ENERGY PRODUCTION IN THE UNIVERSE: STELLAR NUCLEAR REACTIONS

GAETANO VALENTINI

The stellar energy production is one the most important issues in the present astrophysics.
To understand the various celestial phenomena, the phases of the stellar evolution, the chemical content in the interstellar medium and in the planetary systems and, finally, the appearance of life on Earth is necessary to have a deep knowledge on the physics of the stellar energy production.

A star bears from the gas contraction of an interstellar cloud, when the gravitational energy wins the thermal particle energy.
This contraction is in action until the equilibrium condition is reached: as demonstrated by Virial theorem:

$$2T+\Omega=0$$

In particular, to support the star's spherical symmetry is necessary that pressure radial forces, which favour expansion, and gravitational radial forces, which favour contraction, are equal:

$$dP[r]/dr=[-G\cdot M_r[r]\cdot \rho[r]/r^2]dr$$

This equilibrium is one of the major characteristics during stellar evolution and it will be finally broken only during the possible supernova explosive phase.

Moreover, the Virial theorem indicates also the relation between gravitational energy and thermal energy: an increase of the gravity causes a growth of the gas temperature and then of the pressure:

$$dT=-d\Omega/2$$

In other words, half of the gravitational energy emitted during the contraction must increase the thermal content of the protostellar structure.

In the interstellar gas cloud the temperature progressively rises, favouring the nuclei ionization, until the nuclear reactions become efficient.
Then the energy production starts, with the energy being transferred through transport mechanisms (conduction and convection) in the outer stellar region: a star is born. The direct observable quantity of a star is the luminosity, directly connected with the energy production rate ε:

$$dL_r/dr=4\cdot\pi\cdot r^2\cdot\rho\cdot\varepsilon$$

The first active nuclear reactions are those that transform hydrogen in helium, following two different types of burnings: the proton-proton chain PP, and the carbon cycle CNO.

In the proton-proton chain the first interaction between two protons develops a deuterium nucleus, releasing also a positron (that interacts with an electron, forming a gamma ray) and a neutrino. The interaction of the deuterium with a third proton produces a helium He^3 nucleus:

$$H^1[p,e^+\upsilon)D^2[p,\gamma]He^3$$

After this interaction, the PP chain can follow three different ways. In the first, called PPI, the process proceed through the interaction with another nucleus of helium He^3, formed in an analogous reaction, producing a helium He^4 nucleus and two protons:

$$He^3(He^3,2p)He^4$$

But the He^3 nucleus can interact with an He^4 nucleus (α particle) forming a beryllium Be^7 nucleus,

$$He^3[\alpha,\gamma]Be^7$$

In the second chain, PPII, the beryllium nucleus captures an electron producing lithium and a neutrino; the lithium interacting with a proton finally forms two helium nuclei:

$$Be^7[e^-,\upsilon]Li^7[p,\alpha]He^4$$

In the third chain, PPIII, the beryllium interacts with a proton forming boron B^8, an instable nucleus that decays in beryllium Be^8, a positron and a neutrino. The beryllium, also instable, decays in two α particles:

$$Be^7[p,\gamma]B^8[,e^+\upsilon)Be^8[,\alpha]He^4$$

The probability that is active a chain instead of another is related to the temperature in the stellar nucleus.

For temperatures between 1 and 14 million degrees the PPI chain dominates, between 14 and 23 million starts to prevail the PPII, whereas for temperatures greater then 23 million is active also the PPIII. In the Sun, for example, the central temperature is 16 million degree, so the active chains are mainly the PPI, and PPII.

Every interaction releases a fixed quantity of energy: the PPI chain energy release is 26,2 Mev ($4{,}2\cdot10^{-5}$ erg), the PPII emits 25,67 Mev ($4{,}1\cdot10^{-5}$ erg) and the PPIII produces 19,27 Mev ($3{,}1\cdot10^{-5}$ erg).

After the proton-proton chain, we consider the second burning hydrogen typology: the so called carbon cycle CNO. In this cycle we have also two different types of burnings.

In the first, called principal, a carbon nucleus C^{13} interacts with a proton forming a nitrogen N^{13} nucleus and a gamma ray. Nitrogen decays in carbon C^{13}, releasing a positron and a neutrino.

The C^{13} captures another proton forming nitrogen N^{14}, and a gamma ray.

The nitrogen nucleus interacting with a proton produces oxygen O^{15}, which decays in nitrogen N^{15} emitting a positron and a neutrino.

