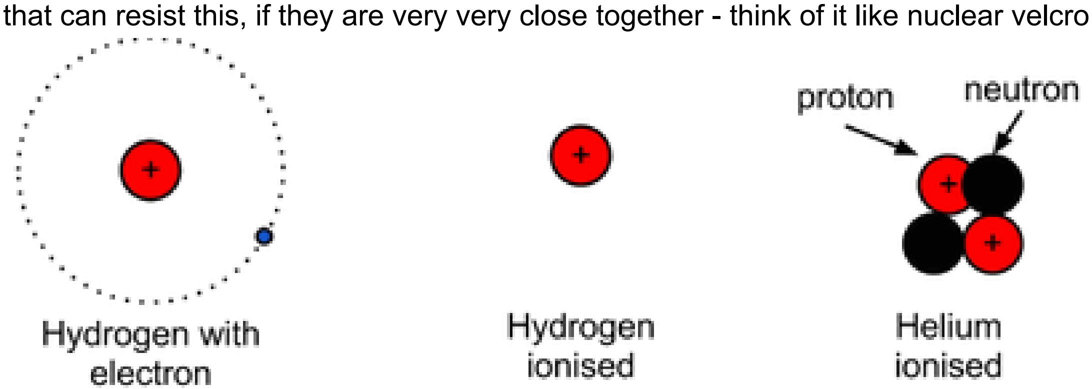
How do BIG stars shine?

So last time we went through the nuclear reaction that powers the Sun. Its called the proton-proton chain (PP), and it wasn't so hard - was it? OK there is a lot of maths and quantum physics in the details, but hopefully you got the basics, and can now class yourself as a trainee astrophysicist.

However, just to check everyone is on the same page, and because we rather skated over some of the details last time to get to the punchline of how stars shine, lets just recap.

So - we have atoms. That's what everything is made out of, at least everything we see in everyday life. An atom has been likened at times to a model of the solar system. There is a nucleus at the centre, like the Sun. This nucleus is made up of protons with a positive charge, and neutrons which are neutral. The number of protons tells you what sort of atom it is (1 for hydrogen, 2 for helium etc) and the neutrons act as a sort of glue. Like charges repel, so two protons in a helium nucleus are struggling to get apart. Luckily there is another force stronger that can resist this, if they are very very close together - think of it like nuclear velcro.



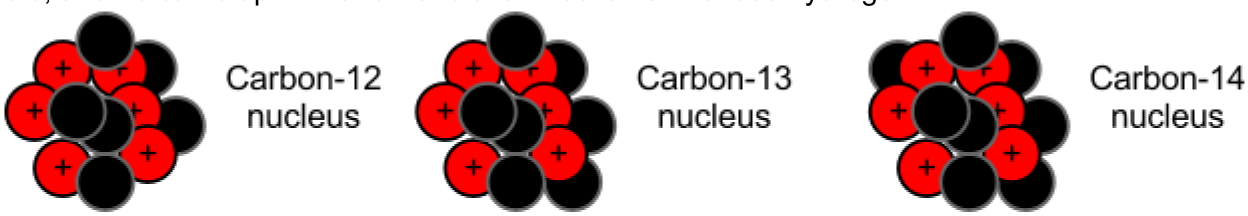
Then orbiting the nucleus are the same number of negatively charged electrons as there are protons in the nucleus, making the atom electrically neutral normally. This is a gross simplification but works as a model.

An atom is mostly empty space. If the nucleus was magnified to the size of a marble, you could place it on the centre spot of a football field, and the electron would be out flying around the stadium seats. Similarly if you think of the nucleus as about the size of a street rubbish bin in London, the electron would be flying around the M25 - not that many things fly around the M25 - but anyway - you get the idea.

However in the centre of the Sun, the temperature is so high (about 15 million degrees) that the electron will be kicked away, and all nuclei will be ionised. That is they will have no attached electrons, they are just moving too fast to stay with the nucleus. Therefore all nuclei have a positive charge as they have no cancelling electrons. The electrons are also whizzing around bumping into things and generally being a nuisance. So that's the environment we find ourselves in.

