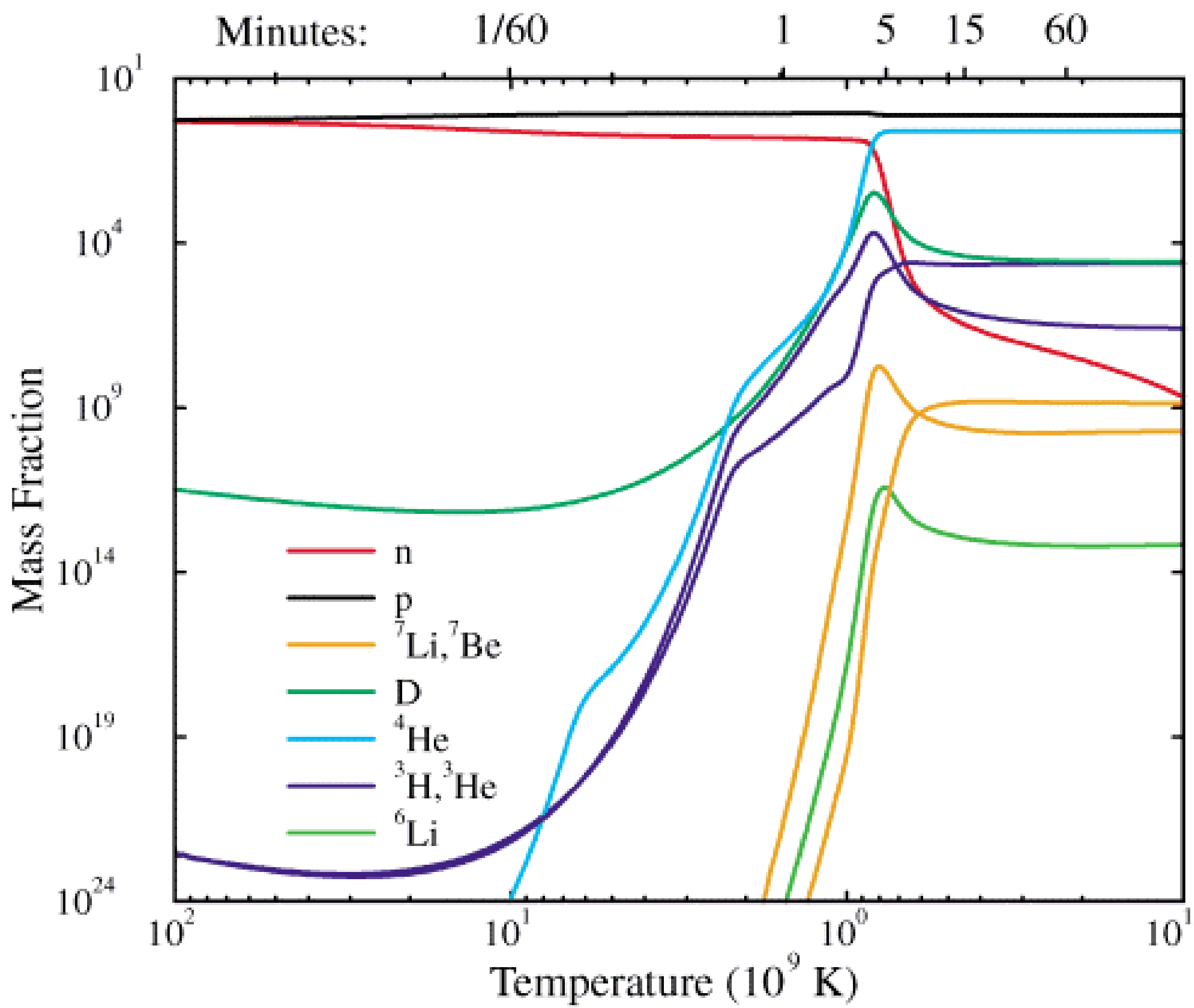
Nucleosynthesis: Building New Elements in Stars

Prof. Jay Gallagher-- Astronomy

- Stars as natural thermonuclear reactors
- Basic nuclear burning processes
- Special nucleosynthesis processes:
  - Big Bang
  - Supernovae: r-process
  - Asymptotic giant branch (AGB) stars: s-process
- Element dispersal
- (Special conditions in solar system formation)

First nucleosynthesis in the cooling Universe:



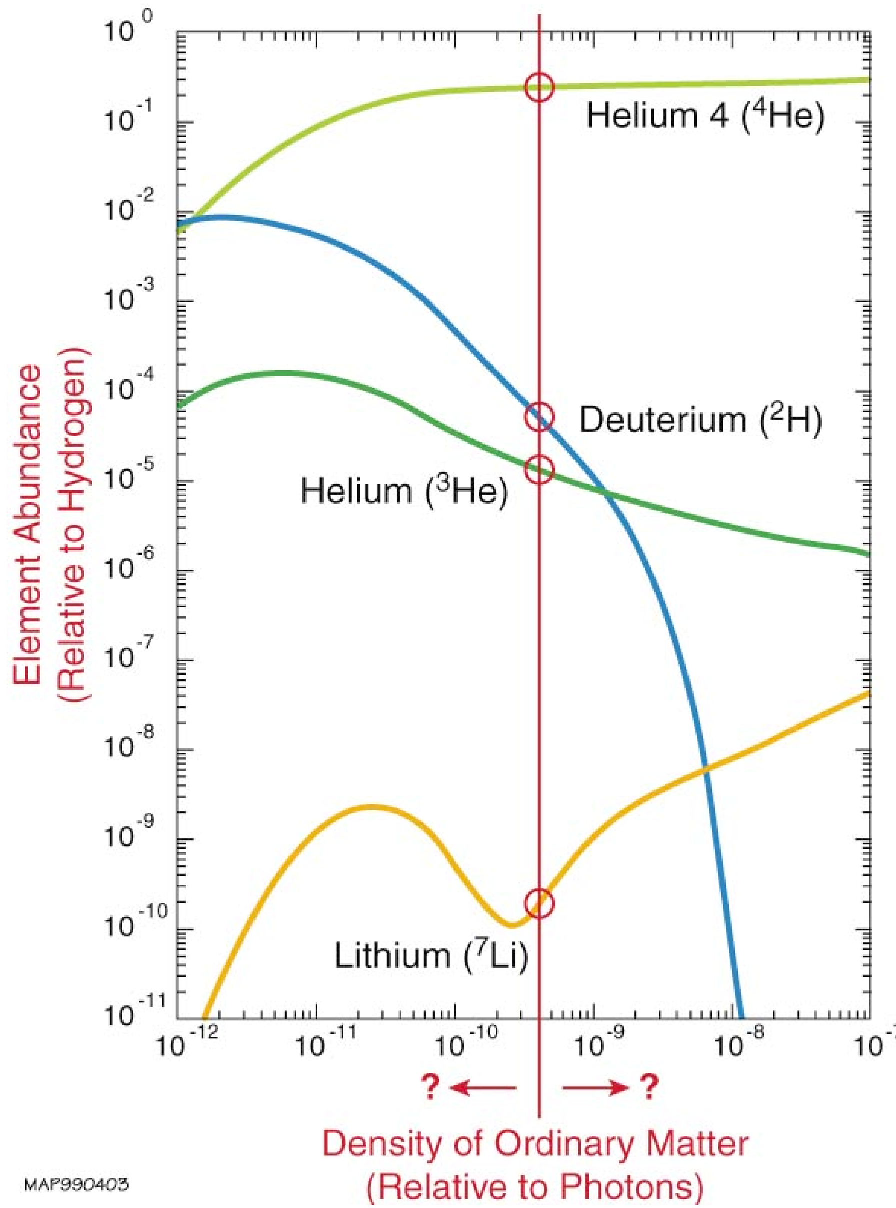
Products of Big Bang:

1. Helium

2. Deuterium

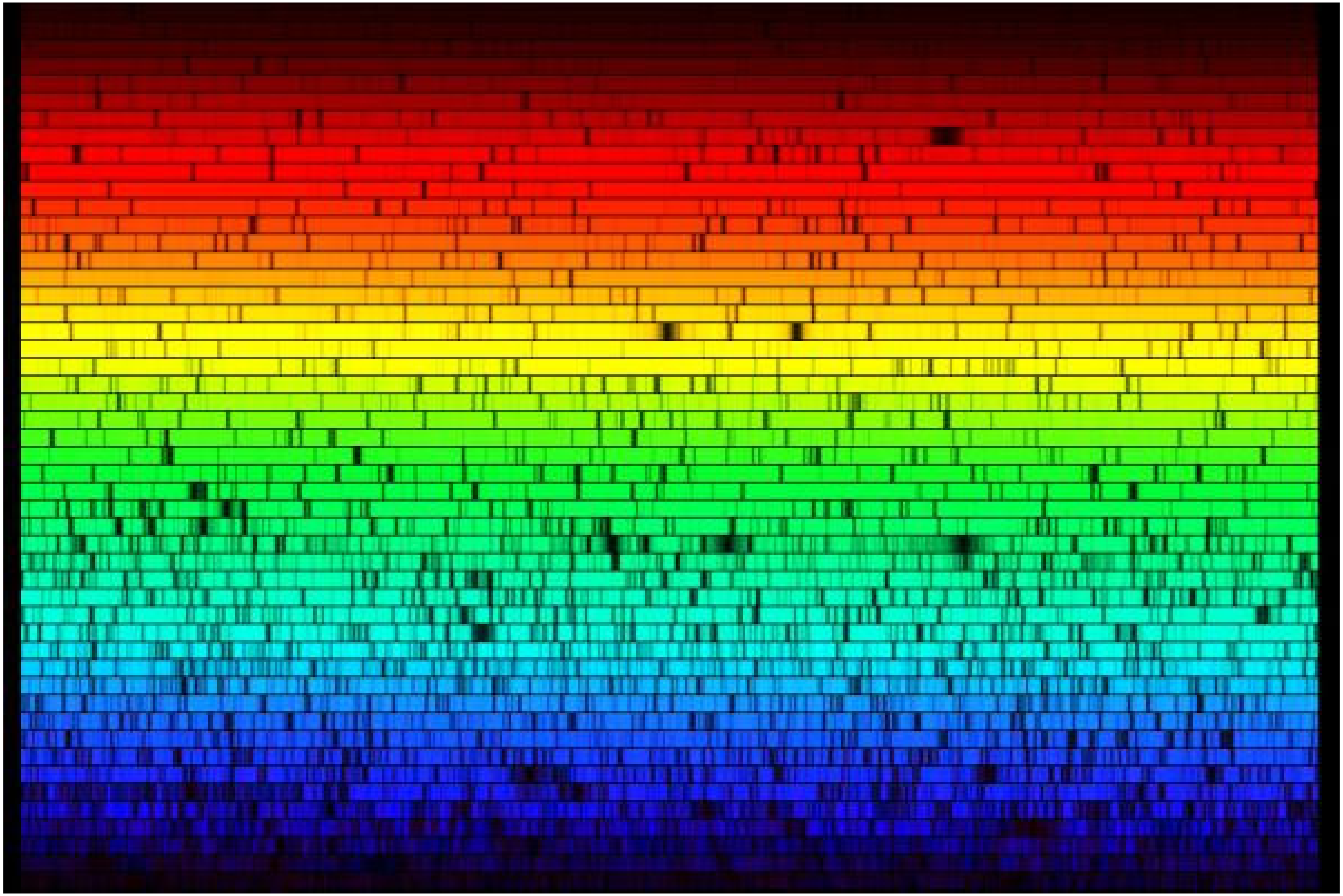
3. Lithium

But nucleosynthesis stopped by absence of stable element 8. All “metals” Z>8 must be made from H & He later.



