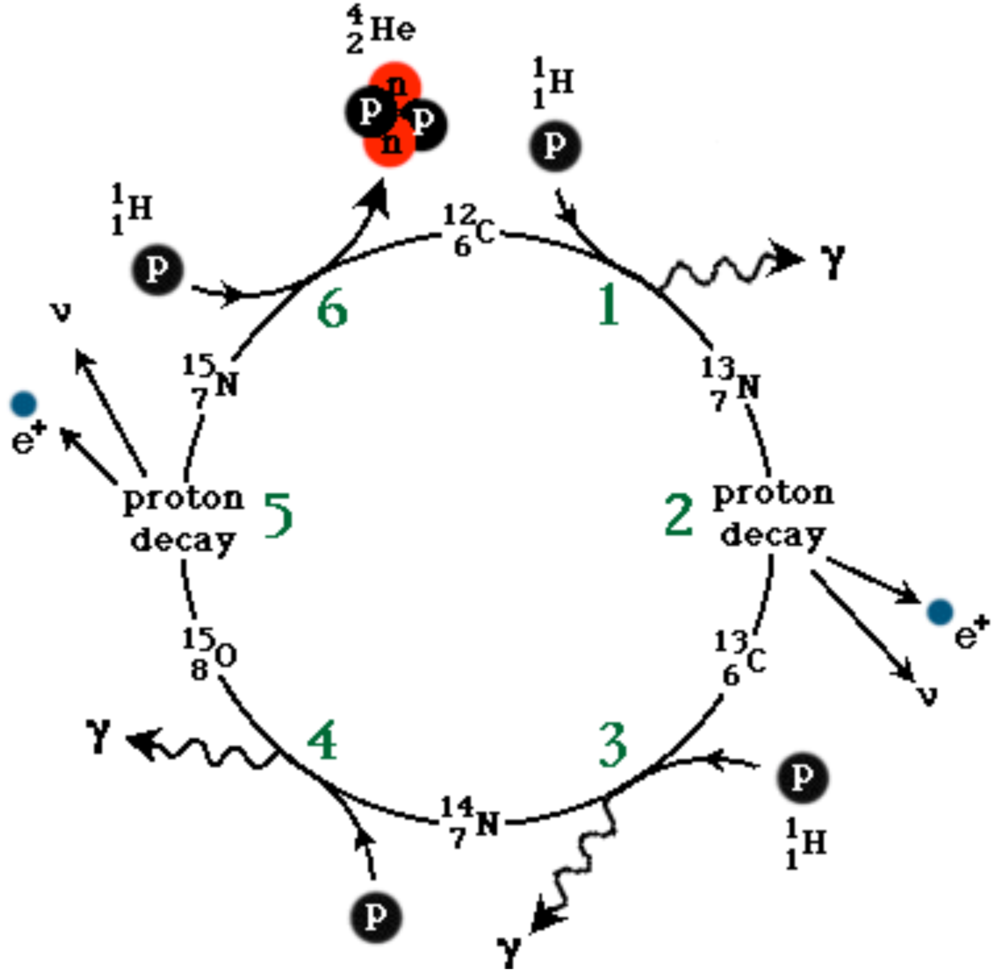
We can work out how much mass is being converted to energy each second: knowing the luminosity of the Sun, for instance (3.8 x 10^{26} W), then the amount of mass lost each second is L/c^2, which comes to 4,200,000,000 kg every second.

Which sounds like a lot, except that the mass of the Sun is 2 x 10^{30} kg, so even after a billion years, the Sun has only lost 0.006% of its mass.

Hydrogen can also be fused to helium in a different sequence of steps: the CNO *cycle*.

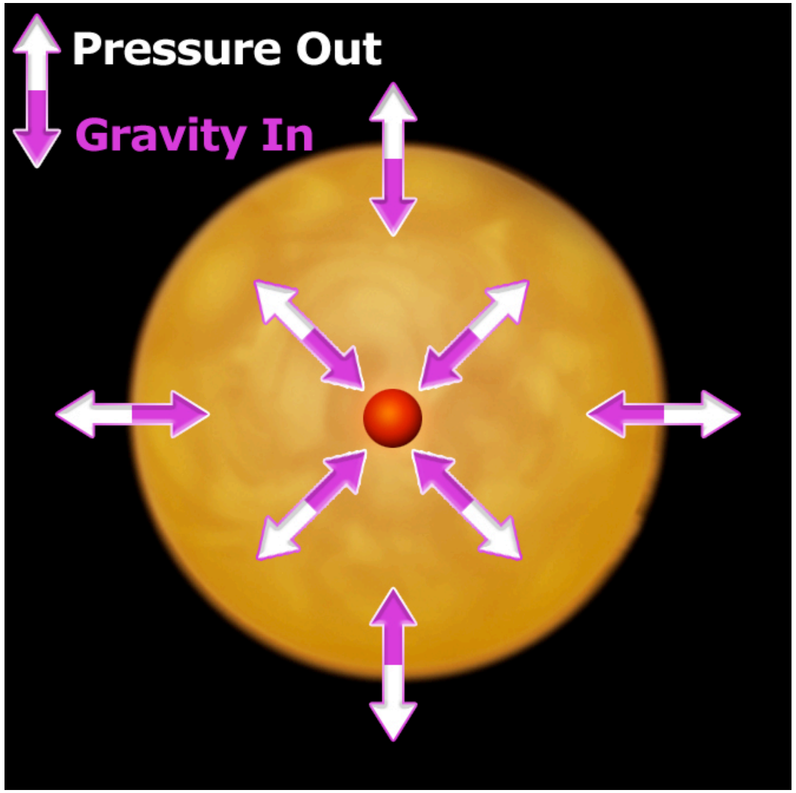
The carbon atom is used as a catalyst, but is not consumed during the reaction, so reappears at the end ready to start the cycle over again.

The CNO cycle requires much higher temperatures than the *p*–*p* chain.



Hydrogen fusion will only take place above temperatures of about ten million degrees, and the rate of fusion reactions increases *dramatically* as the temperature increases: the rate is $\propto T^4$ (or T^{20} for the CNO cycle in hot stars).

