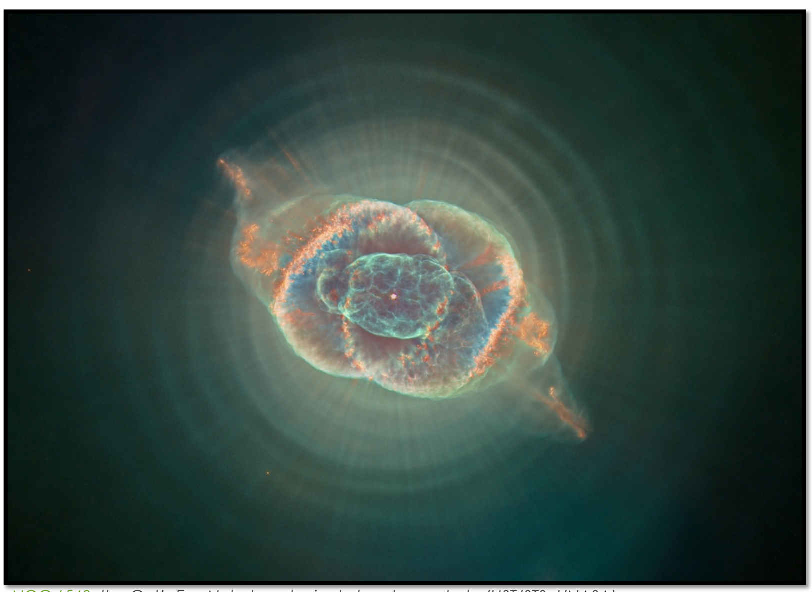
12 September
2019

THE ORIGIN OF HEAVY ELEMENTS AND MOLECULES

Homework #2 on WeBWorK – due Wednesday by 7pm



NGC 6543, *the Cat's Eye Nebula, a typical planetary nebula (HST/STScI/NASA)*

The origin of heavy elements and molecules

Big Bang nucleosynthesis

Nucleosynthesis in stars: heavy-element enrichment of the ISM

Today's chemical elements: summary of the nuclear-chemical evolution of the Universe

Molecules

Chemistry of the ISM: the simpler of the molecules of life in outer space

Nucleosynthesis

The Universe started out with all its mass in light elements.

To make heavier elements out of lighter ones requires very high density and temperature (at least tens of millions of K)

Such conditions are found in two sorts of places in the cosmos:

- Blast waves from exploding stars or the Big Bang. This is called **explosive nucleosynthesis**.
- The very center of stars. This is called **stellar-core nucleosynthesis**.

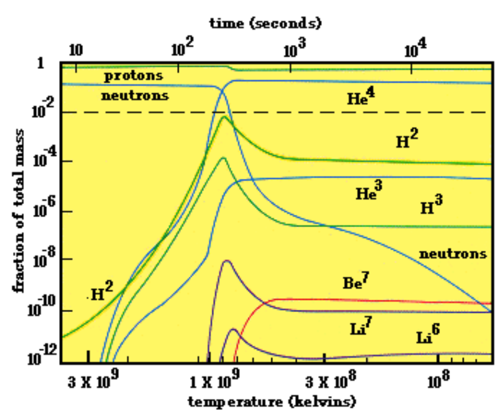
The different kinds of mechanisms are good at producing different kinds of elements.

Big Bang nucleosynthesis

Within about 1 second of the Big Bang, the temperature had cooled to around 10^{10} K, and protons, neutrons, and electrons could form without being immediately destroyed.

Between 100 and 180 seconds, the temperature dropped below 10^9 K, and bound combinations of protons and neutron could form by fusion, prominently ^{4}He, ^{3}He, ^{3}H (a.k.a. T), and ^{2}H (a.k.a. D).

We know this through measurement of abundances in very primitive, low-mass galaxies.

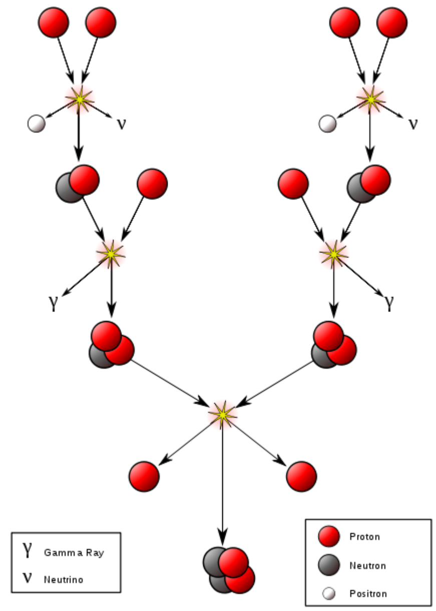


From Ned Wright's *Big Bang Nucleosynthesis page*

Hydrogen (H) fusion

Ordinary fusion in ordinary stars: **p-p chain I**

- Main fusion in the Big Bang
- Also main fusion process in stars throughout the Universe's history, and the source of heat and pressure that prevents stars from collapsing under their own weight
- Mainly fuses four H into ^{4}He
- Intermediate products include D and ^{3}He



