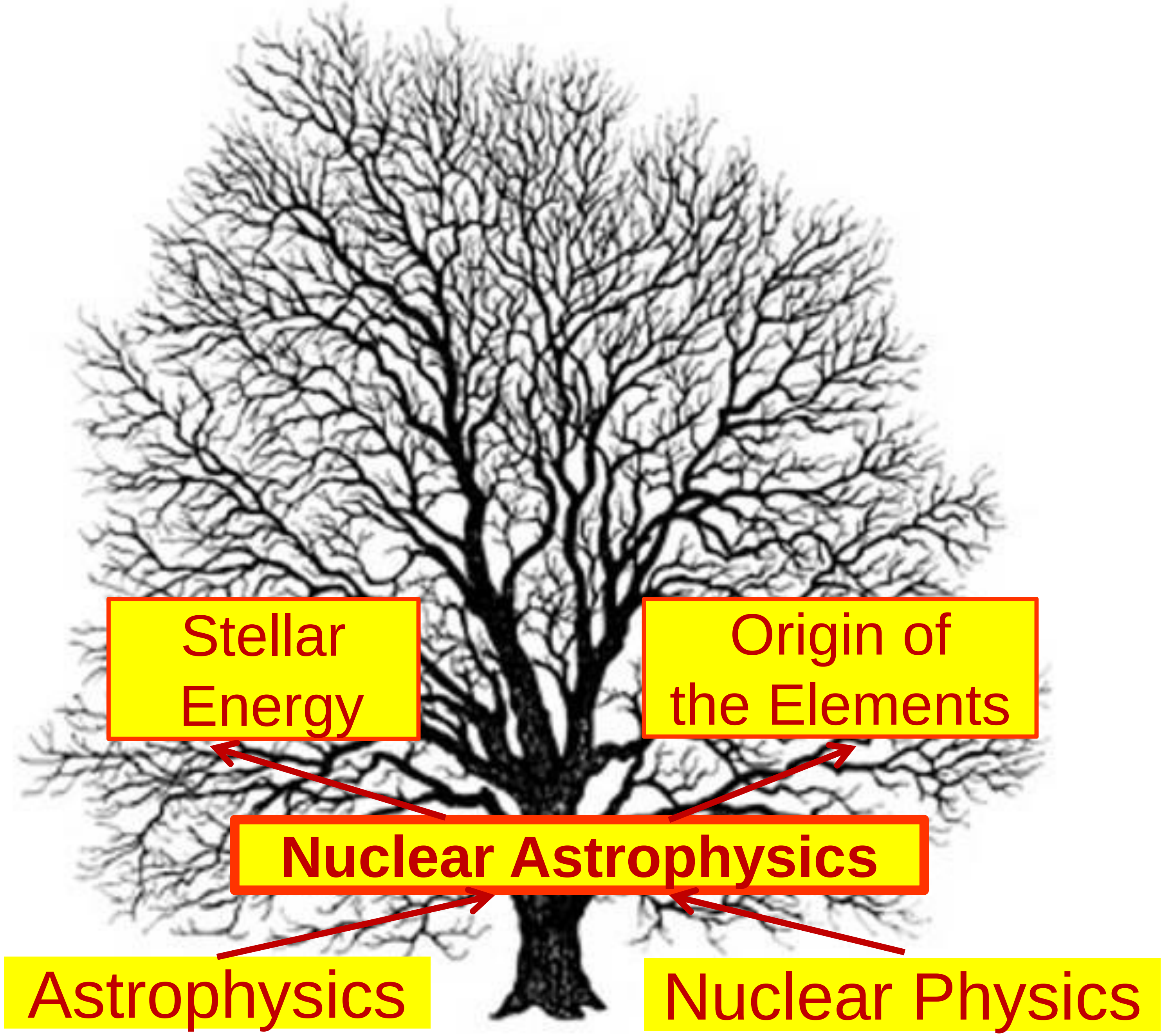
A BRIEF HISTORY OF

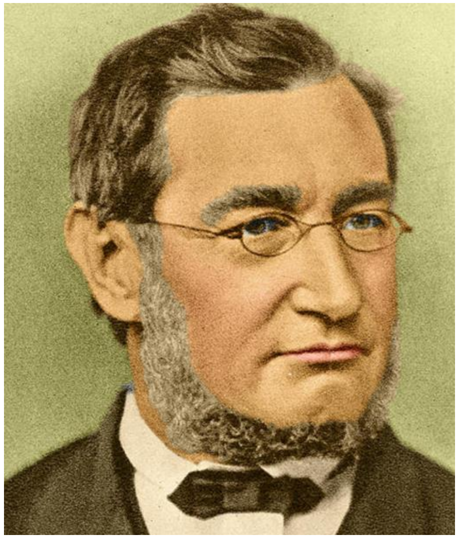
NUCLEAR ASTROPHYSICS


Stellar Energy
Origin of the Elements
Nuclear Astrophysics
Astrophysics
Nuclear Physics

A BRIEF HISTORY OF NUCLEAR ASTROPHYSICS

PART I
THE ENERGY OF STARS

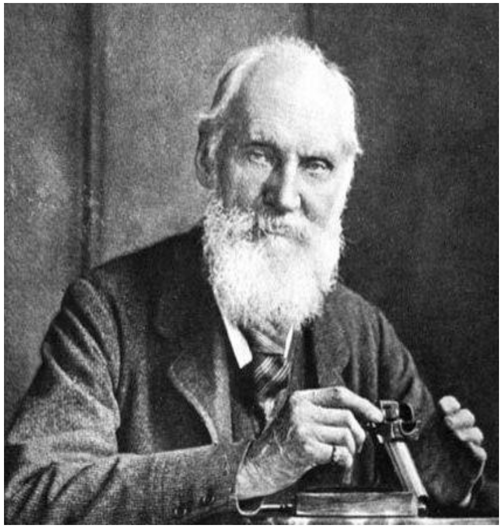
Thermodynamics: the age of the Earth and the energy of the Sun

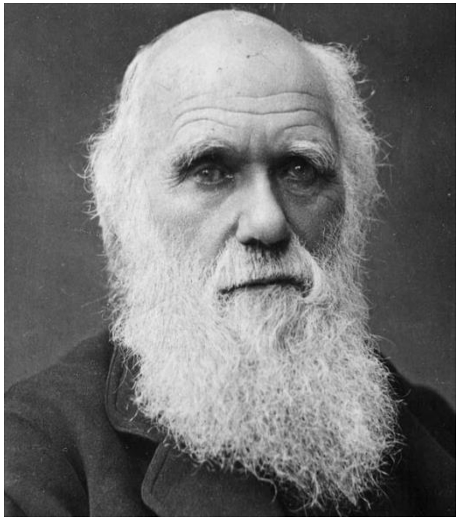


1847 : Robert Julius von Mayer
Sun heated by fall of meteors

1854 : Hermann von Helmholtz
Gravitational energy of protosolar nebula
turns into kinetic energy of meteors
Time ~ E_{Grav}/L_{Sun} ~ **30 My**

1850s : William Thompson (Lord Kelvin)
Sun heated ***at formation*** from meteorite fall,
now « an incadescent liquid mass » cooling
age 10 – 100 My





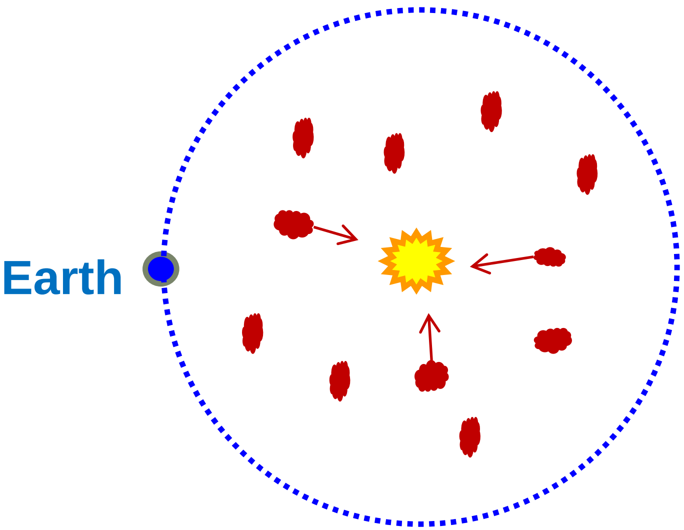
1859: Charles Darwin ***Origin of species*** :
Rate of erosion of the Weald valley is 1 inch/century
or 22 miles wild (X 1100 feet high) **in 300 My**

A gaseous, contracting and heating Sun

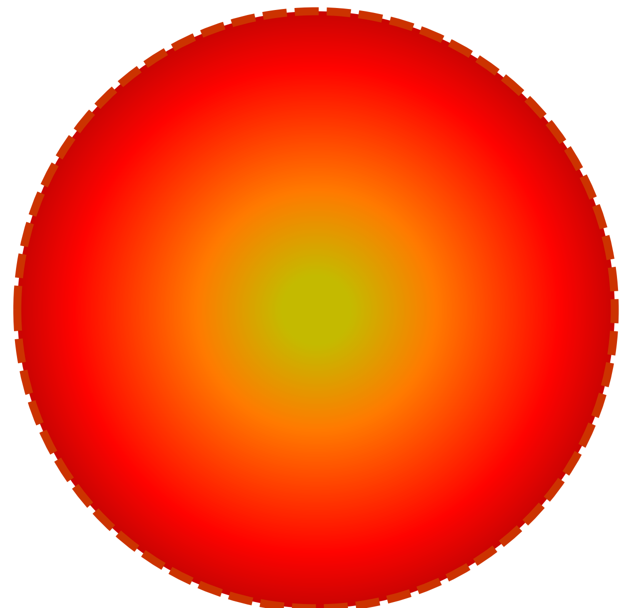
Mean solar density : $\rho = \frac{M_\odot}{\frac{4\pi}{3} R_\odot^{\ 3}}$ ~1.35 g/cc   Sun liquid $\Rightarrow$ Incompressible

1860s: J. Homer Lane ; 1880s :August Ritter : Sun gaseous $\Rightarrow$ Compressible

As it shrinks, it releases gravitational energy AND it gets hotter



Mayer – Kelvin - Helmholtz



Helmholtz - Lane -Ritter

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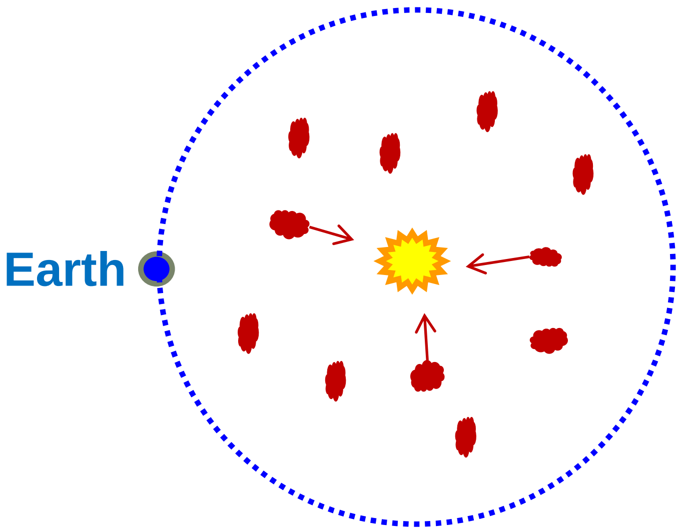

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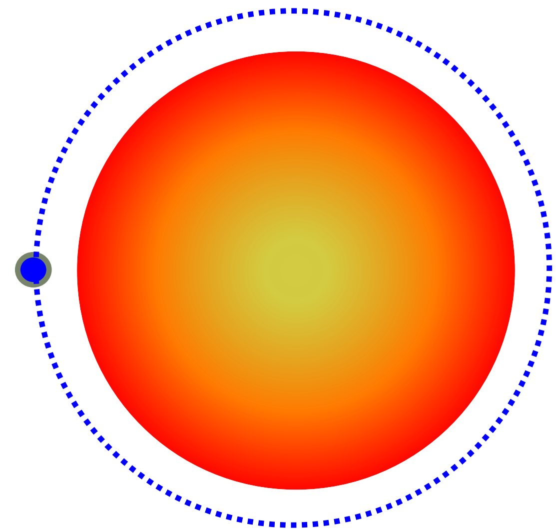

Helmholtz - Lane -Ritter

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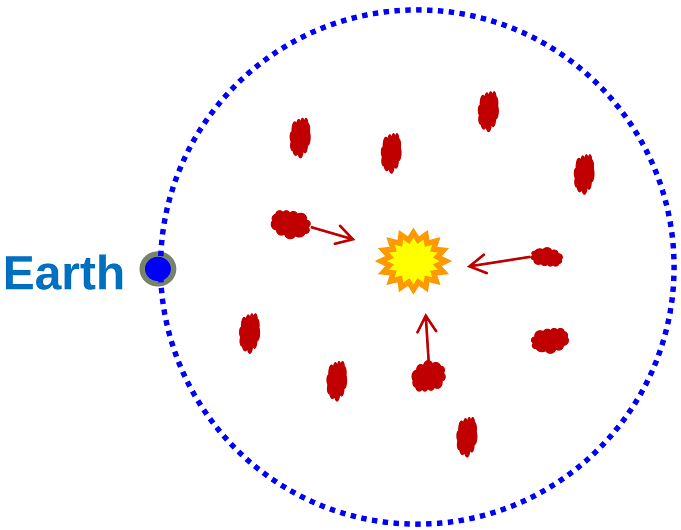
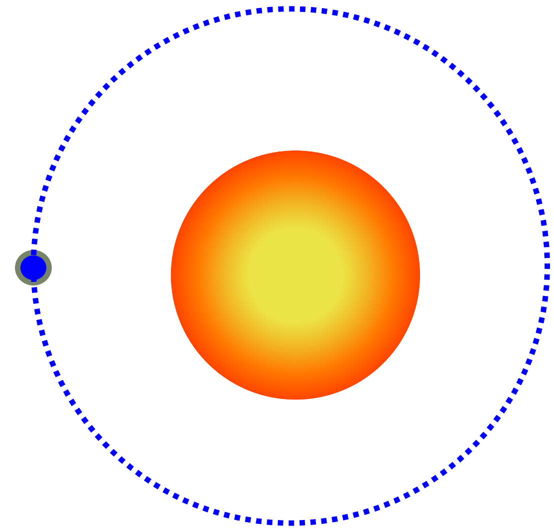


Mayer – Kelvin - Helmholtz



Helmholtz - Lane -Ritter

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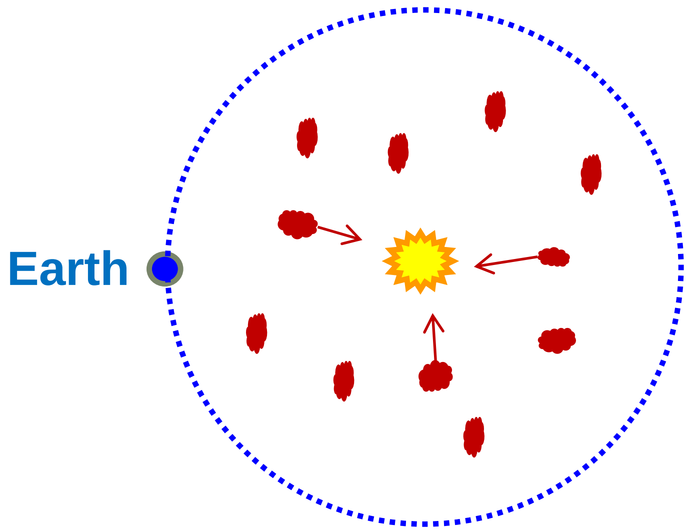
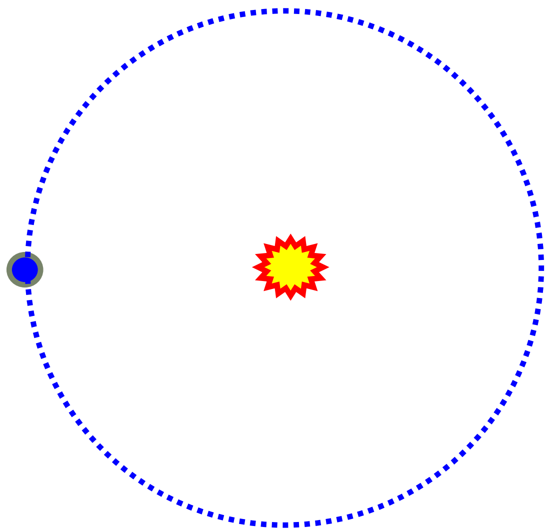


Mayer – Kelvin - Helmholtz



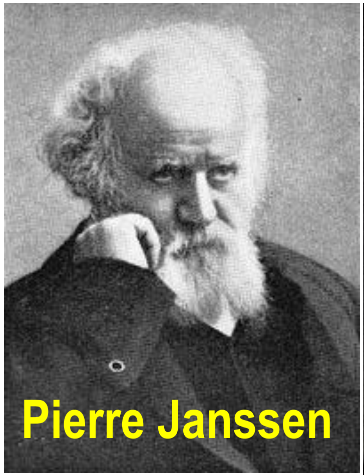
Helmholtz - Lane -Ritter

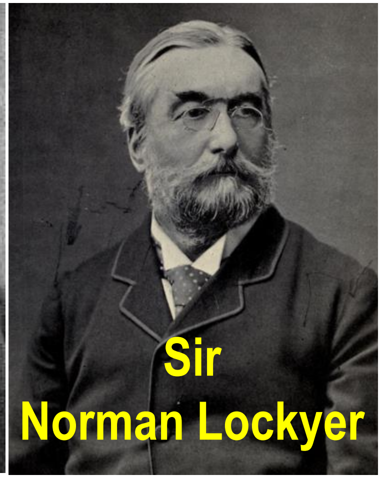
Source of solar energy : gravitational contraction $\text{Energy} \sim \dfrac{G\ M_\odot^2}{R_\odot}$

Characteristic timescale of contraction : $T_{contraction} \sim = \dfrac{\text{Energy}}{\text{Luminosity}}$ ~ 30 My

