Today in Astronomy 106: the origin of heavy elements and molecules

- Nucleosynthesis in normal stars; Populations II and I; heavy-element enrichment of the interstellar medium

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

- Molecules

- Chemistry of the interstellar medium: the simpler of the molecules of life, in outer space.

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

Enter all choices that apply.
Review. What is the mass number, $A$ (total of protons and neutrons), of the heaviest element made by the Big Bang?

A. 6
B. 7
C. 8
D. 9
E. 10
The death of Population III

The first stars were so massive that their typical lives, and deaths, were completely different from those of subsequent generations:

- No Giant phase (see below), 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 most important to our story.
The death of Population III (continued)

The explosion compresses and heats the outer layers of the star extremely:

- This fuses much of the hydrogen 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.
Explosive nucleosynthesis of the “alpha” elements

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

These account for most of the heavy-element enrichment of the interstellar medium by the First Stars (contra the textbook, pp. 12-13).

\[ 3(\text{He}^4) \rightarrow \text{C}^{12} \]
\[ \text{C}^{12} + \text{He}^4 \rightarrow \text{O}^{16} \]
\[ \text{O}^{16} + \text{He}^4 \rightarrow \text{Ne}^{20} \]
\[ \text{Ne}^{20} + \text{He}^4 \rightarrow \text{Mg}^{24} \]
\[ \text{Mg}^{24} + \text{He}^4 \rightarrow \text{Si}^{28} \]
\[ \text{Si}^{28} + \text{He}^4 \rightarrow \text{S}^{32} \]
\[ \text{S}^{32} + \text{He}^4 \rightarrow \text{Ar}^{36} \]
\[ \text{Ar}^{36} + \text{He}^4 \rightarrow \text{Ca}^{40} \]
\[ \text{Ca}^{40} + \text{He}^4 \rightarrow \text{Ti}^{44} \rightarrow \text{Sc}^{44} \] (60 years) \[ \rightarrow \text{Ca}^{44} \] (4 hours)
\[ \text{Ti}^{44} + \text{He}^4 \rightarrow \text{Cr}^{48} \rightarrow \text{V}^{48} \] (22 hours) \[ \rightarrow \text{Ti}^{48} \] (16 days)
\[ \text{Cr}^{48} + \text{He}^4 \rightarrow \text{Fe}^{52} \rightarrow \text{Mn}^{52} \] (8 hours) \[ \rightarrow \text{Cr}^{52} \] (6 days)
\[ \text{Fe}^{52} + \text{He}^4 \rightarrow \text{Ni}^{56} \rightarrow \text{Co}^{56} \] (6 days) \[ \rightarrow \text{Fe}^{56} \] (77 days)
\[ \text{Ni}^{56} + \text{He}^4 \rightarrow \text{Zn}^{60} \rightarrow \text{Cu}^{60} \] (2 minutes) \[ \rightarrow \text{Ni}^{60} \] (24 minutes)
\[ \text{Ni}^{60} + \text{He}^4 \rightarrow \text{Ge}^{64} \rightarrow \text{Ga}^{64} \] (1 minute) \[ \rightarrow \text{Zn}^{64} \] (3 minutes)
So which of the elements necessary for life existed after the first generation of stars?

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

Enter all choices that apply.
Note: the periodic table is available on the AST 106 website. Click here.
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

Enter all choices that apply.

Note: the periodic table is available on the AST 106 website. Click here.
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 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, 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 > 10 $M_{\odot}$ still died in supernovae. Those of mass 2-10 $M_{\odot}$ 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.

Abbreviation: $M_{\odot} = \text{mass of the Sun (solar mass)}$
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 til it’s 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: $^{14}\text{N}$, $^{17}\text{F}$, $^{22}\text{Na}$, $^{27}\text{Al}$, and so on. (See next pages.)

- 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 gets mixed into 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

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

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

[Diagram of the CNO cycle]

**Wikimedia Commons**
Slow fusion processes in stars

Fusion in stars near death, starting with Pop II: the s-process.

- Some of the lighter-nucleus fusion processes have neutrons as a byproduct; for instance, $^{13}\text{C} + ^4\text{He} \rightarrow ^{16}\text{O} + n$.
- These neutrons tend to be gobbled up by heavier nuclei, especially those heavier than Fe.
- Add beta decay, and this process fills in a lot of the gaps between the “alpha” elements made in explosions.

Example: s-process from Ag to Sb. (Wikimedia Commons)
New ways of stellar death (continued)

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

- After a few million years, when helium and carbon fusion has 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)
New ways of stellar death (continued)

And some of the white dwarfs can even re-die, as **Type Ia supernovae (SNeIa)**.

- Many stars live in close multiple systems. The death of one does not disturb the others much.

- Thus white dwarfs can wind up close to ordinary or giant stars, close enough to **accrete** matter from them.

- White dwarfs have a maximum mass of $1.4M_\odot$. If accretion tips a WD 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.
New ways of stellar death (continued)

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.

The 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.
Mid-lecture Break

- Homework problem set #1 is due tomorrow at 7PM.

Clusters of young stars, extreme Pop I: the Pleiades (upper right) and Hyades (lower left; the brighter ones comprise the Zodiac constellation Taurus). By Alson Wong.
Population I

So, as one might expect, there is a population of stars with higher abundances of heavy elements than Pop II, accurately in accord 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 only 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

Large factor between odd and even $Z$: mostly explosive nucleosynthesis.

Oldest stars
The nuclear-chemical evolution of the Milky Way

Number of atoms per hydrogen atom

Atomic number, Z

Population II
- Experiment
- Theory
- Post-Pop III

Older stars
Oldest stars
Smaller factor between odd and even Z: CNO, s-process more important as time goes on.
The nuclear-chemical evolution of the Milky Way

![Graph showing the nuclear-chemical evolution of the Milky Way](image)

- **ISM**
- **Pop I**
- **Pop II**
- **Post-Pop III**

**Newborn stars**

**He**, **O**, **Ne**, **Si**, **S**, **Ar**, **P**, **Cl**, **Fe**, **Ni**

**Youngest stars**

**Younger stars**

**Older stars**

**Oldest stars**
The nuclear-chemical evolution of the Universe

So, 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 stars’s own internal fusion products.

- The composition change is small between consecutive generations, but adds up steadily over time: a form of evolution.

- And as the composition changes, the structure of galaxies and their interstellar medium changes drastically, 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: 100-100000000 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 can have complex structure.
  - Nothing obliges them to be neutral (not ionized).
Molecular binding (continued)

- 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 waves instead of particles.
  - Probability-density waves, again.
  - Waves can interfere with one another, constructively or destructively. (Particles can’t.)
  - As a result, electrons in molecules can’t 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 correspond typically to visible and ultraviolet wavelengths (0.1-1 \( \mu \text{m} \)).

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 correspond typically to near and mid infrared wavelengths (1-50 \( \mu \text{m} \)).
Energies of different bound states of molecules (continued)

Rotational energies

- Different states: rotation of the molecule by quantized amounts, about various different axes.

- Energy differences correspond typically 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 hard to detect and identify, even if they are relatively abundant.
Molecular upshot: we can identify molecules in interstellar clouds and measure their abundances

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

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

- Also again, 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.

15 September 2015  Astronomy 106, Fall 2015
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

Carbon monoxide (CO) is in fact the second most abundant molecule in the ISM, after molecular hydrogen (H$_2$).
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### Today’s interstellar molecules

Note the long carbon chains (11 Cs!), many radicals and ions, and quite a few of the simpler molecules of life.

(Al Wooten, NRAO)