Today in Astronomy 106: the origin and evolution of the chemical elements

- Atoms and nuclei
- Measurement of the relative abundances of the elements in stars and nebulae
- The Big Bang and nucleosynthesis
- The first stars and the first supernovae create the first heavy elements

The Crab Nebula, remnant of the supernova of 1054 AD (HST/STScI/NASA)
Review. The mixture of the essential ingredients in *Life As We Know It* is most similar to that in

A. Earth’s crust

B. Earth’s oceans

C. Comets

D. The Sun

E. Wildly different from all of these
The origin of life’s ingredients: the parts of atoms

- **Electrons**, the lightweight ingredients of outer shells.
  Mass: \( m_e = 9.1093897 \times 10^{-28} \text{ gm} \)
  Electric charge: \( q_e = -4.803206 \times 10^{-10} \text{ esu} \)
  Immune to the strong nuclear force.

- **Protons**, the charged nuclear particle
  Mass: \( m_p = 1.6726231 \times 10^{-24} \text{ gm} \approx 1836m_e \)
  Electric charge: \( q_p = 4.803206 \times 10^{-10} \text{ esu} = -q_e \)
  Attracted by the strong nuclear force.

- **Neutrons**, the neutral nuclear particle
  Mass: \( m_n = 1.674929 \times 10^{-24} \text{ gm}, 0.14\% \text{ larger than } m_p \)
  Electric charge: 0 (thus immune to electricity)
  Attracted by the strong nuclear force exactly as a proton is.
The forces that hold atoms together

- Electrons and nuclei are held together by the **electrostatic force**, typically about $10^{-8}$ cm apart.
  - Protons in the nucleus and electrons are oppositely charged, and attract each other.

- Protons and neutrons are held together in nuclei by the **strong nuclear force**.
  - This force, always attractive, is much stronger than the electrostatic force, but is short ranged: it doesn’t act between objects much further apart than the effective radius of the proton, $10^{-13}$ cm.
  - Neutrons and protons are identical from the viewpoint of the strong nuclear force.
The force that holds nuclei together

Outside the range of the strong force, protons repel each other, but once within range they stick. Thus there is a threshold which must be overcome to stick two protons together that start off far apart.

- Threshold very large: in temperature units, \( > 10^9 \text{ K} \).
Quantum behavior of subatomic particles

- On the distance scale of atoms (about $10^{-8}$ cm), electrons behave as waves instead of particles. (See PHY 100, next semester)
  - Probability-density waves, to be precise.
  - Waves can interfere with one another, constructively or destructively. Particles can’t.
  - As a result, electrons in atoms can’t have any energy they want: they can only have energies corresponding to constructive interference of the electron waves. This is called energy-level quantization.
  - Also as a result: if an atomic electron changes from one energy level to another, it either absorbs a particle of light (a photon) to do so, or emits one, depending upon whether it’s changing up or down in energy.
Here, for example, are the sixteen lowest-energy states of Fe\(^+\) (singly-ionized iron), showing some of the transitions that are most productive of light emission, and the wavelengths at which Fe\(^+\) emits light when moving down the energy ladder.
Example atomic emission spectrum

Fe\(^+\) can only emit, or absorb, light at these specific wavelengths. This is called a line spectrum, in contrast to the continuous spectrum emitted, for instance, by an incandescent light bulb.

![Fe\(^+\) emission spectrum diagram]
Quantum behavior of subatomic particles (continued)

On the distance scale of the strong force’s range (about $10^{-13}$ cm), protons and neutrons behave as waves instead of particles.

- Again: probability-density waves, to be precise.
- Waves extend over finite ranges of space. (Particles don’t; they’re infinitesimally small.)
- As a result, protons and neutrons can come together and stick even when their kinetic energies aren’t quite enough to exceed the threshold. This is called tunneling.
- Tunneling reduces the temperature required for fusion somewhat; very high temperatures still required.
Fusion by tunneling

Classical turning point

Classical

Quantum

Probability density

Nonzero probability!

Distance

Distance

$10^{-13} \text{ cm}$

Proton-proton potential energy
Nuclear upshot: heavier elements can be made by fusion of lighter ones

- Needs high density and temperature if lots of the products are desired.

- Some combinations, e.g. $^4\text{He}$ (the alpha particle), are peculiarly robust and stable.

- Because the strong force has range smaller than nuclei and the electrostatic force does not, the binding energy per nuclear particle reaches a peak at a certain nuclear size, and thereafter decreases with increasing nuclear size.
  - Peak at $^{56}\text{Fe}$, the normal isotope of iron.

