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Viewing the core of the sun

The sun is a central feature to the human experience. It is found in many familiar idioms like “nothing new under the sun.” It defines our days, makes our planet habitable, and is the ultimate origin of your last meal. Yet how do we understand how it works?

Over the last century or so, astronomers have learned a great deal about our sun by observing its outer layers. This has led to significant progress in envisioning the processes that power it, while still leaving the full picture incomplete Recent exciting measurements of subatomic particles called neutrinos have given us our first detailed view of the dominant nuclear processes inside its core. These observations have provided a detailed view of the phenomena that generate the sun’s energy. But, before I describe these fascinating new measurements, it is perhaps valuable to set the stage.

The sun is a huge ball of plasma, located ninety three million miles (150 million kilometers) from Earth. Its mass is about 2 x 10^{30} kg and it has a radius of 433,000 miles (969,000 km.) So it’s very big. It is about 300,000 times more massive than the Earth and about a hundred times larger in diameter. Its surface temperature is about 5,800 K and it is powered by nuclear fusion [1].

That last set of facts is of particular interest. We know that the dynamo that heats the sun is predominantly the fusion of hydrogen into helium and the temperature at which that occurs in vacuo is about one hundred million Kelvin, although that number is strongly affected by the pressure under which the hydrogen is found. Because of pressure, fusion occurs at the center of our sun, which has a temperature of about thirteen million Kelvin. However, the temperatures on the sun’s surface are well below those required to sustain nuclear fusion.

Surrounding the core is the sun’s radiation zone, which extends to about seventy percent of the sun’s radius. Its name arises from how energy is transported within i. Photons from the core travel through the radiation zone, but the density of the environment is very high. Photons can travel of order a millimeter before being absorbed or scattered by the charged particles they encounter. These photons then must follow a stochastic “drunken walk” path, taking a long time to pass through the sun. Estimates of the amount of time required to make that passage are very sensitive to a number of parameters, including the radial dependence of the density of the sun, and those estimates can range from as little as ten thousand to a million years. And, of course, it’s not that the initial photon makes its way out of the sun. It is constantly absorbed and reemitted. The time duration mentioned here is an estimate of how long it takes the energy to flow from the core to the surface. The range of estimated durations depends on assumptions on the conditions of the solar core and the choices one makes while estimating. These numbers are more of a back of an envelope kind of thing, rather than a formal calculation.

Outside the radiation zone is the convection zone. In it, photons are transported in a process very similar to a lava lamp. The photons enter the plasma of the convective

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zone and continue to be emitted and scattered much like in the radiation zone. However, the matter in the convective zone is mobile and it rises due to temperature and density differences. The scattering photons rise along with the matter until they reach the surface of the sun. At that point, they escape the sun and travel to Earth, taking about eight minutes before they warm you sitting on the beach, where you might be wondering if maybe you need a little more sunscreen.

The most common wavelength of light from the sun hitting the earth is about 500 nm, with a color of cyan or light green. This is to be contrasted with the wavelength emitted in the fusion reactions that power the sun. Fusion photons are gamma rays, with energies around a million electron volts and a wavelength of a fraction of a nanometer.

This means that astronomers have never actually directly observed the solar nuclear fusion process. Their understanding arises from combining laboratory-based measurements of nuclear physics processes with extensive computer modeling. Measurements such as the temperature of the sun, the size of the speckles on the sun's surface (i.e. the size of convective cells) and variations in the sun's shape are used to constrain theoretical models of the sun's internal structure.

However, there is a method that allows researchers a direct window on the processes that power the sun. Scientists detect neutrinos emitted during nuclear fusion at the sun's core. Neutrinos interact via the weak nuclear force and therefore they escape the sun without interacting with the sun's plasma. While gamma rays emitted during fusion take tens or hundreds of thousands of years to reach the sun's surface, the neutrinos scientists observe were created a mere eight minutes before observation. In addition, the electromagnetic energy emitted by the sun isn't gamma rays produced during fusion, but rather longer wavelength light that reflects the end process of millennia of thermalization. In contrast, solar neutrinos detected on Earth retain their original energy and momentum, providing a direct measurement of the conditions of matter in the solar core.

Fusion processes

When people talk about fusion in the sun, they often say that hydrogen is fused into helium. And that is correct, at least in a manner of speaking. However, the process is impressively more complicated.

For instance, a hydrogen nucleus consists of a single proton, while helium nuclei consist of two protons and two neutrons. For hydrogen to turn into helium, a source of neutrons must be found.