Kelvin – Helmholtz - Ritter timescale

Stellar spectroscopy reveals *Helium* in the Sun

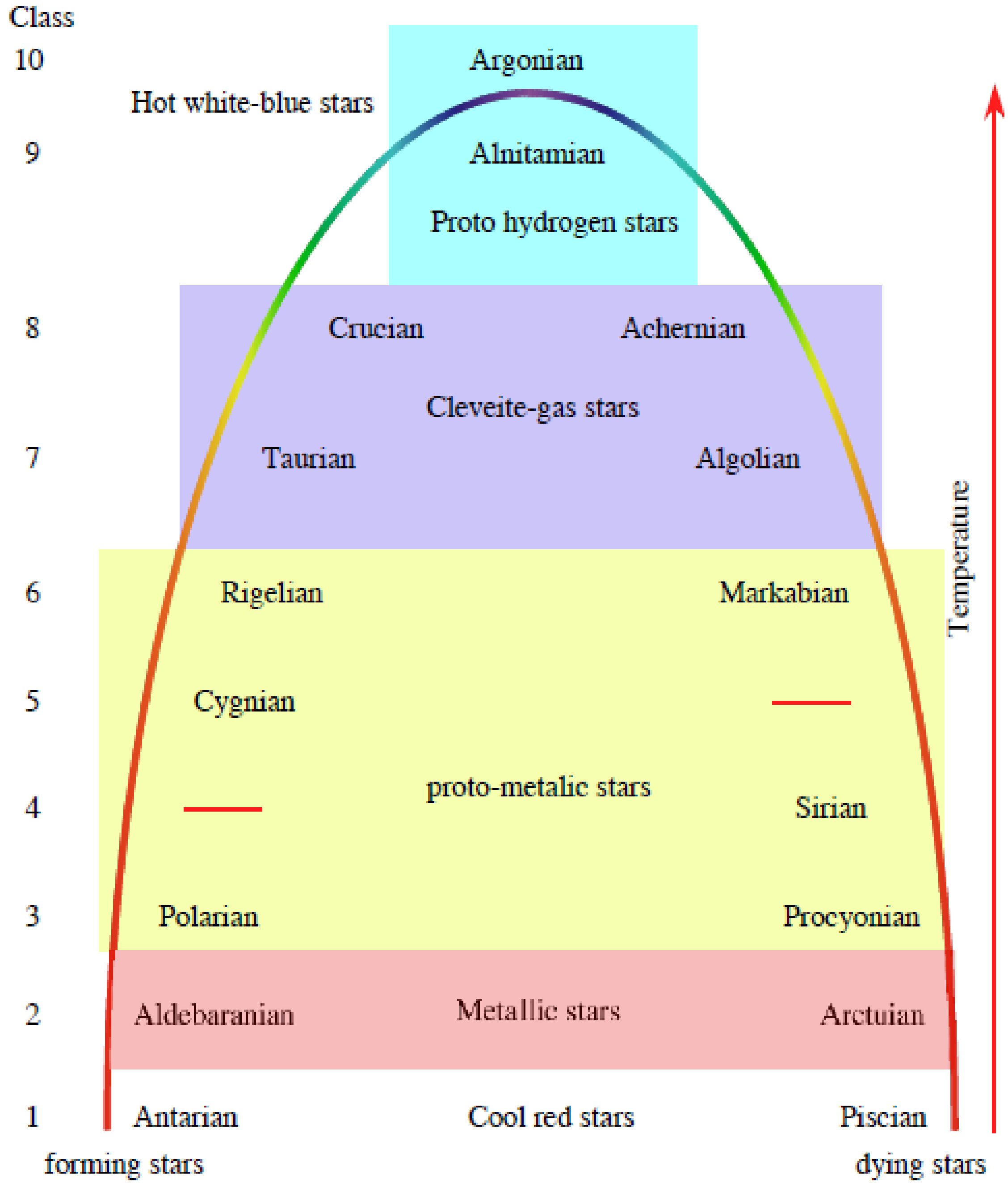




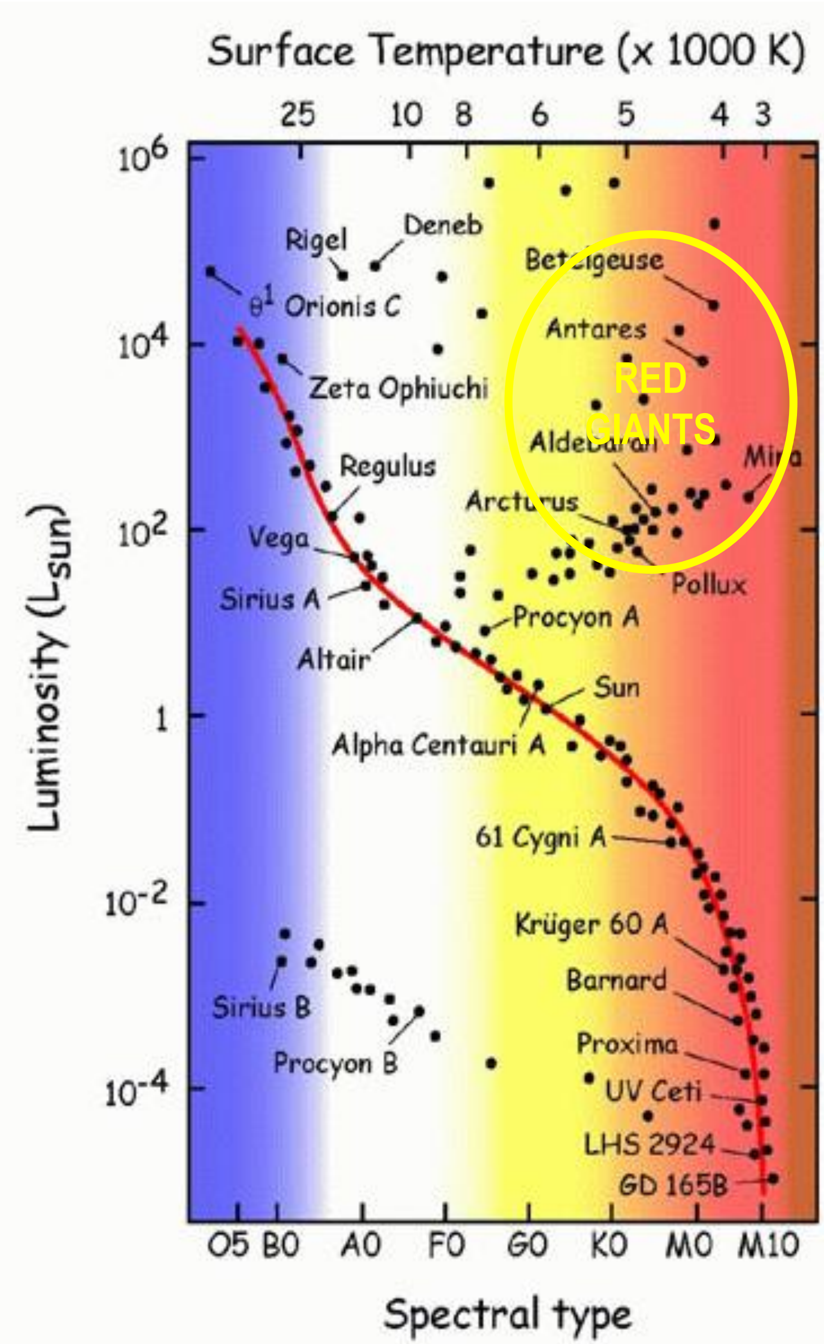
1868 : co-discovery of *Helium* in the Sun during a solar eclipse

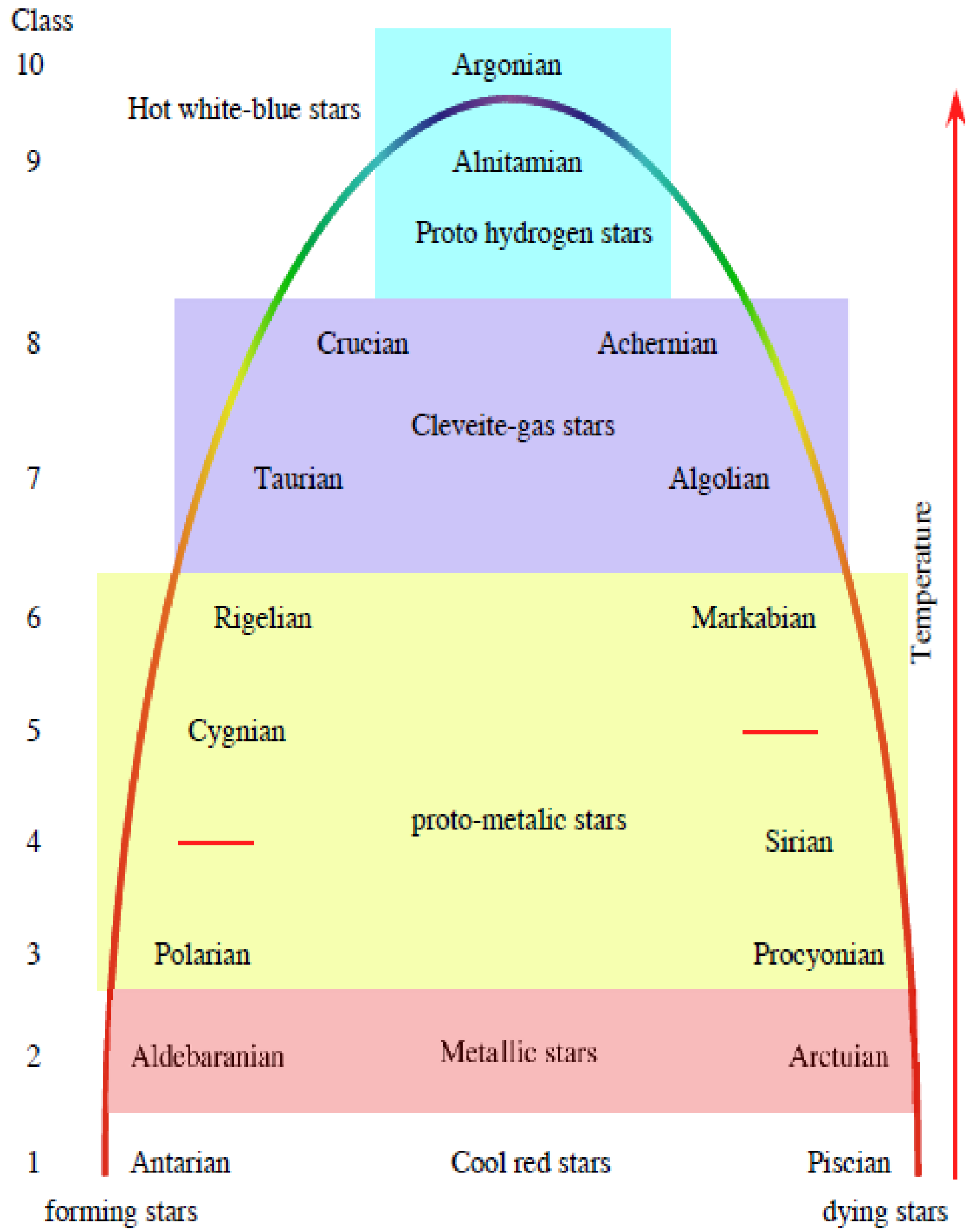
(Ηλιος = Sun)

Lockyer's theory of stellar evolution

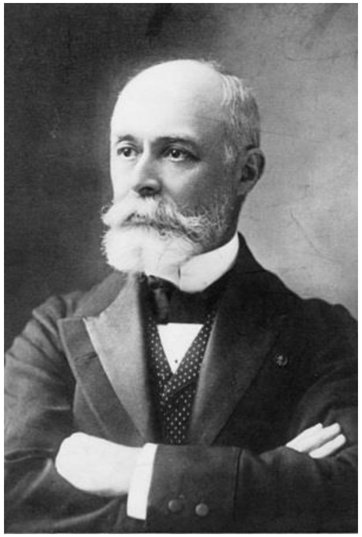


Lockyer's theory of stellar evolution: running OPPOSITE to current





Subatomic physics



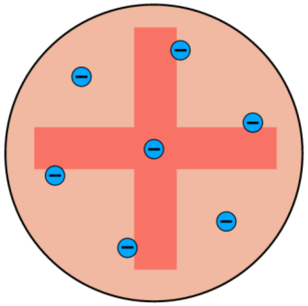
1896 : discovery of *radioactivity* (Uranium) by Henri Bequerel

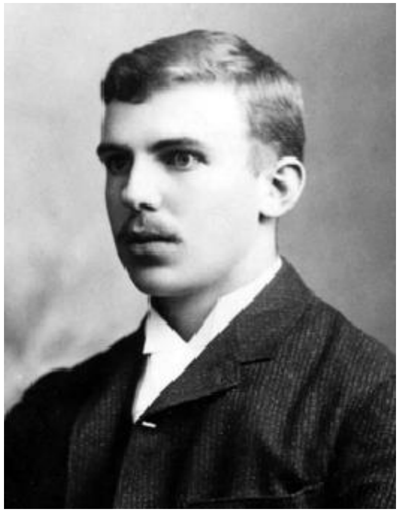
1896-1897 : identification of radioactive polonium and radium by Pierre et Marie Curie

(*Physics Nobel 1903*)

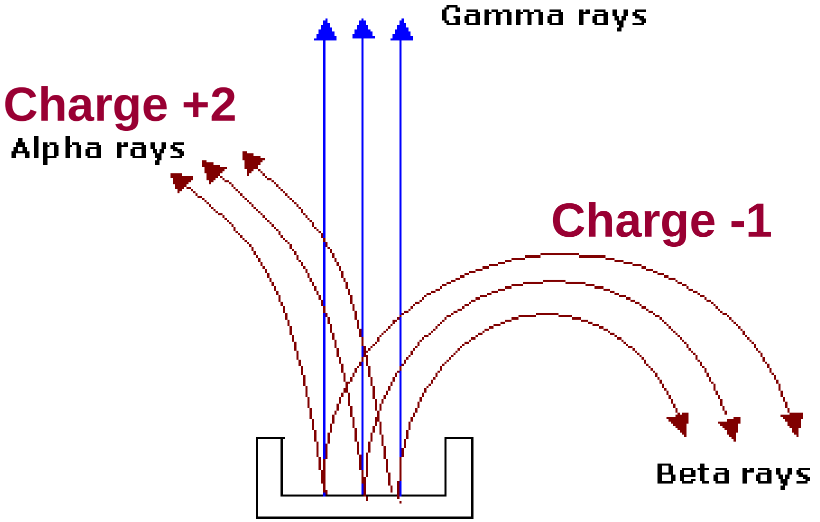
1897 : discovery of the *electron* by Joseph John Thomson (*Physics Nobel 1906*)

1903: Thomson's atom



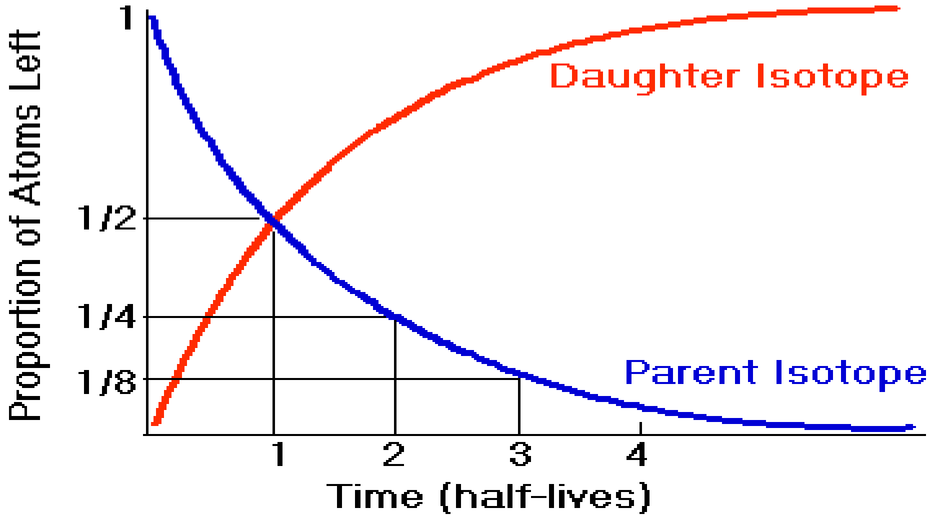


1897 : identification of *alpha, beta, gamma rays* by Ernest Rutherford (*Chemistry Nobel 1908*)



Radioactivity: dating of rocks and energy source

1900: Rutherford's law of radioactive decay $N = N_0 \exp(-t/\tau)$



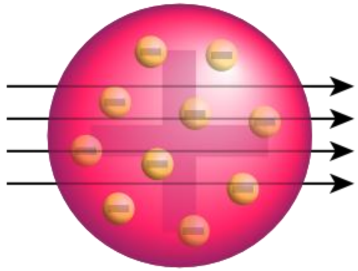
1902: Rutherford shows that alpha radiation is Helium nuclei
suggests to use Uranium/Helium for dating

1904 : Robert Strutt (Baron Rayleigh) ***: Old rocks from 400 My to 2 Gy < Age Earth***

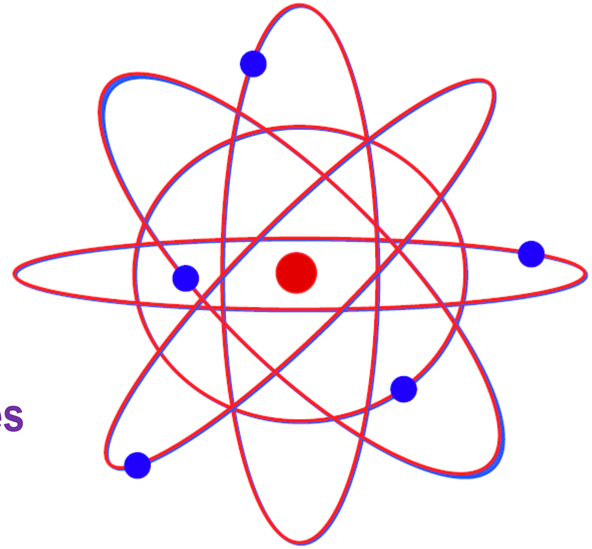
The maintenance of solar energy [. . .] no longer presents any fundamental difficulty if the internal energy of the component elements is considered to be available, i.e., if processes of sub-atomic change are going on. ***Rutherford and Soddy 1903***

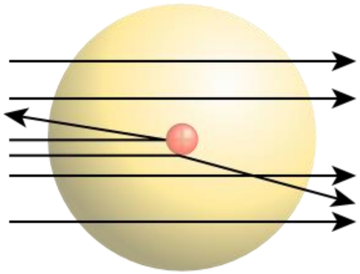
1907 Rutherford : ***Helium in Sun results from radioactivity***
Solar energy also !