Stellar spectra--Line strengths + models = abundances

Dark regions are absorption lines where light is intercepted by specific species of atoms



Spectrum is light sorted by wavelength--this example covers the visible region where most lines from Fe-peak elements

WIYN Telescope

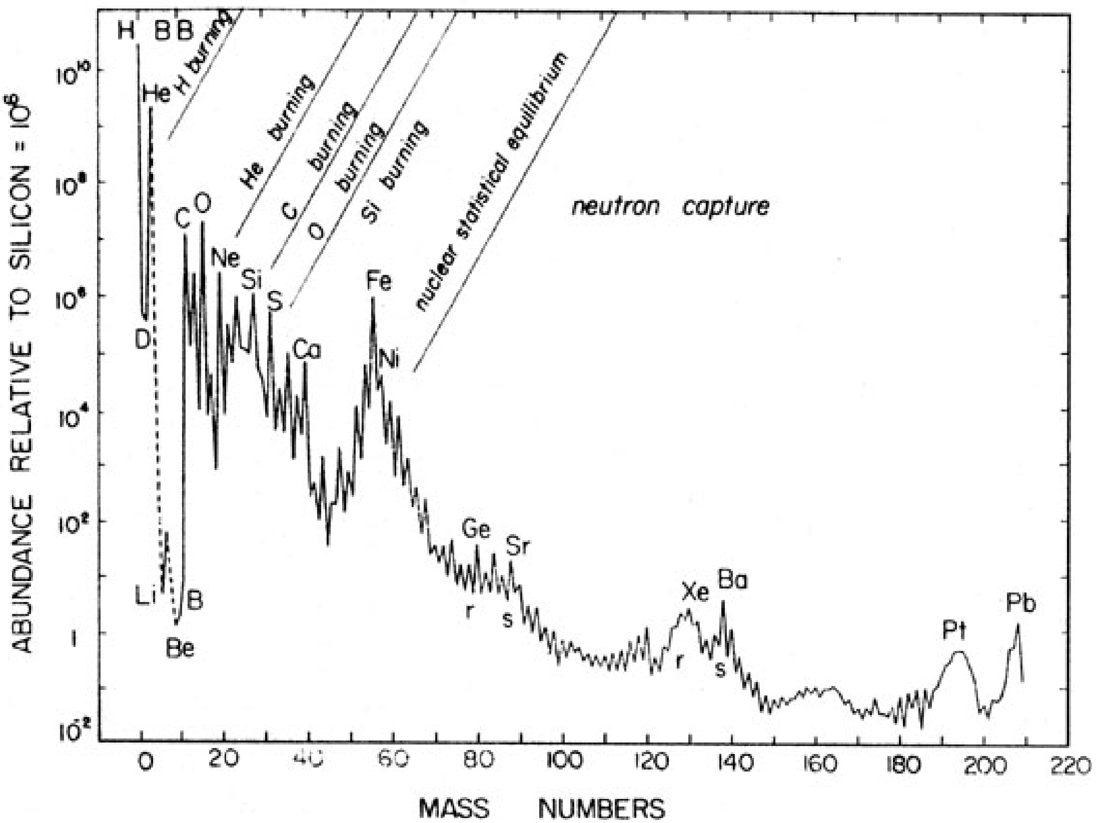
Spectroscopy drives astronomers to higher performance and larger optical telescopes.

Globular stars cluster: oldest coeval groupings of stars (12 Gyr) have low metals-->>heavy elements produced by **STARS**!

Ages of stars can best be determined for systems of stars that formed at the same time.

Lagoon nebula: Gas ionized by young, hot stars with high masses (20-100 x Sun) cools by atomic emission from α-elements: N,O,Ne,S, allowing their abundances to be measured from spectra of the nebula.

Cosmic abundances--most “metals”=CNO + Fe peak.



Pagel, Nucleosynthesis and Chemical Evolution of Galaxies

Classifying stars by their nuclear burning characteristics

- low mass, ≤ 2 Msun; H->C, white dwarf remnants
- intermediate mass, 2-8 Msun H->C/O/Ne, white dwarf remnants. Slow neutron captures during late evolution as “asymptotic giant” stars. C from He, N from CNO cycle burning.
- binary star evolution yields type I supernovae from intermediate mass stars; Fe-peak elements.
- massive 8-30 Msun; H->Fe; type II supernovae, neutron star remnants, α-elements, O-Ca, & r-process elements.
- very massive 30-100+ Msun, type II supernovae, black hole remnants, r-process

Nuclear mass defects & nuclear energy:

$$\Delta M_n = M_n - ZM_p - NM_n$$

$$\Delta E = \Delta M_n c^2$$ Conversion of mass to energy

Nucl.	Total Binding E (MeV)	Binding E/A (Mev)
He(2p,2n)	-28.3	-7.07
C(6p,6n)	-92.16	-7.68
O(8p,8n)	-127.62	-7.98
Ca(20p,20n)	-342.05	-8.55
Fe(26p,30n)	-492.26	-8.79
U(92p,146n)	-1801.70	-7.57

Fusion releases

Energy only to near Fe-peak

Star as a perfect gas sphere:

$$\Delta U = -1/2\Delta\Omega \; contraction\ heats\ star$$

Equations of stellar structure:

$$dp/dr = -Gm\rho/r^2 \; pressure\ equilibrium$$

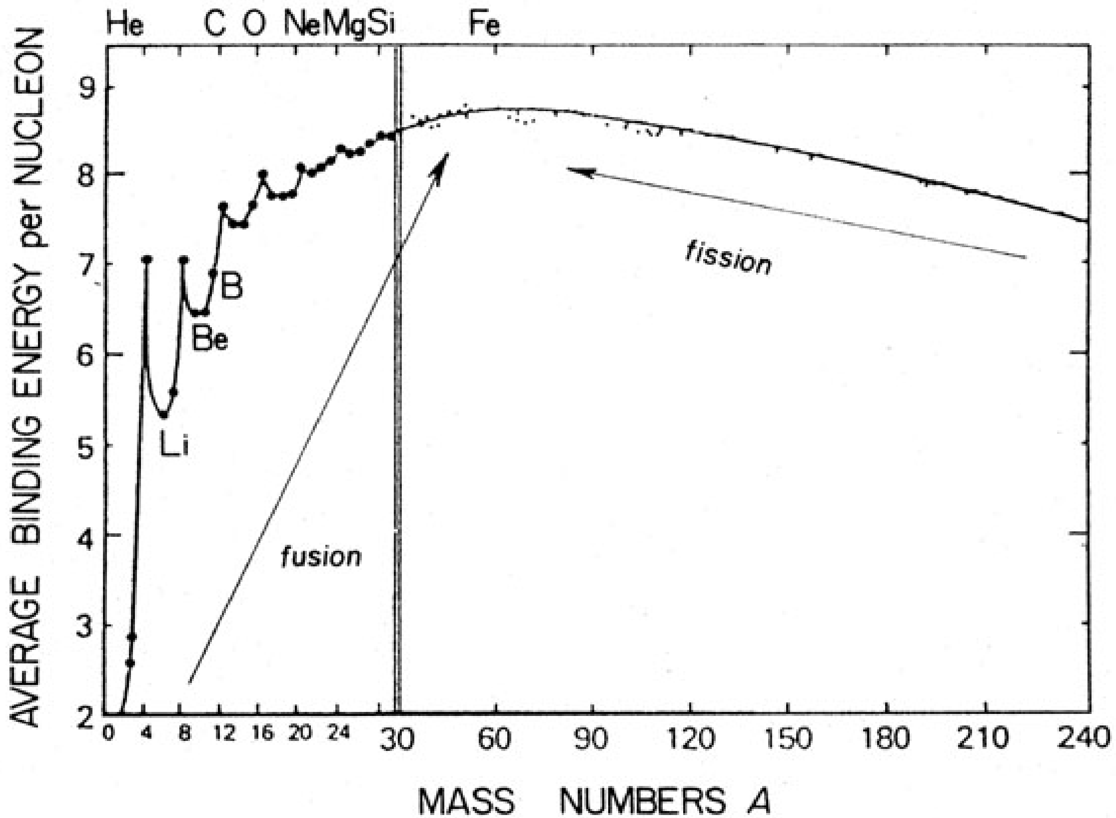
$$dm/dr = 4\pi\rho r^2 \; mass\ conservation$$

$$Power = L = -4\pi r^2 (ac/3\rho\kappa)[{dT^4}/{dr}] \; radiation\ diffusion$$

$$\varepsilon = {dL}/{dm} \; conservation\ of\ energy$$

Binding energy/nucleon: 80% of energy in H->>He

Thus most fusion energy is released in the H-> He step of the process.



Basic physics:

$$U_{elec} = Z_1 Z_2 e^2 / r^2 = 550 keV \ for \ r = r(p)$$

$$\Rightarrow U_{elec} = E_{th} \ for \ T = 6x10^9 K \ \ (E_{th} = 0.086 T_6 keV)$$

$$but \ T(0) \approx (m_p G / k)(M / R) \approx 10^7 K$$

Electric repulsion dominates!!!

Solution: quantum mechanical effects:

$$P = \exp(-2\pi\eta) \ probability \ to \ tunnel \ where$$

$$2\pi\eta = 31.3 Z_1 Z_2 (\mu / E)^{1/2} \ \ \mu \ in \ amu; E \ keV$$

$$\rightarrow \sigma(E) \propto (1/E) \exp(-2\pi\eta) S(E)$$

Thermonuclear reactions can occur at stellar core temperatures

The proton-proton cycle is the first major H-burning process and occurs at the lowest central temperatures in stars. It consists of 3 distinct channels: PPI, PPII, & PPIII.