Because of this, solar fusion occurs in a series of steps, each with a name. The dominant energy-producing process begins with two protons (p) fusing together and, in the process, one of the protons transforms into a neutron (n), a positron (antimatter electron, e^+) and a neutrino (ν). The nucleus containing a proton and neutron is called a deuteron (^{2}H). The process is denoted (pp) and can be written: $p^+ + p^+ \rightarrow\ ^2H + e^+ +$

ν. The pp process accounts for 99.77% of the conversion of protons into deuterium in the sun.

In the next step in the process of transforming hydrogen to helium, a deuteron fuses with a proton and makes helium-3 (^{3}He) and emits a high energy photon (γ) in the process. Helium-3 consists of two protons and one neutron. This process is $^2H + p^+ \rightarrow {}^3He + \gamma$. Direct fusion of two deuterium nuclei is energetically unfavorable. When they do fuse, the end result is either a helium-3 nucleus and a neutron or a hydrogen-3 nucleus and a proton.

The dominant final step to convert helium-3 into helium-4 is called (pp-1). In this step, two helium-3 nuclei (e.g. a total of four protons and two neutrons) fuse together into helium-4 (two protons and two neutrons) and two protons, e.g. $^3He + {}^3He \rightarrow {}^4He + 2p^+$.

A sub-dominant step fuses helium-3 and helium-4 into beryllium-7 and a gamma ray. Beryllium-7 absorbs an electron, becoming lithium-7. Lithium-7 then absorbs a proton and makes two helium-4 nuclei. Figure 1 gives a full accounting of all of the processes involved in converting hydrogen nuclei into helium nuclei. The step involving boron-8 is not very important in the sun's energy budget, but it has an outsized role in the history of studies of solar neutrinos. This will be discussed a little later.

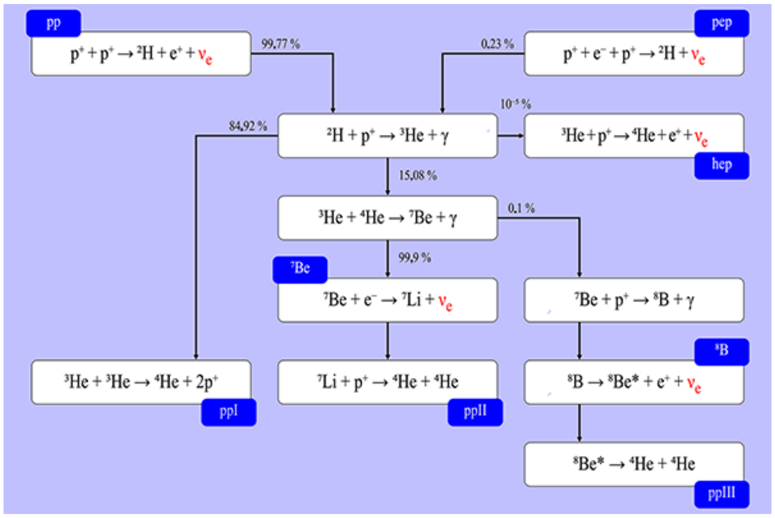

Figure 1 [caption] The dominant nuclear fusion process in the sun converts hydrogen nuclei into helium nuclei via a multistep process. Neutrino emission is denoted in red. **[end caption]**

While these are the dominant processes that take place at the core of our sun, they are not the only ones. Nuclear fusion of all elements up to iron releases energy. Iron-56 is the heaviest element that can be manufactured in the core of a star. Elements heavier than that are only made in extreme stellar processes, including supernovae, colliding neutron stars, and other cosmic fireworks [2].

However, synthesis of very heavy elements is uncommon in our sun. They are more commonly found in stars older than our own, which have fused most of their hydrogen into helium. This fusion process is called alpha capture, as it involves heavy nuclei capturing alpha particles. Alpha particle is a historical name for helium nuclei (^{4}He). Examples of alpha capture include ${}^{12}C + {}^{4}He \rightarrow {}^{16}O + \gamma$. Gamma rays ($\gamma$) are highly energetic photons.

Alpha capture continues, with oxygen capturing an alpha particle and making neon. Neon converts to magnesium. Magnesium becomes silicon, and so on.

