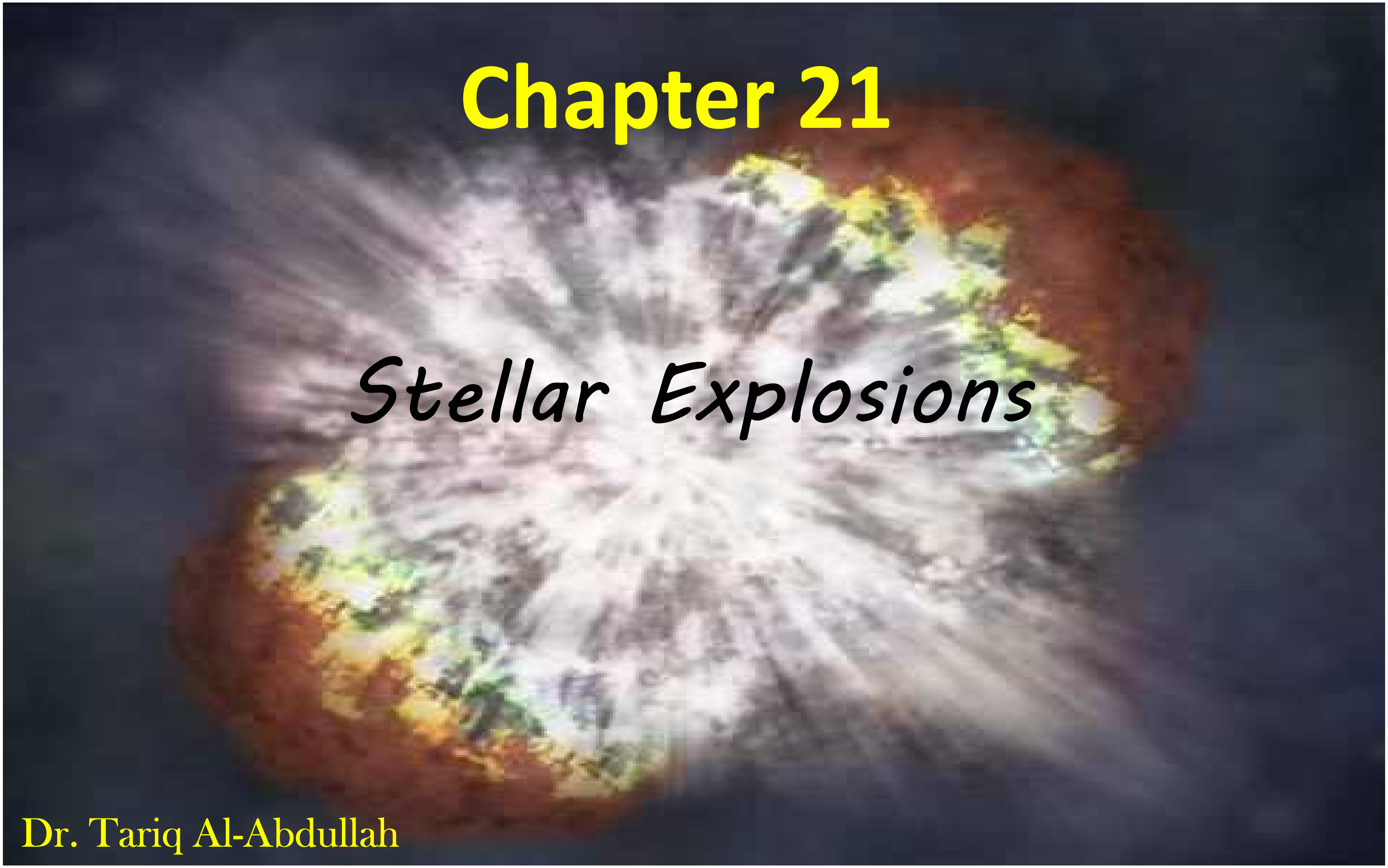


Chapter 21

Stellar Explosions

Dr. Tariq Al-Abdullah

Learning Goals:

21.1 Life After Death for White Dwarf

21.2 The End of a High-Mass Star

21.3 Supernovae

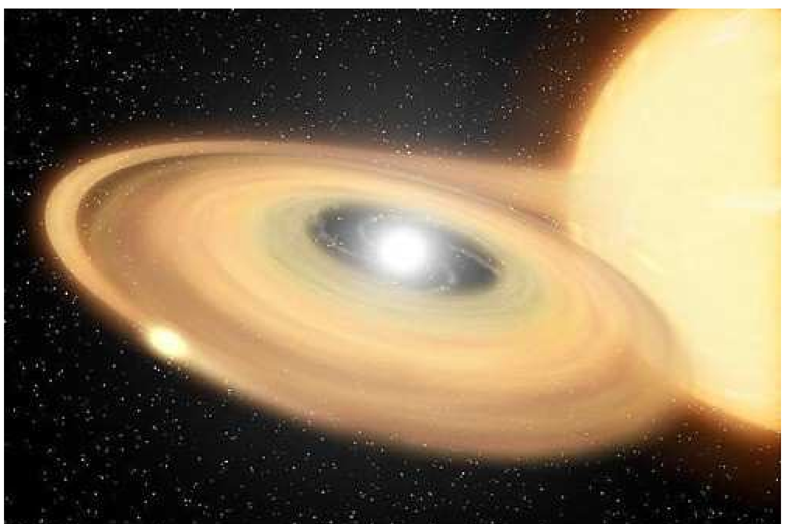
21.4 Formation of Elements

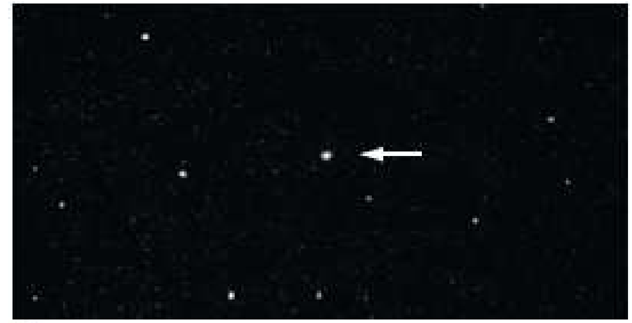
21.5 The Cycle of Stellar Evolution

21.1 Life After Death for White Dwarfs

A nova: a new star that flares up very suddenly and then returns slowly to its former luminosity

- Typically 2-3 novae are observed each year.
- Recurrent novae: stars that “go nova” several times.
- What cause such an explosive on a faint-dead star?
- A binary system gives the answer:





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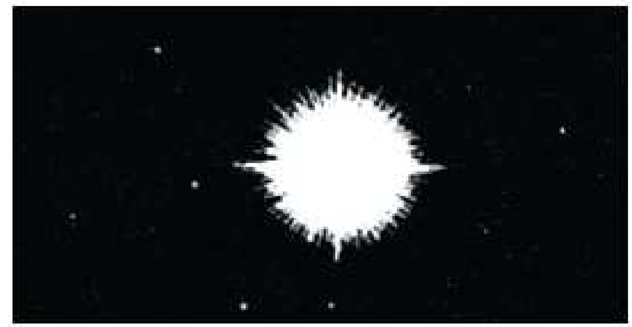

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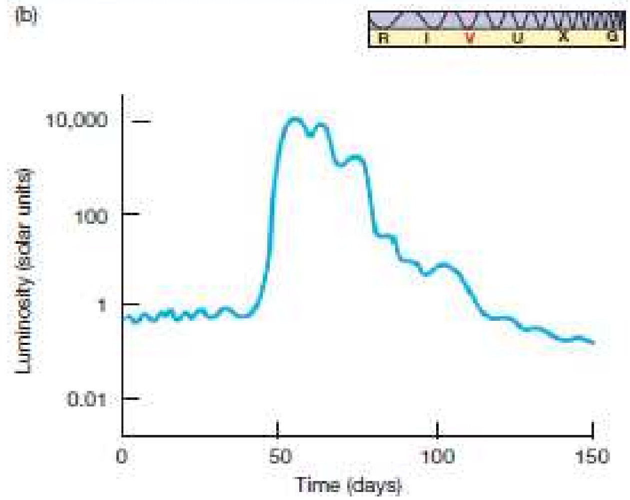

