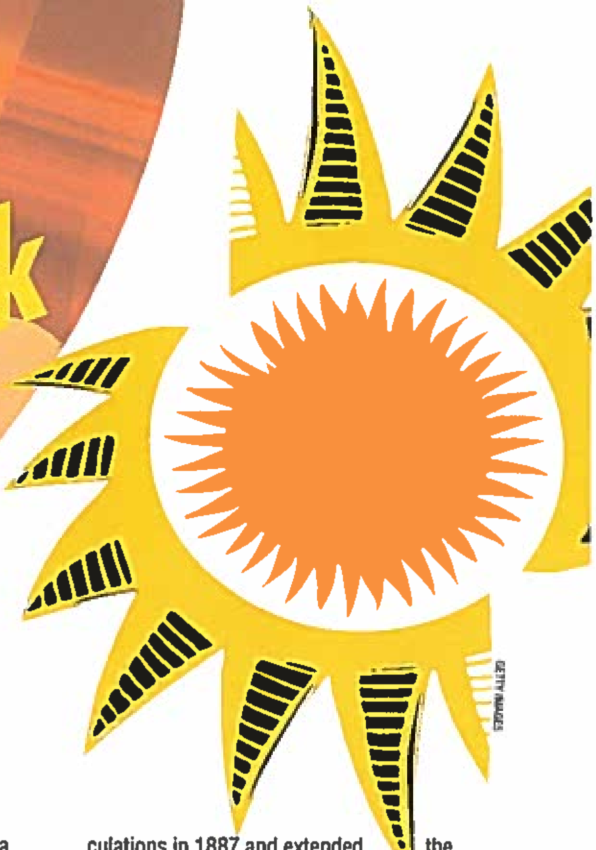
THE SUN

Fusion at Work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By Clair Wood

Throughout the ages, people have worshipped the Sun as the giver of light, warmth, and life. They instinctively knew that the seasons were somehow controlled by the Sun's movements and, from the Neolithic to the Bronze Age, elaborate monuments were built to track equinoxes, solstices, eclipses, and other solar events important to their lives and religious beliefs. The best known, Stonehenge, was built over a period of 1500 years by three separate cultures. The ancients also spent a great deal of time trying to understand the nature of the Sun. What made it work? As civilizations became more sophisticated, elaborate mythologies grew up around the Sun. To the Egyptians, the Sun was Ra, the god of life, who ruled the seasons and day and night. The Greeks named the Sun Helios, who rode his golden chariot across the sky daily and disappeared beneath the waves at night. The Roman's Sun god, Sol, was described pretty much as the Greek's Helios.

Early theories of the Sun

The first attempts to describe the Sun in other than mythological terms were made by the Greeks. Anaxagoras, a Greek philosopher born about 500 BC, described the Sun as a great ball of molten iron, an idea likely stemming from his having observed the impact of an iron-nickel meteorite and thinking it to be a piece of the Sun. He also described the Sun as a mass of blazing metal that had been torn from the Earth and ignited by rapid rotation.

When the theory of chemical combustion came into being through the efforts of Antoine Lavoisier and others in the 18th century, it was soon applied to the Sun. One popular theory was that the Sun was a gigantic chunk of burning coal, but this was quickly seen as unworkable when calculations showed the Sun would burn out in a few thousand years.

In 1854, the German physician and physicist Hermann von Helmholtz proposed that the Sun was powered by the conversion of gravitational energy into heat as it collapsed upon itself under its own weight. He calculated that the Sun's lifetime would be on the order of 20 million years. Lord Kelvin redid the calculations in 1887 and extended the Sun's lifetime to 30 million years if it were producing the observed amounts of energy by contraction. However, geologists insisted the Earth was hundreds of millions of years older than Kelvin's figure, and it made no sense that the Earth could be older than the Sun. Also Darwin's theory of evolution by natural selection required a far older Earth and Sun than accounted for by contraction. By 1900, scientists knew that the contraction theory had serious flaws, but no serious alternative surfaced until decades later.


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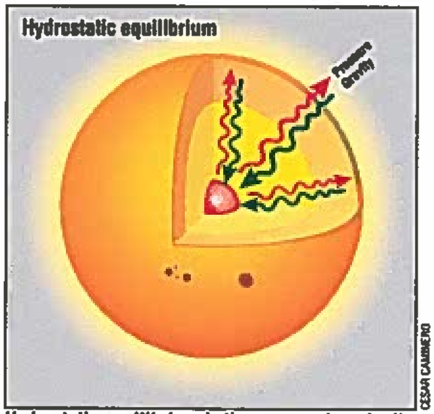
Stonehenge is one of over 40,000 megalithic sites across the British Isles.