Spanning the realm of light nucleus and heavy nucleus nucleosynthesis, stars must convert helium nuclei to carbon. There are two processes that play a role. The first is the triple-alpha process, in which two helium-4 nuclei fuse to beryllium-8, emitting a gamma ray in the process. The beryllium-8 nucleus fuses with another helium-4 nucleus to make carbon-12.

$${}^{12}C + p^{+} \rightarrow {}^{13}N + \gamma$$

$${}^{13}N \rightarrow {}^{13}C + e^{+} + \nu$$

$${}^{13}C + p^{+} \rightarrow {}^{14}N + \gamma$$

$${}^{14}N + p^{+} \rightarrow {}^{15}O + \gamma$$

$${}^{15}O \rightarrow {}^{15}N + e^{+} + \nu$$

$${}^{15}N + p^{+} \rightarrow {}^{12}C + {}^{4}He$$

Figure 2 [caption] CNO nuclear fusion is a sub-dominant process in the sun converts hydrogen nuclei into helium nuclei using heavier elements as a catalyst. Neutrino emission is denoted in red. **[end caption]**

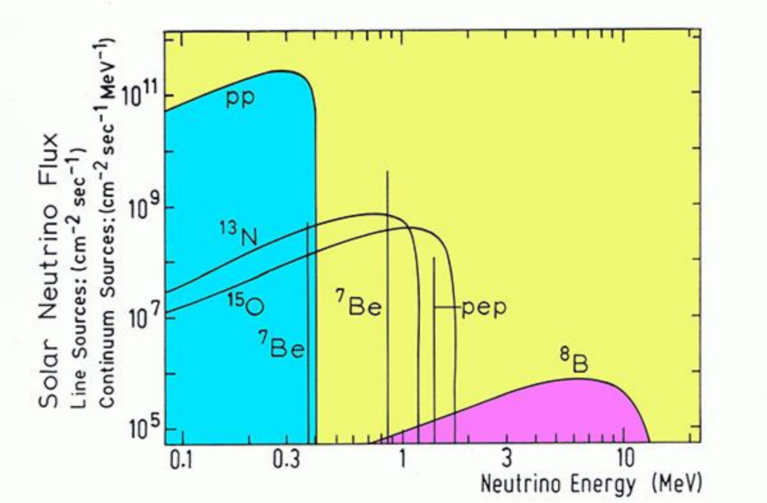

Figure 3 [caption] Neutrinos from a variety of solar fusion processes are emitted at different energies. The dominant pp process (blue) is much lower energy than the much rarer and more energetic boron-8 neutrino emission (pink). **[end caption]**

The triple-alpha process occurs at temperatures much higher than those present in our sun (of order 10^8 K at stellar pressures). It generally occurs much later in the lifecycle of a star.

However, there is another mechanism whereby helium-4 creates carbon-12, called the CNO process, or CNO cycle. The CNO process occurs in the sun, although it is quite rare. It is also fascinating. A six-step process of proton-nucleus fusion, interspersed with nuclear decay, transmutes a carbon-12 nucleus through intermediate stages that use nitrogen and oxygen, resulting finally back in a carbon-12 nucleus plus a helium-4 one. Along the way, neutrinos, positrons, and gamma rays are emitted at various steps. The carbon-12 then repeats the cycle. The full process is shown in figure 2.

There are a myriad of nuclear processes that occur in the sun and some of them are ones that emit neutrinos. Figure 3 shows the energy spectrum of neutrinos expected from a selection of nuclear processes in the sun. Figure 4 shows qualitatively the contribution of the various fusion processes as a function of temperature. For a star like our sun, it is totally dominated by the array of pp processes, with small contributions from the CNO process.

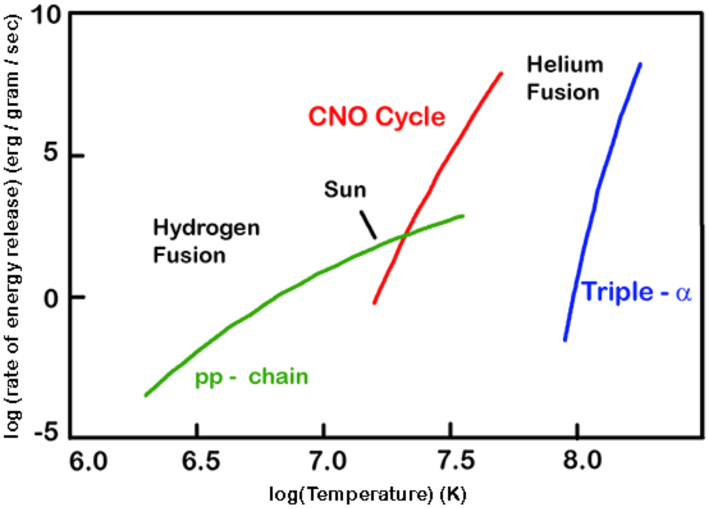

Figure 4 [caption] Energy release of various fusion processes as a function of temperature. pp (green) dominates at solar temperatures, although some CNO (red) is present. Triple-alpha processes are not found in our sun. **[end caption]**

Neutrino detection

The first effort to detect solar neutrinos began in 1967 when a clever experiment was performed by American chemist Raymond Davis [3]. He employed a tank of 100,000 gallons of perchloroethylene (C_2Cl_4), a commonly used dry-cleaning chemical, to search for neutrinos coming from the sun. The tank was located nearly a mile underground in the Homestake Mine, in South Dakota.

