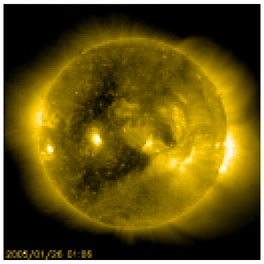
The Evolution of Elements (also simpler version)

In the universe's original stars and in present suns that cannot attain core temperatures beyond 10^6 K, the main source of energy results from the **proton-proton chain**.



Four hydrogen nuclei initially fuse to produce two deuterium nuclei, two positrons and two neutrinos:

$$4\,^{1}_{1}H \rightarrow 2\,^{2}_{1}H + 2\,^{0}_{1}e + 2\nu \qquad (1)$$

The big coefficient acts as a multiplier .The lower number next to each atomic symbol reveals the number of protons in each atom. The upper number(mass number) minus the number of protons reveals the number of neutrons.

Notice that we originally have four protons and no neutrons becoming only two protons and suddenly two neutrons, two positrons ($^{0}_{1}e$) and two neutrinos (ν). Two of the protons that disappeared have become neutrons. If we divide through by 2:

$$^{1}_{1}p \rightarrow ^{0}_{1}n + ^{0}_{1}e + \nu \qquad (2)$$

A neutron has no charge but a mass unit of 1. The positron is a component of anti-matter. Like the electron it has very little mass but the positron bears a positive charge. When created, it soon meets an electron in the star's plasma; they annihilate each other and release energy. The neutrino is an even lighter particle than the electron, which even before being detected, was postulated to balance the amount of kinetic energy on both sides of the equation.

If we go back to equation (2), and remember that a proton consists of two up quarks and a down quark, and that the reverse combination makes up a neutron, than what is happening at a more fundamental level, is that an upquark is being converted into a down quark with the accompanying release of a positron and a neutrino.

After the reaction of equation (1), two different isotopes of hydrogen fuse to create a second isotope of helium. This leads to a small mass-loss which according to $E = mc^2$ translates into an enormous amount of energy:

$$2\,^{1}_{1}H + 2\,^{2}_{1}H \rightarrow 2\,^{3}_{2}He + \gamma \qquad (3)$$

Then

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

Overall by combining (1), (3) and (4) we obtain:

$$4\,^{1}_{1}H \rightarrow ^{4}_{2}He + 2\,^{0}_{1}e + 2\nu + \gamma$$

In suns that benefit from the formation of elements from previous generations of stars, and if the core temperature exceeds 16 X 10^6 K, carbon acts as a catalyst:

$$^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{13}_{7}N + \gamma$$
$$^{13}_{7}N \rightarrow {}^{13}_{6}C + {}^{0}_{1}e + \nu$$
$$^{13}_{6}C + {}^{1}_{1}H \rightarrow {}^{14}_{7}N + \gamma$$
$$^{14}_{7}N + {}^{1}_{1}H \rightarrow {}^{15}_{8}O + \gamma$$
$$^{15}_{8}O \rightarrow {}^{15}_{7}N + {}^{0}_{1}e + \nu$$
$$^{15}_{7}N + {}^{1}_{1}H \rightarrow {}^{12}_{6}C + {}^{4}_{2}He$$

Overall the reaction is the same as that of the proton-proton chain:

$$4\,{}^{1}_{1}H \rightarrow {}^{4}_{2}He + 2\,{}^{0}_{1}e + 2\nu + \gamma$$

When hydrogen is depleted at the core of the star, radiative pressure decreases and gravity causes contraction. When temperature increases to 1 X 10^8 K, He begins to fuse and the star swells into a red giant (figure 2)

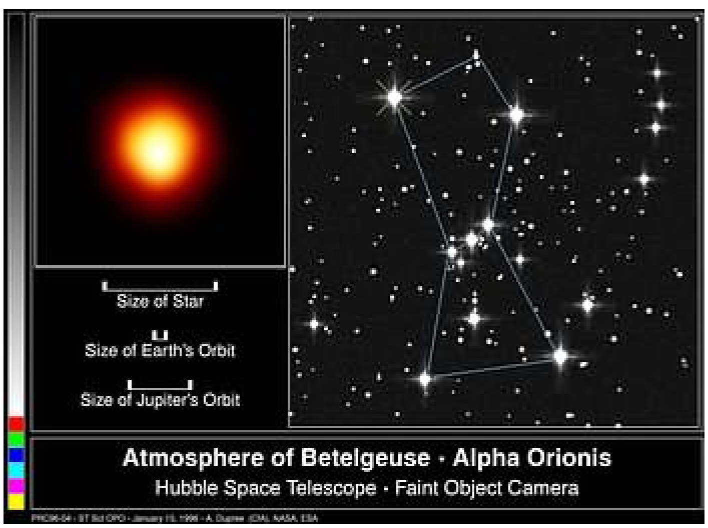


Figure 2
Betelgeuse: a red giant

$$ {}_{2}^{4}He + {}_{2}^{4}He \rightarrow {}_{2}^{8}Be $$

$$ {}_{4}^{8}Be + {}_{2}^{4}He \rightarrow {}_{6}^{12}C + \gamma $$

When the core is left with only C and O, the star becomes a planetary nebula (figure 3) and ejects its outer shell.

