Cosmic Evolution

Part 1: Protons to heavy elements

Big Bang occurred 13.7 Billion yrs ago (13.7×10^9 yr)
Only fundamental particles existed for first few minutes

Name	**Symbol**	**Charge**	**Mass**
Proton	p	+	1.7×10^{-24} g
Neutron	n	0	1.7×10^{-24} g
Electron	e	–	1×10^{-27} g
Photon	γ	0	0
Neutrino	ν	0	$< 10^{-33}$ g

Building blocks of nuclei but only one kind of nucleus

Proton = nucleus of Hydrogen

The Bigger Picture

The ordinary matter (protons, neutrons, …) contain only 4.5% of the mass energy of the Universe. Dark matter contains 22.7% and the even stranger dark energy accounts for 72.8%.
(most recent numbers)

A Bit of Physics

Energy of Motion (Kinetic Energy)

$E = \frac{1}{2} mv^2$ (if v not close to c)

Gas at Temperature T,
Avg. Energy $E = \frac{3}{2} kT$

So avg. v : $\frac{1}{2} mv^2 = \frac{3}{2} kT$

$$v = \sqrt{\frac{3kT}{m}} \equiv \left(\frac{3kT}{m}\right)^{\frac{1}{2}}$$

Higher T → Higher v, E on avg.

Simulation of gas properties on the web

http://phet.colorado.edu/new/simulations/sims.php?sim=Gas_Properties

Early Universe so hot that collisions broke apart any complex things that might have formed

As Universe expanded, T dropped
at ~ 3 min, T ~ 10^9 K
A few nuclei form (nucleosynthesis)
at ~ 30 min, T ~ 3×10^8 K end of nucleosynthesis

Composition of Universe at 30 min.

~ 94% proton H
~ 6% alpha particle He
(and electrons)
At 380,000 years T ~ 3000 K
Nuclei + electron → Atoms H He

First Generation Stars

Expanding Universe
But, Gravity collected matter into Stars
Stars now 0.1 to 100 $M_\odot$; first stars more massive
Later into Galaxies ($M \sim 10^{10}$ to 10^{12} $M_\odot$)

Oldest stars in disk: age ~ 10^{10} years

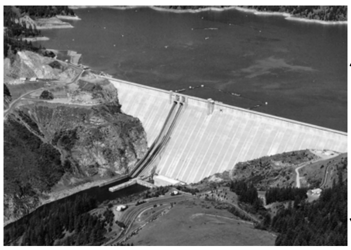
First generation stars → No C, O, N, …
⇒ No life No Si, Fe ⇒ No Earthlike planets
But they **made** some "heavy" elements
So later stars could have solid planets, life

Movie illustrating galaxy formation

From http://cosmicweb.uchicago.edu/group.html

Gravitational Potential Energy

For example: Reservoir of water behind dam



Higher GPE

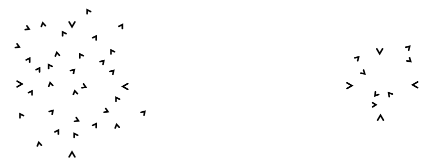
Energy released as water falls

Lower GPE

Consider a clump of Gas collapsing to form a star

Apply to collapsing gas

GPE → Heat



Atoms move faster
Temperature is higher

Pause for Demonstration

Back to Formation of First Stars

Collapse released Gravitational Potential Energy

The gas heats up

The Temperature in core reaches 10^7 K

Nuclear reactions begin

Collapse stops **Why?**

Nuclear Potential Energy

Four basic forces: gravity, electromagnetic, weak and strong nuclear force

Each has potential energy. Nuclear potential energy can be released by nuclear reactions.

e.g. 1st step: $p + p \rightarrow d + e^+ + \nu$

d = deuteron = proton + neutron
e^+ = positron (antiparticle of electron)

Nuclear Potential Energy

Nuclear Potential Energy

$p + p$

^ Energy Released
↓
Kinetic Energy
↓
Heat

$d + e^+ + \nu$ ˅

Separation of two protons

The energy released by nuclear reactions supplies heat → pressure

Resists gravity ⇒ stable star

Electromagnetic Barrier

Why do we need high T (~ 10^7 K)?

Protons have positive electric charge
Like Charges Repel

As protons approach, repulsion grows, corresponds to climbing hill of electromagnetic potential energy

Electromagnetic Barrier

Potential Energy

Barrier ˄ ˅

$p + p$

$d + e^+ + \nu$

Separation

Barrier is really much higher than $\frac{3}{2}\,k \cdot 10^7$ K

Very few can get over barrier

⇒ Stars live a long time rather than exploding

Questions

- Why do nuclear reactions produce a long-lived system in star, but an explosion in a bomb?
- What will happen when a star's fuel runs out?

Nucleosynthesis Again

proton	p
neutron	n
positron	e^+
neutrino	ν
photon	γ

$p + p \rightarrow d + e^+ + \nu$

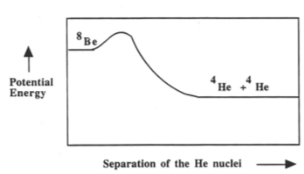
$d + p \rightarrow {}^3He + \gamma$

${}^3He + {}^3He \rightarrow {}^4He + 2p$ ${}^4He = 2p + 2n$

How to get past helium? We need C, O, N, P, S, …

${}^4He + {}^4He \rightarrow {}^8Be$ ${}^8Be = 4p + 4n$

Problem: ${}^8Be$ has more nuclear potential energy than parts;
It is unstable (radioactive).



To get carbon, we need another ${}^4He$ to hit ${}^8Be$ before ${}^8Be$ falls apart

${}^4He + {}^4He \rightarrow {}^8Be$ ${}^8Be = 4p + 4n$

${}^8Be + {}^4He \rightarrow {}^{12}C + \gamma$ ${}^{12}C = 6p + 6n$

${}^4He + {}^{12}C \rightarrow {}^{16}O$ ${}^{16}O = 8p + 8n$

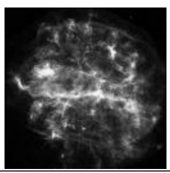
${}^{16}O + {}^{16}O \rightarrow {}^{32}S + \gamma$ Sulfur

${}^{16}O + {}^{16}O \rightarrow {}^{31}P + p$ Phosphorus

${}^{16}O + {}^{16}O \rightarrow {}^{28}Si + {}^4He$ Silicon

Questions

- What was needed to make the bioelements?
- Are any missing?
- How do the bioelements get out of the star?



Summary

Heavy elements needed for life were created by early generations of massive stars.

Except for H, we are made of star debris

Natural forces (Gravity, EM, Nuclear) produced first evolution of matter from simple to complex
(protons → heavy elements)