

FUNDAMENTALS OF EARTH SCIENCES

(ESO 213A)

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DEPARTMENT OF EARTH SCIENCES

Lecture: Solar System and Origin of Earth
'we are stardasts'

Origin of the Universe

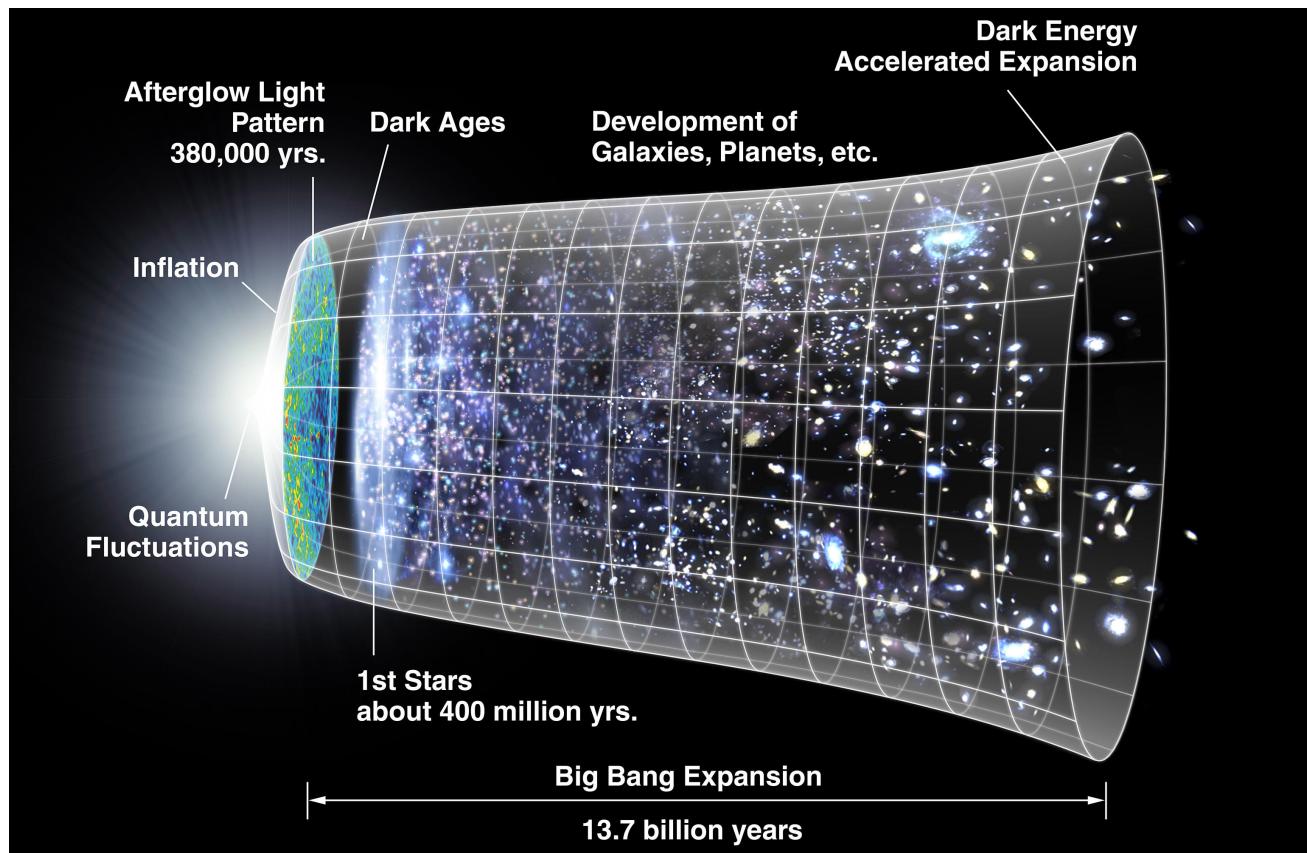
The universe began about ~ 13.7 billion years ago

The **Big Bang**

Theory states that, in the beginning, the universe was all in one place

All of its matter and energy were squished into an infinitely small point (smaller than an atom), and then it exploded. In millionths of a millionth second from smaller than a size of atom to galaxy!

After about 10 billion years, our solar system began to form



Source: Nasa.gov

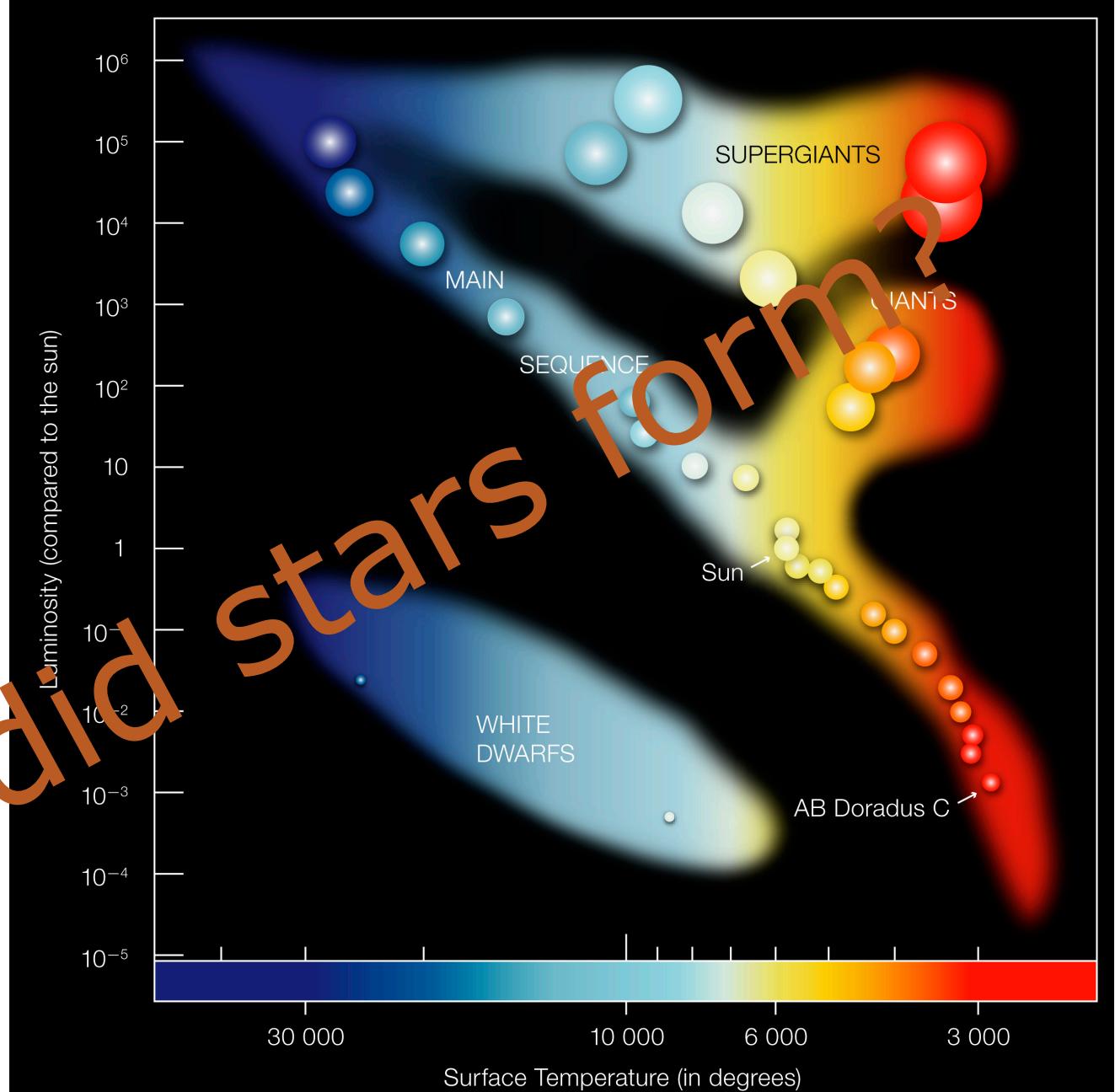
The Big Bang mainly created H and He, and the first stars were formed (but still no planets)

Hertzprung-Russel (H-R) diagram

Most stars, including the sun, are “main sequence stars,” fueled by nuclear fusion converting hydrogen into helium.

• As stars begin to die, they become giants and supergiants. These stars have depleted their hydrogen supply and are very old. The core contracts as the outer layers expand. These stars will eventually explode (becoming a planetary nebula or supernova, depending on their mass) and then become white dwarfs, neutron stars, or black holes (again depending on their mass).

Smaller stars (like our Sun) eventually become faint white dwarfs (hot, white, dim stars) that are below the main sequence.



Luminosity is the total amount of energy that a star radiates each second

How did elements form?