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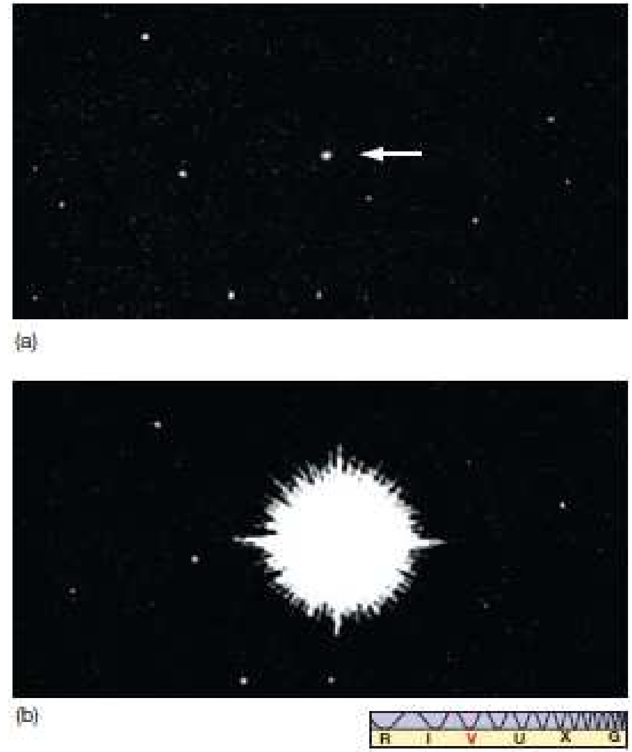
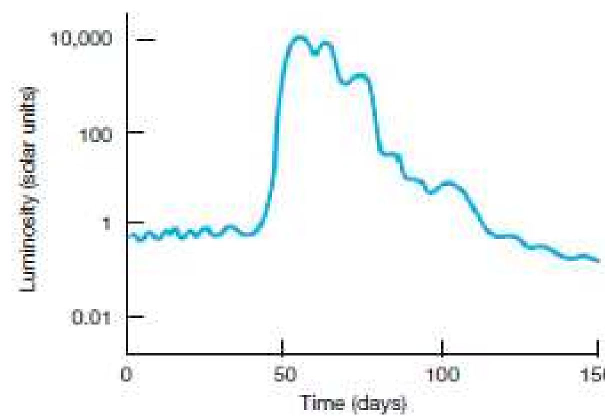
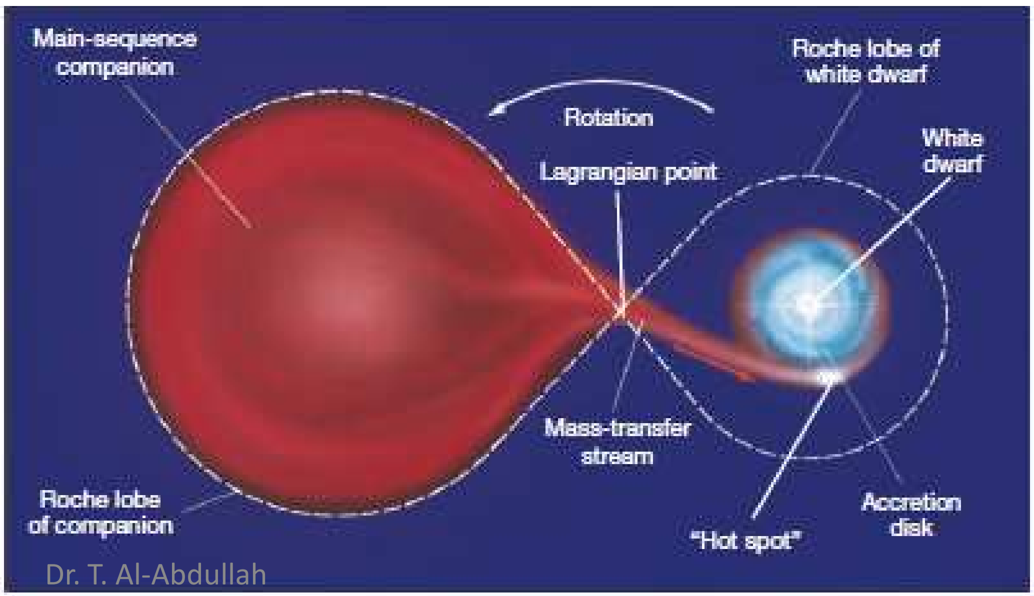


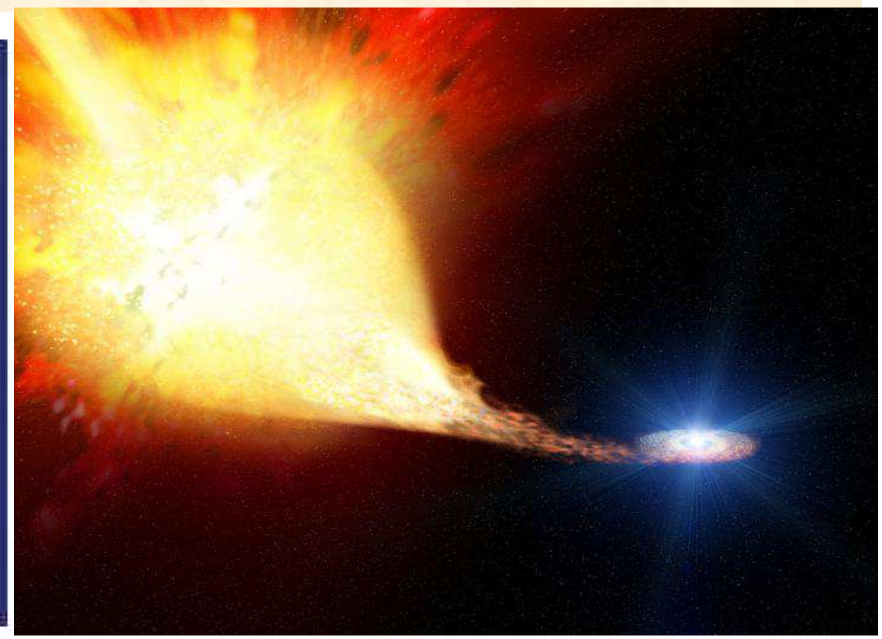


21.1 Life After Death for White Dwarfs

Accretion disk: missed materials from the giant companion loops around the white dwarf, goes into orbits around it forming swirling flattened disk of matter.

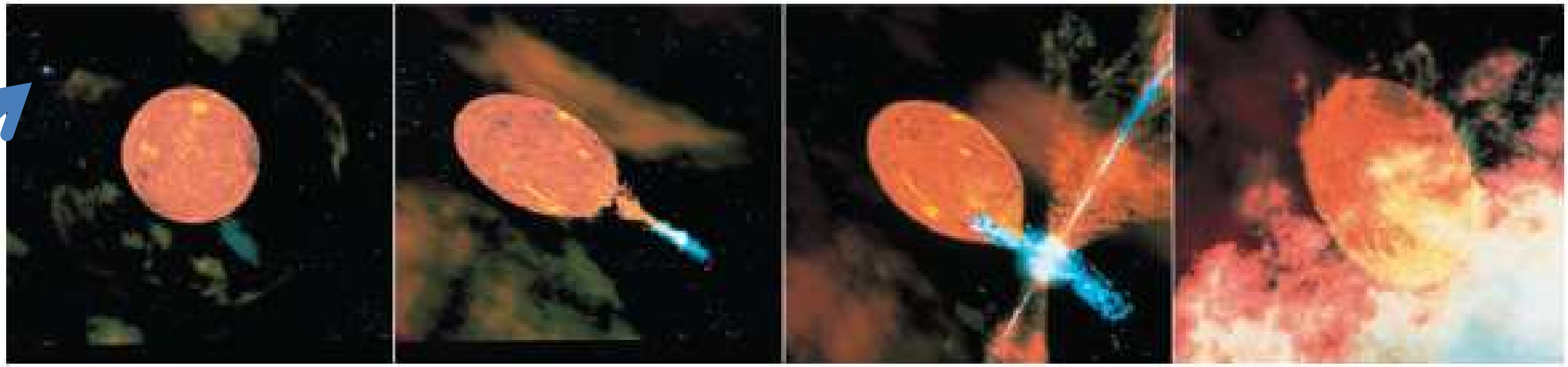
- **Temperature on the outer surface increased → 10^7 K, transferred gas denser.**
- **H fused into He at a fast rate → surface burning is violent.**
- **The star suddenly flares up it luminosity and fades away.**
- **Part of the disk is blown off into space.**



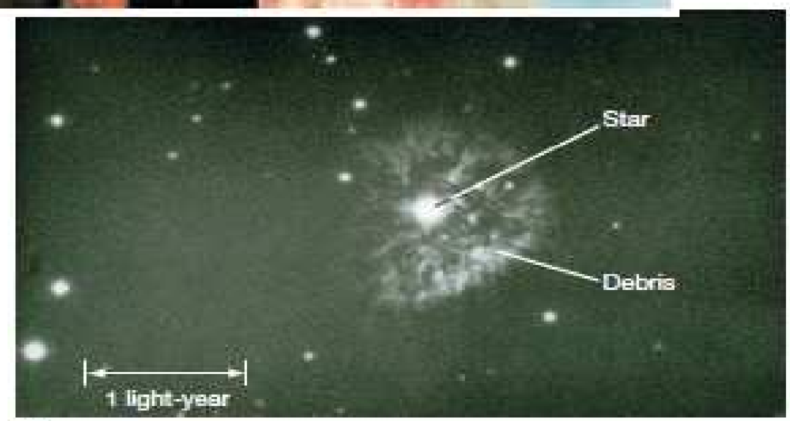


21.1 Life After Death for White Dwarfs

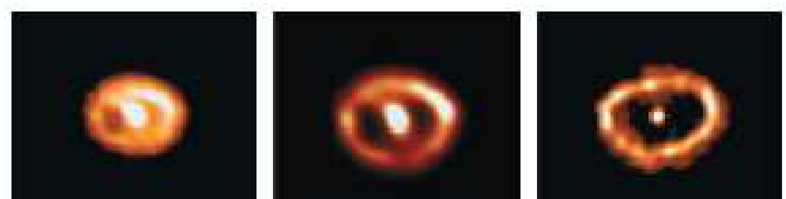
WD



- Spectrum: visible, UV and X-rays
- Matter strikes the accretion disk form a turbulent “hotspots” ➔ fluctuation in the emitted light.
- A nova’s decline in brightness due to cooling of its surface layers as they are blown in the space
- Two novae spelling mass from their surfaces.
- Extending the life of the white dwarf.



(a) Nova Persei, 1901, fig after 50y.



