

The Universe in my pocket



We come
from the stars



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Atoms are the elementary constituents of matter. They consist of a **nucleus** (which contains **protons** and **neutrons**) and of **electrons**. **Atoms** combine into **molecules** by sharing their **electrons**. The cells of the human body are made up of billions of **molecules**.

The history of stellar nucleosynthesis:

Robert d'Escourt Atkinson **A** published his article "Atomic synthesis and stellar energy" in 1931. Hans Bethe **B** identified in 1938 and 1939 the two mechanisms that transform hydrogen into helium in stars. Fred Hoyle showed in 1946 how the elements are synthesized from hydrogen. Margaret and Geoffrey Burbidge, William Fowler and Fred Hoyle **B²FH** published in 1957 their very detailed article "Synthesis of the elements in stars" and, the same year, Alastair Cameron **C** published "Nuclear reactions in stars and nucleogenesis".



Our bodies are made up of water (63%), proteins (20%), fat (10%), sugars (2%) and various minerals (5%).

Since chemistry was developed, at the end of the 18th century, we know that all these materials are composed of complex **molecules** which contain **atoms** of hydrogen, carbon, oxygen and other **elements** in smaller quantities.

These **elements** are exactly the same as those found in plants, in the Earth's crust and in the atmosphere.

Using spectroscopy, astronomers have shown that these same **elements** are also found in stars. But it was not until the middle of the 20th century that astronomers succeeded in understanding the origin of these **elements** and in discovering the very close link which connects us to the stars.

Proton: formed of three elementary particles, the quarks. It has a positive electric charge and its mass is $1.672\ 649 \times 10^{-24}$ g.

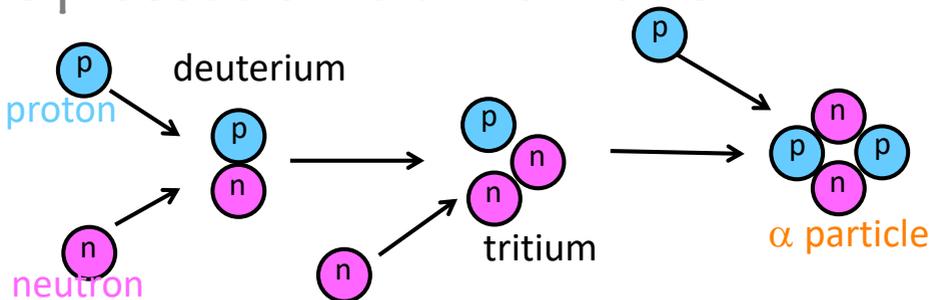
Neutron: also formed of three quarks but does not have an electric charge. Its mass is $1.674\ 93 \times 10^{-24}$ g.

Electron: particle of negative electric charge, whose mass is about 1/2000 of that of the proton.

Hydrogen: the lightest of the elements. It consists of a proton and an electron.

Helium: the lightest stable element after hydrogen. It consists of an α particle and 2 electrons.

One process of helium formation



It was George Gamow, in an article with Alpher and Bethe in 1948, who proposed the theory of the formation of primordial hydrogen and helium. In this article, the authors further argued that all the other elements were also formed in the Big Bang by successively adding neutrons. But on this point they were wrong.

Hydrogen and helium

When the Universe was very dense and hot ($T = 10^{12}$ K), shortly after the Big Bang*, it contained only elementary particles of matter (quarks, electrons, neutrinos) and 'grains' of light called photons.

As they cooled, the quarks combined into **protons** and **neutrons** in equal amounts. But as the temperature dropped, most neutrons turned into **protons** which are less massive. When the temperature fell below 10^9 K, there were 7 **protons** for every **neutron**.

Neutrons and **protons** then combined to form **nuclei**. The most stable **nucleus** that could be formed at that time was **helium**. All the available **neutrons** were used to form **helium**, giving one **helium nucleus** for every 12 **hydrogen nuclei** at the end of the primordial epoch.