Periodic Table of the Elements



1 IA	2 IIA
H Hydrogen 1.008 1	
Li Lithium 6.94 2-1	Be Beryllium 9.012 2-2
	State of matter (color of name) GAS Liquid Solid Unknown
Na Sodium 22.9897028 2-6-1	Mg Magnesium 24.31 2-2



Subcategory in the metal-metalloid-nonmetal trend (color of background)

- Alkali metals
- Alkaline earth metals
- Transition metals
- Lanthanides
- Actinides
- Post-transition metals
- Metalloids
- Reactive nonmetals
- Noble gases

B Boron 10.81 2-2	C Carbon 12.01 2-4	N Nitrogen 14.017 2-5	O Oxygen 15.999 2-6	F Fluorine 18.998 2-7	Ne Neon 20.180 2-8
Al Aluminum 26.982 2-8-2	Si Silicon 28.085 2-8-4	P Phosphorus 30.974 2-8-5	S Sulfur 32.08 2-8-6	Cl Chlorine 35.45 2-8-7	Ar Argon 39.948 2-8-8
Zn Zinc 65.38 2-8-18-2	Ga Gallium 69.723 2-8-18-3	Ge Germanium 72.638 2-8-18-4	As Arsenic 74.922 2-8-18-5	Se Selenium 78.911 2-8-18-6	Br Bromine 79.904 2-8-18-7
Cd Cadmium 112.41 2-8-18-7	In Indium 114.82 2-8-18-8	Tl Thallium 119.91 2-8-18-9	Sn Tin 118.71 2-8-18-10	Sb Antimony 121.76 2-8-18-11	I Iodine 126.90 2-8-18-12
Ag Silver 107.87 2-8-18-18-1	Pd Palladium 106.42 2-8-18-18	Ag Silver 107.87 2-8-18-18-1	Cd Cadmium 112.41 2-8-18-18-2	Te Tellurium 121.60 2-8-18-18-3	Xe Xenon 131.29 2-8-18-18-8
Ru Ruthenium 101.07 2-8-18-18-1	Rh Rhodium 102.91 2-8-18-18-2	Pt Platinum 195.08 2-8-18-18-3	Au Gold 196.97 2-8-18-18-4	Hg Mercury 200.59 2-8-18-18-5	Po Polonium 209 2-8-18-18-6
Ta Tantalum 180.168 2-8-18-18-12	W Tungsten 183.84 2-8-18-18-12	Re Rhenium 186.21 2-8-18-18-12	Os Osmium 191.23 2-8-18-18-12	Pt Platinum 195.08 2-8-18-18-12	At Astatine (210) 2-8-18-18-12
Hf Hafnium 178.69 2-8-18-18-12	Ta Tantalum 180.168 2-8-18-18-12	Ir Iridium 192.22 2-8-18-18-12	Pt Platinum 195.08 2-8-18-18-12	Tl Thallium 120.49 2-8-18-18-12	Rn Radium (222) 2-8-18-18-12
Fr Francium (223) 2-8-18-18-12	Ra Radium (226) 2-8-18-18-12	Rf Rutherfordium (267) 2-8-18-18-12	Db Dubnium (268) 2-8-18-18-12	Sg Seaborgium (266) 2-8-18-18-12	Bh Bohrium (265) 2-8-18-18-12
La Lanthanum (138) 2-8-18-18-12	Ce Cerium (140) 2-8-18-18-12	Pr Praseodymium (141) 2-8-18-18-12	Nd Neodymium (142) 2-8-18-18-12	Pm Promethium (143) 2-8-18-18-12	Sm Samarium (145) 2-8-18-18-12
Ac Actinium (227) 2-8-18-18-12	Th Thorium (232) 2-8-18-18-12	Pa Protactinium (231) 2-8-18-18-12	U Uranium (238) 2-8-18-18-12	Np Neptunium (237) 2-8-18-18-12	Pu Plutonium (244) 2-8-18-18-12
Am Americium (243) 2-8-18-18-12	Cm Curium (247) 2-8-18-18-12	Bk Berkelium (247) 2-8-18-18-12	Cf Californium (250) 2-8-18-18-12	Es Einsteinium (252) 2-8-18-18-12	Er Erbium (258) 2-8-18-18-12
Fm Fermium (257) 2-8-18-18-12	Tm Thulium (169) 2-8-18-18-12	Yb Ytterbium (173) 2-8-18-18-12	Lu Lutetium (175) 2-8-18-18-12		

Nucleosynthesis

Nucleosynthesis is the process that creates new atomic nuclei from pre-existing nucleons and nuclei.

Time	T (K)	Density
10^{-43} (s)	10^{32}	10^{96}
10^{-35} (s)	10^{28}	10^{80}
10^{-13} (s)	10^{16}	10^{32}
15s	3×10^9	10^4
3min	10^9	10^2
10^5 y	4000	10^{-20}
10^9 y	18	10^{-27}
13.6×10^9	2.73	10^{-30}

1. Big Bang/ Primordial Nucleosynthesis:

According to current theories, the first nuclei were formed a few minutes after the Big Bang. At the beginning, the universe was only made of “elementary particles”. protons, neutrons do not exist, they were not stable (too hot!).

After 10^{-4} seconds temperature was cool enough to form protons and neutrons

After 3 minutes the universe was cool enough to produce ^2H (proton and neutron combined)

2. Stellar Nucleosynthesis:

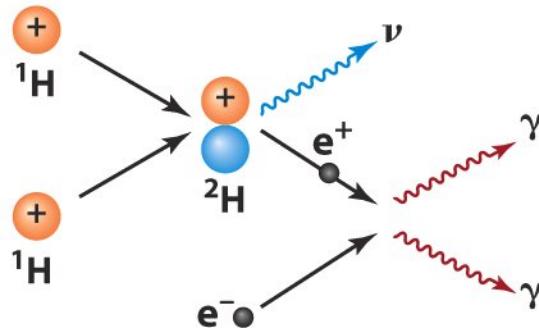
Stellar Nucleosynthesis started more than 12 billion years ago.

Stars are not only the source of light, its an element factory!

Nucleosynthesis

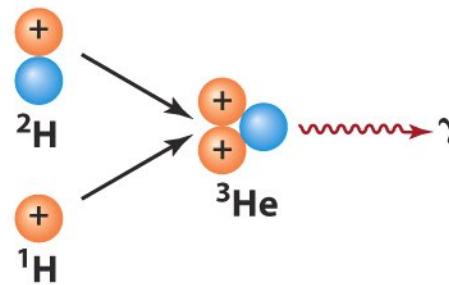
Star “turns on” when nuclear fusion occurs

main sequence star – either proton-proton chain or CNO cycle nucleosynthesis



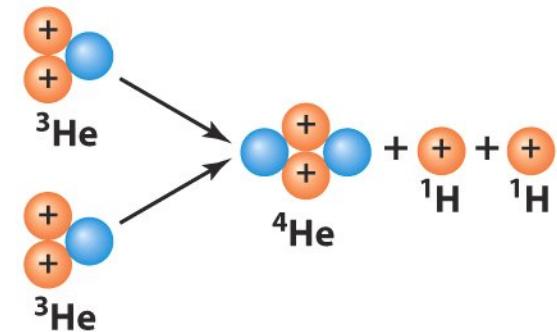
(a) Step 1:

- Two protons (hydrogen nuclei, ^1H) collide.
- One of the protons changes into a neutron (shown in blue), a neutral, nearly massless neutrino (ν), and a positively charged electron, or positron (e^+).
- The proton and neutron form a hydrogen isotope (^2H).
- The positron encounters an ordinary electron (e^-), annihilating both particles and converting them into gamma-ray photons (γ).



(b) Step 2:

- The ^2H nucleus from the first step collides with a third proton.
- A helium isotope (^3He) is formed and another gamma-ray photon is released.



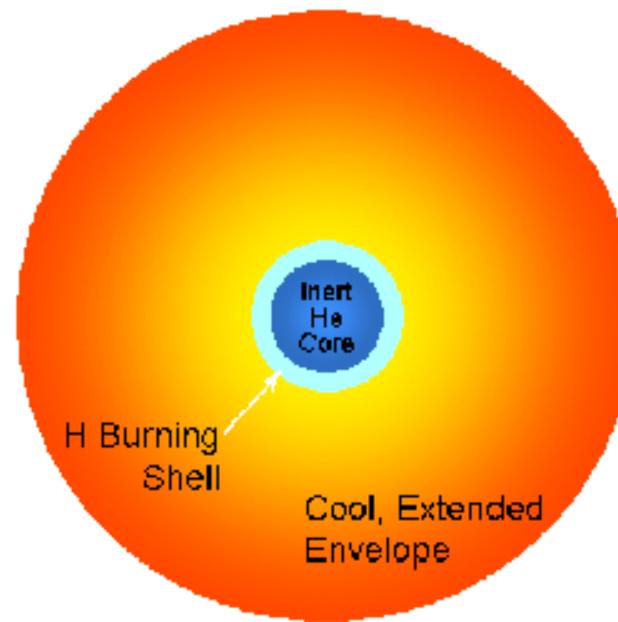
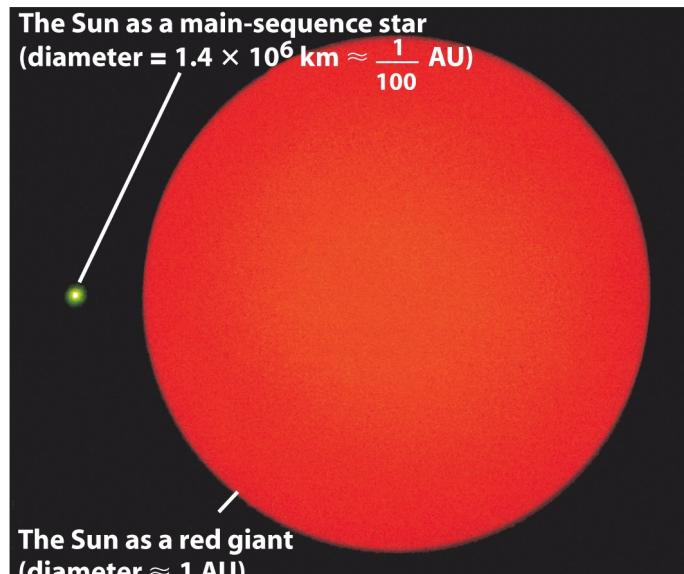
(c) Step 3:

- Two ^3He nuclei collide.
- A different helium isotope with two protons and two neutrons (^4He) is formed and two protons are released.

P-P chain net: 4 H to 1 He

So, what happens when the core runs out of hydrogen?

