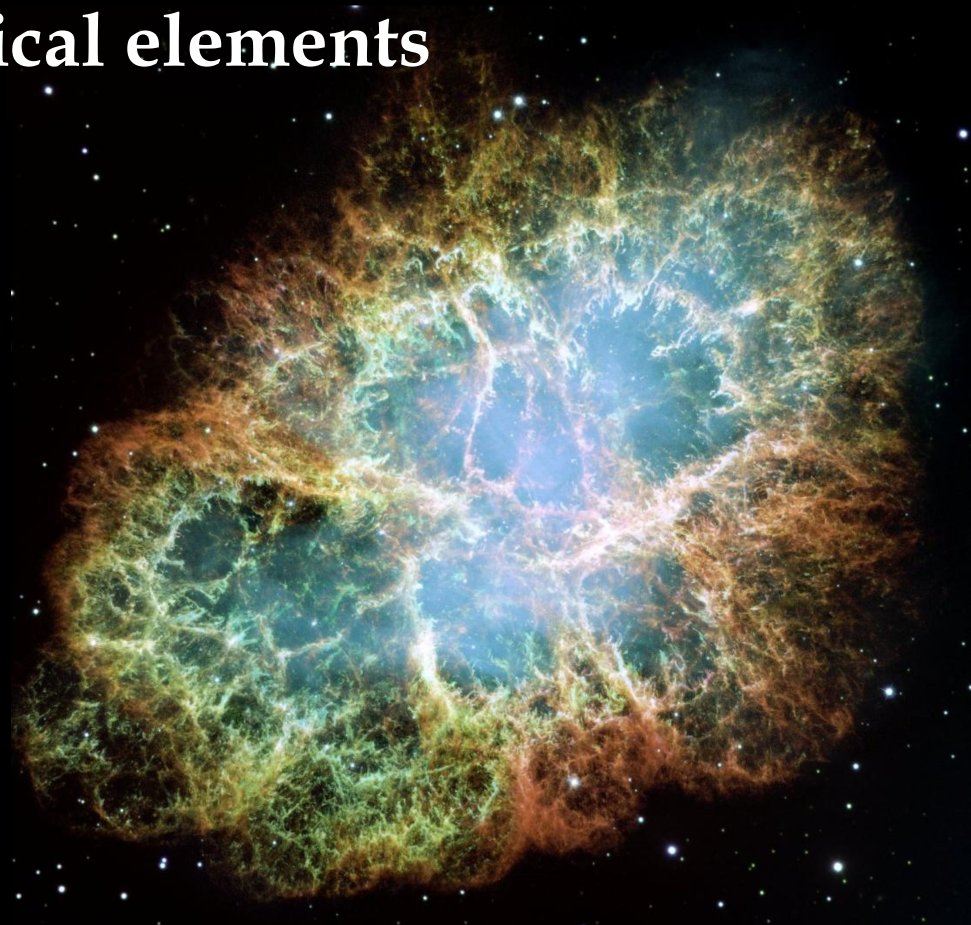
Today in Astronomy 106: the origin and evolution of the chemical elements

- The Big Bang and nucleosynthesis
- The first stars
- The first steps of nuclear-chemical evolution of the Universe: explosive nucleosynthesis vs. fusion processing in stellar cores and "Population II."
- Nucleosynthesis in normal stars, the enrichment of interstellar matter, and Population I



The Crab Nebula, remnant of the supernova of 1054 AD (HST/STScI/NASA)

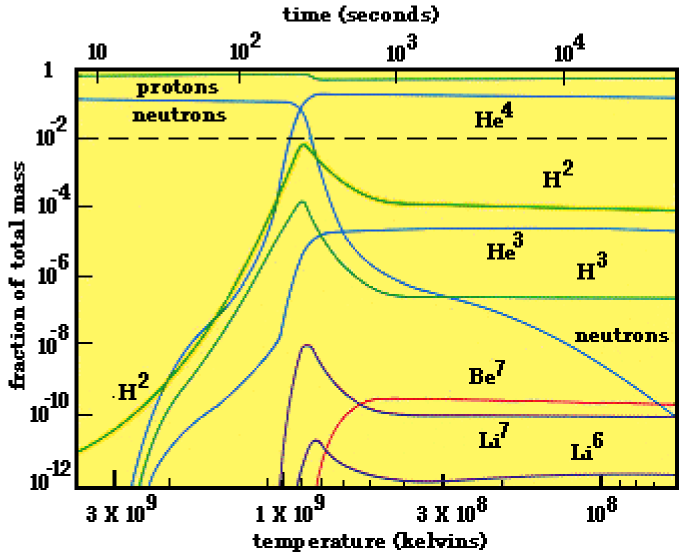
Nucleosynthesis

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, 10^7 K, 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.