Sun's nuclear furnace

It turns out that the contraction theory works up to a point. In young stars, contraction causes heat and pressure to build up. Eventually, both of these build to the point of so-called "nuclear ignition," where the nuclei of hydrogen atoms begin to join or fuse together to form the nuclei of heavier elements. This process releases tremendous amounts of energy—the missing source of energy that was unknown in the 19th century.

Once the nuclear fusion begins, a balance between gravitational contraction and expansion due to heating from fusion is established, which eventually halts contraction. This balance of forces, called hydrostatic equilibrium, keeps the star's volume fairly constant.



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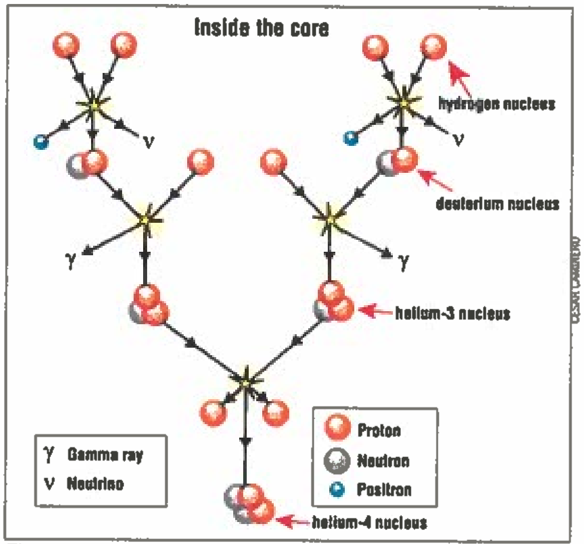
Hydrostatic equilibrium is the reason stars don't implode or explode.

In the case of the Sun, the major element produced is helium. The conditions at which the natural repulsive forces of positive nuclei can be overcome and forced to join together are tremendous. Here are a few facts about the Sun to show the conditions that bring about the nuclear fusion or "burning" of hydrogen to helium. The Sun has a radius 109 times that of the Earth and weighs about 333,000 times as much or roughly 2×10^{27} tons. Over 1.3 million Earths would fit into it. The Sun makes up nearly 99.8% of the mass of the solar system with Jupiter making up most of the rest. As impressive as its mass is, it is the Sun's temperature and pressure that caused nuclear fusion to begin in the core of the Sun. The temperature at the core is estimated to be 15.5 million Kelvin. Sir James Jeans, British physicist and astronomer, in his book *The Universe Around Us*, writes that a pinhead at this temperature would radiate enough heat to kill a man 100 miles away! The core pressure is about 230 billion times standard atmospheric pressure on Earth at sea level.

In 1938 German-American physicist Hans Bethe and others determined that the conditions in the core of the Sun were sufficient to fuse smaller nuclei together into larger ones. Bethe initially proposed that a chain of events brought about fusion: Four hydrogen nuclei fused to form a helium nucleus, involving carbon, nitrogen, and oxygen as intermediates. Later, American physicist Charles Critchfield showed that the pathway proposed by Bethe actually did not occur to a significant extent in the Sun's core. It is simply not hot enough. Instead, the nuclei fuse directly in what is known as the "proton-proton" fusion cycle.



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The proton-proton fusion cycle.

