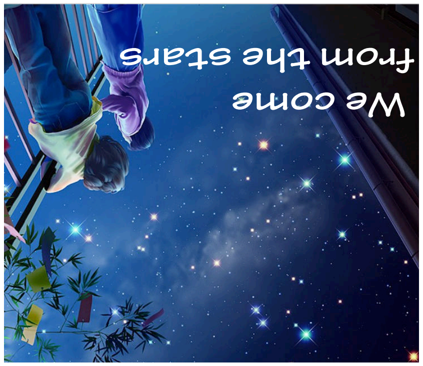
The Universe in my pocket



Grażyna Stasińska
Paris Observatory

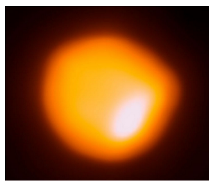
TUIMP No. 14

Quiz

What is the origin of gold ?








Answer on overleaf

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.

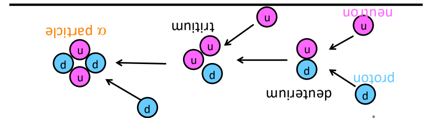
As they cooled, the quarks combined into protons and neutrons in equal amounts. But as the temperature dropped, most neutrons turned into protons which are less massive. When the temperature fell below 10^9 K, there were 7 protons for every neutron.

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

Proton: formed of three elementary particles, the quarks. It has a positive electric charge and its mass is 1.672 649 x 10^{-24} g.
Neutron: also formed of three quarks but does not have an electric charge. Its mass is 1.674 93 x 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 consist 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.

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 in X-rays. Credit : NASA/CXC/SAO .

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.

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.

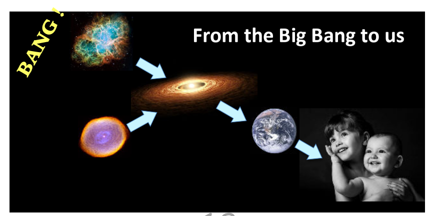
Stars with a mass of less than 8 times that of the Sun disperse their outer layers in a peaceful manner, ejecting nitrogen, carbon and some elements heavier than iron.

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.

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.

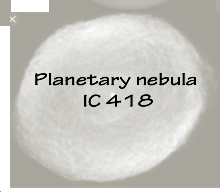
Finally, it is from the materials in the crust that living beings are formed.

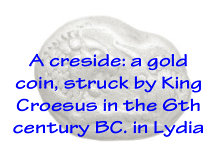
Atoms are the elementary constituents of matter. They consist of a nucleus (which contains protons and neutrons) and of electrons. Atoms combine into molecules by sharing their electrons. The cells of the human body are made up of billions of molecules.

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 B^2FH 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".


The star Betelgeuse

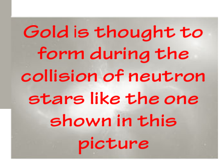

Planet Jupiter


Planetary nebula IC 418


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


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.

Cover image : extract of a painting by japanese artist KAGAYA

To learn more about this series and about the topics presented in this booklet, please visit http://www.tuimp.org

Translation: Stan Kurtz

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.

Fusion in stars

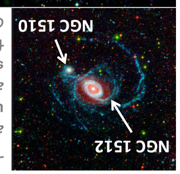
The very hot and dense core of a star provides ideal conditions for producing larger and larger nuclei.

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.

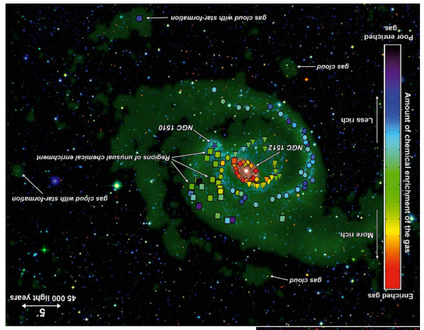
Once the hydrogen is used up, the helium core condenses and its temperature rises. Then the helium nuclei fuse in groups of three to form carbon, while hydrogen continues to produce helium in the outer layers of the star.

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 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.

Carbon formation from three helium nuclei

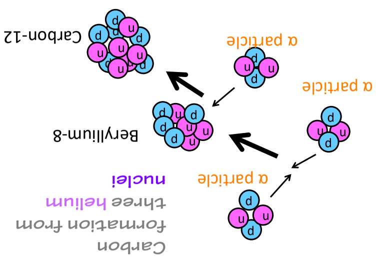


Diagram of the onion structure of a massive star at the end of its evolution. Each layer has a different composition. Elements heavier than iron are produced by neutron capture.