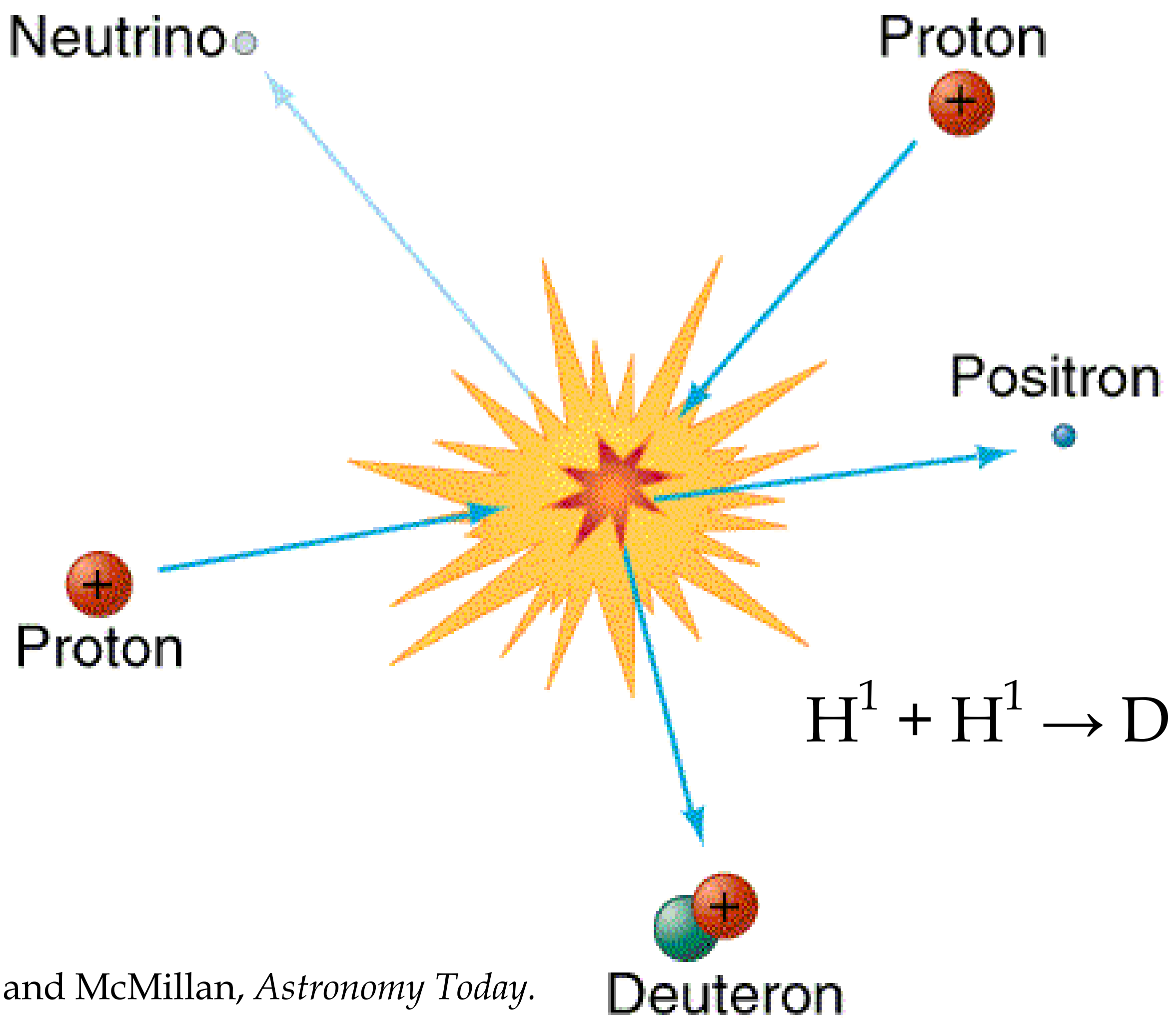
Big Bang nucleosynthesis

- 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 10^9K, and bound combinations of protons and neutrons could form, prominently ^{4}He, ^{3}He, ^{3}H and ^{2}H (a.k.a. D).



From [Ned Wright's Big Bang Nucleosynthesis page]

Fusion of two protons to make deuterium



$$H^1 + H^1 \rightarrow D + e^+ + \nu$$

Figure: Chaisson and McMillan, *Astronomy Today*.

Big Bang nucleosynthesis (continued)

- That's where it stops, though; besides relatively small amounts of lithium and ^{7}Be, no heavier elements are made at all in the Big Bang.
- The reason is the robustness of the alpha particle: when ^{8}Be is made it falls apart into two ^{4}Hes within 3×10^{-16} sec. This is the famous mass-8 bottleneck.
- If within this time the ^{8}Be is hit by another ^{4}He it will stick and make ^{12}C. This is called the **triple alpha process**.
- By the time ^{4}He is made, though, the density of the Universe is so small that the chances of such an encounter are close to zero: no triple-alpha.

Thus all the hydrogen and helium, and most of the lithium and ^{7}Be, in the Universe is made during the Big Bang.