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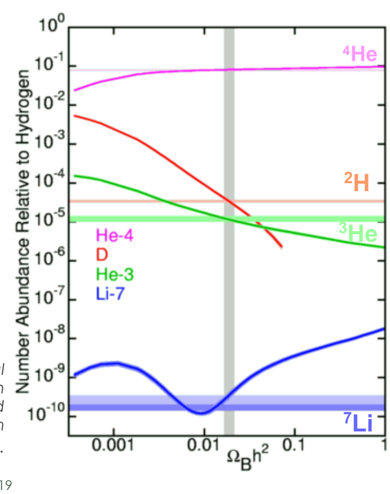
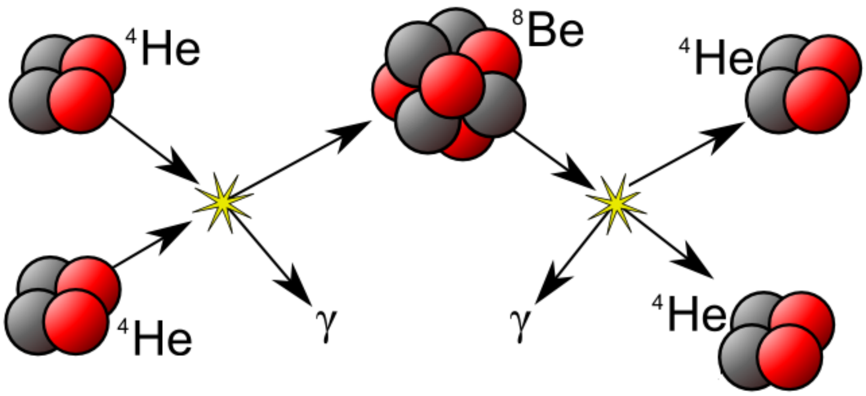
Big Bang nucleosynthesis

That is where it stops, though; besides relatively small amounts of lithium and ^{7}Be, no heavier elements are made at all in the Big Bang.



Theory (curves) vs. experiment (horizontal stripes) for abundances of elements made in the Big Bang. Baryons are protons and neutrons; density is mass per unit volume (from Ned Wright's Big Bang Nucleosynthesis page).



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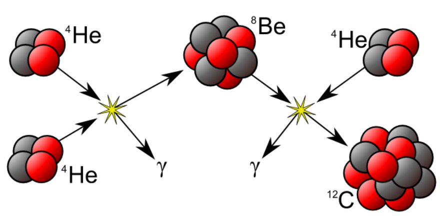
Big Bang nucleosynthesis

The reason it stops is the robustness of the ^{4}He nucleus: when ^{8}Be is made, it decays back into two ^{4}He, with a half-life 3×10^{-16} sec. This situation is called the **mass-8 bottleneck**.

Big Bang nucleosynthesis

If, within 3×10^{-16} sec, the ^{8}Be is hit by another ^{4}He, it will stick and make ^{12}C. This is called the **triple-alpha process**:



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By the time much ^{4}He was made, though, the density of the Universe was so small that the chances of such an encounter were close to zero: no triple-alpha, and therefore no ^{12}C.

Thus, all the hydrogen and helium, and most of the lithium and ^{7}Be, in the Universe is made during the Big Bang. And nothing else.

The first stars

Fast forward about 300 million years. Dense clumps have developed in the expanding Universe that will develop into galaxies; denser knots within them become the first stars.

The first stars in the Universe were unlike any we have today: **typically $300 - 1000M_{\odot}$** instead of today's $0.5 - 2M_{\odot}$.

Astronomers call this original set of stars **Population III**.

These stars lived very short lives: within only a million years or so, fusion exhausted the hydrogen in their centers, robbing them of the heat and pressure that held up their weight.

The first stars

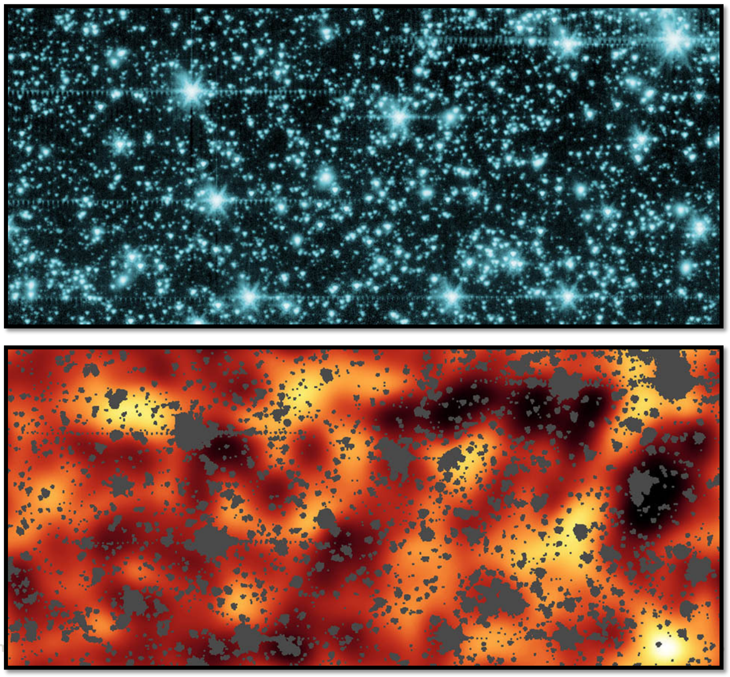
Thereupon their cores collapsed to form black holes, and their outer parts exploded with great violence. These events are called **core-collapse supernovae**.

