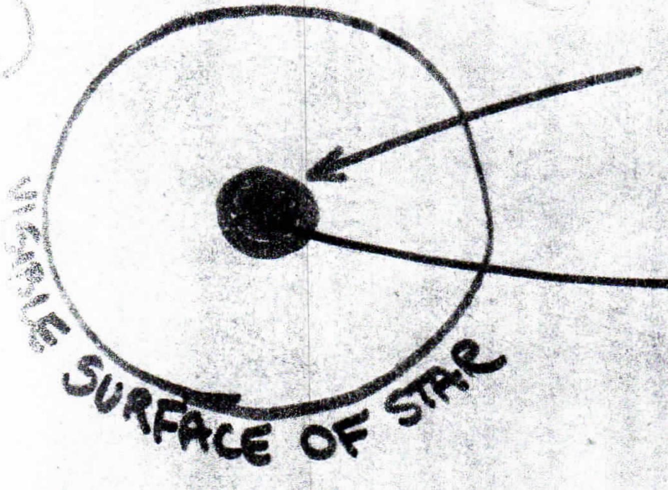
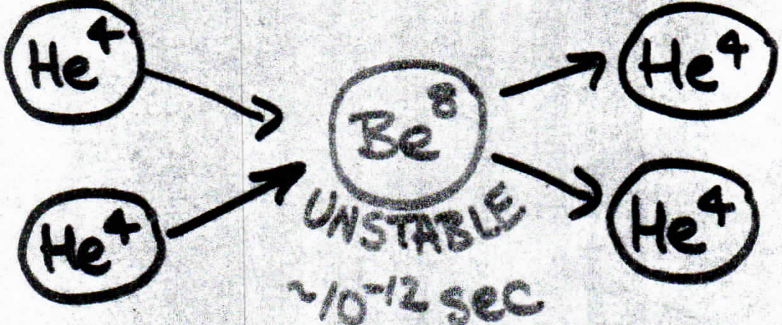
What happens when helium accumulates in a stellar core ?



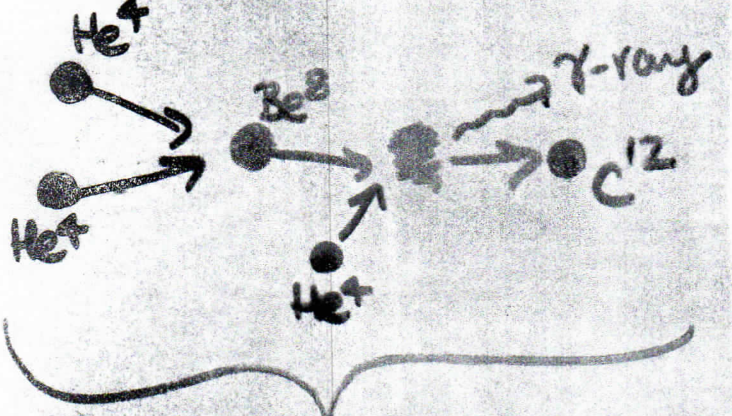
Hydrogen-fusing level of star moves upwards

Helium <u>core</u> builds up at centre of star, temperature initially still few x 10 million degrees Kelvin.