(b) Nova Cygni, 1992, ring after 7 months

21.2 The End of a High-Mass Star

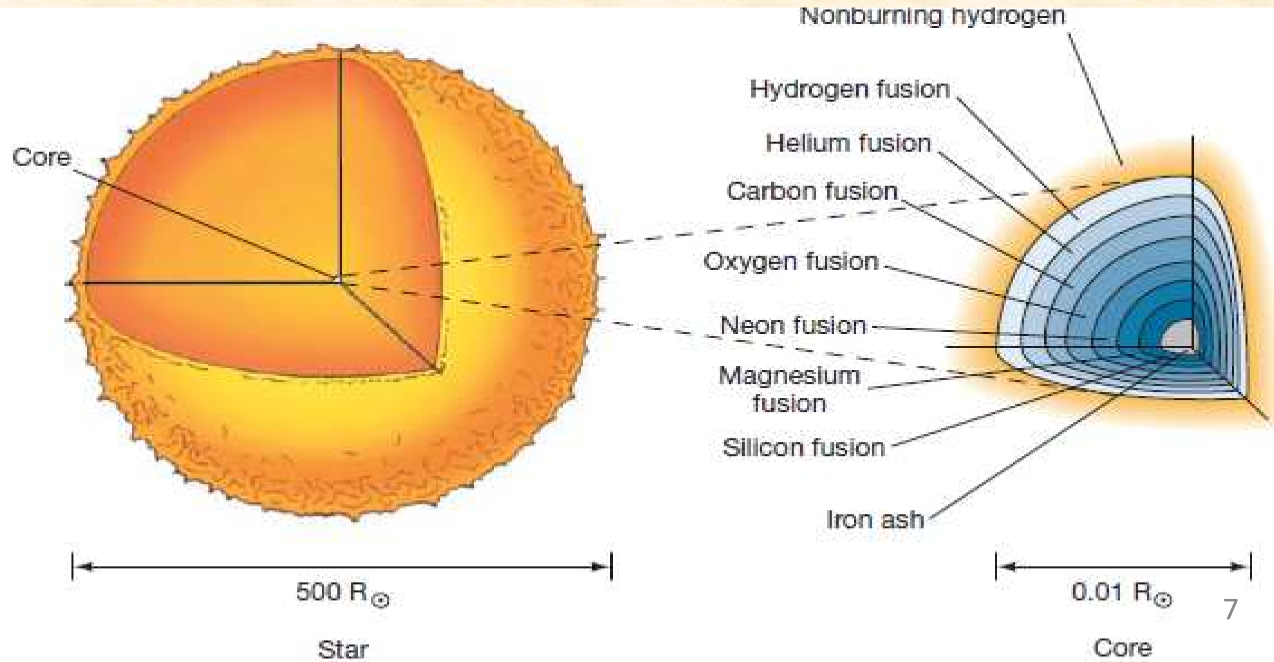
➔ **Fusion of Heavy Elements > 8 M_{sun}??**

• **As the Temperature increases, the ash of the each burning stage becomes a fuel for the next stage.**

•**As each element is burned at the center, the core contracts, heats up, and start to fuse the ash of the previous stage ➔ new element created.**

• **Inner core: Iron – Si – Mg – Ne – O – C – He – H – non-burning H**

• **Burning stages:**
*** H: 10 million years**
*** He: 1 million year**
*** C: 1000 year**
*** O: one year**
*** Si: one week**
*** Fe: < a day**



21.2 The End of a High-Mass Star

➔ Collapse of the Iron Core

• Once the core is Fe → the high mass star is in trouble.

• Iron is the most stable element; ratio: mass / number of nucleons.

• Fusion versus, Fission reactions, both ends to Fe ➔ central fires cease for the last time ➔ destroy equilibrium forever.

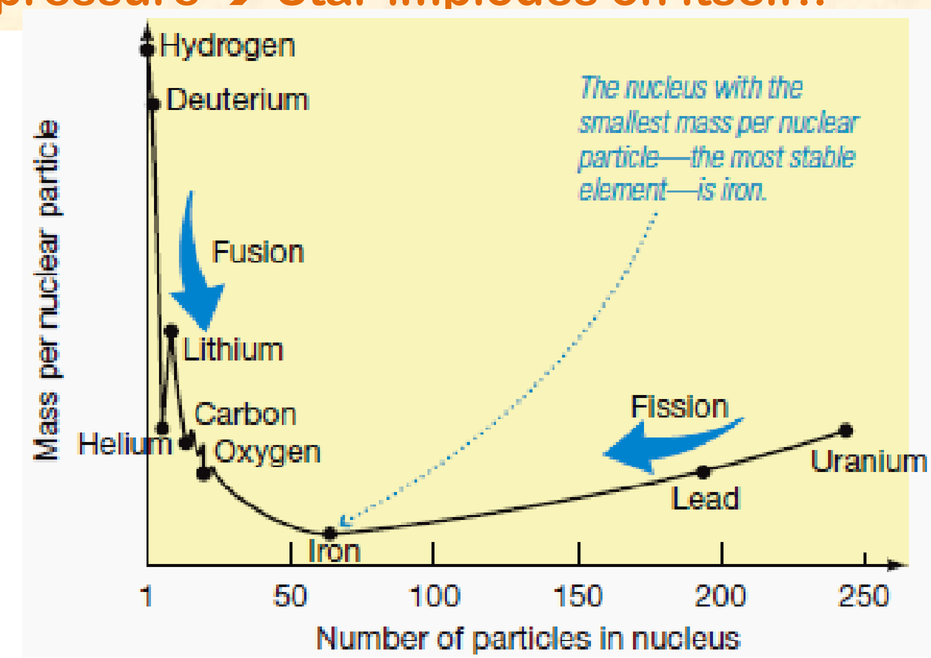
• Enormous inward gravity >> thermal pressure ➔ Star implodes on itself!!

A+B → C ± Energy

• $M_A + M_B > M_C$ → exothermic

• $M_A + M_B < M_C$ → endothermic

• Triple-alpha up to ^{56}Ni decays ^{56}Fe



21.2 The End of a High-Mass Star

➔ Collapse of the Iron Core

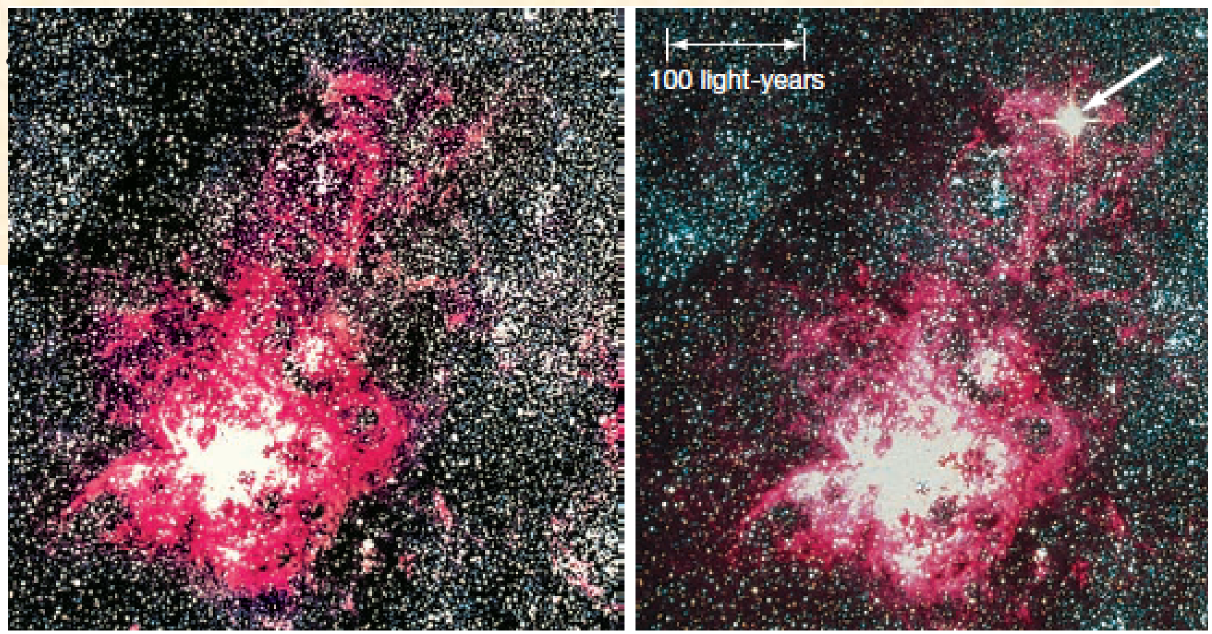
- The temperature rises to 10^{10} K ➔ Wien's Law ➔ photons have high Energy
- Photo disintegration: Photons split heavy elements into lighter ones.
- 10 million years to build Fe-core, 1 sec to destroy everything back to H & n.
- The process absorbs thermal energy, not producing it ➔ cooling the core.
- Core unable to support itself against its own gravity ➔ Accelerate core-collapsing
- Core consists of elementary particles: protons, electrons, neutrons, photons.
- Because of the high density: p + e → n + neutrino, neutrinos don't support the thermal pressure ➔ reducing the core's pressure support.
- This process is called: **neutronization** of the core.
- Density now: 10^{12} kg/m^3.