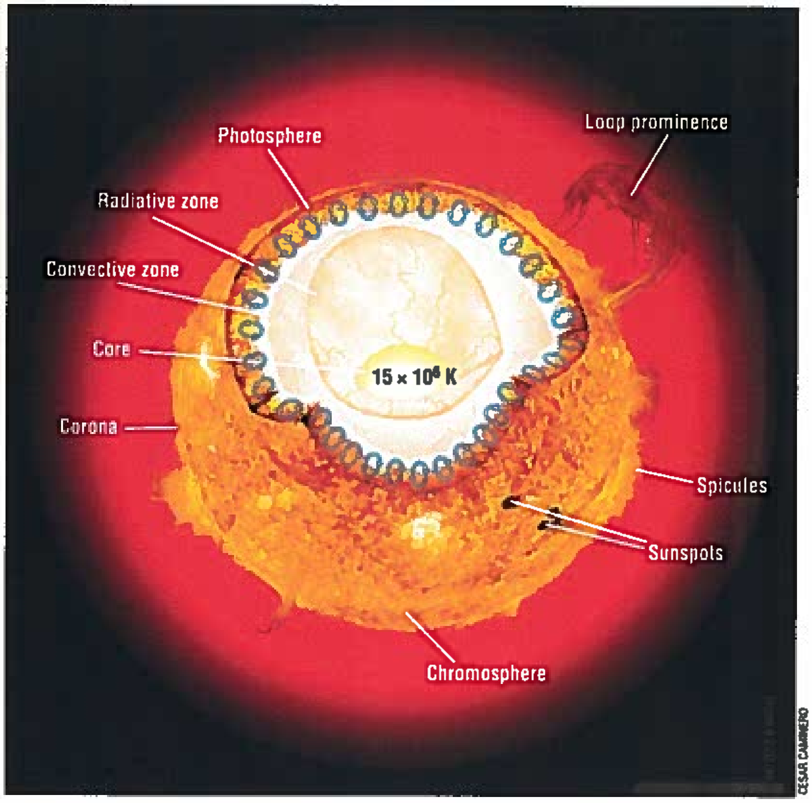
The fusion cycle begins when two protons, or hydrogen nuclei, collide to form a nucleus of deuterium (^2H). This fusion is accompanied by the conversion of a minute amount of mass into energy—a lot of energy. In fact, it is enough energy to cause one of the protons to be converted into a neutron, releasing energy in the form of a positron (●) and a neutrino (ν). The positron annihilates an electron, and two gamma rays (γ) are created (this is omitted from the figure for clarity). The deuterium combines with another proton forming a helium-3 nucleus (^3He), releasing a gamma ray in the process. Then two ^3He nuclei fuse together to form a normal helium nucleus (^4He), ejecting two protons, which start the process over again.

The proton-proton cycle described by Bethe does take place in larger stars and, to a minor extent on the Sun. In 1967, Hans Bethe was awarded the Nobel Prize in physics for his discoveries of how energy is produced in the stars. It has been calculated that the high-energy gamma rays produced in this reaction take millions of years to find their way out from the core of the Sun because of repeated scattering. Each collision reduces their energy, and they finally emerge from the Sun's surface in the form of light and heat.

Spectroscopy reveals that the Sun is made up of hydrogen (73.5%) and helium (24.8%), with the remainder being only a smattering of the elements oxygen, carbon, neon, nitrogen, magnesium, iron, and silicon. It is interesting to note that helium was discovered on the Sun before it was found on Earth. In 1868, British scientist and astronomer Norman Lockyer found the spectral lines of an unknown element in the Sun's spectrum and named the element helium after the Greek god Helios. In 1895, William Ramsey, the Scottish chemist found helium in the mineral uraninite and verified that it had the same spectrum as the element Lockyer observed on the Sun.

Tiny mass loss, huge energy gain

The end result of the proton-proton pathway is that four hydrogen nuclei are fused together to form helium accompanied by the loss of a small amount of matter and the release of a tremendous amount of energy. The Sun converts 564 million tons of hydrogen to 560 million tons of helium every second with the equivalent of 4 million tons of mass being transformed to energy. If the mass loss is substituted into Einstein's famous equation for the relationship between mass and energy, $E = mc^2$, (where c is the velocity of light), a fantastic amount of energy results. Even the conversion of a tiny amount of mass releases a gigantic amount of energy, as the equation requires the speed of light, 3×10^8 m/s, to be *squared*! The complete conversion of an object with a mass of 1 gram would release 90 trillion joules of energy. That is roughly equivalent to the energy released in the explosion of 20,000 metric tons of TNT.



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According to one author, the energy output in one second by the Sun would supply the entire energy consumption by the United States for 1 million years.

Luckily, only one two-billionths of the Sun's energy reaches the Earth. Otherwise, we would all be cooked to a cinder! Even though the Sun is losing mass at a rate of 4 million tons per second, it is so massive that Isaac Asimov, in *Asimov's Guide to Science*, estimates it has lost only 1/40,000 of its mass since it became a star. The Sun has been around for at least 5 to 6 billion years, and it will last for at least as long again before entering its death throes as a red giant expanding in size to beyond the orbit of Earth, which will be vaporized. Finally, the dying Sun will cool, collapse, and eventually become a white dwarf.