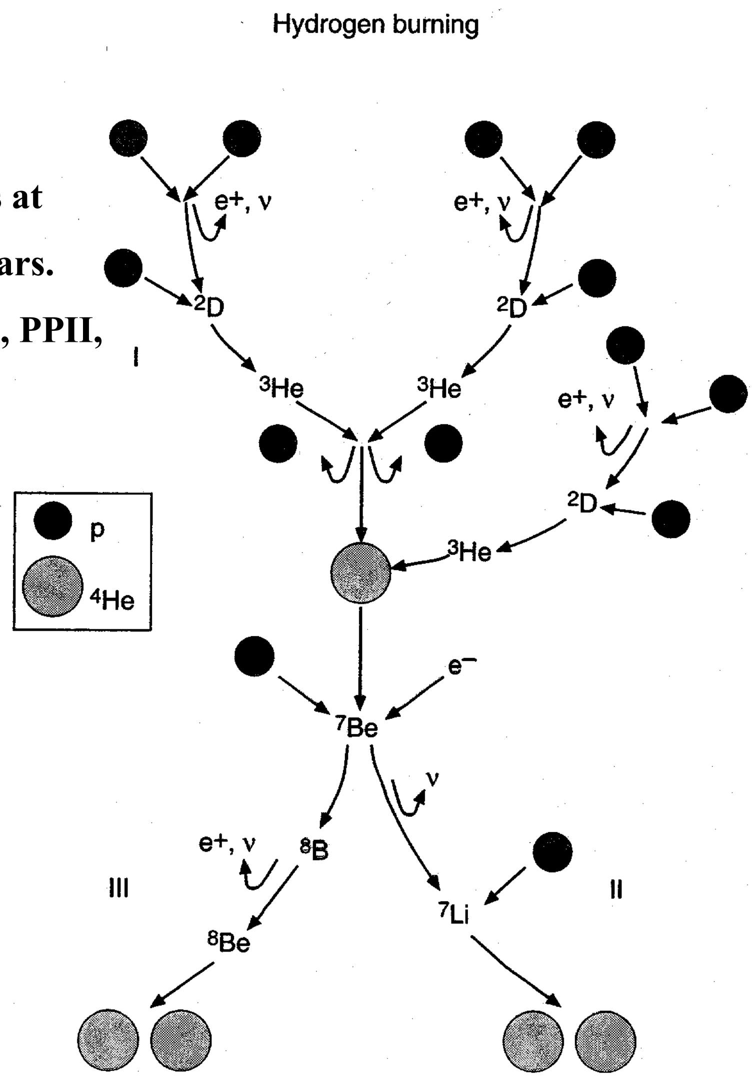


Figure 4.3 The nuclear reactions of the *p–p* I, II, and III chains.

At higher temperatures, H->He via the CNO cycle which depletes O and enhances the N abundances. The CNO cycle dominates H-burning for stars slightly more massive than the Sun.

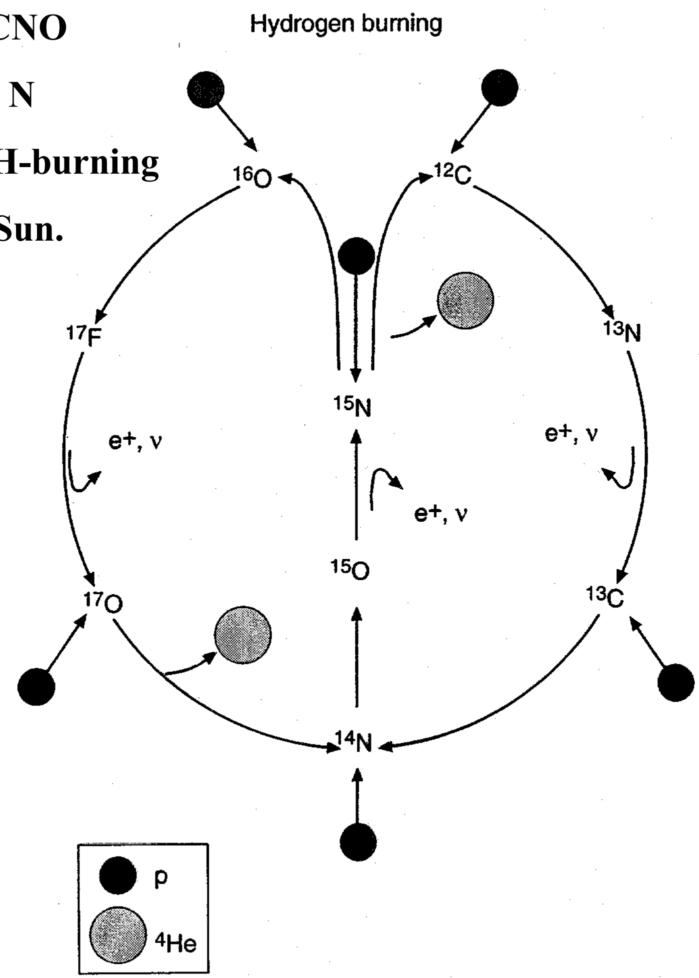


Figure 4.4 The nuclear reactions of the CNO bi-cycle.

This diagram shows how abundances vary with time during the CNO cycle. Note how the N abundance increases as this cycle operates over long times

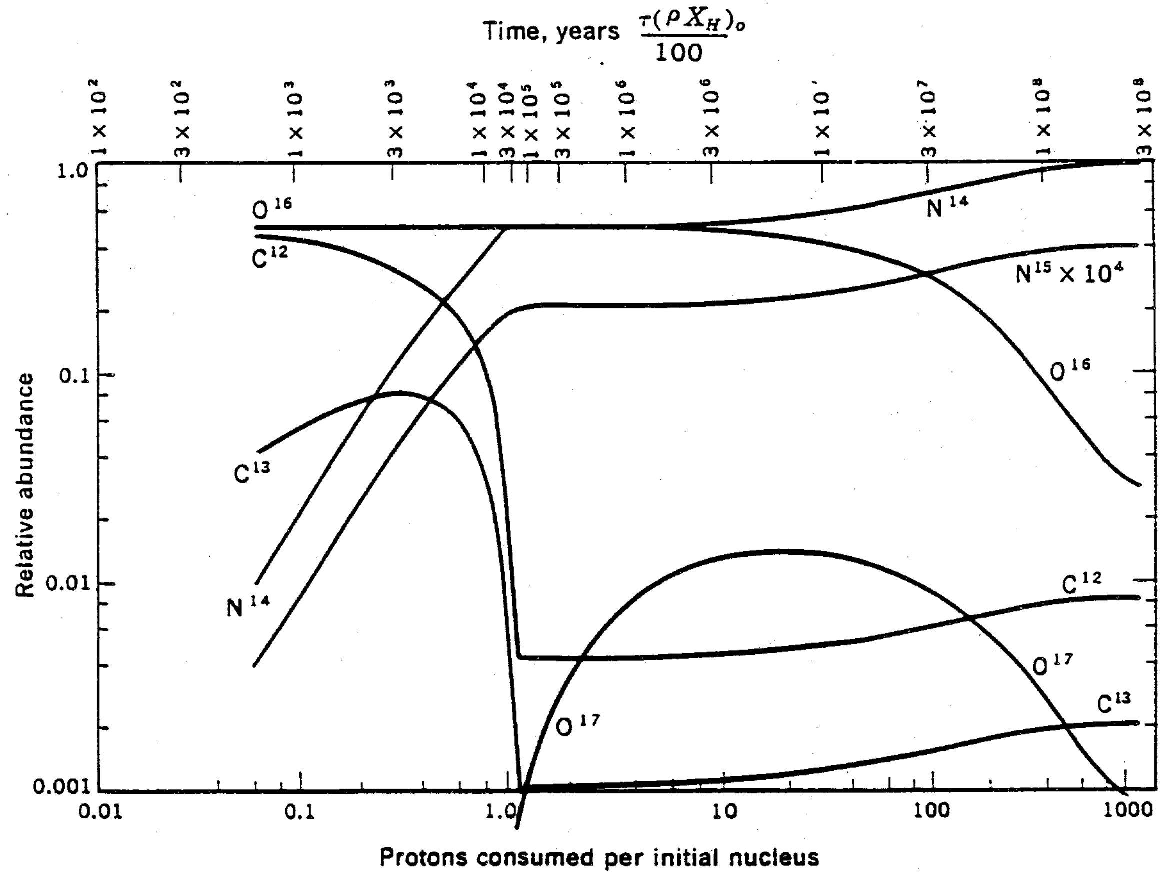
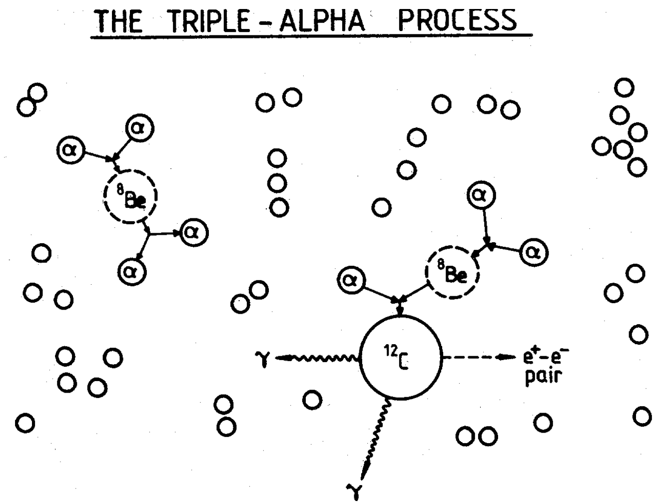
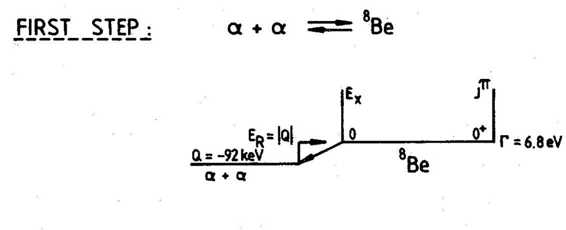


Fig. 5-15 The approach to equilibrium in the CNO bi-cycle as a function of the number of protons captured per initial CNO nucleus. This particular calculation started with equal concentrations of C^{12} and O^{16}. [*After G. R. Caughlan, Astrophys. J.*, **141**:688 (1965). *By permission of The University of Chicago Press. Copyright* 1964 *by The University of Chicago.*]



The conversion of He->C is tricky because no stable A=8 nucleus exists. Instead, the triple alpha process involves 3 fast collisions which go directly to C.