Core mainly <u>He^{4} NUCLEI</u> and <u>ELECTRONS</u>



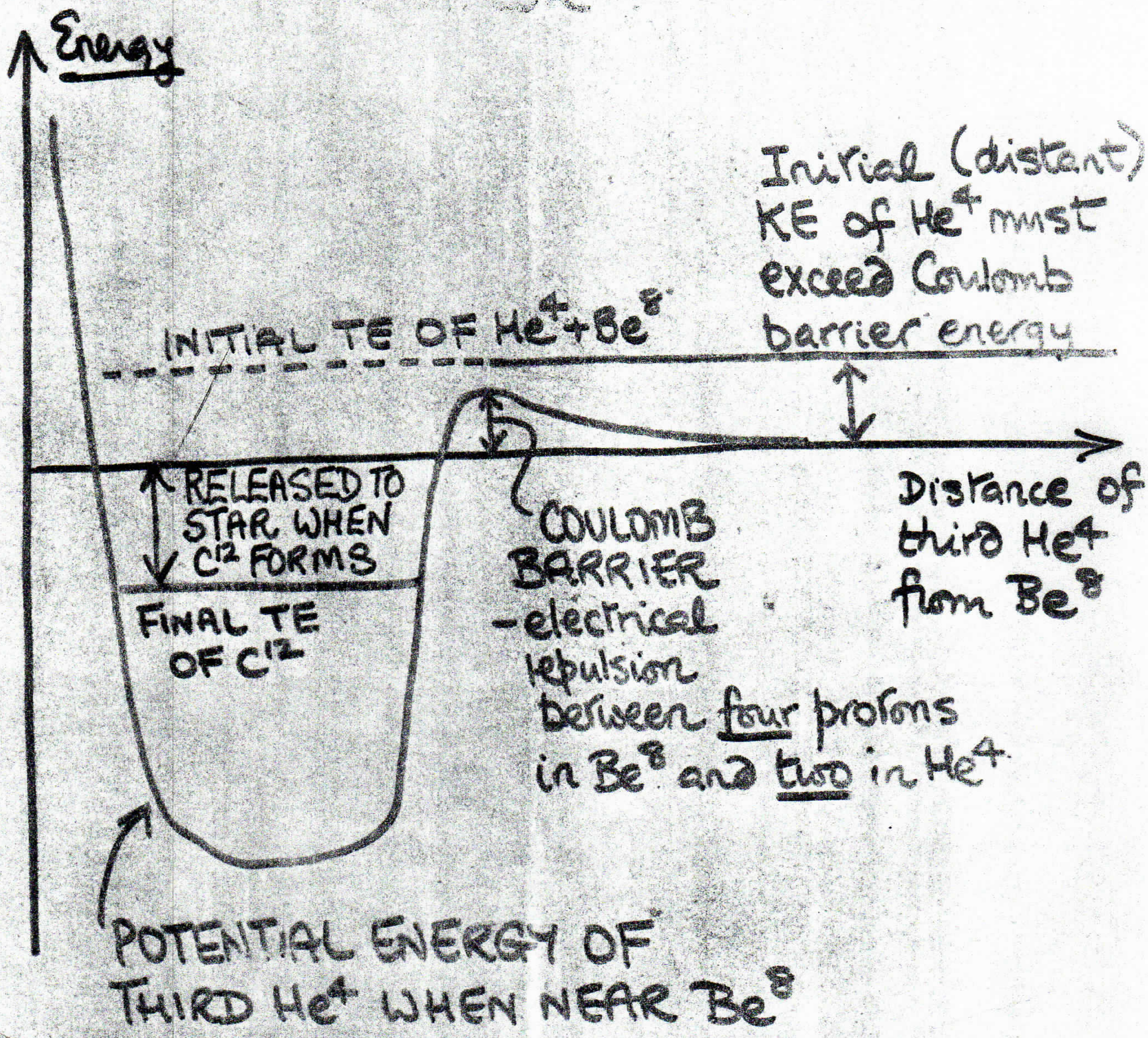
FUSION OF TWO He^{4} NUCLEI DOES NOT WORK



"TRIPLE-ALPHA" PROCESS FORMS CARBON-12 NUCLEUS

ALMOST SIMULTANEOUS (WITHIN 10^{-12} sec) FUSION OF <u>THREE</u> He^{4}'s IS NEEDED

Potential Well for Triple-Alpha Process



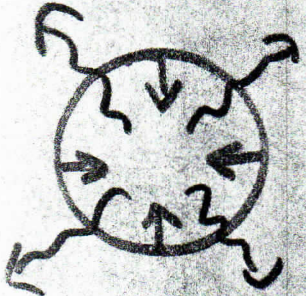
To allow the third He^4 to surmount Coulomb barrier, temperature of helium must be at least 100 million degrees Kelvin.

To have reasonable chance for second collision before Be^8 falls apart, density must be well over 100,000 times that of water.

He core not dense enough To have many three-nucleus collisions.

Not hot enough To overcome Coulom

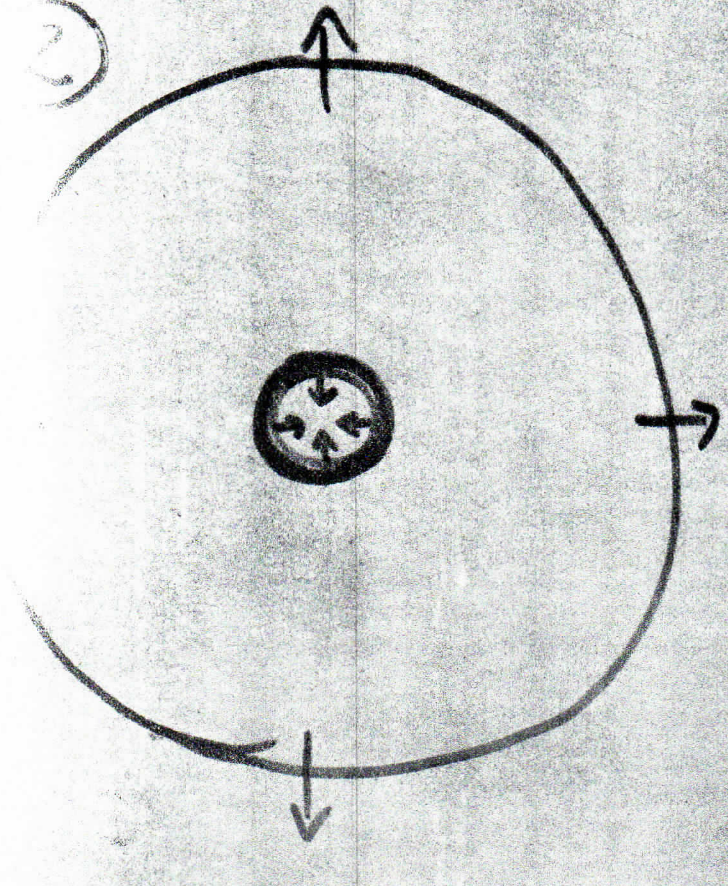
barrier to fusion



CORE COLLAPSES UNDER GRAVITY

GRAVITY THEN DOES WORK ON CORE. CORE COMPRESSES, HEAT UP, RADIATES MORE ENERGY WHILE CONTINUING TO SHRINK

2.