* see tuimp 12

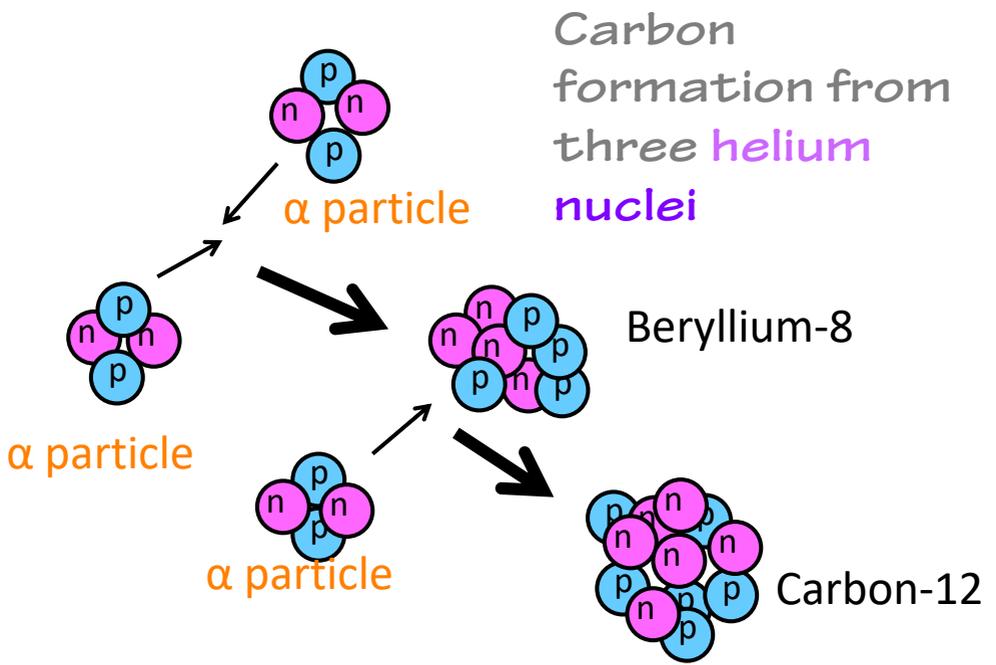
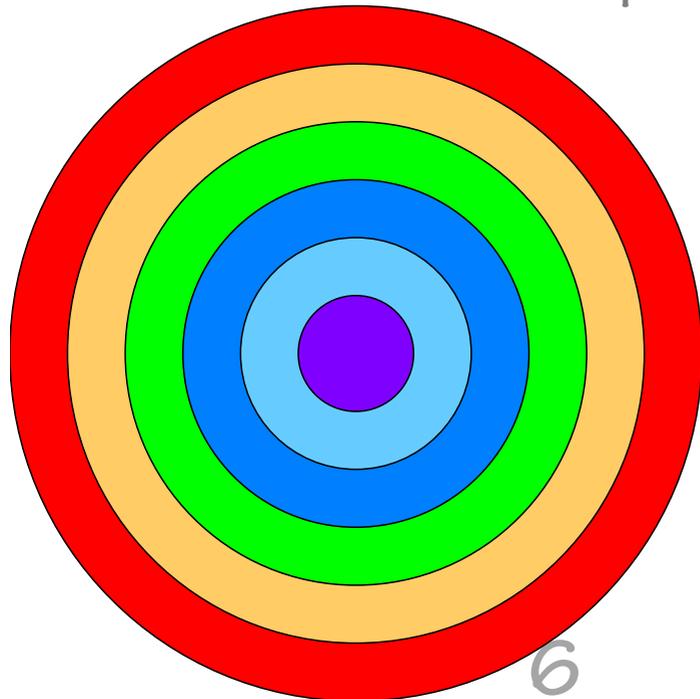


Diagram of the onion structure of a massive star at the end of its evolution. Each layer has a different composition. **Elements**

heavier than iron are produced by **neutron capture**.



hydrogen
helium
carbon
oxygen
silicon
iron

Fusion in stars

The very hot and dense core of a star provides ideal conditions for producing larger and larger **nuclei**.

First, **hydrogen** atoms combine to form **helium**. This corresponds to the longest phase in the life of a star. Almost all of the stars we see shining get their energy from this process.

Once the **hydrogen** is used up, the **helium** core condenses and its temperature rises. Then the **helium nuclei** fuse in groups of three to form carbon, while **hydrogen** continues to produce **helium** in the outer layers of the star.

Heavier **nuclei** are then formed, by further additions of **α particles** in different layers. If the star is massive enough, this process continues until the core is made of iron, the most stable element.

Nuclei heavier than iron are created under different conditions by the addition of **neutrons**.



The Cat's Eye planetary nebula. (Credit: R. Corradi with the NOT telescope).

Composite image of the Cat's Eye planetary nebula. This object results from several episodes of stellar winds emanating from the central star which is now in the process of becoming a white dwarf.

G292.0+1.8: A supernova remnant coming from a star of great mass which ejected a lot of oxygen, magnesium and neon into the interstellar medium.



G292.0+1.8 in X-rays. Credit : NASA/CXC/SAO .



Artist view (Dana Berry, SkyWorks Digital).

Representation of the collision of two **neutron** stars. Gold, uranium and other heavy elements in the Universe are believed to have formed during such an event.

