The Sun and Solar Wind: A Search for the Beginning

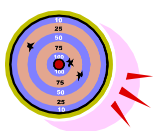
The Invisible Fire

STUDENT TEXT

In the Student Activity, "The Invisible Fire," how many of your tries resulted in "hits" and "sticks" in one minute? Any ratio greater than one in 14,000 million years is better than the rate of fusion in the sun's core. That's right, you were modeling one step,

$$^{1}H + {}^{1}H \rightarrow {}^{2}D + {}^{o}e^{+} + \nu_c$$

in the fusion reaction that occurs in the sun's core. It has been calculated that it takes a given solar proton 14,000 million years to find a "hot partner" with which to fuse. Protons may travel for long periods without colliding with another proton in the sun's core. They may also collide with one another many times without "fusing." You may have noticed that they must collide at the right speed, at the right angle, and with enough energy for fusion to occur.



And what was the significance of your trying to hit the "target" while blindfolded. Well, if we could see the sun's core it would be black, since all the photonic energy produced from the proton-proton fusion is too great to be visible to the human eye. So, protons are colliding with other protons "in the dark," just like you modeled when you were blindfolded.

You have just modeled some important properties of the sun's core: it's innermost zone. Actually, you "modeled the model" of the Standard Solar Model. No one has every seen the sun's core, and for obvious reasons, probably no one ever will.

[*For more detailed information about the fusion processes that occur in the sun's core, read "The Nuclear Fire of the Sun" found in Appendix A.*]

Early Models of the Sun's Energy

Image courtesy of NASA

How does "invisible fire" fit with our visual observation that the sun is a "ball of fire" in the sky. The ball of fire model appears to be very reasonable. Our eyes perceive lots of light from the sun—so much, in fact, that we are cautioned NEVER TO LOOK DIRECTLY AT IT. And we feel the heat of the sun on our skin, just like we do when we are close to a fire.

So, isn't it understandable that early scientists observing the exterior of the sun with the only scientific instruments available—their eyes and telescopes—thought the sun could be a cooling ball of hot iron or a gigantic globe of burning coal?

Later, the concept of a gravitationally-energized sun led to proposals that the sun was fueled by:

a) meteors falling into it from outer space;
b) consuming whole planets that released their gravitational energy upon impact with the sun;
c) contraction in which its potential energy was changed to thermal energy; and,
d) the collision of small rock-like pieces from outer space that formed the original sun.

New Scientific Instruments and Discoveries Lead to New Model

The analysis of materials by the technique of **mass spectrometry** played a seminal role in the development of the Standard Solar Model. It was through the mass spectrometric determination of the "exact" mass of helium that it was learned that the mass of an atom of helium was 0.8% less than the mass of four hydrogen atoms. This observation was at odds with the then-current theory that the atomic weight of any element is an exact multiple of the atomic weight of hydrogen. It was this finding that gave physicists in the 1920's the final clue needed to propose that the furnace in the interior of stars is fueled by sub-atomic energy. [*For a more detailed history of solar theories and models, see "The Nuclear Fire of the Sun" in Appendix A.*]

Scientists have calculated a model of the sun, using information that employed current technology and analytical instrumentation. Over the past 25 years, hundreds of changes have been made in the Standard Solar Model in an effort to obtain increasingly good numerical agreement between the model and the observed sun.

The Standard Solar Model predicts that the sun's structure consists of a core that is surrounded by three shells or layers. [*Use the handout "Standard Model of the Sun" as a reference as we explore the sun and solar wind.*] These shells are referred to as the **radiative layer** (or zone), the **convection layer**, and the **photosphere**, which is the surface layer. The photosphere separates the opaque solar mass from the atmospheric regions, which are the **chromosphere** and the **corona**.

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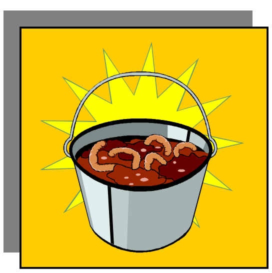
Although much remains unknown about the structure of the sun, particularly in its interior, the current model includes an extremely dense core. About 50% of the sun's total mass, but only about 1.5% of the total volume, are found in the core.

The temperature is thought to be around 15 million °Kelvin. These conditions are so extreme that all atomic materials present are stripped of their electrons, forming a hot brew of protons, neutrons, nuclei, and free electrons.

The pressure at the core is perhaps 250 billion times greater than the pressure of the Earth's atmosphere. The sun does not suffer gravitational collapse only because of this stupendous outward pressure, which is generated by the heat produced in the core. Nor does it explode like a hydrogen bomb, because the enormous mass of the gases above the core contains its explosiveness.



As noted above, the core density is extremely high. A bucket full of core material would be so heavy that you would be unable to lift it. At the core we find the nuclear inferno that produces the energy which ultimately is spewed forth into space. The sun's energy is manifested in the form of short wavelength gamma rays, which can be regarded as tiny packets of energy called **photons**, the particle component of electromagnetic radiation. If we could see into the core it would appear black, since none of the energy produced there lies in the visible part of the spectrum. Through collisional losses, the gamma ray photons are soon reduced to longer wavelength and less energetic x-ray photons, which remain outside of the visible part of the electromagnetic spectrum.

