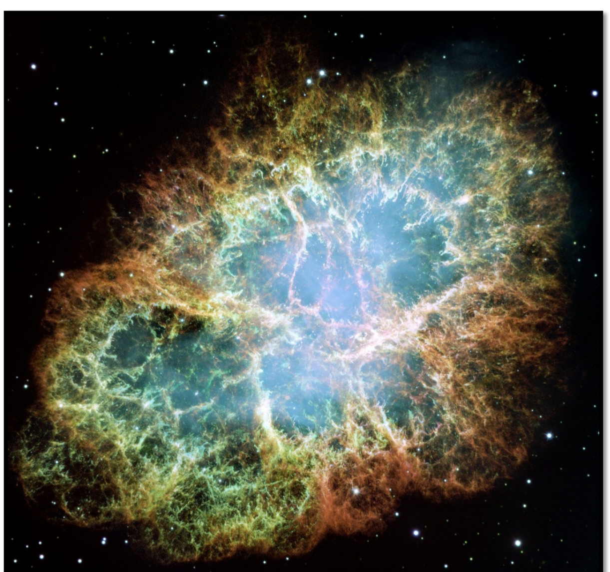
10 September 2019

ORIGIN & EVOLUTION OF THE CHEMICAL ELEMENTS

Homework #2 due next Wednesday (9/18) at 7pm



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

Chemical elements: their origin and evolution

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 mixture of the essential ingredients in Life As We Know It is most similar to that in:

Review question!

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 the atom

Electrons, the lightweight ingredients of outer shells.

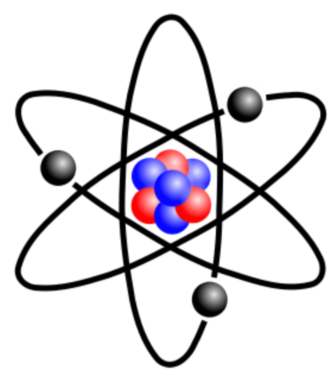
- Mass: $m_e = 9.1093897\times10^{-28}$ g
- Electric charge: $q_e = -4.803206\times10^{-10}$ esu
- Immune to the strong nuclear force

Protons, the charged nuclear particle

- Mass: $m_p = 1.6726231\times10^{-24}$ g $\approx 1836 m_e$
- Electric charge: $q_p = 4.803206\times10^{-10}$ esu $= -q_e$
- Attracted by the strong nuclear force

Neutrons, the neutral nuclear particle

- Mass: $m_n = 1.674929\times10^{-24}$ g, 0.14% larger than m_p
- Electric charge: 0 (thus immune to electricity)
- Attracted by the strong nuclear force exactly as a proton is



^{6}Li atom, not drawn to scale or anything like reality (Wikimedia Commons)

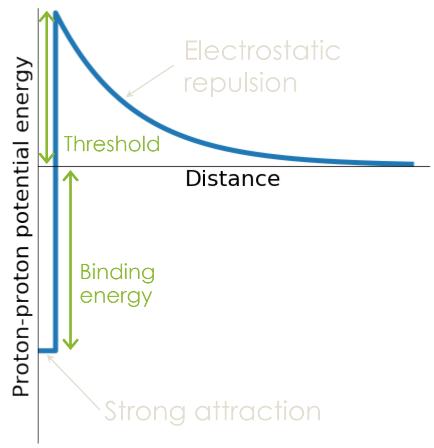
The forces that hold the atom together

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 therefore 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 does not 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.
- 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, $> 10^9$ K)



Quantum behavior of subatomic particles

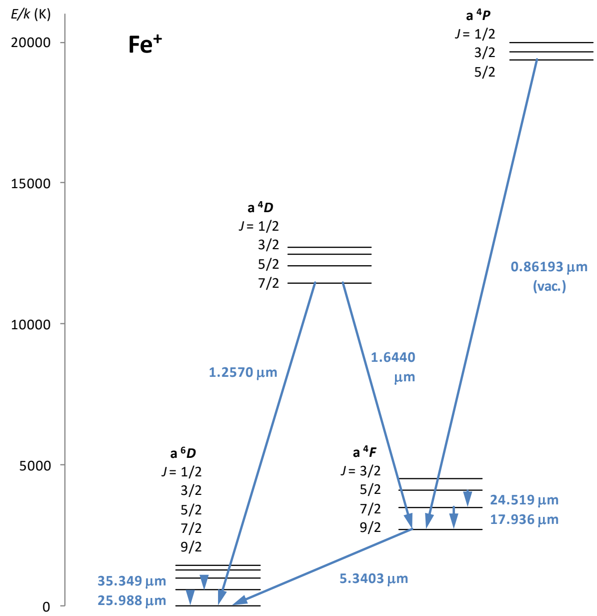
On the distance scale of atoms (about 10^{-8} cm), electrons behave as waves instead of particles. (See PHY 100 next semester.)