The atomic nucleus and the proton



1909: *Geiger-Marsden experiment*
Strong deflection of a minority of α particles bombarding a foil of gold





1911: *Rutherford*
The atom is mostly void : the volume of the positive charge (nucleus) is 1000 trillion times smaller than the volume of the atom
Nuclear radius ~ 10^{-13} cm

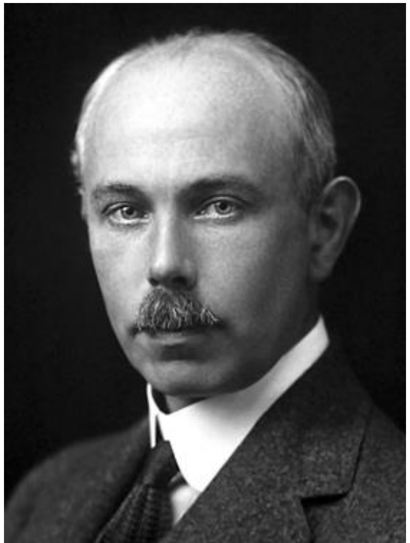
1919: *Rutherford* produces hydrogen nuclei bombarding nitrogen with alpha particles

$$N14 + \alpha \Rightarrow O17 + H$$

1920 : *Rutherford* names the hydrogen nucleus **proton** (charge +1)

1910ies : development of mass spectrograph, identification of isotopes and measurements of their masses *(=multiples of same « elementary » mass)*

by Francis William Aston
(*Chemistry Nobel 1922*)

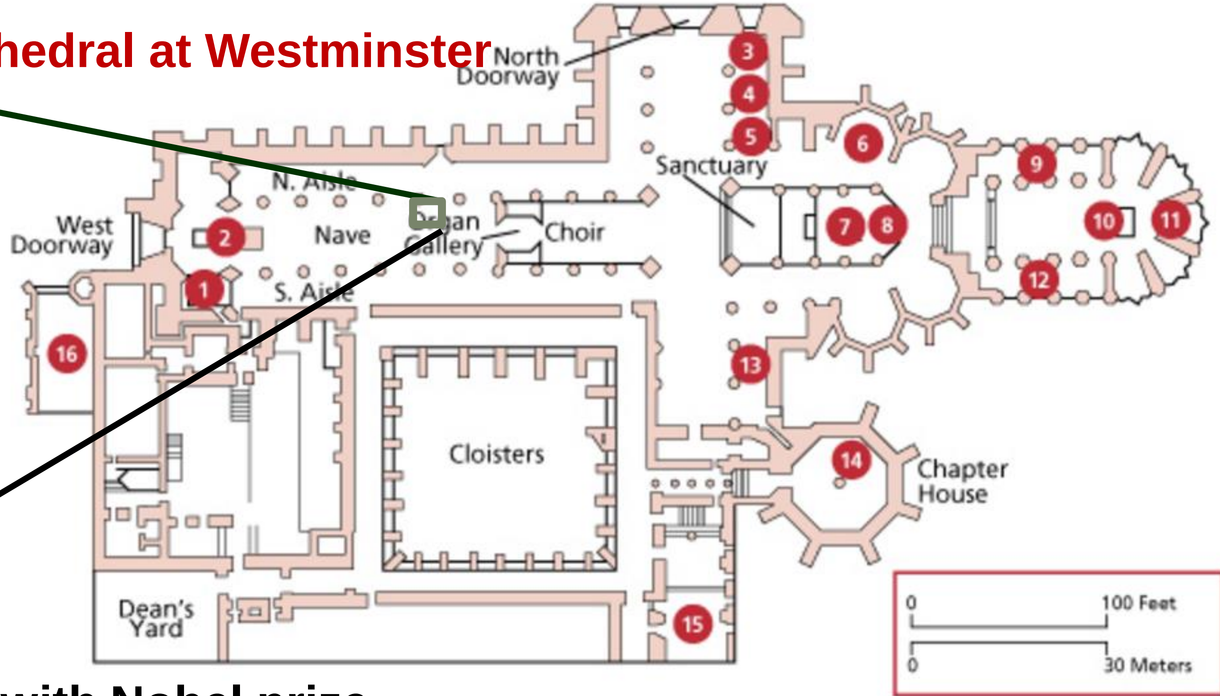


1919: Mass(He4) = (1 – 0.007) x Mass(4 protons)

In the Nave of St Peter's Cathedral at Westminster

GRAVES OF

Charles Darwin
Sir John Herschel
Sir Isaac Newton
Ernest Rutherford
William Thomson (Kelvin)
Joseph John Thomson



Students of J. J. Thompson with Nobel prize

Ernest Rutherford	**Chemistry**	**1908**	**Radioactivity**
Francis William Aston	**Chemistry**	**1922**	**Mass spectrograph,isotopic masses**
William Henry Bragg	**Physics**	**1915**	**Crystal structure**
Charles Glover Barkla	**Physics**	**1917**	**X-ray spectroscopy**
Niels Bohr	**Physics**	**1922**	**Atom model, QM**
Max Born	**Physics**	**1954**	**Wave function QM**
Owen Willans Richardson	**Physics**	**1928**	**Thermionic emission**
Charles T. Rees Wilson	**Physics**	**1927**	**Cloud chamber**
George Paget Thomson	***Physics***	***1937***	***Electron diffraction***

Paul Langevin
J. Robert Oppenheimer

Sun's energy:

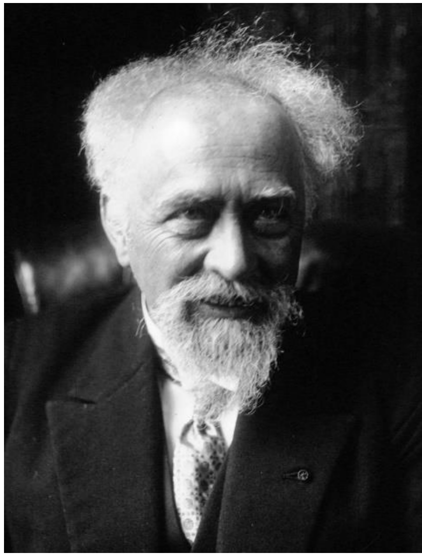
Conversion of H to He

Energy production : $E = \Delta m\, c^2$

First ideas (rather confused):

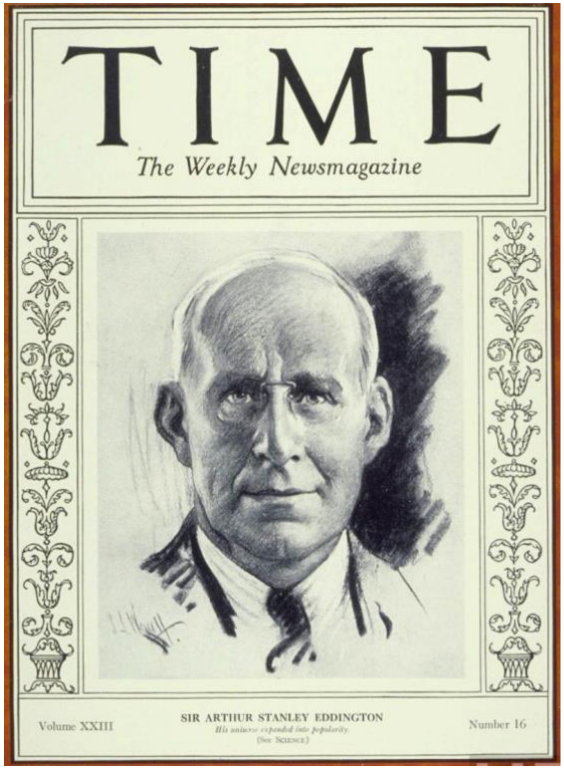
1915: William Draper Harkins

1919: Jean Perrin *(Physics Nobel 1926)*



Sir Arthur Stanley Eddington

and the Internal constitution of the stars (1916 – 1917)



Mean molecular weight - Stellar opacities - Radiative transfer

Role of radiation pressure - Mass-luminosity relation

Eddington limit on stellar luminosity – Cepheid pulsations

Standard model of stellar structure : $T_{CENTRAL}$(Sun)~20 MK

The energy source of the Sun

Eddington's Presidential address to the British Association (24/8/1920)

No one seems to have any hesitations, if it suits him, in carrying back the history of the Earth long before the supposed date of formation of the Solar System […] Lord Kelvin's dates […] are treated with no more respect than Archbishop Ussher's.

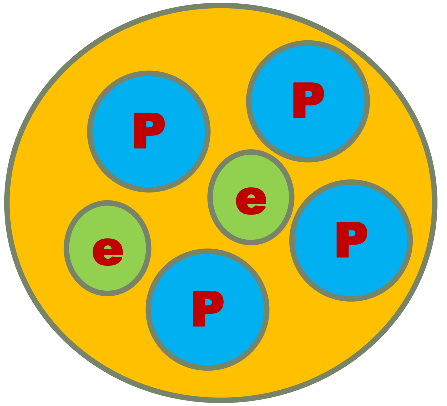
Only the inertia of tradition keeps the contraction hypothesis alive – or rather, not alive, but an unburied corpse. A star is drawing on some vast reservoir of energy by means unknown to us. This reservoir can scarcely be other than the subatomic energy which, it is known, exists abundantly in all matter; we sometimes dream that man will one day learn how to release it and use it for his service.

If only 5% of the mass of the star consists initially of hydrogen, the total heat liberated will more than suffice for our demands. *Is this possible?* pondered Eddington and argued: *If Rutherford could break down the atoms of oxygen in his lab, driving out an isotope of helium, then what is possible in the Cavendish laboratory may not be too difficult in the Sun.*

If indeed the subatomic energy is set free in stars […] it seems to bring a little nearer to fulfillment our dream of controlling this latent power for the well-being of the human race – or for its suicide.

From H to He : an impossible reaction ?

Problem 1: To make an alpha particle
(masse = 4 m_P ; charge = 2 +)

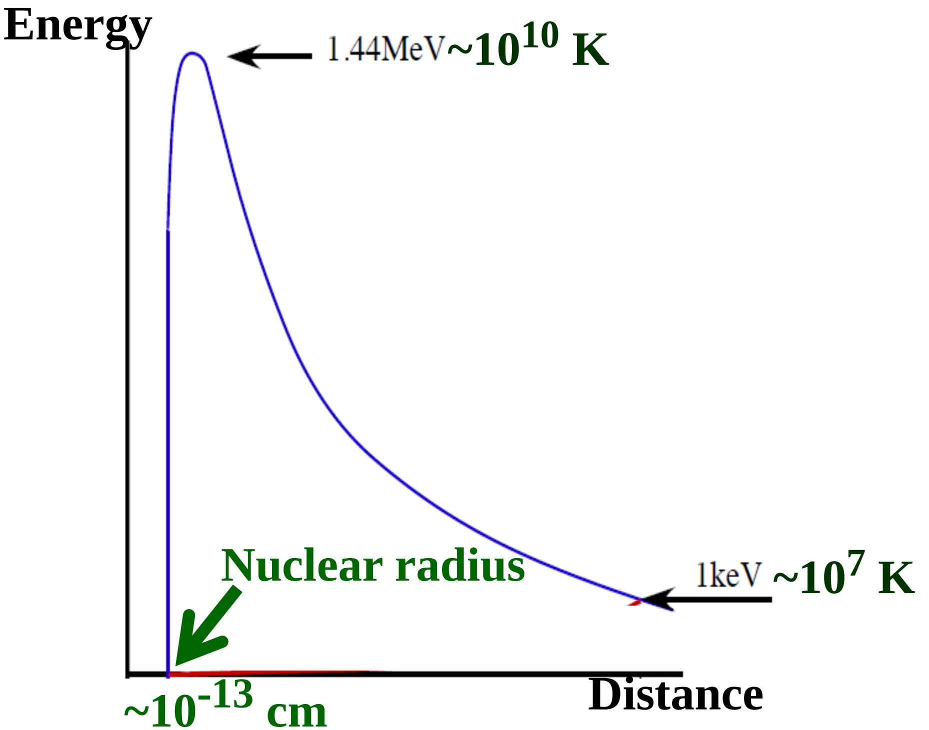


4 protons + 2 electrons should be brought together
HOW ?
(neutron unknown then)

Problem 2: To bring just 2 protons together

enormous temperatures (T> 10^{10} K)
are required, so that particles have
enough kinetic energy E~kT
to overcome their
repulsive Coulomb barrier

whereas Eddington's stellar model suggested
T~10^7 K



We do not argue with the critic who urges that the stars are not hot enough for this process; we tell him *to go and find a hotter place.*
A. S. EDDINGTON, The Internal Constitution of Stars (1926)

1928 : Light in the end of the tunnel !

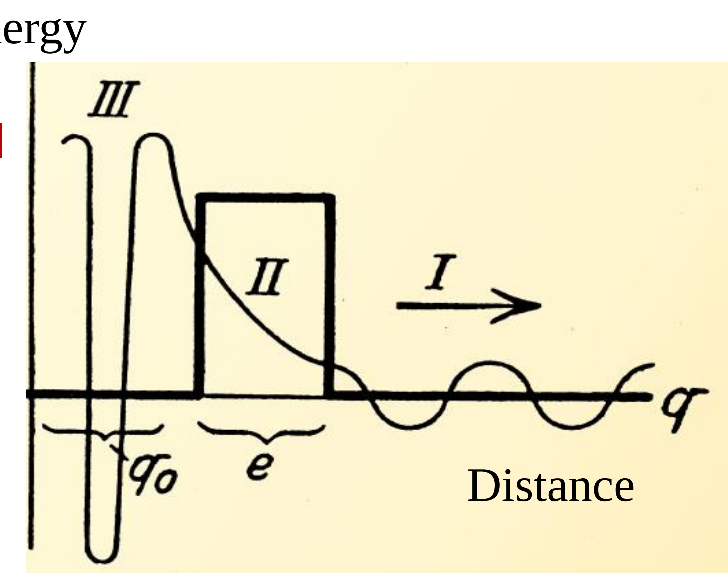
How do the emitted α particles get out of the potential well of radioactive nuclei ?
Why their observed energies are < $E_{COULOMB,\ max}$ of those nuclei ?
($E_{COULOMB,\ max}$ being observed in scattering experiments)

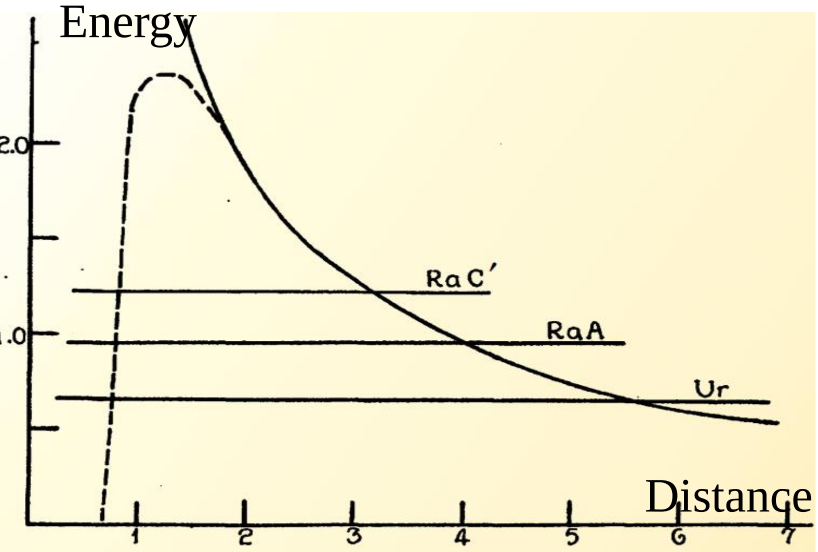
1928 G. Gamow

Probabilistic quantum-mechanical TUNNEL EFFECT

Particles with E < $E_{COULOMB,\ max}$ have a finite probability to escape

$$e^{-\frac{2\pi Z_1 Z_2 e^2}{h\upsilon}}$$ Gamow factor





It also explains quantitatively why nuclei with larger half-lives eject α particles with smaller energies

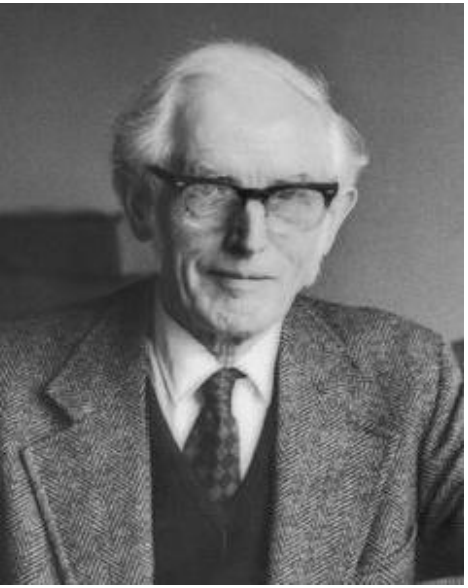
1928-1929
R. Gurney & E. Condon

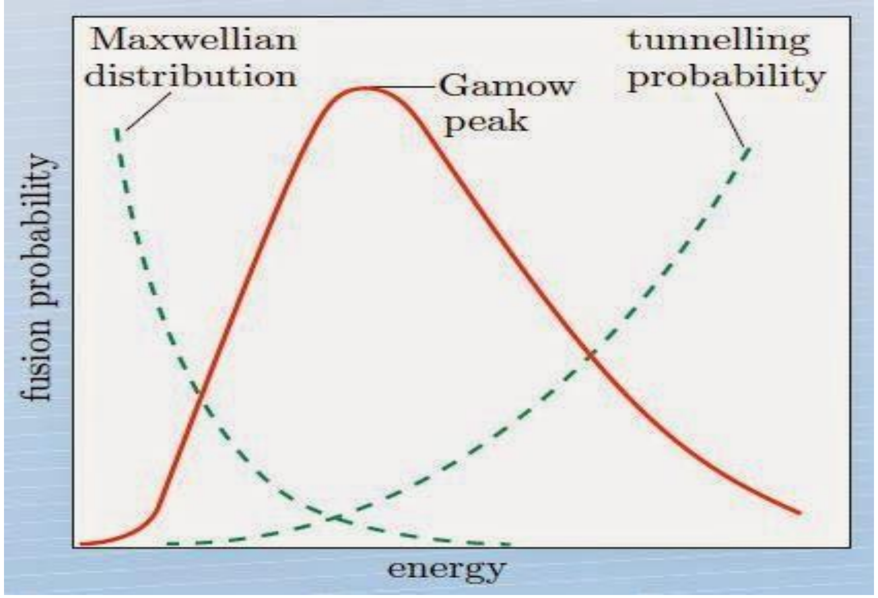
Zur Frage
der Aufbaumöglichkeit der Elemente in Sternen.