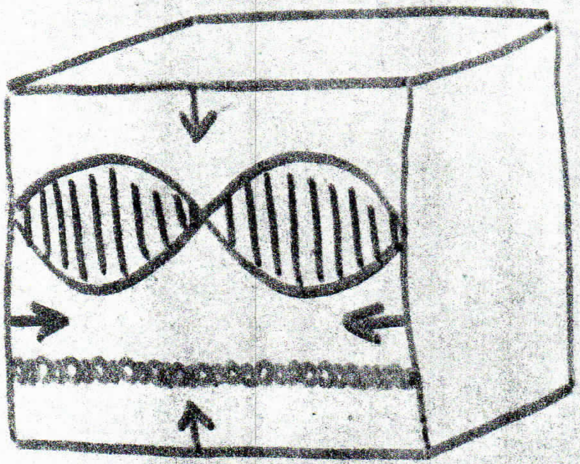
ENERGY RELEASED FROM CORE COLLAPSE OVERHEATS H-FUSING LEVEL.

PROTON FUSION RUNS FASTER THAN NEEDED TO SUPPORT OUTER LEVELS OF STAR

INFLATES OUTER PART OF STAR

Core ~ $\frac{1}{4}$ mass of *, approaches size of Earth

Envelope ~ $\frac{3}{4}$ mass of *, approaches size of Earth orbit.



long wavelengths will not fit in as box shrinks

Short wavelengths can still fit in

For electrons, $\boxed{\text{wavelength} = \frac{h}{\text{momentum}}}$

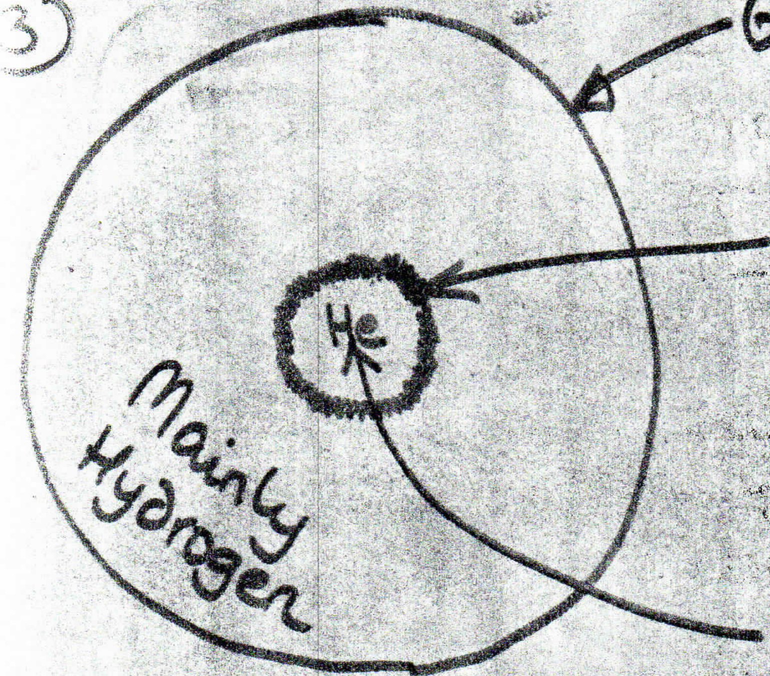
(DE BROGLIE RELATION)

As free space per electron decreases, long-wavelength electron waves will no longer fit in → momenta of electrons must <u>increase</u>

→ new source of <u>pressure</u> in highly compressed gas (DEGENERACY PRESSURE)

Degeneracy pressure depends on number of electrons and box size, <u>not on temperature</u>

③



Greatly disrended Surface (RED GIANT)

H → He FUSION SUPPORTS ENVELOPE AND ADDS He TO CORE

CORE SUPPORTED BY DEGENERACY PRESSURE OF ELECTRONS. NEARLY RIGID, VERY SLOWLY SHRINKS AS He ADDED FROM ABOVE

④ **"HELIUM FLASH"**

Onset of triple-alpha process in degenerate core

→ SUPERFLUOUS energy release in core

→ re-expansion of He. core

→ overheating of H-fusing level

→ rapid growth of inner CARBON CORE

→ different levels of star supported by different kinds of pressure, not always in equilibrium with energy flow → UNSTABLE

WHITE DWARF

Mass of Sun contained in volume ~ that of Earth

Densities ~ 100,000 × water

Supported by degeneracy pressure of electrons

Contains individual nuclei

Cools to "dead" remnant

Theoretical upper limit to mass ~ $1.4\ M_\odot$

(CHANDRASEKHAR LIMIT)

What if star's mass exceeds $1.4\ M_\odot$?

