PLASMAS AND FUSION REACTIONS

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INTRODUCTION

When geologists realized that fossil fuels such as coal and oil are the remains of living matter that existed millions of years ago, the conclusion is that their origin is from the sun, which has been shining steadily for a long time. It is obvious that chemical energy and gravitational potential energy are too small to have kept it going for such a long time. It was obvious that their origin can only be the fusion reactions occurring in the sun and reaching the Earth as solar radiation. The sun is composed primarily of hydrogen at a temperature of 40 million degrees Fahrenheit near its center. These hydrogen nuclei when energized to huge temperatures, act like biological cells and can "fuse" into helium, He^4.
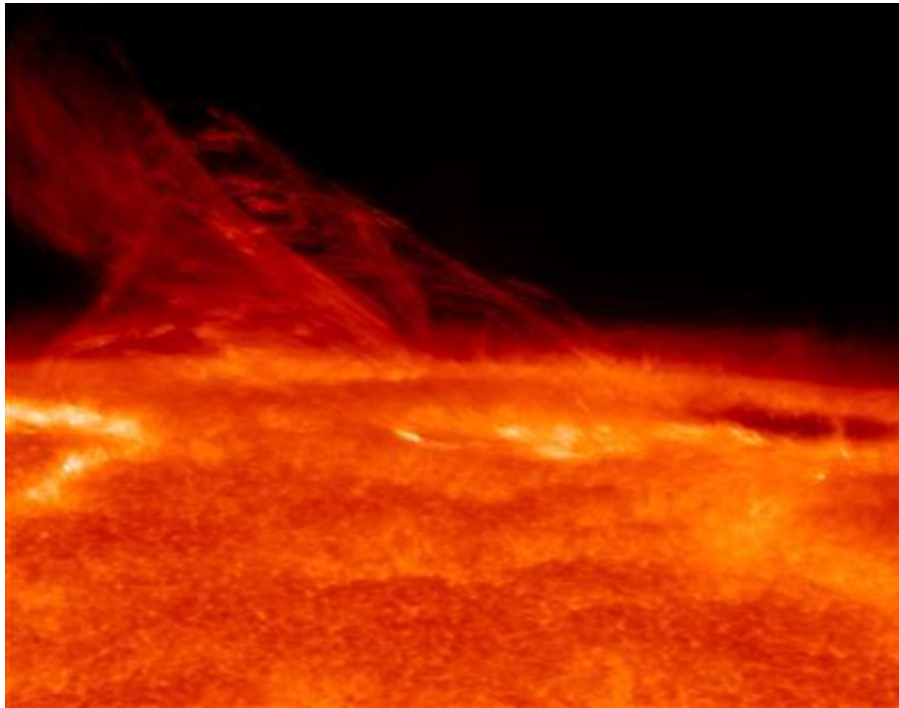

Figure 1. Surface of the sun. Hinode satellite photograph, December 2007. Photo: NASA

The mass of the He nucleus is less than its parts. The difference in mass is made up of energy according to the energy and mass equivalence equation:

$$E = mc^2 \qquad (1)$$

where: E is the energy in [ergs],
           m is the mass in [grams],

c is the speed of light = 3 x 10^{10} [cm/sec].

The subjects of plasmas and fusion are fertile fields of research for engineers, physicists, and applied mathematicians. Recently, the research in plasma physics has been directed toward the possible technological applications, particularly, controlled thermonuclear fusion, as well as ionic propulsion for space flight, direct conversion of heat energy into electricity, and other applications. Some of the problems encountered include the magnetic confinement of plasmas into future devices providing ample energy supplies since they involve the fusion of nuclei of hydrogen ($_1D^2$) and elements (Lithium) that are plentiful in the ocean waters and the Earth's crust. The realization of these fusion phenomena has been achieved in a fast release manner in thermonuclear devices. It has however remained a challenge to build devices that would release fusion energy in a controlled manner.

There seems to be a gap existing between the experimental knowledge and the theoretical knowledge in those fields. As described by the Nobel Prize laureate Alfvèn:

> "Since thermonuclear research started with Zeta, Tokamaks, Stellarators - not to forget the Perhapsastron - plasma theories have absorbed a large part of the energies of the best physicists of our time. The progress which has been achieved is much less than was originally expected. The reason may be that from the point of view of the traditional theoretical physicist, a plasma looks immensely complicated. We may express this by saying that when, by an immense numbers of vectors and tensors and integral equations, theoreticians have prescribed what a plasma *must* do, the plasma, like a naughty child, refuses to obey. The reason is either that the plasma is so silly that it does not understand the sophisticated mathematics, or it is that the plasma is so clever that it finds other ways of behaving, ways which the theoreticians were not clever enough to anticipate. Perhaps the noise generation is one of the nasty tricks the plasma uses in its IQ competition with the theoretical physicists."

As discussed by Peratt:

> "… the Universe is predominantly matter in its plasma state and electromagnetic forces are stronger than gravitation by 39 orders of magnitude. The "missing mass" problem that plagues astronomy at every facet in its size hierarchy may not exist at all when electromagnetism augments gravitation. If the properties of plasma are the same everywhere from the micrometer-dimensioned structures produced in the dense plasma focus, to the Hubble distance, then not only can our knowledge of the Universe be improved, but also a *backflow* of data to laboratory experiments can be expected."

PLASMAS

Langmuir introduced the word "Plasma" in 1928 in a paper on "Oscillations in Ionized Gases." He does not give a motivation for using this word, but it appears he is inspired from medical terminology. He states: "We shall use the name 'plasma' to describe this region

containing balanced charges of ions and electrons." His adoption of this biological term may be related to the behavior of the plasma like a living cell. A plasma is known to protect itself from the environment by a *double-layer* or *plasma sheath*, in the same way that a living biological cell protects itself with a cell wall from its environment.

In its most general sense, as defined by Boyd and Sanderson, "plasma" is any state of matter that contains enough free charged particles for its dynamical behavior to be dominated by electrodynamics forces. The field largely covers ionized gases, even though it encompasses the solid state, where electrons in metals and semiconductors fall under this category. At a very low level of 0.1 percent ionization, a gas achieves an electrical conductivity of 1/2 its possible maximum, and thus exhibits some electromagnetic properties. At 1 percent ionization, the conductivity is at 1/2 its maximum value with significant electromagnetic interaction.

Almost all matter in the Universe can be described as plasma, as shown in Table 1. The sun and the stars are completely ionized, as well as interstellar gas, due to the effect of stellar radiation as shown in Fig. 2.

Figure 2. Different plasma phenomena. Large loop plasma prominences on the surface of the sun, associated with locally intense magnetic fields on the left. A laboratory produced plasma in the middle. A lightning bolt discharge at the right.

The Earth from that perspective is thus a very special situation, where plasma formation is rare, except for transient plasmas generated by lightning occurrences. On the other hand, the Earth's upper atmosphere is ionized, and is known as the *ionosphere*. It was in terms of the plasma properties of the ionosphere that the transmission of radio waves over long distances was first explained. Farther out the Earth's radiation belts known as the Van Allen belts contain electrons and protons trapped from the solar wind by the Earth's magnetic field.

SOLAR WIND

The solar wind is a stream of electrically charged gas mostly composed of hydrogen that blows outward from the sun in all directions at a speed of about a million mph or1.6 million kilometers per hour. The existence of the solar wind was first theorized about a half century ago and its existence was confirmed in the 1970s. It buffets planetary atmospheres. On Earth, it can disrupt satellites, power grids and communications, under certain circumstances. The Earth's magnetic field protects against the solar wind, creating a bubble around which the solar wind flows.

Driving the solar wind are s Alfvèn waves which are strong magnetic waves that ripple through the plasma of the sun's atmosphere, or corona, transferring energy from the star's surface and into the solar wind.

The waves are named after Swedish physicist Hannes Alfvèn, whose prediction of their existence helped earn him a Nobel Prize in physics 1970. He died in 1995.

Two mechanisms appear to power the solar wind. The first involves the way the sun's magnetic field undergoes rapid changes in its shape: as the magnetic field changes shape, it generates Alfvèn waves along its length that accelerate the charged gas and blow it into space. A second mechanism powering the solar wind involves the sun's chromosphere, the region sandwiched between the solar surface and its corona. Images from the Hinode's Solar Optical Telescope found that the chromosphere is filled with Alfvèn waves, which when they leak into the corona are strong enough to trigger the solar wind.

THE EARTH'S RADIATION PROTECTIVE BELTS

In 1958, Van Allen and his coworkers identified the Earth's radiation belts as adiabatic mirror traps generated by the Earth's magnetic field and trapping electrons and protons from the solar wind. The Van Allen radiation is trapped in a toroidal shape region centered around the geomagnetic equator. Were it not for these traps, the solar wind particles would have bombarded the Earth's surface with radiation stripping it of water and consequently of biological life, as is thought to have happened on Mars. Mars possesses only localized magnetic fields associated with local volcanic activity.

Energetic particles injected into the Earth's magnetic field describe helical trajectories from the North Pole to the South Pole called *banana orbits*. In fact they are trapped in a magnetic mirror, reversing their trajectories and getting reflected in the stronger field regions around the magnetic poles. The transit time from one pole to the other is of the order of 1 second. Those particles leaking to the Earth's surface, while rotating around the magnetic field lines, lose their energy by emitting electromagnetic radiation and leading in the northern climates to the Northern Lights or *Aurora Borealis* displays. In the southern hemisphere there are designated as *Aurora Australis*.

Table 1. Plasma Types and their Parameters

Plasma Type	Density, [n cm^{-3}]	Temperature, T [K]	Magnetic Induction, B [Gauss]
Interstellar Gas	1	10^4	10^{-6}
Solar Corona	10^6	10^6	10^{-4}
Ionosphere	10^6	10^3	10^{-1}
Q-plasma	10^8	10^5	10^2
Dense Q-plasma	10^{11}	10^4	10^3
Tenuous, hot plasma	10^{12}	10^6	10^3
Arc discharge	10^{14}	10^4	10^3
Dense, hot plasmas	10^{16}	10^6	10^4
Thermonuclear	10^{16}	10^8	10^5

plasmas			

Figure 3. Northern lights at Traverse City, Michigan, USA and at Norway.