- Star begins to collapse, heats up
 - Core contains He, continues to collapse
 - But H fuses to He in shell– greatly inflating star
- RED GIANT (low mass)
or SUPERGIANT (high mass)



Red Giant
(RGB) star:
H burning in
shell

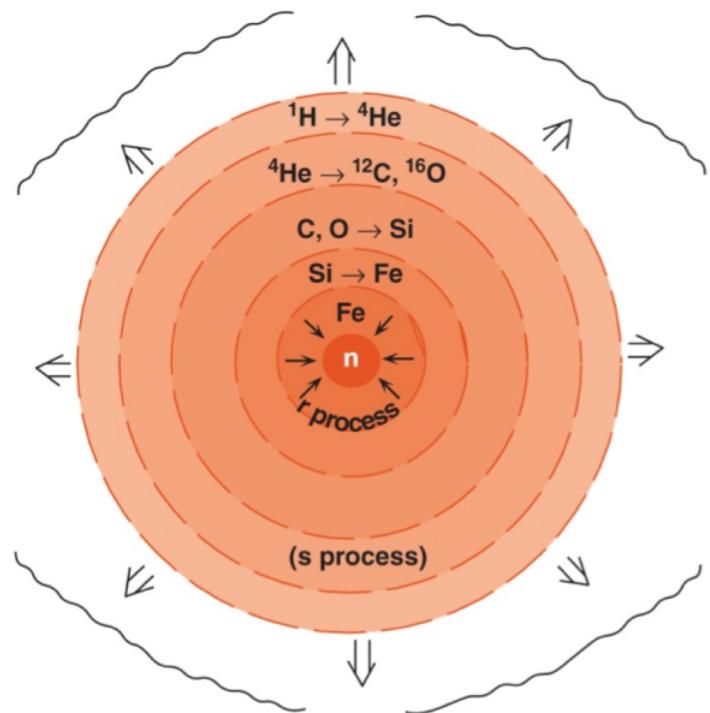
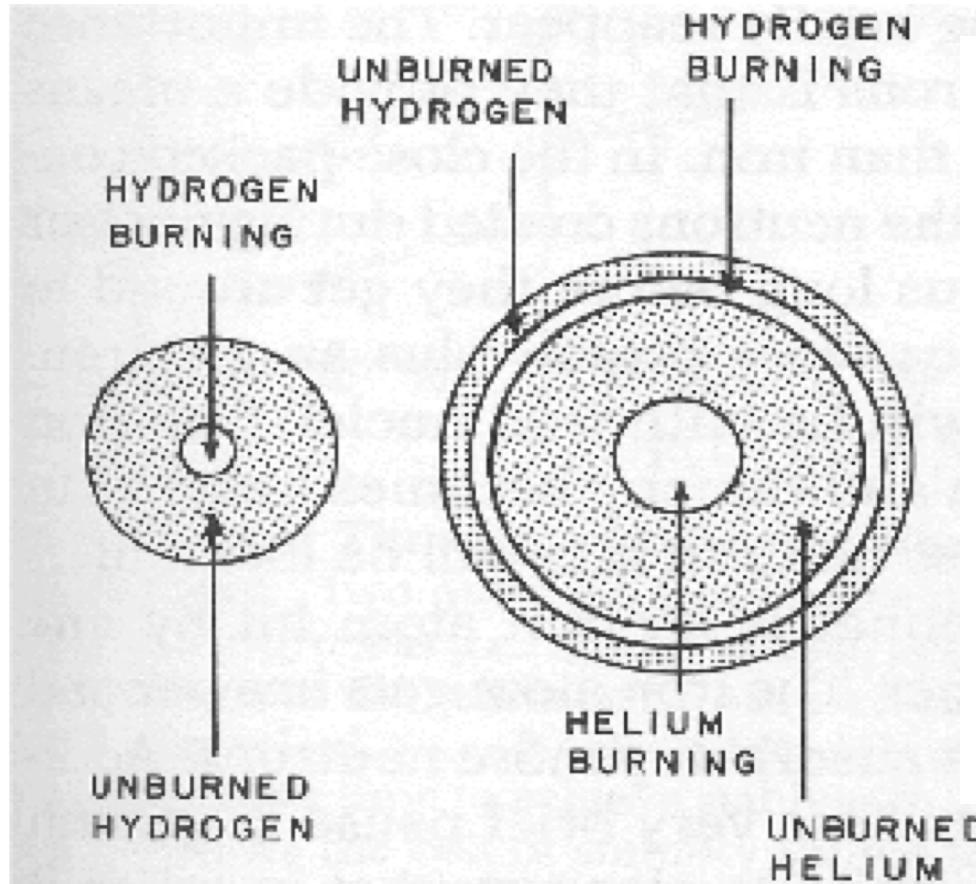
The Sun today and as a red giant

CNO cycle – more efficient method, but requires higher internal temperature, so only for stars with mass higher than 1.1 solar masses



