Origin of the Elements in Stars

Harriet Dinerstein, UT Austin, June 27, 2018
“Understanding Planetary Habitability” Pop-Up Institute

Crab Nebula: a dying high mass star

“Glowing Eye” Nebula: a dying low mass star

Cooking the cosmic soup

“Origins: Back to the Beginning” (NOVA/PBS 2004)
The Story

• Stars synthesize new elements in their interiors

• Stars distribute these newly created elements

• Elements are supplied on various timescales

• Composition “evolves” as the stars do; stars and planets that form later have higher concentrations of elements essential for Earth-like planets and life
Composition of the Sun, Earth, and Life

Note the role of O: the third-most abundant element in stars, the most abundant element in rocks and life.
The Essential Elements of Life

CHON + PSCaKNaMgCl + FeZnSel etc, etc

main | additional | trace

| Essential for humans | Suggested to be essential for humans | Nonessential for humans |

https://chem.libretexts.org/Textbook_Maps/General_Chemistry/Map%3AChemistry_(Averill_and_Eldredge)/01%3AIntroduction_to_Chemistry/1.8%3A_Essential_Elements_for_Life

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High Mass Stars (over 8 suns)

Low Mass Stars (under 8 suns)

Brown Dwarfs (below 0.08 suns or 80 Jupiters)

Fig. 15.11, The Cosmic Perspective, Bennett et al. (Pearson)
What low-mass (Sun-like) stars make

\[ \text{H} \Rightarrow \text{He}, \text{Main Sequence to Red Giant stages} \]

\[ \text{He} \Rightarrow \text{C}, \text{after the first Red Giant stage} \]
Aging & End-States of Low-Mass Stars

Fig. 17.8, Bennett’s Cosmic Perspective
What high-mass stars make

After fusing H into He and He into C, they continue to build heavier nuclei by adding one He nucleus at a time. Since He nuclei are known as alpha particles, these products, even numbered elements, are called “alpha species.”

Eventually these heavier nuclei fuse, until they reach the region of Fe.

Fig. 17.11, Bennett’s Cosmic Perspective
The Trouble with Iron

All of these charged-particle fusion reactions up to Fe are \textit{exothermic}, yielding energy that powers and stabilizes the star. But Fe and Ni are the tightest-bound nuclei in nature. Reactions that add charged particles to them are \textit{endothermic}; they \textit{use up} instead of producing energy.

The Fe core collapses, forming a neutron star or black hole; the outer layers explode as a supernova.

Figs. 17.12 & 14, Bennett’s Cosmic Perspective
Core Collapses, Outer Layers Explode

The Fe nuclei break up into protons, electrons, neutrons, and other particles. This uses up heat, so the thermal pressure drops and the core collapses so violently that electrons and protons are forced together into neutrons. The core becomes a neutron star.

This “pulls the rug” out from under the outer layers, triggering an implosion that reverses into an explosion, throwing the products of nucleosynthesis out into space as a Supernova Remnant. This event is called a “Type II” supernova.
Aging & End-State of High-Mass Stars

Fig. 17.13, Bennett’s Cosmic Perspective
Stellar Life Stages and End Points

Credit: slideplayer/C. Alexander

High mass stars

Low mass stars
Exploding White Dwarfs also make Fe

When a white dwarf in a close binary star system receives too much mass from its companion, increasing its mass to over 1.4 suns, it becomes unstable and explodes violently. This is called a “Type Ia” supernova, and it produces lots of Fe, Ni, and other Fe-peak elements.

(above) credit: NASA/CXC/M Weiss
(right) Fig. 17.15, Bennett’s Cosmic Perspective
On Beyond Fe: How are these made?

Making nuclei beyond the iron group (everything in yellow!) requires a new process: **neutron captures**.
Neutron Captures in Evolved Red Giants

In the late red giant stage of low mass stars, free neutrons are released under conditions of high temperature and density. This enables “slow” (one at a time) neutron captures or the “s-process.” One of the products is Technetium (Tc), a radioactive element whose discovery in 1952 provided the first solid proof that nuclear reactions occur in stars.

Karakas & Lattanzio (2014), PASA, 31, id.e010
How does the s-process work?

1. A neutron is captured
2. If the new nucleus is stable, nothing more happens
3. If the new nucleus is unstable, one of the neutrons changes into a proton, converting the nucleus into the next higher chemical element

Legend: a $\gamma$-ray is a photon, a $\beta$ particle is an electron, & an $\alpha$ (alpha) particle is a He nucleus.

source: Wikipedia article on the “s-process”
Merging Neutron Stars: Rapid n-captures

In August 2017, a neutron star-neutron star merger was detected though its gravitational wave radiation. Spectroscopic observations showed evidence for neutron capture elements, in particular the lanthanides. These more rapid neutron captures (the “r-process”) produce a different set of isotopes & elements than the s-process.
How Stars Disperse the Elements

Supernova Remnants: debris from SN explosion

(左) Cassiopeia A supernova remnant as observed by NASA’s Chandra X-ray Observatory; lower panel shows blobs of newly-made Si, detected via an X-ray emission line

(右) HST images of the “Cat’s Eye” (上左) and “Ring” (上右) Nebulae, and M 2-9, in optical light.

Planetary Nebulae: cast-off skins of low-mass stars

NASA/HST/Hubble Heritage

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Cosmic Chemical Evolution (or “Cooking the Universe”) 

Most of the elements on the Periodic Table are synthesized in stars and dispersed back into the environment by planetary nebulae and supernovae. The newly-made elements “dissolve” into the raw material (gas and dust) that makes new stars and their planetary systems. Thus, dying stars “pay it forward.” 

Fig. 19.3, Bennett’s Cosmic Perspective
The Cooking of the Cosmic “Soup”

Timescales for Different Ingredients

- The life span of a star depends on its initial mass.
  - Higher-mass stars age *and die* faster: \( t(M) \propto M^{-2} \)

- Stars release (most of) their nuclear products at the ends of their lives.

- High mass stars produce and disperse nuclear products promptly, whereas …

- For lower mass stars there is a long delay before their nuclear products are available.

- This introduces another dimension to the process.
Enrichment Timescales of Elements

When an ensemble of stars forms, O and other alpha species made by short-lived, high-mass stars are enriched quickly, while Fe builds up more slowly since it comes mainly from white dwarfs from long-lived, low mass stars.

The ratio of [Fe/alpha] starts out low, but increases with time as white dwarf supernovae begin to contribute Fe.

Credit: Fig. 10(a), Wheeler, Sneden, & Truran 1989, Ann.Rev.Astron.Ap., vol. 27, 279
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If we plot [alpha/Fe] instead of [Fe/alpha] the trend is inverted, declining with time and the buildup of elements.

Credit: Fig. 10(a), Wheeler, Sneden, & Truran 1989, Ann.Rev.Astron.Ap., vol. 27, 279
O and Mg are both alpha elements. Their ratios to Fe are shown in this plot, for a large number of local stars. Such data are usually displayed with an x-axis of [Fe/H] because its abundance is more reliably determined than other elements.

Enabling Terrestrial Exoplanets and Life

• The first stellar generation has no heavy elements.

• Short-lived high mass stars quickly make a lot of alphas including O, Mg, Si -> rocky planets, and a little (maybe enough?) of the Fe-group, C, and N

• Still potentially relatively quickly, pairs of neutron stars in decaying tight orbits merge and make trans-iron nuclei via r-process neutron captures.

• Low mass stars finish their long lifetimes and make more C and N, and s-process n-capture products.
Recap: Origins of the Essential Elements

Credit: Cmglee, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=31761437

- main elements
- trace elements