The Sun and Solar Wind: A Search for the Beginning

The Nuclear Fire of the Sun

APPENDIX A

The Pre-Twentieth Century Sun

Philosophers and scientists have been intrigued with the sun since the days of Athens and even before. It is hard to imagine ancient cavemen viewing the sun without a sense of awe and wonderment. Over recorded history numerous pronouncements were made about the sun, and up through the 18th century, various crude astronomical measurements on the sun were carried out with varying degrees of accuracy. Also during this time period, remarkable discoveries were being made about Earth itself, most notably about the age of Earth. In the 18th century it was widely accepted that the Earth was 6,000 years old based on biblical history as interpreted by Archbishop Ussher. However, in the latter part of the 18th and then in the 19th century scientific estimates began to appear that pushed the age of the Earth up to almost 100,000 years. These estimates began to cause serious concerns about the means by which the Earth was kept warm for such a long period of time. For a while it was assumed that the Earth was formed as a molten ball of rock that was slowly cooling down. But calculations, most notably those by Newton, showed that even if the Earth were formed as a hot molten ball of iron it would cool to its present temperature in 50,000 to 75,000 years. The question of Earth's warmth remained a central problem for all of the 19th and part of the 20th centuries.

In the 1800s the problem was further complicated by the advances of geology coupled with the appearance of Darwin's theory of the origin of species, which was published in 1859. It was becoming increasingly clear that the geological processes that have shaped the Earth and the time required for evolution to have produced life as we know it today required the Earth and sun to be much older than seemed possible based on the models of the Earth that were in use at that time. Clearly something had to give. New intellectual discoveries were needed in order to solve the puzzle.

A piece of the puzzle was provided by the development of the science of thermodynamics during the latter half of the 19th century. Of particular importance was the development of the concept of heat and the idea that energy in its various forms could be quantified. With these new ideas in hand some individuals began to wonder about the energy of the sun—where it comes from, how long has it been there, and how long will it last. Of paramount importance was the realization that chemical energy in any form was insufficient to keep the sun going for more than several thousand years. The sun was not a cooling hot ball of iron, nor was it a gigantic globe of burning coal. So, if chemistry could not do it, what could the solar physicists of the day turn to? It was clear that a source was needed that would function for millions and millions of years and provide energy in the form of heat.

The source that attracted a large following for many years centered on the concept of gravity. Initially it was proposed that the sun could be fueled by meteors falling into it from outer space. This idea was simple and it had great initial appeal. If a meteor fell into the sun by virtue of the sun's immense gravitational attraction, the kinetic energy (1/2 mass x velocity^2) of the meteor would be converted to heat when the meteor collided with the sun, thus heating both the sun and the remains of the meteor. Upon further consideration, however, it was realized that this proposal fell short because there simply were not enough meteors available to do the job, nor was there evidence for the consequent sizeable increase in solar mass. Lord Kelvin (William Thomson), who was a leading researcher of the day and a major contributor to the science of thermodynamics, even proposed that the sun was kept hot through consuming whole planets, thus releasing their gravitational energy upon impact with the sun. This proposal also fell short upon closer inspection, and it was concluded fairly quickly that the meteoric idea and its modifications were not the solution to the problem. Nevertheless, the idea that gravitation played a key role in maintaining the sun's energy output was too attractive to be dropped by many, perhaps because there were no other ideas that were more reasonable at the time. For example, in 1854 Helmholtz proposed that the sun was gradually contracting and was thus converting gravitational energy into heat. Helmholtz also suggested that the sun initially was divided into small rock-like pieces or even dust-like particles that were spread out in space. These bits of matter fell inward to what is now the sun's position, releasing their huge gravitational energy upon colliding to form a very hot molten ball. Calculations showed that this hot ball would possess enough stored energy to provide no more than 10 million years or so of solar output at current rates. Based on his continued studies of heat flow, the age of the Earth, and the output of a gravitationally energized sun, Kelvin declared in 1897 that the age of the Earth and sun was 24 million years. This figure remained in direct conflict with evolutionary biology and historical geology, both of which required a much greater age for the Earth and, by implication, the sun. It is ironic to note that Kelvin, although dogmatic in stating the correctness of his calculations, hinted that new laws of physics might someday resolve the problem. It would be another 30 years before these new laws and phenomena were discovered and applied to the problem of the energy output and the age of the sun.