- Probability-density waves, to be precise.

Waves can **interfere** with one another, constructively or destructively. Particles cannot.

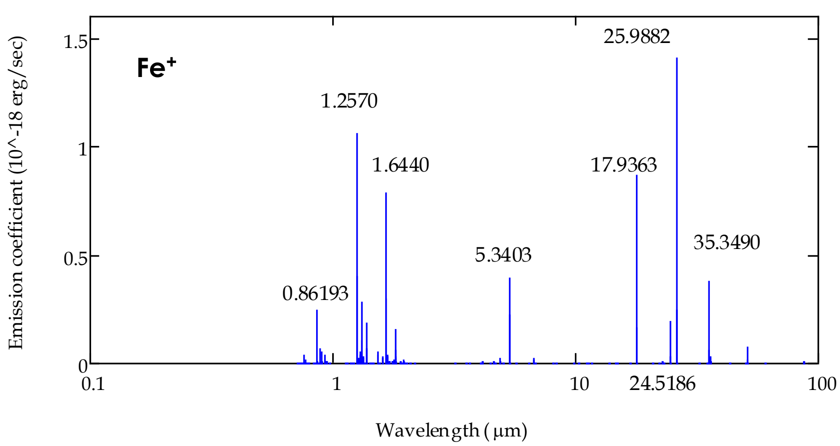
As a result, electrons in atoms cannot have any energy they want: they can only have energies corresponding to constructive interference of the electron waves. This is called energy-level **quantization**.

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 is changing up or down in energy.



Example atomic energy levels

Here, for example, are the sixteen lowest-energy states of Fe^+ (singly-ionized iron), showing some of the transitions that produce most of the 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 an **line spectrum**, in contrast to the continuous spectrum emitted by an incandescent light bulb, for example.

Quantum behavior of subatomic particles

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

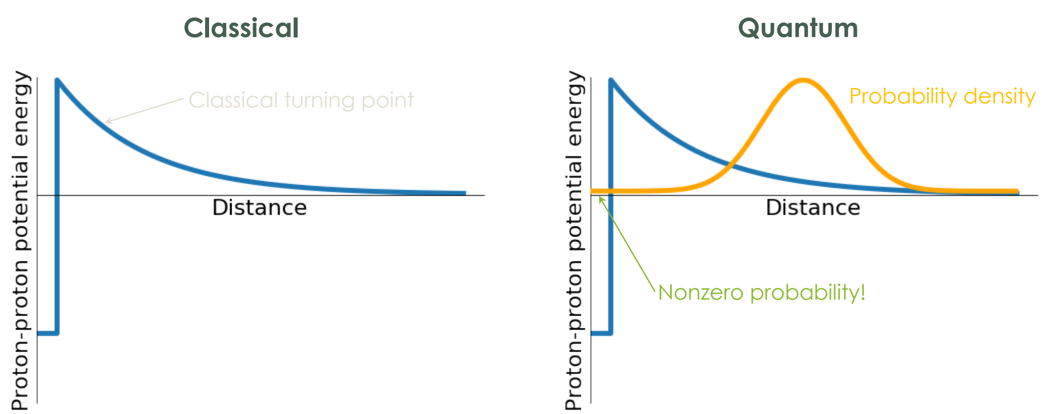
- Again: probability-density waves.

Waves extend over finite ranges of space. (Particles do not; they are infinitesimally small.)

As a result, protons and neutrons can come together and stick even when their kinetic energies are not quite enough to exceed the threshold. This is called **tunneling**.

Tunneling somewhat reduces the temperature required for fusion; very high temperatures are still required.