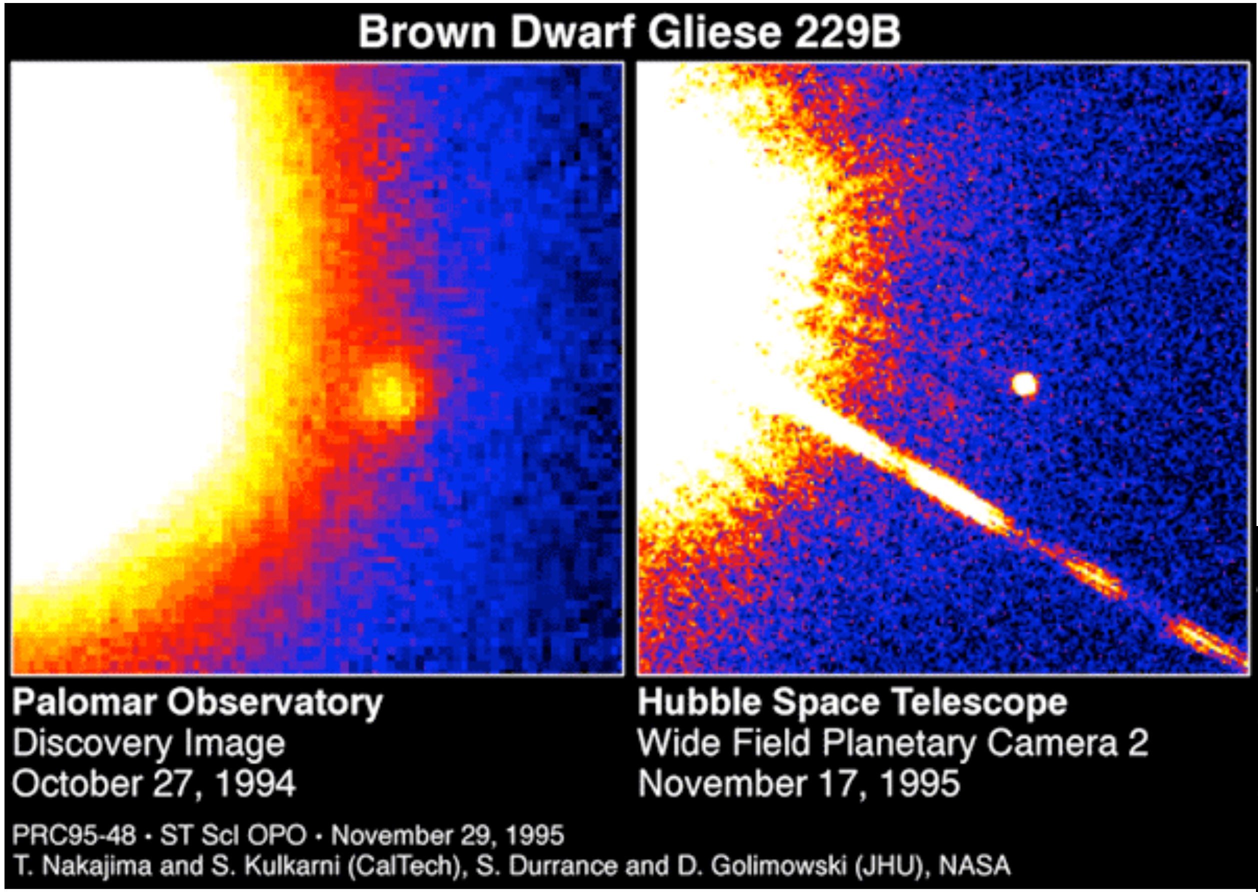
One consequence of this is that the central temperature of stars doesn't vary very much: a 100 solar mass star has a central temperature only a factor of 4 higher than a 0.1 solar mass red dwarf.

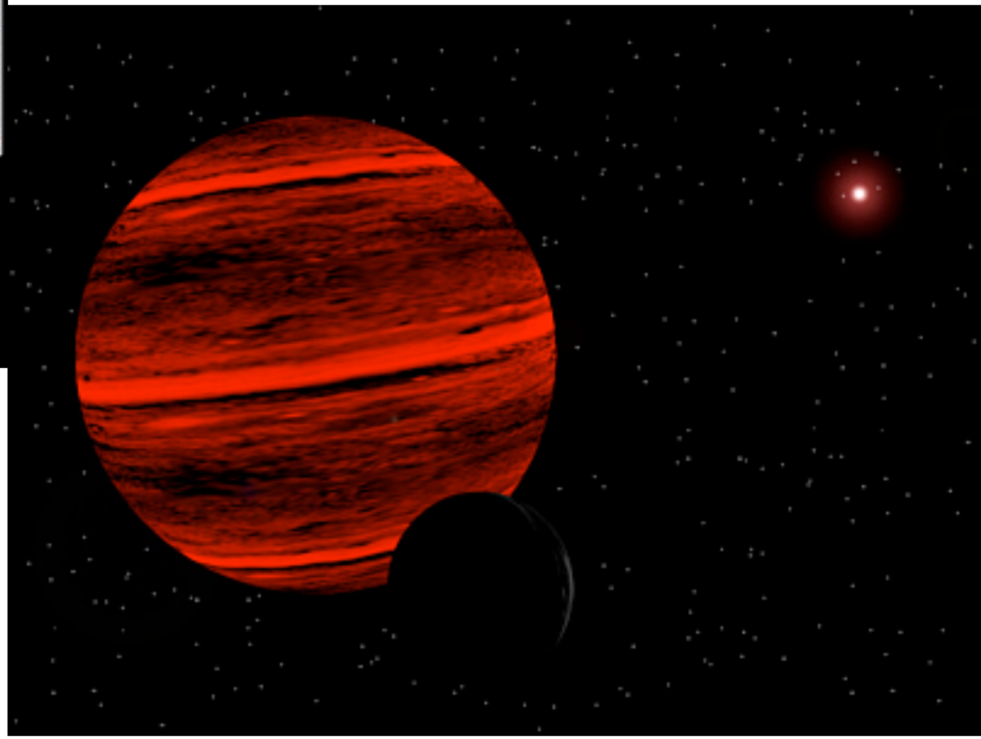


This provides the thermostat which maintains the star in pressure equilibrium. If the pressure in the core increases, the temperature increases, which increases the fusion reaction rate, which would produce more energy and increase the temperature, which would expand the star, until the pressure drops again.

This also explains the lower limit to a star’s mass. If the collapsing star is too small, the central temperature and density never get high enough for fusion to take place, so the almost-star never ignites.

The lowest mass require to produce fusion is about 0.08 solar masses, or about 80 Jupiter masses. Objects smaller than this are called *brown dwarfs*.





Discovery image of the first confirmed brown dwarf, Gliese 229B; artist's impression of the system.

There is also an upper limit to the mass a star can have, but this is because of *radiation pressure*.

Because a photon is also a particle, the photons can also transfer momentum to particles: they add to the pressure.