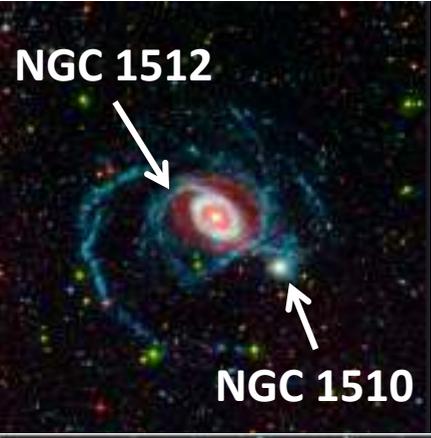
Winds, collisions, explosions

Some of the **elements** formed in stars are ejected into the interstellar medium while the rest are locked up forever in the 'stellar corpses' that are white dwarfs, **neutron** stars and black holes.

Stars with a mass of less than 8 times that of the Sun disperse their outer layers in a peaceful manner, ejecting nitrogen, carbon and some **elements** heavier than iron.

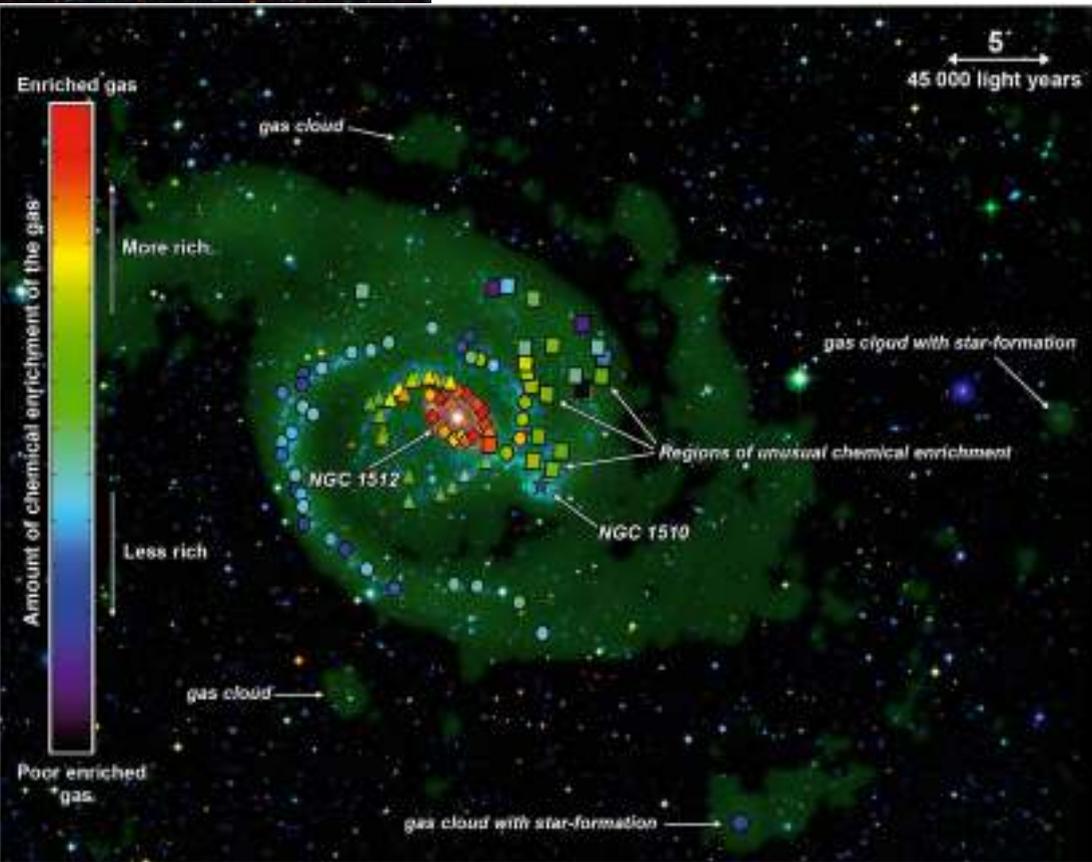
The more massive stars end their life in a spectacular explosion, a supernova, and expel carbon, oxygen, neon, magnesium and silicon, among others.

Other heavy **elements**, such as gold and uranium require a very high density of **neutrons** to form, and this is more likely to happen in neutron star collisions.



The galaxies NGC 1512 and NGC 1510 seen in ultraviolet light. Bright areas are regions where stars have recently formed.

Credit: GALEX (NASA)



The symbols indicate the abundance of oxygen (red where abundant, blue where scarce).

Credit: López-Sánchez (AAO/MQU) & Koribalski (CSIRO).

The cosmic odyssey of the elements

Once released into the interstellar medium, the **elements** begin a long journey across the galaxies, before being trapped during the formation of new stars. Thus, successive generations of stars become increasingly rich in carbon, nitrogen, oxygen and other elements.