21.2 The End of a High-Mass Star

➔ Supernova Explosion

- Disappearance of electrons and escaping the neutrinos ➔ nothing to prevent the collapsing all the way to the point where neutron are in contact.
- Density 10^{15} kg/m^3. Neutron slow compression, density up to $10^{17,18}$ kg/m^3
- Rebounding process, expansion again ➔ Shock Wave
- Blasting all the overlying layers, including heavy elements.
- Computer models uncertain
- Most energetic events;
- Core-collapse supernova

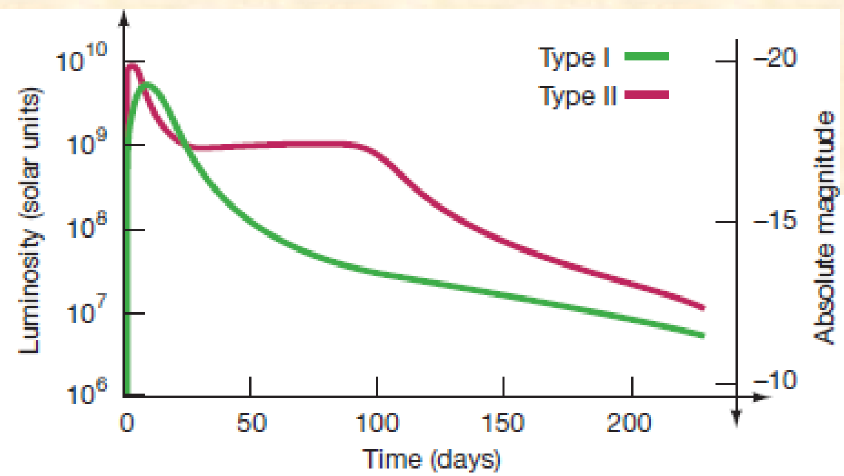
SN 1987A



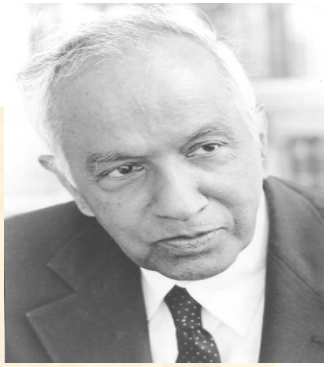
21.3 Supernovae

Novae and Supernovae

- Supernova is million times brighter than nova
- Energy radiated by supernova in few months, 10^{43} J = Energy radiated by the Sun in 10 billion years.
- Same star may become a nova several times, but becomes a supernova only once.
- Supernova contain very little H, while others contain no H
- Type I supernova: H-poor kind, light curve similar to nova
- Type II Supernova: H-rich kind
- SN is either Type I or Type II.



21.3 Supernovae

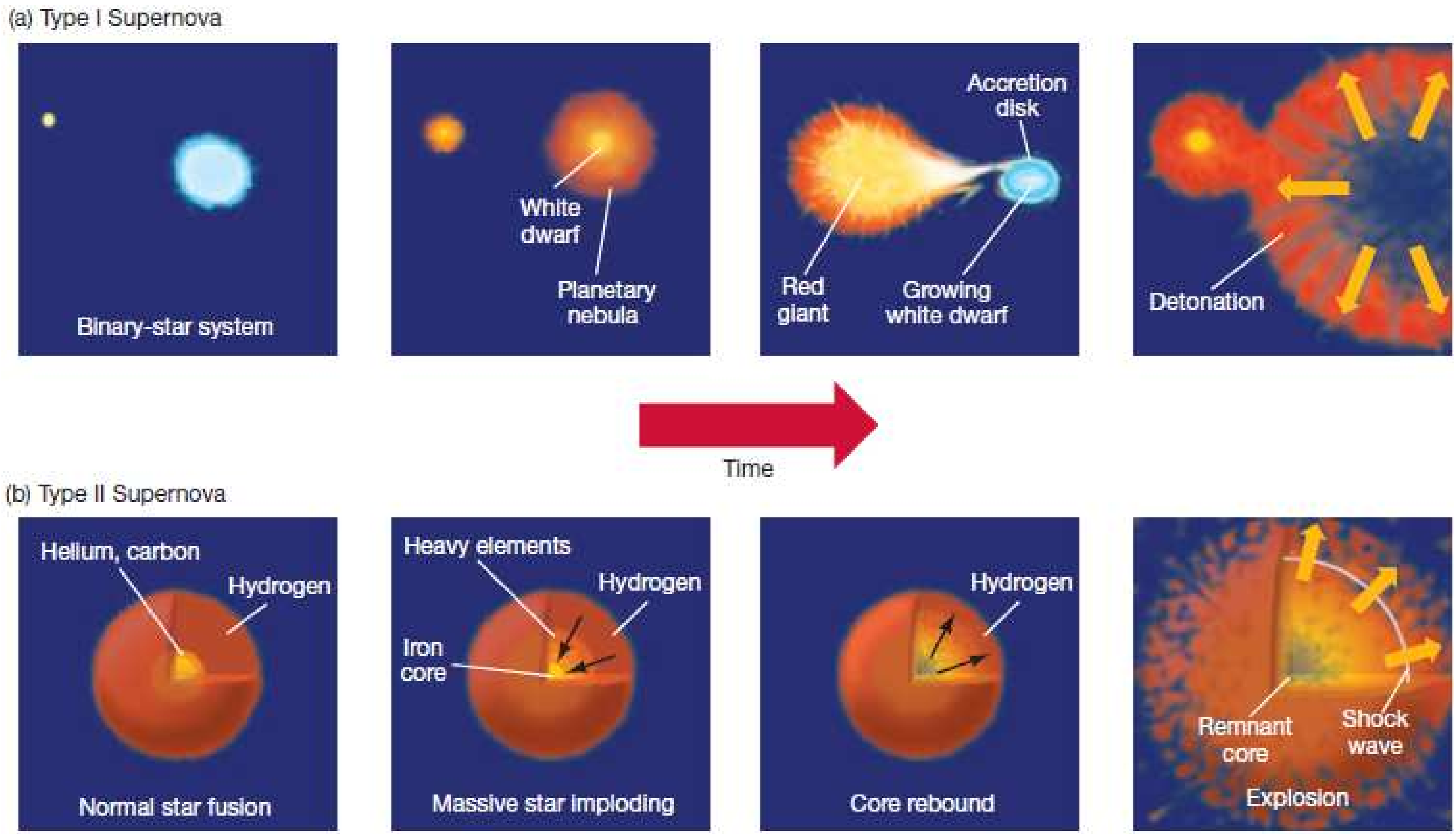


Carbon-Detonation Supernovae (SN-I)

- ***What is the responsible for the differences among supernovae?***
- White dwarf maximum mass limit is $1.4M_{sun}$, Chandrasekhar mass.
- White dwarf: supported by electron-degeneracy pressure against the gravity
- Its mass, not all ejected, grows from the companion ➔ new period of instability.
- If $M > 1.4M_{sun}$, the gravity wins → collapsing & heating → Fusing Carbon everywhere.
- The whole star explode ➔ Carbon-Detonation supernova
- Two white dwarfs may emerged ➔ massive unstable star ➔ Type I SN
- SN-I origin is white dwarf ➔ No H. Light curve results from the radioactive decay of unstable heavy elements.
- Implosion-explosion of SN produces Type II. Unburned H and He.

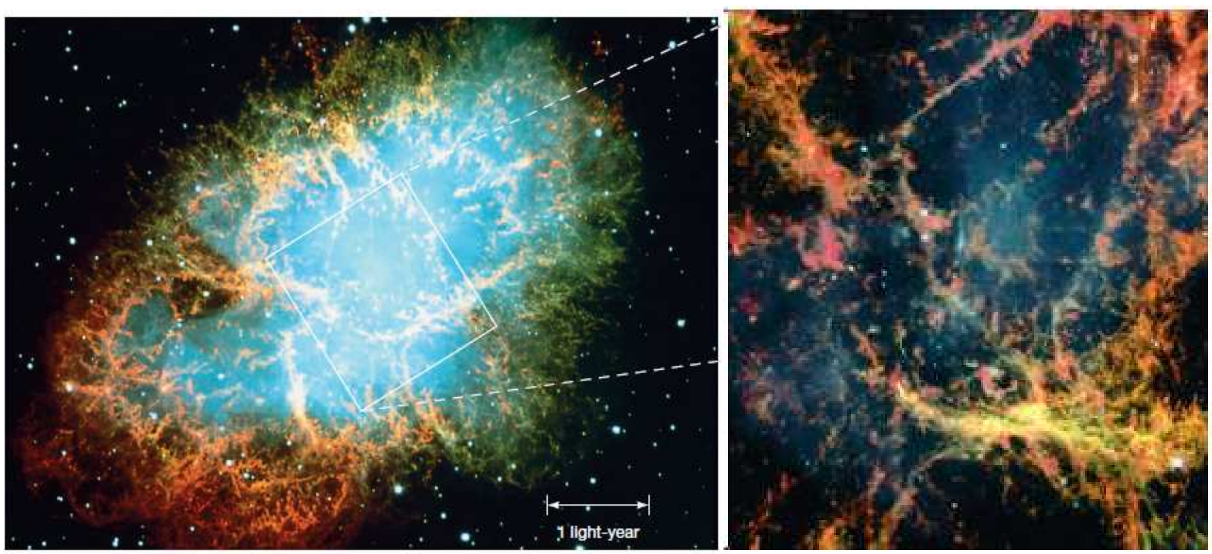
21.3 Supernovae

Two-types of supernova occur at roughly the same rate.



Supernova Remnants

- ***Several evidences that SN occurs.***
- Their glowing remains (**Remnants**).
- Example: Crab Nebula was huge SN in 1054 A.D. Chinese and Middle Eastern astronomers.
- Was as large as Venus, some said as moon for almost one month.
- Mass ejected from central explosion➔ Type II, expanding into space at several thousands km/s.

