The Sun: Crash Course Astronomy #10

Crash Course: Astronomy
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The sun is a star.

That's a profound statement, and one that's not really all that obvious. Those little sparks in the night sky are pretty, but don't look anything at all like the hot, blazing orb that lights up our days. It was a pretty remarkable intellectual leap to understand the Sun and the stars are just different flavors of the same kind of object. The only difference is that the Sun is close, but the stars are terribly far away, so they're fainter.

Right away, let's clear up a misconception: A lot of people say the Sun is a middle-sized, average star. But that's not fair. Sure, it's somewhere in the middle of the size range of stars, but the vast majority of stars are dim red dwarfs, far smaller than the Sun. By size and number, the Sun ranks in the top 10% of stars in the galaxy!

In our solar system, it's clearly the dominant object: brighter, more massive, and more influential than anything else.

But, what is it?

The Sun is, essentially, a big hot ball of mostly hydrogen gas. It's 1.4 million kilometers across — more than 100 times the Earth's diameter, and big enough that well over a million Earths could fit inside of it. And it's massive: 300,000 times more massive than the Earth, a staggering two octillion tons of gas.

But if we want to truly understand the Sun, we have to look into its heart.

At the very core of the Sun, conditions are hellish. The pressure is a crushing 260 billion times the Earth's atmospheric pressure, and it's a searing 15 million degrees Celsius.

Under those conditions, hydrogen is completely ionized, which means the electrons in the atoms are stripped from their protons. This makes the core a thick soup of ultra-hot subatomic particles. In fact, the protons are squeezed together so hard by the octillions of tons of mass lying on top of them that an amazing thing happens: they fuse together.

Through a complicated series of steps, the hydrogen atoms fuse together to form the heavier element helium. Along the way, some of the nuclear energy stored in those atoms is released. That amount of energy is described by Einstein's famous equation $E=mc^2$, which states that mass can be converted into energy, and vice-versa.

Atoms are pretty small, though, so each helium atom made in the Sun's core generates only a tiny bit of energy… but a lot of helium atoms are made. A lot. Get this:

Every second of every day, the Sun converts 700 million tons of hydrogen into 695 million tons of helium. The missing 5 million tons — the equivalent weight of 15 Empire State Buildings — is converted into energy, and that's a lot of energy.

Enough, in fact, to power a star.

It's equivalent to detonating 400 billion one megaton nuclear bombs every single second. That's millions of times the entire nuclear arsenal of our planet. Every second.

And that's why, even from a distance of 150 million kilometers, the Sun is so bright you can't even look at it. Even from that distance, its heat can be felt on your skin when you stand outside.

Hydrogen fusion occurs in the core of the Sun. The energy released heats the gas above the core, but not quite enough to fuse hydrogen into helium. Further from the Sun's center the gas becomes less dense, and at some point the heat pouring up from below makes the gas buoyant: it rises, in the same way a hot air balloon on Earth rises. This process is called convection, and it's an efficient way of transferring heat. Huge columns of rising hot gas stretch hundreds of thousands of kilometers high, bringing the Sun's internal heat to the surface. The gas then cools and sinks back down into the interior. We can actually see the tops of these columns, packed together across the Sun's face.

Above the convecting layer is a much thinner, cooler layer very near the Sun's surface called the photosphere, or literally the sphere of light. This is where the density of the material inside the Sun gets thin enough that it becomes transparent; light can shine right through it. At this point, the energy from inside the Sun is free to travel into space. It's this light that we see when we look at the Sun.

The Sun is a gas and doesn't have a solid surface, but the gas in the photosphere thins so rapidly compared to the Sun's huge size that you can think of it as the Sun's surface. And there's one final layer above that: The ethereally thin corona, sort of like the Sun's atmosphere. It's less than 1% as dense as the photosphere, but actually much hotter; temperatures there can reach over a million degrees! However, it's so thinly dispersed that it's incredibly faint, and can only be seen during a total eclipse, or using special telescopes that block the intense light from the Sun itself. The corona extends for millions of kilometers.

And in a sense it doesn't actually end. The corona merges into what's called the solar wind, a stream of subatomic particles moving away from the Sun. It blows out in all directions, though mostly along the Sun's equator. The speed of the wind is usually well over a million kilometers per hour — yes, seriously — and can reach speeds even much higher even than that.

When hydrogen fuses into helium in the Sun's core, the energy is released in the form of light. This light immediately smacks into a subatomic particle, which absorbs it, converts a little bit of the energy into motion, and re-emits the light with a little bit less energy. The light works its way out of the Sun this way, losing energy every time it encounters a particle, until eventually it gets to the surface, and is free to fly away into the Universe as a much lower-energy photon of visible light.

So how long does this process take?

I've seen different numbers for it, some as much as a million years. But a lot of those calculations don't model conditions inside the Sun accurately; for example they don't take into account the gas convecting for hundreds of thousands of kilometers. More modern calculations show that it takes closer to 1 or 200,000 years for the energy to work its way out. That's still a pretty long time: The light you see from the Sun now got its start in the Sun's core around the time *Homo sapiens* first appeared in Africa!