The Explorer I satellite had cosmic radiation detectors on board. These detectors stopped functioning at distances about 700 km and beyond from the Earth. Below 700 km, the detectors started functioning again. Tests showed that the detectors became choked when the radiation level became 10,000 times the level of the cosmic radiation that they were designed to detect. Further tests with the Explorer series of satellites such as Explorer IV and VI, and Pioneer III, as well as by lunar probes, helped establish the morphology of the Earth's radiation belts.

They consist of two zones of high intensity particle radiation surrounding the Earth, with no clear boundary between them. The inner belt is a few thousand kilometers from the Earth's surface, while the outer belt is at 20,000 km away. The particles in the belts are primarily electrons and protons. In the inner belt, the protons have a kinetic energy of 40 MeV and above. Some deuterons and tritons are also present at 1 percent of the proton densities. The energies of the protons trapped in the outer belts are lower at 0.1 MeV to a few MeV. In fact there exists several low energy overlapping proton belts surrounding the Earth, and taking the shape of its geomagnetic field lines. The outer belt of electrons is separate from the protons belts at about a distance of 30,000 km, and possessing kinetic energies above 40 keV.

Project Argus in 1958 exploded nuclear devices at a height of about 650 km to demonstrate the process of the trapping of charged particles in the Earth's geomagnetic field. Electrons from the explosion were injected in the magnetic field of the Earth, and an artificial radiation belt established itself and persisted from a few days to a few weeks. The Explorer IV satellite measured the thickness of these artificial belts at about 40 km. Aurora Borealis displays resulted over the Hawaiian Islands as a result of the charged particles trapping.
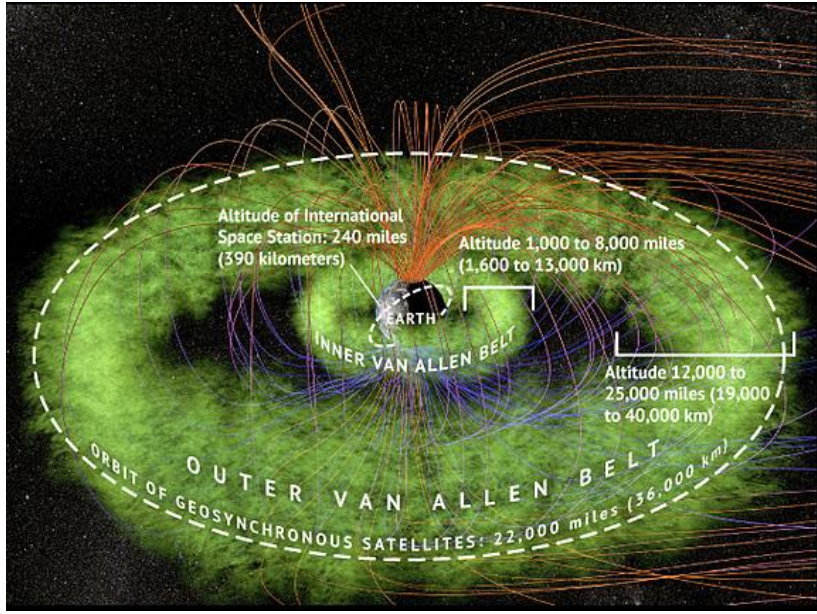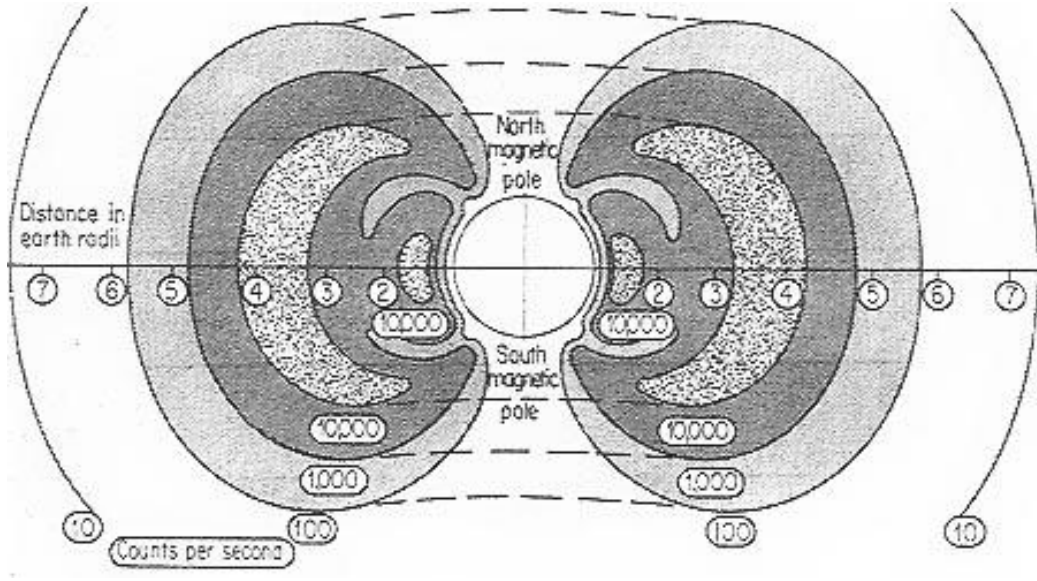
Figure 4. Structure of the Earth's Van Allen Belts, and the charged particles banana orbits between the magnetic poles. Source: NASA.
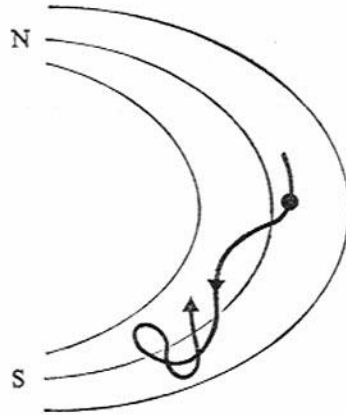
Figure 5. Banana orbits of charged particles trapped in the Earth's magnetic field.

In the inner zone, the particle density appears to be constant with time. The radiation intensity in the outer zone can vary by several orders of magnitude depending on solar activity. The particles in the outer belt originate primarily from the sun, and some of those in the inner belt may originate from the decay of neutrons in the upper atmosphere by cosmic rays. The intensity of the particles in the outer zone correlates with major solar flares with duration from 10-100 hours.

Large numbers of protons with energies larger than 10 MeV, and some low energy electrons as shown in Table 2, dominate the radiation environment in the inner belt. In the outer region, electrons with energies less than 1 MeV predominate, with a small number of protons with energies larger than 30 MeV.

The inner zone of the belt has its lower edge at an altitude of 400 km at 300 degrees East longitude, and at about 1300 km at 100 degrees to the east. The energy fluxes in the inner belt are as high as 100 [ergs / (cm^2.sec.streradian)], beneath an absorber of 1 [mg/cm^2] in thickness. Exposure levels of about 10 Roentgens/hr have been observed in the inner zone with equipment shielded by an ordinary structure of low Z material with a thickness of 1 [gm/cm^2].
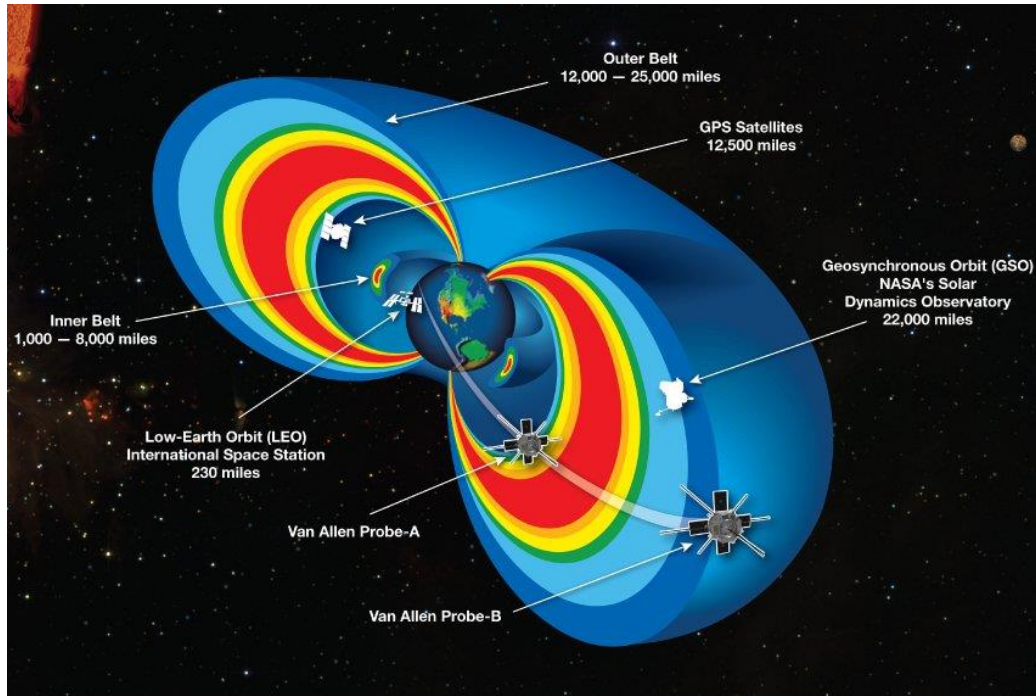
Figure 6. The inner and outer Van Allen belt zones. Source: NASA.

Table 2. Radiation intensities in the Van Allen Belts.