- Matter in the black holes disappears from our story; see AST 102 next semester to follow it further.

The supernova explosions created the conditions under which the triple-alpha process could proceed, albeit briefly.

And thus the gas in between the stars – the **interstellar medium (ISM)** – was polluted with its first elements heavier than $A = 7$. This had profound effects on the nature of subsequent generations of stars.

NASA/CXO/A. Hobart



The first stars

Top: Infrared image of a piece of the sky in Draco, showing several stars and numerous galaxies in the foreground.

Bottom: Same scene with the known stars and galaxies removed. What remains is the glow from the first stars and the supernovae they created.

(SSC/NASA)

Review question

What is the heaviest element made during the first three minutes after the Big Bang?

A. Uranium
B. Oxygen
C. Beryllium
D. Lithium
E. Helium
F. Deuterium

Review question

What is the mass number, *A* (total number of protons and neutrons), of the heaviest element made by the Big Bang?

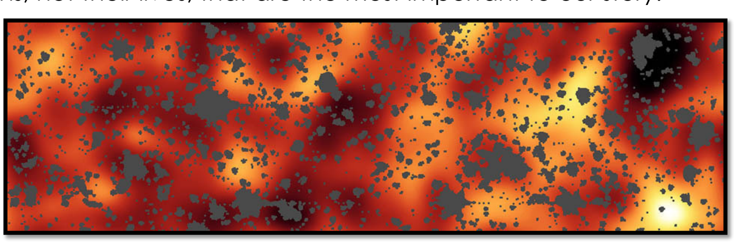
A. 6
B. 7
C. 8
D. 9
E. 10

The life of Population III

The first stars were so massive that their typical lives and death were completely different from those of subsequent generations.

- No Giant phase, and thus very little mixing between the deep interior – where fusion takes place – and the outer layers.
- All die in a million years or less, producing black holes (from the interiors) and violent explosions (outer layers): core-collapse supernovae.

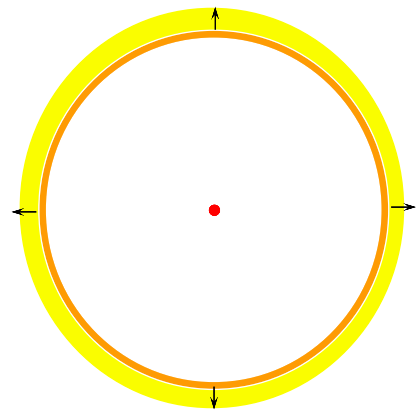
It is their deaths, not their lives, that are the most important to our story.



The death of Population III

The explosion compresses and heats the outer layers of the star

- This fuses much of the hydrogen (H) into ^{4}He (a.k.a. alpha)
- Such high density and temperature are reached that the triple-alpha process can proceed, making the Universe's first carbon.
- Continual bombardment and fusion by ^{4}He makes a sequence of heavy nuclei consisting of round numbers of alpha particles: the **alpha elements**.
- The explosion's expansion mixes the products into the interstellar medium (ISM).



Explosive nucleosynthesis of the alpha elements

(Neglecting light particles like positrons, neutrinos, etc.)

These account for most of the chemical enrichment of the interstellar medium by the First Stars.

$3(^{4}He) \rightarrow {}^{12}C$

$^{12}C + {}^{4}He \rightarrow {}^{16}O$

$^{16}O + {}^{4}He \rightarrow {}^{20}Ne$

$^{20}Ne + {}^{4}He \rightarrow {}^{24}Mg$

$^{24}Mg + {}^{4}He \rightarrow {}^{28}Si$

$^{28}Si + {}^{4}He \rightarrow {}^{32}S$

$^{32}S + {}^{4}He \rightarrow {}^{36}Ar$

$^{36}Ar + {}^{4}He \rightarrow {}^{40}Ca$

$^{40}Ca + {}^{4}He \rightarrow {}^{44}Ti \rightarrow {}^{44}Sc$ (60 years) $\rightarrow {}^{44}Ca$ (4 hours)

$^{44}Ti + {}^{4}He \rightarrow {}^{48}Cr \rightarrow {}^{48}V$ (22 hours) $\rightarrow {}^{48}Ti$ (16 days)