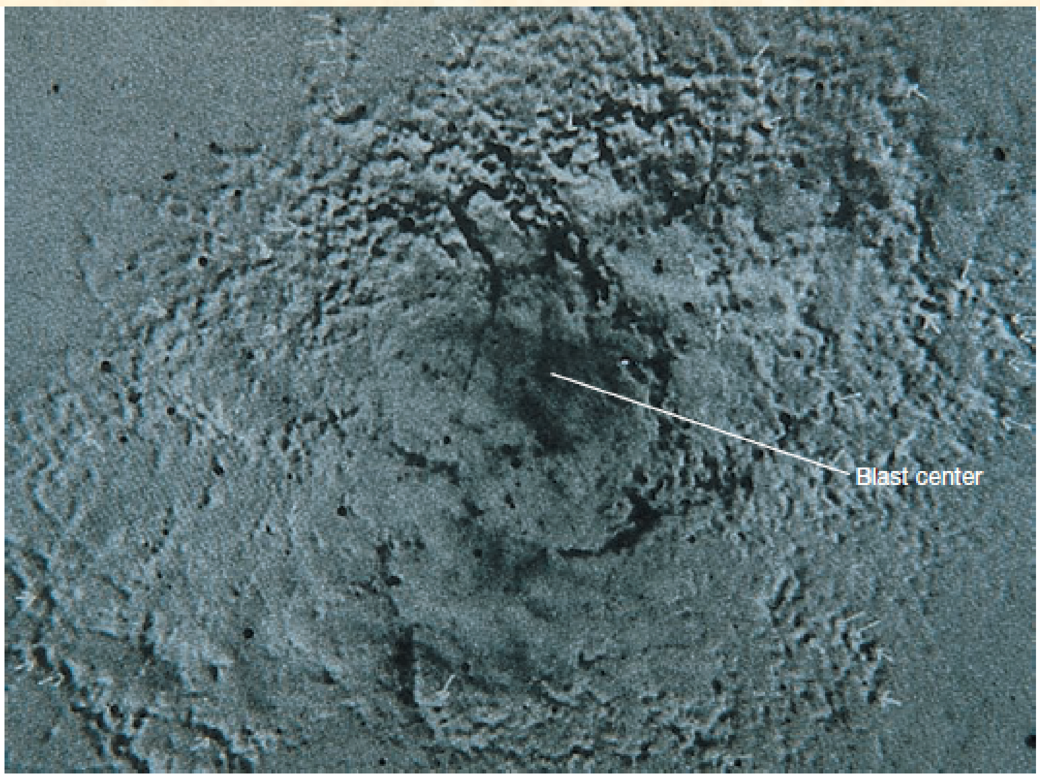


21.3 Supernovae

Supernova Remnants

Vela SN: Expansion velocities imply that its center explode 9000 B.C.

- **Remnant is only 1600 ly from us, was as bright as moon for several months.**
- **Stone-Aged humans**



21.3 Supernovae

Supernova Remnants

No SN in Milky-Way galaxy has been observed since Tycho (1572) and Kepler (1604).

- **Expected: 1/100 yr**

Vela SN now

Interactive FIGURE 21.12 Vela Supernova Remnant The glowing gases of the Vela supernova remnant are spread across 6° of the sky. The inset shows more clearly some of the details of the nebula's extensive filamentary structure. (The long diagonal streak was caused by the passage of an Earth-orbiting satellite while the photo was being exposed.) *(D. Malin/AAT)*

21.4 Formation of the Elements

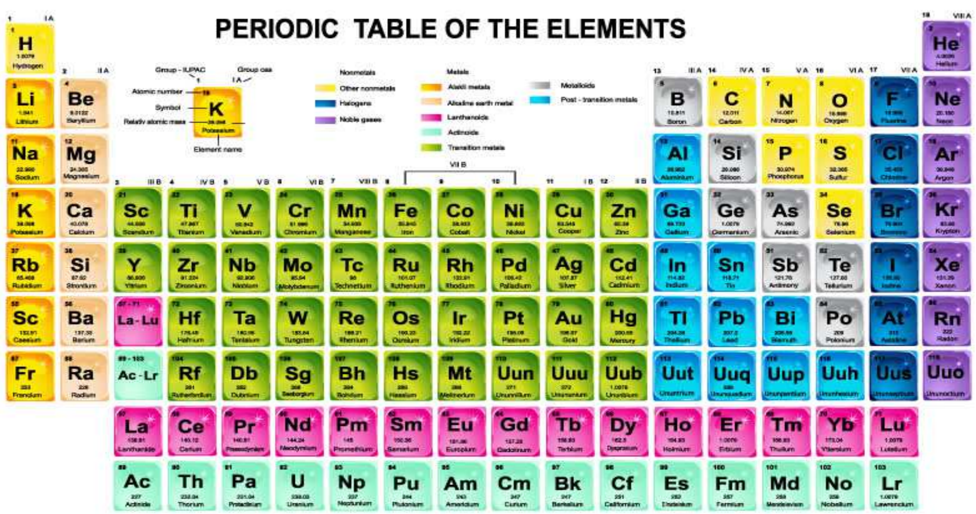
Types of Matter:

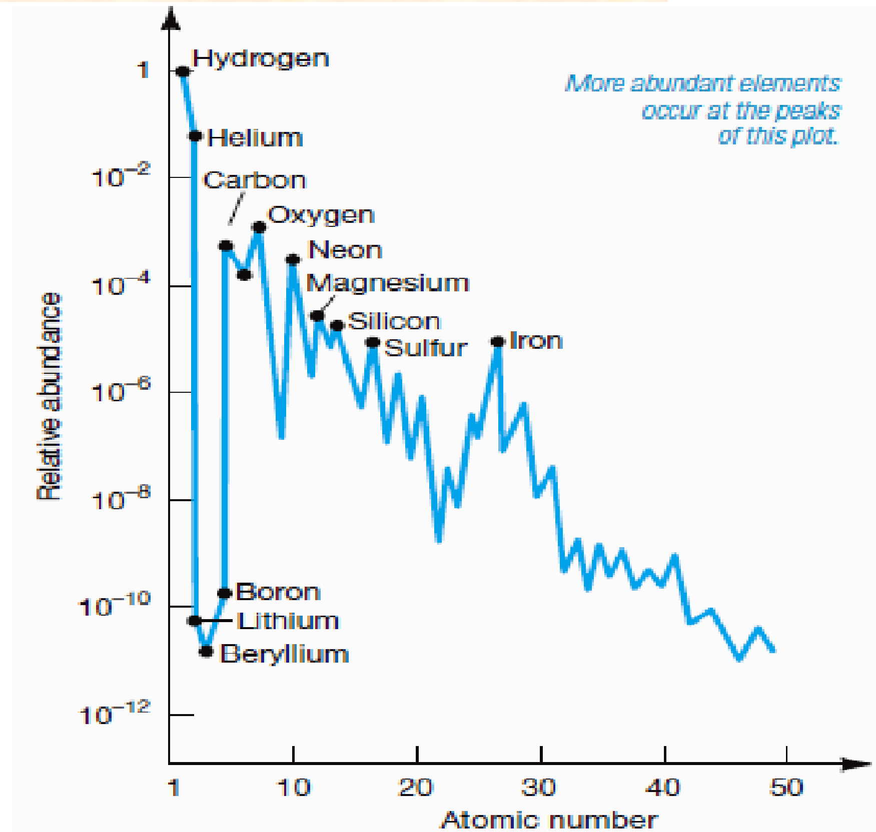
• 115 elements : H (1p) → Ununpentium (115p & 184n) are known.

• 81 stable elements + 10 radioactive elements found on Earth.

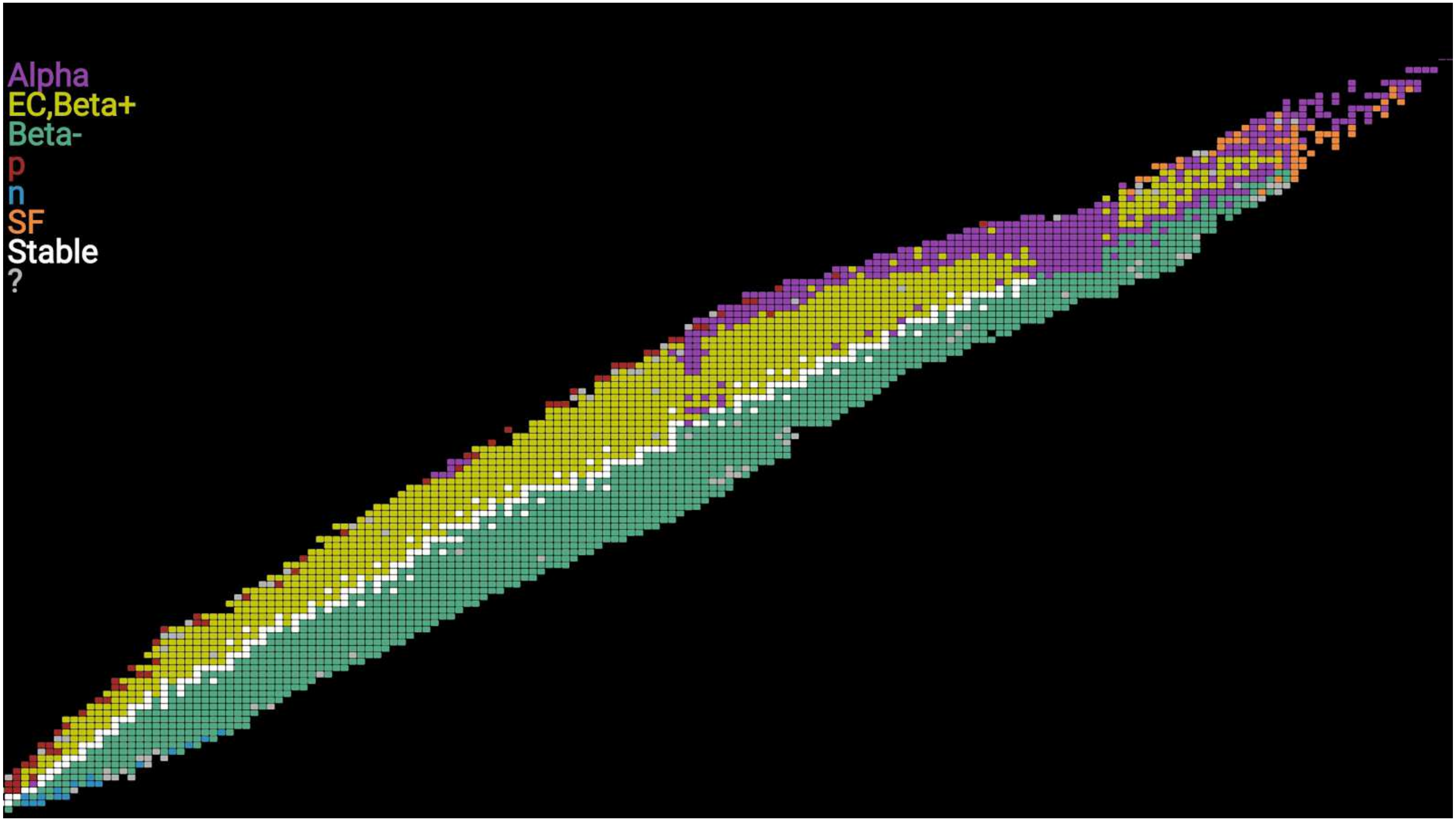
•Radon and Uranium exist long time ago, very long half-life times.