Twentieth Century Developments

With the 20th century came the beginnings of the atomic era. At the very end of the 19th century, x-rays were discovered, the Curies discovered radioactivity in uranium minerals, and evidence that atoms can be subdivided was announced. Alpha particles (helium atoms that have lost both their electrons) were identified, as were beta rays, which were later shown to be fast moving electrons. It was established that radioactivity results from the transformation of atoms of one type of element into atoms of a different element. It was further learned that elements release energy through their radioactivity. In fact, in 1903 a calculation appeared in which it was shown that 3.6 grams/m^3 of radium in the sun would provide all of the heat being produced at the solar surface. (Note: Heat from radioactive sources is often used as a power source in modern day spacecraft.) It should be noted, however, that there is no spectroscopic evidence for the existence of radium on the sun in this quantity.

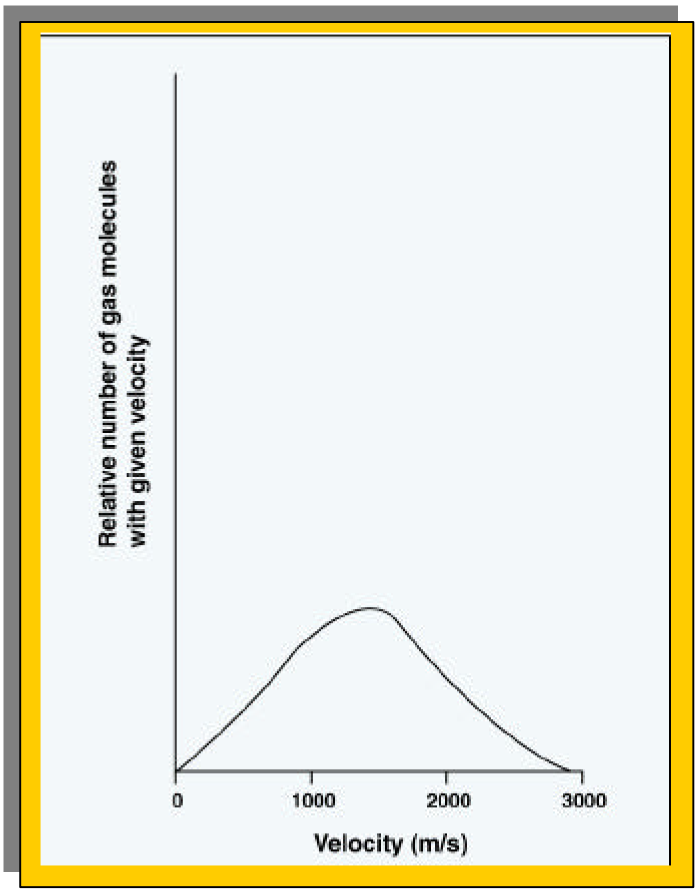
The discovery of radioactivity led rather quickly to another challenge to Kelvin's estimate of the age of the Earth, since studies of the half-life of uranium in rocks showed that the Earth must be at least a billion years old. By the 1920s it was widely accepted that Kelvin's estimate was simply wrong and that the Earth was a few billion years old (current estimates are that the solar system formed around 4.5 billion years ago).