$^{48}Cr + {}^{4}He \rightarrow {}^{52}Fe \rightarrow {}^{52}Mn$ (8 hours) $\rightarrow {}^{52}Cr$ (6 days)

$^{52}Fe + {}^{4}He \rightarrow {}^{56}Ni \rightarrow {}^{56}Co$ (6 days) $\rightarrow {}^{56}Fe$ (77 days)

$^{56}Ni + {}^{4}He \rightarrow {}^{60}Zn \rightarrow {}^{60}Cu$ (2 minutes) $\rightarrow {}^{60}Ni$ (24 minutes)

$^{60}Ni + {}^{4}He \rightarrow {}^{64}Ge \rightarrow {}^{64}Ga$ (1 minute) $\rightarrow {}^{64}Zn$ (3 minutes)

Question

Select all that apply.

Which of the elements that are necessary for life existed in abundance after the first generation of stars?

A. Carbon
B. Hydrogen
C. Oxygen
D. Nitrogen
E. Sulfur
F. Phosphorous

Question

Select all that apply.

Besides hydrogen and lithium – atomic numbers 1 and 3, respectively – which *odd-numbered* elements existed abundantly in the ISM after the Pop III stars died?

A. Boron
B. Nitrogen
C. Fluorine
D. Sodium
E. Aluminum
F. All of these
G. None of these

The second stars

Subsequent generations of stars, which formed from interstellar matter containing a few heavy elements, differ from the first in several ways.

- **Much smaller**. Even though heavy elements were still rare, they increased the cooling rates of interstellar matter dramatically, in a way that promoted the formation of smaller-mass stars.
- **MUCH longer lived**. The decrease in mass leads to a disproportionate decrease in **luminosity** (total power output in the form of light).
- **Produce new elements.** Additional fusion processes in their cores, and additional nucleosynthetic options
- **New ways to die**, signified by planetary nebulae and a new kind of supernova.

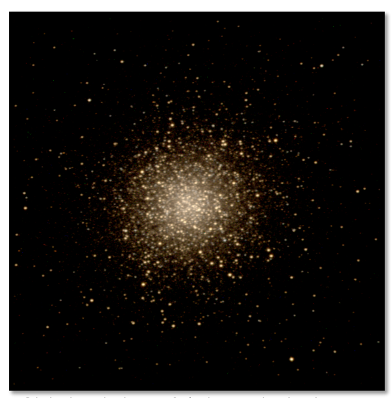
The more massive stars of this type are gone, but smaller-mass examples are still alive today…

Population II

- There is a distinct population of stars with larger random motions within our Galaxy, and greater range outside the plane of our Galaxy, than stars like our Sun.
- Some live in **globular clusters**; these are all about 13 Gyr old and so formed very early in the Galaxy's life.
- Their heavy-element abundances are small, and most of the abundances indicate an origin in explosive nucleosynthesis.

Astronomers call this set of stars **Population II**.

Pop II stars of mass $> 10M_\odot$ still died in supernovae. Those of mass $2 - 10M_\odot$ lived at most a few billion years, but ended their lives in less spectacular fashion than Pop III.



Globular cluster M13, in true color (UR/Mees Observatory). Contains about 500,000 stars.

New ways of stellar death: Pop II, $M < 10M_{\odot}$

As the last of the hydrogen in a star's core has fused to helium, the core collapses, compresses, and heats until it is hot enough to make C through triple-alpha (**helium-burning**).

Elements between the alphas were manufactured by fusion processes which add baryons to nuclei one at a time: ^{14}N, ^{17}F, ^{22}Na, ^{27}Al, and so on.

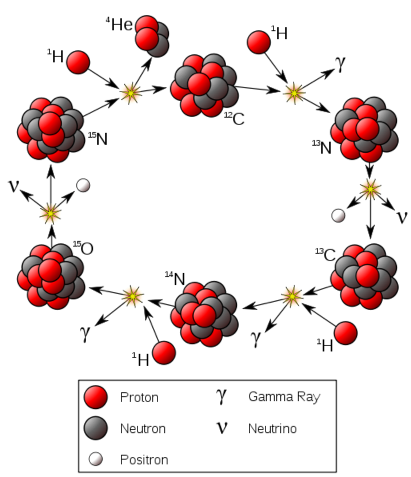
But helium burning makes the star mechanically unstable: the outer parts swell up (making the star a **giant** or **supergiant**), and material from the dense interior mixes with the outer layers.

Globular cluster M13, with the colors adjusted to show the helium-burning stars distinctively in blue (UR/Mees Observatory)

Slow fusion processes in stars: CNO cycle

Starting with Pop II: **CNO cycle I**

- Like the p-p chains, it fuses four H into ^{4}He, but…
- …requires preexisting ^{12}C (and higher temperatures).
- …involves different elements as intermediate products: notably ^{13}C, ^{14}N, ^{15}N.