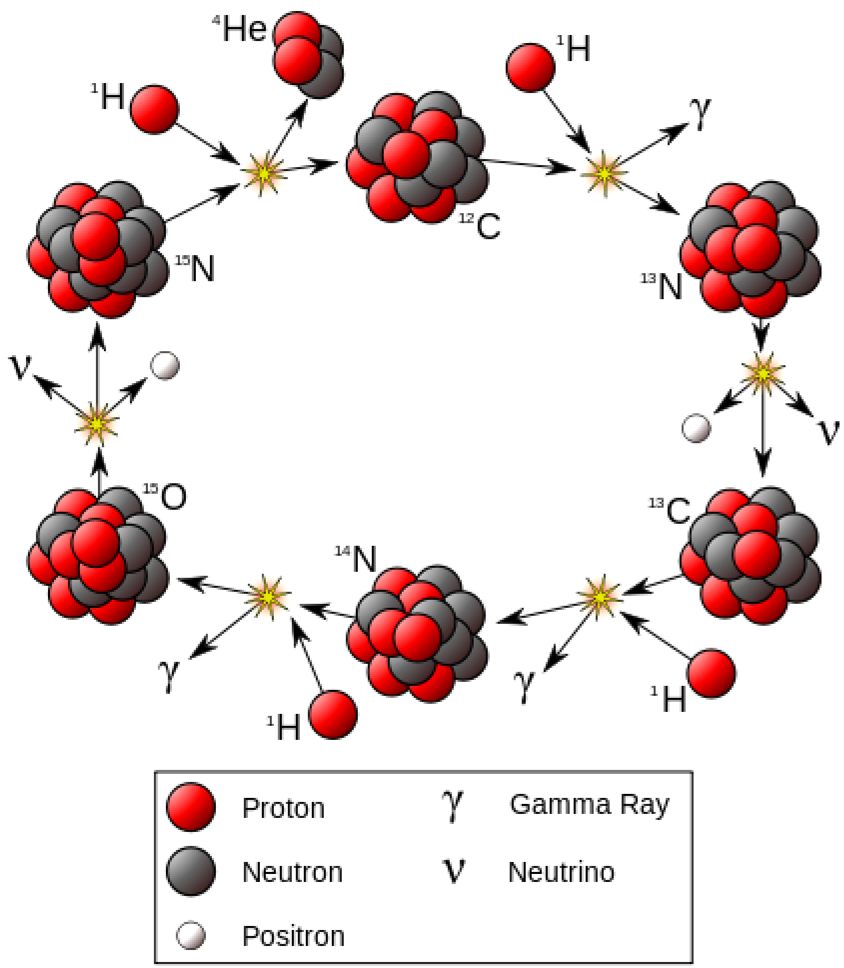
When people were first trying to work out how stars shine, Hans Bethe had a crack at it, knowing a bit about nuclear physics, he came up with a scenario that might work. It involved carbon, that common or garden atom that most of us are made of (liquid metal terminators being the primary exception).

It's not the most obvious of ideas, you want to fuse two hydrogens (atomic number 1) into a helium (atomic number 2), why would you think of using carbon (atomic number 6)? Anyway he did, and he came up with a rather clever mechanism to fuse hydrogen.



It starts as I said with carbon. Carbon has 6 protons and 6 neutrons normally in its nucleus, and for this reason it is called carbon-12, or ^{12}C for short (the number indicates the number of protons + neutrons). There are other types of carbon, as shown above. Carbon is a relatively big target compared to proton, being 12 times as big, but also 6 times as positive. So a proton (which is just a hydrogen nucleus) that comes whizzing along fast enough, and bumps into the carbon can get absorbed.

This changes it, from carbon which always has 6 protons, to nitrogen which always has 7 protons, ^{13}N. Some energy is given off, but ^{13}N is not a stable nucleus, and the weak decay force jumps in after about 10 minutes, turning one of its protons into a neutron losing an anti-electron (positron) and a neutrino in the process to balance the books. So now this is carbon again, as it has 6 protons again but 7 neutrons. This is a heavier form of carbon, ^{13}C. These different forms of the same atom are known as isotopes. They are the same thing chemically, but heavier or lighter forms as they have more neutral velcro. There is a further sequence of proton absorption and decay, through ^{14}N, ^{15}O, to ^{15}N ending up with oxygen ^{16}O, which emits a Helium nucleus (a well known process called alpha decay) which gives back ^{12}C and ^{4}He. So carbon is used in this cycle like a catalyst. It starts off as ^{12}C, collects protons (^{1}H) and ends up as ^{4}He and ^{12}C ready for reuse. In the process 4 protons are converted to a ^{4}He.



[CNO cycle - courtesy wikipedia]

So this is a cycle, involving carbon, nitrogen and oxygen, and is known without much cleverness as the CNO cycle. Quite how Hans came up with this - apparently on a train journey - is beyond me, but all the maths apparently works out. There are also variations on this cycle which happen under different conditions.

This is all well and good, but it needs two things to work. First, it needs carbon - clearly! Without this it isn't going to work. This can be an issue, because just after the big bang, there was nothing much really but hydrogen and helium. It took various nuclear processes within stars - usually during their death throes, to make heavier elements. A topic we might cover another time.

The other thing needed is sufficient temperature for the reaction to start working. It turns out to need things hotter than the PP reaction discussed last time. Whilst PP can start at about 10 million degrees, the CNO reaction doesn't really get going until well after 15 million degrees. Our own sun is just hot enough to do a tiny bit of CNO - and it has carbon so it can - but its not a very significant part. Stars about a third bigger than our Sun get hot enough for this reaction to become significant.

Why is this important? Well it comes down to how fast the reactions happen. We saw last time the PP reaction has a very slow step to begin with. It gets faster in hotter stars. However roughly speaking the reaction rate of the PP reaction is proportional to the fourth power of the temperature or $rate \propto T^4$. What does this mean? It means if we double the temperature of the star, the reaction runs not twice, not 4 times, not 8 times but 16 times as fast.

However the CNO cycle has approximately a $rate \propto T^{20}$. This means if the star is twice as hot, the rate of burning speeds up by a factor of about a million. This means in hot stars, they burn their fuel at prodigious rates and so have comparatively short lives. Our Sun has a life of about 10 billion years. A very large star might only burn for 25 million years - that's less time than back to the dinosaurs!

It also means things were different in the universe, with no carbon around, the earliest stars burned slower, and could therefore be bigger. This could hold the clue to various early universe phenomena.