Against this background was the proposal by Einstein in 1905 that energy and mass are equivalent, as expressed through the now-famous equation: $E=mc^2$. It became tantalizingly clear that the atom was the key to an understanding of energy production in the sun and other stars. Armed with the new physics and isotopic masses, physicists including Arthur Eddington, Hans Bethe, Carl von Weizacker, and others in the 1920s and 1930s, firmly established that the sun's reservoir of energy is sub-atomic in nature, thus sealing the fate forever of Kelvin's contraction theory. This also marks the point at which the current Standard Model of the Sun began to take shape, a model in which protons collide within the core, fuse together, and ultimately produce helium along with energy in the form of photons. Nevertheless, there remained in the 1920's a significant dilemma for the astrophysicists to solve. The kinetic energy of the particles in the sun at the temperature Eddington calculated based on mass and luminosity considerations was too low for nuclear interactions (fusion) to occur. The sun simply was not hot enough to boost the velocity of the protons sufficiently for them to overcome the strong repulsive forces (electrostatic) that prevent them from approaching each other close enough (10^{-15} m) to fuse together. Yet another revolution was needed, the heyday of physics. That revolution turned out to be the development of the quantum theory and an understanding of the "weird" physics of subatomic particles.

Two important quantum physics concepts arose in the 1920's with regard to the fusion dilemma. 1. There exists the so-called strong nuclear force, which acts only over extremely short nuclear distances and which, at these distances, can overwhelm the electrostatic forces between like-charged particles such as protons. 2. In the quantum world of sub-atomic particles such as protons and electrons, it frequently is necessary to ascribe wave character to particles. The wave character confers a certain amount of mysterious uncertainty on the particles, since waves by their very nature are spread out and do not occupy a definite volume in the same way that particles do. Armed with these two concepts, it became possible to offer a reasonable scenario for nuclear fusion in the sun's core at "low" temperatures. The idea is first that if the protons can ever approach one another closely enough, the nuclear strong force will overwhelm the electrostatic repulsive force, and second, that if the particles are wavelike in nature, they can "tunnel" into each other, thus allowing the particles to get close enough together for the nuclear strong force to exert itself. With these concepts in hand, it was quickly shown that the energy of the sun might indeed arise from gluing protons together, even though at that juncture the chemical composition of the sun was still extremely uncertain. It was not until the 1930's that scientists using spectroscopic techniques established beyond a doubt that hydrogen is the most abundant element in the sun. Nevertheless, it should be noted that lack of knowledge about the *exact* composition of the sun continued to be a roadblock to progress. It was not until the 1950's that astrophysicists were able to say with certainty that proton-proton fusion is of utmost importance.

The composition of the sun by modern estimates is: by mass 71% H, 27% He, and 2% other heavier elements; by number of atoms of a given type 91% H, 9% He, and 0.1% other heavier elements. At this point it is useful to recognize that we need to be precise about our language. When we say "hydrogen" it can mean either H atoms or H_2 molecules and context is needed to make the meaning of the word clear. In the case of the sun's core this is slightly more complicated because neither neutral hydrogen atoms containing a single proton in the nucleus with the accompanying orbital electron, nor hydrogen molecules are present. Rather at the hot, violent core atoms are ripped apart into their constituent parts-protons, electrons and other bare atomic nuclei. So, when we refer to "hydrogen" in the core we really are talking about ionized H, which is of course a bare proton, represented by the symbol p. It is these protons that fuse together with the release of energy.

Figure 1



Of course a question immediately arises: "What keeps the sun from exploding when all of those hydrogen nuclei (protons) collide and fuse together?" Or to put it another way "How has the sun managed to ration its supply of hydrogen nuclei in such a way as to preserve most of them for millions of years?" The answer to this question is readily available since the core, like the rest of the sun, can be regarded as a gaseous body and analyzed according to the principles of the Kinetic Molecular Theory of Gases, which is well understood. In this model the temperature of a moving gas particle is directly proportional to its velocity squared. Also, according to this model there is a bell-shaped statistical distribution of particle velocities in a sample of a gas, as shown in Figure 1, where the abscissa might represent either particle velocity or particle temperature.

It should be clear that in a sample of gas a few particles are almost motionless, while another few particles are moving at extraordinarily high velocities. In other words some particles are cold (slow moving) and others are extraordinarily hot (extremely fast moving). However, as indicated by the shape of the curve, the largest fraction of particles has a specific velocity that corresponds to the average temperature of the sample. So in the sun's core, even at its average "low" temperature, there are present a relatively few extraordinarily hot protons that are moving with much higher velocities than the "average" proton. It is only these few speed demon protons that can muster enough kinetic energy to tunnel through the electrostatic repulsion barrier and fuse together, initiating the chain of events that ultimately provides the energy that emanates from the sun's core. The average proton simply does not have enough energy to tunnel through the barrier and fuse with a collision partner. In other words the vast majority of collisions do not lead to a fusion event.