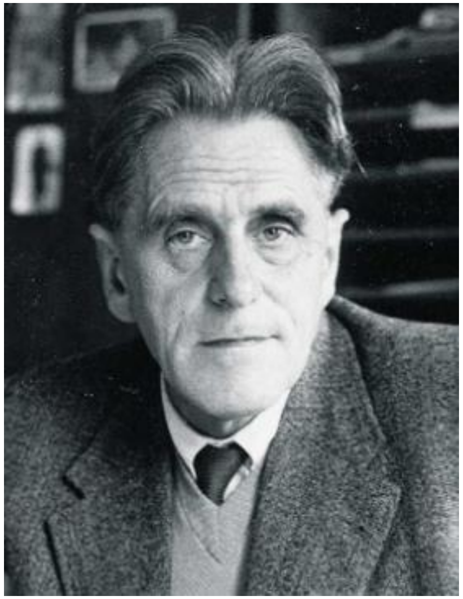
Von **R. d'E. Atkinson** und **F. G. Houtermans** in Berlin-Charlottenburg.

(Eingegangen am 19. März 1929.)

Die quantenmechanische Wahrscheinlichkeit dafür, daß ein Proton in einen Atomkern eindringt, wird nach der Methode von Gamow berechnet. Dabei zeigt sich, daß unter den Temperatur- und Dichteverhältnissen im Innern der Sterne die Ein-







Proton fusion may indeed occur in temperatures at the center of the Sun

thanks to the tunnel effect

But fusion of two protons gives a di-proton which cannot exist !

1931: Discovery of **Deuterium**

(heavy hydrogen with mass ~2 m_P)

Harold Urey (*Chemistry Nobel 1934*)

1932 : Discovery of **neutron**

(mass ~ m_P , charge =0)

James Chadwick *(Physics Nobel 1935)*

1932 : Discovery of **positron**

(mass ~ m_e , charge =1 +)

Carl Anderson *(Physics Nobel 1936)*

1930 : Prediction of the **neutrino**

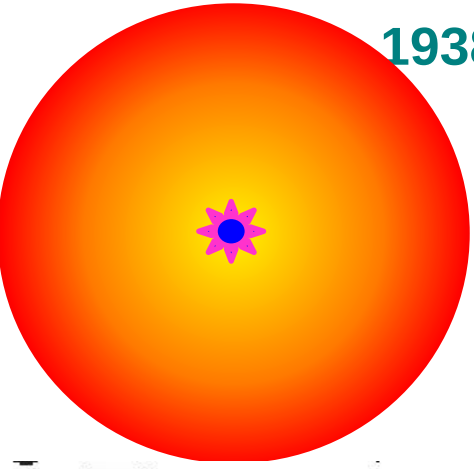
(mass ~ 0 , charge =0)

Wolfgang Pauli *(Physics Nobel 1945)*

1934 : development of the **theory of β decay**

(weak interactions of radioactivity)

Enrico Fermi *(Physics Nobel 1938)*



1938 : Lev Davidovich Landau

(Physics Nobel 1962)

source of stellar energy :
accretion of inner layers
onto a small neutron star
found in the center of stars

Thus we can regard a star as a body which has a neutronic core the steady growth of which liberates the energy which maintains the star at its high temperature ; the condition at the boundary between

As regards the question of how the initial core is formed, I have already shown[2] that the formation of a core must certainly take place in a body with a mass greater than $1{\cdot}5\ \odot$. In stars with smaller mass the conditions which make the formation of the initial core possible have yet to be made clear.

L. LANDAU.

Institute for Physical Problems,
Academy of Sciences,
Moscow

The Problem of Stellar Energy

NATURE MAY 28, 1938

S. CHANDRASEKHAR (Yerkes Observatory).

G. GAMOW (George Washington University).

M. A. TUVE (Carnegie Institution of Washington).

THE problem of stellar energy was the subject of discussion of the Fourth Annual Conference on Theoretical Physics sponsored by the George Washington University and the Carnegie Institution of Washington, and held in Washington, D.C., on March 21–23. The Conference was attended by astrophysicists studying the internal constitution of the stars (S. Chandrasekhar, B. Strömgren, T. Sterne, D. Menzel and others) as well as by physicists working on different branches of nuclear physics (H. Bethe, G. Breit, G. Gamow, J. v. Neumann, E. Teller, M. Tuve, L. Hafstad, N. Heydenburg and others).

As another possibility the reaction ${}^1_1H + {}^1_1H \rightarrow {}^2_1H + \beta^+$ was suggested. It seems that the rate of such a reaction under the conditions in stellar interiors would be just enough to account for the radiation of the sun, though for stars much brighter than the sun other more effective sources of energy are required.

The possibility of an extremely dense neutron core at the centre of the star (as proposed by L. Landau) was also discussed. The study of a number of known stars does not indicate a central condensation of more than what corresponds to 90 per cent of the total mass within half the radius. Thus, so far as astro-

AUGUST 15, 1938 PHYSICAL REVIEW VOLUME 54

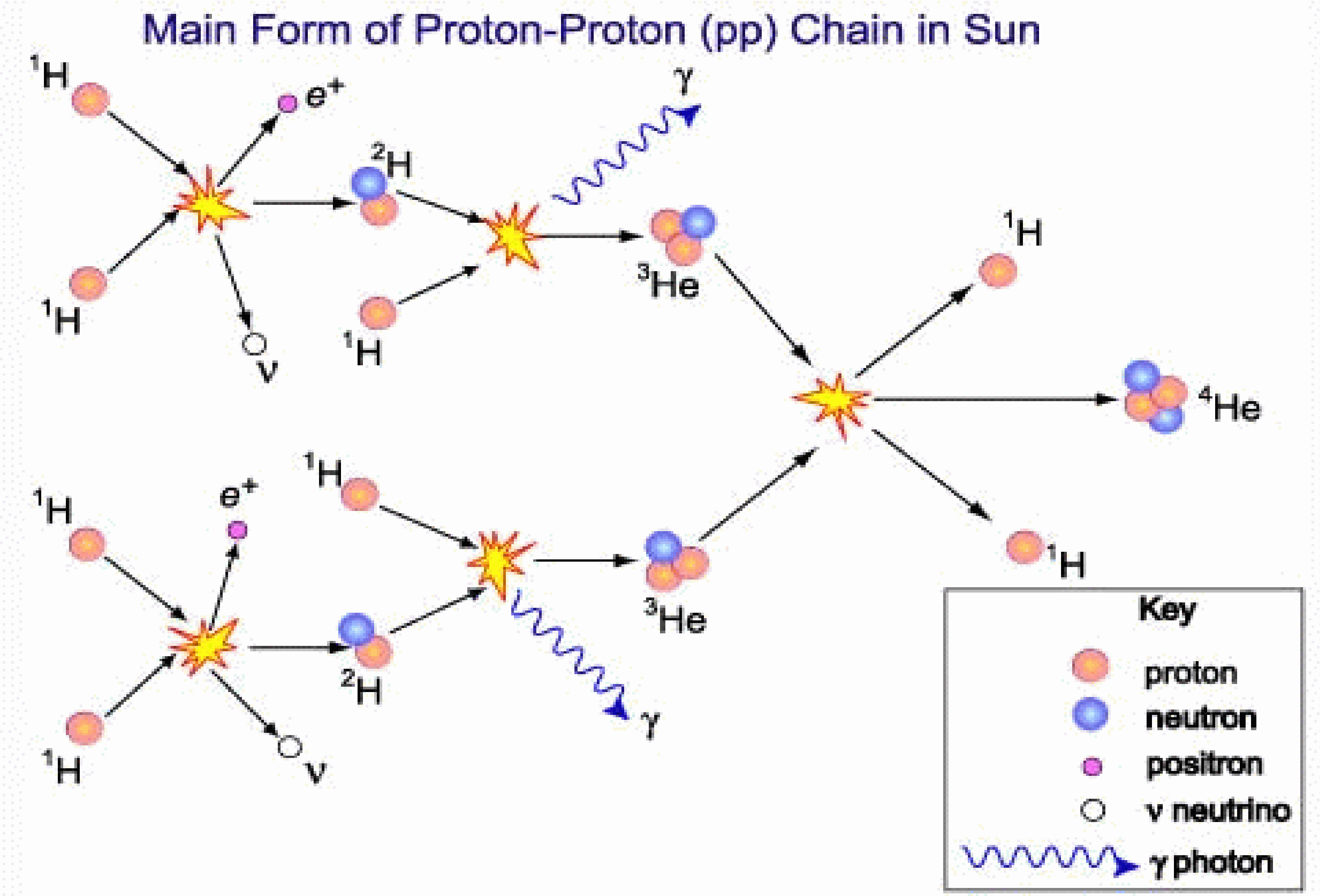
The Formation of Deuterons by Proton Combination

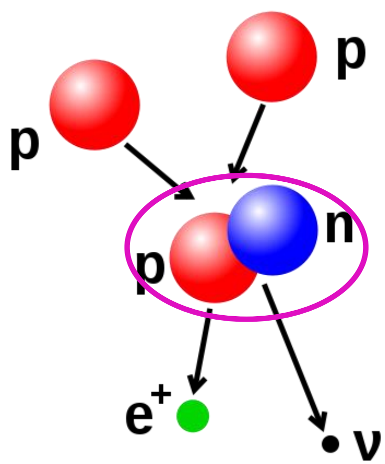
H. A. BETHE, *Cornell University, Ithaca, N. Y.*

AND

C. L. CRITCHFIELD, *George Washington University, Washington, D. C.*

The probability of the astrophysically important reaction $\boxed{H+H=D+\epsilon^+}$ is calculated. For
the probability of p
through their mutua
can be calculated e
evolution due to the r
at the center of the s
degrees). This is alm
tion of the sun (2 er

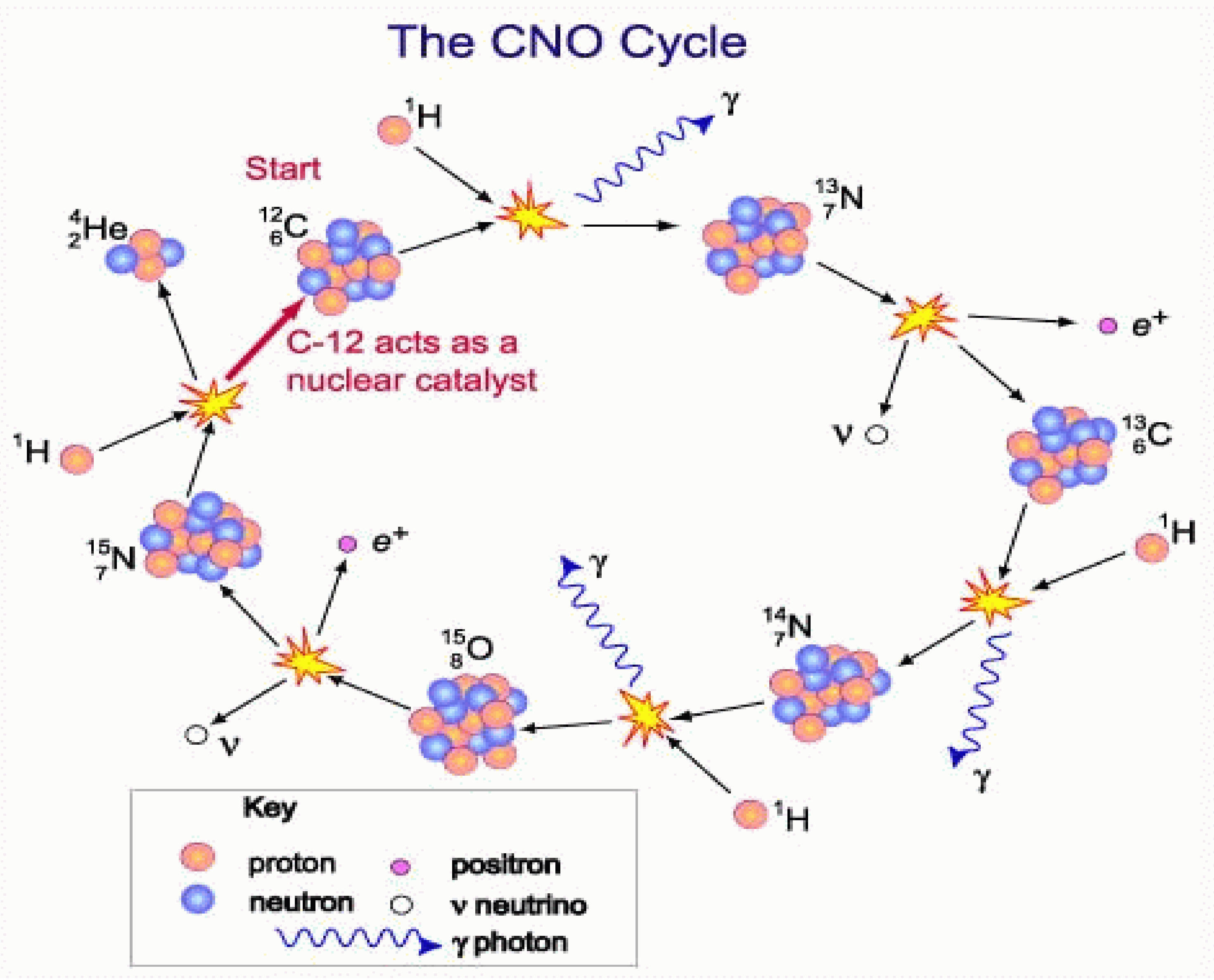


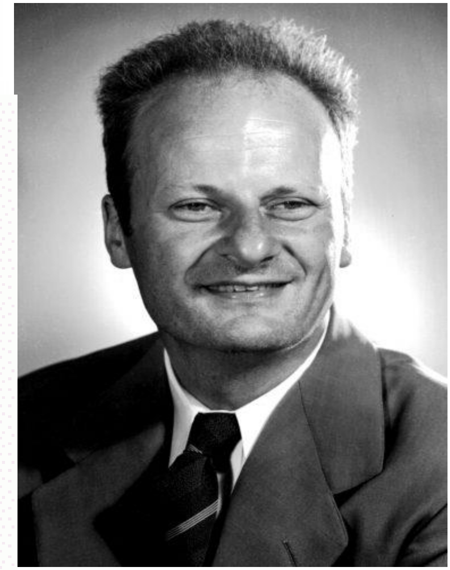


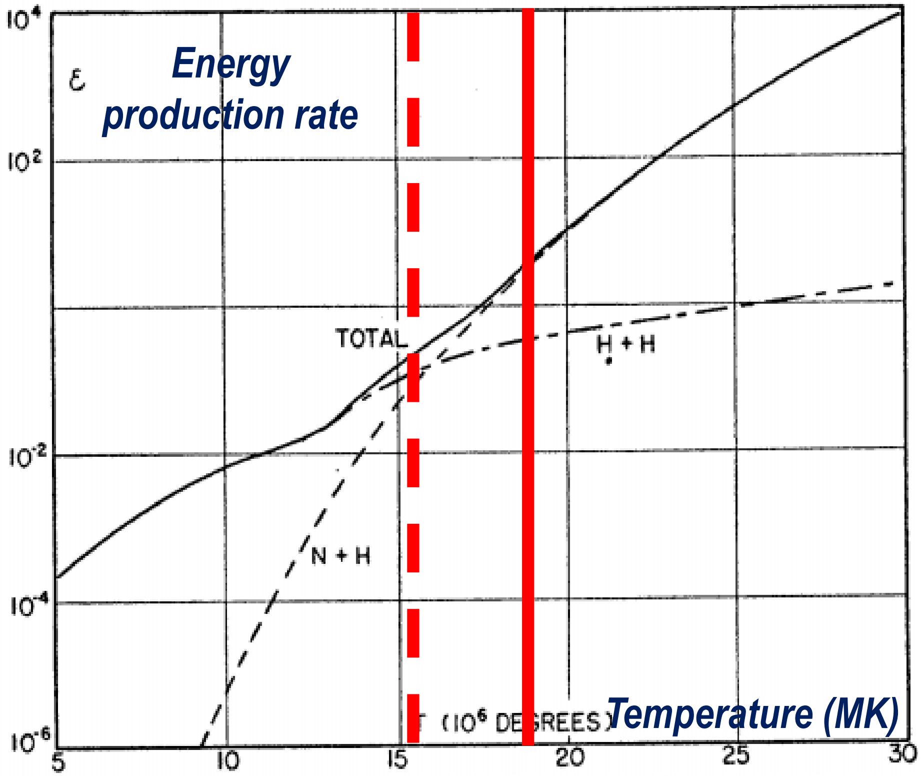
Energy Production in Stars*

MARCH 1, 1939 PHYSICAL REVIEW

H. A. Bethe
Cornell University, Ithaca, New York







The agreement of the carbon-nitrogen reactions with observational data (§7, 9) is excellent. In order to give the correct energy evolution in the sun, the central temperature of the sun would have to be 18.5 million degrees while integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

It is shown further (§5–6) that *no elements heavier than* He^4 *can be built up in ordinary stars*. This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment (α-emission!) rather than built up (by radiative capture). The instability of Be^8 reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

What about elements heavier than He ?