Finally, the N^{15} nucleus captures a fourth proton to create carbon C^{12} and helium He^4:

$$C^{12}[p,\gamma]N^{13}[,e^{+}\upsilon]C^{13}[p,\gamma]N^{14}[p,\gamma]O^{15}[,e^{+}\upsilon]N^{15}[p,\alpha]C^{12}$$

With very low probability (4 times on 10^4), nitrogen N^{15}, capturing a proton, can alternatively produce oxygen O^{16} instead of carbon and helium. The oxygen can interact with a proton obtaining fluorine F^{17}, and a gamma ray. The fluorine decays in oxygen O^{17} emitting a positron and a neutrino.
Finally, the oxygen interacts with a proton producing an α particle and nitrogen N^{14}.

$$N^{15}[p,\gamma]O^{16}[p,\gamma]F^{17}[,e^{+}\upsilon]O^{17}(p,\alpha)N^{14}$$

The energy product in both cycles is about 25 Mev ($4,0\cdot10^{-5}$ erg).
When the hydrogen is fully converted in helium in the stellar nuclei, the central regions begin to contract, rising the temperature and pressure of the gas, until is activated the burning of a second combustible: the helium. The nuclear process of helium is called 3α-burning, in which the nuclei of helium are transformed first in beryllium and then in carbon:

$$He^{4}[\alpha,\gamma)Be^{8}[\alpha,\gamma)C^{12}$$

The reaction that produces beryllium is endothermic (it not produces energy, but it needs about 0,1 Mev) and moreover the beryllium nucleus is instable and decays quickly in two α particles: the probability to have this reactions is very low. The energy produced by the entire reactions is 7,3 Mev ($1,17\cdot10^{-5}$ erg).
At the temperature of the 3α burning are possible other particle captures that form oxygen and, with very low probability, neon and magnesium nuclei:

$$C^{12}[\alpha,\gamma)O^{16}[\alpha,\gamma)Ne^{20}[\alpha,\gamma)Mg^{24}$$

At the end of the helium burning the mixture of elements in the stellar nuclei is composed essentially by carbon and oxygen, with traces of neon.
Although it is not relevant, we need to consider other reactions based on α particle capture by nitrogen N^{14} (product by CNO hydrogen burning):

$$N^{14}[\alpha,\gamma)F^{18}[,e^{+}\upsilon]O^{18}[\alpha,\gamma]Ne^{22}[\alpha,n]Mg^{25}$$

When the entire helium in the central region of the star is converted, the minor production of energy does not support the equilibrium of the internal stellar structure and so the nucleus starts to contract. When is reached a central temperature of $7\cdot10^{8}$ K, the carbon burning is activated, producing neon, sodium and, at low probability, magnesium and oxygen:

$$C^{12}[C^{12},\alpha]Ne^{20}$$
$$C^{12}[C^{12},p]Na^{23}$$
$$C^{12}[C^{12},p]Mg^{23}$$
$$C^{12}[C^{12},\gamma]Mg^{24}$$
$$C^{12}[C^{12},2\alpha]O^{16}$$

In addition new α particles, protons and neutrons are emitted. Since the temperatures are greater then the typical for hydrogen and helium burning, this proton and this α particles immediately react with other nuclei:

$$C^{12}[p,\gamma]N^{13}[,e^{+}\upsilon]C^{13}[\alpha,n]O^{16}$$

The total energy produced from carbon burning reactions is about 7,16 Mev.
At higher temperature ($2\cdot10^{9}$ K), the reaction between two oxygen nuclei is activated, forming silicon, phosphor, sulphur and magnesium:

$$O^{16}[O^{16},\alpha]Si^{28}$$
$$O^{16}[O^{16},p]P^{31}$$
$$O^{16}[O^{16},n]S^{31}$$
$$O^{16}[O^{16},\gamma]S^{32}$$
$$O^{16}[O^{16},2\alpha]Mg^{24}$$

These elements are then involved in a series of reactions that form new elements up to titanium Ti^{46} nuclei.

The energy produced from oxygen burning is about 7 Mev.

At temperature of 10^9 K the photodisintegration process (the disintegration of the nuclei by thermal photon) starts to dominate.

One of the nuclei mostly involved is neon Ne^{20} nucleus, that is broken into oxygen and helium, and produces an energy of 5,63 Mev:

$$Ne^{20}[\gamma,\alpha,]O^{16}$$

This particles are immediately captured in reactions that form elements up to iron Fe^{56} nuclei.

At this point the reactions stop, because with the iron nuclei is reached the maximal nucleon binding energy.

One of the possible reactions to produce iron starts from oxygen O^{16}, that produces silicon Si^{28} and finally is formed an instable nickel Ni^{56} nucleus that decays immediately in Fe^{56}:

$$O^{16}[O^{16},\alpha]Si^{28}[Si^{28},\gamma]Ni^{56}[,e+\upsilon)Fe56$$

An important issue is that in the nickel decays there is a strong energy emission by neutrinos.

Also the iron formed is affected by the photodisintegration, thus it is finally broken into helium nuclei and neutrons:

$$Fe^{56}\rightarrow 13\alpha+4n$$

This disintegration causes the collapse of the entire structure, up to the explosion of the star: we have a supernova, one of the most interesting and energetic events in the universe.

In the entire explosion phase, the energy release is equal to the total energy emitted by all the stars in a typical galaxy (10^{48} erg): but this is another argument.