- So fusion which produces elements lighter than $^{56}\text{Fe}$ releases heat, and fission of elements heavier than $^{56}\text{Fe}$ produces heat.
  - This makes stars, and nuclear reactors, possible.
Nuclear upshot: heavier elements can be made by fusion of lighter ones (continued)

Figure: Shu, *The Physical Universe*

Atomic mass number $A$ (protons plus neutrons)
What element would make the best fusion fuel, producing the most heat for the smallest number of protons and neutrons?

A. Hydrogen (H)
B. Helium (He)
C. Carbon (C)
D. Iron (Fe)
E. Lead (Pb)
F. Uranium (U)
What element would make the best fission fuel, producing the most heat for the smallest number of protons and neutrons?

A. Hydrogen (H)
B. Helium (He)
C. Carbon (C)
D. Iron (Fe)
E. Lead (Pb)
F. Uranium (U)
Atomic upshot: we can measure the relative abundances of the elements in celestial objects

- Every element and isotope has a distinctive set of energy levels, and thus a distinctive spectrum: thus elements and their ions can be identified positively.

- 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 measure relative abundances. This works for stars and lots of different kinds of interstellar nebulae.
  - The abundances of the chemical elements in various different settings are thus a large set of precisely-known facts.
Mid-lecture Break

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

Superposed infrared (purple) and X-ray (blue) images of the Crab Nebula (SSC/NASA).
How to measure element abundances, from a great distance

Collect light from the object, using a telescope, and disperse the light into the spectrum, using instruments such as prisms and diffraction gratings.

Wikimedia Commons
How to measure element abundances, from a great distance (continued)

In stars, this reveals atomic absorption in the star’s atmosphere of light generated from the hotter interior.

Cross-dispersed spectrum of the Sun (R. Kurucz and NOAO): one really long spectrum of the sort on the previous page, sliced up and rearranged for easier display.
How to measure element abundances, from a great distance (continued)

From the strength of the absorptions relative to one another, the abundances (ratio of numbers of atoms in the object) of elements can be determined. In this short piece of the Solar spectrum, several atomic abundances can be measured.

(R. Kurucz and NOAO)
Hydrogen is the most abundant element in the Sun. What’s the second most abundant element, by mass, among those for which spectral lines appear in the previous spectrum?

A. Barium (Ba)
B. Iron (Fe)
C. Nickel (Ni)
D. Silicon (Si)
E. Tungsten (W)
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 degrees K).

- Such conditions are found in two sorts of places in the cosmos:
  - Blast waves from exploding stars or the Big Bang itself. 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 through $10^9$K, and bound combinations of protons and neutrons could form by fusion, prominently $^4\text{He}$, $^3\text{He}$, $^3\text{H}$ (a.k.a. T) and $^2\text{H}$ (a.k.a. D).

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

From Ned Wright’s Big Bang Nucleosynthesis page
Hydrogen 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 hold stars up against their weight.
- Mainly fuses four Hs into $^4\text{He}$.
- Intermediate products include D and $^3\text{He}$.
Big Bang nucleosynthesis (continued)

That’s where it stops, though; besides relatively small amounts of lithium and $^7\text{Be}$, 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.)
Big Bang nucleosynthesis (continued)

- The reason it stops is the robustness of the $^4\text{He}$ nucleus: when $^8\text{Be}$ is made it falls apart into two $^4\text{He}$s, with half-life $3 \times 10^{-16}$ sec. This situation is called the mass-8 bottleneck.

\[
^4\text{He} + ^8\text{Be} \rightarrow ^{12}\text{C} + 2^4\text{He}
\]

\[
t = 0 \text{ sec} \quad \text{and} \quad t = 3 \times 10^{-16} \text{ sec}
\]
If within $3 \times 10^{-16}$ sec the $^8\text{Be}$ is hit by another $^4\text{He}$, it will stick and make $^{12}\text{C}$. This is called the **triple-alpha process**:

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

Thus all the hydrogen and helium, and most of the lithium and $^7\text{Be}$, 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 – 1000$M_\odot$ instead of today’s 0.5 – 2$M_\odot$.

- Astronomers call this original set of stars Population III.

- These stars lived very short lives: within only a million years or so, fusion exhausts the hydrogen in their centers, robbing them of the heat and pressure that holds up their weight.
The first stars (continued)

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 create. (SSC/NASA)
The first stars (continued)

- Thereupon their cores collapse to form black holes, and their outer parts explode 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.

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