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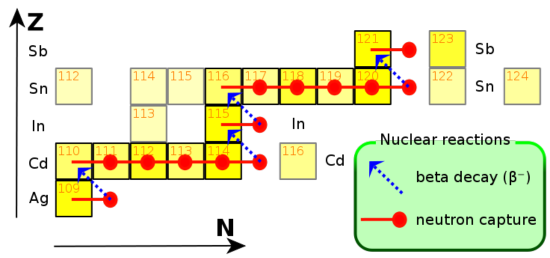
Slow fusion processes in stars: s-process

Fusion in stars near death, starting with Pop II: the **s-process** (slow neutron-capture)

- Some of the lighter-nucleus fusion processes have neutrons as a byproduct; for instance,

$$^{13}C + {}^{4}He \rightarrow {}^{16}O + n$$

- These neutrons tend to be gobbled up by heavier nuclei, especially those heavier than Fe.
- Add beta decay, and this process fills in many of the gaps between the "alpha" elements made in explosions.



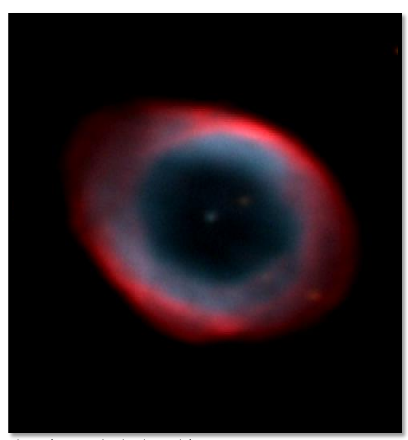
Example: s-process from Ag to Sb (Wikimedia Commons)

Stellar death: white dwarfs

The star begins to shed its outer layers, sending the heavy-element enriched material back out to the ISM.

After a few million years, when helium and carbon fusion have ceased, only the dead core, as a **white dwarf**, and surrounding shells of expanding material are left.

The last gasp of ejected material is called a **planetary nebula**; it decorates the scene for a few thousand years as its contents merge into the interstellar medium.



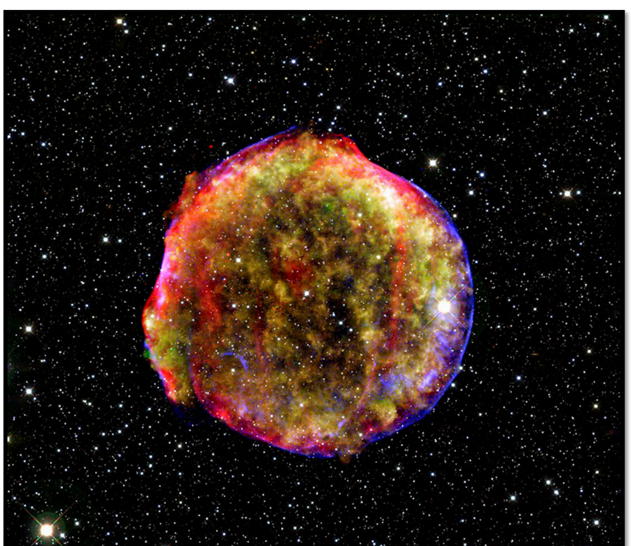
The Ring Nebula (M57) in Lyra near Vega (UR/Mees Observatory)

Stellar death: Type Ia supernovae

Some of the white dwarfs can die again, as **Type Ia supernovae (SN Ia)**

- Many stars live in close multiple systems. The death of one does not disturb the others much.
- White dwarfs can wind up close to ordinary or giant stars, close enough to **accrete** matter from them.
- While dwarfs have a maximum mass of $1.4M_{\odot}$. If accretion tips a white dwarf over the maximum, rapid collapse and the ignition of C and O fusion explode it with great violence, spewing highly-concentrated heavy elements into space.

European Southern Observatory



Remnant of Tycho's Supernova (1572), which was a SNIa. Blue = X-ray (Chandra, NASA/CXC/SAO), green = visible light (MPIA, Calar Alto), red = mid-infrared (Spitzer, SSC/NASA). By Olivier Krause.

SN Ia nucleosynthesis

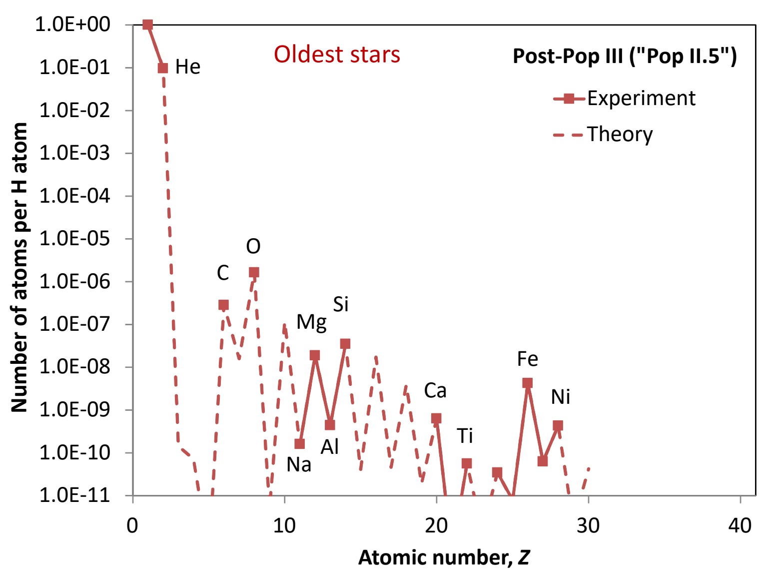
SNeIa are particularly productive of iron-peak elements. Though the events are rare, they are thought to have produced about half of the iron in the present-day ISM.