The success of the 3-alpha process rests on the presence of an excited nuclear state of C, which was hypothesized to exist by F. Hoyle and is the physical key to much of stellar nucleosynthesis.

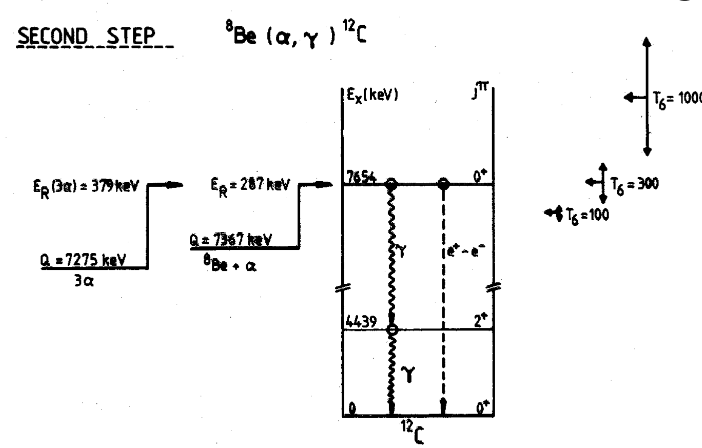
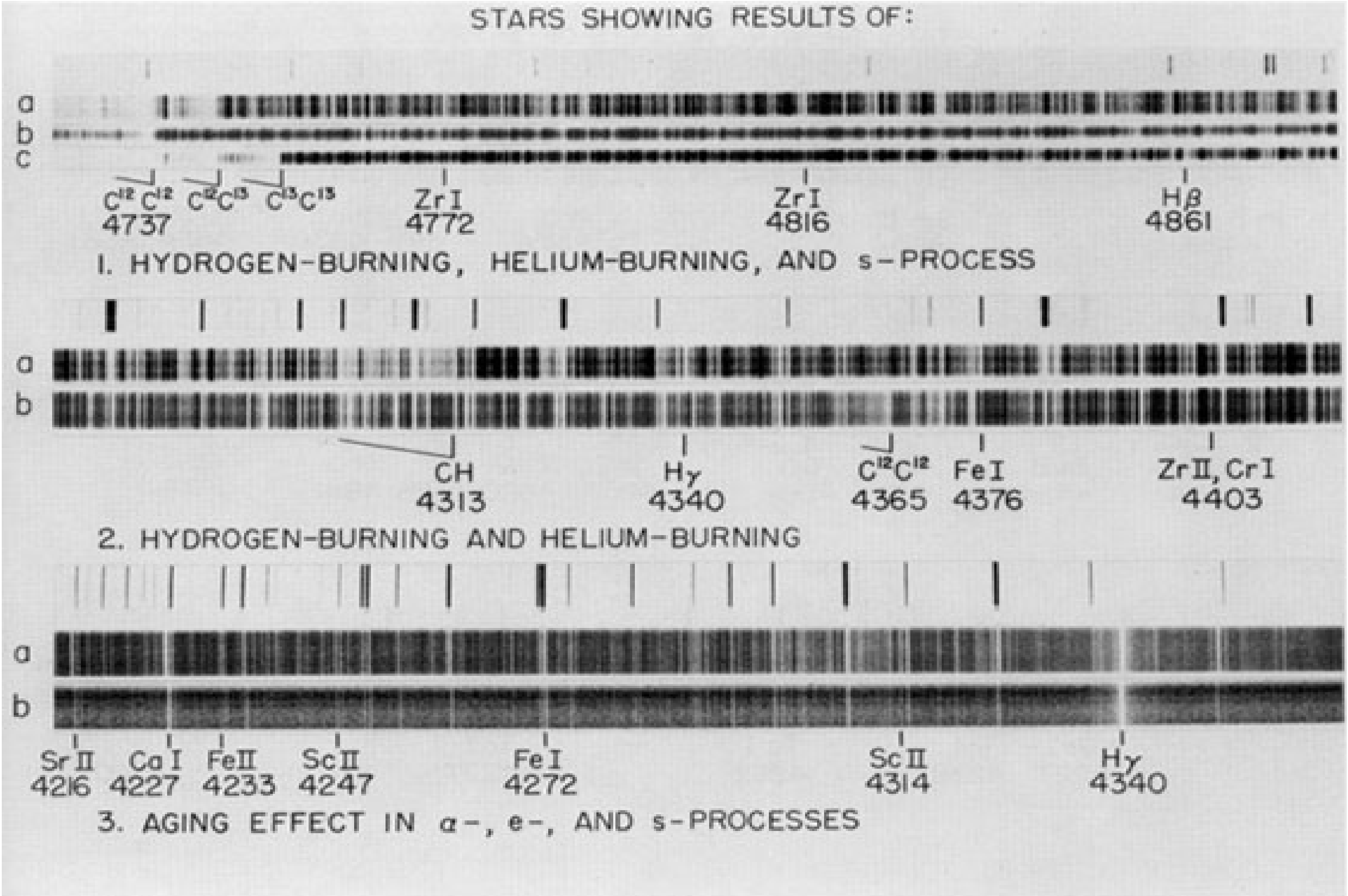


FIGURE 7.3. Schematical representation of the process by which ^{12}C can be synthesized using only ^{4}He nuclei, commonly called the triple-α process or "Salpeter-process." In the first step of this process, a small abundance of ^{8}Be nuclei is built up to equilibrium with its α-particle decay products. An additional α-particle is captured by the ^{8}Be nuclei, thus completing the ^{12}C creation process. This capture reaction proceeds via an s-wave resonance, which is located close to the Gamow energy region indicated for several temperatures.

Primary Stellar Nuclear burning phases

- H-> He via CNO (converts O->N
- 3He -> C (triple alpha)
- advanced burning C or O + α -> α-rich
- equlibrium process Si -> Fe



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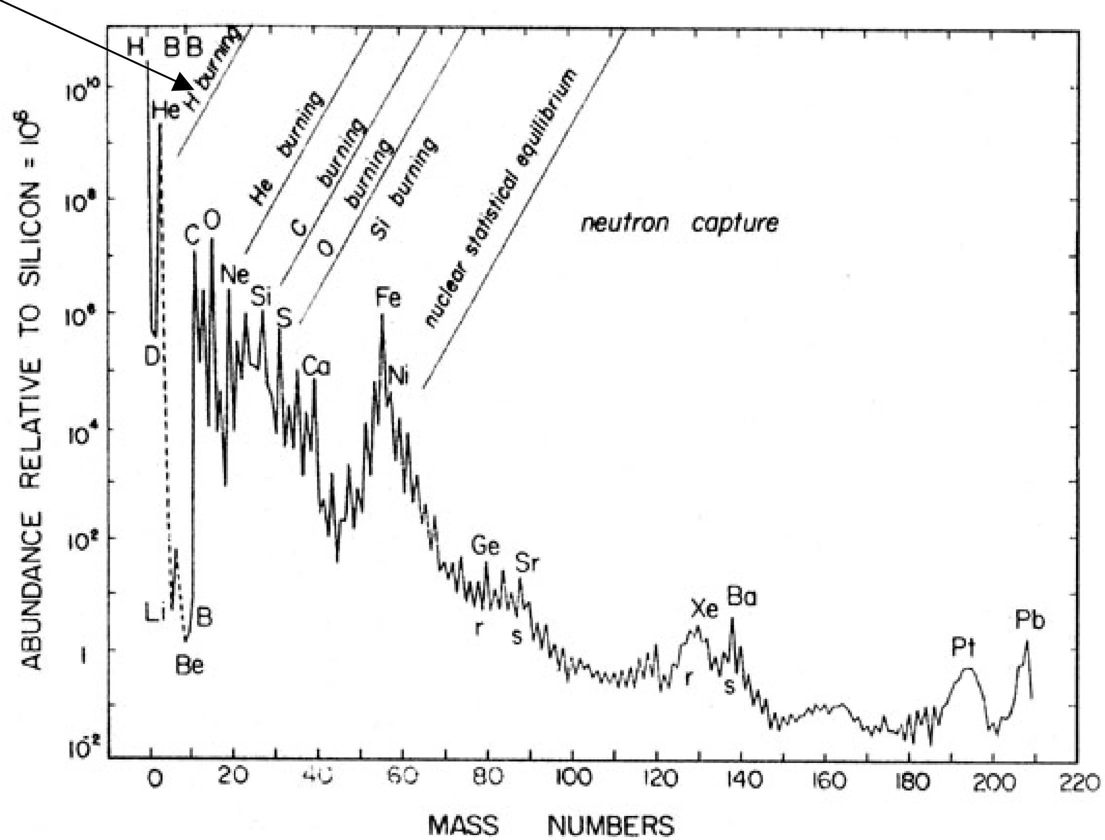
Cosmic abundances--most “metals”=CNO + Fe peak.