• 19 radioactive elements produced artificially in nuclear laboratories.





- **All elements exist in different isotopes. Thousands of isotopes**



21.4 Formation of the Elements

Abundance of Matter: Stellar nucleosynthesis.

TABLE 21.1 Cosmic Abundances of the Elements

Elemental Group of Particles	Percent Abundance by Number*
Hydrogen (1 nuclear particle)	90
Helium (4 nuclear particles)	9
Lithium group (7–11 nuclear particles)	0.000001
Carbon group (12–20 nuclear particles)	0.2
Silicon group (23–48 nuclear particles)	0.01
Iron group (50–62 nuclear particles)	0.01
Middle-weight group (63–100 nuclear particles)	0.00000001
Heaviest-weight group (over 100 nuclear particles)	0.000000001

* *The total does not equal 100 percent because of uncertainties in the abundance of helium. All isotopes of all elements are included.*

H & He burning

10 million K, pp-cycle

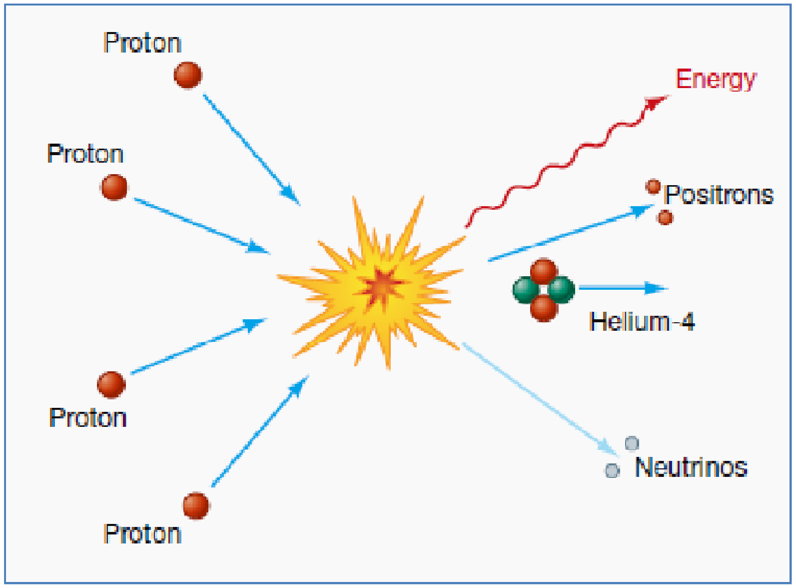
-- $4(^1H) \rightarrow {}^4He + 2\,e^+ + 2\,\nu$ + energy

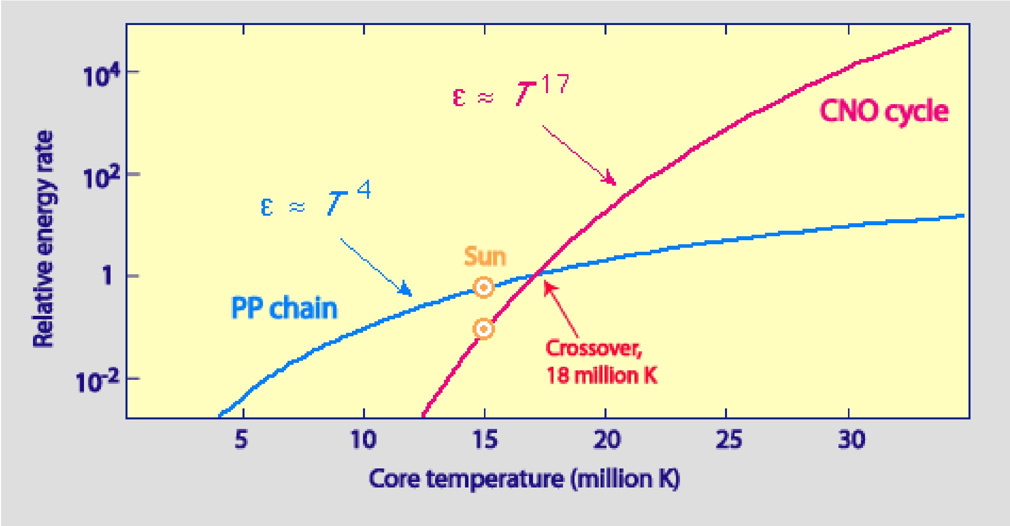
-- e^+ annihilate directly with e^- ➔ γ = 511 keV

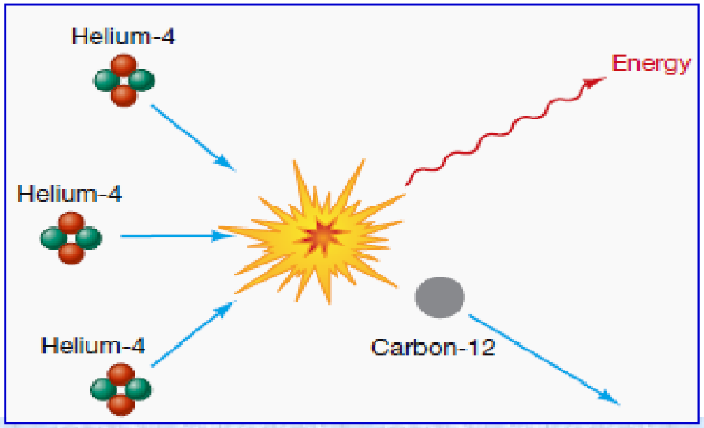
-- neutrinos rapidly escape, play no role.

20 million K (accelerate the H-burning)

-- In massive stars: CNO takes over.







100 million K, triple-alpha process

-- $3(^4He) \rightarrow {}^{12}C$ + energy

CNO cycle

$$^{12}C + p \rightarrow {}^{13}N + \gamma$$

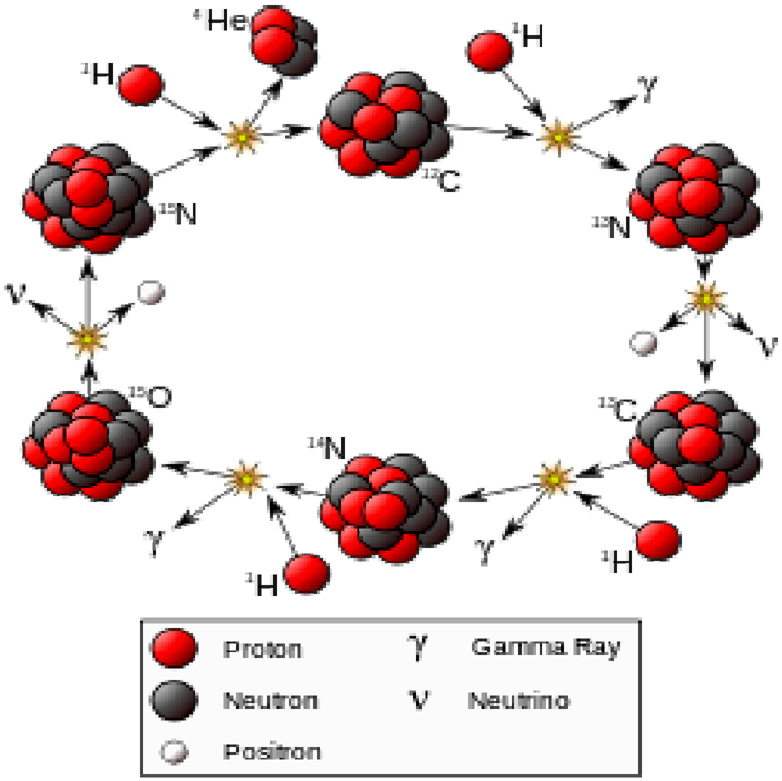
$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu_e$$

$$^{13}C + p \rightarrow {}^{14}N + \gamma$$

$$^{14}N + p \rightarrow {}^{15}O + \gamma$$

$$^{15}O \rightarrow {}^{15}N + e^{+} + \nu_e$$

$$^{15}N + p \rightarrow {}^{12}C + {}^{4}He$$



The abundance of carbon, nitrogen, and oxygen is unchanged.

Simply H nuclei are combined to form helium.

Same result as: $4(^{1}H) \rightarrow {}^{4}He + 2\,e^{+} + 2\,\nu$ + energy.