1) It must shed mass – planetary nebula, etc before becoming white dwarf

or 2) Still further collapse.

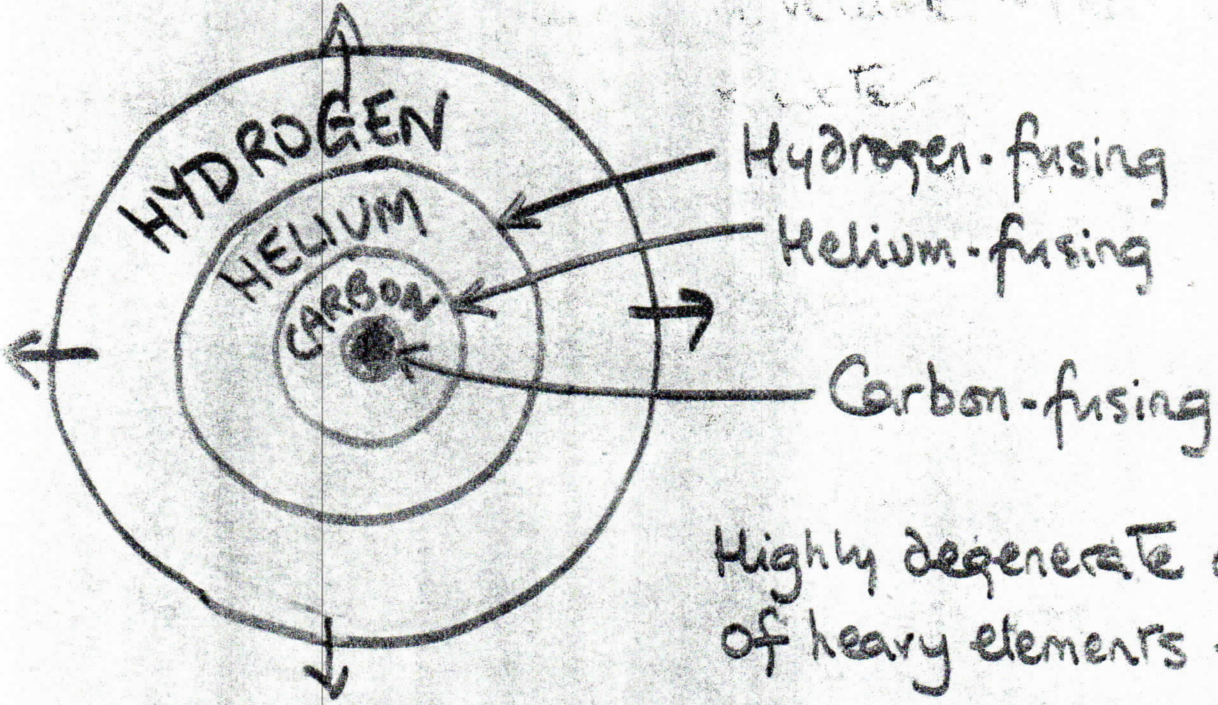
NEUTRON STAR – (close to repulsive-core regime)

Electrons forced into nuclei → degenerate neutron gas. Star sizes ~ 10km radius, densities ~ 10^{14} × water. Separate nuclei no longer exist.

BLACK HOLE (uncertain internal physics)

Stellar mass in ~1km radius → escape velocity exceeds velocity of light. No radiation could escape: object detectable only by gravitational pull on outside world.