Fusion by tunneling



Heavier elements can be made by fusion of lighter ones

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

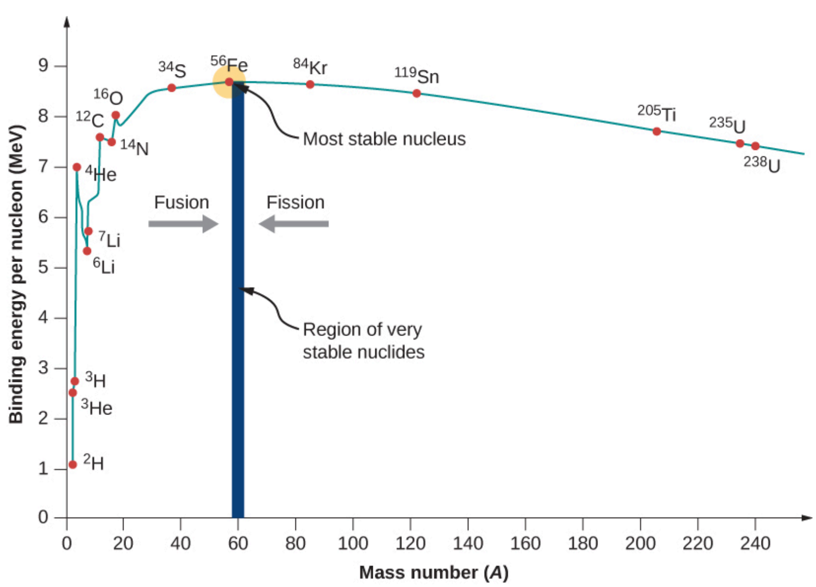
Some combinations, e.g. ^{4}He (the **alpha particle**), are particularly robust and stable.

Because the strong force has a 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}Fe, the normal isotope of iron.

So **fusion which produces elements lighter than ^{56}Fe releases heat**, and **fission of elements heavier than ^{56}Fe produces heat**.

- This makes stars and nuclear reactors possible.



Nuclear upshot

Heavier elements can be made by the fusion of lighter ones

Question

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)

Question

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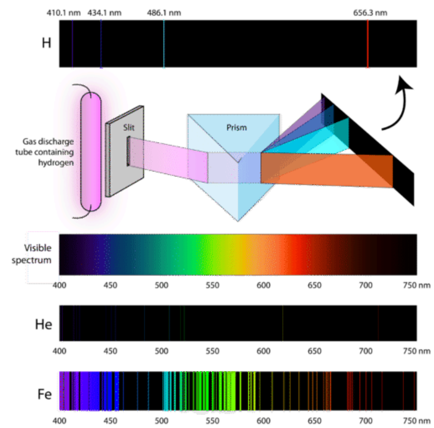
We can measure the relative abundances of the elements in celestial objects

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

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



We can measure the relative abundances of the elements in celestial objects

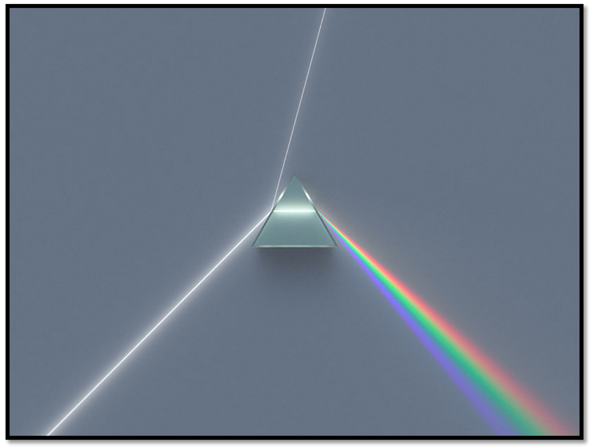
The relative brightness of lines of a given species can be used to determine density, temperature, and pressure of the emitting region.

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**.