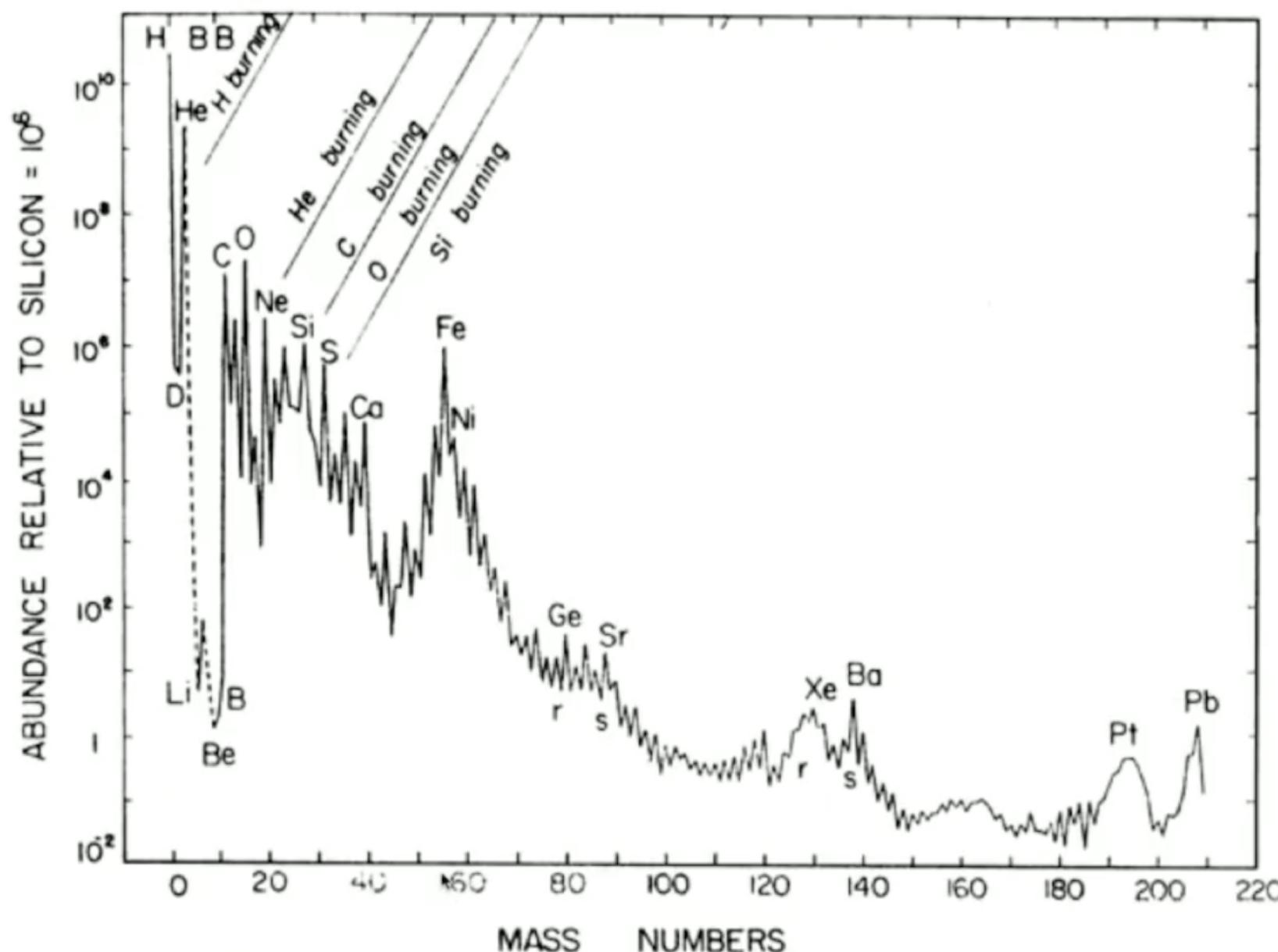
CNO cycle net reaction : 4 H to 1 He

Nucleosynthesis in a Supergiant star



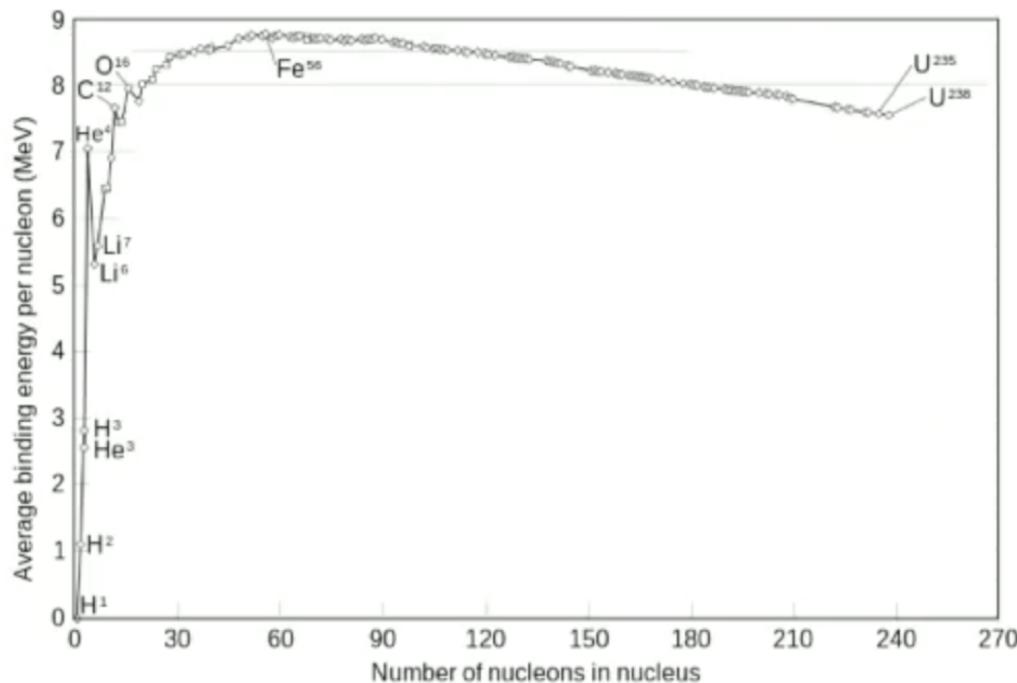
Name of Process	Fuel	Products	Temperature
Hydrogen-Burning	H	He	60×10^6 °K
Helium-Burning	He	C, O	200×10^6 °K
Carbon-Burning	C	O, Ne, Na, Mg	800×10^6 °K
Neon-Burning	Ne	O, Mg	1500×10^6 °K
Oxygen-Burning	O	Mg to S	2000×10^6 °K
Silicon-Burning	Mg to S	Elements near FE	3000×10^6 °K

Is the universe made of iron?



So what happens beyond iron?

- capture of particles requires energy
- capture of charged particles very unlikely
- neutrons still can be captured
- iron from the earlier burning processes exposed to the neutron flux
- two processes possible:
 - slow neutron capture: s-process
 - rapid neutron capture: r-process



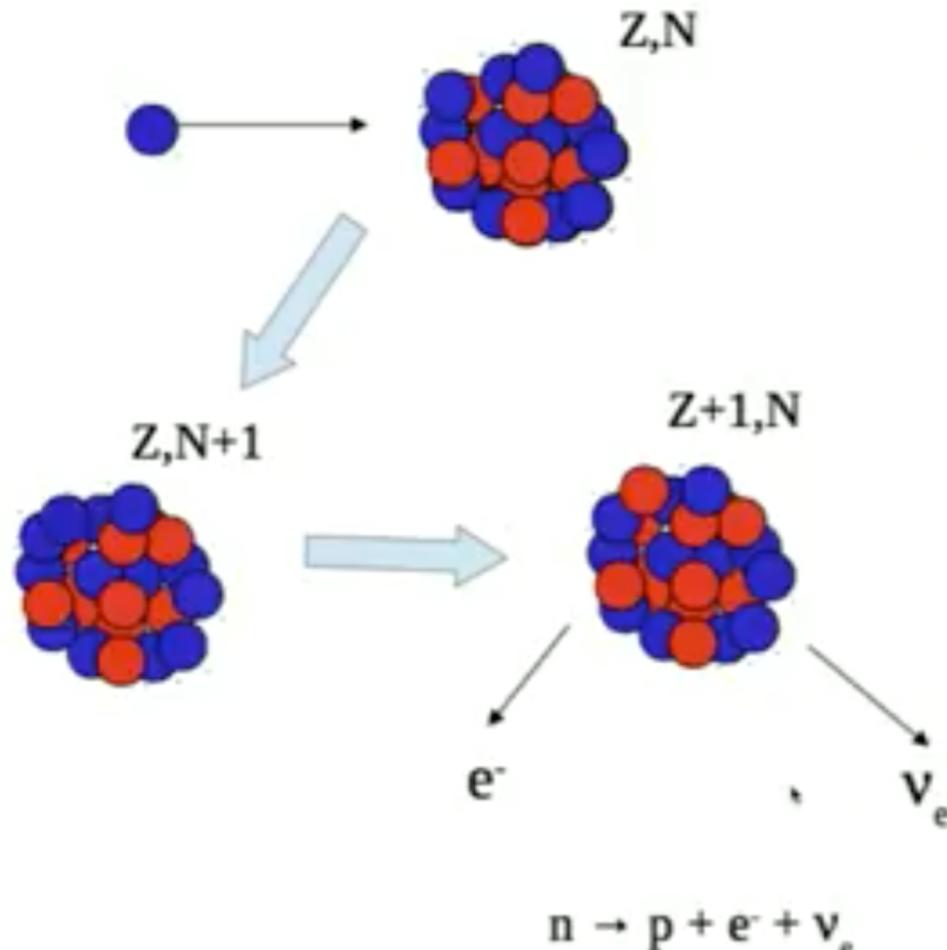
Supernova Explosion

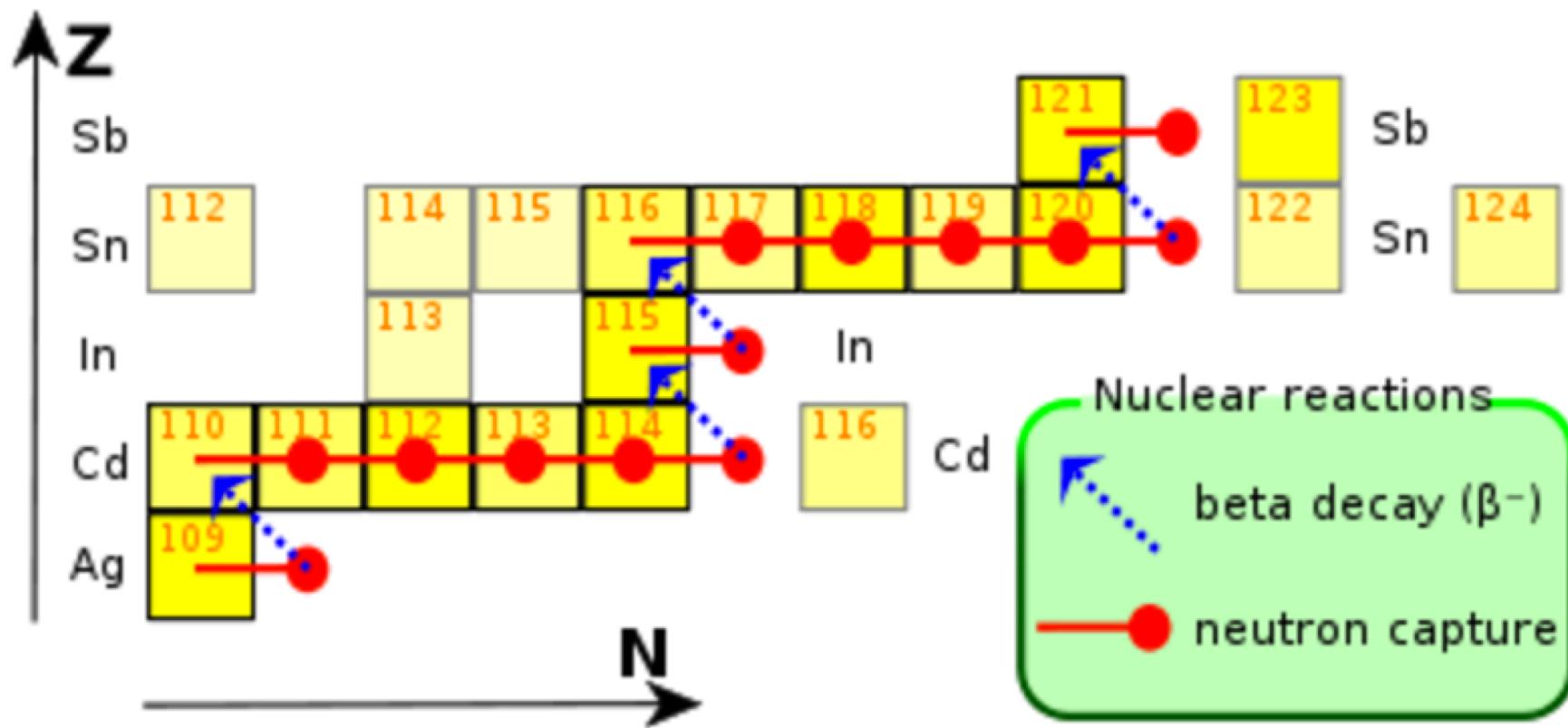
s-process – slow neutron capture

What does it mean 'slow'?