Eventually it becomes a white dwarf. Electron degeneracy pressure (Pauli exclusion principle prohibits two electrons from having the same quantum state.) prevents further contraction.
If the mass of the star was at least 4 solar masses prior to ejection, then:

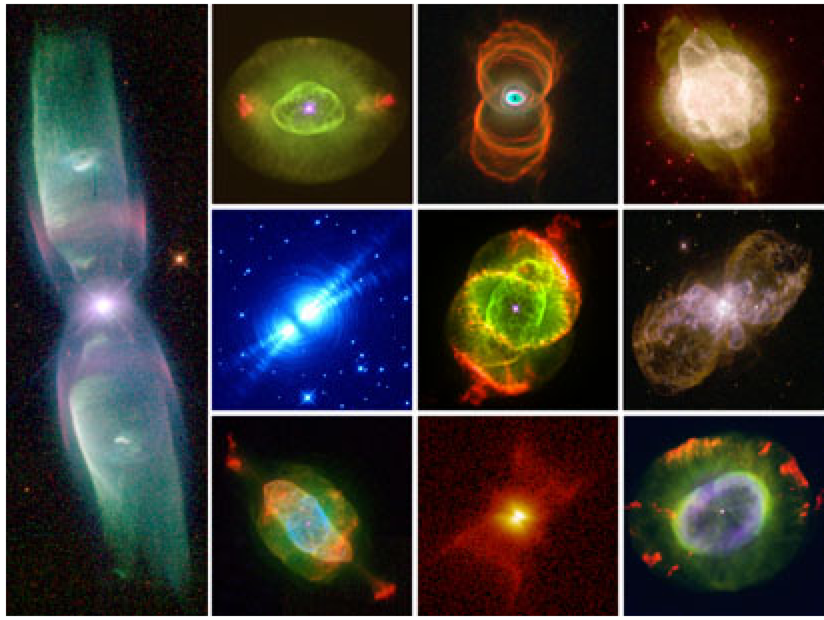


Figure 3 planetary nebulae

$$ {}_{6}^{12}C + {}_{6}^{12}C \rightarrow {}_{10}^{20}Ne + {}_{2}^{4}He $$

$$ {}_{6}^{12}C + {}_{6}^{12}C \rightarrow {}_{12}^{24}Mg + \gamma $$

$$ {}_{6}^{12}C + {}_{6}^{12}C \rightarrow {}_{8}^{16}O + 2\,{}_{2}^{4}He $$

If the star was at least 9 solar masses prior to ejection and if the T > 10^9 K:

$$ {}_{10}^{20}Ne + \gamma \rightarrow {}_{8}^{16}O + {}_{2}^{4}He $$

$$ {}_{10}^{20}Ne + {}_{2}^{4}He \rightarrow {}_{12}^{24}Mg + \gamma $$

If T > 1.5 X 10^9 K, then

$$ {}_{8}^{16}O + {}_{8}^{16}O \rightarrow {}_{16}^{32}S + \gamma \text{ or} $$

$$ \rightarrow {}_{14}^{28}Si + {}_{2}^{4}He + \gamma $$

$$ \rightarrow {}_{15}^{31}P + {}_{1}^{1}H + \gamma $$

$$\rightarrow {}^{31}_{16}S + {}^{1}_{0}n + \gamma$$

$$\rightarrow {}^{24}_{12}Mg + 2\ {}^{4}_{2}He$$

$$\rightarrow {}^{30}_{14}Si + 2{}^{1}_{1}H + \gamma$$

In a star of 25 solar-masses, temperatures reach 3 X 10^9 K; next we obtain:

$${}^{28}_{14}Si + {}^{28}_{14}Si \rightarrow {}^{56}_{26}Fe + 2{}^{0}_{1}e$$

With such a large mass, electron degeneracy pressure is exceeded by gravity and protons and electrons fuse to create a neutrons and neutrinos:

$${}^{0}_{-1}e + {}^{1}_{1}H \rightarrow {}^{1}_{0}n + \nu$$

When mass from surrounding layers converge on the extremely dense core of neutrons, an extremely violent event known as a supernova (type II) occurs. (figure 4) Some of the ensuing energy released is used to create a variety of both lower and higher isotopes.

First a nucleus must absorb neutrons. An excess of neutrons will spark the conversion of a neutron to a proton and an electron, thus increasing the atomic number.