H-burning processes



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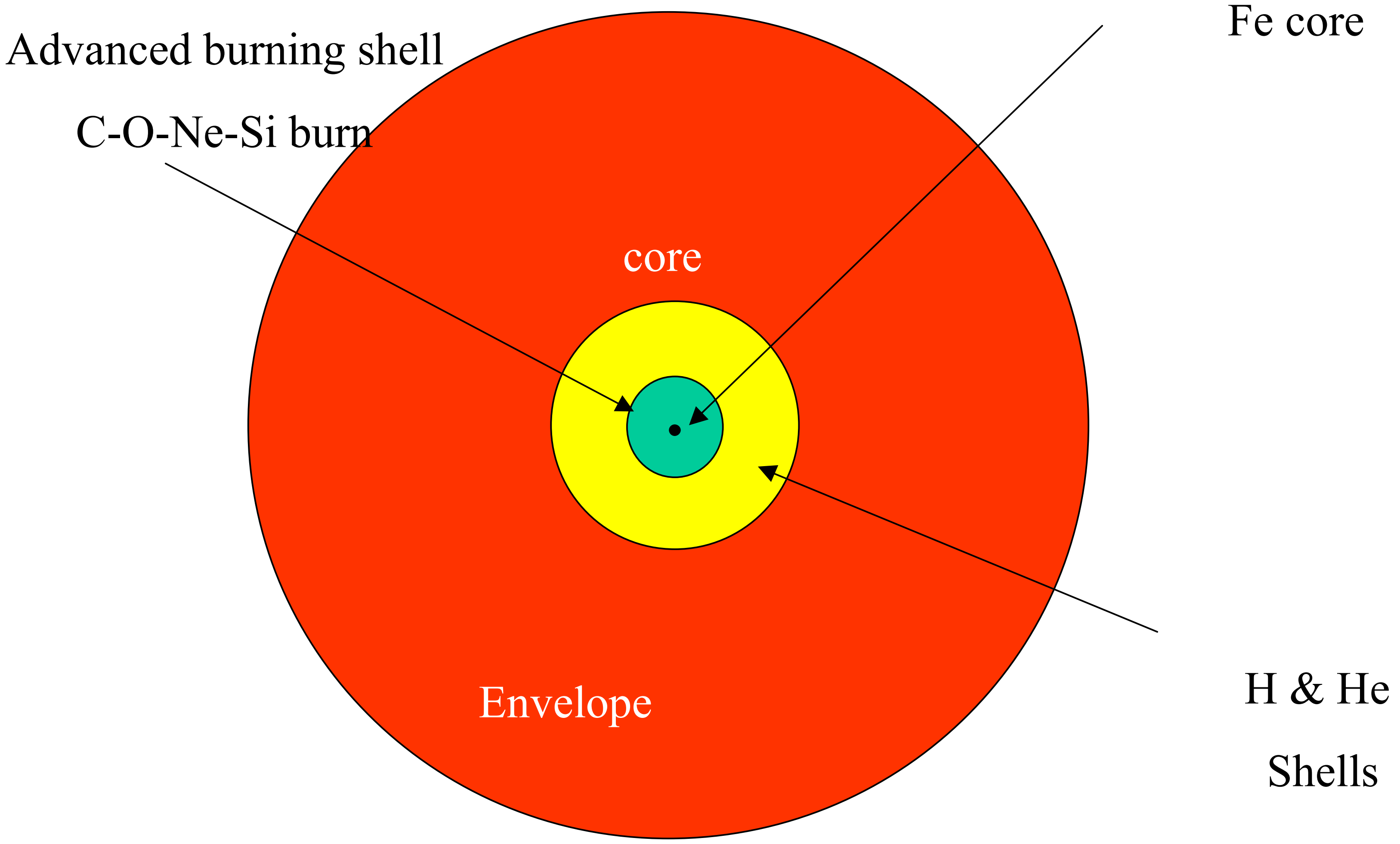
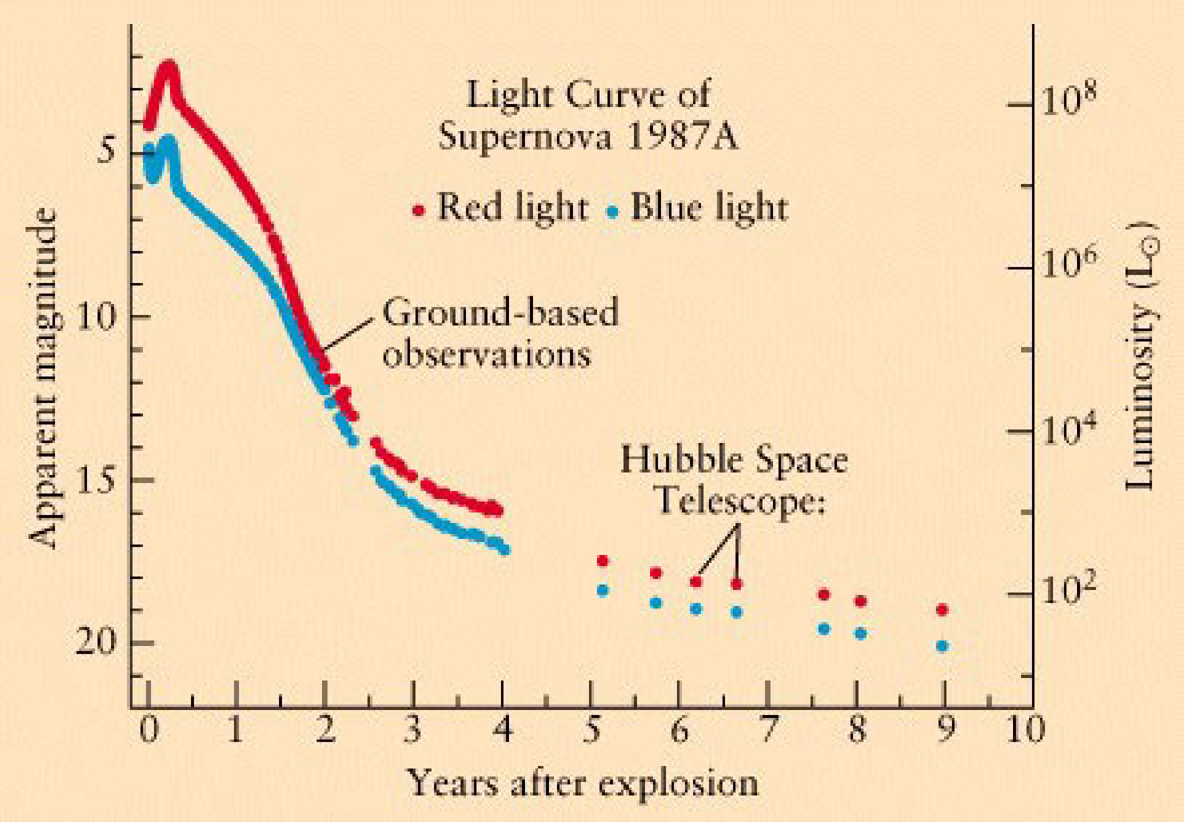
Pre-supernova Massive Star

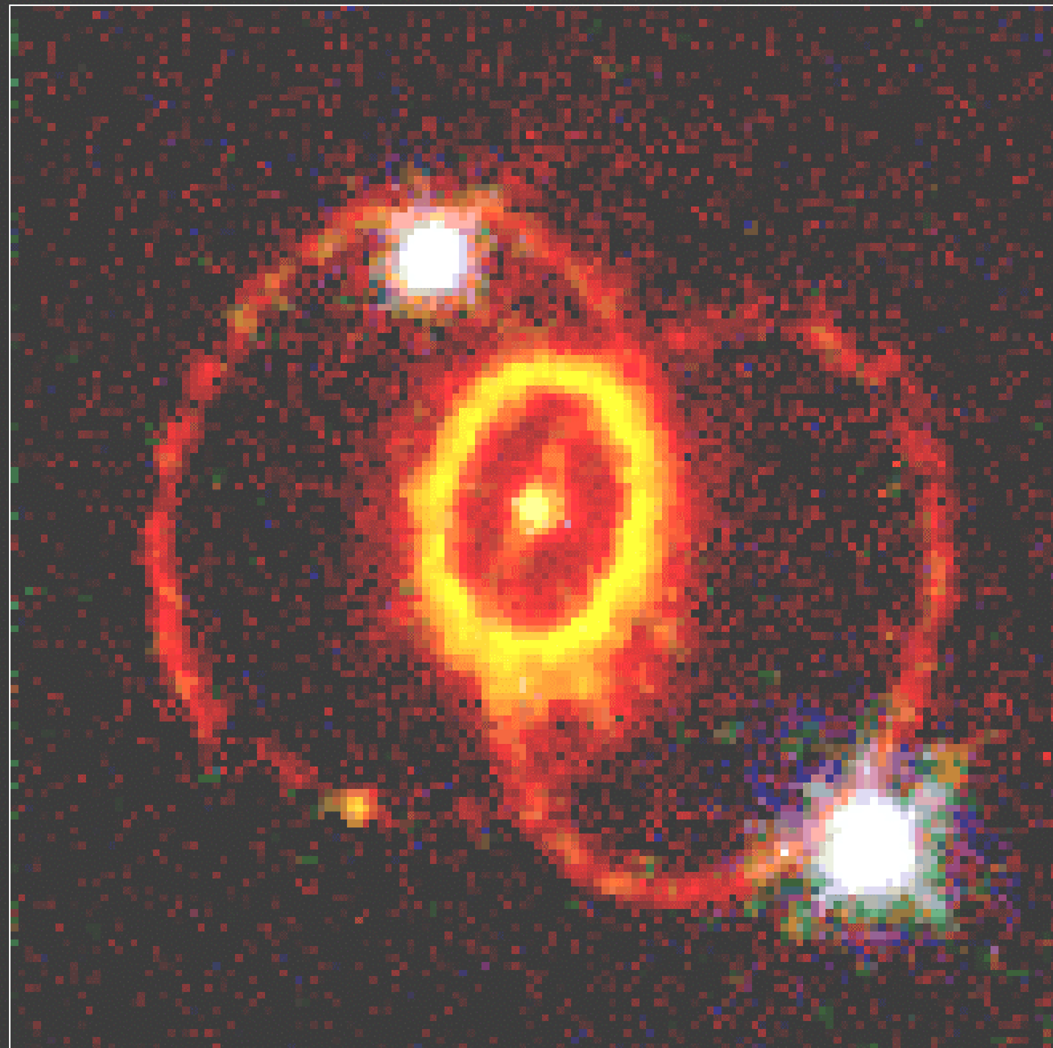


Supernova 1987a-death of 25 Msun star



Light Curve of
Supernova 1987A
Red light
Blue light
Ground-based
observations
Hubble Space
Telescope:
Apparent magnitude
Luminosity ($L_\odot$)
Years after explosion
5
10
15
20
10^8
10^6
10^4
10^2
0
1
2
3
4
5
6
7
8
9
10