Nucleus half-life – life time of a nucleus before it decays

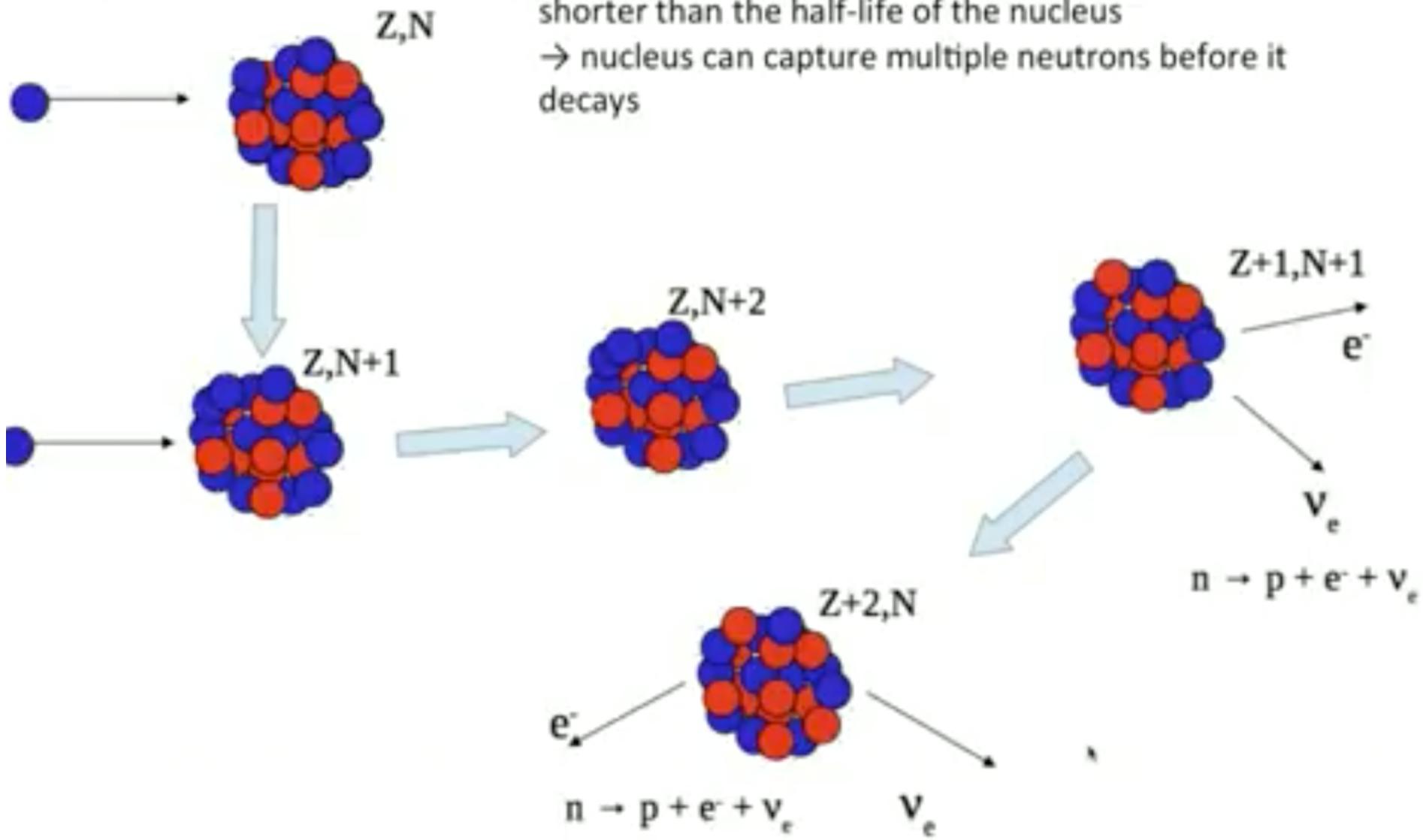
→ 'slow' = time until a neutron is captured is longer than the half-life of the nucleus





r-process – rapid neutron capture

→ 'rapid' = time until a neutron is captured is much shorter than the half-life of the nucleus
→ nucleus can capture multiple neutrons before it decays



r-process nucleosynthesis:

rapid neutron addition

beta decay does not
keep pace with
n addition

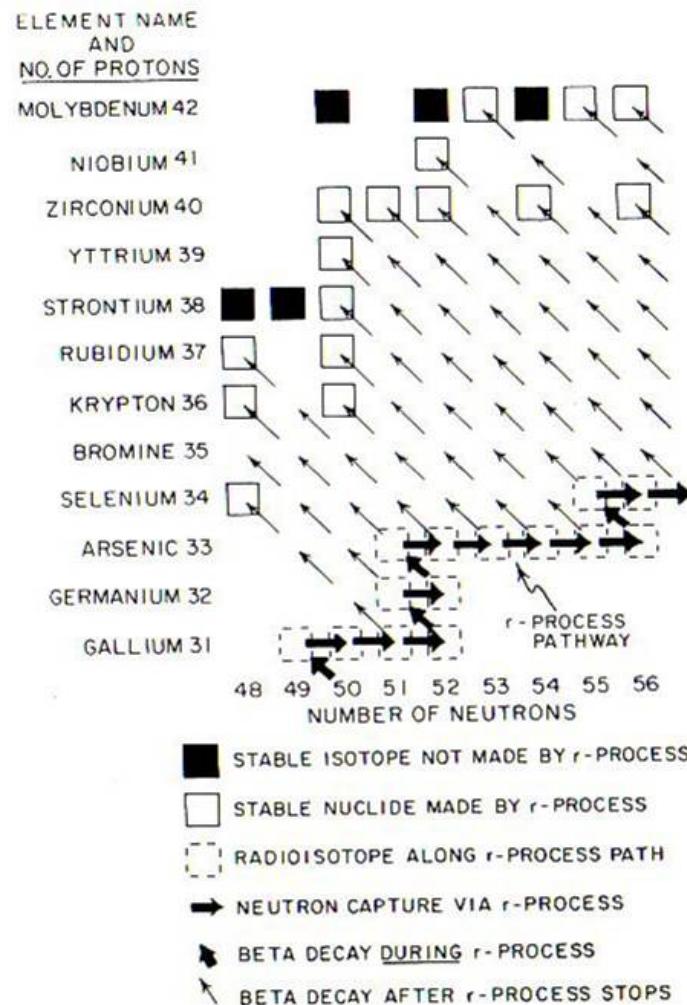
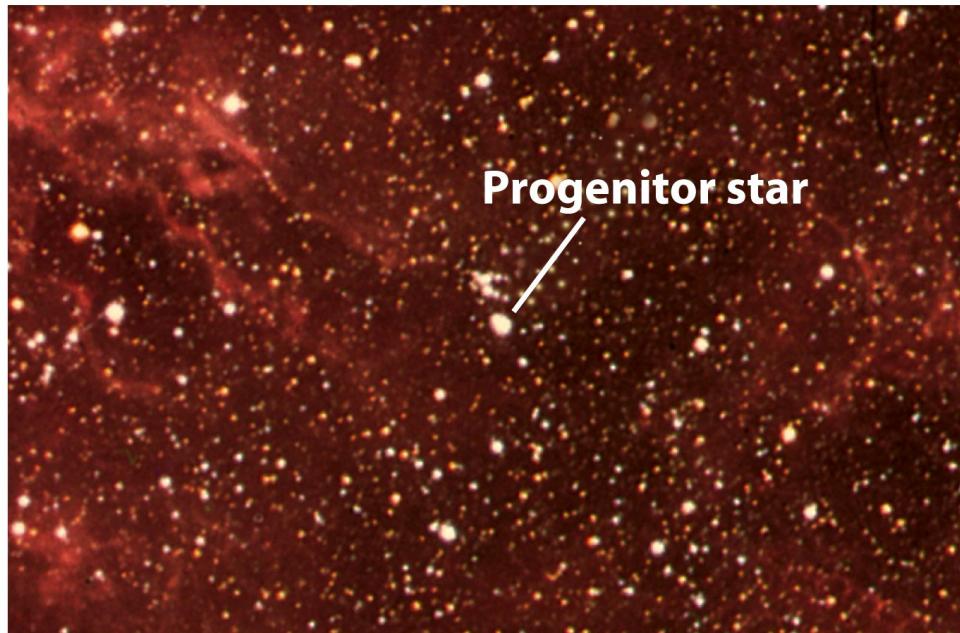


Figure 2-7. A segment of the r-process pathway: Rapid-fire neutron bombardment adds neutrons until a nuclide cannot hold any more. Only then does the nuclide undergo beta decay to become the next heavier element. This process—neutron capture to saturation followed by beta decay—is repeated over and over again, producing successively heavier elements. The r-process buildup occurs during the explosion that destroys the red giant. Hence it ends abruptly. The neutron flux stops and the highly radioactive isotopes on the r-process pathway emit beta particles one after another until stability is achieved. Note that in the case of those isobars for which two stable nuclides exist, only the neutron-rich nuclide of the pair is produced by the r-process.

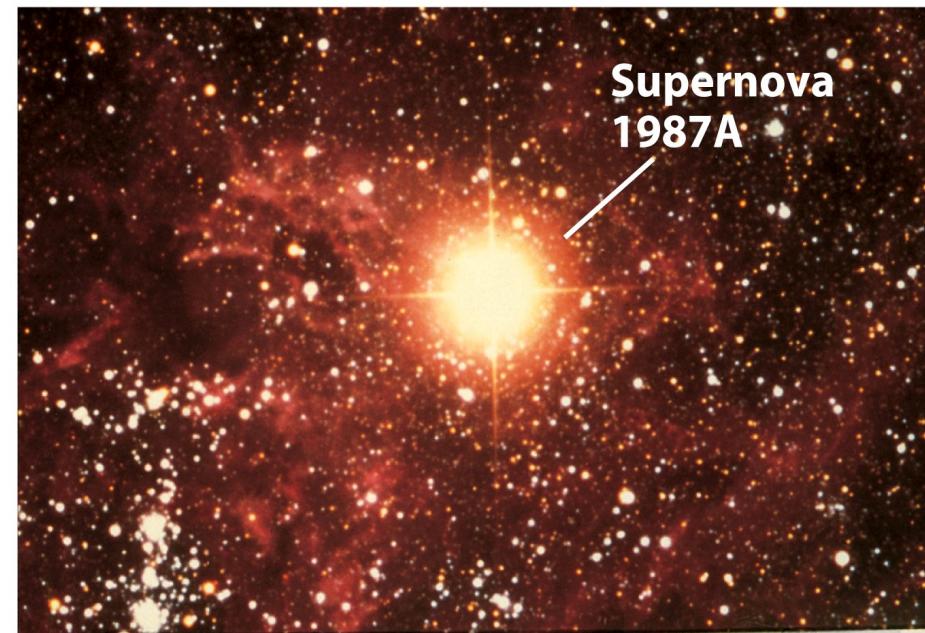
Supernova Explosion

End for high mass star comes as it tries to fuse core Fe into heavier elements- and finds this absorbs energy