Example of Possibly Very Complex Late Stage in Stellar Development

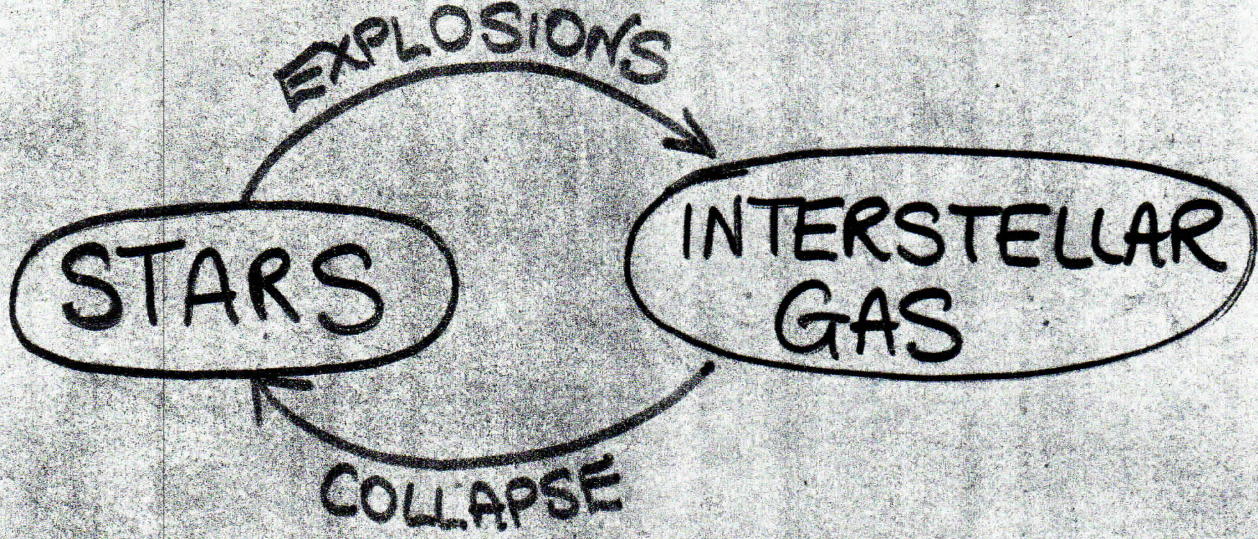


Highly degenerate core of heavy elements – e.g. oxygen, neon, etc.

Energy flows through different levels no longer need be those producing equilibrium

→ EXPLOSIVE phenomena

Planetary Nebulae
Novae
Supernovae

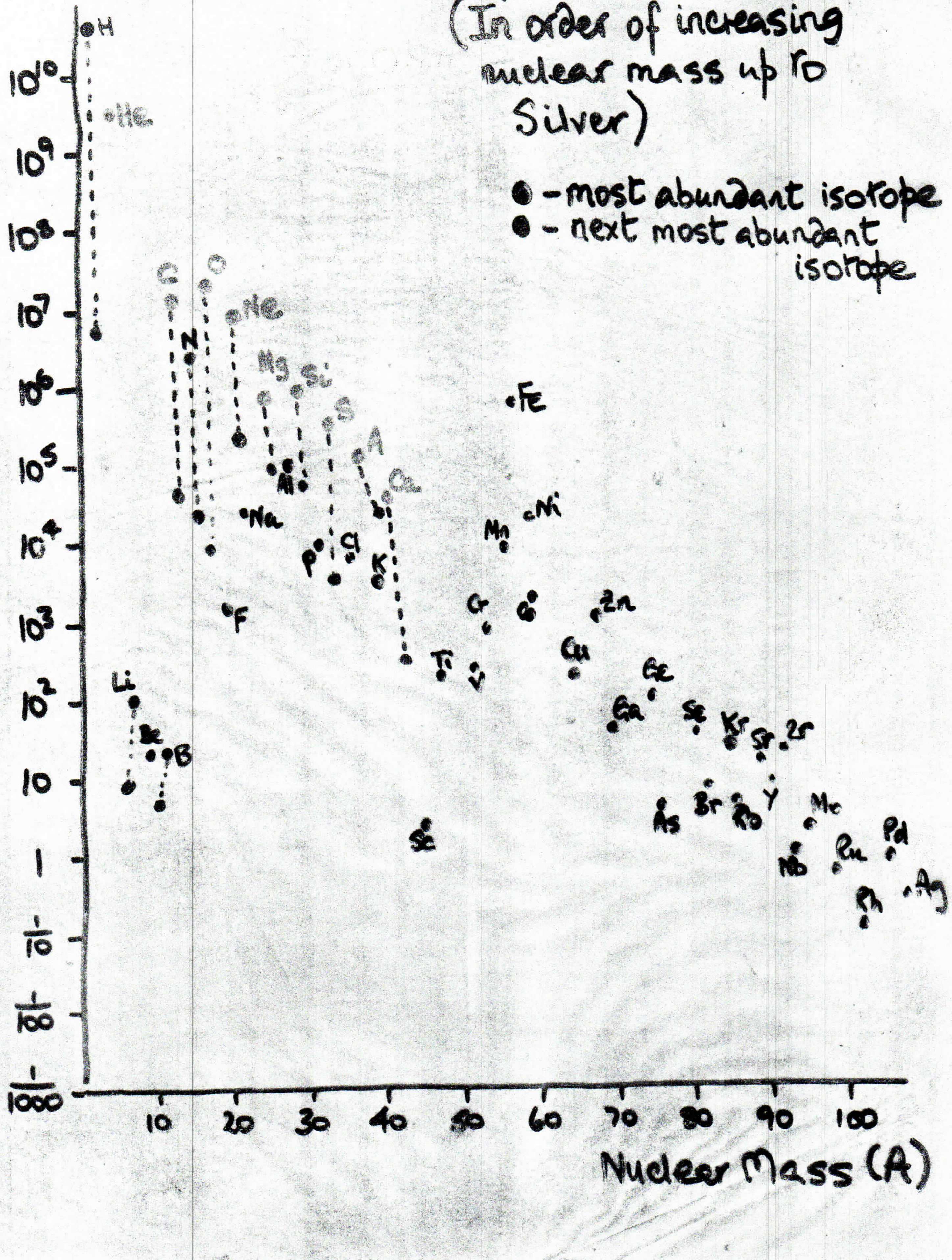


Fusion of light elements into heavy elements, which end up in
WHITE DWARFS
NEUTRON STARS
BLACK HOLES
INTERSTELLAR GAS