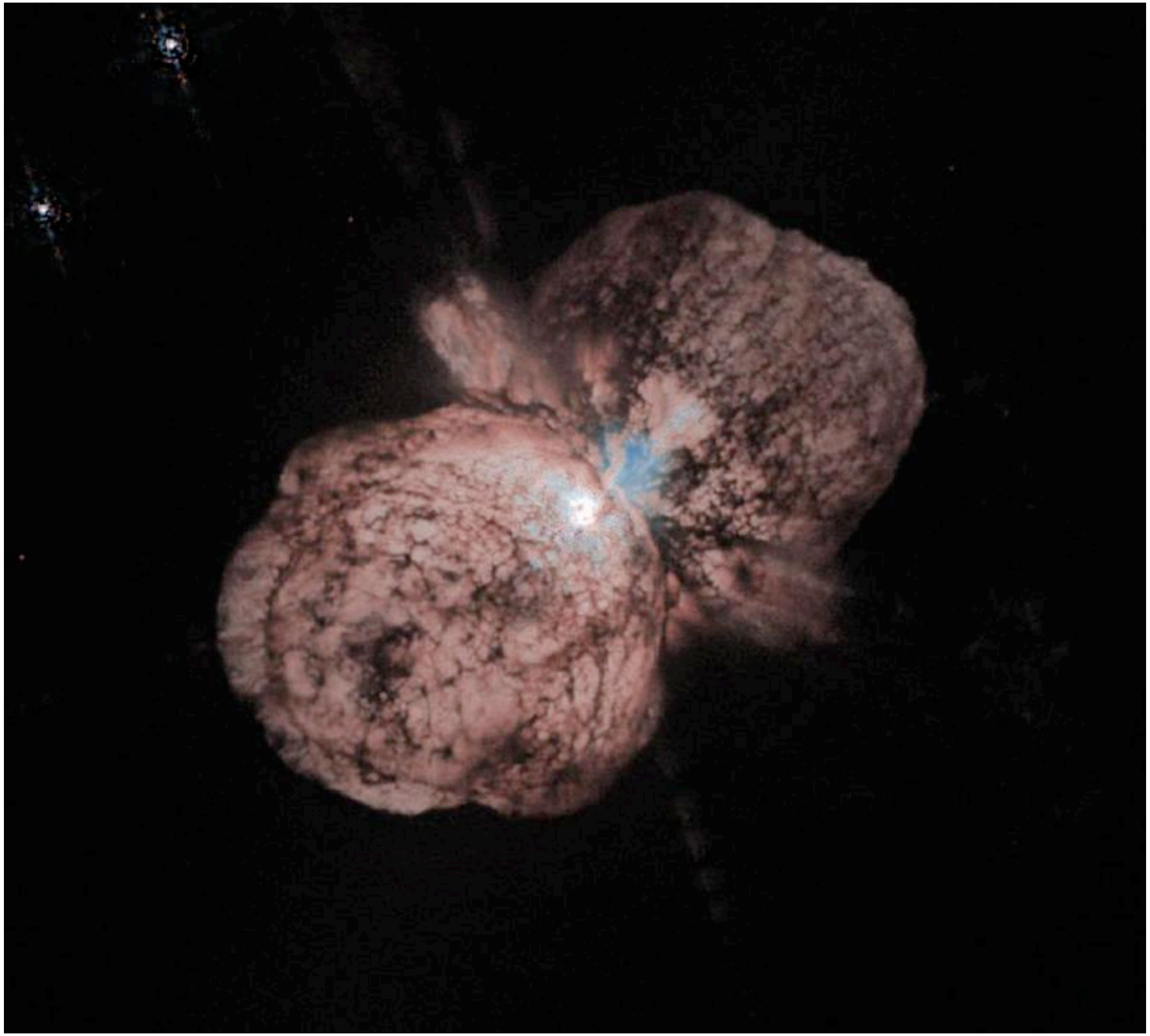
For the centre of the Sun,

$$P_{\mathrm{rad}} = 0.06\% \text{ of } P_{\mathrm{gas}}$$

But for a star of mass 60 times solar,

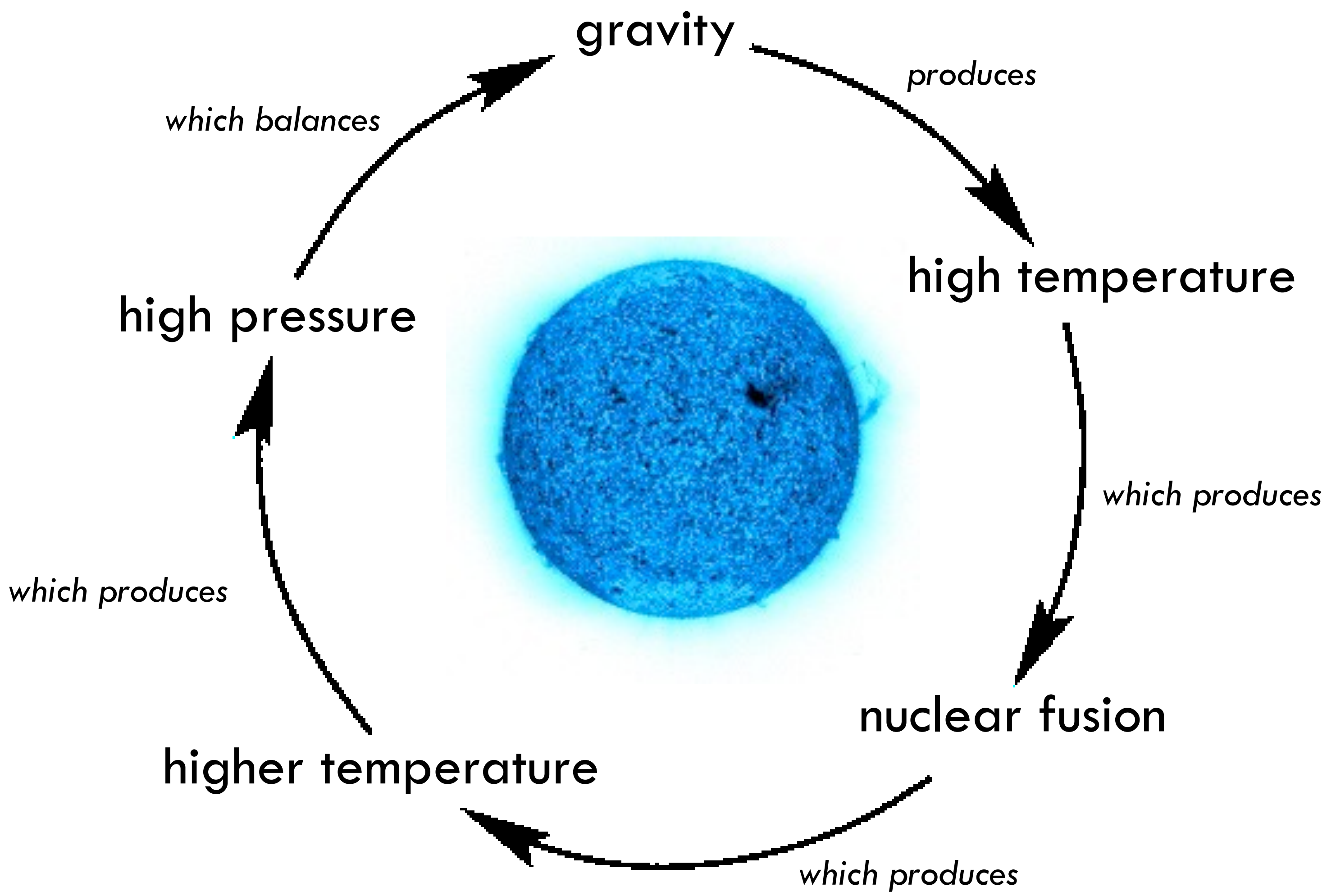
$$P_{\mathrm{rad}} = P_{\mathrm{gas}}$$

When the star's mass reaches about 100 solar masses, the radiation pressure becomes high enough to blow off the outer layers of the star.

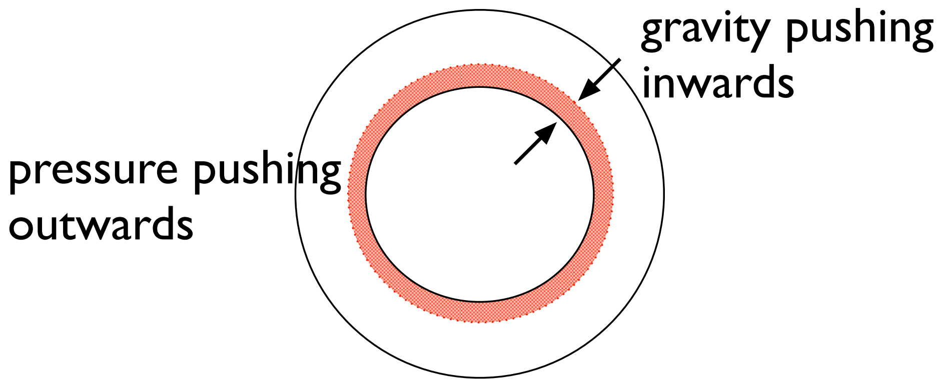


Hubble picture of the star Eta Carinae, one of the most massive stars in the Galaxy. The lobes are remnants from the star ejecting its outer layers.

So a star is a finally balanced system:



That's the general outline. We can actually find out the exact details of a star's interior by mathematical modelling: Divide the star into very narrow shells, like an onion. Then we can write down equations showing the density, temperature and pressure in each one of these shells, so when we put them all together we have a star.



Now, there are four simple laws which must be satisfied:

- *Conservation of mass*: total mass equals the sum of shell masses
- *Conservation of energy*: total luminosity equals the sum of energy generated in each shell
- *Hydrostatic equilibrium*: the outward pressure in each shell balances the inward gravitational pull on that shell
- *Energy transport*: energy moves from hot to cool by conduction, radiation or convection

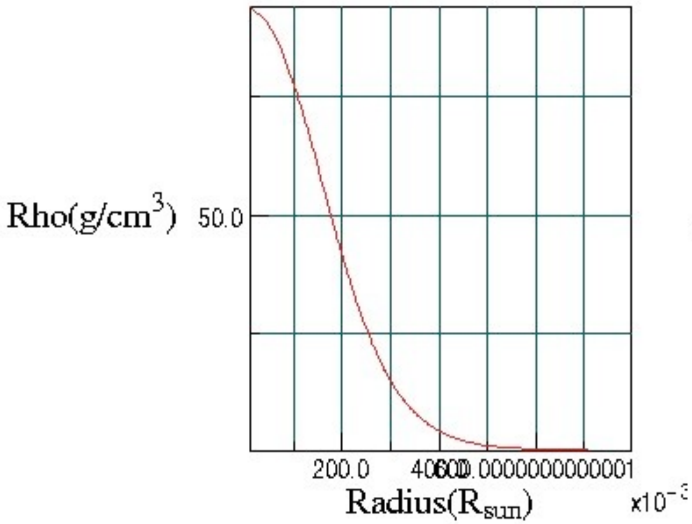
We solve these equations simultaneously for each shell in the star, to give us a *stellar model*: a model for how the density, mass and temperature change as we move from the inside to the outside of the star.