STAR COLLAPSES & EXPLODES AS SUPERNOVA



Before the star exploded



After the star exploded

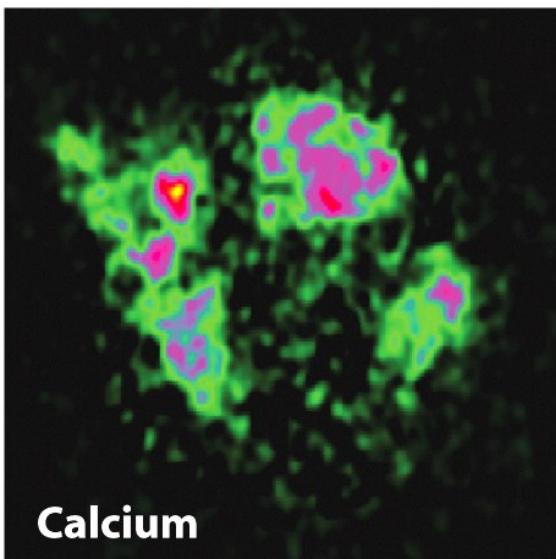


A supernova remnant

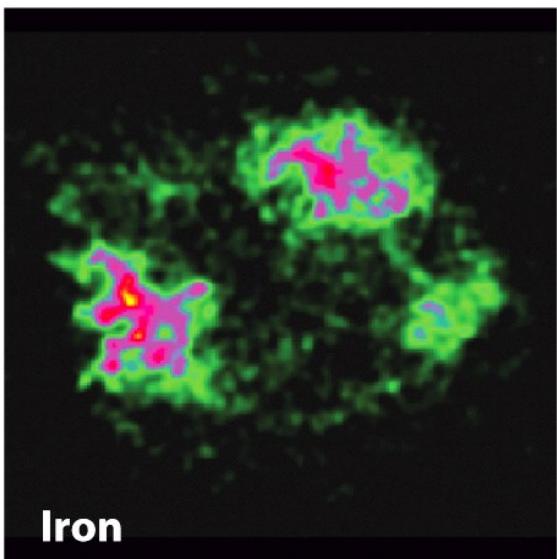
Supernova remnants



Silicon



Calcium



Iron

Material was ejected in “blobs” from the supernova that produced the Cassiopeia A supernova remnant

Element (H-Fe) factory “stars”, supernova explosion along with s-and r-process continued to produce the building blocks of our universe (hydrogen to uranium)

Life cycle of a star

Protostar looks like a star but its core is not yet hot enough for nuclear fusion to take place



Nebula

A red giant is formed when a star runs out of hydrogen at its core and starts fusing hydrogen into helium just outside the core releasing energy and expanding the star

Small Star → Red Giant

Red Giant

Large Red giants are hot enough to turn the helium at their core into heavy elements like carbon

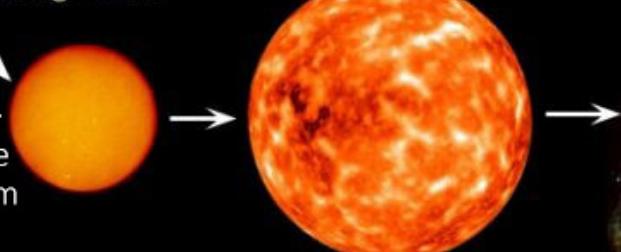


Red Supergiant



Main sequence stars fuse hydrogen atoms to helium atoms in their cores

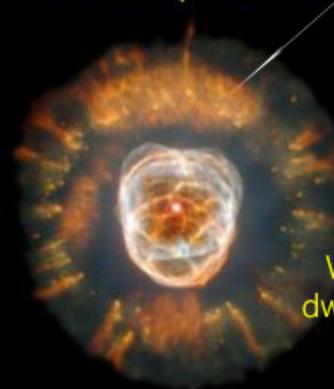
Large Star → Red Supergiant



As the large red giant star condenses, it heats up even further, burning the last of its hydrogen and causing the star's outer layers to expand outward

Once the star runs out of fuel, the star will collapse under the influence of gravity and the outer layers will be ejected into the vastness of space

Planetary Nebula



Remains of stars devoid of fuel. They consist of degenerate matter with a very high density.

White Dwarf



White dwarf becomes a black dwarf when it stops emitting light

Protons and electrons left after a supernova are forced to combine to produce very dense neutron star.

Supernova

Explosive death of a star.



Neutron Star

If the mass is significantly greater, the gravity will be so strong that the neutron star will shrink further to become a black hole.



Black Hole

Summary of nucleosynthesis processes

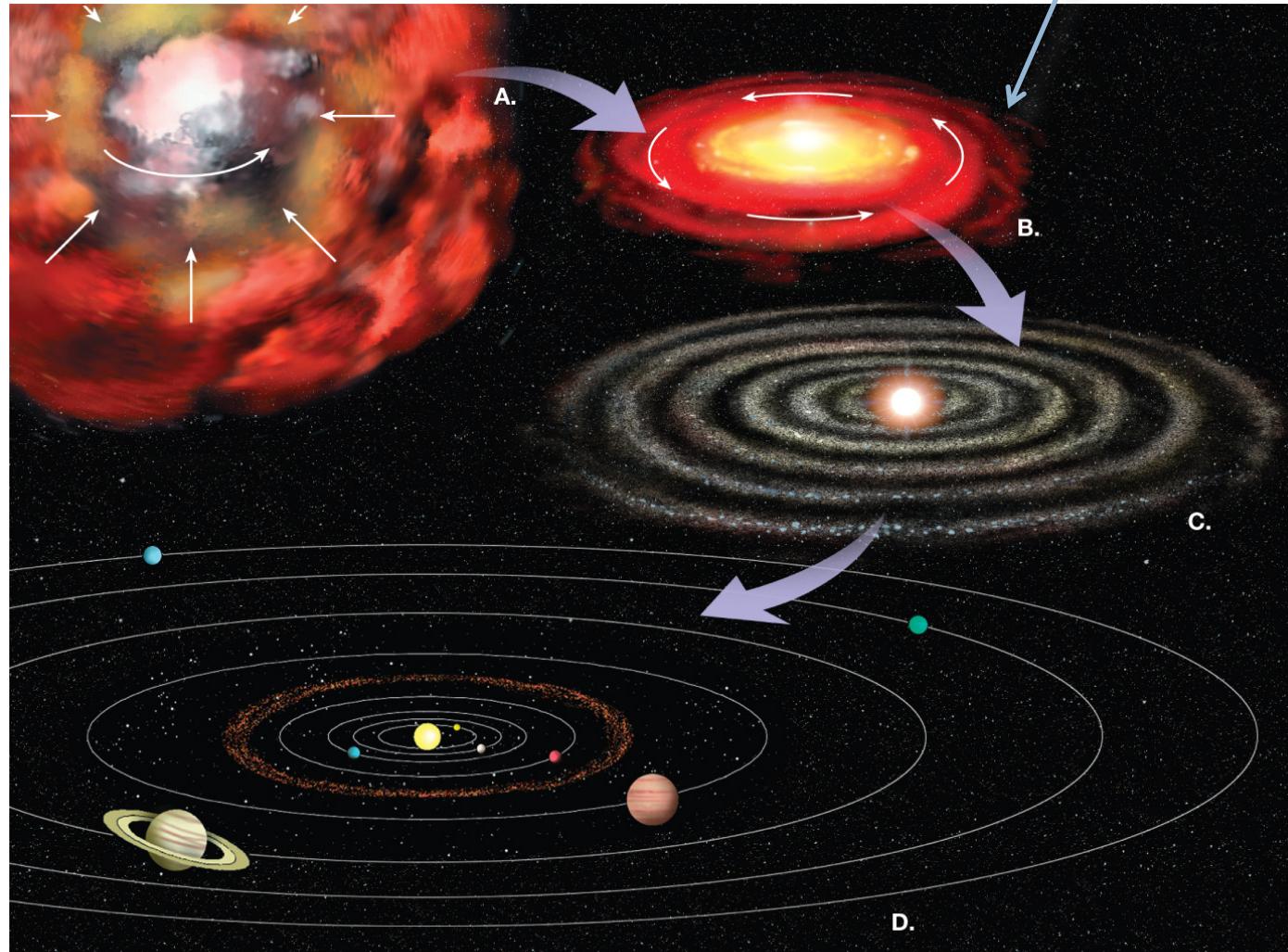
process	main products	comment
H-burning	^4He	main seq.
He-burning	^{12}C , ^{16}O	Red Giant
C-O-Ne-Si burning	^{20}Ne , ^{28}Si , ^{32}Si , up to ^{56}Fe	Supergiants
s-process	many elements	Red Giants, Supergiants
r-process	many heavy elements	Supernova

Formation of Solar System

4.57 billions years ago

The Nebular Theory

1. Cosmic cloud formed from dust of previous Supernovae
2. Gravity pulls particle closer and increase rotation
3. Nuclear reaction begins \sim 5 billion years ago at the centre of the cloud due to high concentration of material
4. Remaining particle continues to come closer and accretion took place
5. Eventually larger particles accreted and formed 'planets'