Zone	Particles	Threshold Energy	Intensity, Omnidirectional or Unidirectional
Inner Zone			
	Electrons	>20 keV	2×10^9 [particles/(cm^2.sec.ster)]
Heart: 3600 km.	Electrons	>600 keV	1×10^7 [particles/(cm^2.sec.ster)]
Altitude: 2240-5450 km	Protons	>40 MeV	2×10^4 [particles/(cm^2.sec)]
Outer Zone			
	Electrons	>20 keV	1×10^9 [particles/(cm^2.sec)]
Heart: 16,000 km	Electrons	>200 keV	1×10^9 [particles/(cm^2.sec)]
Altitude: 12,800-19,200 km	Protons	>60 MeV	1×10^9 [particles/(cm^2.sec)]
	Protons	<30 MeV	-

The radiation exposure constitutes a hazard to astronauts on space missions. With a rapid passage through the belt, the radiation dose may be small enough. Any orbits that require astronauts to remain within the inner belt are to be avoided.

The outer belt is primarily composed of electrons of solar origin. The exposure levels are several Roentgens per hour. With a thickness of lead shielding of 4 gm/cm^2, the radiation level can be reduced by a factor of 50.

THE COULOMB BARRIER

It is not easy to transmute the nucleus into another by adding protons to it. It is easier to achieve this with neutrons. The reason is that the projectile protons must have sufficient kinetic energy to overcome the electrical repulsion of the protons in the nucleus. This repulsion acts as a barrier described by Coulomb's law. It states that the repulsion of like particles is proportional to their charges, and inversely proportional to the square of the distance between them. Because the nuclei have small dimensions, the inverse square law requires that the Coulomb repulsion increase to a large value at the distance of approach required for contact between projectile and target, as shown in Fig. 4.

For instance, the uranium nucleus has a nuclear radius of about 10^{-12} cm. The barrier to the approach of protons or deuterons is about 12 million electron Volts (MeV), and to the approach of helium nuclei is 23 MeV. The eV is a unit of energy corresponding to the kinetic energy acquired by an electron as it is accelerated through a potential drop of 1 Volt.

For comparison, a railroad locomotive traveling at 100 miles per hour has a large amount of kinetic energy, but the energy of a single atom of iron is just 0.006 eV. A bullet traveling at 3,000 ft/sec has a large amount of energy, but each atom has only 1 eV of energy. Chemical explosions raise the kinetic energy of the explosion products to a few electron Volts.

The observation here is that the amount of energy required for chemical reactions are minute compared to the energies involved in nuclear reactions. The ratio between the two magnitudes is a factor of one million.
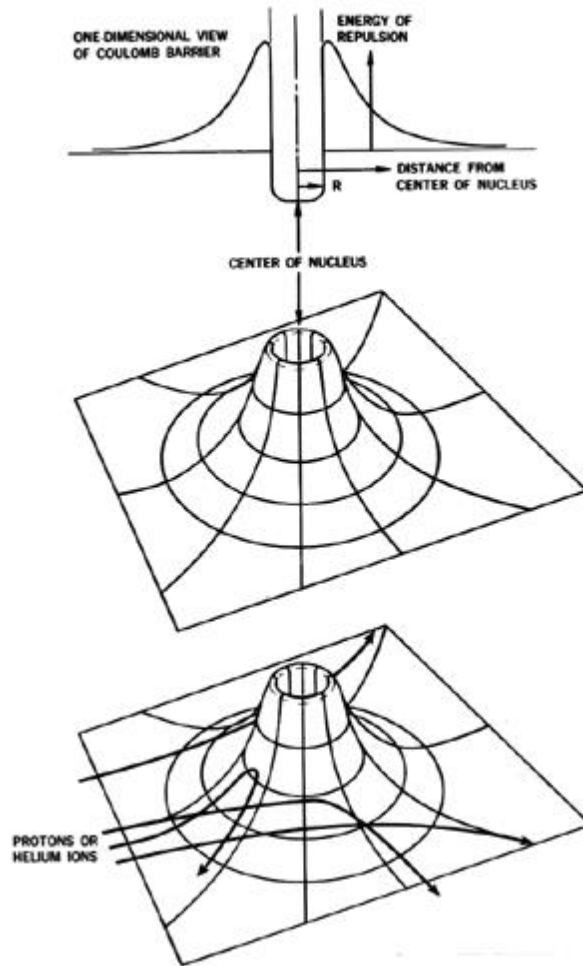
Figure 7. The Coulomb Barrier.

Thus the problem in causing two nuclei to fuse together is that they have to be brought to a close proximity of the order of the nuclear diameter, which is double the radius R, given by:

$$D = 2R = 5 \times 10^{-13} \ A^{1/3} \ [\text{cm}], \tag{2}$$

where A is the mass number of the element.

These nuclei being charged ions, will repel each other through the Coulomb inverse square force F given by:

$$F = \frac{(Z_1 e)(Z_2 e)}{r^2} \ [\text{dynes}], \tag{3}$$

where Z_1 and Z_2 are the atomic numbers of the two nuclei, and e is the electron charge:

$$e = 4.8 \times 10^{-10} \text{ esu(statcoulomb)}$$

If the two nuclei are made to collide head on with enough kinetic energy, they can get close enough for the short-range nuclear force to overcome the potential energy E due to Coulomb repulsion:

$$E = \frac{Z_1 Z_2 e^2}{R_1 + R_2} \text{ [ergs]}, \tag{4}$$

and fusion can occur.
Here R_1 and and R_2 will be the nuclear radii of the two nuclei.
     If we take $R_1 = R_2 = R$, the energy needed to overcome the Coulomb barrier is:

$$
\begin{aligned}
E &= \frac{Z_1 Z_2 e^2}{2R} [ergs] \\
&= \frac{(4.8 \times 10^{-10})^2 Z_1 Z_2}{5 \times 10^{-13} A^{1/3}} \\
&= 4.608 \times 10^{-7} \frac{Z_1 Z_2}{A^{1/3}}
\end{aligned}
\tag{4'}
$$

Since:

$$1 \text{ MeV} = 1.60 \times 10^{-6} \text{ [ergs]},$$

we can write that:

$$
\begin{aligned}
E &= \frac{4.608 \times 10^{-7}}{1.60 \times 10^{-6}} ergs \frac{MeV}{ergs} \frac{Z_1 Z_2}{A^{1/3}} \\
&= 0.288 \frac{Z_1 Z_2}{A^{1/3}} MeV
\end{aligned}
\tag{4''}
$$

     The last equation shows that the energy that the nuclei must acquire to overcome the Coulomb barrier increases with the atomic numbers of the nuclei.
     For the hydrogen isotope $_1H^1$ where $Z_1 = Z_2 = 1$, $A = 1$, the minimum energy, according to classical theory, to overcome the Coulomb barrier is:

$$E_{min} = 0.288 \ MeV$$

     Because of the increased electrostatic repulsion, larger energies would be required to overcome the Coulomb barrier for higher atomic number Z nuclei. This favors light nuclei for fusion reactions.

NUCLEAR BARRIER PENETRATION AND TUNNELING:

Experiments with accelerated nuclei have shown that nuclear reactions can occur at energies far below the energies required by the last equation to surmount the Coulomb electrostatic barrier. The implication is that an underlying quantum mechanical process is at work where the particles behaving as waves can *tunnel* through the nuclear barrier at much lower energies, rather than jump over it as implied by the classical approach. There does not exist a threshold energy determined by the maximum electrostatic repulsion of the interacting nuclei.

The probability of penetrating the nuclear barrier, and consequently the cross section for a given nuclear reaction, is high when the particle's energy is high. It decreases with decreased energy below the height of the barrier, but remains finite at energies much below the height of the barrier.

THE PROTON-PROTON FUSION CHAIN:

Fusion reactions converting hydrogen into helium occur in stars of comparatively small mass like our sun. These are reactions occurring in stars with central temperature of less than 2×10^7 Kelvin. This set of fusion chain reactions is designated as the proton-proton chain. This proton-proton chain was first described by Hans A. Bethe and C.L. Critchfield in 1938. C. C. Lauritsen and William A. Fowler further developed it.

In the main reaction, two protons approach each other with relative ease since a nuclear charge on the protons of $Z = 1$ is involved. If the charge were higher the reaction would go slower at a given temperature, since charges of equal sign repel each other through the Coulomb force, and the repulsion will be larger with higher values of the nuclear charge. Thus the fusing nuclei must approach each other at higher speeds and at higher temperatures when the nuclear charge of the fusing nuclei is larger than for protons. A peculiar property of the proton-proton reaction that slows it considerably at low plasma temperatures is that the two protons come apart after fusing:

$$_1H^1 + {_1}H^1 \rightarrow {_1}H^1 + {_1}H^1 \tag{5}$$

Occasionally, a proton turns into a neutron through the reaction:

$$_1H^1 \rightarrow {_0}n^1 + {_{+1}}e^0 + \nu_e \tag{6}$$

where ν_e represents an electron neutrino, and $_{+1}e^0$ is a positron.

The neutron and a proton can then stick together as a deuteron. The nucleo-synthesis of $_2He^4$ can be attained directly through the reaction:
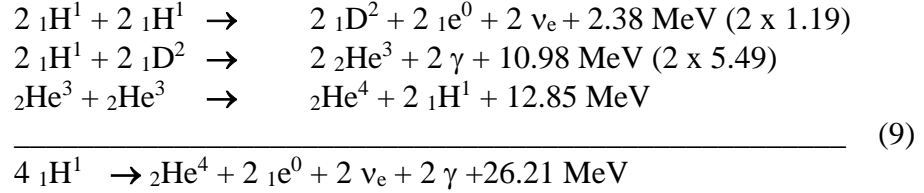
$$_2He^3 + {_2}He^3 \rightarrow {_2}He^4 + 2 {_1}H^1 \tag{7}$$

or another reaction :

$$_2\text{He}^3 + {_2}\text{He}^4 \rightarrow {_4}\text{Be}^7 \tag{8}$$

can occur.