In the mid 1930s, after the discovery of the neutron in 1932 and the construction of machines that could accelerate particles, fusion reactions were demonstrated in earth-bound laboratories and the essential correctness of the theoretical predictions regarding fusion in the sun was established. It is now estimated that at core temperatures, only one proton in 100 million is hot enough to fuse during a collision. Or putting it another way, the reaction rate is so very slow that a specific proton would require 14,000 billion 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 a fusion partner.

So, what are the details and consequences of this rare event? First, as said above, two exceedingly "hot" protons, which, remember, are hydrogen ions, 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:

$$^{1}H + {}^{1}H \rightarrow {}^{2}D + {}^{0}e^{+} + \nu_c \qquad \text{(Equation 1)}$$

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 the neutrino, since it has 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, which is required to balance energy. 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 equations 4. Equation 6 is the overall net reaction. The photons are the packets of energy in which the sun's power is manifested and which ultimately work their way outward from the core.

If we keep in mind that the hydrogen nuclei (protons) at the core are hydrogen atoms from which electrons have been ripped away (ionized), we recognize that the boiling cauldron of colliding protons is also populated by an immense number of ionized electrons. And therein lies the end of this part of the story. The positrons formed in Step1 instantaneously encounter their antipartners—the electrons—and there ensues a kiss of death, with the particles annihilating each other and producing a flash of pure energy in the form of gamma ray photons.

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

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 $E= mc^2$. Detailed calculations actually show that mass is lost and converted to energy in each of the primary steps and these collective mass losses account for the total energy output of the sun. It all fits together nicely.

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

Given all of this, one can question how it is that the prodigious energy production from the sun can arise from the proton-proton chain when the reaction rate is so low. That is, when it takes a given proton 14,000 million years to find a hot partner. The answer is, of course, that there are a stupendous number of protons available in the sun. Based on the sun's luminosity and the energy released per proton-proton chain event, it is easy to show 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, when one considers the fact that presently 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!

Other fusion reactions

At even higher temperatures other nuclei undergo fusion reactions. Some examples are given in the table below.

Temperature		
$\sim 2 \times 10^{8}\ {}^{0}K$	$\sim 5 \times 10^{8}\ {}^{0}K$	$\sim 10 \times 10^{8}\ {}^{0}K$
<u>He burning occurs</u> $3\,{}^{4}He \rightarrow {}^{12}C + \gamma$ ${}^{4}He + {}^{12}C \rightarrow {}^{16}O + \gamma$ ${}^{4}He + {}^{16}O \rightarrow {}^{20}Ne + \gamma$ ${}^{4}He + {}^{20}Ne \rightarrow {}^{24}Mg + \gamma$	<u>C burning occurs</u> ${}^{12}C + {}^{12}C \rightarrow {}^{24}Mg + \gamma$ ${}^{12}C + {}^{12}C \rightarrow {}^{23}Na + {}^{1}H$ ${}^{12}C + {}^{12}C \rightarrow {}^{20}Ne + {}^{4}He$	<u>myriad reactions occur</u> ${}^{20}Ne + \rightarrow {}^{4}He + {}^{16}O$ ${}^{20}Ne + {}^{4}He \rightarrow {}^{24}Mg + \gamma$ $2\,{}^{20}Ne \rightarrow {}^{16}O + {}^{24}Mg + \gamma$ ${}^{24}Mg + {}^{4}He \rightarrow {}^{28}Si + \gamma$ ${}^{44}Ca + {}^{4}He \rightarrow {}^{48}Ti + \gamma$

Above $\sim 30 \times 10^{8}\ {}^{0}K$ many nuclear processes can occur in profusion.