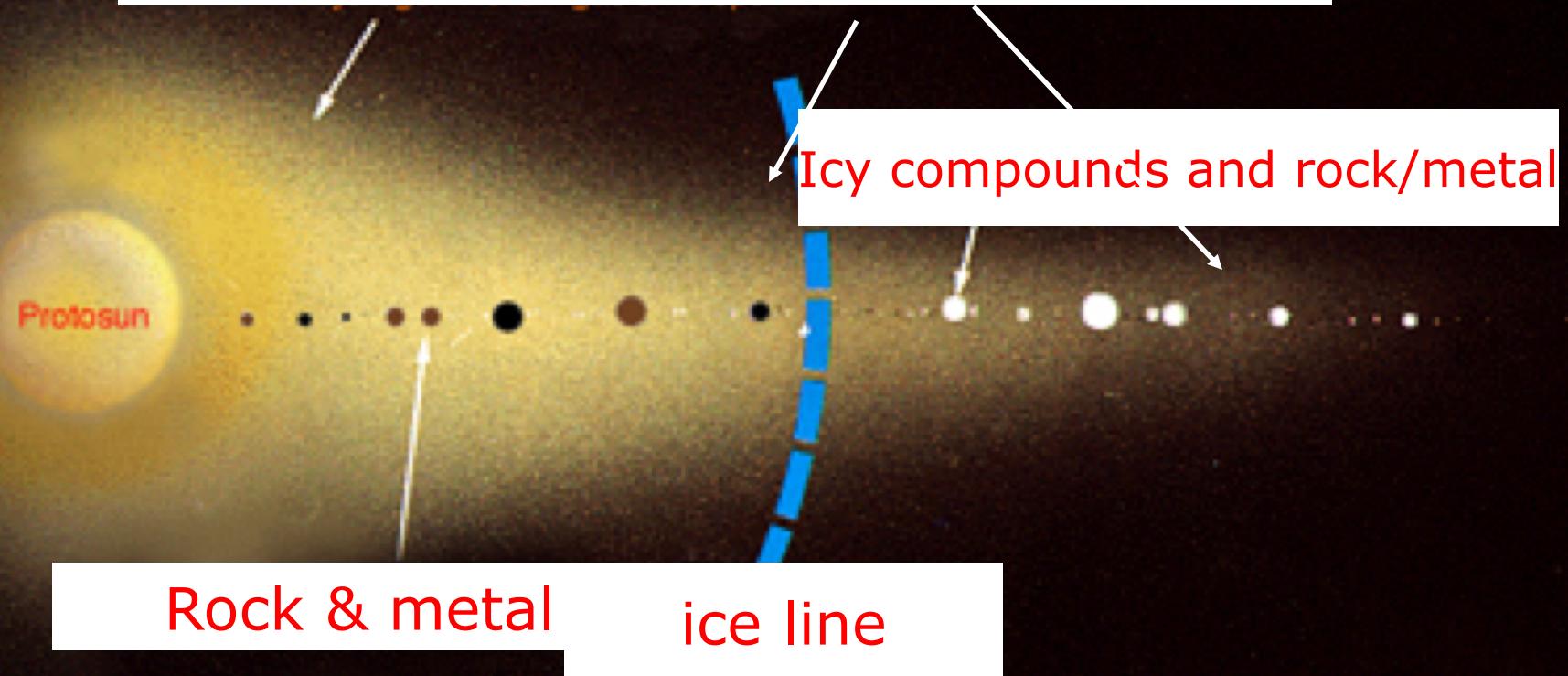


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Formation of Solar System

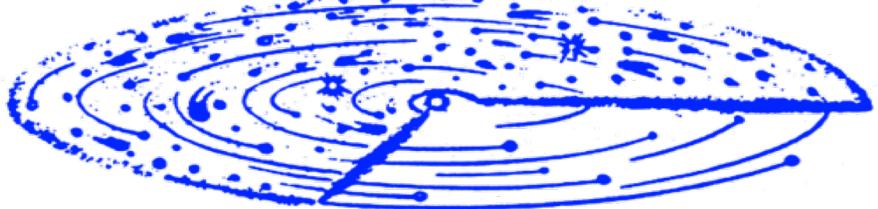
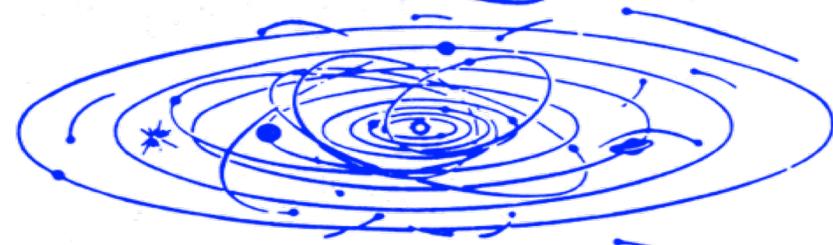
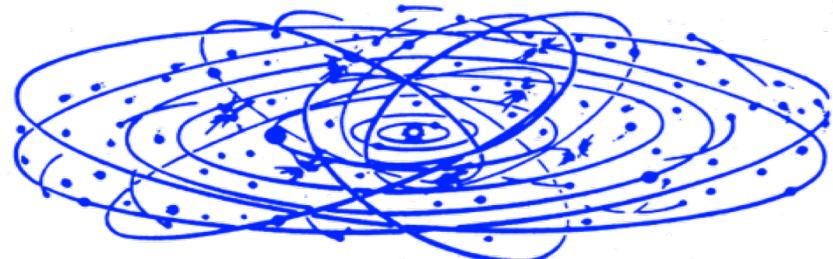
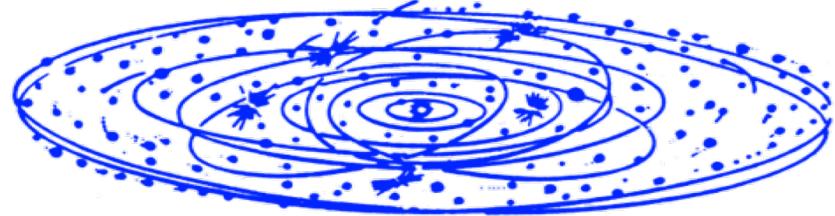
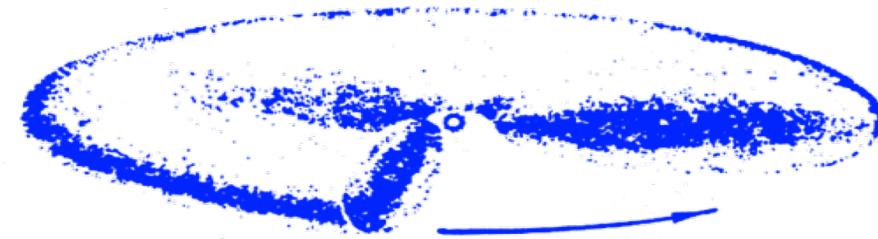
H, He gas is present throughout the disk



Condensation: gas becomes solid

Terrestrial planets form by accretion of solids

Dust >rocks >planetesimals >embryos >planets



Planet formation: Terrerstrial vs. giant planets

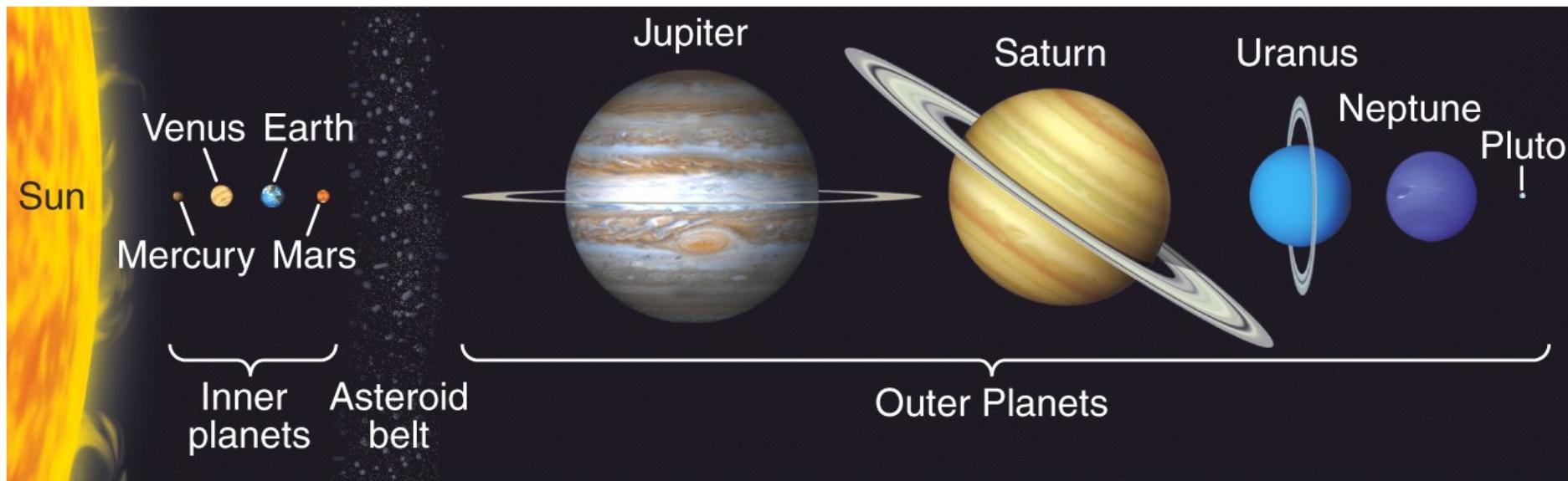
Giant ("jovian")

1. Lots of solids in the disk (cold > 5 AU)
2. Cores form from ice, rock and metal
3. Grow large, quickly (~1 million years)
4. Big enough to trap H and He gas from disk

