

How *do* stars shine?

What makes a star shine? It's a question, more often asked of the Sun over millennia, but it applies to stars as well. It is only relatively recently we've had an answer to that.



We should probably discount ideas based around various gods and chariots having nothing much better to do all day than ride across the sky, and presumably spend all night preparing to do it all again tomorrow. If you were a god, would this really be the limit of your ambition? Anyway, the first reasonable ideas centred around a large structure of burning coal. It's a reasonable idea, and makes some sort of sense. Take what you know and make it bigger.

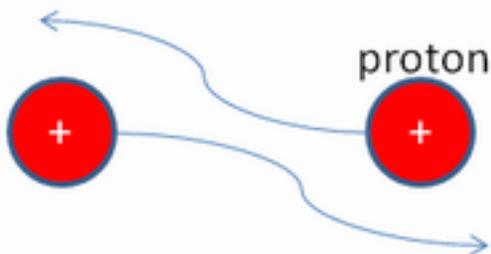
However come the scientific age, and a good understanding of thermodynamics, it was soon found to be untenable. The Sun weighs in at about 330,000 times the weight of the Earth, but even if it were all coal, and presumably sitting in some sort of oxygen rich environment, it would only provide around 5,000 years worth of burning. It might stretch to a few thousand more, or perhaps less - we can't really do the experiment - but regardless, it is not going to keep us warm very long, at least historically speaking, never mind geologically speaking.

Another idea was dropping stuff onto the Sun. As things fall onto the Sun, they speed up and hit it with quite a whack. This gives off heat, and if you had enough stuff its a very efficient way to produce power. It powers the brightest objects known in the universe, objects that outshine entire galaxies, but it does require a lot of stuff to be consumed in the process. Lord Kelvin did a lot of these calculations in the mid 1800's, saying he couldn't see any way the Sun could shine for more than about 100 million years, unless there were some unknown mechanism at work.

Come the twentieth century, and the era of radioactivity and nuclear physics, bringing with it the famous equation $E=mc^2$, and suddenly new possibilities opened up for sources of power. Einstein's famous equation means we can convert mass into energy, and c , being the speed of light, and a very big number, then squared, means a small amount of mass can make a lot of energy.

It was known through spectroscopy that the Sun was made mostly of hydrogen and helium, so it was a good bet that whatever it was doing involved those elements in some way. Now if you weigh an atom of Helium, it is about four times heavier than an atom of Hydrogen. This is not surprising as everyday Helium is made up of 4 particles in its nucleus (two protons, two neutrons), and Hydrogen just one (a proton). However if you weigh it very very carefully, you find that 4 times the mass of Hydrogen, is a little bit more than a single Helium. That bit of missing mass would add up to quite a bit of energy, and if a lot of H's are coming together to make He, we have a plausible source of energy, nuclear fusion.

Problem solved? Well not quite. There are a few awkward issues. First a Hydrogen atom consists of a single nuclear particle, a proton. A Helium nucleus is two protons and two neutrons. So you can't just add 4 H's together to make a He, somehow you've got to either borrow or make neutrons. There is also the tricky issue of getting two or more protons to stick together. You see protons have a positive charge, and like charges repel. So as you bring them closer together, there is a repulsion between them. It gets stronger as they get closer too. It's like pushing two magnets together, they try to avoid each other. Even if you could squash them together, there is no such thing as an element with two protons on its own. It would be called Helium-2 or ${}^2\text{He}$, but if it does ever exist, it falls apart back into two protons almost instantaneously.

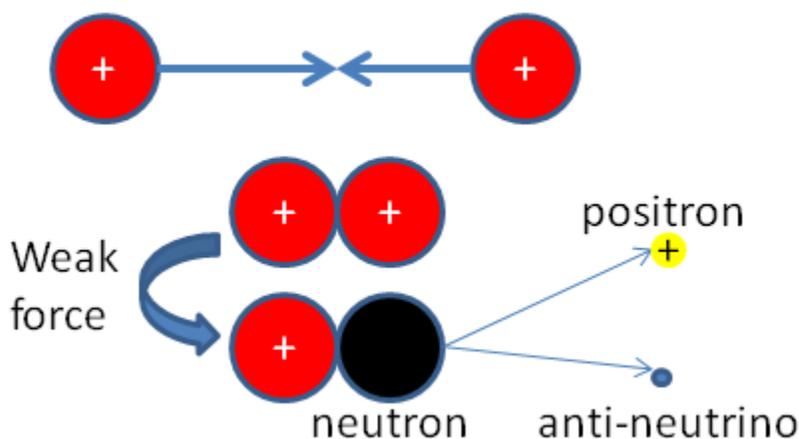


When two nuclear particles get very very close a new force can get to work, called the strong nuclear force. This can hold things together despite the electric force trying to push them apart. In this case though, it is just not strong enough to hold them, without some additional help, so it falls apart back into two protons.