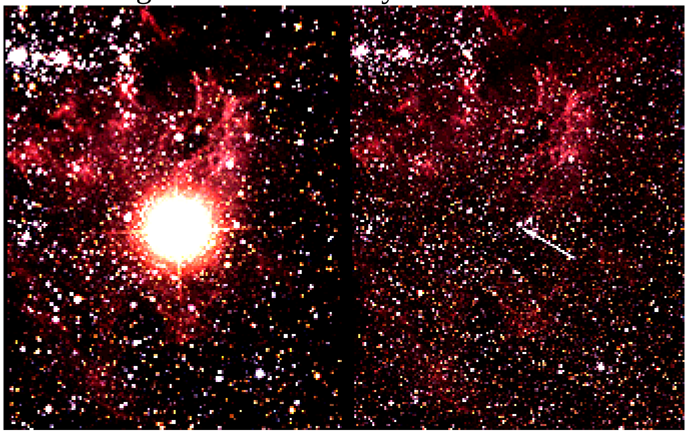
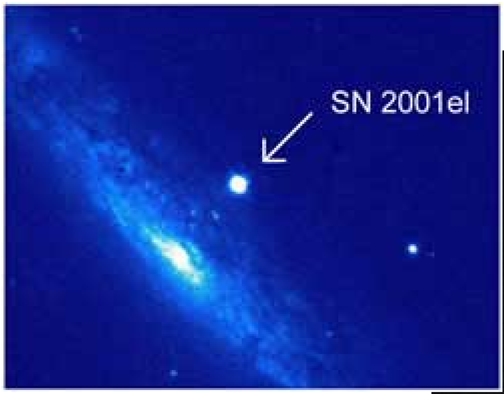


Figure 4 Type II supernovae: *after* and before

$${}^{1}_{0}n \rightarrow {}^{0}_{-1}e + {}^{1}_{1}H + \nu$$

In a main sequence star such reactions are slow because of the low likelihood that a neutron will encounter a nucleus, but a supernova implosion creates an abundance of neutrons needed for neutron decay.

If a white dwarf has a companion star, it may draw additional material to its surface, leading to either a nova or if there is even more mass (more than 1.4 solar masses) drawn a higher density and temperature leads to the fusion of carbon and oxygen into iron. This happens uncontrollably; the violent event is known as a supernova type I (figure 5), and it leads to a different array of isotopes from the ones produced in a type II supernova



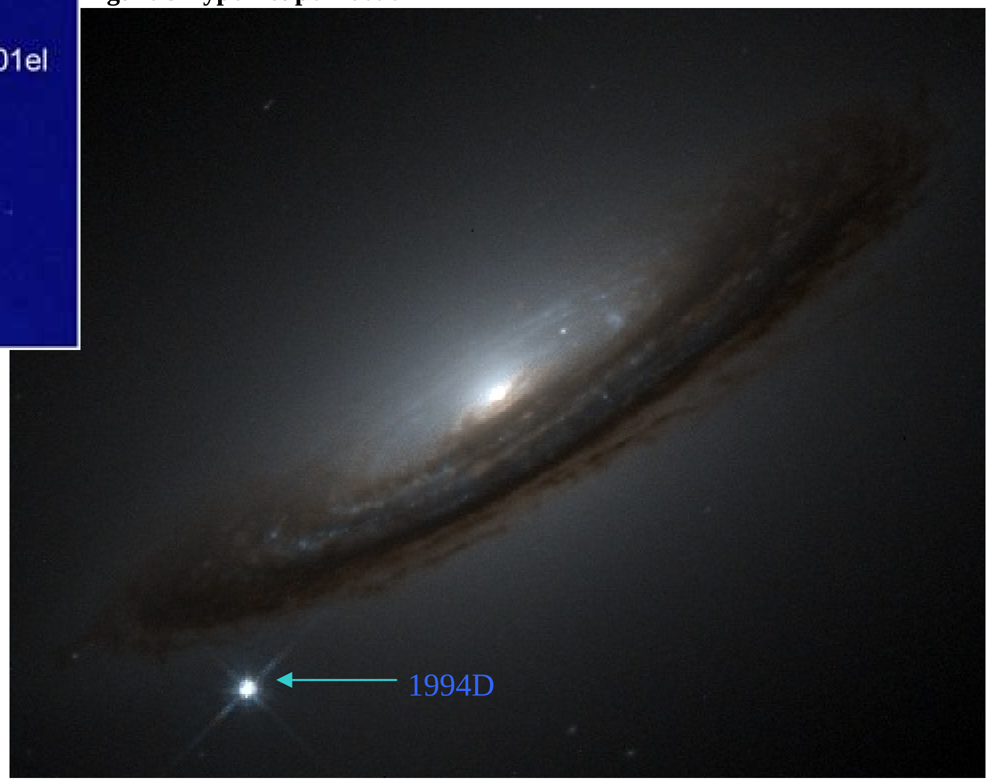


Figure 5 Type 1 supernovae

References:

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