How to measure element abundances from great distances

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



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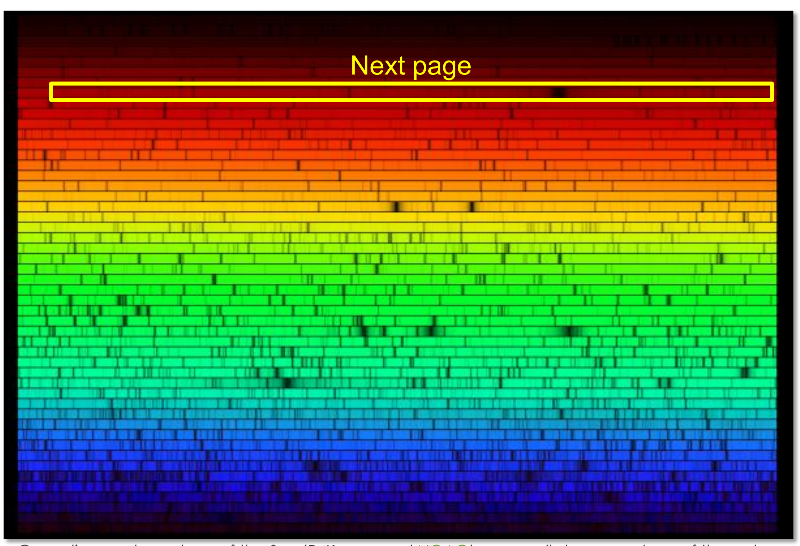


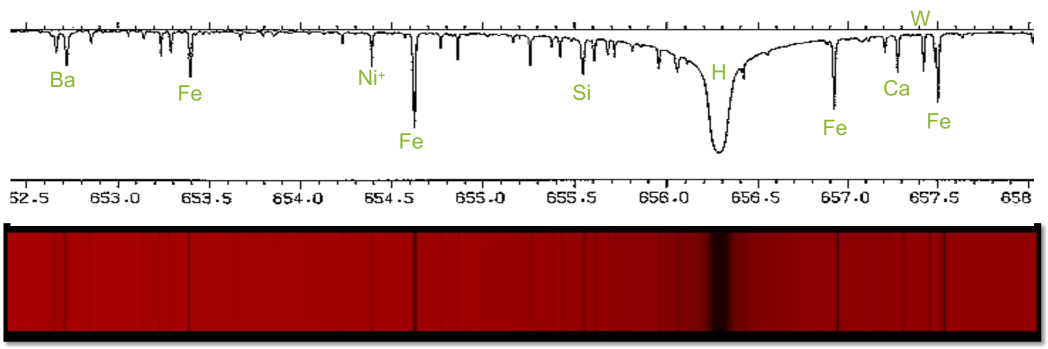
Cross-dispersed spectrum of the Sun (R. Kurucz and NOAO): one really long spectrum of the sort on the previous page, sliced up and rearranged for easier display.

A star's spectrum

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

Measuring abundances from a spectrum

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.



Question

Hydrogen (H) is the most abundant element in the Sun. What is 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 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**.

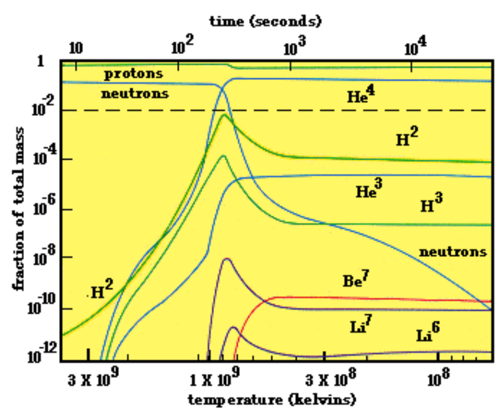
The different kinds of mechanisms are good at producing different kinds of elements.

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.

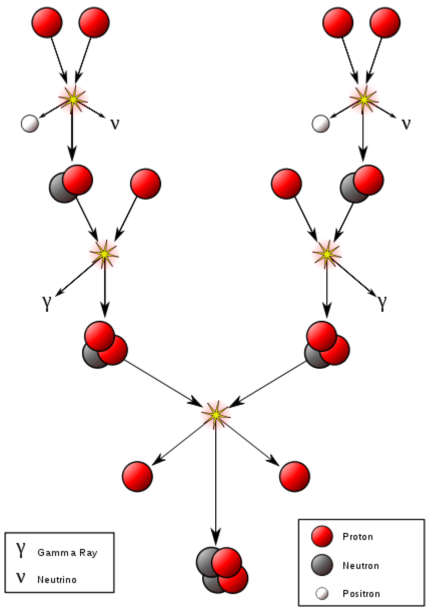


From Ned Wright's *Big Bang Nucleosynthesis page*

Hydrogen (H) fusion

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

- Main fusion in the Big Bang
- Also main fusion process in stars through the Universe's history, and the source of heat and pressure that hold stars up against their weight
- Mainly fuses four H into ^{4}He
- Intermediate products include D and ^{3}He