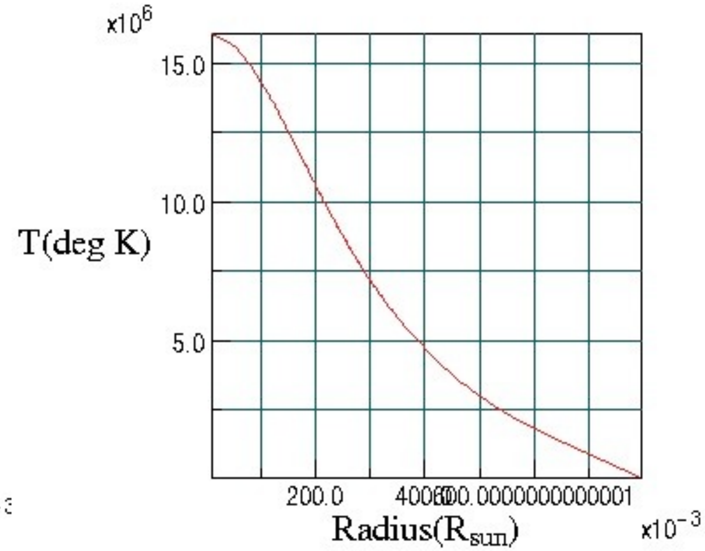
It takes a computer to solve the hundreds of simultaneous equations needed for a typical model.

An example on the web:
http://www.astro.umass.edu/~weinberg/a451/msapplet.html

Results of stellar modelling

What we get out of the model is a description of the conditions inside the star: the temperature, density, mass and luminosity as a function of radius.



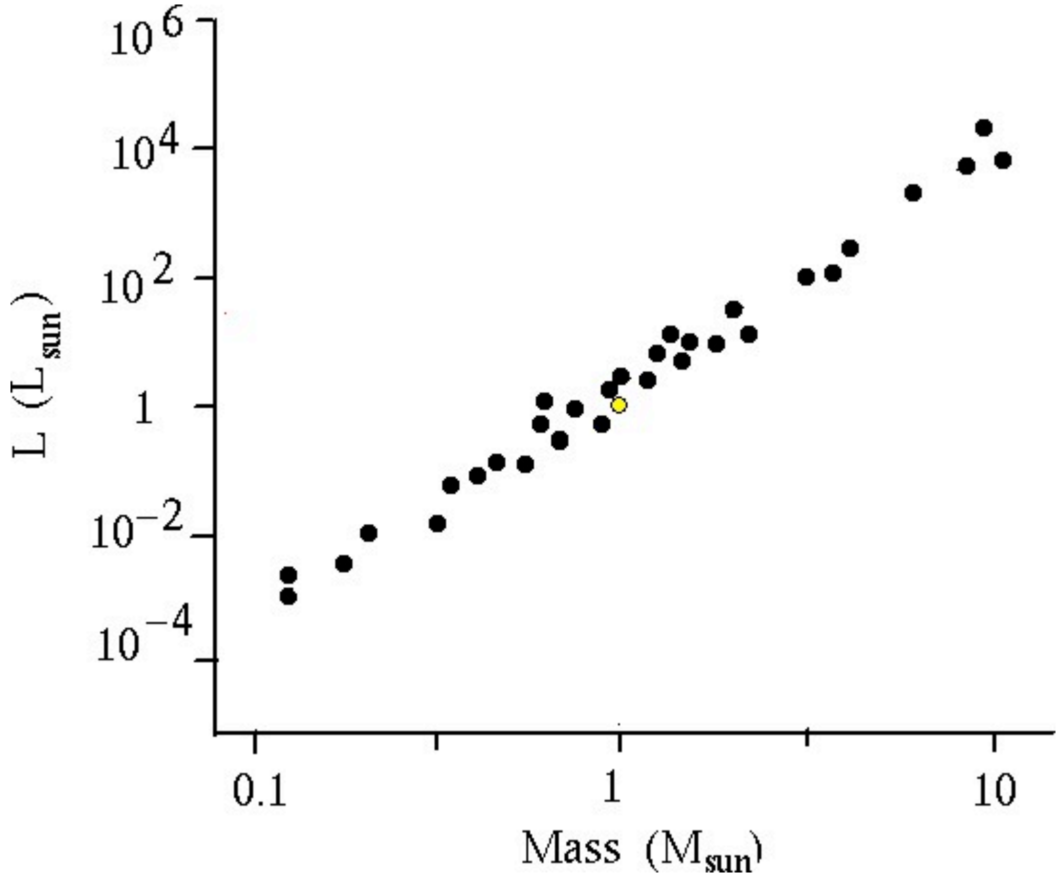


What can we learn from stellar models?

1. *Mass-luminosity relation*

As we change the mass of the star, the luminosity of the star (= the energy that reaches the surface) changes in a systematic way: the more massive a star is, the more luminous it is.

More mass → higher pressure in centre
→ higher temperature in centre
→ more energy produced
→ higher luminosity

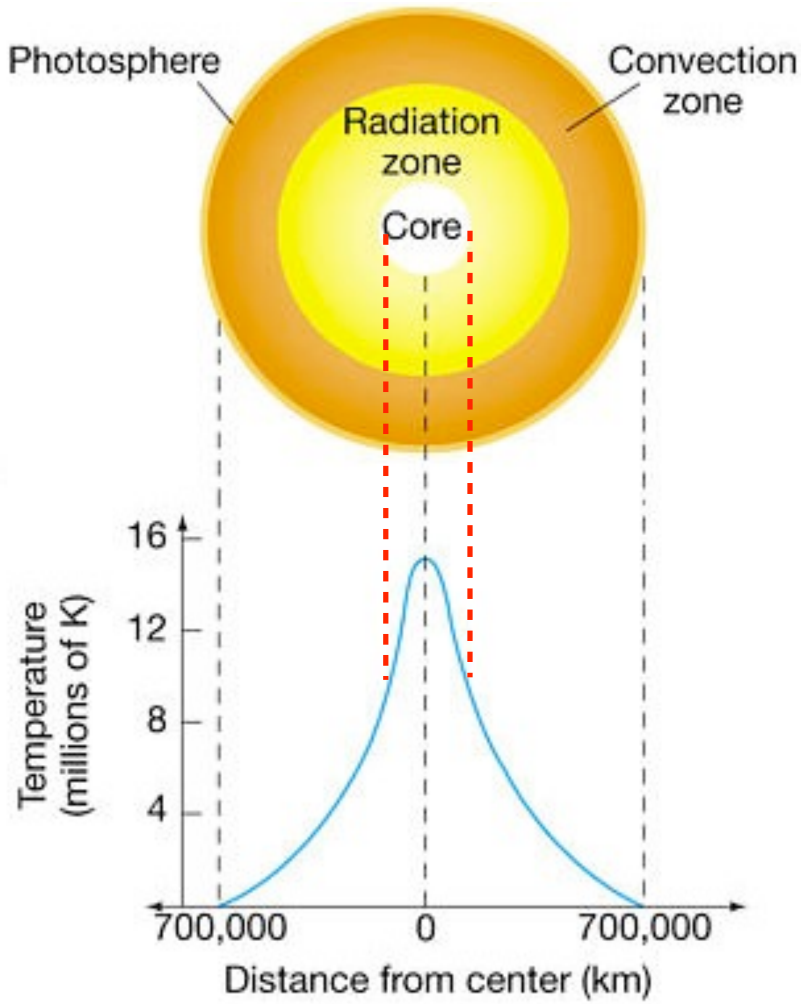


As we increase the mass of the star, the luminosity increases *enormously*: a factor of 10 increase in mass corresponds to a factor of 3000 increase in luminosity.