      The relative probability of occurrence of the main reaction and this branch is known from experimental data. There exists a second branch depending on whether $_4\text{Be}^7$ first decays to $_3\text{Li}^7$ through electron capture, or first fuses with a proton resulting in the formation of $_5\text{B}^8$. Whether the main reaction or the two branches are followed, the end result is still the nucleo-synthesis of $_2\text{He}^4$ from protons as building blocks.
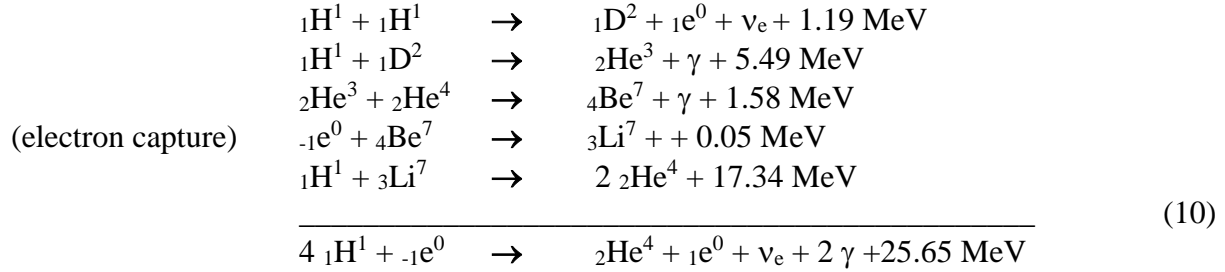
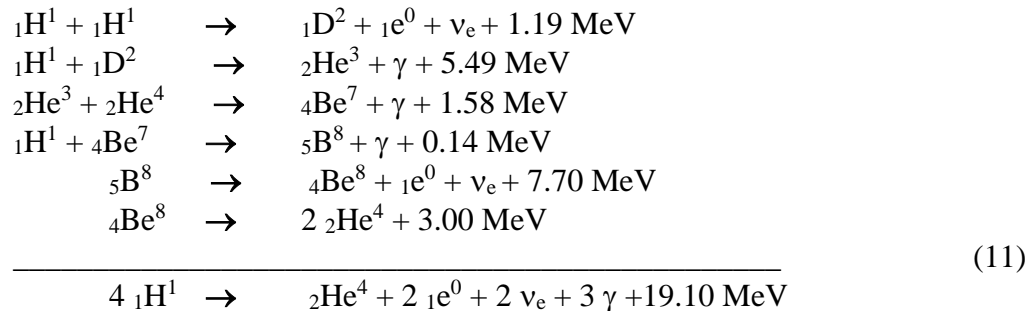   The main reaction in the proton-proton chain consists of a collective of three reactions:

$$
\begin{aligned}
2\ {_1}\text{H}^1 + 2\ {_1}\text{H}^1 &\rightarrow & 2\ {_1}\text{D}^2 + 2\ {_1}\text{e}^0 + 2\ \nu_e + 2.38\ \text{MeV}\ (2 \times 1.19) \\
2\ {_1}\text{H}^1 + 2\ {_1}\text{D}^2 &\rightarrow & 2\ {_2}\text{He}^3 + 2\ \gamma + 10.98\ \text{MeV}\ (2 \times 5.49) \\
{_2}\text{He}^3 + {_2}\text{He}^3 &\rightarrow & {_2}\text{He}^4 + 2\ {_1}\text{H}^1 + 12.85\ \text{MeV} \\
\hline
4\ {_1}\text{H}^1 &\rightarrow & {_2}\text{He}^4 + 2\ {_1}\text{e}^0 + 2\ \nu_e + 2\ \gamma + 26.21\ \text{MeV}
\end{aligned}
\tag{9}
$$

where γ represents a gamma photon.

      In this case $_1\text{D}^2$ and $_2\text{He}^3$ act as nuclear rather than chemical catalysts, since they take part in the nuclear reactions, but cancel out from the left and right hand sides of the overall reaction in Eqn. 9. The end result of the overall reaction is that four hydrogen nuclei are converted into a helium nucleus in addition to other forms of radiation as positrons, neutrinos and gamma photons. In addition, the reaction is exothermic leading to the release of 26.21 MeV as kinetic energy of the reaction products.

      The $_2\text{He}^3$ nucleus can interact in a different way leading to a first branch of the main reaction:

$$
\begin{aligned}
{_1}\text{H}^1 + {_1}\text{H}^1 &\rightarrow & {_1}\text{D}^2 + {_1}\text{e}^0 + \nu_e + 1.19\ \text{MeV} \\
{_1}\text{H}^1 + {_1}\text{D}^2 &\rightarrow & {_2}\text{He}^3 + \gamma + 5.49\ \text{MeV} \\
{_2}\text{He}^3 + {_2}\text{He}^4 &\rightarrow & {_4}\text{Be}^7 + \gamma + 1.58\ \text{MeV} \\
\text{(electron capture)}\quad {_{-1}}\text{e}^0 + {_4}\text{Be}^7 &\rightarrow & {_3}\text{Li}^7 + + 0.05\ \text{MeV} \\
{_1}\text{H}^1 + {_3}\text{Li}^7 &\rightarrow & 2\ {_2}\text{He}^4 + 17.34\ \text{MeV} \\
\hline
4\ {_1}\text{H}^1 + {_{-1}}\text{e}^0 &\rightarrow & {_2}\text{He}^4 + {_1}\text{e}^0 + \nu_e + 2\ \gamma + 25.65\ \text{MeV}
\end{aligned}
\tag{10}
$$

      In the last branch in Eqn. 10, $_4\text{Be}^7$ can interact differently, leading to the following second branch of the main reaction:

$$
\begin{aligned}
{_1}\text{H}^1 + {_1}\text{H}^1 &\rightarrow & {_1}\text{D}^2 + {_1}\text{e}^0 + \nu_e + 1.19\ \text{MeV} \\
{_1}\text{H}^1 + {_1}\text{D}^2 &\rightarrow & {_2}\text{He}^3 + \gamma + 5.49\ \text{MeV} \\
{_2}\text{He}^3 + {_2}\text{He}^4 &\rightarrow & {_4}\text{Be}^7 + \gamma + 1.58\ \text{MeV} \\
{_1}\text{H}^1 + {_4}\text{Be}^7 &\rightarrow & {_5}\text{B}^8 + \gamma + 0.14\ \text{MeV} \\
{_5}\text{B}^8 &\rightarrow & {_4}\text{Be}^8 + {_1}\text{e}^0 + \nu_e + 7.70\ \text{MeV} \\
{_4}\text{Be}^8 &\rightarrow & 2\ {_2}\text{He}^4 + 3.00\ \text{MeV} \\
\hline
4\ {_1}\text{H}^1 &\rightarrow & {_2}\text{He}^4 + 2\ {_1}\text{e}^0 + 2\ \nu_e + 3\ \gamma + 19.10\ \text{MeV}
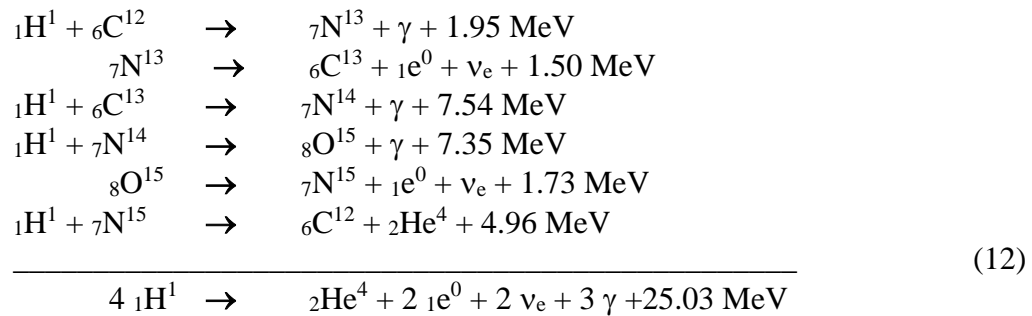\end{aligned}
\tag{11}
$$

In the main branch two percent of the energy is carried by neutrinos, in the first branch this value is four percent, and in the second branch it is 29 percent. Earthly biological life on Earth, and the fossil, solar and wind energy supplies are dependent on this fusion nuclear reaction. Man-made reactors burning H as fuel and producing He are a dream for the very far future. However, this process that cannot be achieved on Earth is a common source of energy production in the stars.

