

ENERGY PRODUCTION IN THE UNIVERSE: STELLAR NUCLEAR REACTIONS

The stellar energy production is one of 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 :

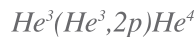
$$dL_r/dr = 4 \cdot \pi \cdot r^2 \cdot \rho \cdot \epsilon$$

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.

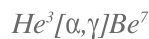
In the proton-proton chain the first interaction between two protons develops a deuterium nucleus, releasing also a positron (that interacts with an electron, forming a gamma ray) and a neutrino. The interaction of the deuterium with a third proton produces a helium He³ nucleus:



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 He³, formed in an analogous reaction, producing a helium He⁴ nucleus and two protons:



But the He³ nucleus can interact with an He⁴ nucleus (α particle) forming a beryllium Be⁷ nucleus,

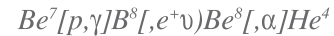


In the second chain, PPII, the beryllium nucleus captures an electron producing lithium and a neutrino; the lithium interacting with a proton finally forms two helium nuclei:



In the third chain, PPIII, the beryllium interacts with a proton forming boron B⁸, an instable nucleus

that decays in beryllium Be⁸, a positron and a neutrino. The beryllium, also instable, decays in two α particles:



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 ($4,2 \cdot 10^{-5}$ erg), the PPII emits 25,67 Mev ($4,1 \cdot 10^{-5}$ erg) and the PPIII produces 19,27 Mev ($3,1 \cdot 10^{-5}$ erg).

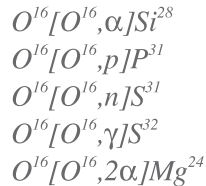
After the proton-proton chain, we consider the second burning hydrogen typology: the so called carbon cycle CNO. In this cycle we have also two different types of burnings.

In the first, called principal, a carbon nucleus C¹³ interacts with a proton forming a nitrogen N¹³ nucleus and a gamma ray. Nitrogen decays in carbon C¹³, releasing a positron and a neutrino.

The C¹³ captures another proton forming nitrogen N¹⁴, and a gamma ray.

The nitrogen nucleus interacting with a proton produces oxygen O¹⁵, which decays in nitrogen N¹⁵ emitting a positron and a neutrino.

Finally, the N¹⁵ nucleus captures a fourth proton to create carbon C¹² and helium He⁴:

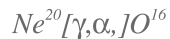


These elements are then involved in a series of reactions that form new elements up to titanium Ti^{46} nuclei.

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.

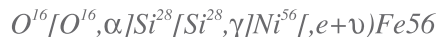
One of the nuclei mostly involved is neon Ne^{20} nucleus, that is broken into oxygen and helium, and produces an energy of 5,63 Mev:



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

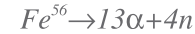
At this point the reactions stop, because with the iron nuclei is reached the maximal nucleon binding energy.

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} :



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:



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.