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Why is the Sun hot?

If the Sun were made of bananas, it would not make any difference. Well, not much difference! It is all to do with why the Sun is hot. It is hot for an incredibly simple reason: because it contains a lot of mass. All that matter bearing down on the solar core squeezes the material there. And, when things are squeezed, they get hot, as anyone who has squeezed the air in a bicycle pump knows. The temperature at the centre of the Sun is about 15 million degrees. And, at such a temperature, matter dissolves into an amorphous, anonymous state known as a "plasma". It does not matter what the matter is, it always ends up in this state.

Now, the Sun is about a billion billion billion tonnes of mostly hydrogen. But, if you put a billion billion billion tonnes of microwave ovens in one place or a billion billion billion tonnes of bananas, you would get something equally as hot as the Sun. The point is that the temperature of the Sun is determined essentially by the amount of matter it contains, not the type of that matter (although the latter has a minor effect by governing how effectively heat is bottled up in the Sun).

But all that this explains is why the Sun is hot at this very instant, not why it stays hot. The Sun is continually losing heat into space, yet its temperature does not change noticeably. This tells us that something must be replacing the heat exactly as fast as it is lost. But what?

In the 19th century, in an era powered by steam, it was natural to think of the Sun as a lump of coal: the mother of all lumps of coal. But, according to the calculations of the physicist Lord Kelvin, a coal-powered Sun would burn out in only about 5000 years – not even enough for Irish Archbishop James Ussher, who calculated from The Bible that the Earth (and so Sun) was born on 23 October 4004 BC.

But geologists, who had discovered fossil sea creatures on mountaintops and consequently deduced that the mountains had once been beneath the ocean, required tens of millions of years for those mountains to have risen up. And Charles Darwin required hundreds of millions, if not billions, of years for today's profusion of living things to have diverged by a process of natural selection from a simple common ancestor. In fact, the radioactive dating of meteorites – the builders' rubble left over from the birth of the Solar System – showed the Sun to be 4550 million years old. In other words, whatever is powering the Sun is an energy source about a million times more concentrated than coal. In the 20th century, such a source came to light: nuclear energy.

The Sun is fusing nuclei of hydrogen, the lightest element, into the second lightest, helium, the mass difference between the initial and final product appearing as the energy of sunlight, according to $E=mc^2$. Because of this process, the Sun gets lighter by the mass equivalent of 1 million elephants every second (by comparison, the biggest H-bomb turned only about a kilogram of mass-energy into other forms of energy, chiefly heat).

The sunlight-generating nuclear reactions in the Sun are very sensitive to temperature, slowing if the Sun cools and racing if it heats up. So, if they generate too much heat, the gas of the Sun, like any gas that is heated, expands and cools, throttling back the nuclear reactions; if they generate too little, the gas shrinks and heats up, revving up the nuclear reactions.

The Sun therefore has a perfect thermostat. The upshot is that the nuclear reactions maintain the Sun at precisely the temperature determined by its mass alone. Incredibly, then, the temperature of the Sun has nothing to do with the details of its energy source.

The first step in assembling a helium nucleus is for two hydrogen nuclei to meet and stick, a process which on average takes 10 billion years, which is why the Sun will shine for 10 billion years. This nuclear reaction is just about the most inefficient nuclear reaction imaginable. Imagine your stomach and a volume of the core of the Sun the size and shape of your stomach. Your stomach generates more energy.

You might wonder, then, how the Sun stays so hot. The answer is that the Sun does not consist of one chunk the size and shape of your stomach but countless quadrillions of such chunks all stacked together.

Next time your skin is being warmed by the Sun on a summer's day, be thankful for the mind-boggling inefficiency of its nuclear reactions. If this were not the case, the Sun could not have shone for the billions of years necessary for the evolution of complex life like you. ●