2. *Fusion occurs in the central regions*

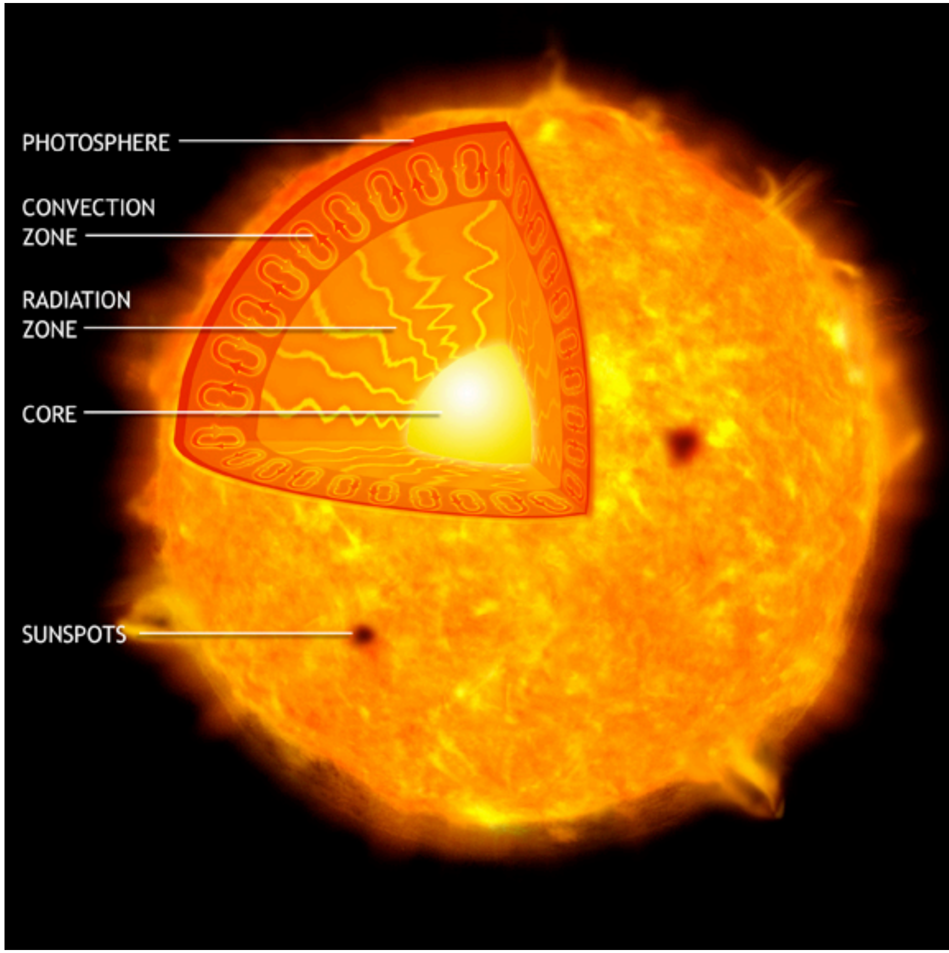
We saw how we need temperatures of at least 10 million degrees for fusion to occur.

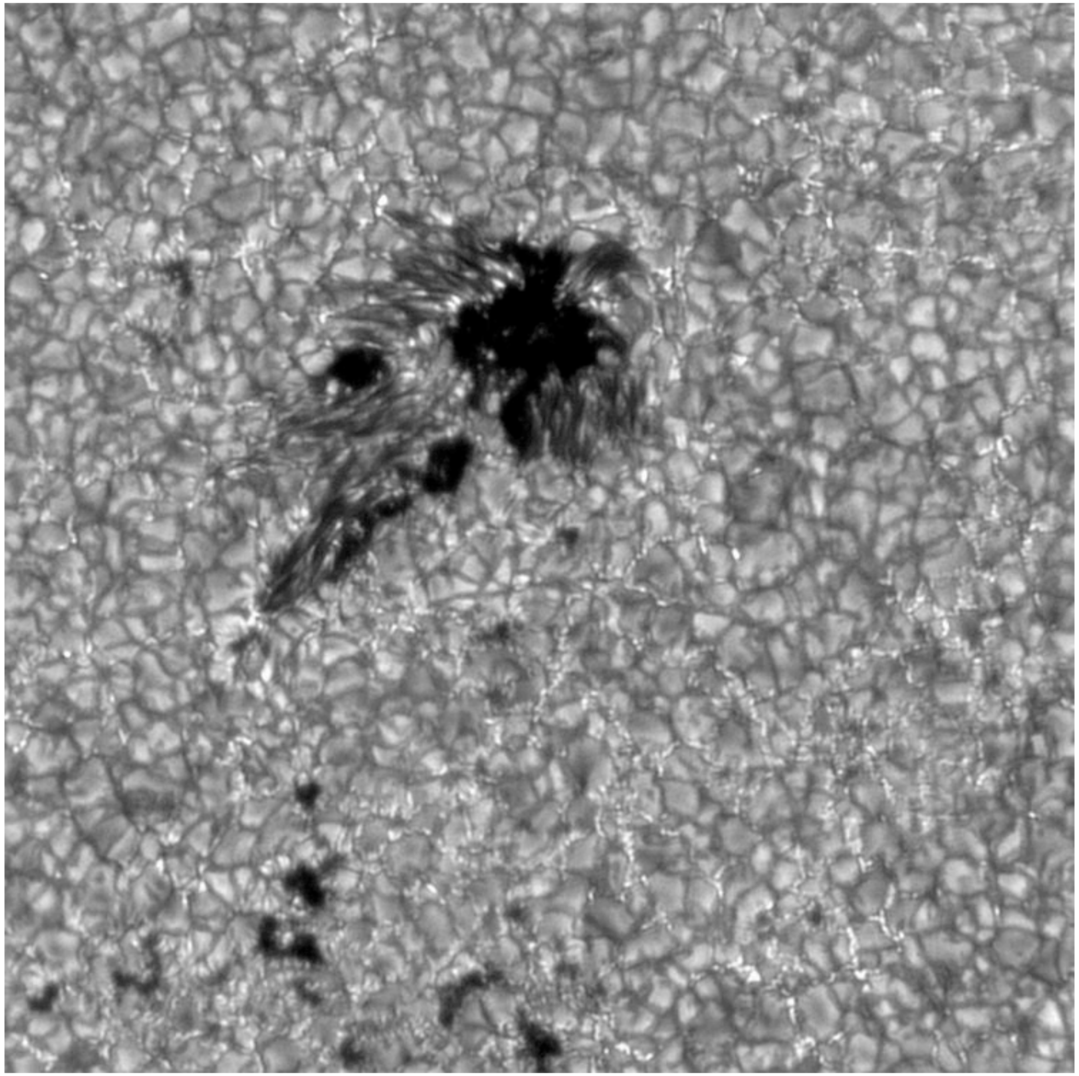
In the Sun, these temperatures are reached in the inner 25% of the radius, in the zone known as the core.



Complications: Convection

There are complications to the structure of stars that we haven't touched on. The interior of a star is divided into different zones, depending on whether energy is being transported by *radiation* or *convection*.