Why does the Sun shine?

Because it is hot
and it is hot because it is massive

Why does the Sun shine *for so long*?

Because its interior is so hot that thermonuclear reactions ignite and produce huge amounts of energy released in long timescales

Hans Albrecht Bethe (1906 - 2005)

Atomic physics and spectroscopy
Interactions of fast particles with matter
Solid state physics
Hydrodynamics, especially shock waves
Nuclear physics (from 'pure' physics to bombs)
Nuclear astrophysics (stellar energy, SN, solar ν)
Gravitational wave sources
Nuclear weapons, the arms race, national security
Energy policy, including fission power

1947 Henry Draper Medal
1959 Franklin Medal
1961 Eddington Medal
1961 Enrico Fermi Award
1963 Rumford Prize
1975 National Medal of Science
1989 Lomonosov Gold Medal
1993 Oersted Medal
2001 Bruce Medal
2005 Benjamin Franklin Medal

First publication: 1924 (aged 18) A. Bethe and Y. Terada
"Experiments Relating to the Theory of Dialysis" Zeitschrift f. Physik. Chemie, **112**, pp. 250-269
Last research publication : 2002 (aged 96) G. C. McLaughlin, R.A.M.J. Wijers, G. E. Brown, H. Bethe
"Broad and Shifted Iron-Group Emission Lines in Gamma-Ray Bursts as Test of the Hypernova Scenario"
Astrophysical Journal, **567**, 454-462

Physics Nobel prize 1967

for his discoveries concerning the energy production in stars

"Professor Bethe, you may have been astonished that among your many contributions to physics, several of which have been proposed for the Nobel Prize, we have chosen one which contains less fundamental physics than many of the others and which has taken only a short part of your long time in science […]. Your solution of the energy source of stars is one of the most important applications of fundamental physics in our days, having led to a deep going evolution of our knowledge of the universe around us." *from the presentation speech of Professor Oskar Klein, member of the Swedish Academy of Sciences*

Head of Theory Division of Manhattan Project (1943-1946)

- calculation of critical mass and efficiency of U-235
- with Richard Feynman : formula for the atomic bomb's explosive yield

President's Science Advisory Committee, 1956-59

Member, US Delegation to Discussions on Discontinuance of Nuclear Weapons Tests, 1958-59

Scientists movement against the projects of anti-ballistic missiles (60ies) and Star wars (80ies)

If there were a computation to make,
with the survival of mankind depending on its outcome,
the only person I would trust for that would be Hans Bethe

After HB showed (1942) that nuclear explosion would not ignite atmospheric N

Bethe: « *The supreme problem solver of the 20th century* » *(Freeman Dyson)*

A BRIEF HISTORY OF NUCLEAR ASTROPHYSICS

PART II
THE ORIGIN OF THE ELEMENTS

The energy source of the Sun

Eddington's Presidential address to the British Association (24/8/1920)

No one seems to have any hesitations, if it suits him, in carrying back the history of the Earth long before the supposed date of formation of the Solar System [...] Lord Kelvin's dates [...] are treated with no more respect than Archbishop Ussher's.

Only the inertia of tradition keeps the contraction hypothesis alive – or rather, not alive, but an unburied corpse. A star is drawing on some vast reservoir of energy by means unknown to us. This reservoir can scarcely be other than the subatomic energy which, it is known, exists abundantly in all matter; we sometimes dream that man will one day learn how to release it and use it for his service.

If only 5% of the mass of the star consists initially of hydrogen, the total heat liberated will more than suffice for our demands. Is this possible? pondered Eddington and argued:

If Rutherford could break down the atoms of oxygen in his lab, driving out an isotope of helium, then what is possible in the Cavendish laboratory may not be too difficult in the Sun.

The energy of the Sun

Luminosity $L_\odot = 4\ 10^{33}$ erg/s
Time $T = 4{,}5$ Gy $= 1.35\ 10^{17}$ s

Energetic demands: Energy = Luminosity x Time = $5\ 10^{50}$ ergs (1)

Efficiency of transformation of mass to energy through $4p \rightarrow He4$: $\varepsilon = 0.007$

Mass $M_\odot = 2\ 10^{33}$ gr

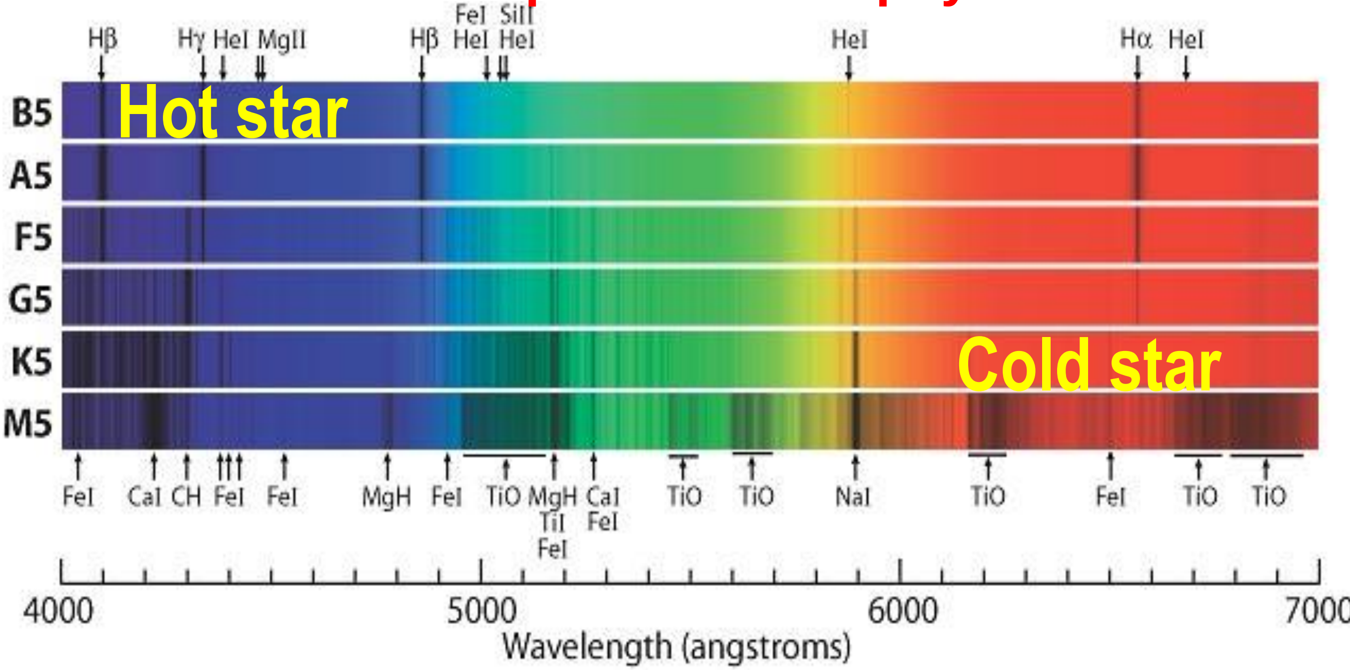
Nuclear energy available : E(nuclear) = $\varepsilon\ f\ M_\odot\ c^2$ (2)

(1) + (2) : Fraction of Sun's mass (<u>in hydrogen</u>) which participated in nuclear reactions in the past **T=4.5 Gy** ***:***

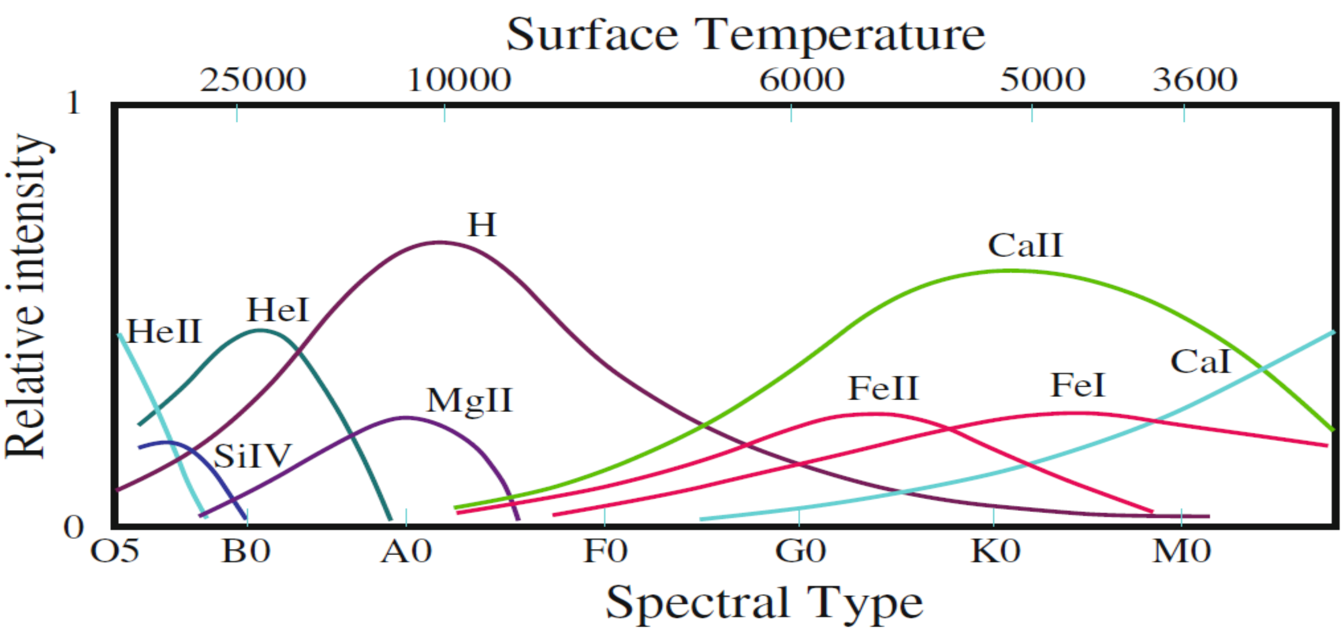
$$f \sim \frac{L_\odot T}{\epsilon M_\odot c^2} \sim 0.05$$

How much hydrogen is there in the Sun ?

Stellar spectroscopy reveals the chemical composition AND physical conditions of stellar surfaces



The intensity of spectral lines depends not only on the abundances of the elements, but also on the temperature and density of the stellar atmosphere



Abundant elements may appear underabundant *(e.g. H in the Sun)*

Models are required to infer true abundances, through the *Saha ionisation equation (1925)*

1925: Cecilia Payne

H and He are the most abundant elements in stellar atmospheres

Table 3.2 The first table of relative abundances in stellar atmospheres

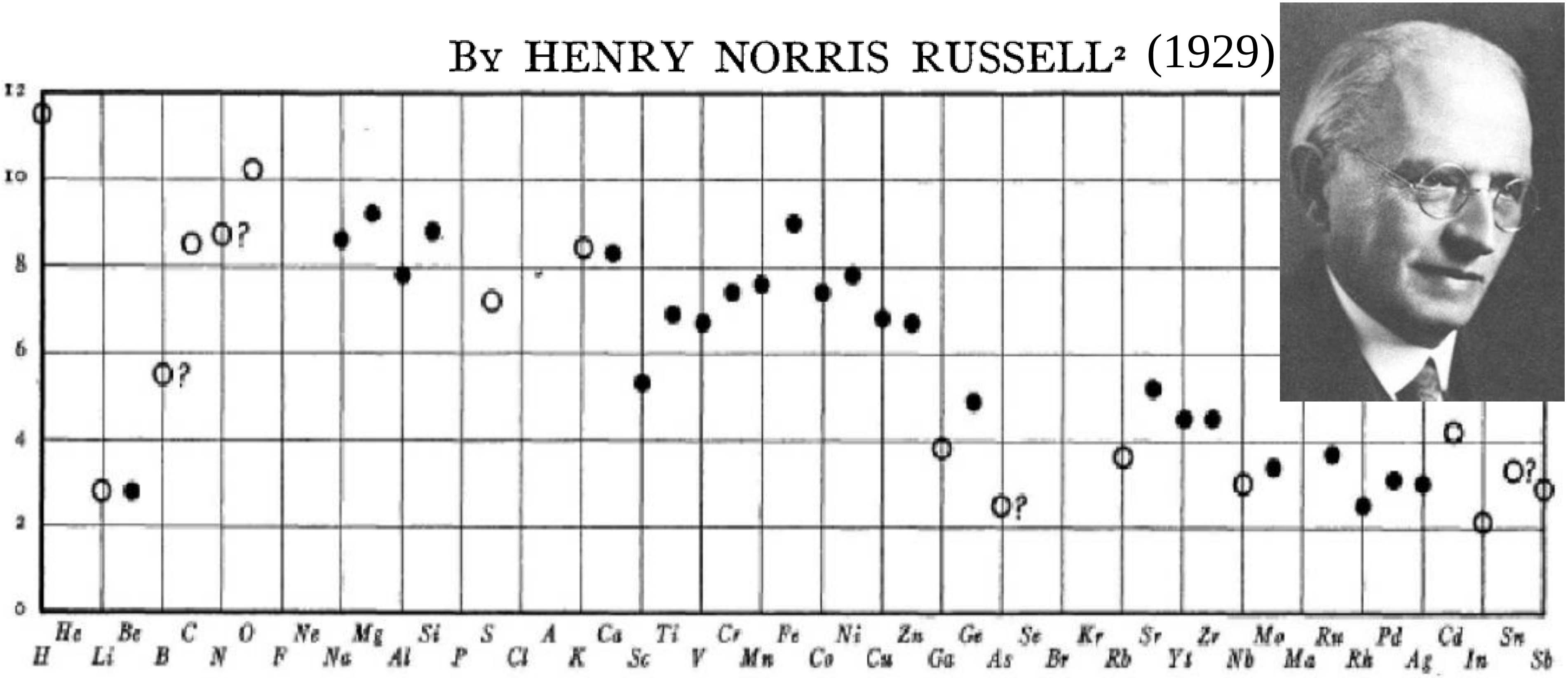
Z	Atom	[A]	Z	Atom	
1	H	11	19	K	
2	He	8.3	20	Ca	
2	He^+	12	20	Ca^+	
3	Li	0.0	22	Ti	
6	C^+	4.5	23	V	
11	Na	5.2	24	Cr	
12	Mg	5.6	25	Mn	4.6
12	Mg^+	5.5	26	Fe	4.8
13	Al	5.0	30	Zn	4.2
14	Si	4.8	38	Sr	1.8
14	Si^+	4.9	38	Sr^+	1.5
14	Si^{+++}	6.0	54	Ba^+	1.1

Payne's Ph.D. thesis, 1925. H and He were omitted from the PNAS publication. The notation is $[A] \equiv \mathrm{Log}A$. All abundances are relative to hydrogen, which is 10^{11}

The outstanding discrepancies between the astrophysical and terrestrial abundances are displayed for hydrogen and helium. The enormous abundance derived for these elements in the stellar atmosphere is almost certainly not real. Probably the result may be considered, for hydrogen, as another aspect of its abnormal behavior, already alluded to; and helium, which has some features of astrophysical behavior in common with hydrogen, possibly deviates for similar reasons. […] The observations on abundances refer merely to the stellar

ON THE COMPOSITION OF THE SUN'S ATMOSPHERE

By HENRY NORRIS RUSSELL[2] (1929)



solar atmosphere contains 60 parts of hydrogen (by volume), 2 of helium, 2 of oxygen, 1 of metallic vapors, and 0.8 of free electrons, practically all of which come from ionization of the metals. This great abundance of hydrogen helps to explain a number of previously puzzling astrophysical facts. The temperature of the reversing layer is finally estimated weight is 32 and their total mass 42 mg/cm². The well-known difference between elements of *even* and *odd* atomic number is conspicuous—the former averaging *ten times as abundant* as the latter. The *heavy metals*, from *Ba* onward, are but little less abundant

Harkins rule (1915) **: elements with specific properties are more abundant than other (e.g. even vs odd charge or mass number)**

ATOMIC SYNTHESIS AND STELLAR ENERGY. II

ROBERT D'ESCOURT ATKINSON
(1931)

ABSTRACT

A *synthesis theory of stellar energy and of the origin of the elements* is developed, in which the various chemical elements are built up step by step from lighter ones in stellar interiors, by the successive incorporation of protons and electrons one at a time. The essential feature is that *helium*, which cannot well be formed in this way, is supposed to be *produced entirely indirectly*, by the spontaneous *disintegration* of unstable nuclei which must first themselves be formed.

Russell has recently shown that the percentage of hydrogen in stars is probably very much greater even at the present time than had generally been supposed; in the sun's atmosphere, for example, sixty out of every sixty-five atoms are hydrogen. Since in addition the hydrogen nucleus is probably much simpler than any other, it seems very reasonable to assume that in its initial state any star, or indeed the entire universe, was composed solely of hydrogen; the

Atkinson (1931) : Formation of all elements from successive captures of protons and electrons, inside the stars themselves *except Helium, produced from radioactivity (!)*

from hydrogen to any other element is the formation of helium according to the reaction $4H^{+}+2e=He^{++}+h\nu$, and this is almost certainly so improbable a process, and depends in any case so extremely on the density, that we cannot regard it as playing an important part in supplying stellar energy at all. For the same reasons a direct synthesis of any other element is even more objectionable.

If, however, helium can be supplied otherwise, progressive synthesis from this element onward is much less difficult to imagine.