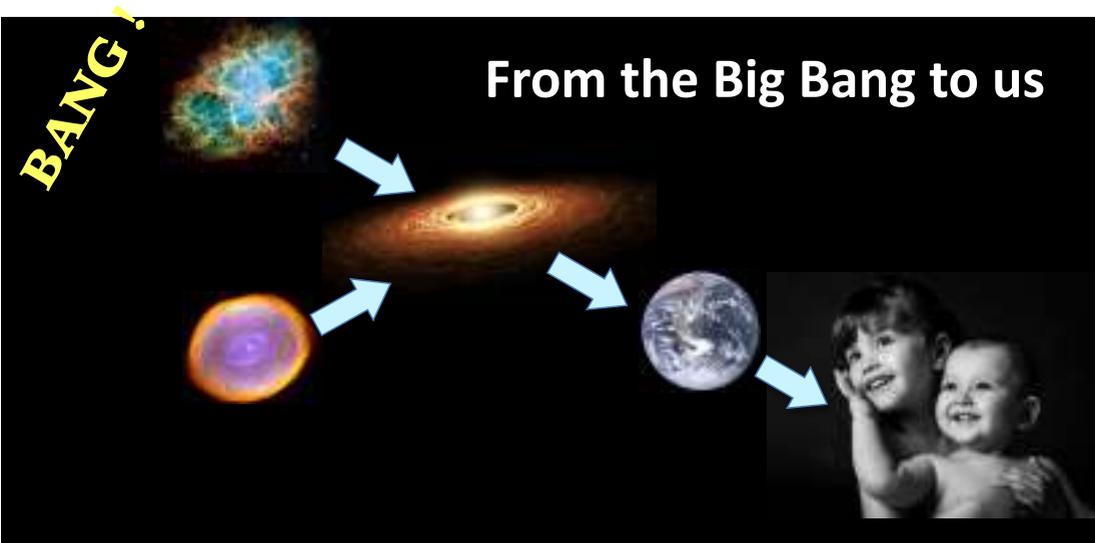
The journey of the **elements** through the interstellar medium can be very tortuous, with perturbations linked to collisions between galaxies.

Elements released during supernova explosions can even make incursions into the intergalactic medium, and finally end up in other galaxies.

In fact, recent numerical simulations suggest that many of the **elements** present in the Milky Way came from other galaxies.

Mass percentage of the chemical **elements** in different locations

	Num. of protons	Solar system	Earth's crust	Human body
H	1	70.5	0.14	9.5
He	2	27.5	-	-
C	6	0.30	0.030	18.5
N	7	0.11	0.005	3.2
O	8	0.96	46.6	65
Si	14	0.065	27.7	0.00002
S	16	0.040	0.050	0.3
Ca	20	0.006	3.6	1.5
Fe	26	0.117	5.0	0.006



From stars to living beings

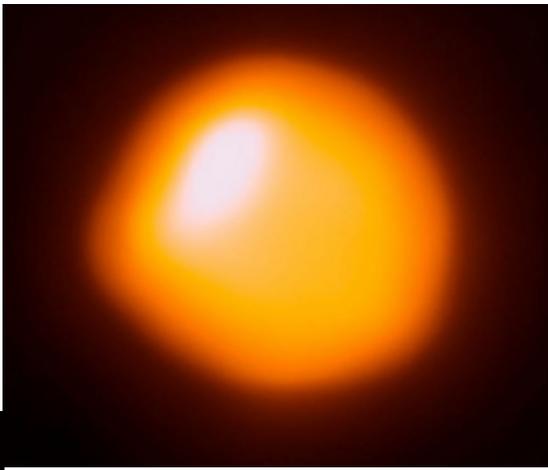
Before becoming part of a living being, **elements** must pass through many stages that are still poorly understood.

First there is the formation of clouds of **molecules** and dust, in which stars are born. While still very young, these stars are surrounded by a protoplanetary disk, made up of clumps of dust and ice.

It is from this disk material that planets are formed. Their chemical composition differs according to the distance from the star: The smaller the distance, the easier it is for the volatile **elements** to dissipate. It also depends on the planets' mass: The smaller the mass, the easier it is for the lighter particles to escape.

As the planet forms, a segregation of **elements** occurs so that the core has a different composition from the crust.

Finally, it is from the materials in the crust that living beings are formed.



Quiz

What is the origin of gold ?



Answer on overleaf



The star
Betelgeuse

Planet Jupiter

A creside: a gold
coin, struck by King
Croesus in the 6th
century BC. in Lydia

Planetary nebula
IC 418

The Crab supernova
remnant

Answer

Gold is thought to
form during the
collision of neutron
stars like the one
shown in this
picture

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This booklet was written in 2020 by Grażyna Stasińska of the Paris Observatory (France) and revised by Nikos Prantzos from the Paris Institute of Astrophysics.

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