THE CARBON-NITROGEN FUSION CHAIN

Brought together under the proper conditions, this fusion chain involving isotopes higher in atomic mass than in the proton-proton chain occurs in at temperatures above 2×10^8 K. This makes this reaction operative in main-sequence stars of large mass.
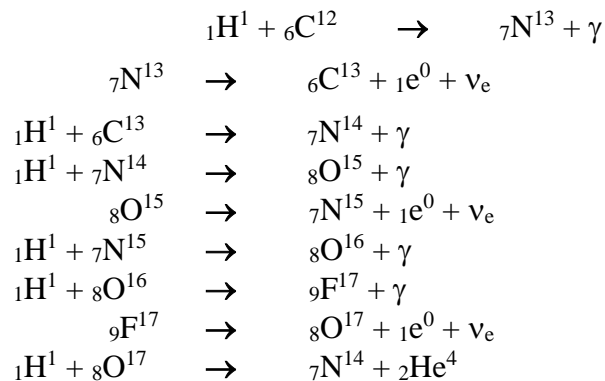
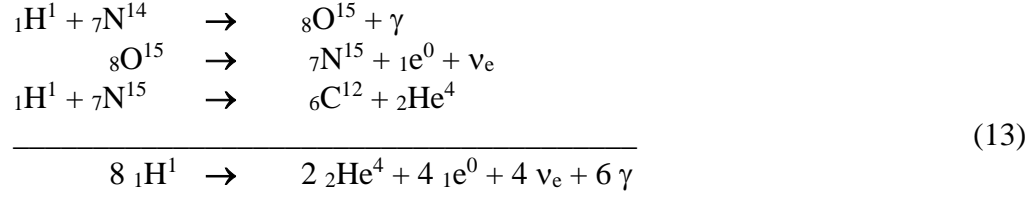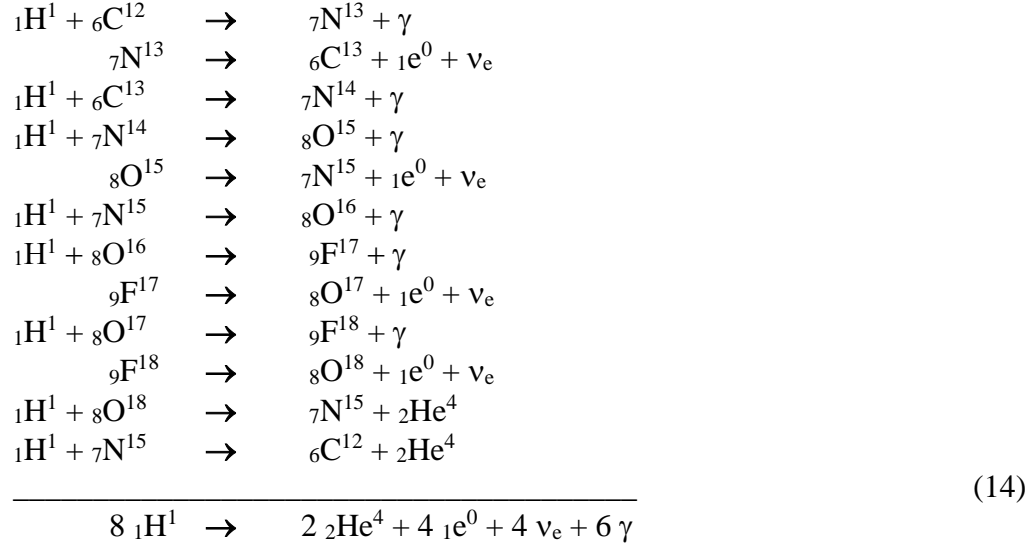The main reaction in the Carbon-Nitrogen chain consists of a collective of six reactions:

$$
\begin{aligned}
_1H^1 + {}_6C^{12} &\rightarrow {}_7N^{13} + \gamma + 1.95 \text{ MeV} \\
_7N^{13} &\rightarrow {}_6C^{13} + {}_1e^0 + \nu_e + 1.50 \text{ MeV} \\
_1H^1 + {}_6C^{13} &\rightarrow {}_7N^{14} + \gamma + 7.54 \text{ MeV} \\
_1H^1 + {}_7N^{14} &\rightarrow {}_8O^{15} + \gamma + 7.35 \text{ MeV} \\
_8O^{15} &\rightarrow {}_7N^{15} + {}_1e^0 + \nu_e + 1.73 \text{ MeV} \\
_1H^1 + {}_7N^{15} &\rightarrow {}_6C^{12} + {}_2He^4 + 4.96 \text{ MeV} \\
\hline
4\,{}_1H^1 &\rightarrow {}_2He^4 + 2\,{}_1e^0 + 2\,\nu_e + 3\,\gamma + 25.03 \text{ MeV}
\end{aligned}
$$

(12)

where: γ represents a gamma photon.

In this main branch six percent of the energy is carried by neutrinos. Here $_7N^{13}$, $_6C^{13}$, $_7N^{14}$, $_8O^{15}$, $_7N^{15}$ and $_6C^{12}$ act as catalysts since they take part in the nuclear reactions, but cancel out from the left and right hand sides of the overall reaction. The end result of the overall reaction is that four hydrogen nuclei are converted into a helium nucleus in addition to other forms of radiation as positrons, neutrinos and gamma photons. In addition, the reaction is exothermic, leading to the release of 25.03 MeV as kinetic energy of the reaction products.

With a branching ratio of 1/1000, the $_7N^{15}$ nucleus can interact in a different way in the last reaction above leading to a first branch of the main reaction:

$$
\begin{aligned}
_1H^1 + {}_6C^{12} &\rightarrow {}_7N^{13} + \gamma \\
_7N^{13} &\rightarrow {}_6C^{13} + {}_1e^0 + \nu_e \\
_1H^1 + {}_6C^{13} &\rightarrow {}_7N^{14} + \gamma \\
_1H^1 + {}_7N^{14} &\rightarrow {}_8O^{15} + \gamma \\
_8O^{15} &\rightarrow {}_7N^{15} + {}_1e^0 + \nu_e \\
_1H^1 + {}_7N^{15} &\rightarrow {}_8O^{16} + \gamma \\
_1H^1 + {}_8O^{16} &\rightarrow {}_9F^{17} + \gamma \\
_9F^{17} &\rightarrow {}_8O^{17} + {}_1e^0 + \nu_e \\
_1H^1 + {}_8O^{17} &\rightarrow {}_7N^{14} + {}_2He^4
\end{aligned}
$$

$$_1H^1 + {_7N^{14}} \rightarrow {_8O^{15}} + \gamma$$
$$_8O^{15} \rightarrow {_7N^{15}} + {_1e^0} + \nu_e$$
$$_1H^1 + {_7N^{15}} \rightarrow {_6C^{12}} + {_2He^4}$$

$$\overline{\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad}$$

$$8\ {_1H^1} \rightarrow 2\ {_2He^4} + 4\ {_1e^0} + 4\ \nu_e + 6\ \gamma \qquad (13)$$

In the last branch, $_8O^{17}$ can also interact differently with a proton, leading to the following second branch of the main reaction:

$$_1H^1 + {_6C^{12}} \rightarrow {_7N^{13}} + \gamma$$
$$_7N^{13} \rightarrow {_6C^{13}} + {_1e^0} + \nu_e$$
$$_1H^1 + {_6C^{13}} \rightarrow {_7N^{14}} + \gamma$$
$$_1H^1 + {_7N^{14}} \rightarrow {_8O^{15}} + \gamma$$
$$_8O^{15} \rightarrow {_7N^{15}} + {_1e^0} + \nu_e$$
$$_1H^1 + {_7N^{15}} \rightarrow {_8O^{16}} + \gamma$$
$$_1H^1 + {_8O^{16}} \rightarrow {_9F^{17}} + \gamma$$
$$_9F^{17} \rightarrow {_8O^{17}} + {_1e^0} + \nu_e$$
$$_1H^1 + {_8O^{17}} \rightarrow {_9F^{18}} + \gamma$$
$$_9F^{18} \rightarrow {_8O^{18}} + {_1e^0} + \nu_e$$
$$_1H^1 + {_8O^{18}} \rightarrow {_7N^{15}} + {_2He^4}$$
$$_1H^1 + {_7N^{15}} \rightarrow {_6C^{12}} + {_2He^4}$$

$$\overline{\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad}$$

$$8\ {_1H^1} \rightarrow 2\ {_2He^4} + 4\ {_1e^0} + 4\ \nu_e + 6\ \gamma \qquad (14)$$

The proton-proton chain occurs in stars of small size like our sun. These are characterized by transport of energy in the interior of the star by radiation, and transport of energy in the outer part of the star by convection, or by the boiling motion of the stellar material. This convective energy transport in the outer layer of the sun causes the giant prominences of 200,000 km in extent appearing under the influence of both gravity and magnetic forces in the sun's corona. In massive main-sequence stars the carbon-nitrogen chain predominates, and leads to a reversed behavior than in the proton-chain: transport is by convection in the inner region of the star, and by radiation in the outer parts.

NUCLEO-SYNTHESIS REACTIONS

The sun's supply of hydrogen will be sufficient to keep it burning into helium for several billions years. A star that has burned its hydrogen will have a central region, which consists primarily of helium. The outer hydrogen layer will expand while the core contracts to higher densities, turning the star from a main sequence star into a red giant. The higher densities and temperature in the core makes helium burning possible.

1.   Helium Burning:

Occurs at densities of 10^5 [gm/cm^3] and temperatures of 10^8 K:

$$_2\text{He}^4 + {}_2\text{He}^4 \quad \rightarrow \quad {}_4\text{Be}^8 \tag{15}$$

The $_4\text{Be}^8$ has a short half-life at about 10^{-16} sec, builds a concentration of $_4\text{Be}^8 / {}_2\text{He}^4 = 10^{-9}$, but can nevertheless support the reaction:

$$_4\text{Be}^8 + {}_2\text{He}^4 \quad \rightarrow \quad {}_6\text{C}^{12} + \gamma. \tag{16}$$

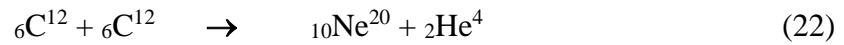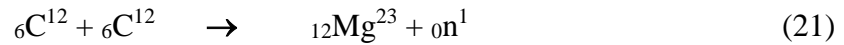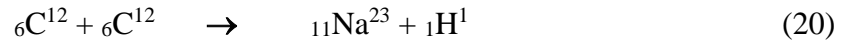If we add the last two reactions, beryllium cancels out as a catalyst, and the overall helium burning reaction becomes:

$$3\,{}_2\text{He}^4 \rightarrow \quad {}_6\text{C}^{12} + \gamma. \tag{17}$$

Some additional helium burning can proceed with the produced carbon at a temperature of 2×10^8 K as:

$$_2\text{He}^4 + {}_6\text{C}^{12} \quad \rightarrow \quad {}_8\text{O}^{16} + \gamma \tag{18}$$