Population I

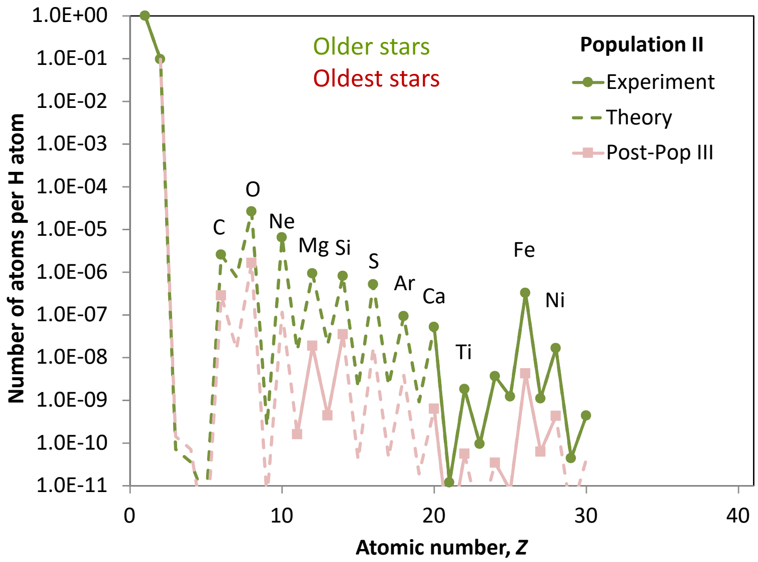
There is a population of stars with higher abundances of heavy elements than Pop II, in accordance with the combination of explosive and stellar-core nucleosynthesis in Pop III and Pop II:

- Much smaller random motions than Pop II and confined much more tightly to the plane of the Milky Way where most of the ISM also resides
- Absent from globular clusters
- Can belong to clusters, but these **open clusters** are smaller, less organized, and rarely older than 1 Gyr
- The Sun is one of these stars.

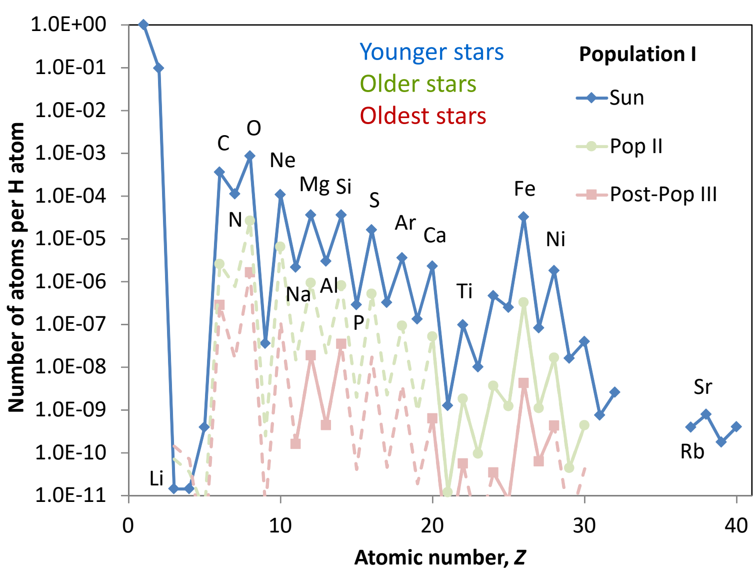
We call these stars **Population I**.



