# How long can the Sun go on shining for?

The Sun produces energy by fusing Hydrogen nuclei into Helium in its core. This results in a mass defect which gives a net release of energy as electromagnetic radiation (heat and light). Clearly, though, the Sun must eventually run out of Hydrogen sooner or later.

You may have read elsewhere that the Sun's remaining lifespan is about four to five billion* years, but where does this number come from? You can use what you know about mass defects and binding energy, together with measurements of the power output of the Sun, to work out how long the Sun has got left before it runs out of Hydrogen.

**Background Information**
In the core of the Sun, the most common fusion process is a series of three reactions, the net result† of which is the formation of Helium from Hydrogen:

$$4\,{}^{1}_{1}\mathrm{H}^{+} \rightarrow {}^{4}_{2}\mathrm{He}^{2+} + 2\,{}^{0}_{0}\nu + 2\,{}^{0}_{1}\mathrm{e}^{+}$$

This reaction‡ results in a mass defect, which is where the energy comes from.

1) Calculate the mass defect of the above reaction, in kg:

Proton mass = 1.007276 u
Positron mass = 0.000549 u
Helium nucleus mass = 4.001505 u
(*Assume neutrino mass = 0!*)

2) Calculate the energy released per Helium nucleus produced.

* billion nowadays usually means an American billion *i.e.* 1 x $10^9$
† This is actually the net result of several reactions, including some natural decay processes. If you Google 'proton-proton chain in stars' you should find more details if you're interested.
‡ Here, ν denotes a neutrino, and $e^+$ denotes a positron.

We can work out the total power released by the Sun, nearly all of which comes from Hydrogen fusion, by measuring how much solar energy we receive from the Sun per second on Earth (= *I*), then correcting for the distance between us and the Sun using $P = 4\pi r^2 I$.[§] This calculation shows that the Sun emits $\mathbf{4 \times 10^{26}}$ **W** in total.

3) Calculate the number of Helium nuclei produced per second to give this total Power.

4) Calculate how many kilogrammes of mass the Sun loses per second whilst maintaining its Power output.

This probably sounds like a wrong answer –can the Sun really be losing 4 million tonnes every second? Yes: the mass of the Sun is so huge, it makes practically no difference from day to day, or even from year to year. In fact, you lose billions of times more mass (compared to your total body mass) when you trim your little toenail.

Using measurements of how far planets are from the Sun and how long it takes them to orbit the Sun once, we can use Kepler III and Newton's law of Gravitation to work out the mass of the Sun. It comes out to be $\mathbf{2 \times 10^{30}}$ **kg**, 74% of which is Hydrogen.

5) If the Sun carries on shining until it uses up <u>all</u> its Hydrogen, what is its remaining lifetime?

[§] r is the distance between us and the Sun. The factor of $4\pi r^2$ occurs because you are imagining the radiation being spread over the surface area of a sphere centred on the Sun, and the surface area of a sphere is given by...

This time (14 million million years) is far longer than the usual quoted figure of 4-5 billion years. However, we have assumed that <u>all</u> the mass of the Sun will be fused. In reality, it is only the mass lost in the core which is relevant, since only in the core is the temperature and pressure high enough to overcome the Coulomb repulsion between the protons to cause fusion.

In fact, fusion reactions will start to reduce long before *all* the mass in the core is fused. Theoretical calculations suggest that reactions will slow down once the Sun uses up 0.03% of its existing mass.

6) Taking the data above, show that the remaining stable lifetime of the Sun is between 4 and 5 billion years.