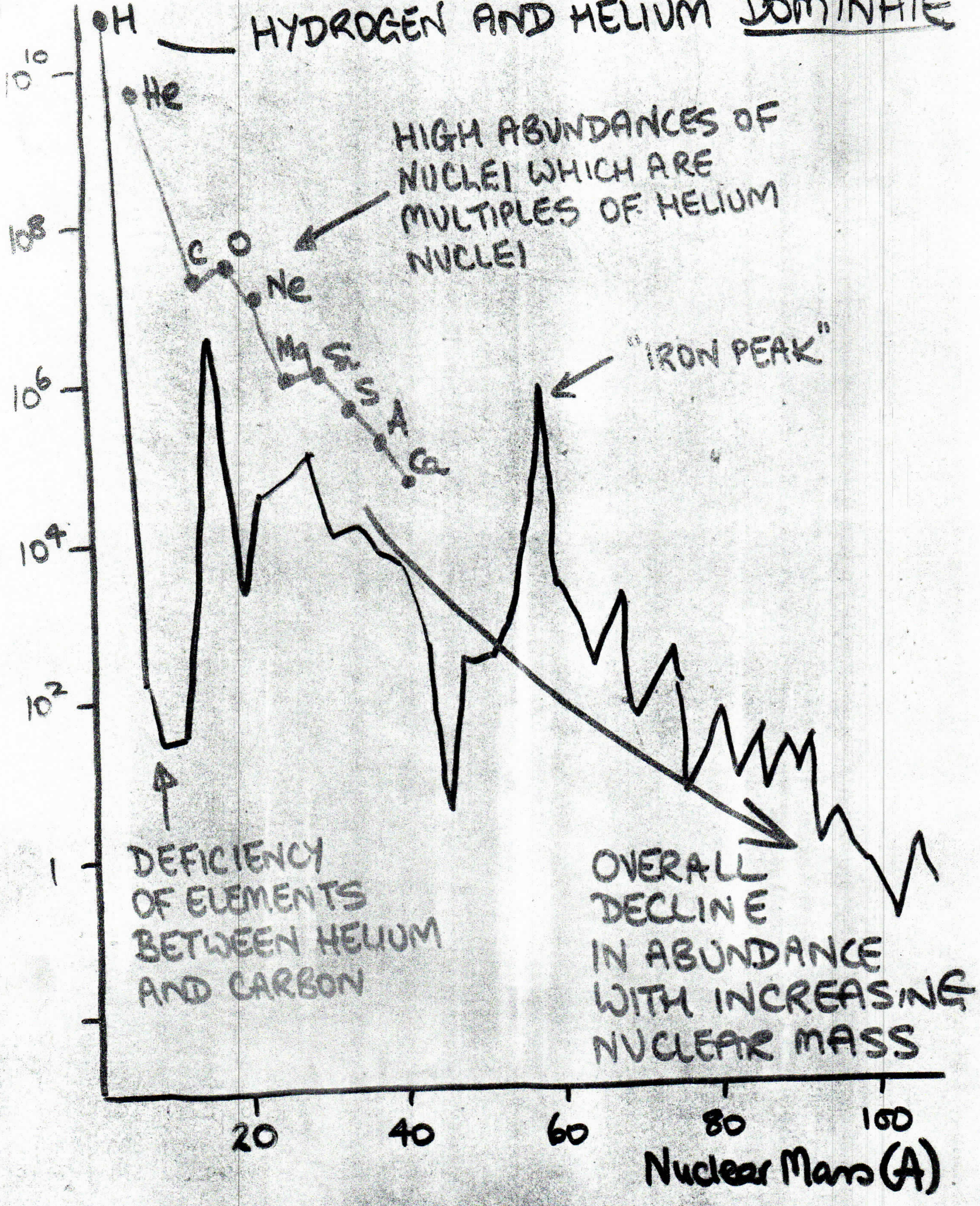
Mixed, agitated compressed by stellar radiation and explosions
→ formation of new stars and planets

Relative Abundances of Chemical Elements

(In order of increasing nuclear mass up to Silver)



Major Features of Abundance Curve



NOTATION FOR NUCLEAR REACTIONS

nuclei: E^n

n — number of nucleons (protons + neutrons) in nucleus

E — chemical symbol of element whose atom might contain such a nucleus

e.g. C^{12}, Fe^{56} etc

nucleons:

H^1 - proton

n - neutron

Byproducts:

e^- - electron

e^+ - positively-charged electron (positron)

ν - neutrino

γ - γ-radiation (high-energy electromagnetic radiation)

HYDROGEN FUSION IN STARS

$$\left.\begin{array}{l} H^1 + H^1 \rightarrow H^2 + e^+ + \nu \\ H^1 + H^2 \rightarrow He^3 + \gamma \\ He^3 + He^3 \rightarrow He^4 + H^1 + H^1 \end{array}\right\}$$

main proton-proton reaction chain

favoured because the result is particularly stable.