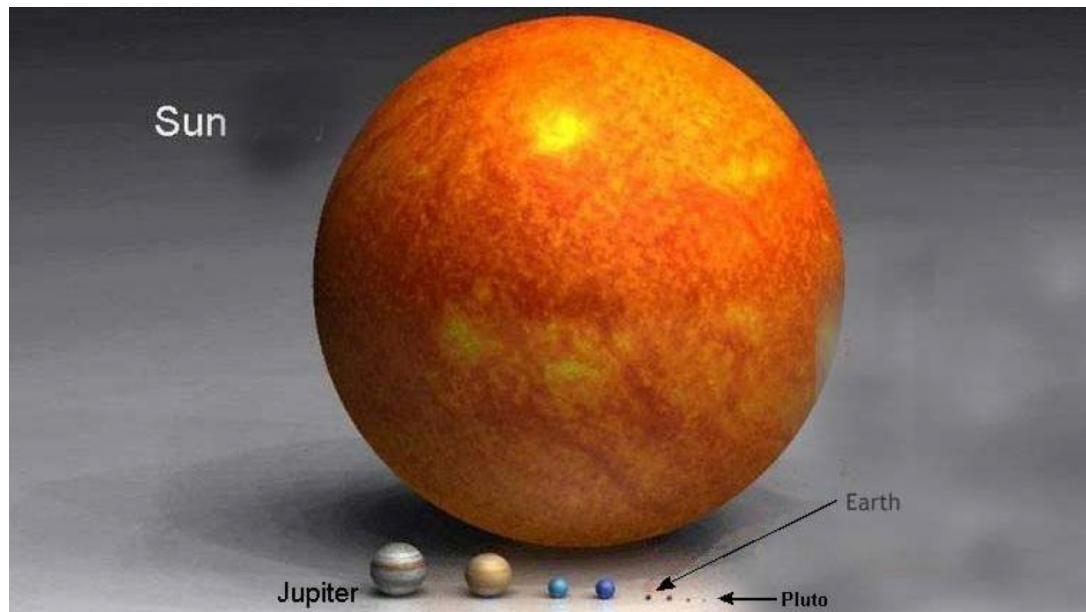
Terrestrial ("earth like")

1. Very little solid material in disk at 1 AU
2. Form from rock and metal only
3. Grow slowly (~100 million years)
4. Too small to trap any gas from disk

Solar System



Sizes of the planets relative to Sun



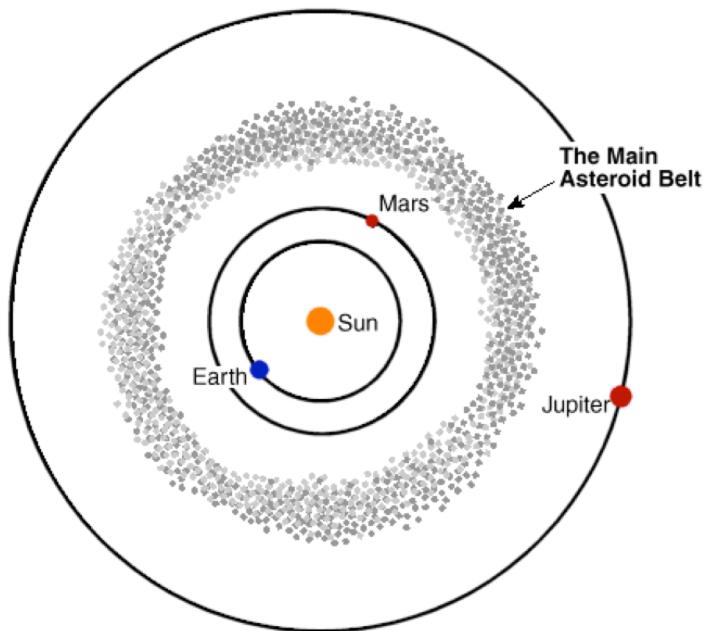
Sun-planet distance
(relative to Earth: AU)

Mercury	0.4	AU
Venus	0.7	
Earth	1.0	
Mars	1.5	
Jupiter	5.2	
Saturn	9.5	
Uranus	19	
Neptune	30	

1 AU = 150 million km

Other residents of the solar system

1. Moons - orbit planets, some are larger than Mercury
2. Asteroids - rocky, $d < 1000$ km, orbit the sun



(Orbits drawn approximately to scale)

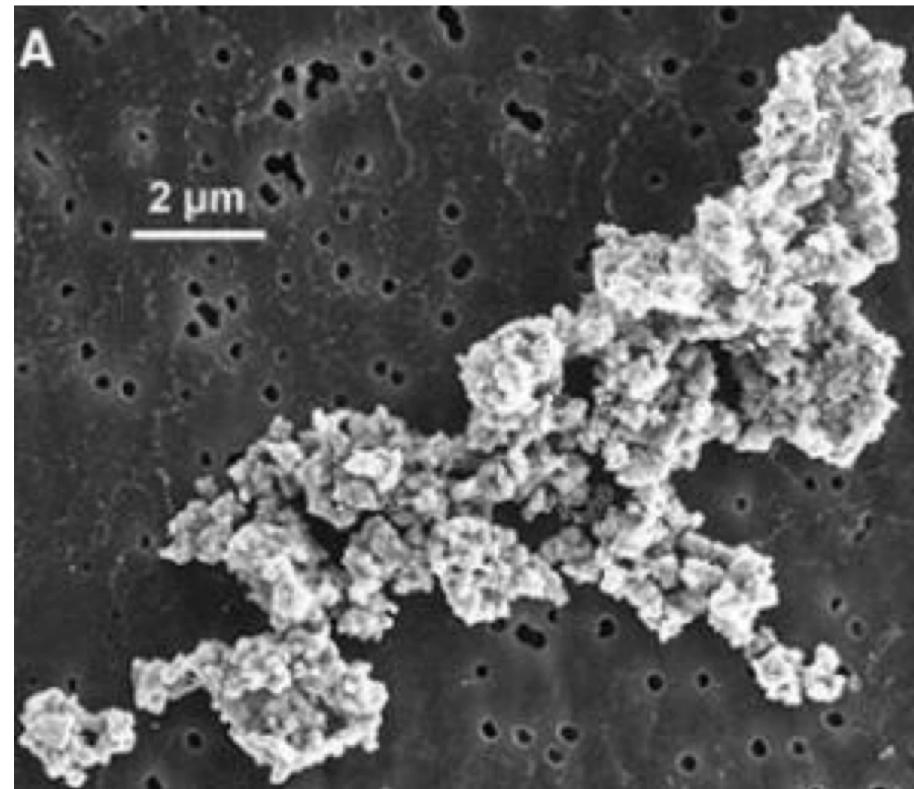
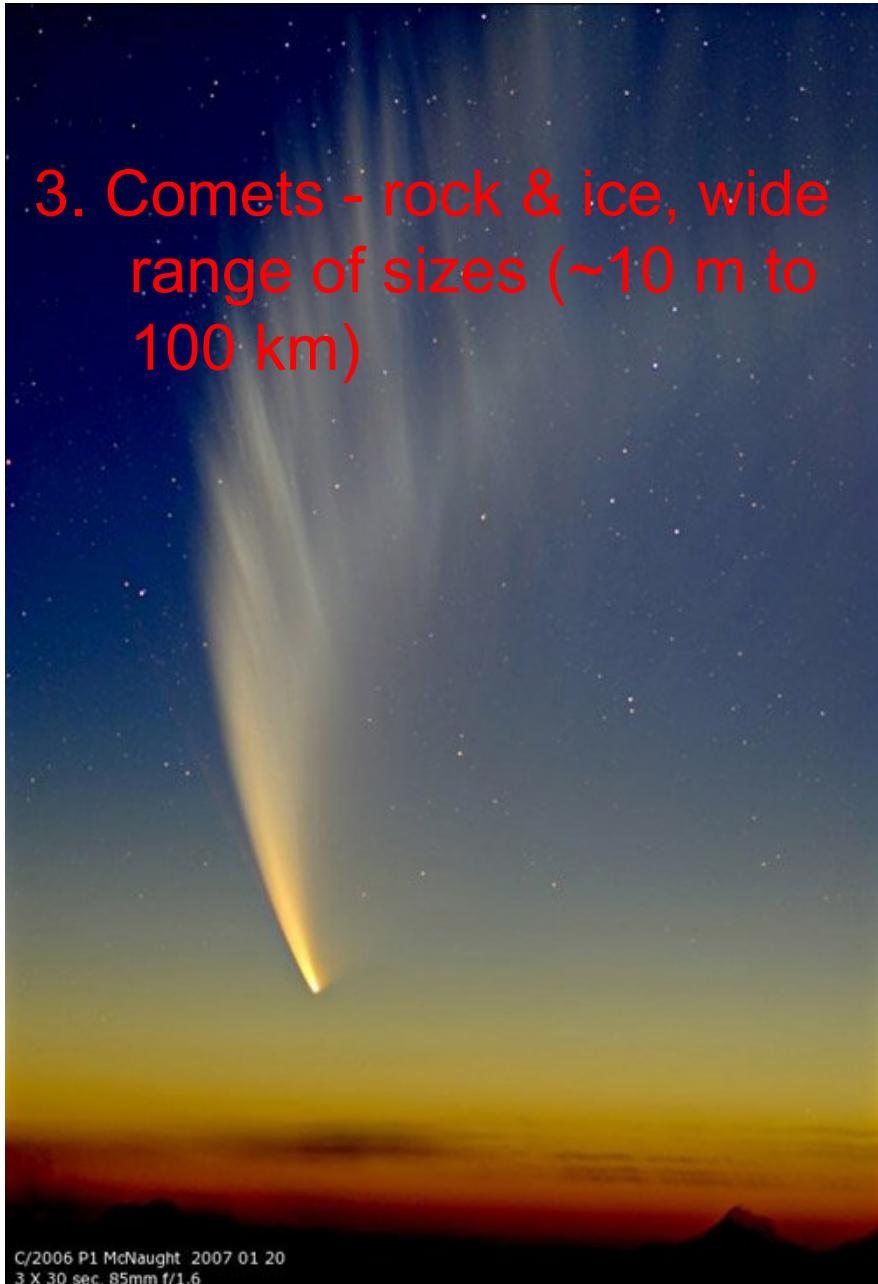
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Other residents of the solar system

3. Comets - rock & ice, wide range of sizes (~10 m to 100 km)



4. Meteoroids - small fragments of asteroids that enter earth's atmosphere (dust to boulder sized)