His detection mechanism used neutrino capture by chlorine ($\nu + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$). This process requires that the neutrino have a minimum energy of 0.81 MeV to proceed, which is fairly high for solar neutrinos.

Davis would run for several weeks and then bubble helium through the perchloroethylene to extract a few tens of atoms of argon. Davis worked in parallel with American physicist John Bahcall, who calculated the neutrino flux expected through Davis's detector. Davis and subsequent experiments reliably detected about a third of the neutrinos predicted by Bahcall. The deficit was a mystery for several decades, although the scientific community long suspected that a phenomenon called neutrino oscillation was the cause. This hypothesis was definitively confirmed by a series of experiments performed between 1998 and 2001 [4].

Neutrino oscillation occurs when neutrinos change their identity. There are three types of neutrinos called electron, muon, and tau. Solar neutrinos are 100% electron-type neutrinos and, during their travels from the sun to the earth, two thirds of them were changed into the other types of neutrinos. Davis's experiment was unable to detect these other types. Neutrino oscillation is described in more detail in Ref [5]

While neutrino oscillation is a fascinating field of study, it is largely understood, and correcting for the effect is now straightforward. The (corrected) Davis measurement was able to accurately determine the flux of solar neutrinos arriving from the sun.

There is an important caveat. Davis's experiment was sensitive only to neutrinos with an energy greater that 0.81 MeV. Figure 3 shows that neutrinos of this energy are dominated by the beryllium-7 process, with contributions from pep, boron-8, and nitrogen-13 and oxygen-15 (both part of the CNO process). These are a very small fraction of the overall neutrino flux from the sun.

The experiments of the 1990s, which established the existence of neutrino oscillations were the Super Kamiokande (SuperK) experiment in Japan and the Sudbury Neutrino Observatory (SNO) in Canada. Both experiments used water or deuterated water to detect neutrinos. Initially, the SuperK experiment could only detect neutrinos with an energy in excess of 6 MeV, although that was eventually lowered to 3.5 MeV [6]. The SNO experiment was sensitive to neutrinos with an energy in excess of 5 MeV [7]. From figure 3, we can see that these experiments were only sensitive to boron-8 neutrinos, which comprise a tiny fraction of the solar neutrino flux.

The situation changed in 2014, when the Borexino experiment first detected neutrinos coming from the dominant pp process in the sun [8]. Borexino is located in the Gran Sasso laboratory, nestled under the Italian Apennines. It consists of liquid scintillator, which emits light when sub-MeV energy neutrinos interact in the detector. A few previous experiments had observed low energy solar neutrinos, but without the capability of distinguishing specific neutrino processes.

Improvements in the purity of the Borexino scintillator and better shielding from the radioactive environment led to the recent announcement that the collaboration had also measured neutrinos from the CNO solar process [9].

With the observation of both pp and CNO solar neutrinos, astronomers now have a direct window into the nuclear fusion process that power the sun. This provides scientists measurements of the metallicity of the solar core. (For astronomers, metallicity is the fraction of a star's elemental makeup that is not hydrogen or helium.)

Other estimates of the sun's metallicity come from measurements of Fraunhofer absorption lines in the sun's emission spectrum in visible light [10]. However, Fraunhofer lines samples only the outer layers of the sun.

Astronomers use many solar observations to determine the sun's metallicity, but the different measurements disagree [11]. While early observations settled on a solar metallicity of 1.8 percent, helioseismology measurements favor 1.3 percent. Helioseismology is the study of how sound waves propagate through the sun.

Borexino's measurements favor the 1.8 percent number. This is crucial, as measurements of the sun's metallicity are used to calibrate the metallicity of stars in general. Thus the ability to directly observe nuclear fusion processes in the sun's core will have consequential impact on astronomy.

Borexino and other experiments will continue to flesh out our understanding of the sun. The age of solar neutrino astronomy has arrived.

Author's endnote: As of this writing, the measurements of Ref. [9] have not yet been submitted for publication or undergone peer review. However, they have been presented publicly at a leading international conference.

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