Roughly speaking, for every proton which enters and remains within a nucleus, energy corresponding to .007 units of atomic weight will be liberated. This number varies a little according as the mass

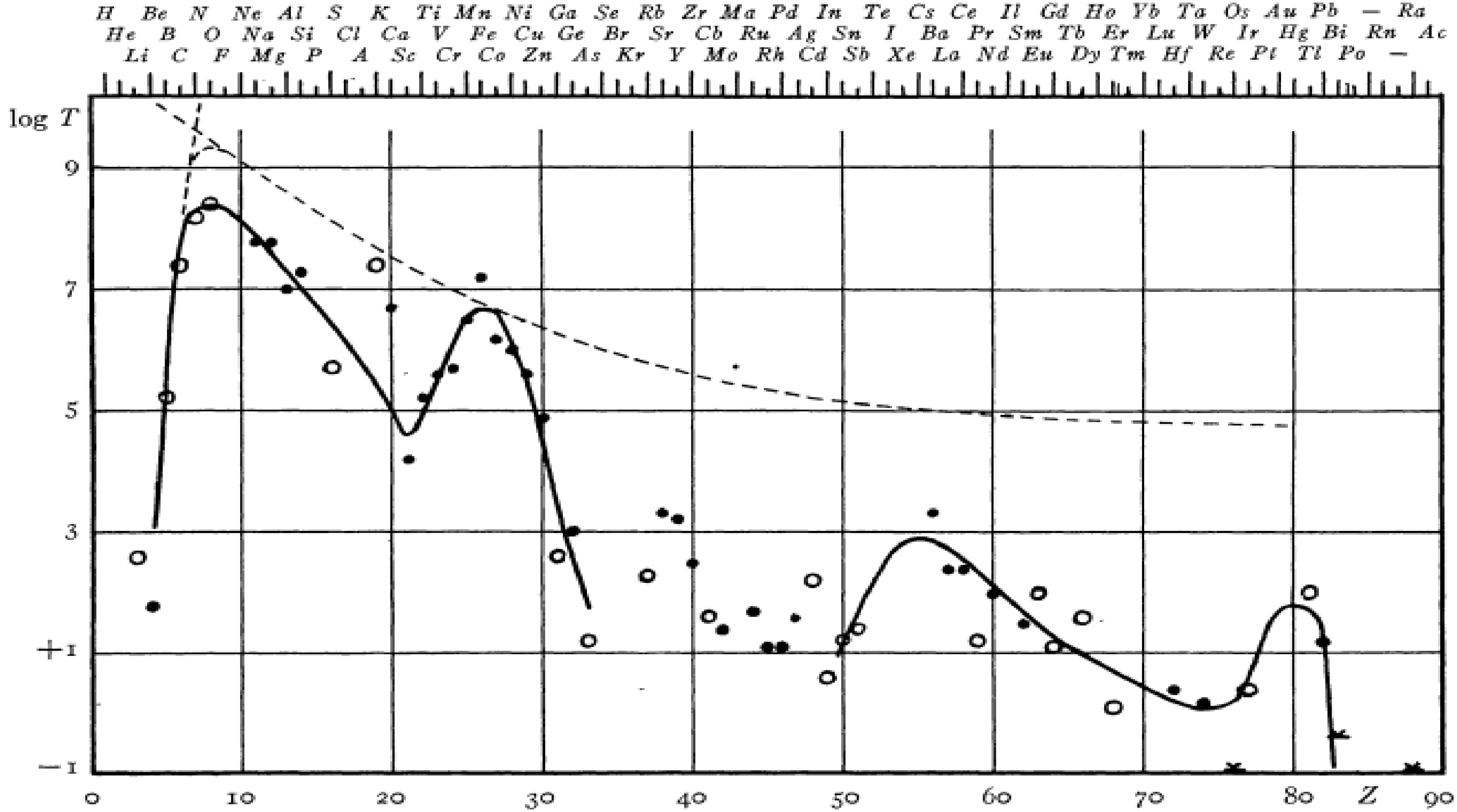
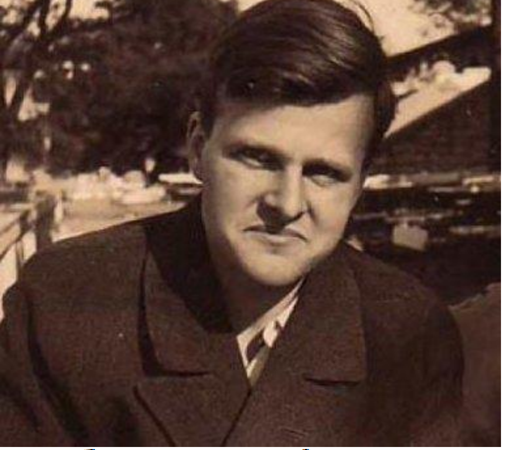


FIG. 2.—Amount of the elements in the sun's atmosphere. (After Russell; ordinates at odd Z values increased by 0.6.) ---- Equilibrium amounts; • First class determinations; ○ Second class determinations.

The *relative proportions of the elements* in stars of the main sequence follow from the theory, in *excellent qualitative agreement* with Russell's figures for the sun. The scarcity of the lightest elements, the principal maximum at a fairly early point, a minimum before the iron group, a maximum in it, a scarcity of all elements above it, and minor maxima in the barium and lead regions all follow (Fig. 2) without any special assumptions, from Gamow's theory of nuclear stability, owing to the peculiarities of the Aston mass-defect curve.



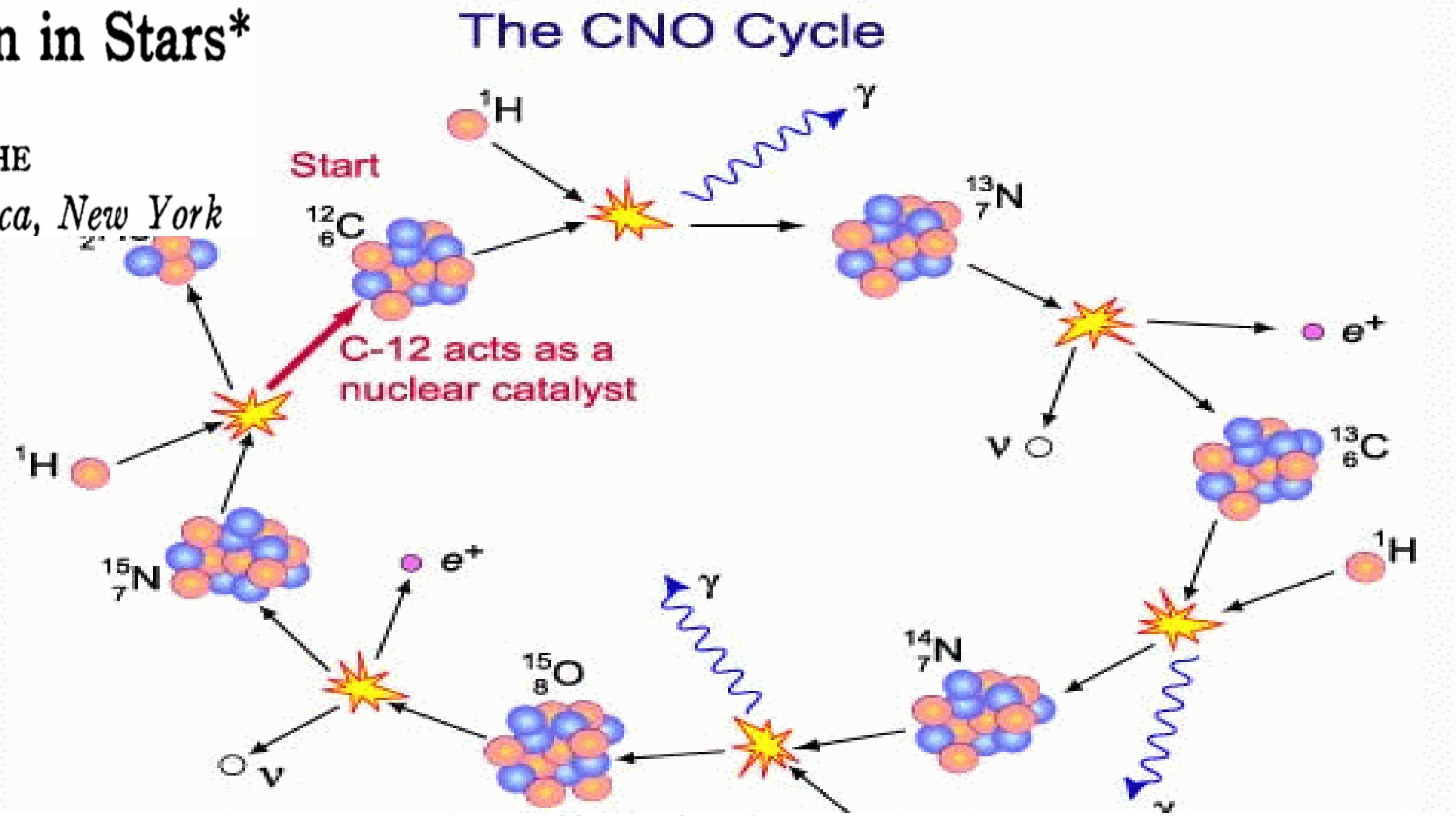
On Elementary Transmutations in the Interior of Stars: Paper II (1937)

Carl Friedrich von Weizsäcker
(1912 - 2007)

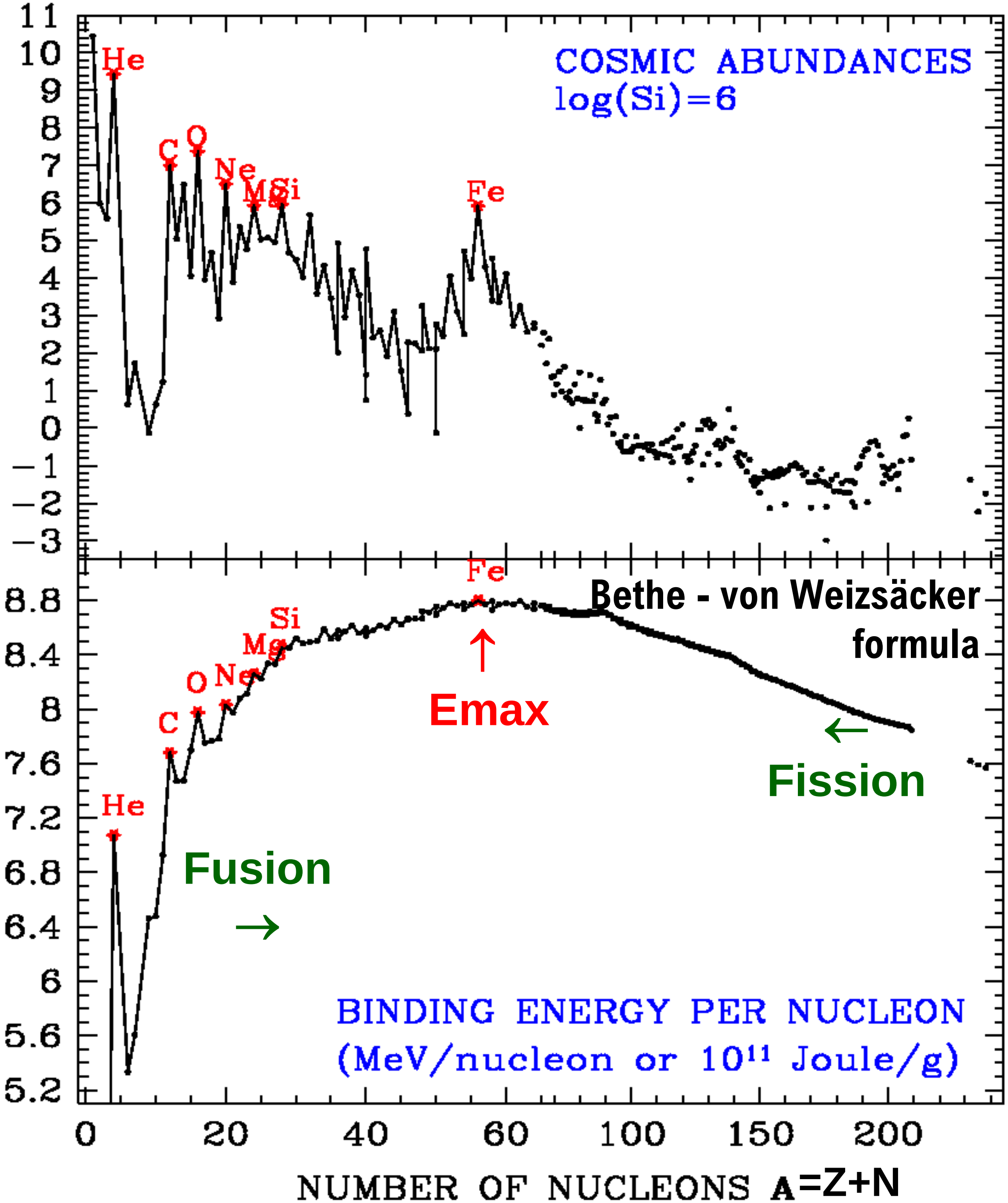
nuclear reactions exert two different influences at the same time: They change the physical state of the matter by releasing energy and its chemical composition by transmuting the elements. The generation of energy is the unproblematic part of the theory to consider: Nuclear reactions or effects of similar energy yield are necessary to explain stellar radiation; and the build-up hypothesis is equivalent to the assumption that the nuclear processes sufficed for that on their own as well. Transmutation of the elements, however, is to a certain extent a side-effect of the nuclear reactions, yet nothing is known about its importance in the history of stellar lifetimes. The empirical frequency distribution of the chemical elements exhibits characteristic regularities apparently quite uniformly valid throughout the entire cosmos, which compel us to attempt to explain it by assuming a uniform formation process. It would suggest itself to look for this process in the element transmutations necessarily connected with the generation of energy in the stars. Yet we cannot exclude at the outset the possibility that the chemical elements were formed by another process prior to the formation of the stars as we know them

Energy Production in Stars*

H. A. BETHE
Cornell University, Ithaca, New York



It is shown further (§5–6) that *no elements heavier than* He^4 *can be built up in ordinary stars*. This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment (α-emission!) rather than built up (by radiative capture). The instability of Be^8 reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.



Cosmic abundances of nuclides are locally correlated with nuclear stability (*Binding energy per nucleon):*

alpha-nuclei (A=multiple of 4), "magic" nuclei, Fe peak nuclei or nuclei with even A or Z are more abundant than their neighbors

Nuclear processes have shaped the cosmic abundances of the chemical elements

WHERE ? HOW ?

AN ATTEMPT TO INTERPRET THE RELATIVE ABUNDANCES OF THE ELEMENTS AND THEIR ISOTOPES

S. CHANDRASEKHAR AND LOUIS R. HENRICH 1942

1. *Introduction.*—It is now generally agreed that the chemical elements cannot be synthesized under conditions now believed to exist in stellar interiors. Consequently, the question of the origin of the elements is left open. On the other hand, the striking regularities which the relative abundances of the elements and their isotopes reveal (e.g., Harkins' rule) require some explanation. It has therefore been suggested that the elements were formed at an earlier, *prestellar*, stage of the universe.

discussion of this problem by von Weizsäcker[1] has indicated that we should distinguish at least two distinct epochs in the prestellar state: an initial epoch of extreme density and temperature, when the heaviest elements, like gold and lead, were formed; and a later epoch of relatively "moderate" conditions, during which the present relative abundances of the lighter elements beyond oxygen (to at least sulphur, as we shall see in

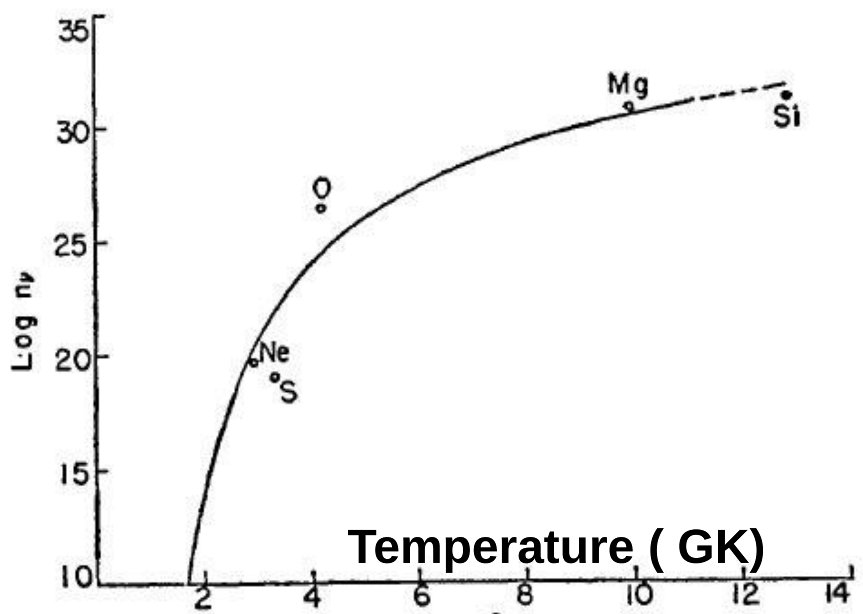
Starting at temperature T~10 GK ($10\ 10^9$ K)
and density ρ~10^8 g/cc
built nuclei around Si

In conditions of nuclear equilibrium

$$A + B \Leftrightarrow C + D$$

then at lower T and ρ
built lighter nuclei

But Fe and heavier nuclei NEVER produced



Expanding Universe and the Origin of Elements

G. Gamow
The George Washington University, Washington, D. C.
September 13, 1946

It is generally agreed at present that the relative abundances of various chemical elements were determined by physical conditions existing in the universe during the early stages of its expansion, when the temperature and density were sufficiently high to secure appreciable reaction-rates for the light as well as for the heavy nuclei.