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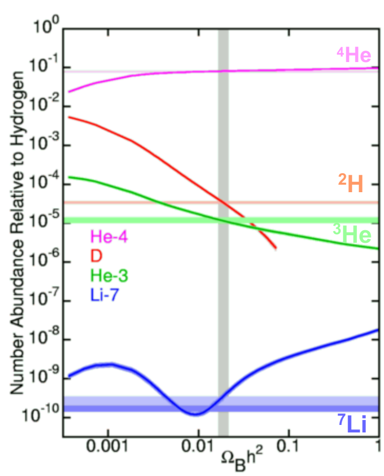
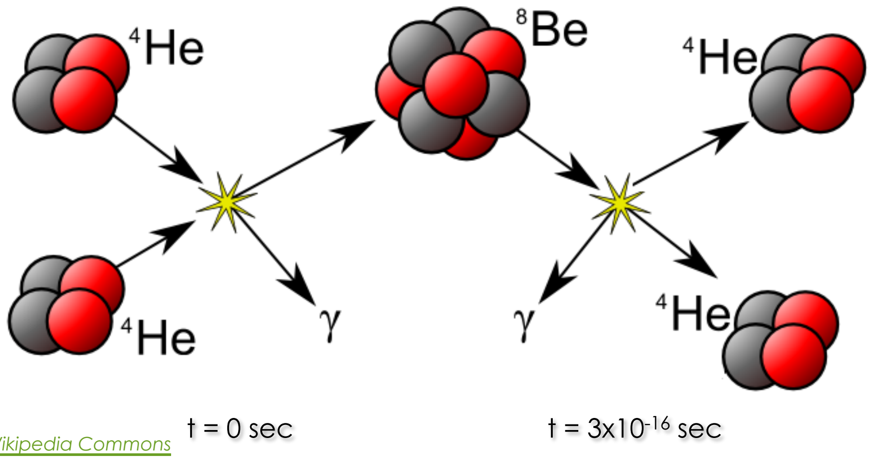
Big Bang nucleosynthesis

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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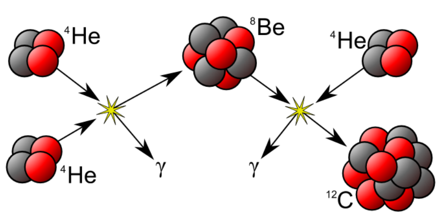
Big Bang nucleosynthesis

The reason it stops is the robustness of the ^{4}He nucleus: when ^{8}Be is made, it falls apart into two ^{4}He, with a half-life 3x10^{-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

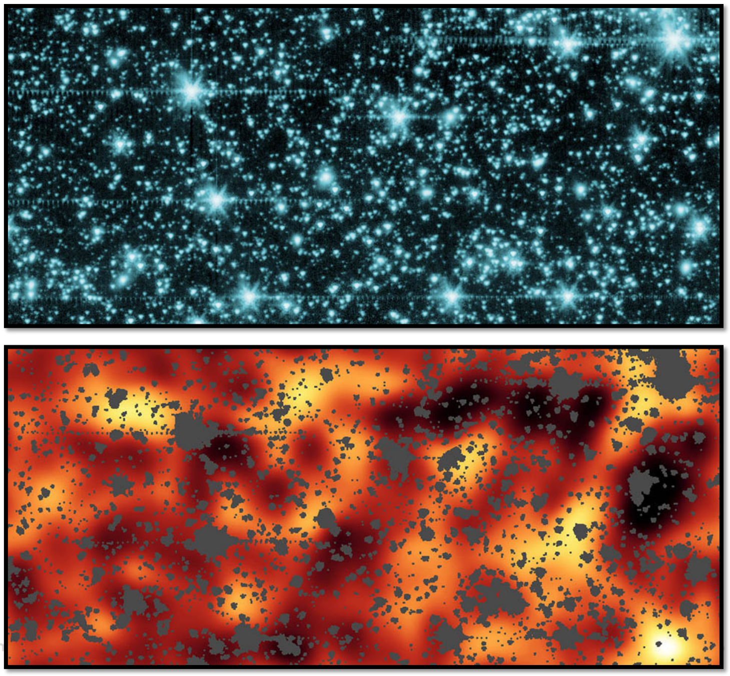
Thereupon their cores collapsed to form black holes, and their outer parts exploded with great violence. These events are called **core-collapse supernovae**.

- 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)