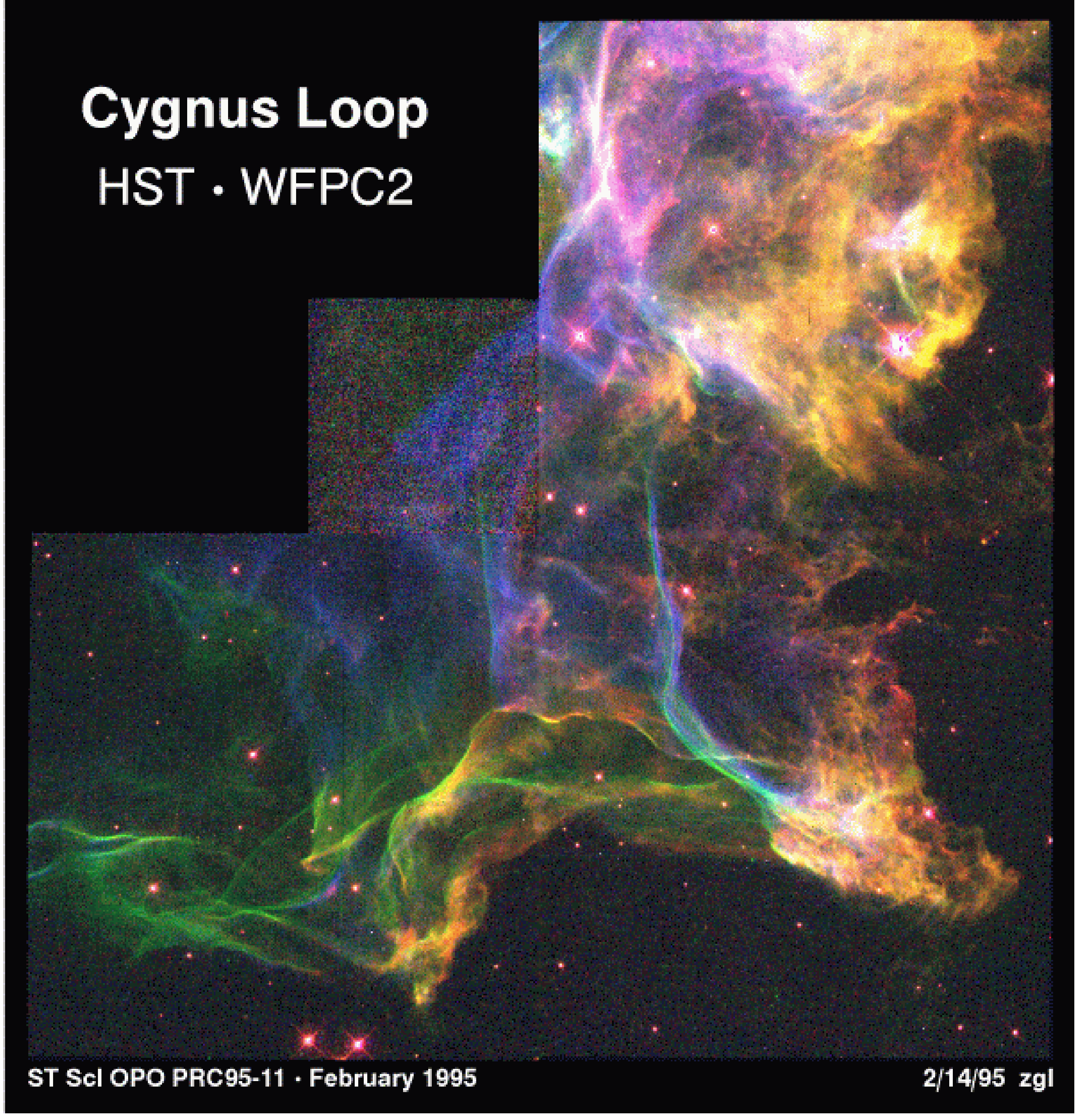
Supernova 1987A Rings



Hubble Space Telescope

Wide Field Planetary Camera 2

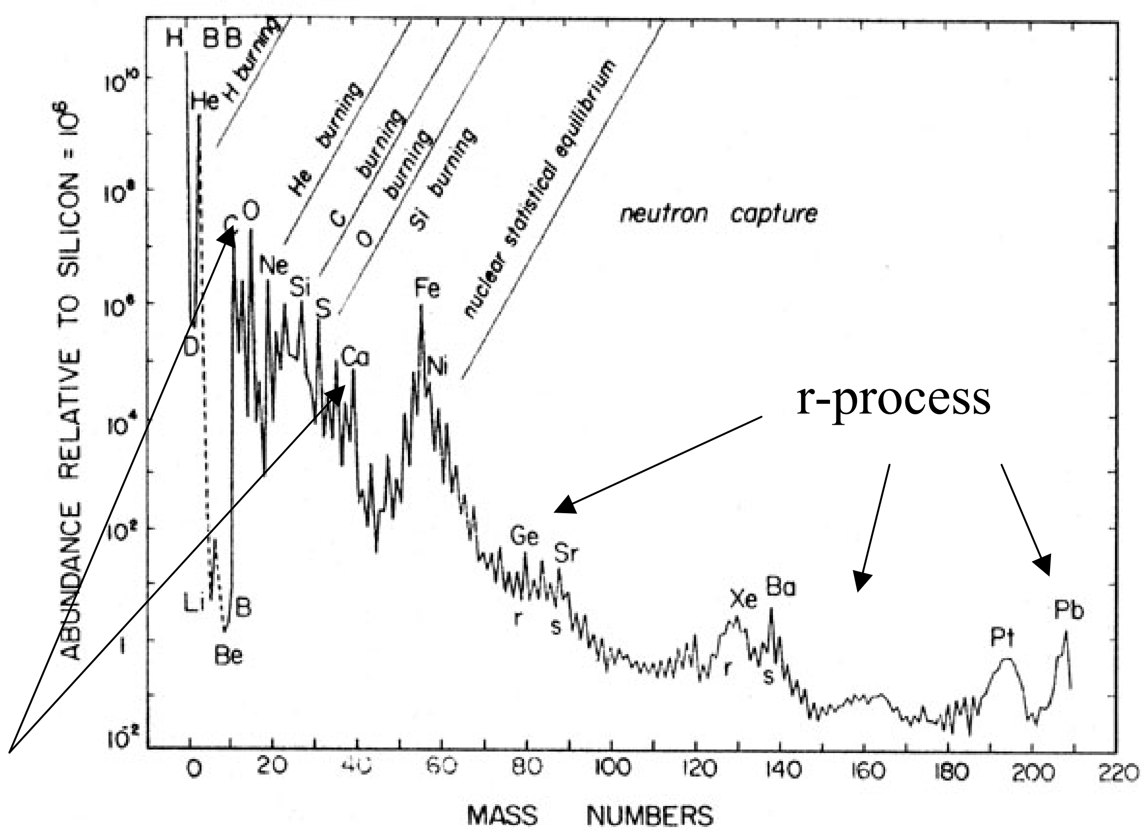
SPACE TELESCOPE SCIENCE INSTITUTE


Cygnus Loop
HST • WFPC2
ST ScI OPO PRC95-11 • February 1995
2/14/95 zgl


Crab Nebula--a supernova
remnant --WIYN Telescope

Cosmic abundances--most “metals”=CNO + Fe peak.

The r-process=rapid capture of neutrons onto Fe seed nuclei--makes some very heavy elements above Fe-peak



Massive star supernovae-->

α-elements O,Ne,Si, Ca

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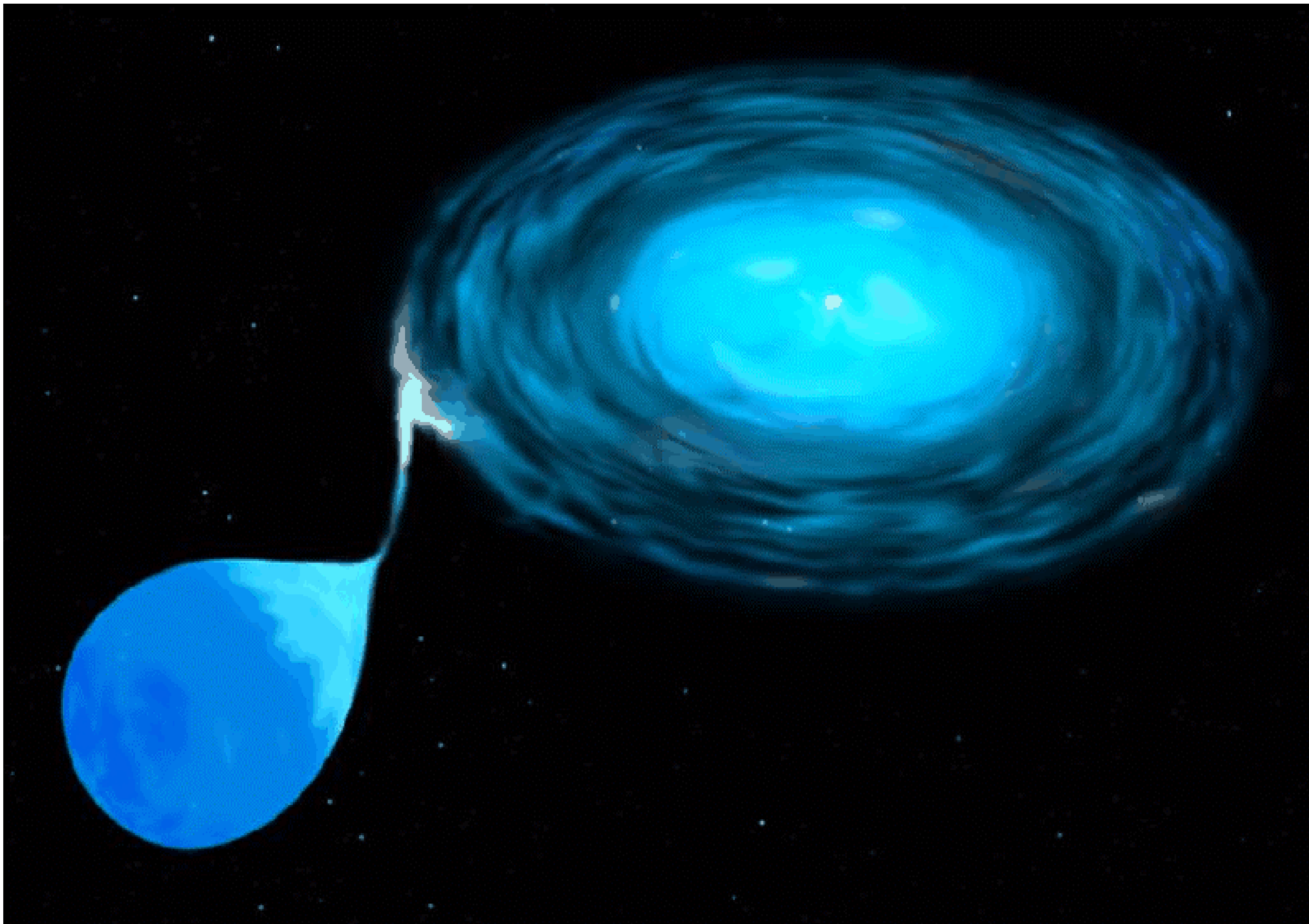
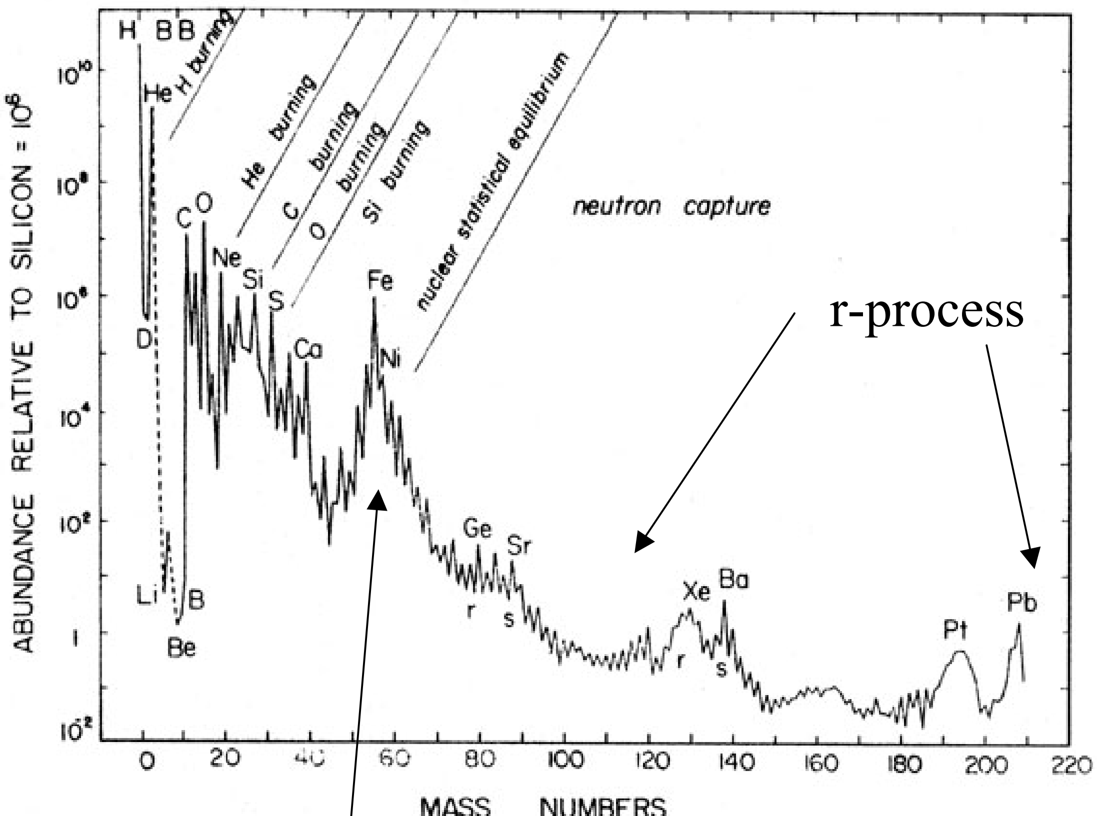
Binary star mass transfer--overload white dwarf. One path to type I supernovae in which much of the Fe-peak is synthesized.