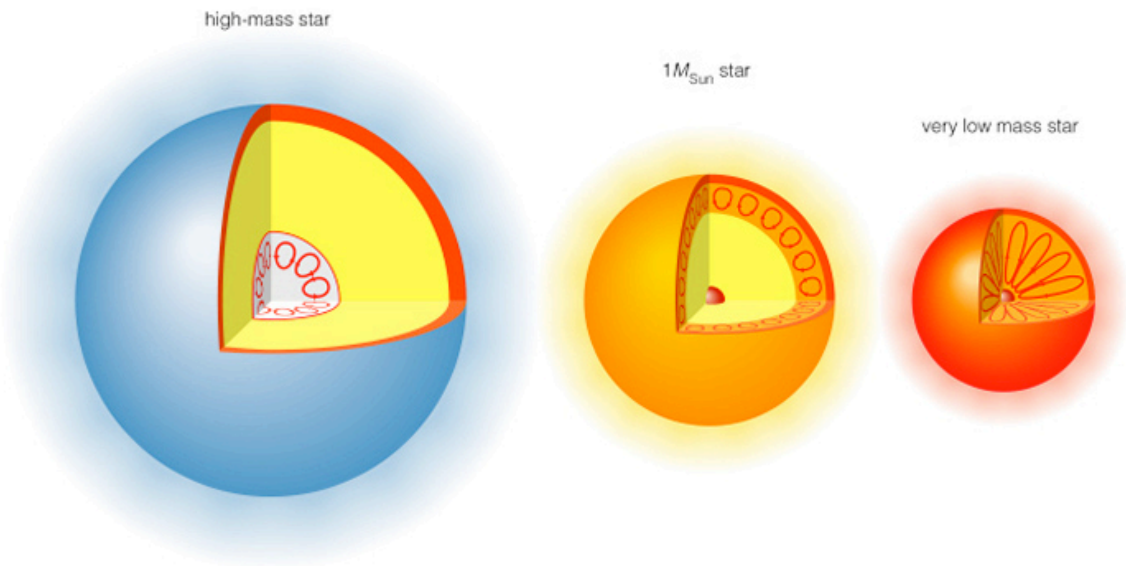
Convection cells visible on the Sun's surface as granularity

Whether the energy is transferred by radiation or convection depends on the *opacity* of the envelope: how well the material lets radiation through.

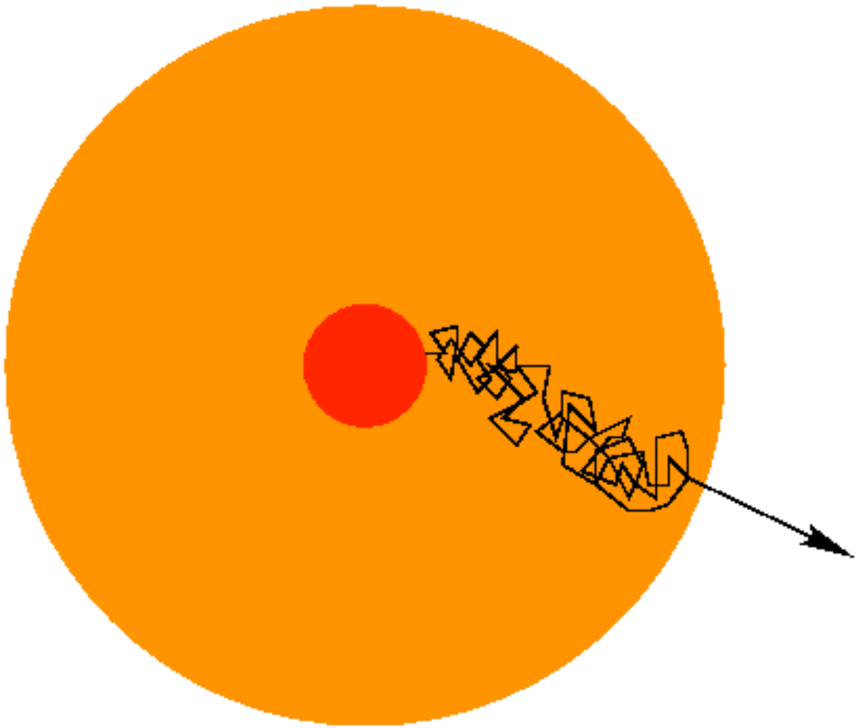
If the temperature is high and the atoms are all ionised, the opacity is low and the energy streams out by radiation. As the temperature drops, the protons and electrons recombine, and the electrons start absorbing photons, which slows down the transport. This traps the heat, leading to bubbles of hot material, which begin to rise and start convecting.

In high-mass stars, the hydrogen stays ionised even in the outer regions, so radiation is not easily absorbed: high mass stars have radiative envelopes.

In their cores, however, so much energy is being produced that radiative transport doesn't work, so high mass stars have convective cores.

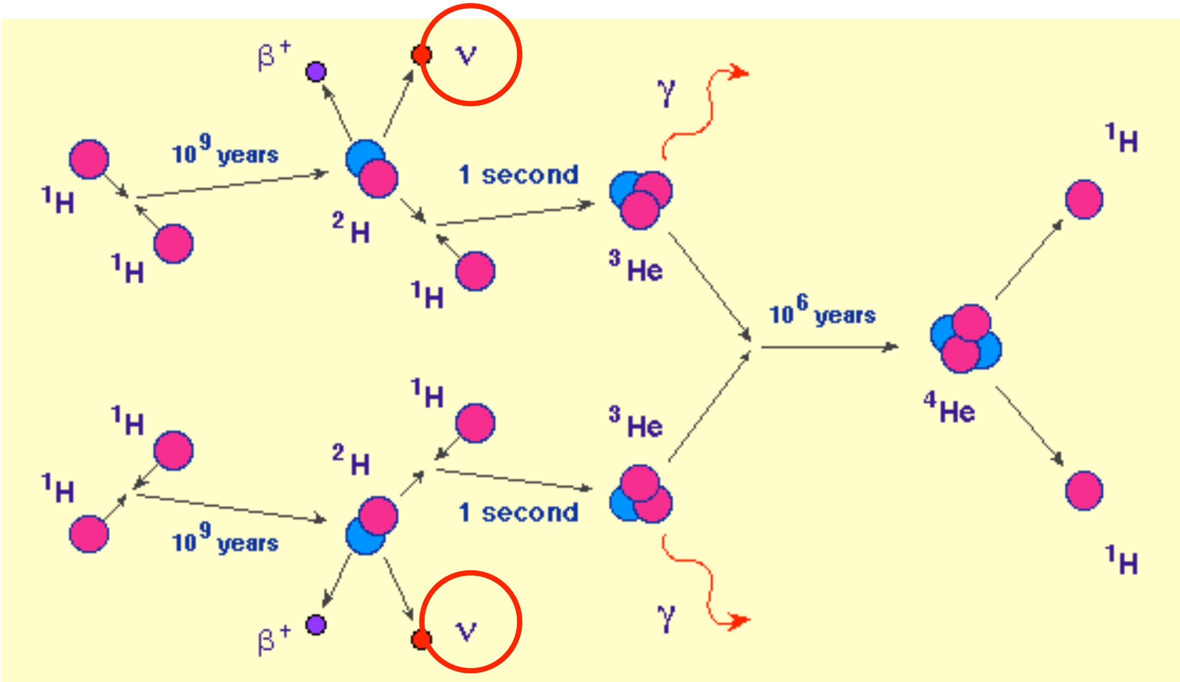


Photons don’t reach the surface of the sun unimpeded. Instead, they undergo many scatterings on the way and only slowly diffuse outwards, taking several thousand years to reach the surface: the photosphere.