The Sun's surface is, to put it kindly, a mess. And the key to that mess is magnetism.

I've been saying the Sun is made of gas, but that's not entirely accurate. It's so hot inside the Sun that electrons are stripped from their parent atoms in the gas, creating what's called a plasma, a gaseous soup of charged particles. We'll learn more about that in a later episode. But, what's important now is the fact that a moving electric charge generates a magnetic field.

The interior of the Sun is essentially all charged particles in motion.

Convection, coupled with the Sun's rotation, sets up rivers or streams of plasma inside the Sun, each generating and carrying its own magnetic field. When this plasma reaches the Sun's surface, their magnetic fields do too.

Maybe you've seen those looping arcs of magnetism around a bar magnet when it affects iron filings on a piece of paper. The solar magnetic fields are like that, except there can be zillions of them all over the Sun's surface, where they can interact and even get tangled up.

When the plasma reaches the surface, it cools. But if the magnetic loops tangle up, they prevent the plasma from sinking back down into the Sun, like a knot in a shoelace prevents it from going through the eyelet on your shoe. Plasma shines because it's hot, but as it cools it dims. It sits on the surface, dimming, producing a dark spot on the surface of the Sun, which we call… a sunspot.

Sunspots can be huge; they commonly dwarf the entire Earth, and some are so big they can be seen without using a telescope (as long as you're wearing adequate eye protection, of course).

Around the edges of sunspots, the magnetic field lines are concentrated. This can energize the plasma even further, heating it up. This creates a bright rim around sunspots called faculae (Latin for "little torch"). The dark parts of sunspots dim the overall light from the Sun, but faculae can be so intense they compensate for that, and even add more light. Ironically, sunspots actually increase the energy output of the Sun.

Plasma on the Sun's surface can flow along these magnetic loops, too. This can create huge arcs of material called prominences or filaments, stretching for hundreds of thousands of kilometers across the Sun, looking like fiery arches.

We think these magnetic field lines are feeding energy from the Sun's surface into the corona, which is why it's so much hotter. It's not exactly clear how this happens, but scientists are following several leads right now. This long-standing mystery may soon be solved.

Magnetic fields on the Sun also have a huge amount of energy stored in them. You can think of them like very tightly wound and very stiff springs. But remember, these magnetic field lines get tangled up. If conditions are right, they can actually snap, in essence creating a gigantic short circuit. When this happens, all that vast energy stored in the lines explodes outwards all at once in an event we call a solar flare.

Even an average solar flare is mind-crushingly powerful; a big one can release as much as 10% of the entire Sun energy output. This explosion blasts out high-energy light and launches material off the surface of the Sun at high speeds, sending it into interplanetary space.

Another type of solar eruption is called a coronal mass ejection, or CME. It's similar to a flare, but if a flare is like a tornado — intense and localized — a CME is like a hurricane, huge and strong. Like flares, they form when tangled magnetic field lines erupt, blasting out energy, but they occur higher off the Sun's surface.

Both flares and CMEs eject material into space — billions of tons of it, in fact. This blast of debris can hit the Earth, and when it does, there can be profound effects. Our atmosphere absorbs the high-energy light, protecting us. Also, the subatomic particles are generally deflected by the Earth's magnetic field, so we're OK.

But, if conditions are right, the Earth's magnetic field can interact with the particles. Massive numbers are funneled down into Earth's atmosphere near the poles, causing the air to glow. This is what we call the aurora, or the northern (and southern) lights. Depending on the shape of the magnetic field, the auroras can form spectacular multicolored ribbons and sheets.

Not all the effects are benign, though. As the magnetic fields interact, they can induce very strong currents of electricity in the Earth's crust. This can overload power grids, causing blackouts; in 1989 Quebec suffered a massive power outage from a solar storm.

The very first such storm ever detected was in 1859, and it was also the most powerful ever seen. If an event like that were to happen today, it could cause worldwide blackouts and potentially be very damaging. Satellite electronics would be fried, too, and we depend on those satellites for our modern civilization. In fact, in 2012, a huge storm, probably the equal of the 1859 event, blasted away from the Sun… in another direction, missing the Earth. Had it hit us, well, you probably wouldn't be watching this video now. We'd still be recovering.

This is why studying the Sun is so important. We depend on it for light and heat and the very basis of life itself, but it's entirely capable of knocking our society to its knees. Understanding it is critical to our future.

The Sun is the 2 octillion ton gorilla in the room. We need to respect that.

Today you learned that the Sun is a star, powered by nuclear fusion in its core. Hot plasma moves inside the Sun, creating magnetic fields, which in turn can create sunspots, solar flares, and coronal mass ejections. These events can generate aurorae on Earth, cause power blackouts, and damage satellites.

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