Solar Fusion

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for the BDAS Astronomy Course
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Sources

Books


Simon Singh, Big Bang, Fourth Estate, 2004

Web Sites

Solar Heliospheric Observatory SOHO
http://sohowww.nascom.nasa.gov/

Ulysses Solar Polar Explorer
http://ulysses.jpl.nasa.gov/index.html

University Corporation for Atmospheric Research UCAR
Windows to the Universe, at http://www.windows.ucar.edu/

Stanford Solar Centre
http://solar-center.stanford.edu/

Los Alamos National Laboratory Chemistry Division
http://periodic.lanl.gov/default.htm

Web Elements
http://www.webelements.com
Introduction

For most of human history, people have taken the Sun to be an inexhaustible source of heat and light. That fact that it must be consuming energy to produce its radiant output was, for a long time, unthinkable.

The principle of conservation of energy emerged during the industrial age. *Energy cannot be created or destroyed. It can only be transformed from one form to another.* The question of how the Sun produced heat and light then became a serious enquiry for which rational answers were sought.

By the early 1800s, geologists had established that plants and animals had been living on Earth for millions of years. This led to the realization that the Sun’s fire could not be ordinary. Its rate of energy production was known. If the Sun were burning combustible material in air, its fuel supply would be exhausted in a few thousand years.

Other explanations were sought. Contraction of the Sun’s matter by gravity releases heat and light. The Sun’s mass was sufficient for that mechanism to generate heat and light for around a hundred million years.

But geologists and palaeontologists were uncovering evidence that indicated the Earth was billions of years old. The nature of the process that enabled the Sun to shine for such an extraordinary length of time was major unsolved problem at the turn of the 20th century.

The solution lay in an understanding of the incredible energies bound up in the nuclei of atoms*. To understand how the Sun works, we must first understand a little about atoms.

*In the forty years between 1895 and 1935, atomic physicists made an astounding series of discoveries that set the stage for the modern world. Matter and energy were found to be related. Nuclear fission and fusion were discovered and understood. Tools for probing atoms and nuclei were sought – cathode ray tubes, X-ray generators, mass spectrometers and particle accelerators were developed. Medical X-ray machines, fluorescent lights, radio valves and television tubes were among the spin-offs that ushered in the electronics age. Crystallography was developed to gain insights into the arrangement of atoms and molecules in materials – that led eventually to the discovery of DNA. Procedures for dating rocks by radioactive decay were developed. Astrophysicists were able to frame testable hypotheses. The processes by which nuclei are synthesised in stars were charted. The life cycles of stars were elucidated. How the primordial universe generated matter became knowable. Cosmologists were able to frame and test rational hypotheses about the origin of the universe.*
Atomic Structure of the Elements

There are 92 naturally occurring elements, ranging from hydrogen (H), the lightest, to uranium (U), the heaviest. Among the others are: Helium (He), Carbon (C), Nitrogen (N), Oxygen (O), Chlorine (Cl), Sodium (Na), Aluminium (Al), Silicon (Si), Sulphur (S), Iron (Fe), Copper (Cu), Silver (Ag), Gold (Au), Mercury (Hg) and Lead (Pb).

Each of the elements has a definitive atomic structure – they can be arranged, according to their structural similarities, into a periodic table such as below. Note the elements heavier than Uranium in the table – they have been synthesised in nuclear reactors and atomic accelerators.

An atom has a compact positive nucleus surrounded by a diffuse shell of negative electrons.

The nucleus contains both protons with positive charges and neutral particles, neutrons.

A proton’s charge is equal, but opposite to the negative charge of an electron.

Atoms have equal numbers of protons and electrons. The two sets of charges balance out – intact atoms are neutral.

Protons and neutrons are of a similar size and mass and are quite heavy. Electrons are much smaller and have a minute mass, 1/1800 that of a proton.
The positively charged protons in a nucleus attract an equal number of negatively charged electrons to form an atom. Quantum restraints prevent electrons from spiralling into the nucleus – they settle into orbitals, a considerable distance from the nucleus. Rapidly moving electrons enclose the nucleus in cloud-like shells that give atoms their size.

At inter-atomic distances, protons repel each other by electric force.

If protons are forced to within nuclear distances, an attractive atomic force, strong enough to overpower the electric repulsive force begins to act and binds the protons into a nucleus.