However, there is another force that can be useful. The weak nuclear force. As its name implies, it is weaker than the strong nuclear force, and indeed weaker too than the electromagnetic force. In truth its not much of a force either, but it does have a useful role. It is the agent of

change, and in this case it can change a proton into a neutron, and should we get in the lucky position of getting two protons very very close, and the weak force jumping in just at the right point, we will end up with the change happening and a proton and a neutron stuck together. This is a very rare event, but luckily we have numbers on our side. It might take a billion years for this to happen to a given proton, but when you have billions upon billions of protons milling around in close proximity in the Sun, it will happen quite often. This is actually a good thing, otherwise the Sun would go off literally like an H-bomb!

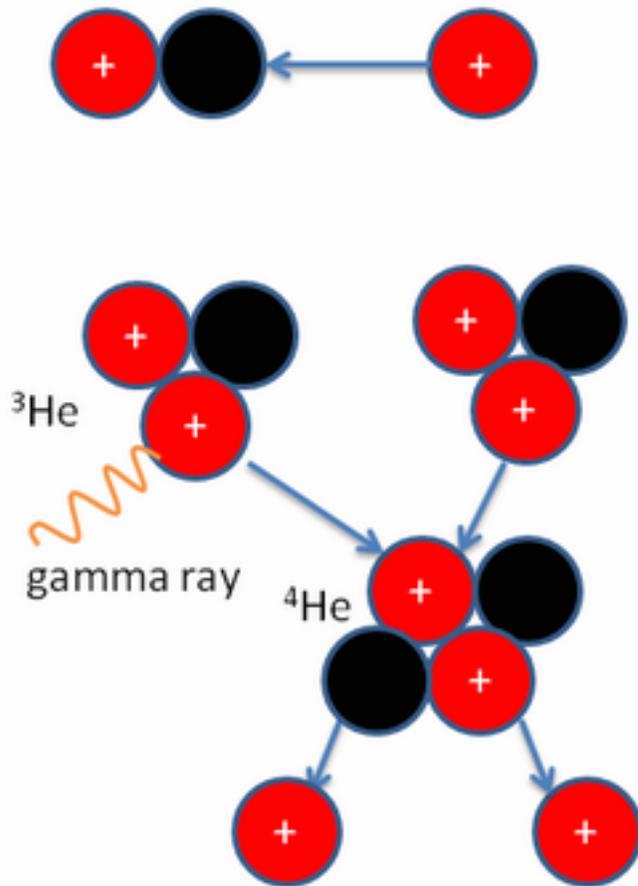
To get two particles really close, they still need to overcome the repulsion, and you can do this by throwing them at each other fast enough (this works with magnets too - but can get messy). How do you make protons move faster? Well one way is to heat them up. This is one reason the Sun needs to be hot, otherwise the particles would never even get close. In fact, the Sun is not “hot enough” to make this happen. If you do the calculations, and throw in the temperature of the Sun, they should never get close enough. Luckily the weird world of quantum mechanics they live in helps save the day, and sometimes they are allowed to break the rules a little and “tunnel” into each other. Another key thing is to be all squashed together, so these fast moving tiny tiny particles might stand a chance of running into each other.



So, this whole process makes a nucleus of deuterium, or heavy hydrogen as it is sometimes called. To balance the books, a positron is produced (an anti-electron) so that we start with two units of charge and finish with two, and an anti-neutrino which helps balance energy. The positron will find an electron in short order, and commit mutual suicide with it producing a gamma ray.

After this step, it's all downhill relatively speaking. It's easy now to bump another proton into the deuterium to make Helium-3 - which is stable, the extra neutron acts as a sort of nuclear glue. This probably only takes a few seconds, compared to the billion of so for the first step. Then the next step is two Helium-3's to come together to make Helium-4 with the loss of two spare protons. This also happens relatively quickly, at around 10,000 years or so, peanuts in the life of

a star. These last two steps also give off the most energy too.



At several stages along these steps, energy is released. It is released either as a particle of light - a photon in the gamma ray range, or as an anti-neutrino. The anti-neutrinos hardly ever interact with matter, and leave the Sun never to return. The photon of light meanwhile has a much harder journey. It bumps into protons and electrons and gets jostled around, but after several thousands of years, it makes it to the surface, and there it can escape to make the Sun shine. It is rather wearisome from it's journey, so leaves not as a high intensity gamma ray the way it was born, but more commonly as a visible light ray, which is what we see (occasionally!) in the clear blue sky. This process is known formally as the proton-proton chain reaction 1 (or PP1 chain - there are other variants) and is what most small stars like our own use. Bigger stars have some more options which we might explore later.

How do we know all this? Well some of it by theory and calculation. Some of it by using neutrino telescopes which can look inside the Sun to some extent. Astroseismology (studying of sun-quakes) can also tell us some of the internal structure of the Sun. We've also made fusion reactions on the Earth, but usually in rather uncontrolled H-bombs, as controlled fusion has so

far eluded us.

[[Additional graphics that might be used at http://en.wikipedia.org/wiki/Proton%E2%80%93proton_chain_reaction]]