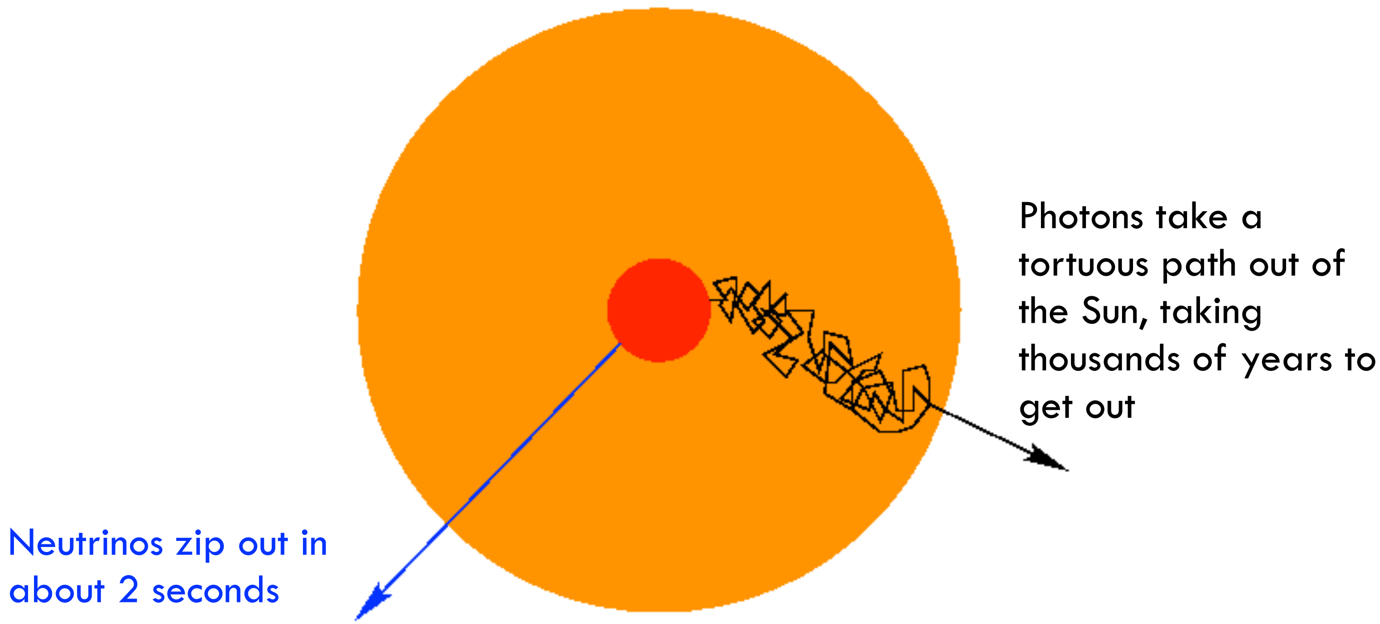


Testing the theory of stellar fusion: The solar neutrino problem

We can't see fusion taking place in the cores of stars, but we can detect it using *neutrinos*: sub-atomic particles which have no mass or charge, and which are produced as by-products of H → He fusion.



Neutrinos have a very low probability of interacting with normal matter, so they escape from the core of the Sun almost directly.



However, it is possible to detect them at the Earth. The number detected should be proportional to the number of fusions taking place.

Raymond Davis built the first neutrino detector in the 1960s. The detector consisted of 400,000 litres of cleaning fluid (C_2Cl_4) one mile underground in an old mine.

When a chlorine atom captures a neutrino, it is turned into a radioactive isotope of argon. A few dozen events are expected every month.

The results of the experiment were astonishing. Davis detected only about a third of the expected number of neutrinos!

In his Nobel Prize lecture (2002), Raymond Davis says

> *"The solar neutrino problem lasted from 1967–2001. Over this period neither the measured flux nor the predicted flux changed significantly. I never found anything wrong with my experiment. John Bahcall never found anything wrong with the standard solar model."*

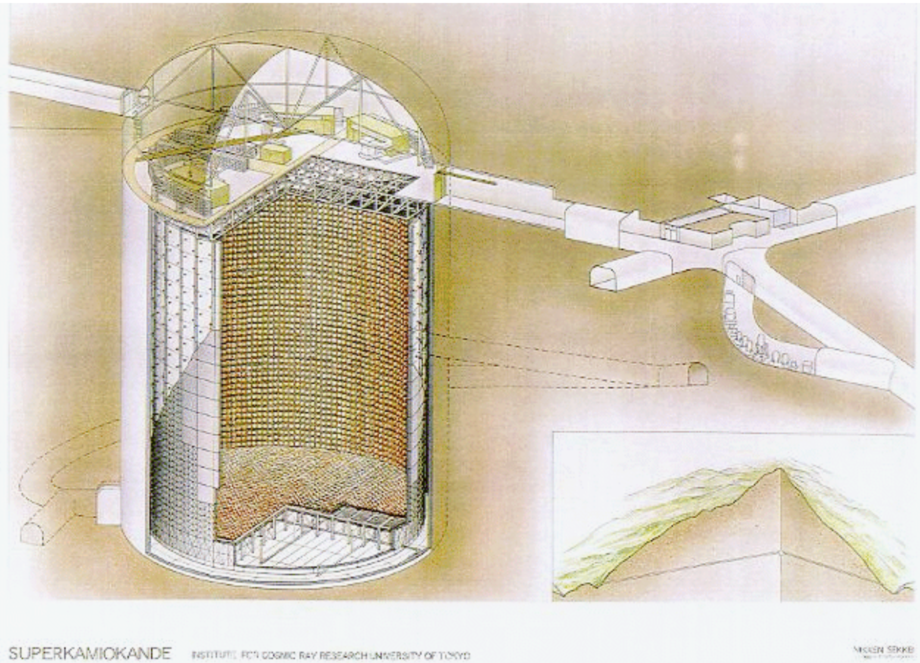
There were several possible explanations for this.

1. Nuclear fusion is not taking place in the Sun *(but other evidence suggests it is)*

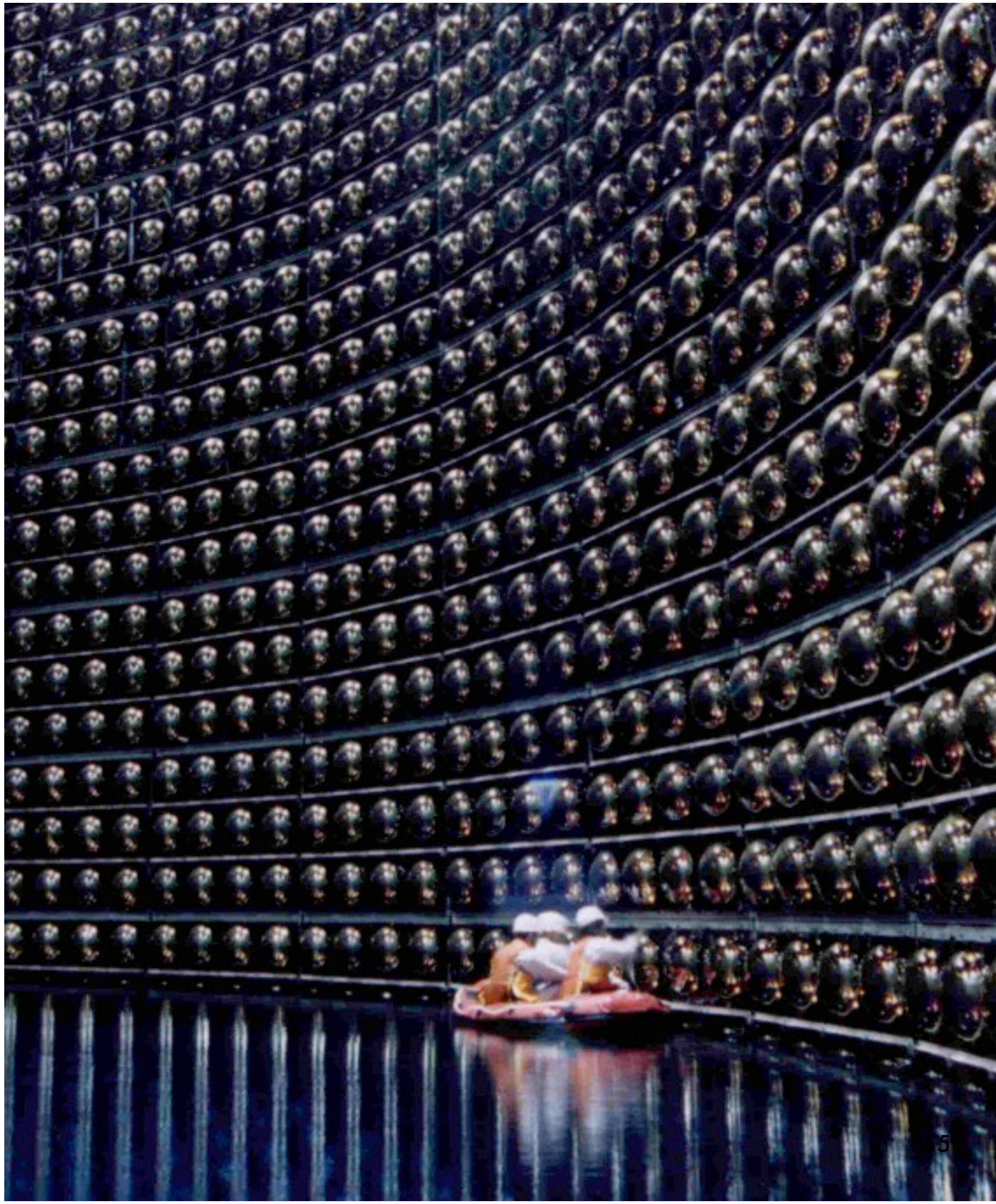
2. The experiment was not calibrated properly *(but several other experiments have detected the same result)*