Returning to our problem of the formation of elements, we see that *the conditions necessary for rapid nuclear reactions were existing only for a very short time*, so that it may be quite dangerous to speak about an equilibrium-state which must have been established during this period. It is also interesting to notice that the calculated time-period during which rapid nuclear transformations could have taken place is considerably shorter than the β-decay period of free neutrons which is presumably of the order of magnitude of one hour. Thus if free neutrons were present in large quantities in the beginning of the expan-

NOT nuclear equilibrium
but

time-dependent
treatment of
nuclear reactions
is necessary

and there is little time
available
(less than
the time for
neutron decay ~1 h)

The Origin of Chemical Elements

R. A. ALPHER*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland

AND

H. BETHE
Cornell University, Ithaca, New York

AND

G. GAMOW
The George Washington University, Washington, D. C.

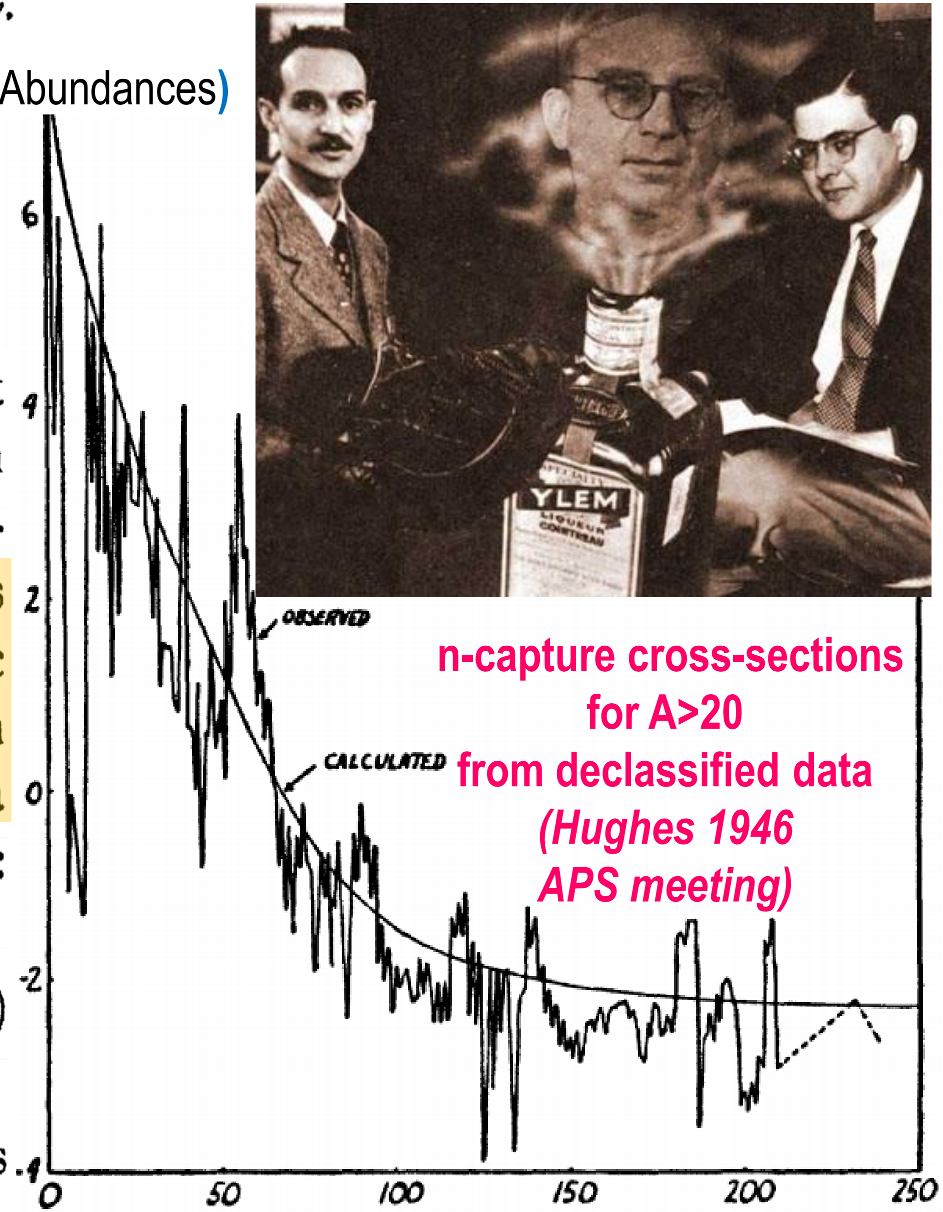
February 18, 1948

αβγ **Published 1 April 1948**

Thus the observed slope of the abundance curve must not be related to the temperature of the original neutron gas, but rather to the time period permitted by the expansion process. Also, the individual abundances of various nuclear species must depend not so much on their intrinsic stabilities (mass defects) as on the values of their neutron capture cross sections. The equations governing such a building-up process apparently can be written in the form:

$$\frac{dn_i}{dt} = f(t)(\sigma_{i-1}n_{i-1} - \sigma_i n_i) \quad i = 1,2,\cdots 238, \qquad (1)$$

where n_i and σ_i are the relative numbers and capture cross sections for the nuclei of atomic weight i, and where $f(t)$ is a factor characterizing the decrease of the density with time.



The Washington Post, 16 April 1948

"World Began in 5 Minutes, New Theory"

At the very beginning of everything, the universe had infinite density concentrated in a single zero point. Then just 300 seconds – five minutes – after the start of everything, there was a rapid expansion and cooling of the primordial matter. The neutrons – those are the particles that trigger the atomic bomb – started decaying into protons and building up the heavier chemical elements. … This act of creation of the chemical elements took the surprisingly short time of an hour. (The Bible story said something about six days for the act of creation)

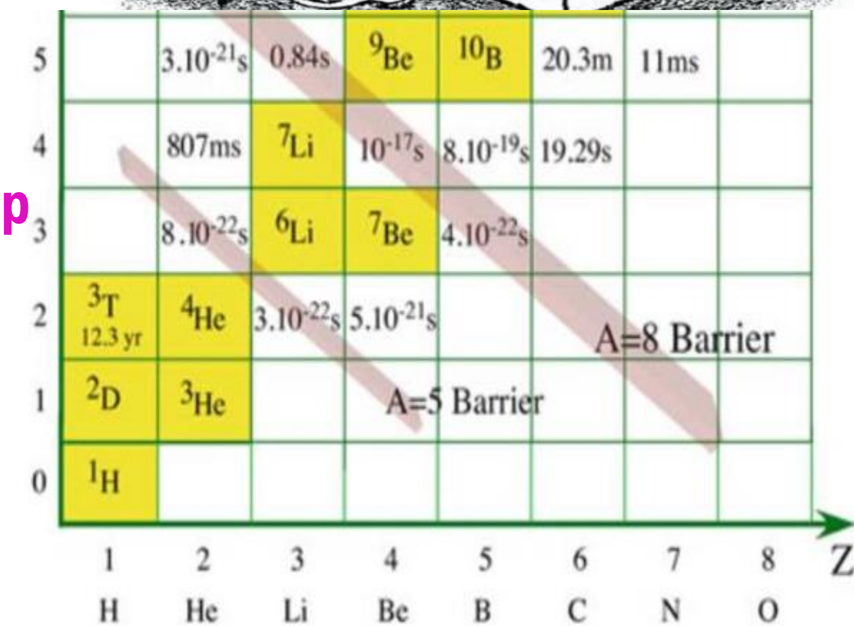
"Five Minutes, Eh?"

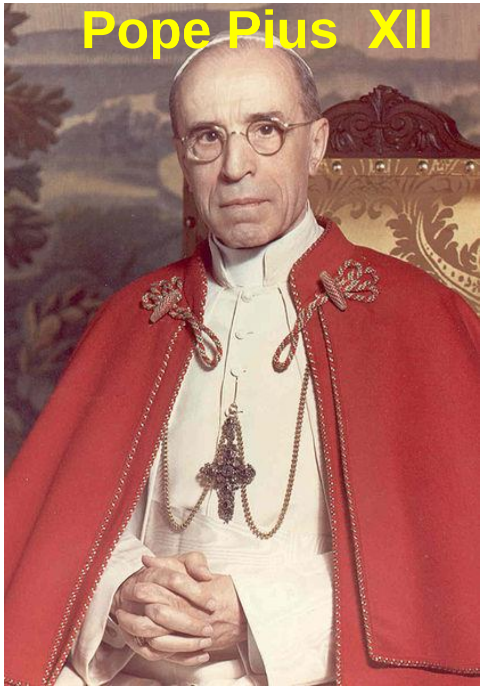
Fermi and Turkevich (1949, unpublished)

No elements beyond He, because of A=5 gap

Hayashi (1950)

At T~10^{10} K : n $\Leftrightarrow$ p equilibrium



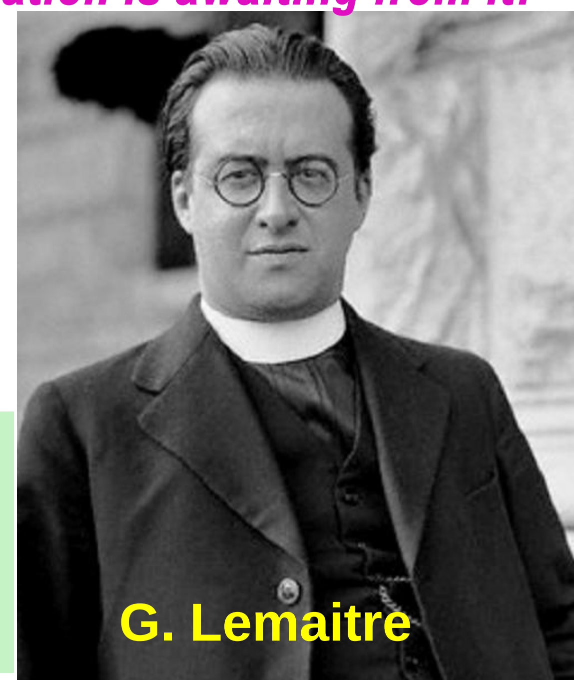


Address to Pontifical Academy of Sciences FIAT LUX (1951)

Present-day science, with one sweeping step back across millions of centuries, has succeeded in bearing witness to that primordial *"Fiat lux"* uttered at the moment when, along with matter, there burst forth from nothing a sea of light and radiation, while the particles of chemical elements split and formed into millions of galaxies…

Hence, creation took place in time. Therefore, there is a Creator. Therefore, God exists! Although it is neither explicit nor complete, this is the reply we were awaiting from science, and which the present human generation is awaiting from it.

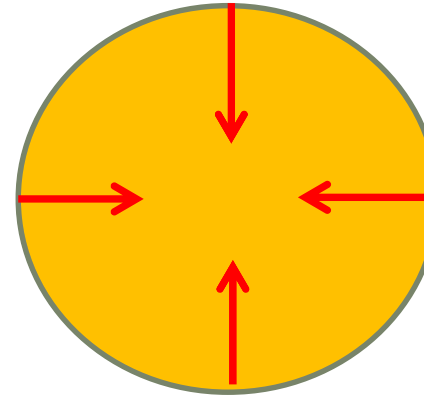
We may speak of this event as of a beginning. I do not say a creation. Physically it is a beginning in the sense that if something happened before, it has no observable influence on the behavior of our universe, as any feature of matter before this beginning has been completely lost by the extreme contraction at the theoretical zero. The question if it was really a beginning or rather a creation, something started from nothing, is a philosophical question which cannot be settled by physical or astronomical considerations



THE SYNTHESIS OF THE ELEMENTS FROM HYDROGEN

F. Hoyle

(Received 1946 April 6 †)



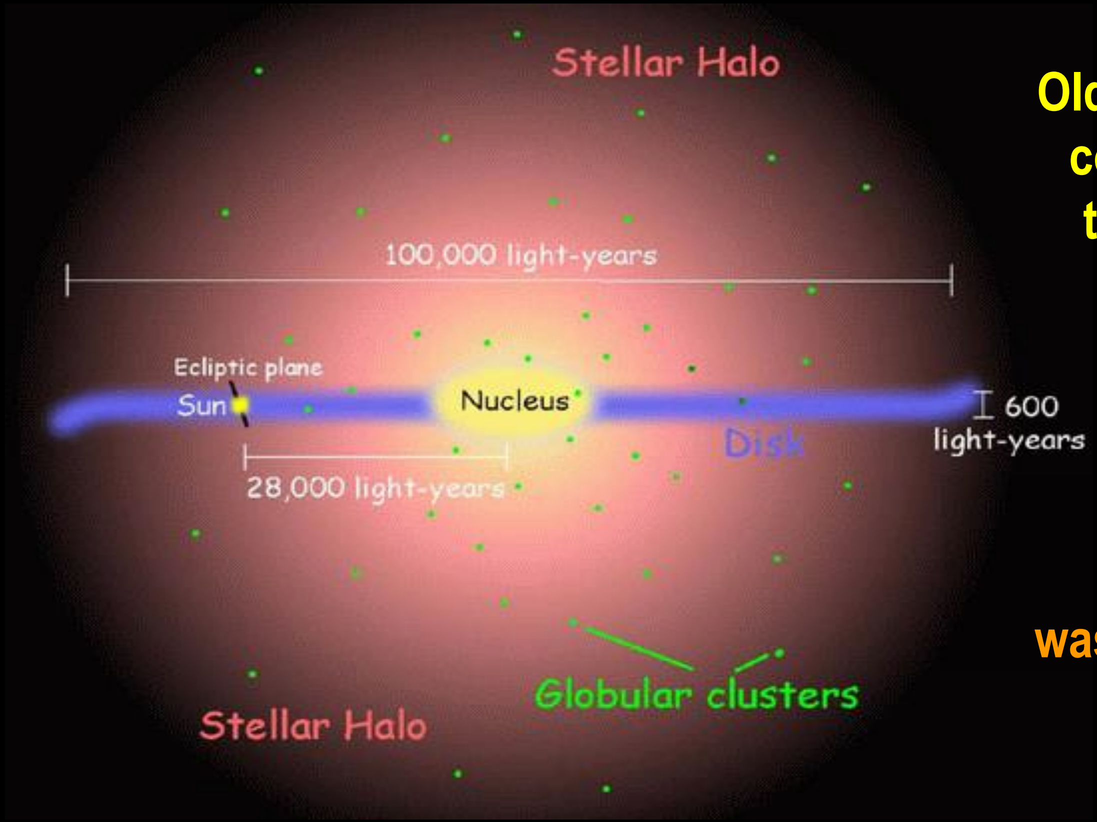
Summary

Stars that have exhausted their supply of hydrogen in regions where thermonuclear reactions are important enter a collapsing phase. If the mass of the star exceeds Chandrasekhar's limit collapse will continue until rotational instability occurs. Rotational instability enables the star to throw material off to infinity. This process continues until the mass of the remaining stellar nucleus becomes of the order of, or less than Chandrasekhar's limit. The nucleus can then attain a white dwarf equilibrium state.

The temperature generated at the centre of a collapsing star is considered and it is shown that values sufficiently high for statistical equilibrium to exist between the elements must occur. The relative abundances of the elements can then be worked out from the equations of statistical mechanics. These equations are considered in detail and it is shown that a roughly uniform abundance of the elements over the whole of the periodic table can be obtained. The process of rotational instability enables the heavy elements built up in collapsing stars to be distributed in interstellar space.

G. Gamow (mid-40ies): all elements produced in the hot primordial Universe (Big Bang) by successive neutron captures

F. Hoyle (mid-40ies): all elements produced Inside stars during their collapsing stage, by thermonuclear reactions



Old stars of galactic halo (Population II) contain less heavy elements (metals) than the younger stellar population (Population I) of the galactic disk
Chamberlain and Aller 1951

The chemical composition of the Milky Way was substantially different in the past

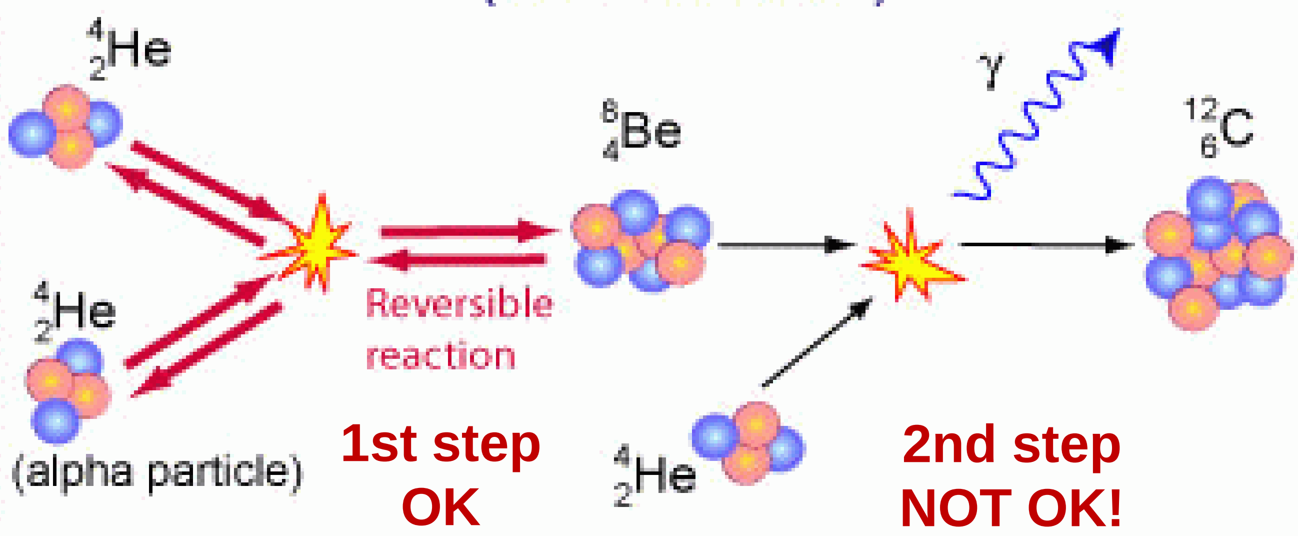
NUCLEAR REACTIONS IN STARS WITHOUT HYDROGEN*

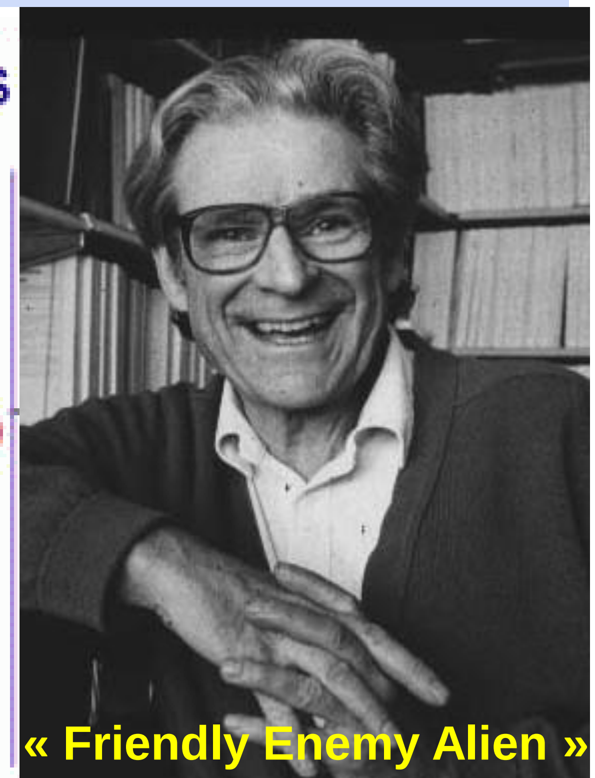
E. E. SALPETER

LABORATORY OF NUCLEAR STUDIES
CORNELL UNIVERSITY
October 2, 1951

verted into helium by means of the carbon-nitrogen cycle. When the energy supply of the carbon-nitrogen cycle has been exhausted, the star undergoes gravitational contraction, and its temperature increases. Various nuclear processes[1, 2, 3] have been suggested for such a contracting star, all of which require temperatures of well over $10^{9\circ}$ K. The main aim of this note is to point out that there is one nuclear process which takes place at a much lower temperature of about $2 \times 10^{8\circ}$ K, namely, the conversion of three helium nuclei into one carbon nucleus.