2.   Carbon Burning:

Within a period of 10^7 to 10^8 years, most of the helium will be used up and the carbon in the core is further collapsed to a temperature of 8×10^8 K, leading to the carbon burning reactions:
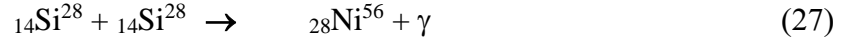
$$_6\text{C}^{12} + {}_6\text{C}^{12} \quad \rightarrow \quad {}_{12}\text{Mg}^{24} + \gamma \tag{19}$$

$$_6\text{C}^{12} + {}_6\text{C}^{12} \quad \rightarrow \quad {}_{11}\text{Na}^{23} + {}_1\text{H}^1 \tag{20}$$

$$_6\text{C}^{12} + {}_6\text{C}^{12} \quad \rightarrow \quad {}_{12}\text{Mg}^{23} + {}_0\text{n}^1 \tag{21}$$

$$_6\text{C}^{12} + {}_6\text{C}^{12} \quad \rightarrow \quad {}_{10}\text{Ne}^{20} + {}_2\text{He}^4 \tag{22}$$
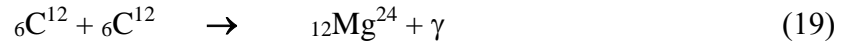
3.   Oxygen Burning:

At temperatures reaching 1.5×10^9 K, oxygen burning becomes possible:

$$_6\text{C}^{12} + {}_8\text{O}^{16} \quad \rightarrow \quad {}_{14}\text{Si}^{28} + \gamma \tag{23}$$

$$_8\text{O}^{16} + {}_8\text{O}^{16} \quad \rightarrow \quad {}_{14}\text{Si}^{28} + {}_2\text{He}^4 \tag{24}$$

$$_8\text{O}^{16} + {}_8\text{O}^{16} \quad \rightarrow \quad {}_{16}\text{S}^{32} + \gamma \tag{25}$$

$$_8\text{O}^{16} + {}_8\text{O}^{16} \quad \rightarrow \quad {}_{15}\text{P}^{32} + {}_1\text{H}^1 \tag{26}$$
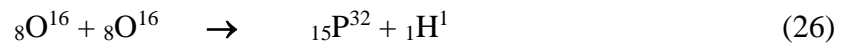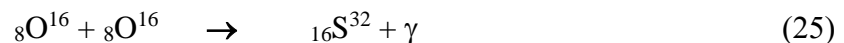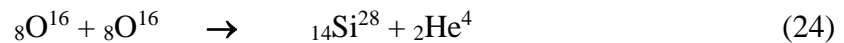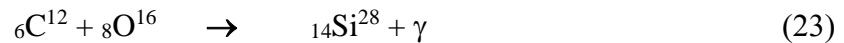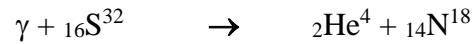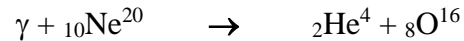
4.   Silicon Burning:

At temperatures reaching 3.5 x 10^9 K, silicon burning becomes possible, leading to the formation of iron:

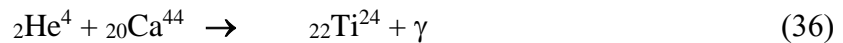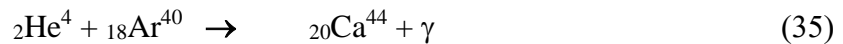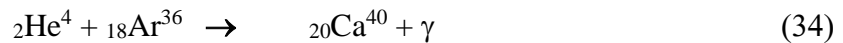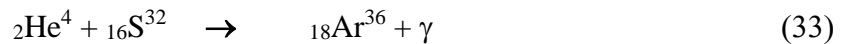$$_{14}Si^{28} + {}_{14}Si^{28} \rightarrow \quad _{28}Ni^{56} + \gamma \tag{27}$$

$$_{28}Ni^{56} \rightarrow \quad _{27}Co^{56} + {}_{+1}e^0 + \nu_e \tag{28}$$

$$_{27}Co^{56} \rightarrow \quad _{26}Fe^{56} + {}_{+1}e^0 + \nu_e \tag{29}$$
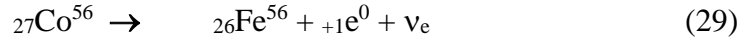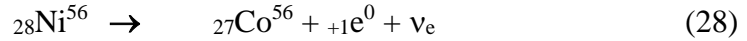
5.   Gamma-Alpha Reactions:

At temperatures higher than 10^9 K, reactions with nuclei that have relatively loose alpha particles can occur:

$$\gamma + {}_{10}Ne^{20} \quad \rightarrow \quad _2He^4 + {}_8O^{16}$$

$$\gamma + {}_{16}S^{32} \quad \rightarrow \quad _2He^4 + {}_{14}N^{18}$$
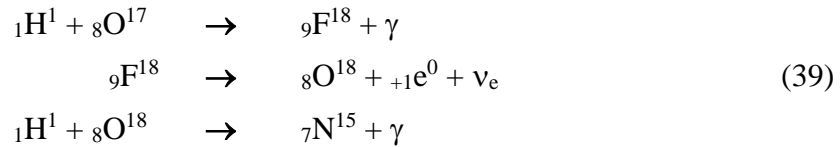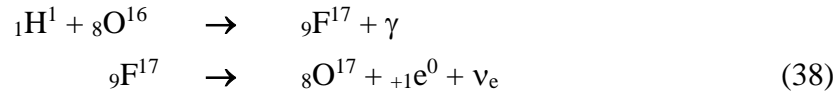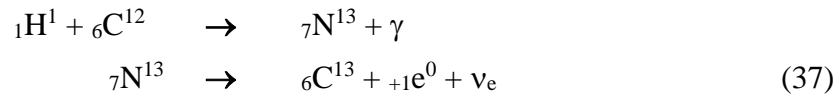
6.   Alpha-Gamma Reactions:

The previous reactions produces alpha particles with large energies above the thermal alphas leading to the reactions that over a period of thousands of years creates magnesium, calcium and other isotopes:

$$_2He^4 + {}_{10}Ne^{20} \rightarrow \quad _{12}Mg^{24} + \gamma \tag{30}$$

$$_2He^4 + {}_{12}Mg^{24} \rightarrow \quad _{14}Si^{28} + \gamma \tag{31}$$

$$_2He^4 + {}_{13}Al^{28} \rightarrow \quad _{15}P^{32} + \gamma \tag{32}$$

$$_2He^4 + {}_{16}S^{32} \quad \rightarrow \quad _{18}Ar^{36} + \gamma \tag{33}$$

$$_2He^4 + {}_{18}Ar^{36} \rightarrow \quad _{20}Ca^{40} + \gamma \tag{34}$$

$$_2He^4 + {}_{18}Ar^{40} \rightarrow \quad _{20}Ca^{44} + \gamma \tag{35}$$

$$_2He^4 + {}_{20}Ca^{44} \rightarrow \quad _{22}Ti^{24} + \gamma \tag{36}$$
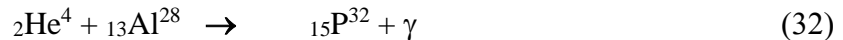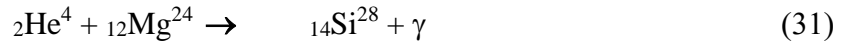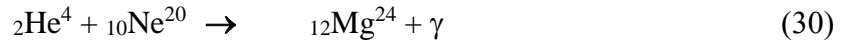
7.   Proton-Gamma Reactions:

At temperatures higher than 10^9 K, reactions with protons, followed by positron decay can occur:

$$_1H^1 + {_6}C^{12} \quad \rightarrow \quad {_7}N^{13} + \gamma$$
$$_7N^{13} \quad \rightarrow \quad {_6}C^{13} + {_{+1}}e^0 + \nu_e \qquad (37)$$

$$_1H^1 + {_8}O^{16} \quad \rightarrow \quad {_9}F^{17} + \gamma$$
$$_9F^{17} \quad \rightarrow \quad {_8}O^{17} + {_{+1}}e^0 + \nu_e \qquad (38)$$

$$_1H^1 + {_8}O^{17} \quad \rightarrow \quad {_9}F^{18} + \gamma$$
$$_9F^{18} \quad \rightarrow \quad {_8}O^{18} + {_{+1}}e^0 + \nu_e \qquad (39)$$
$$_1H^1 + {_8}O^{18} \quad \rightarrow \quad {_7}N^{15} + \gamma$$

Nucleo-synthesis by exothermic fusion reactions can only proceed to the iron region in the binding energy curve. A star that condensed out of hydrogen cannot synthesize elements beyond the iron-nickel region.

The technetium isotope $_{43}Tc^{97}$ with a 2.6×10^6 years half-life is detected in the spectra of some stars. Wide variations in the composition of different types of stars can be observed. This suggests that, in addition to the hydrogen and helium burning reactions previously exposed, other nuclear processes leading to heavy-elements synthesis must be taking place in stellar atmospheres, even at the present time.

This observation contradicts the Big-Bang Theory advanced by G. Gamow which postulates that element synthesis occurred by successive neutron captures in the first hour of the expanding Universe.

NUCLEO-SYNTHESIS IN SUPERNOVAE

How could stars like our sun, which are in the hydrogen burning stage, then contain an abundance of heavy elements? A suggested answer to this question is that their condensation occurred from interstellar clouds which themselves were the ashes of older stars. Supernovae are thought to produce a large proportion of the elements heavier than helium in the Universe. Their occurrences in and near clouds of cold molecular gas may trigger the formation of new stars. The mechanism of ejection of matter in Supernovae explosions involves two types:

TYPE II SUPERNOVAE:

These represent the evolutionary endpoint for a massive star, which would spend up to 10 million years burning the hydrogen at its center into iron. It then explodes suddenly in a series of events lasting only a fraction of a second. During the following two to three months period, the amount of radiation released from the initial explosion rivals that emitted by the rest of the entire galaxy to which the supernova belongs to.

These occur in first generation stars of low heavy element content. They do occur in giant stars in contrast to Type I supernovae occurring in dwarfs. In this case the collapse of the star

occurs because the star has run out of fuel in the core, rather than by gaining more mass like the dwarfs.