3. The rate of fusion inside the Sun is lower than we thought *(but we know how much energy has to come out!)*

4. Something is happening to some of the neutrinos on the way so we can't detect them.



In the late 1990s a new detector called *Super-Kamiokande* was built in Japan, using 50,000 tonnes of pure water and 11,200 photomultiplier tubes in a 40m high x 40m diameter cylinder.



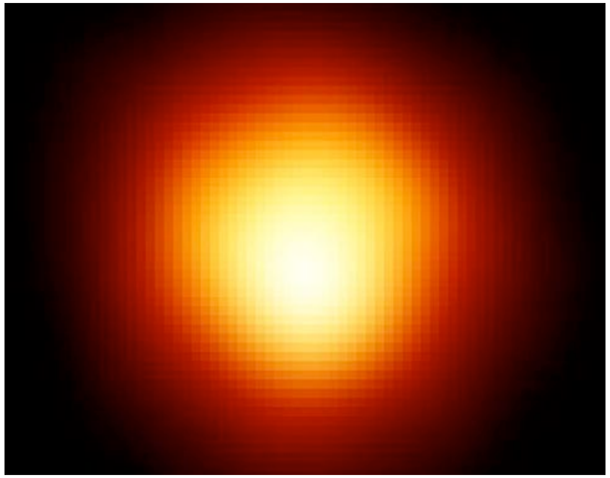
Oscillating neutrinos

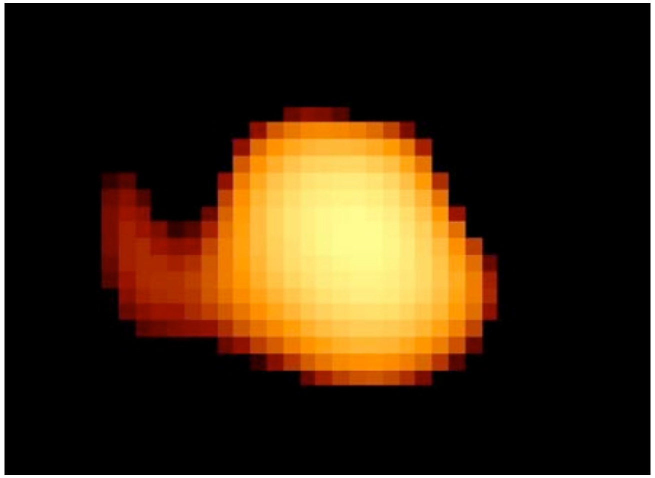
In 1998 a Super-Kamiokande team announced they had detected evidence of neutrinos oscillating between different varieties, only one of which – the electron neutrino – can be detected.

This not only explains the results of the solar neutrino experiment, but also implies that neutrinos have mass. This in turn has enormous implications for the total mass and hence the fate of the universe.

"What appliance can pierce through the outer layers of a star and test the conditions within?"

– *Arthur Eddington*





HST images of Betelgeuse and Mira

What is a star?

"… a gravitationally confined thermonuclear reactor whose composition evolves as energy is lost to radiation and neutrinos"

– Woosley, Heger and Weaver 2002

Next week

…we'll look at our own Sun, and what we have learned when we observe a star really up close and personal

Further reading

- Most books which discuss stars have a good discussion of how stars work and what makes them shine. The books by James Kaler I suggested in Lecture 1 have a good description; so do several of the books I'll be recommending in upcoming lectures, such as "**Cosmic Catastrophes: Exploding stars, Black holes, and Mapping the Universe**" by J. Craig Wheeler (Cambridge UP, 2007).

- John Bahcall, one of the giants of solar neutrino research, has an article on the neutrino problem at the Nobel Prize website called "Solving the Mystery of the Missing Neutrinos", http://nobelprize.org/physics/articles/bahcall/index.html

Sources for images used:

- SOHO image of a solar prominence on the Sun: from SOHO: Best of SOHO Images http://sohowww.nascom.nasa.gov/
- HST images of Betelgeuse and Mira: from the Hubble News Center: http://hubblesite.org/newscenter/newsdesk/archive/releases/1996/04/ and http://hubblesite.org/newscenter/newsdesk/archive/releases/1997/26/
- Four forces: from "All Four Engines Out: Volcanic Ash, St Elmo's Fire and Electrostatics" by David Jamieson http://www.ph.unimelb.edu.au/~dnj/jl/jl99/index.htm
- Structure of atom: from "Introductory Chemistry" by Nivaldo J. Tro, Fig. 04-06, http://wps.prenhall.com/wps/media/objects/476/488316/ch04.html
- Strength of the electromagnetic force: from "All Four Engines Out: Volcanic Ash, St Elmo's Fire and Electrostatics" by David Jamieson, http://www.ph.unimelb.edu.au/~dnj/jl/jl99/index.htm
- Mass-luminosity relation: from Auckland Astronomical Society http://www.astronomy.org.nz/aas/MonthlyMeetings/MeetingMay2002.asp
- Proton-proton chain: from Astronomy 162: Stars, Galaxies and Cosmology: The Proton-Proton Chain http://csep10.phys.utk.edu/astr162/lect/energy/ppchain.html
- CNO cycle: from "Formation of the High Mass Elements (a/k/a What Happens Inside a Star)" http://aether.lbl.gov/www/tour/elements/stellar/CNO.html
- Equilibrium: from Chandra resources http://chandra.harvard.edu/resources/illustrations/normalstars.html
- Brown dwarf Gliese 229B: from Hubble News Center, http://hubblesite.org/newscenter/newsdesk/archive/releases/1995/48/
- Eta Carinae: from Astronomy Picture of the Day 2002 April 28, http://antwrp.gsfc.nasa.gov/apod/ap020428.html
- Sun's temperature structure: from Astronomy 122 Mid-term Exam 2 Review, http://physics.uoregon.edu/~jimbrau/astr122/Notes/Exam2rev.html
- Convection: from Chandra Resource: Normal stars (Illustrations), http://chandra.harvard.edu/resources/illustrations/normalstars.html
- Comparison of energy transport in different types of stars: from "Introduction to Astronomy" by Bram Borosn, http://www.bramboroson.com/astro/apr3.html
- Solar granules: from "Solar Physics: Photospheric features" http://science.nasa.gov/ssl/pad/solar/feature1.htm
- Davis experiment: from "Big World of Small Neutrinos", http://conferences.fnal.gov/lp2003/forthepublic/neutrinos/
- Super-Kamiokande: Diagram: from Super-K at U. of Washington, http://www.phys.washington,edu/~superk/uwgroup.html
- Photo of interior: from Photo Album of the SK detector, http://www-sk.icrr.u-tokyo.ac.jp/doc/sk/photo/index.html
- Solar Dynamics Observatory image of the Sun: from http://sdo.gsfc.nasa.gov/gallery/main/item/151