When protons are brought together, the repulsive force struggles against the binding force, stressing the protons. The tension is released when some of them shed charge and transform into neutrons by ejecting electron-sized, positively charged particles called positrons.

To force free protons into a nucleus requires extraordinarily high temperatures and pressures. Such conditions are found in the cores of stars.

Hydrogen is the simplest atom. Its nucleus has only a proton. The nuclei of all other atoms have both protons and neutrons.

Atoms with the same number of protons and different numbers of neutrons are called isotopes.

Hydrogen forms three isotopes. Hydrogen (¹H) has one proton in the nucleus. Deuterium (²H) has a proton and a neutron. Tritium (³H) has a proton and two neutrons.

The number of protons in an atom is called the atomic number of the atom. Every element has a unique atomic number. Hydrogen has an atomic number of 1.

The total of the protons and neutrons in a nucleus is an approximate guide to an atom’s mass and is termed the atomic weight.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Atomic Number</th>
<th>Atomic Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>hydrogen</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>deuterium</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>tritium</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>
How the Sun Creates Energy

The extraordinarily high temperature and pressure in the cores of stars triggers the fusion of hydrogen into helium. There are two stellar fusion processes:

- The Proton-Proton Chain (PP Chain), which occurs in the cores of small stars.
- The Carbon-Nitrogen-Oxygen Cycle (CNO cycle), which occurs only in larger stars.

In the Sun’s core, the main process is the PP Chain. Each step of the chain produces a heavier particle and releases energy.

The Steps of the PP Process

Step One – produce deuterium

\[ ^1\text{H} + ^1\text{H} \rightarrow ^2\text{H} + \text{positron} + \text{neutrino} \]

positron + electron \rightarrow gamma rays

Step Two – produce light helium

\[ ^2\text{H} + ^1\text{H} \rightarrow ^3\text{He} + \text{gamma ray} \]

Step Three – produce helium

\[ ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2^1\text{H} \]

The end result is the fusion of hydrogen into helium.
The Steps of the PP Process – illustrated

Step One - produce deuterium

The extraordinarily high temperature and pressure in the core of the Sun forces hydrogen atoms together.

The protons coalesce into a single nucleus. A positron is ejected from one of the protons to reduce nuclear stress.

The positron collides with an electron annihilating the particles and producing gamma rays. A deuterium atom (2H) is the result.

A hydrogen atom (1H) combines with a deuterium atom (2H)

Step Two- produce light helium

A light helium atom (3He), with two protons and one neutron, is formed.

A gamma ray is released.

Step Three - produce helium

Two light helium (3H) nuclei combine.

The new nucleus immediately disintegrates into a helium atom (4He) and a pair of hydrogen atoms (1H). The high velocities of the product atoms add to the energy produced by the fusion process.

Note: Steps one and two have to occur twice as often as step three in order to produce the required number of 3He atoms.
The outcome of the PP Chain: four hydrogen atoms fuse to form one helium atom and release an amount of energy.

The four hydrogen atoms that fuel the process weigh slightly more than the helium atom produced. The amount of mass lost is directly related to the amount of energy produced. The relationship is given by Einstein’s equation:

\[ E = mc^2 \]

Where:
- \( E \) is the energy produced
- \( m \) is the amount of mass lost (0.05 \( \times 10^{-27} \) kg)
- \( c \) is the velocity of light (3 \( \times 10^8 \) metres per second)

On substituting the above values, we get

\[ E = 0.05 \times 10^{-27} \times (3 \times 10^8)^2 \]
\[ = 4.5 \times 10^{-12} \text{ joule} \]

A kilogram of hydrogen contains 6 \( \times 10^{26} \) atoms. Dividing by 4 gives the number of helium atoms it would produce: 1.5 \( \times 10^{26} \)
For each atom of helium, 4.5 \( \times 10^{-12} \) joule is released
The total energy released is therefore 1.5 \( \times 10^{26} \times 4.5 \times 10^{-12} = 6.7 \times 10^{16} \) joule

Fusing a kilogram of hydrogen produces 997 grams of helium. The missing 3 grams is converted to heat and light energy. The amount of energy produced is equivalent to that released by burning 100,000 tonne of coal.

The Sun transforms 4.5 \( \times 10^6 \) tonne of matter per second, (equivalent to 4 million car bodies per second). The Sun has been fusing hydrogen for nearly 5 billion years and has enough fuel left to burn for a further 5 billion years.