The nuclear-chemical evolution of the Milky Way

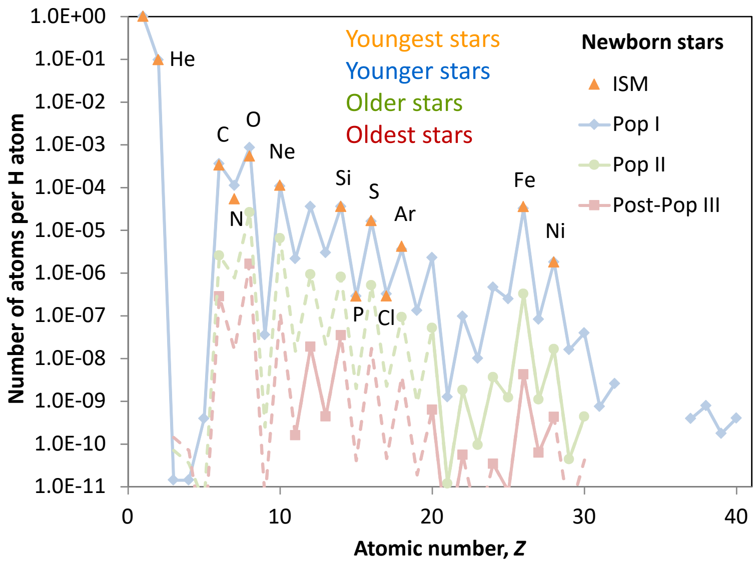


The nuclear-chemical evolution of the Milky Way



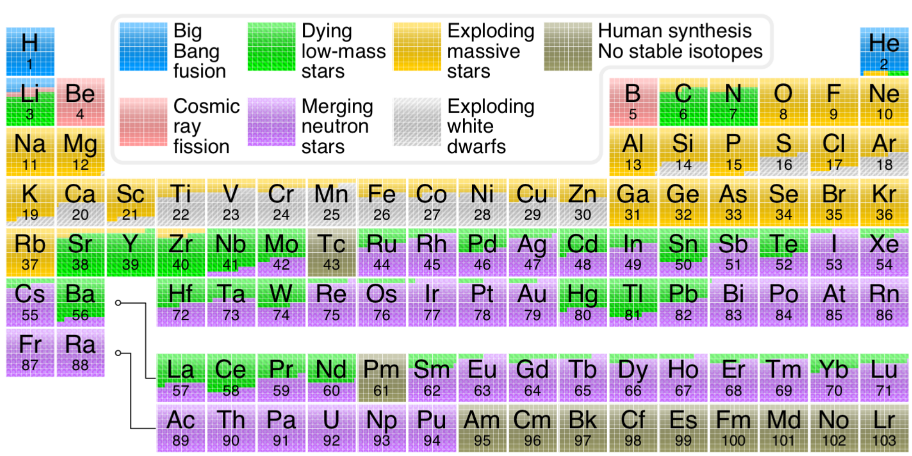
The nuclear-chemical evolution of the Milky Way

Smaller factor between odd and even Z: CNO, s-process more important as time goes on.



The nuclear-chemical evolution of the Milky Way

Origin of the elements



The nuclear-chemical evolution of the Universe

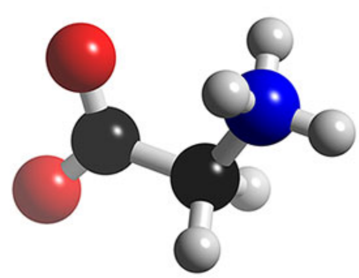
As time has elapsed since the Big Bang,

- Many successive generations of stars have enriched the interstellar medium with elements heavier than those made in the Big Bang.
  - At first via explosive nucleosynthesis
  - Later with the star's own internal fusion products
- The composition change is small between consecutive generations but adds up steadily over time: a form of **evolution**
- As the composition changes, the structure of galaxies and their interstellar medium drastically change, along with the mechanisms of star formation and death.

The evolution of interstellar matter: emergence of molecules

The heavy-element enriched material from normal stellar death via mass loss / planetary nebula / white dwarf comes out in two forms:

- Gas, mostly (99% by mass)
- **Dust**: initially partly-crystalline (mineral!) clumps containing high-melting-point (a.k.a. **refractory**) materials like Si, Mg, and Fe. Small: 100-100,000,000 atoms



The heavy-element enriched gas and dust mixes into the existing ISM and **profoundly** affects the nature of the ISM, as the presence of dust and the higher concentration of heavy elements lead to the formation of lots of molecules.

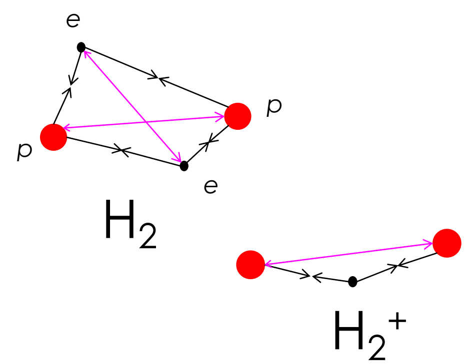
Molecular binding

Like atoms, molecules are held together by the **electrostatic force**, with the nuclei of the participating atoms typically about 10^{-8} cm apart.

Binding is a result of the balance between the attraction of the nuclei for each other's electrons, and the repulsion of the nuclei and the electrons. Bond = electron sharing

Thus, molecules tend to be fragile, but they can have complex structure.

Nothing obliges them to be neutral (not ionized).