After the core of a star has been converted to iron group elements, the nuclear reactions occurring do not generate enough radiation pressure outward and cannot hold the gravitational contraction. Densities in the range of 10^8 [gm/cm^3] and temperatures around 8 x 10^9 K can occur, with an associated equilibrium between Iron as $_{26}Fe^{56}$ and helium is reached. A small perturbation in temperature of about 0.5 x 10^9 K or a gravitational collapse can lead to the dissociation of iron into helium and neutrons. In a fraction of a second a huge implosion would occur. The outer region of the star is suddenly heated. The hydrogen, helium, carbon, and oxygen in the outer region undergo a thermonuclear fusion explosion. This is associated with the ejection of a large amount of stellar material equivalent to a solar mass into space. This process is a called a Type II supernova, and happens at a frequency of once every 50 years per galaxy. Out of the ejected material second generation stars are formed.

Giant stars burn actively, die young, and are found in the arms of the galaxies where the stars originated, and they had not enough time to drift away. Type I supernovae can occur in all types of galaxies where binary systems occur, whereas Type II do not frequently occur in elliptical galaxies where new stars do not form.

Type II supernovae are more powerful than Type I supernovae, but they appear 2.5 times dimmer, because they release 99 percent of their energy in the form of neutrinos, rather than in the form of light. Even though this process occurs at 100 x 10^9 K, this is referred to as neutrino refrigeration.

TYPE Ia SUPERNOVAE:

These result from old, dead stars designated as white dwarfs. White dwarfs have the mass of the sun but with a size comparable to that of the Earth. The white dwarf consumes matter from an evolving companion star via the process of accretion. Accretion is one of the dominant energy conversion processes in the Universe. These are thought to occur in binary systems, where the orbit of a dwarf star carries it close enough to its larger companion, where it can through its gravitational force strip gas from the larger star. The dwarf gains mass until it surpasses a threshold designated as the Chadransekhar limit at 1.44 times a solar mass, at which time it collapses further. The ensuing thermonuclear explosion rips it apart. The entire star is expelled at velocities reaching 1/10 the speed of light. Dwarf stars are already so dense that their protons, electrons, are kept under high pressure by quantum mechanical forces acting primarily on the electrons in the form of degenerate matter. Atoms cannot form in this situation and a spoonful of this degenerate matter on Earth would weigh as much as a large automobile. The collapse of the binary dwarf star overcomes its degenerate structure into an explosion vaporizing the star. Type Ia supernovae indicate a value of the Hubble constant around 50.

It is possible in the distant past that the Universe expanded more slowly than it does now. This implies the possible existence of a fifth repulsive force in nature. An understanding of the relationship between a Type Ia supernova luminosity and its light curve, or the way its brightness changes with time, is still needed to rule out the possibility that supernovae in the distant past differed from younger ones that exploded closer to Earth.

SUPERNOVA OBSERVATIONS:

The light emission from supernovae explosions decreases rapidly within 1-2 months, and decays with a half-life of 55 days. Ancient astronomers in China have observed them in 1054, as well as Tycho Brahe in 1572, and by Johannes Kepler in 1604.

In 1054 the Chinese astronomer Yang recorded observations of what he called a guest star that appeared during the day and lasted for a month. This was the supernova explosion that created the Crab Nebula in the constellation of Taurus.

The Star of Bethlehem in the Bible story at the time of Jesus birth could have been a supernova explosion or a comet visit.

Figure 8 shows the Cas A supernova remnant after its explosion in 2,000 AD.
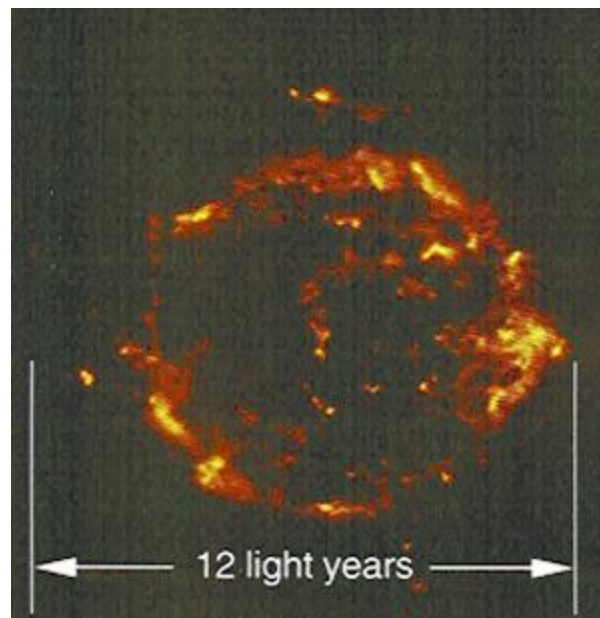
Figure 8. Remnant of the Cas A supernova in the year 2000 AD.

Neutrinos from a supernova in the Large Magellanic Cloud, which is a satellite galaxy that orbits around the Milky Way galaxy at a distance of 165,000 light years from Earth, were detected at underground neutrino detectors in Japan and Ohio. The detection occurred on February 23, 1987, as a rare naked eye supernova, and the brightest to occur in 400 years. It is now designated as the SN 1987A event. At 7:35 am, universal time, its core collapse was announced by a neutrino burst. At 10 am Universal time a hard ultra violet burst accompanied its shock wave breakout. Figure 6 shows the light curve of supernova SN 1987A.

Supernovae are a major tool for the study of the expansion rate and the geometry of the Universe since with their large luminosity; they are visible over vast cosmological distances. Their distances can be calculated by determining their intrinsic luminosity through measuring the apparent brightness by a telescope. By measuring how fast a supernova and its galaxy are receding from Earth, the Hubble constant, which relates recession speed to distance and characterizes the age of the Universe, can be determined.
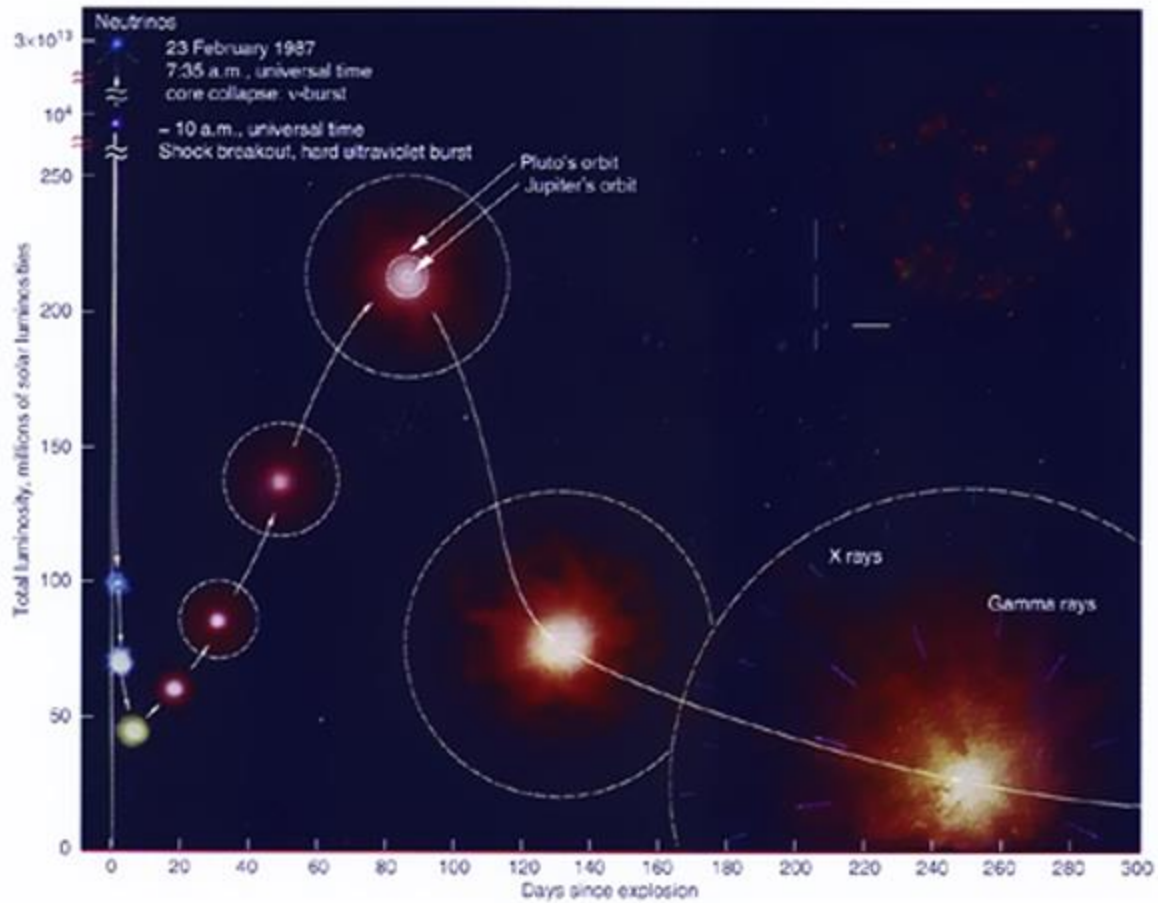
Figure 9. Light Curve of the SN 1987A supernova showing its luminosity in the months after its explosion.

Using NASA's Swift satellite, astronomers have seen a star actually blow up. On January 9, 2008, Alicia Soderberg and Edo Berger of Princeton University, in Princeton, New Jersey, were using the Swift's x-ray telescope to observe a distant spiral shaped galaxy known as NGC 2770. At 9:33 in the morning Eastern Time, the telescope picked up a powerful burst of x rays coming from the galaxy. It lasted 5 minutes before fading away.

The next few weeks, observations made by NASA's Hubble Space Telescope and Chandra x ray observatory, along with Swift and other major telescopes, showed beyond a shadow of a doubt that the January 9, 2008 x ray burst signaled the actual explosion of a giant star. For the first time, astronomers had seen a star blow up in real time.