Sun's structure

The Sun consists of its core where nuclear fusion takes place and regions of gaseous layers collectively known as the solar atmosphere. The regions are differentiated by the various processes that take place in them.

Core

The core is essentially a fusion reactor that is stabilized by gravity. Immense amounts of energy are generated as hydrogen is converted into helium. Helium has an average atomic mass of 4.0026 amu, and the atomic mass of hydrogen is 1.0079 amu. Four hydrogen atoms taken together have a mass of 4.0316 amu. This 0.029 amu difference is the m in Einstein's equation $E=mc^2$. The almost incomprehensible energy released drives the temperature in the core up over 15 million Kelvin. As temperature is related to the kinetic energy of the particles, these particles have a tremendous amount of energy and are moving very fast. Under the extreme pressure in the core, these high-velocity particles slam into one another and become fused. The energy generated is spread outward by radiation and convective fluid flow.

Radiative zone

Right above the core lies the radiative zone. The energy generated in the core is transported by light (photons) through this zone by radiation. The photons undergo countless absorption and emission processes being randomly scattered in the process. This action, known as the "random walk process," results in its taking up to a million years for a photon generated in the core to reach the surface of the Sun. Once free of the Sun, a photon reaches Earth in less than nine minutes.

The radiative zone includes the inner approximately 85% of the Sun's radius, so technically it includes the core.

Convective zone

The method of energy transport that characterizes the convective zone is, you guessed it—convection! Energy is transported via rising and falling gas that extends from a depth of about 200,000 km up to the visible surface. Sunspots and other solar phenomena are generated here.

Photosphere

Next comes the photosphere, a shell of gas about 100 km thick with a temperature of 4500 K to 6000 K. The photosphere is where the solar absorption spectrum, i.e., "what you see," is produced when observing the Sun. This is also where sun spots, cooler regions of the solar atmosphere at a temperature of approximately 4000 K and associated with intense magnetic fields, are located. The surface of the photosphere appears to be granulated because convection produces cells of gas moving at speeds up to 15,000 miles per hour. They rise up from the interior in the bright areas, spread out along the surface, and then sink inward as they cool.

Chromosphere

The chromosphere is a thin, pink layer of gas seen only during a total solar eclipse when the Moon blocks the photosphere. It reaches a depth of over 6,000 miles and varies in temperature from 6000 K at its boundary with the photosphere to 20,000 K at its upper edge. The chromosphere is the origin of prominences, filaments of gas projecting from the Sun to heights of 15,000 miles, and spicules, which are streams of extremely fast-moving streams of gaseous matter erupting outward along magnetic lines of force.

Corona

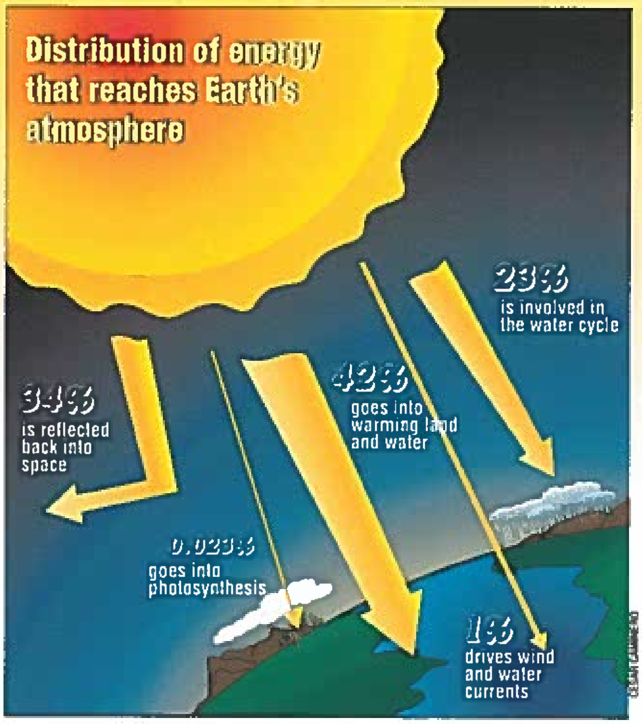
The corona consists of diffuse charged particles, or plasma, that extends for millions of miles into space and has a temperature range of between 500,000 K to 2 million K. At these high temperatures, both hydrogen and helium are completely stripped of their electrons. Even the minor elements carbon, nitrogen, and oxygen are stripped down to bare nuclei. Only the heavier trace elements, like iron and calcium, are able to retain a few of their electrons in this intense heat. This is where the plasma comes from. The rise in temperature here is worth noting because, normally, as you move away from a source of heat, the temperature decreases. The core is about 15 million K, and as you move outward, the temperature drops to about 6000 K in the chromosphere. Then the temperature shoots through the roof in the corona. The cause of the extreme temperatures is a mystery but is thought to be linked to electric currents generated by intense magnetic fields and the Sun's rotation.