21.4 Formation of the Elements

C burning & He Capture

600 million K,

-- $^{12}C + ^{12}C \rightarrow ^{24}Mg$ + energy, but

-- $^{12}C + ^{4}He \rightarrow ^{16}O$ + energy, more probable

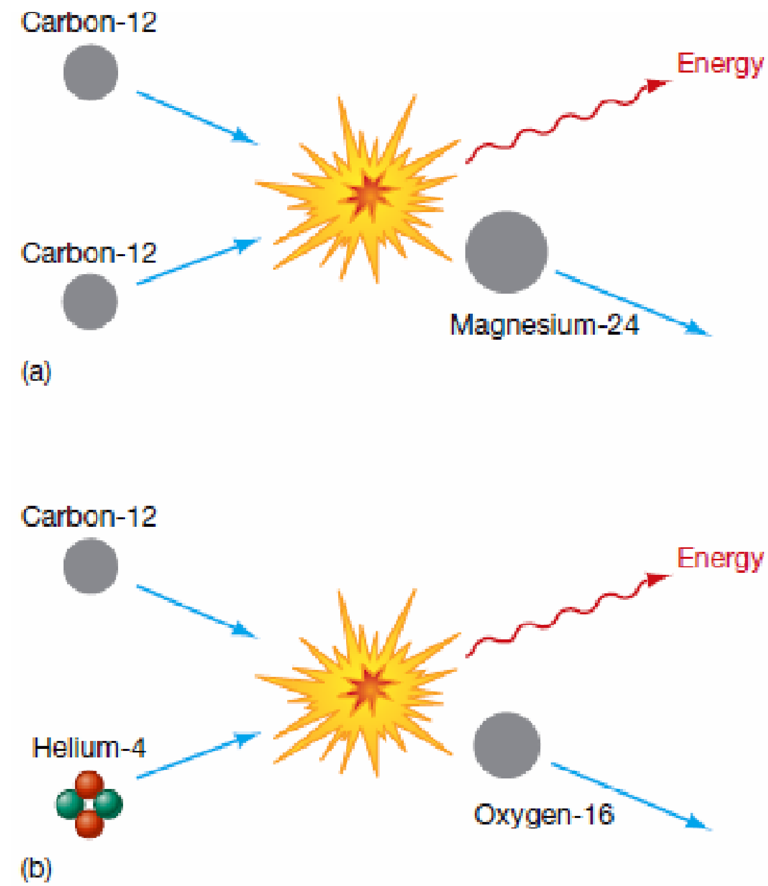
-- Similarly:

-- $^{16}O + ^{16}O \rightarrow ^{32}S$ + energy, but

-- $^{16}O + ^{4}He \rightarrow ^{20}Ne$ + energy, more probable

➔ He-capture process, 4(He)–12(C)–16(O)–20(Ne)–24(Mg)–28(Si) are prominent nuclei.

➔ Other nuclei might be produced in similar way such as: ^{19}F, ^{23}Na, ^{31}P, low abundance.



21.4 Formation of the Elements

Iron Formation (alpha process)

3 billion K

-- Once ^{28}Si appears in the core ➔ struggling begins between He-capture or breaking complex nuclei due to heat (photodisintegration).

➔ 2-step process: photodisintegration then He-capture

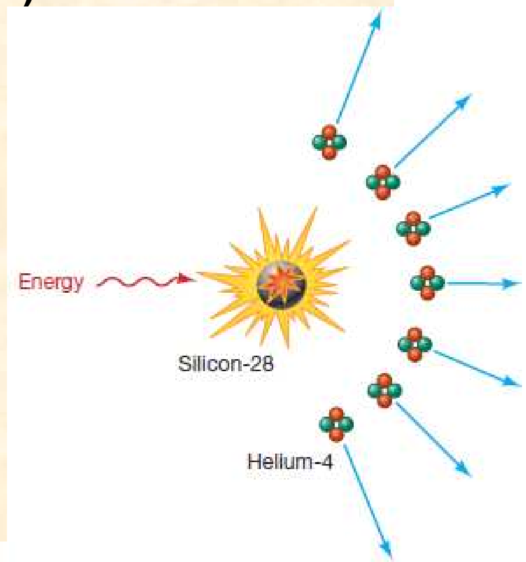
-- ^{28}Si breaks into seven ^{4}He nuclei.

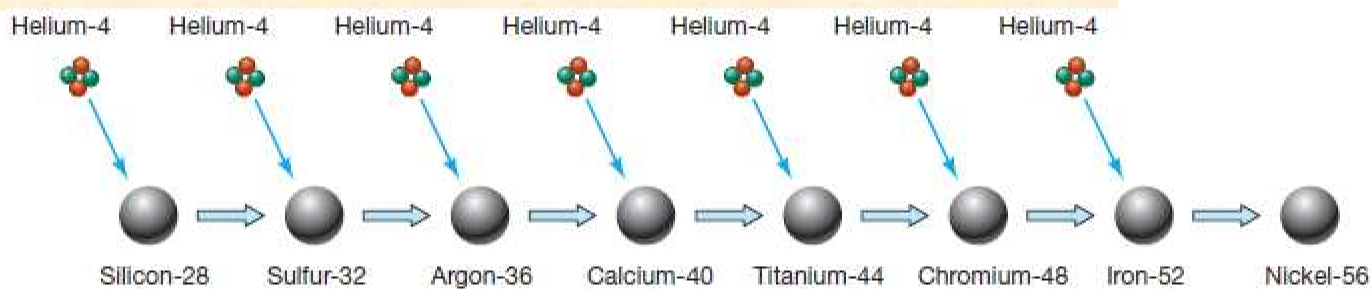
-- Star forms: ^{32}S, ^{36}Ar, ^{40}Ca, ^{44}Ti, ^{48}Cr, ^{52}Fe, ^{56}Ni and others.

-- Summary of the chain reaction:

-- ^{28}Si + 7(^{4}He) → ^{56}Ni + energy

➔ ^{56}Ni → β-decay → ^{56}Co → β-decay → ^{56}Fe (most stable)





Elements beyond Fe

Heavier elements are produced through neutron-capture reactions

-- neutron available "by-products" of nuclear reactions.

-- neutron easily interact with matter?

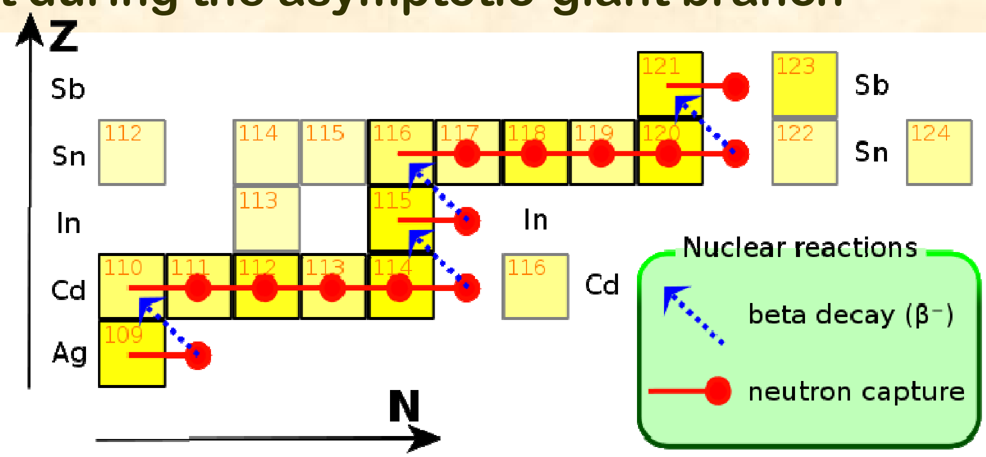
-- $^{56}Fe + n \rightarrow ^{57}Fe$ ➔ $^{57}Fe + n \rightarrow ^{58}Fe$ ➔ $^{58}Fe + n \rightarrow ^{59}Fe$

-- ^{59}Fe radioactive → one month → ^{59}Co stable

-- $^{59}Co + n \rightarrow ^{60}Co$ (unstable) decay to ^{60}Ni

➔Neutron capture: s-process (slow) needs time (a year to capture n)

➔ Are important during the asymptotic-giant branch



Making the Heaviest Elements

-- s-process: stable nuclei up to ^{209}Bi, <u>not</u> for radioactive nuclei: ^{232}Th, ^{238}U, ^{242}Pu.

-- Decay as fast as they produce by s-process, or even before

-- r-process (rapid) occurs during supernova explosion.

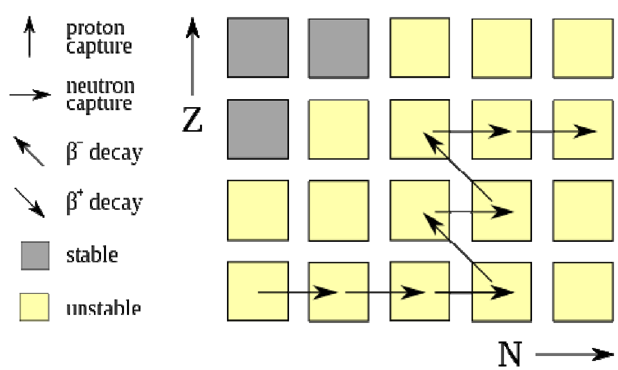
-- Free neutrons increase, fast enough for unstable to capture before decaying.