It is estimated that at core temperatures only one proton in 100 million has enough energy to fuse during a collision. Putting it another way, the reaction rate is so low that a specific proton would require 14,000 million years to find a suitable "hot" partner with which to collide in a successful fusion event! Since the sun is only (!) about 4.5 billion years old, most of its protons have not yet found fusion partners.

So, what are the details and consequences of this rare event? First, remember that the two exceedingly "hot" protons that are hydrogen atoms without electrons, collide. This violent event results in the fusion of the two nuclei and the formation of a deuteron, a positron, and a neutrino. This event can be written conveniently in equation form, where superscripts attached to elemental symbols represent mass number:

$$^{1}H + {}^{1}H \rightarrow {}^{2}D + {}^{o}e^{+} + \nu_c \qquad \text{(Equation 1)}$$

Mass Spectrograph

The instrument called a mass spectrograph was developed in 1919 by Francis Aston in Cambridge, England. The importance of this technology was immediately recognized, and Aston was awarded the Nobel prize for his work in 1922. Read Appendix B for information about how Mass Spectroscopes work.

The symbols ${}^{o}e^{+}$ and ν_c represent a positron and a neutrino, respectively. The deuteron, ${}^{2}D$, differs from a regular hydrogen nucleus in that it contains a neutron in addition to a proton. In this reaction one of the protons has been changed into a neutron, with the formation of a new nucleus containing one proton and one neutron. The key transformation can be written:

$${}^{1}p^{+} \rightarrow {}^{1}n^{o} \qquad \text{(Equation 2)}$$

But wait! There is something wrong with Equation 2. On the left side is a positive charge and on the right side there is no charge. Nature does not permit charge to vanish into thin air, so there must be more to the equation. Note that the mass numbers are conserved, keeping Mother Nature happy in this respect. What is needed is the addition of a species having a mass number of zero and a charge of plus one to the right side of the equation. Enter the positron, ${}^{o}e^{+}$, which is a positively charged electron—a piece of antimatter. So now we can write Equation 2 more correctly as:

$${}^{1}p^{+} \rightarrow {}^{1}n^{o} + {}^{o}e^{+} \qquad \text{(Equation 3)}$$

Now charge and mass number are conserved and mother nature is happy with one small and subtle reservation. Nature also requires momentum to be conserved. If a positron goes flying out of the system (Equation 3), there must be something that flies out in the opposite direction, since it has been determined that the positron momentum is not balanced by recoil of the proton. Enter another weird species in the sub-atomic zoo, the neutrino, which is represented by the symbol ν_c. More is said in the Student Text "Models in Science" about neutrinos, since they have perplexed physicists for sixty years. Suffice it to say that we now have a reasonably good understanding of the necessity of adding positrons and neutrinos in Equation 1.

The next step in the so-called proton-proton cycle that fuels the sun is the collision of another proton with the deuteron formed in Equation 1 to produce a helium nucleus containing 2 protons and one neutron, i.e., ${}^{3}He$.

$${}^{1}H + {}^{2}D \rightarrow {}^{3}He + \gamma \qquad \text{(Equation 4)}$$

The symbol γ represents a gamma ray photon. Finally, as the last step, two helium-3 nuclei collide to form helium-4, (${}^{4}He$), and two protons.

$${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\,{}^{1}H \qquad \text{(Equation 5)}$$

The overall net reaction becomes:

$$4\,{}^{1}H \rightarrow {}^{4}He + 2\,{}^{o}e^{+} + 2\nu_c + 2\gamma \qquad \text{(Equation 6)}$$

To this point nothing has been said about the production of photons in this sequence of events, (Equations 1, 4, and 5), with the exception of the gamma ray photon in Equation 4. Equation 6 is the overall net reaction. Photons are important since they are the packets of energy in which the sun's power is manifested and which ultimately work their way outward from the core.

We also need to keep in mind that the hydrogen nuclei (protons) at the core are hydrogen atoms from which electrons have been ripped away (ionized), and that the boiling cauldron of colliding protons is also populated with an immense number of ionized electrons. And therein lies the end of this part of the story. The positrons formed in step 1 and carried through to reaction 6 instantaneously encounter their anti-partners—the electrons—and there ensues a kiss of death, with the particles annihilating each other and producing a flash of radiant energy in the form of additional gamma ray photons.

Of course the positron and the electron both have mass (albeit small). Their combined masses are destroyed completely and turned into energy, according to the Einstein relationship $E = mc^2$. It turns out that mass is actually lost in each of the steps. It all fits together nicely.

The scenario above is called the proton-proton chain and it is by far the most important process for producing the sun's energy, although it is not the only set of reactions that occurs.

Given all of this, you might ask how the prodigious energy production from the sun can arise from the proton-proton chain when the reaction rate is so low? This is especially puzzling when we know that it takes a given proton 14,000 million years to find a "hot" partner. The answer is that there are great numbers of protons available in the sun. Based on the sun's luminosity and the energy released per proton-proton chain event, it can be shown that the number of core reactions occurring every second is about 9×10^{37} and that mass is being consumed at the astounding rate of 4.4×10^{9} kg per second! This mind-boggling number might seem alarming at first glance. Is the sun in danger of running out of hydrogen? No! Absolutely not! Consider the fact that the mass of the sun is almost 2×10^{30} kg. In other words, the sun still has a lot of hydrogen to work with. In fact, over the 4.5 billion years that the sun has shone, only about 0.03% of its mass has been consumed. Not to worry.