Possible alternative processes (occur occasionally) are:-

$$He^3 + He^4 \rightarrow Be^7 + \gamma$$

$$\left.\begin{array}{l} Be^7 + e^- \rightarrow Li^7 + \nu \\ Li^7 + H^1 \rightarrow He^4 + He^4 \end{array}\right\} \text{ or } \begin{array}{l} Be^7 + H^1 \rightarrow B^8 + \gamma \\ B^8 \rightarrow He^4 + He^4 + e^+ + \nu \end{array}$$

In "late-model" stars with appreciable content of heavier elements, and at higher temperatures where electrical-repulsion barrier can be overcome:

$$\left.\begin{array}{l} H^1 + C^{12} \rightarrow N^{13} + \gamma \\ N^{13} \rightarrow C^{13} + e^+ + \nu \\ C^{13} + H^1 \rightarrow N^{14} + \gamma \\ N^{14} + H^1 \rightarrow O^{15} + \gamma \\ O^{15} \rightarrow N^{15} + e^+ + \nu \\ N^{15} + H^1 \rightarrow C^{12} + He^4 \end{array}\right\}$$

"carbon-nitrogen cycle".

Net effect is

$$4H^1 \rightarrow He^4 + 3\gamma + 2e^+ + 2\nu$$

↑

regenerated

HELIUM FUSION IN STARS

$He^4 + He^4 \rightarrow Be^8 \rightarrow He^4 + He^4$

$He^4 + H^1 \rightarrow Li^5 \rightarrow He^4 + H^1$

unstable

$He^4 + He^4 + He^4 \longrightarrow C^{12} + \gamma$

$$\left.\begin{array}{l} C^{12} + He^4 \rightarrow O^{16} + \gamma \\ O^{16} + He^4 \rightarrow Ne^{20} + \gamma \\ Ne^{20} + He^4 \rightarrow Mg^{24} + \gamma \end{array}\right\} \text{These all fuse } He^4 \text{ with stable products to make heavier stable products}$$

--- etc to Si^{28}, S^{32}, A^{36}, Ca^{40}

CARBON FUSION IN STARS

$C^{12} + C^{12} \rightarrow Ne^{20} + He^4$ — nothing new

$C^{12} + H^1 \rightarrow C^{13} + e^+ + \nu$ — rarer isotope of carbon

$C^{13} + H^1 \rightarrow N^{14} + \gamma$ — common isotope of nitrogen

$C^{13} + He^4 \rightarrow O^{16} + n$ — common isotope of oxygen and a neutron

Neutron-induced reactions (NO electrical repulsive barrier to be overcome)

$C^{13} + n \rightarrow C^{14} + \gamma$ — radioactive isotope of carbon

$N^{14} + n \rightarrow N^{15} + \gamma$ — rarer isotope of nitrogen

etc, etc. (many processes possible)

$$\left.\begin{array}{l} O^{16} + H^1 \rightarrow F^{17} + \gamma \\ F^{17} \rightarrow O^{17} + e^- + \nu \\ O^{17} + H^1 \rightarrow N^{14} + He^4 \end{array}\right\} \text{more complex proton-induced reactions}$$

EQUILIBRIUM NUCLEAR COOKERY

1. Reactions involving commonplace reactants (especially H^1, He^4) will be favoured
2. Reactions with small Coulomb barriers will be favoured.
3. Stable products will be formed <u>easily</u> and broken down <u>only with difficulty</u>.

Results: $3He^4 \rightarrow C^{12}$ <u>bypasses</u> Li, Be, B, which can only be formed by occasional "side-reactions"