-- Responsible to produce the heaviest elements.

r-process

rapid neutron captures

X(n,γ)Y



synthesis of neutron-rich nuclei

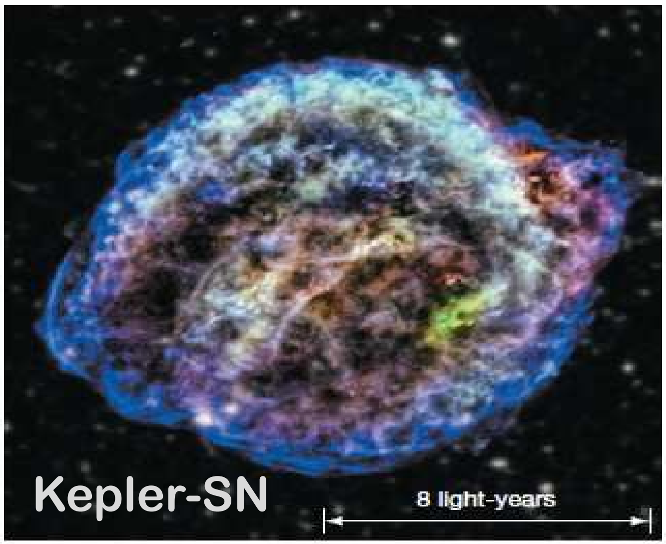
A > 60

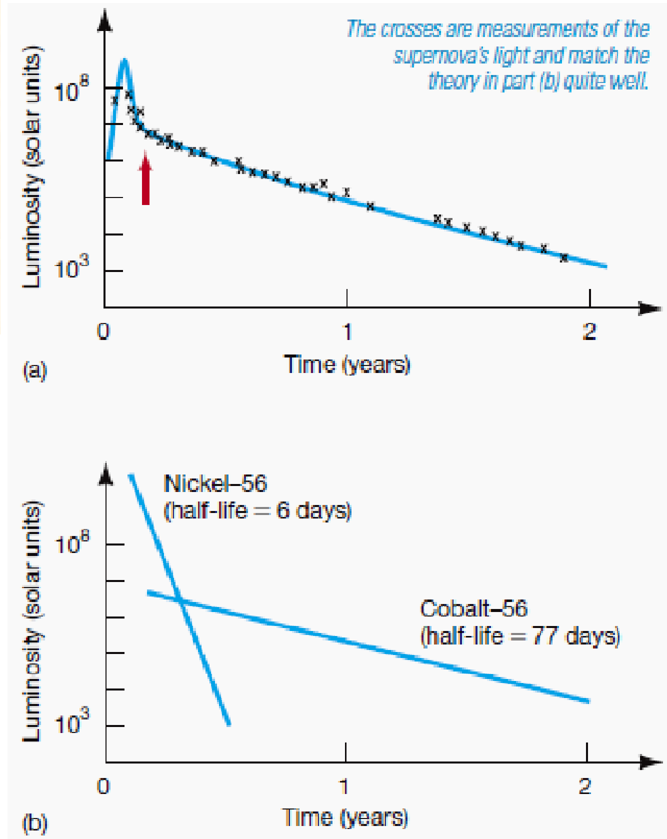
Observational Evidences

-- 1st: comparing nuclear reaction rates with observations

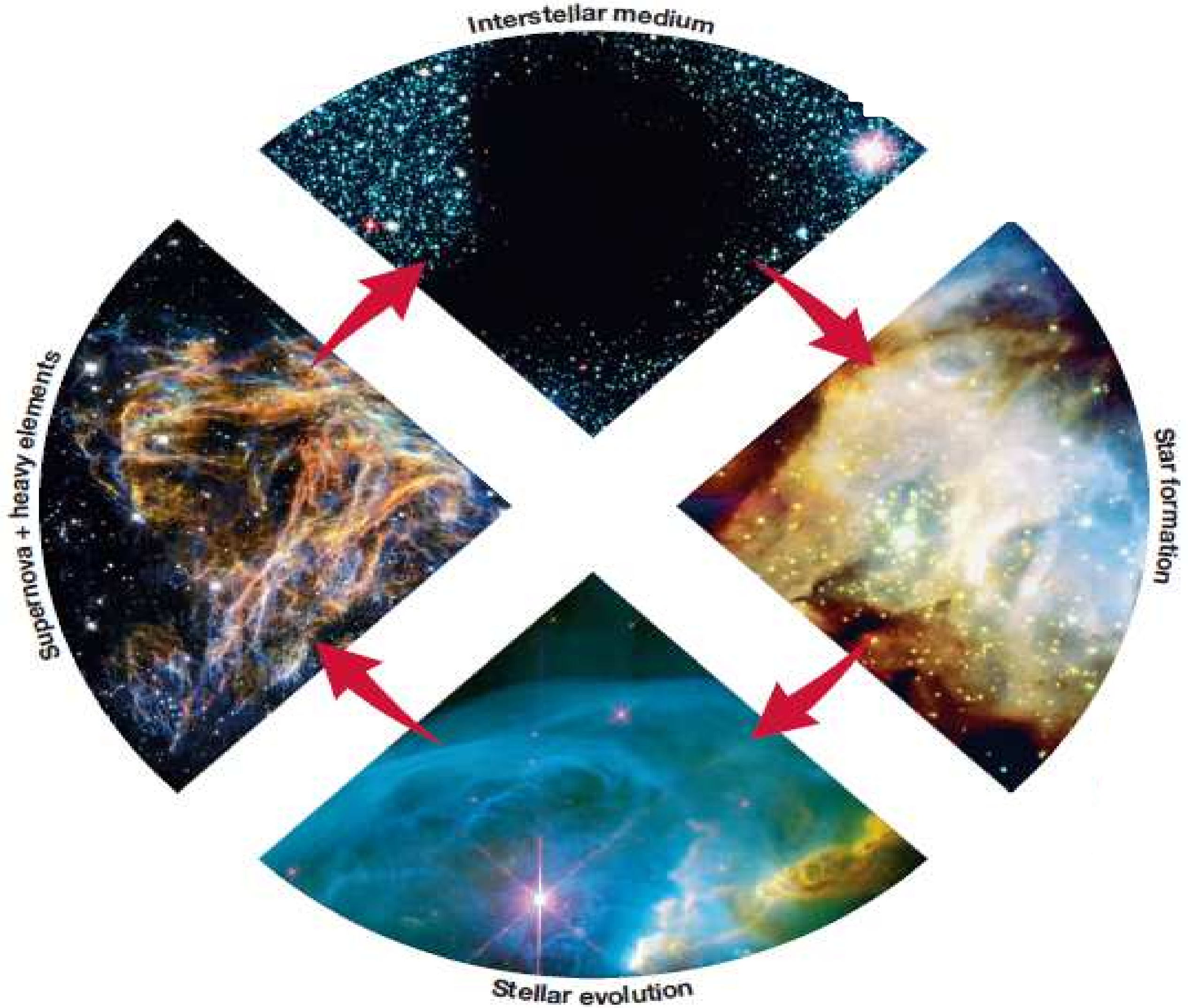
-- 2nd: Technetium-99 ($T_{1/2}$ = 200,000 yr) provides evidence that heavy elements form during SN.

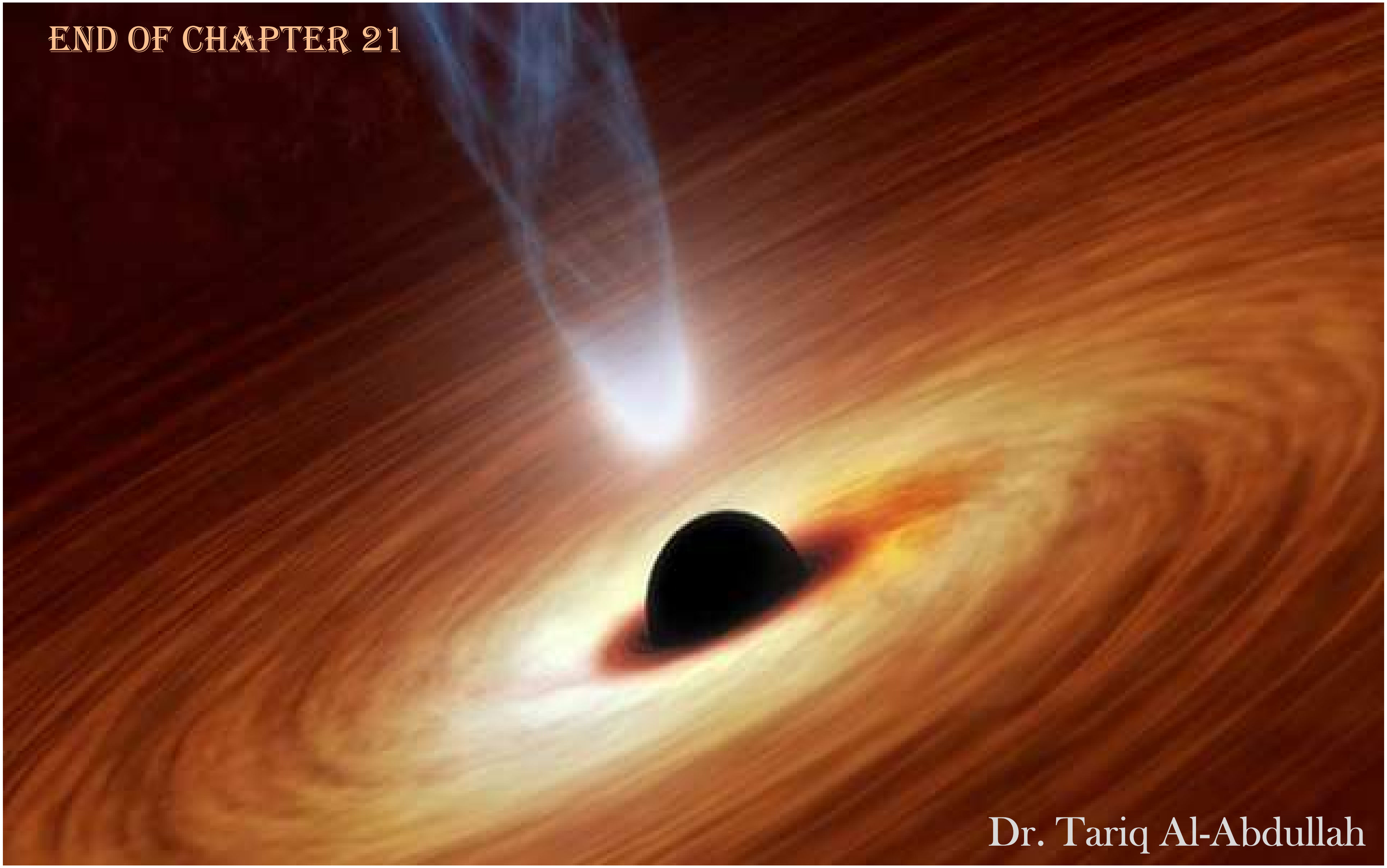
-- 3rd: Studying light-curve from SN-I, indicate which element is produced as a result of the explosion.





21.5 The Cycle of Stellar Evolution




End of Chapter 21
Dr. Tariq Al-Abdullah