Cosmic abundances--most “metals”=CNO + Fe peak.



r-process

Low mass supernovae-->>”iron peak”

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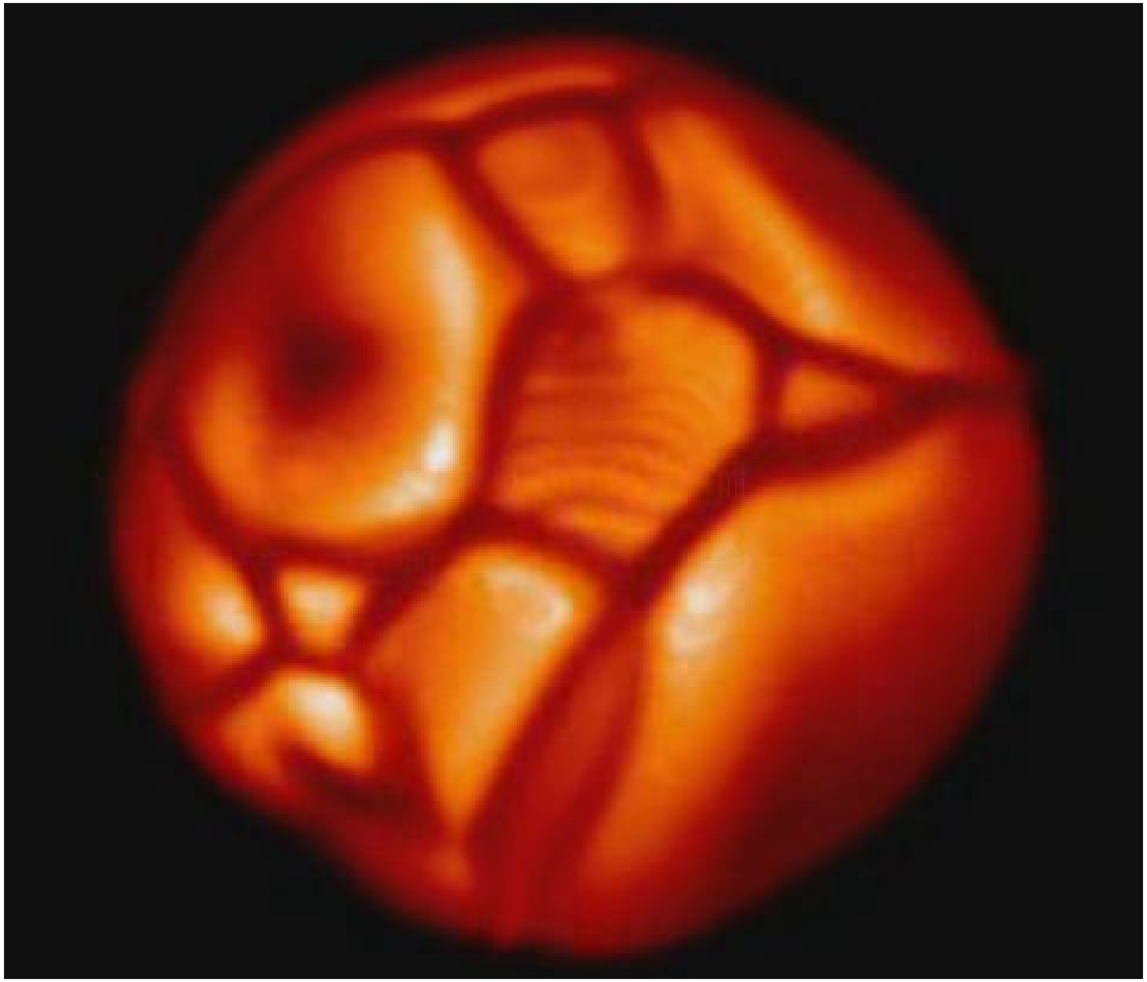
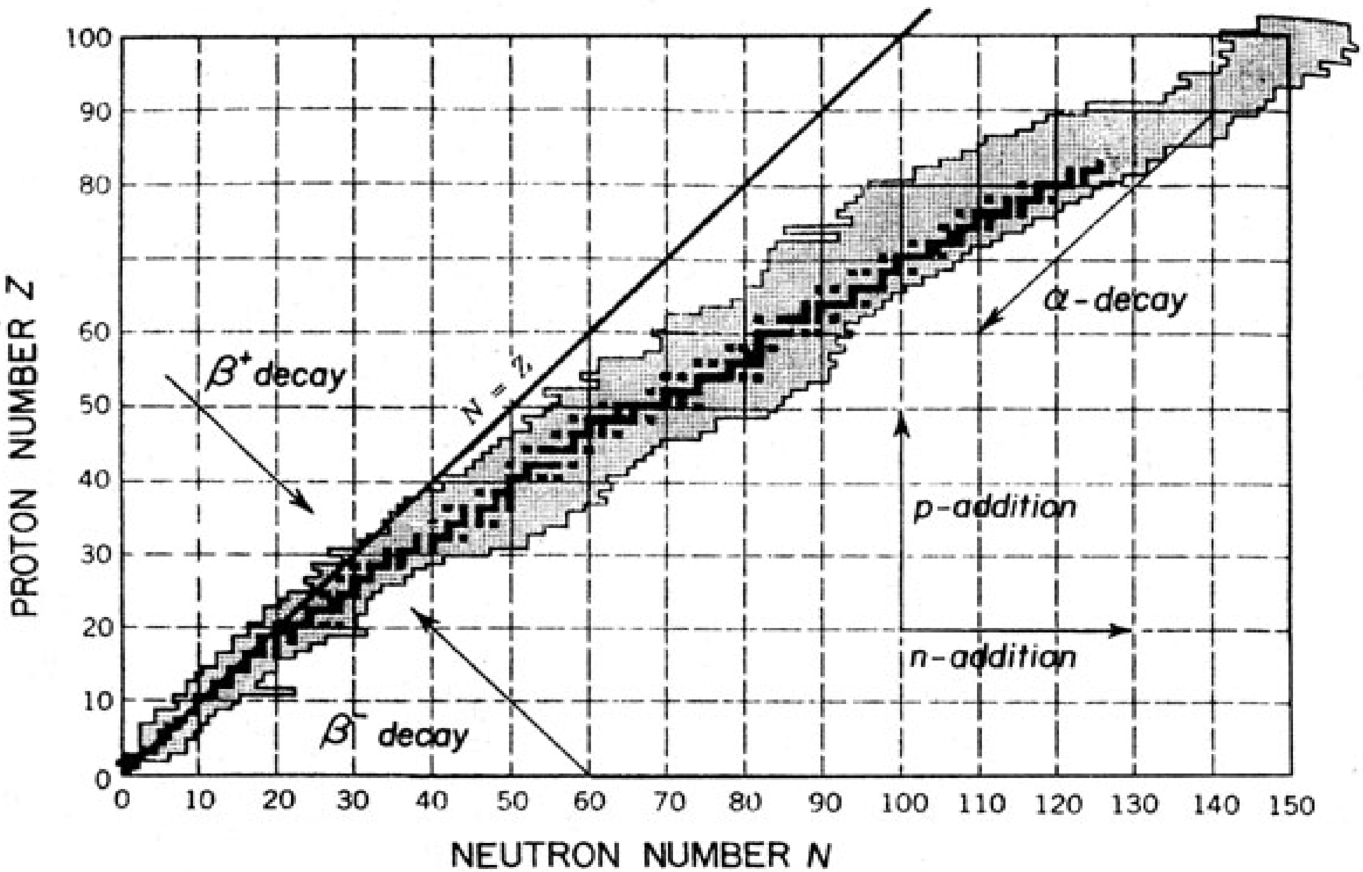
Massive red superginat star with complex atmosphere:

e.g., Antares in the Scorpion



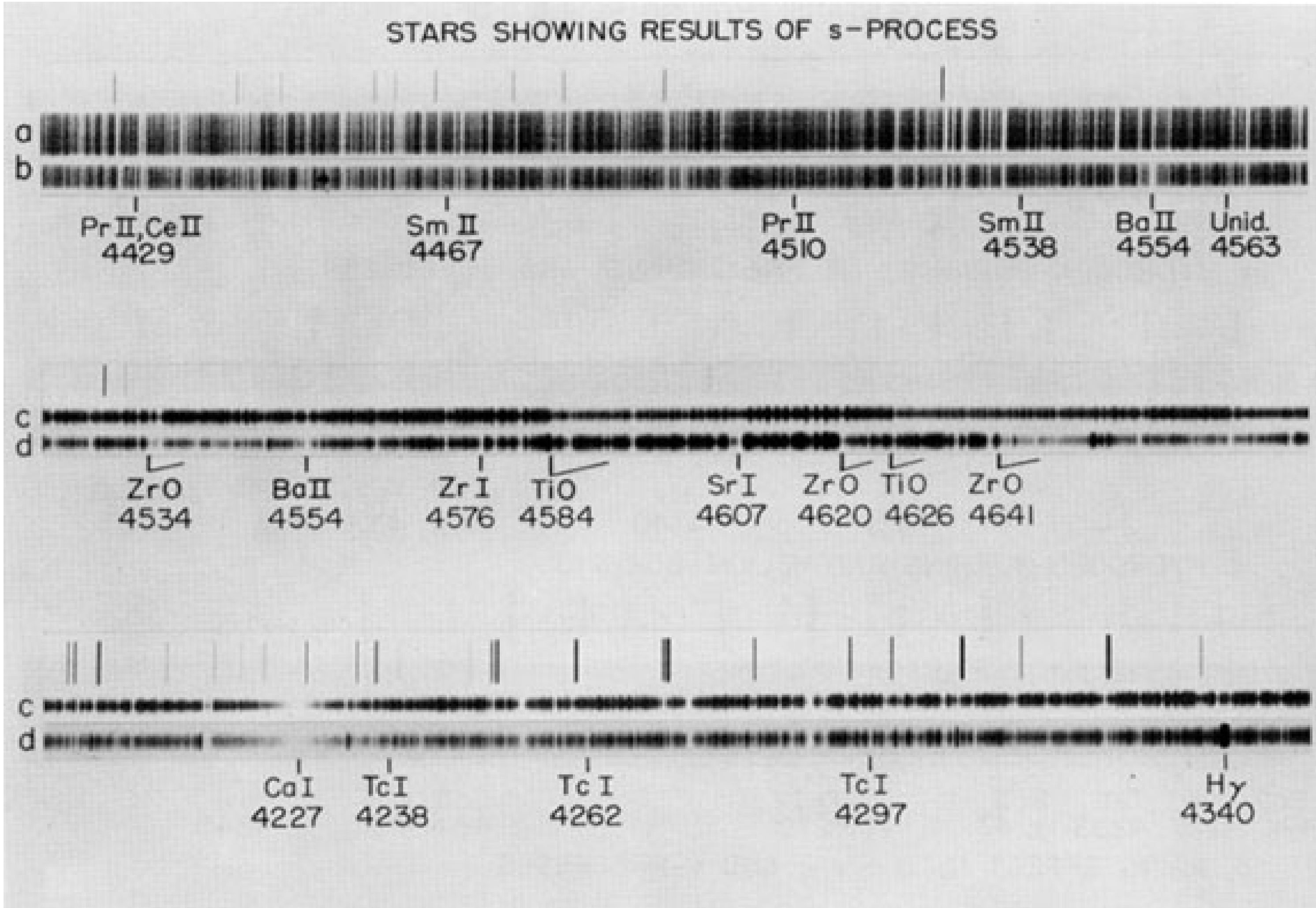
Synthesis of elements of by capture/decay

The s-process is slow neutron capture--elements have time to decay. This occurs in dying moderate mass red stars.



Tc half life:

210,000 yr!

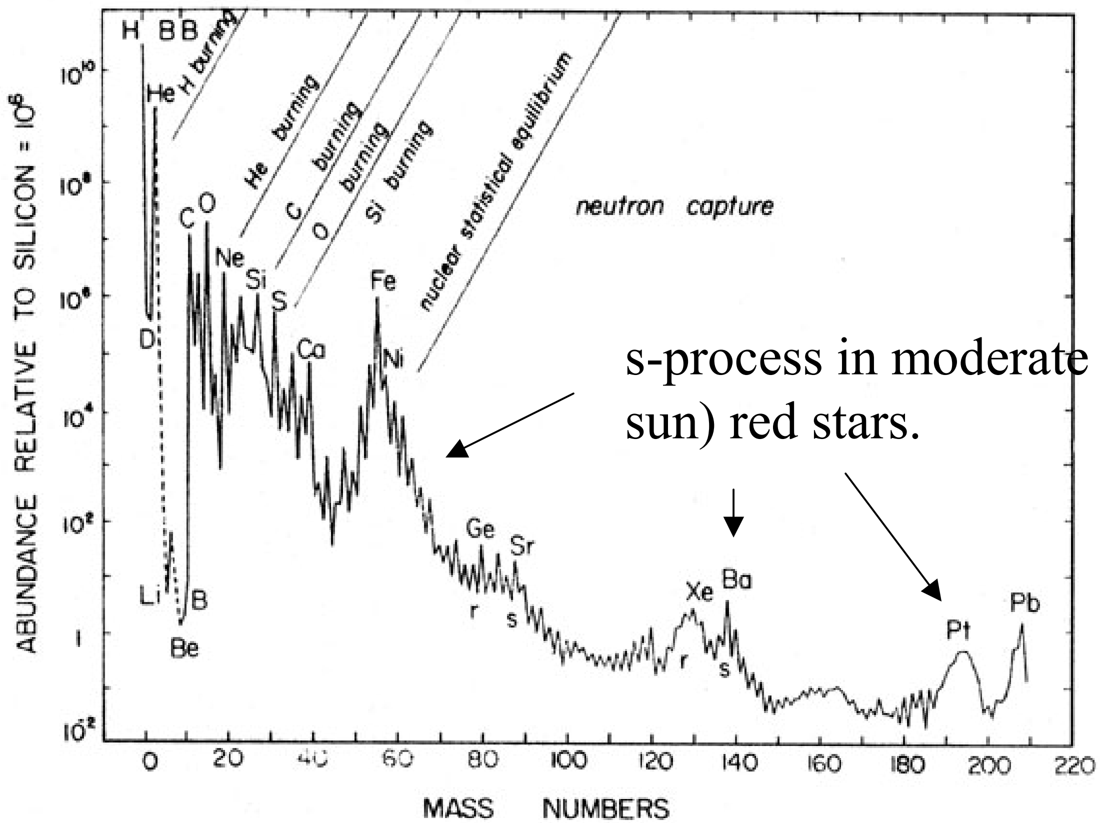


Pagel, Nucleosynthesis and Chemical Evolution...

A young planetary nebula showing interaction with remnants of the cool star’s outer layers.

Planetary nebula around dying star--N+s-process?

Cosmic abundances--most “metals”=CNO + Fe peak.



s-process in moderate (2-8 M-sun) red stars.

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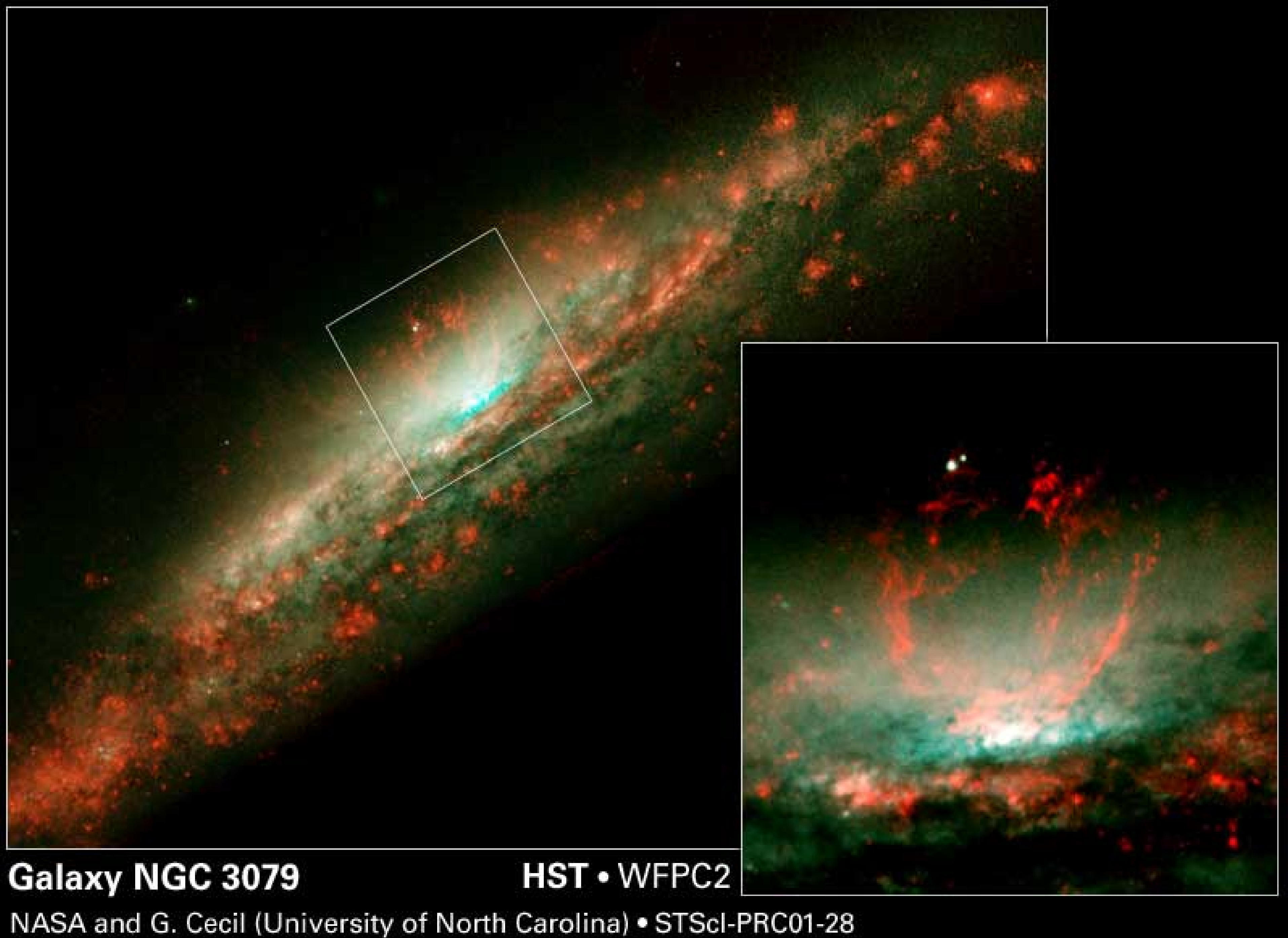
Galaxy NGC 3079
HST • WFPC2
NASA and G. Cecil (University of North Carolina) • STScI-PRC01-28