Sun-Earth interactions

The Sun interacts with the Earth by several means other than that of providing warmth and light through electromagnetic radiation. The solar wind is a stream of charged subatomic particles, mostly protons and electrons that flow from the Sun at speeds of over 2 million miles per hour. Solar flares are intense, relatively short, bursts of matter and energy, likely due to the sudden release of magnetic energy in a small volume of the solar corona.

Coronal mass ejections (CMEs) are associated with solar flares and are described as gigantic magnetic bubbles. They can contain between 5 and 50 billion tons of ionized gases, breaking from the surface of the Sun with energy equivalents of up to 2 billion megatons of TNT, hurling charged particles toward Earth at speeds of over 2 billion miles per hour (1/3 the speed of light). Besides wreaking havoc with electronics, they are behind the production of spectacular auroras or Northern and Southern lights. Another area of the Sun's internal workings that have been studied a great deal are sunspots. Sunspots are regions of the photosphere that are about 2000 K cooler than their surroundings. They arise from the twisting and tangling of magnetic lines of force, much like tangling strands of string that eventually break through to the Sun's surface. Sunspot activity seems to run in 11-year cycles that range from peak activity to quiet and back again. We are presently near the low-point of the current cycle. For reasons not fully understood, the solar cycles appear to have an effect on Earth's weather. An example is the Maunder Minimum, a time of little to no sunspot activity during 1645–1715 that was concurrent with the "Little Ice Age," a period of extremely cold weather in Europe and North America from the late 1600s to early 1700s.

A report issued in March 2006 by the National Center for Atmospheric Research (NCAR) predicted that solar storm activity will increase starting in 2007 and last until 2012. During that period, we can expect occasional disruptions in cell phone service, TV signals, and global positioning systems, as satellites may incur damage. Power surges may cause power grids to crash causing major blackouts.



Using solar energy

The amount of radiant energy reaching the Earth's atmosphere per unit area per second is called the solar constant, and it averages about 1370 joules per meter squared per second ($1370\ \text{J/m}^2 \cdot \text{s}$). The Earth's surface does not get the full benefit of this energy influx, which is roughly distributed as follows: 34% is reflected back into space by snow and clouds, 42% goes into warming land and water, 23% gets involved in the water cycle of evaporation and precipitation, and 1% drives the wind and ocean currents. An estimated 0.023% goes into photosynthesis that is ultimately responsible for life on Earth. Even though only a miniscule fraction of the Sun's total energy output reaches the Earth's surface, it still represents an impressive amount of energy.

Photovoltaic cells generate electricity directly from sunshine, without generating greenhouse gases in the process. In October 2006, the Australian government announced its plans to build the world's biggest solar power station. It will use high-performance solar cells that were originally developed to power space satellites. Fields of mirrors will concentrate and focus sunlight onto the cells in this 154-megawatt (MW) power station.

When most people think of solar power, roof top panels come to mind, but in California and other states, there is another type of solar power plant. The solar energy generating system (SEGS) uses a solar thermal system instead of photovoltaic cells. The system is based on a parabolic trough of curved mirrors connected in a huge array. A closed-loop tube filled with oil is warmed by the Sun and then passes through a heat exchanger, creating steam, which turns a turbine. The turbine generates a staggering 350 MW of electricity, making it the largest solar power system of any kind in the world.

Making use of this energy is not an easy task, but advancements are being made. In certain parts of the United States, solar energy is price competitive with fossil fuels. Consider the words of Thomas Edison when he said "I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait till oil and coal run out before we tackle that." If we can harness the massive amount of power coming from our nearest star, we just may see the Sun set on fossil fuels in our lifetime. ▲

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