The x rays were due to a powerful blast wave bursting through the star's outer layers, and blowing it apart. The blast wave itself was triggered deep inside the star, when the nuclear fusion engine at the center of the star ran out of fuel and caused the gravitational collapse of the star upon itself. This newly born supernova could become the Rosetta stone of supernova studies for years to come.
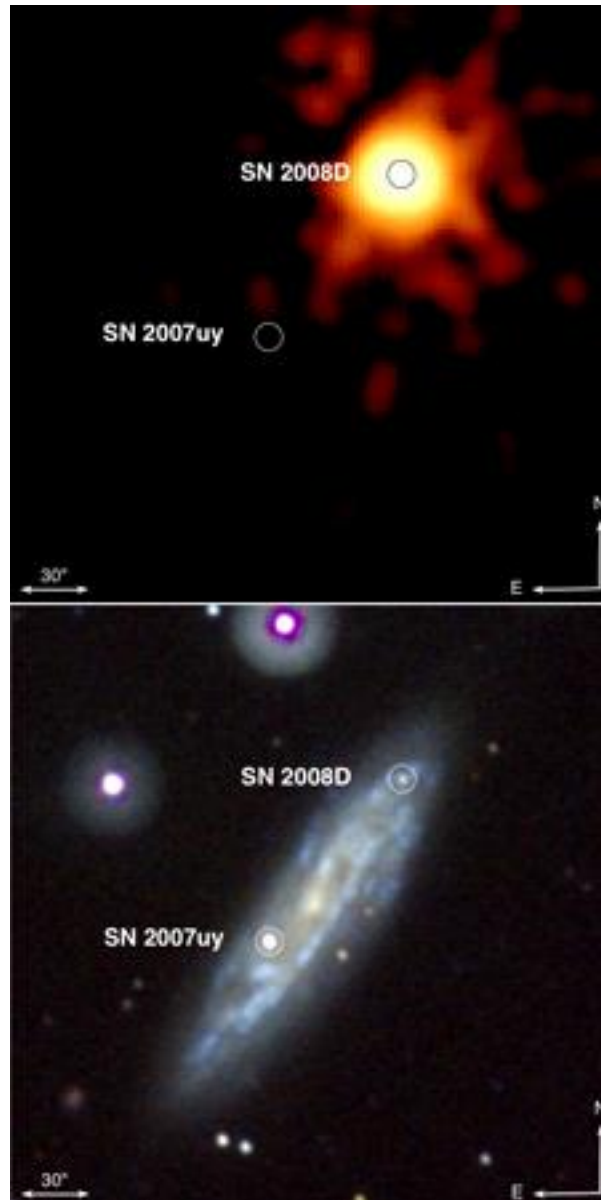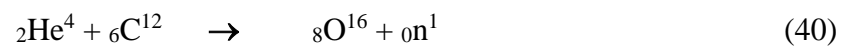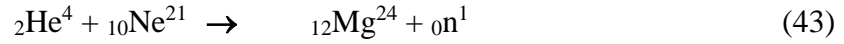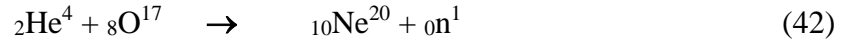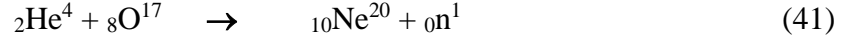
Figure 10. Swift observatory pictures of galaxy NGC 2770 showing on the top an x-ray image and at the bottom a visible light image of supernova SN2008D before its explosion. Also appearing is supernova SN2007uy. Source: NASA/Swift Science Team/Stefan Immler.

HEAVY ELEMENTS FORMATION

In a second-generation star, the presence of the nuclides up to iron makes other reactions possible. Among these reactions are some Alpha-Neutron reactions occurring at 10^8 K such as:

$$_2\text{He}^4 + {_6}\text{C}^{12} \quad \rightarrow \quad {_8}\text{O}^{16} + {_0}\text{n}^1 \tag{40}$$

$$_2\text{He}^4 + {}_8\text{O}^{17} \rightarrow {}_{10}\text{Ne}^{20} + {}_0\text{n}^1 \tag{41}$$

$$_2\text{He}^4 + {}_8\text{O}^{17} \rightarrow {}_{10}\text{Ne}^{20} + {}_0\text{n}^1 \tag{42}$$

$$_2\text{He}^4 + {}_{10}\text{Ne}^{21} \rightarrow {}_{12}\text{Mg}^{24} + {}_0\text{n}^1 \tag{43}$$

The generated neutrons can continue the element synthesis process beyond iron by successive neutron capture reactions emitting gamma photons and followed by negative beta decays. This process accounts for the presence of technetium in some stars, as well as the presence of bismuth. This process has a slow time scale of 10^2-10^5 years per neutron capture, and cannot account for the nucleo-synthesis of thorium and uranium, because of the occurrence of some short lived intermediate isotopes.

The generation of uranium and thorium is thought to have occurred on a much shorter time scale in an extremely large neutron flux with successive neutron captures known as the r process without the intervening alpha or beta decays: these are the Type I supernovae events. These explosions can generate elements up to the mass number value of A = 270.

Multiple captures of neutrons in $_{92}\text{U}^{238}$ in man-made thermonuclear explosions lead to the production $_{98}\text{Cf}^{254}$. This element decays through a spontaneous fission process with a half life of 60.5 days.

With this model, our sun is a third or later generation star formed from the debris of one or several supernova explosion, the last of which may have occurred about 5 billion years ago. We are as humans and the rest of biological life on Earth nothing but the ashes resulting from the fusion and other cataclysmic nuclear reactions that occurred in these stars.

NUCLEO SYNTHESIS IN NEUTRON STARS COLLISIONS AND GAMMA RAY BURSTS (GRBs)

Researchers have been puzzled by data suggesting that supernovae explosions do not produce enough heavy elements to account for their current abundance on Earth. The idea that neutron star collisions create heavy elements was suggested in the 1970s by James Lattimer and colleagues. At the National Astronomy Meeting at Cambridge, England, in April 2001, a team of scientists from the University of Leicester, England, and the University of Basel, Switzerland, led by Stephan Rosswog suggested a new theory for the nucleo-synthesis of the heavy elements. These researchers suggest that massive explosions resulting from collisions between pairs of neutron stars may have been the source of the heavy elements.

Neutron stars are the remnant cores of stars, which have undergone supernovae explosions. These collisions would have occurred hundreds of millions of years before the birth of the solar system.

On June 3, 2013 NASA's Swift satellite observed a short-hard gamma-ray burst GRB 130603B (z=0.356), 3.9 billion light-years away. Astrophysicists believe that a crash between two neutron stars, the dense, neutron-rich cores left over after massive stars explode, released the 0.2-second flash of energy. Images by the Hubble Space Telescope nine days later saw evidence for a bounty of heavy elements amounting to about 1 percent of the sun's mass and including several moon masses of gold. These collisions probably happen once every 10,000 or 100,000 years in any given galaxy [4].

The Hubble pictures show a glow of infrared light that is characteristic of radiation emitted by the radioactive decay of heavy elements. Yet the team can't rule out that the light was produced by the gamma-ray burst itself.

Future space missions such as the Advanced Laser Interferometer Gravitational-Wave Observatory will make it easier to find short gamma-ray bursts and may confirm whether they are triggered by neutron stars. New telescopes such as the Large Synoptic Survey Telescope that monitor larger swaths of sky will make it easier to distinguish between a gamma-ray burst's afterglow and shine coming from the heavy elements. Finding signs of heavy elements, which require a lot of neutrons, in association with short gamma-ray bursts is the best evidence yet that neutron star collisions nucleo-synthesize the heavy elements.

CONTROLLED THERMONUCLEAR REACTIONS

Since fusion of the light nuclei occurs at high energies and temperatures, they are called thermonuclear reactions. The possibility of achieving such reactions to Earth has obviously generated much interest.

Reaction like those burning hydrogen in the stars into helium, would take extremely long times on Earth to be of any practical interest as shown in Table 3. However other reactions can be made to proceed much faster on Earth using isotopes of hydrogen such as deuterium ($_1D^2$)and tritium ($_1T^3$), which, on Earth, would replace the hydrogen fusion in the stars shown in Fig. 1.

These reactions can be achieved in an uncontrolled manner in thermonuclear weapons, or hydrogen bombs, or in controlled fashion in future controlled fusion devices.

Table 3. Comparison of Reaction Characteristic Times for different Fusion Reactions

Fusion Reaction	Energy Release (MeV)	Characteristic Time
$_1H^1 + {_1H^1} \rightarrow {_1D^2} + {_{+1}e^0}$	1.4	100,000,000,000 years
$_1D^2 + {_1H^1} \rightarrow {_2He^3} + \gamma$	5	0.5 second
$_1T^3 + {_1H^1} \rightarrow {_2He^4} + \gamma$	20	0.05 second
$_1D^2 + {_1D^2} \rightarrow {_2He^3} + {_0n^1}$	3.2	0.00003 second
$_1D^2 + {_1D^2} \rightarrow {_1T^3} + {_1H^1}$	4	0.00003 second
$_1D^2 + {_1T^3} \rightarrow {_2He^4} + {_0n^1}$	17	0.0000012 second
$_1T^3 + {_1T^3} \rightarrow {_2He^4} + 2\, {_0n^1}$	11	-

In these future devices, one gallon of seawater contains enough deuterium to release the energy equivalent to 300 gallons of gasoline. Deuterium occurs in nature in the ratio of 1/6500 relative to hydrogen. Achieving the goal of fusion from deuterium amounts to obtaining energy from water with an extremely large reserve base of fuel.

The fusion of the light nuclei in a plasma created in these devices would constitute a cleaner source of energy than fossil fuels and fission fuels. They would not release the greenhouse gases released by fossil fuels. They would not release either the fission products generated by fission fuels. The ashes of the fusion reactions would primarily be helium nuclei.

EXERCISE

1. Compare the Coulomb energy repulsion in MeV in a fusion plasma between the nuclei of:
    1. Deuterium
    2. Lithium
    3. Carbon

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