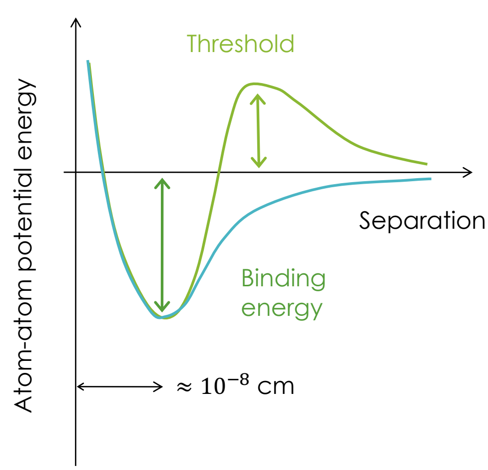


Molecular binding

Atoms bind into molecules if the potential energy is less than that of the separated atoms.

Two neutral atoms or similarly-charged ions exhibit thresholds at separations larger than that for minimum binding energy.

Ion-neutral pairs, or oppositely-charged ions, have zero threshold.



Quantum behavior of molecules

On the distance scale of molecular bonds (about 10^{-8} cm), electrons behave as (probability density) waves instead of particles.

Waves can **interfere** with one another either constructively or destructively (particles cannot).

As a result, electrons in molecules cannot have any energy they want: only certain energies are allowed (quantization of molecular electronic energy levels).

But nuclear position influences the electron structure and vice versa.

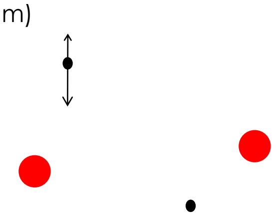
Thus, energies of molecular **vibration** and **rotation** are quantized, too.

Energies of different bound states of molecules

Electronic energies

Different states correspond to electrons in different configurations

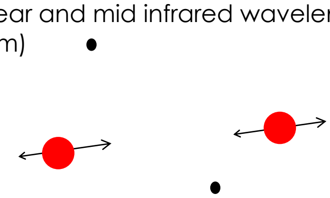
Energy differences typically correspond to visible and ultraviolet wavelengths (0.1-1 μm)



Vibrational energies

Different states: different modes of vibration of the nuclei, either along or transverse to the bonds: like different notes on a guitar string.

Energy differences typically correspond to near and mid infrared wavelengths (1-50 μm)

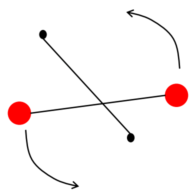


Energies of different bound states of molecules

Rotational energies

Different states: rotation of the molecules by quantized amounts about various different axes

Energy differences typically correspond to far-infrared and millimeter wavelengths (50 μm – 10 mm)



Linear and symmetrical molecules have **fewer vibrational and rotational states than complex, bent ones**.

Thus, they have fewer, and stronger, spectral lines and are easier to detect and identify.

By the same token, complex and misshapen molecules can be quite difficult to detect and identify, even if they are relatively abundant.

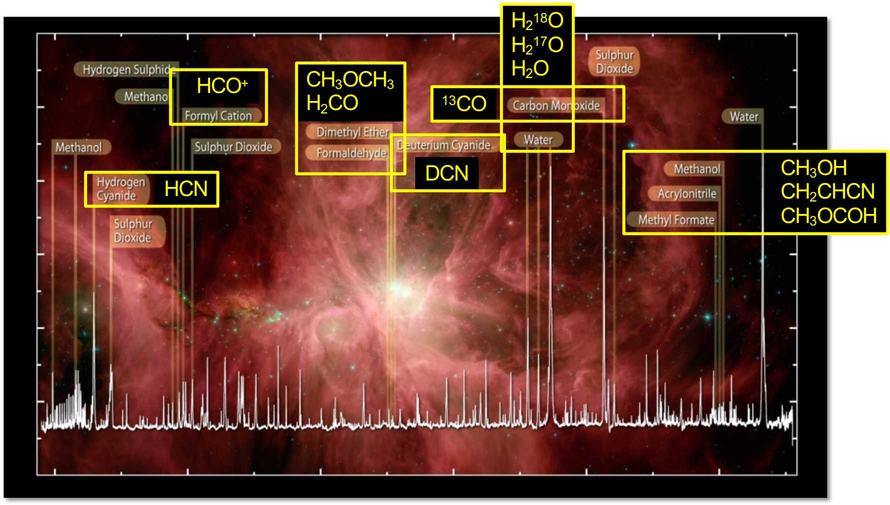
Identifying molecules in interstellar clouds & measuring their abundances

Every molecule has a distinctive set of electronic, vibrational, and rotational energy levels, and thus a distinctive spectrum: molecules can be positively identified.

The wavelengths and strengths of the spectral lines can be measured in the laboratory, usually to very high precision and accuracy.

The relative brightness of lines of a given species can be used to determine density, temperature, and pressure of the emitting region.

Thus, the relative brightness of lines of different species can be used to determine relative abundances.



Example rotational molecular-line spectrum

By Ted Bergin et al., with the HIFI instrument on the ESA Herschel Space Observatory

Which molecule do you suppose would be the most abundant in the cold interstellar medium?

A. CO
B. O_2
C. CaO
D. SiO
E. FeO

Question

Carbon monoxide is, in fact, the second most abundant molecule in the ISM after molecular hydrogen (H_2)