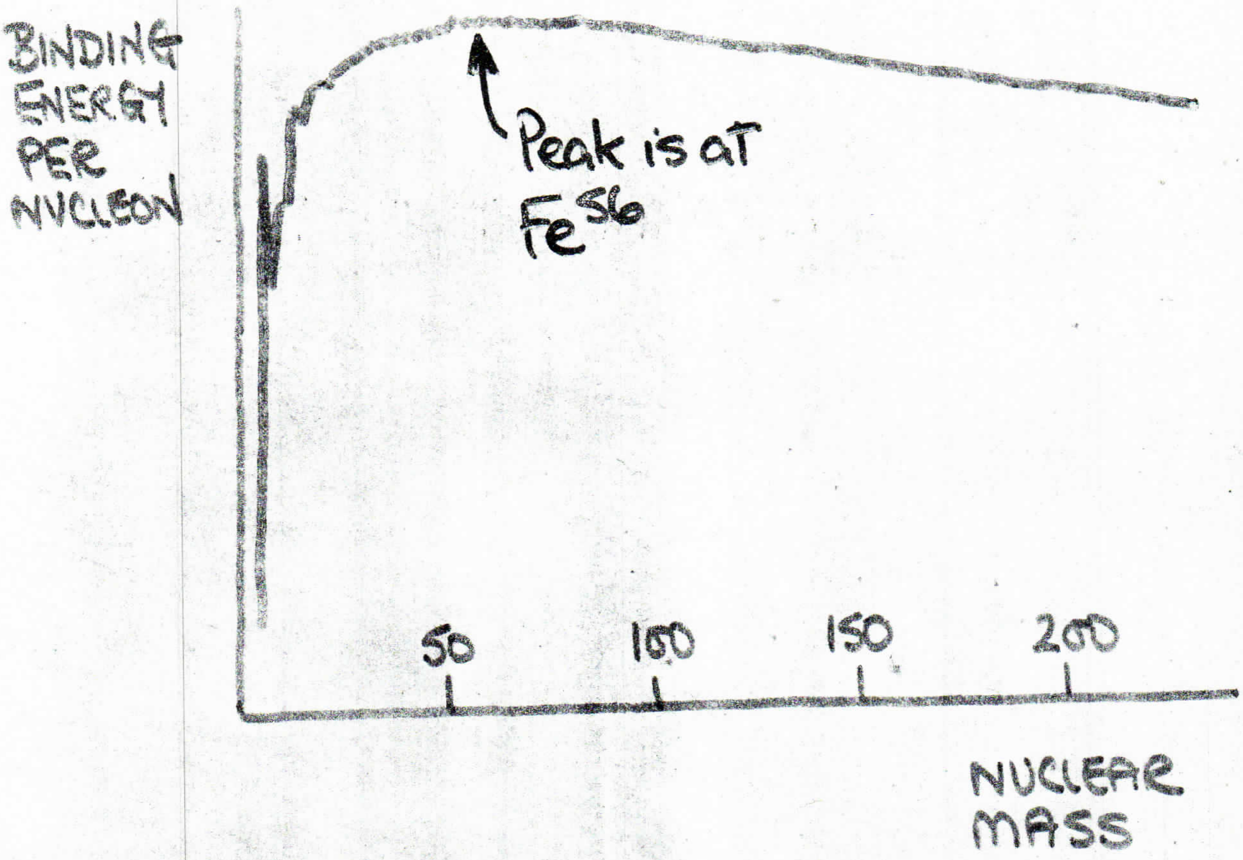
Nuclei which are multiples of He^4 are easily formed and hard to remove

Abundances of other nuclei depend on which processes lead to them, given (1) and (2) above — <u>general</u> decline in abundance with increasing mass because formation is less likely the more steps are needed.

"Piling up" at Fe^{56} because of (3)

— indeed —

HOW DOES ANYTHING BEYOND Fe^{56} IN MASS EVER GET FORMED ?



UP TO Fe^{56}, energy is released when heavier nuclei form from lighter ones by fusion. Above Fe^{56} in mass, repulsions of extra protons no longer compensated by increased nuclear attractive interactions ("saturation" effect).

SO NUCLEI WILL RESIST ADDITION OF EXTRA PROTONS BEYOND Fe^{56}

NO SUCH PROBLEM WITH NEUTRONS.

S-Process

Slow neutron addition (~1 per year)

$Fe^{56} + n \rightarrow Fe^{57}$ (STABLE)

$Fe^{57} + n \rightarrow Fe^{58}$ (STABLE)

$Fe^{58} + n \rightarrow Fe^{59} \rightarrow Co^{59} + e^- + \bar{\nu}$

$Co^{59} + n \rightarrow Co^{60} \rightarrow Ni^{60} + e^- + \bar{\nu}$, etc.

BUILDS UP NUCLEI THAT ARE STABLE AGAINST β-DECAY FOR FEW YEARS OR MORE.

CANNOT EXPLAIN <u>ALL</u> HEAVY NUCLEI THOUG

1) "Bismuth Barrier"

$Bi^{209} + n \rightarrow Bi^{210} \rightarrow Po^{210} + e^- + \bar{\nu}$

$Po^{210} \rightarrow Pb^{206} + He^4$

$Pb^{206} + n \rightarrow Pb^{207}$

$Pb^{207} + n \rightarrow Pb^{208}$

$Pb^{208} + n \rightarrow Pb^{209} \rightarrow Bi^{209} + e^- + \bar{\nu}$

THIS PREVENTS FORMATION OF RADIOACTIVE ELEMENTS SUCH AS THORIUM, URANIUM

2) Some neutron-rich isotopes cannot be reached because intermediate steps form nuclei with RAPID β-decays (SLIDE)

"TROUBLE" WITH THE HELIUM ABUNDANCE

— or, did everything begin as hydrogen

STELLAR ELEMENT COOKING COULD MANUFACTURE OBSERVED ABUNDANCE OF HEAVIER-THAN-HELIUM ELEMENTS IN ~ 20 BILLION YEARS

BUT TO BUILD UP OBSERVED HELIUM ABUNDANCE, NEED ~ 200 BILLION YEAR

ALSO, OLDEST STAR CLUSTERS (only 0.05% heavier-than-helium) CONTAIN ALMOST AS MUCH HELIUM AS YOUNGEST ONES (5% heavier-than-helium)

Suggests that most of the helium has been present as long as there have been stars

"PRIMORDIAL MIX" 70% H, 30% He