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 1000 $M_\odot$ instead of today's 0.5 - 2 $M_\odot$
- 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.
- Thereupon their cores collapse to form black holes, and their outer parts explode with great violence: **core-collapse supernovae.**

The first stars (continued)

- These explosions created the conditions under which the triple alpha process could proceed, albeit briefly.
- Thus small amounts of ^{12}C were released into the interstellar medium…
  - …along with correspondingly smaller amounts of other "alpha" elements whose nuclei are composed of round numbers of helium nuclei (^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, and so forth).
- The amounts of heavy elements, though small by current standards, drastically changed the formation process for subsequent generations of stars: it was possible thenceforth to make smaller, and much longer-lived, stars.

"Population II"

Subsequent generations of stars now had many more ways to manufacture elements.

- Stars more massive than about 10 solar masses still ended their lives via core-collapse supernovae, once again generating more "alpha" elements.
- And since there were heavy elements to start with, supernovae could make even heavier ones: tiny amounts of elements on the periodic table between Fe and U.
- But since the stars were longer lived, and not all die in supernovae, the fusion processes that took place during the stars' lifetimes began to contribute significantly to the composition of the interstellar medium.

Population II (continued)

Stars of mass 5-10 solar masses lived only a couple of billion years, but ended their lives in less spectacular fashion:

- After H, He and C in the core has been exhausted in fusion, the stars became mechanically unstable, and *shed* their outer layers (most of the star's mass), leaving behind dense C-O-Ne-Mg-Si cores: the first **white dwarfs**.
- While the fusion was going on, many elements between the alphas were manufactured from alphas, by slow processes that add protons to nuclei one at a time.
- Some of this material was mixed into the outer layers of the star and dispersed into the interstellar medium. Thus stars began to be made with elements like ^{14}N, ^{17}F, ^{22}Na, ^{27}Al, and so on.

Population II (continued)

The smaller-mass examples of the stars that formed from this mixture, perhaps 8-12 Gyr ago, are still alive today.

- They have been around long enough, and interacted gravitationally with each other long enough, that they have larger random motions within our galaxy than younger stars do.
- Their element abundances are still not large, and most of the relative abundances still indicate a dominant origin in explosive nucleosynthesis.

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

Mid-lecture Break

- Homework problem set #1 is due Wednesday at midnight.

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

Population I

By now, of course, the higher-mass end of the first generations of Population II have gone the way of all things.

- The more massive the star, the shorter the life. Bigger stars start with more fuel (hydrogen, for fusion), but use up the fuel at a much higher rate.
- The mass range of Pop II stars extends well below the mass of the Sun (1 $M_\odot$); very massive stars (>10 $M_\odot$) are rare.
- The very massive stars live short lives and die in the traditional way, via core-collapse supernovae. The lower-mass ones have other ways to die, and even re-die, that spew the stellar-core fusion products out into space, instead of destroying them in the SN blast first.

Population I (continued)

The new way of stellar death:

- As the last of the hydrogen in a star's core has fused to helium, the core collapses, and heats til it's hot enough to make C through triple-alpha.
- This makes the star mechanically unstable: the outer parts swell up (making the star a **giant** or **supergiant**), and begin to be driven away from the star at a fast pace.
- 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.

Typical planetary nebula

The Ring Nebula (M57, in Lyra, not far on the sky from the bright star Vega).

- Note the star in the middle, soon to become a white dwarf; and the shells of expanding material.
- Note also: planetary nebulae have nothing to do with planets.

Image by [Vicent Peris et al.]

Population I (continued)

The novel way of re-death: Type Ia super-novae (**SNeIa**). (Borrowed from AST 102.)

European Southern Observatory

- 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 $1.4\ M_{\odot}$. 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.

Population I (continued)

Subsequent generations of stars form from **interstellar medium (ISM)**, which has been enriched in heavy elements made by Pop II stars in their various activities:

- Core-collapse supernovae, the only process predating Pop II: highly productive of the alpha (even atomic number) elements. Rare, though.
- Slower stellar core nucleosynthetic processes: mostly made with slower processes, adding to nuclei one proton at a time: origin of the odd-atomic-number species and isotopes with a range of mass number. VERY common.
- SNeIa: explosive nucleosynthesis again, but particularly productive of iron-peak elements. Rare, but about half of the iron in the present-day ISM comes from SNeIa.

Population I (continued)

Sure enough, there is a population of stars distinct from Pop II in motion and distribution through the galaxy:

- Much smaller random motions, and confined much more tightly to the plane of the Milky Way, where most of the ISM also resides.
- Can belong to clusters, but the clusters are smaller, less organized, and only rarely older than 1 Gyr.
- The Sun is one of these stars.
- And they have higher concentrations of heavy elements than Pop II, accurately in accord with the combination of explosive and stellar-core nucleosynthesis.

We call these stars **Population I**, of course.

The nuclear-chemical evolution of the Milky Way