The Triple Alpha Process
(Helium Fusion)

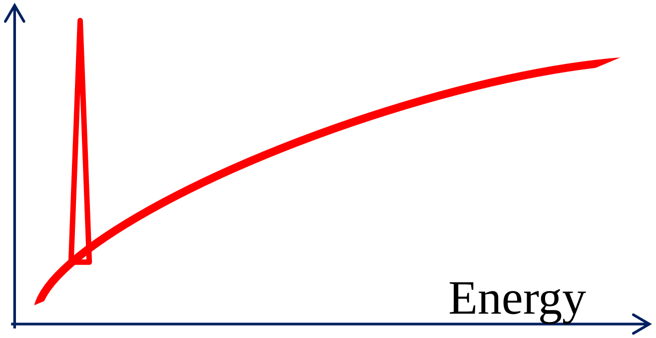


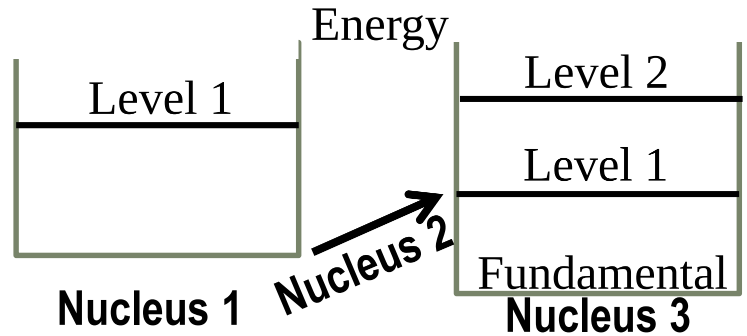


Formation and survival of C-12 in He-burning

Probability of nuclear reaction

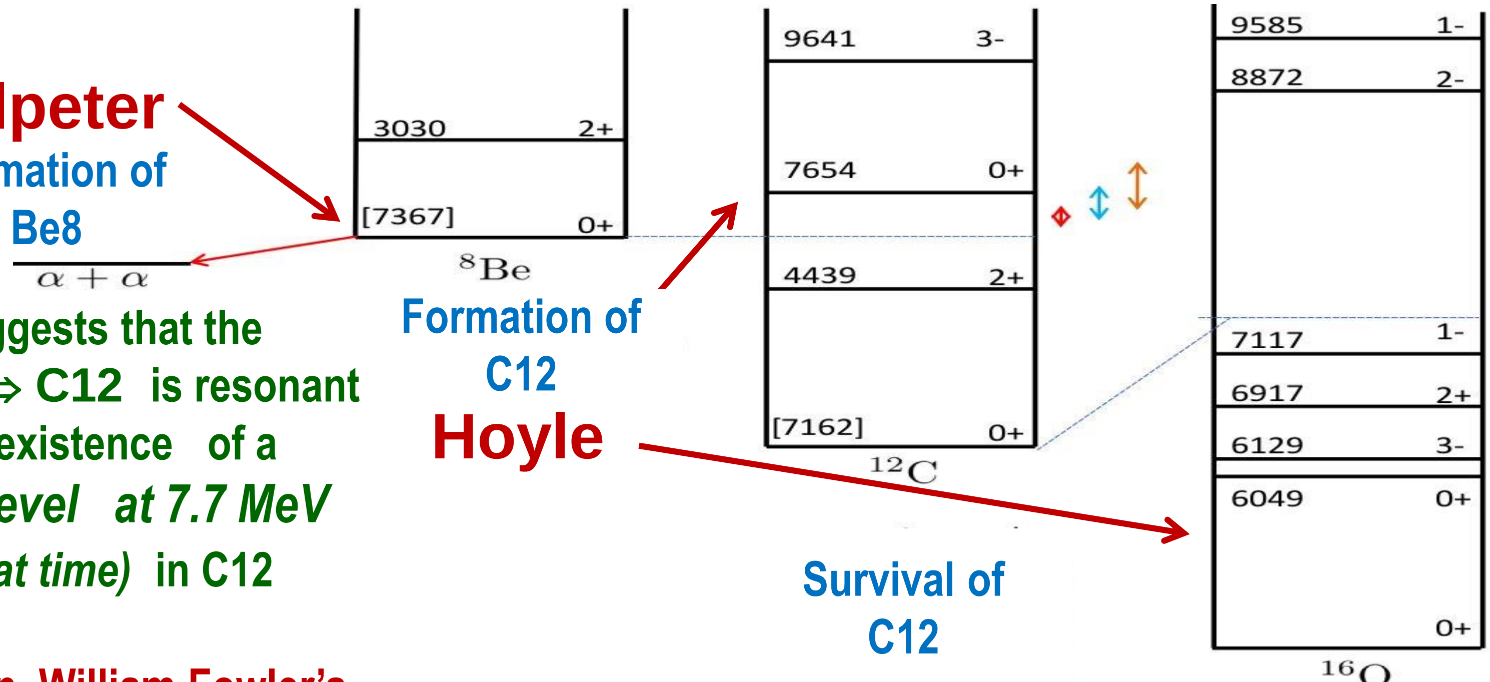
It becomes very high when the reaction is resonant





Salpeter

Formation of Be8



Formation of C12

Hoyle

Survival of C12

Fred Hoyle suggests that the reaction Be8 + α ⇒ C12 is resonant because of the existence of a *nuclear energy level at 7.7 MeV (unknown at that time)* in C12

The level is found in William Fowler's Kellog laboratory in 1953

First quantitative prediction of a microscopic property of matter (structure of C12 nucleus) from a macroscopic one (abundances of C12, O16 and Ne20)

1st and only prediction of the Anthropic Principle ?

Formation of Carbon (C-12)

PHYSICAL REVIEW VOLUME 92, NUMBER 3 NOVEMBER 1, 1953

The 7.68-Mev State in C^{12}

D. N. F. Dunbar,* R. E. Pixley, W. A. Wenzel, and W. Whaling
Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California

(Received July 21, 1953)

Magnetic analysis of the alpha-particle spectrum from $N^{14}(d,\alpha)C^{12}$ covering the excitation energy range from 4.4 to 9.2 Mev in C^{12} shows a level at 7.68±0.03 Mev. At E_d=620 kev, θ_{lab}=90°, transitions to this state are only 6 percent of those to the level at 4.43 Mev.

SALPETER[1] and Öpic[2] have pointed out the importance of the $Be^8(\alpha,\gamma)C^{12}$ reaction in hot stars which have largely exhausted their central hydrogen. Hoyle[3] explains the original formation of elements heavier than helium by this process and concludes from the observed cosmic abundance ratios of $O^{16}:C^{12}:He^4$

* On leave from the University of Melbourne, Melbourne, Australia.

[1] E. E. Salpeter, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1953), Vol. 2, p. 41.

[2] E. J. Öpic, Proc. Roy. Irish Acad. A54, 49 (1952).

[3] F. Hoyle (private communication).

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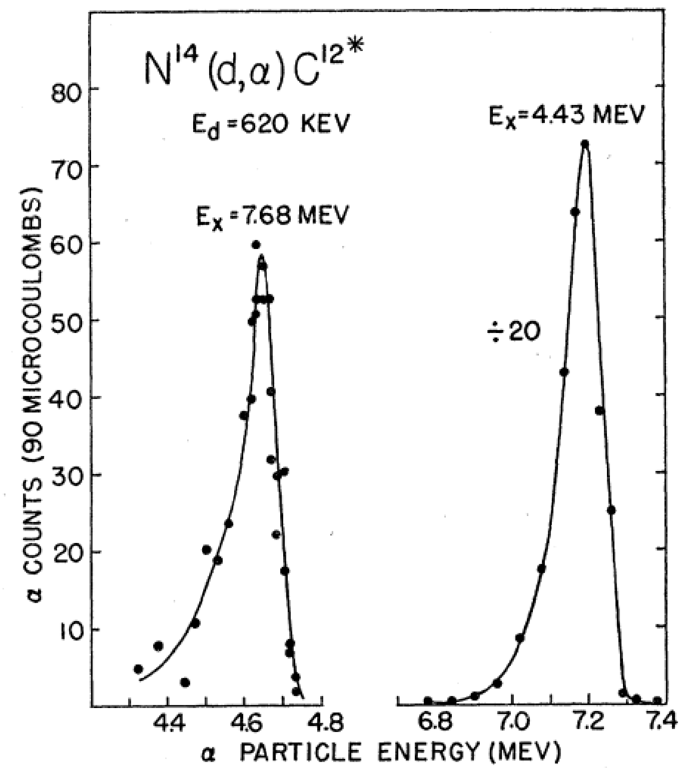

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ON NUCLEAR REACTIONS OCCURRING IN VERY HOT STARS. I. THE SYNTHESIS OF ELEMENTS FROM CARBON TO NICKEL

F. HOYLE* (1954)

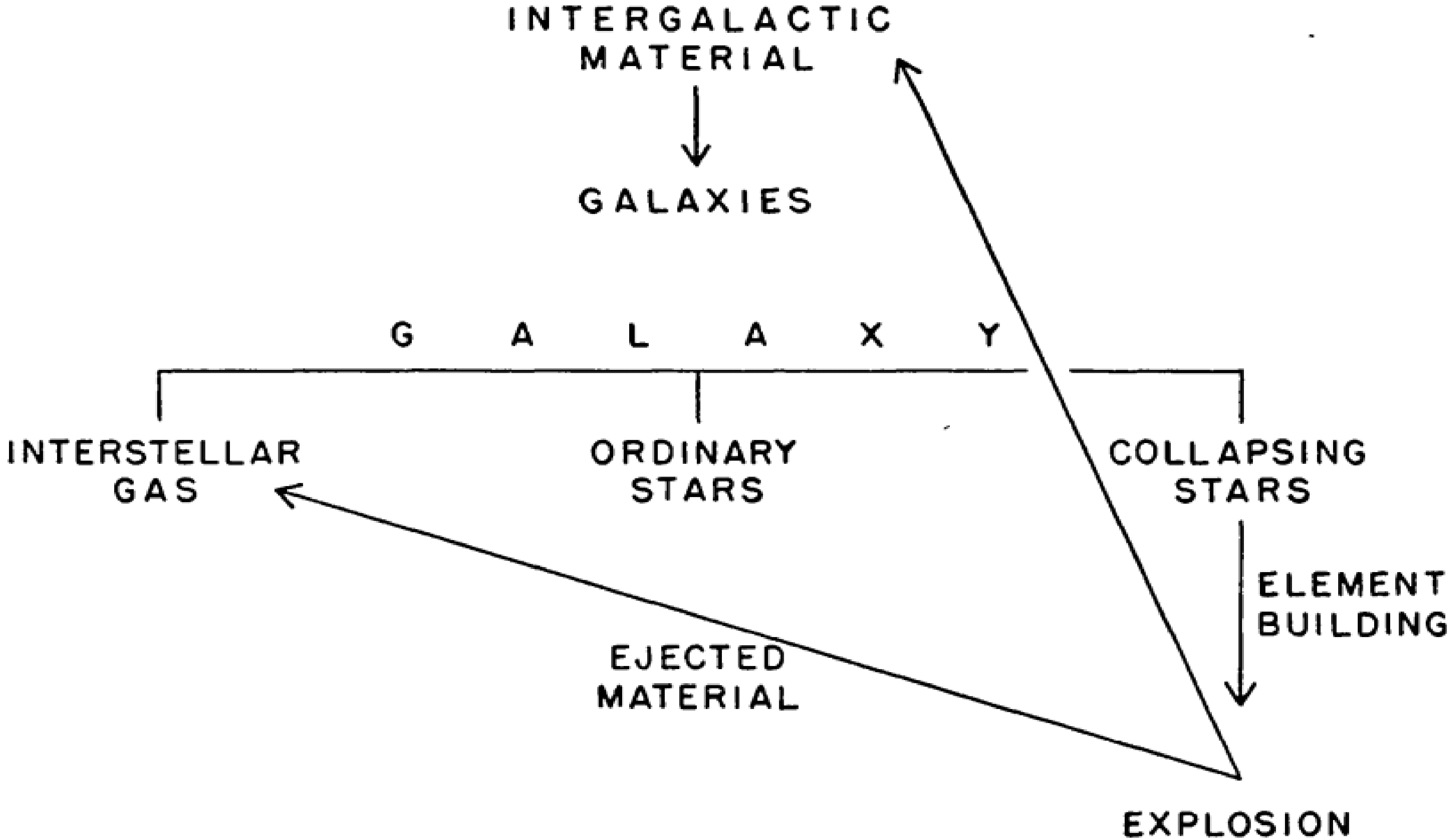


FIG. 1.—The general cosmological framework assumed for this discussion

A MATHEMATICAL DISCUSSION OF THE PROBLEM OF STELLAR EVOLUTION, WITH REFERENCE TO THE USE OF AN AUTOMATIC DIGITAL COMPUTER

C. B. Haselgrove and F. Hoyle

(Received 1956 May 10)

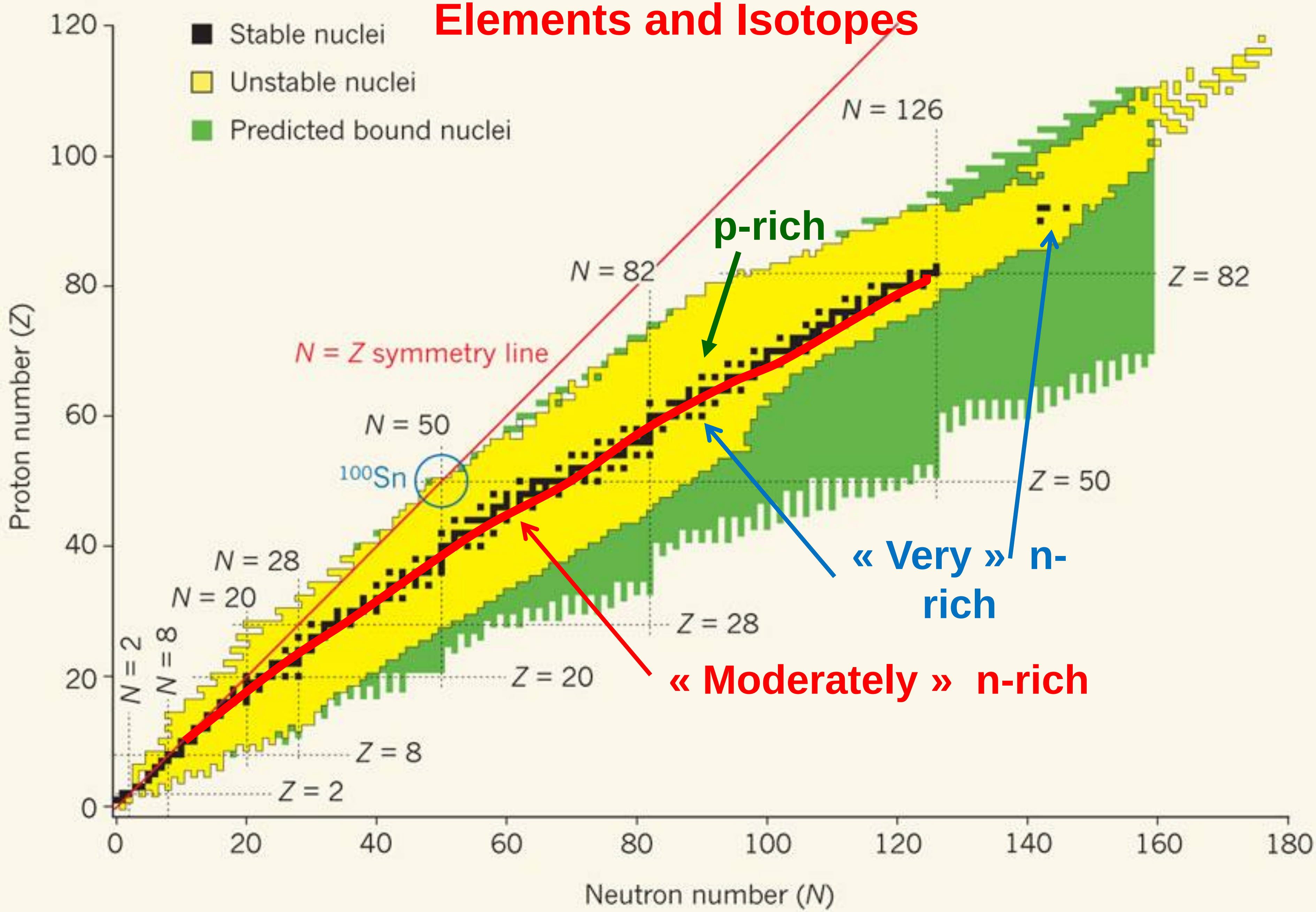
Summary

The partial differential equations describing the evolution of a star have been reduced to a form suitable for numerical integration by an electronic computer. The integration has been programmed for the electronic computer EDSAC I and the results will be discussed in later papers.

If, however, the increments are large it may be necessary to carry out a further set of six integrations. There is no guarantee that either of these processes will converge but if we start with initial conditions which are reasonably good we find that three or four iterations give a fit in the solutions to an accuracy of one part in the fourth decimal of the logarithm.

The EDSAC I performs an integration, inward or outward, in about 15 minutes. This means that the machine is theoretically capable of obtaining a sufficiently accurate solution to the equations in a few hours, but in practice the actual time depends very much on the original estimates of the initial conditions.

Elements and Isotopes



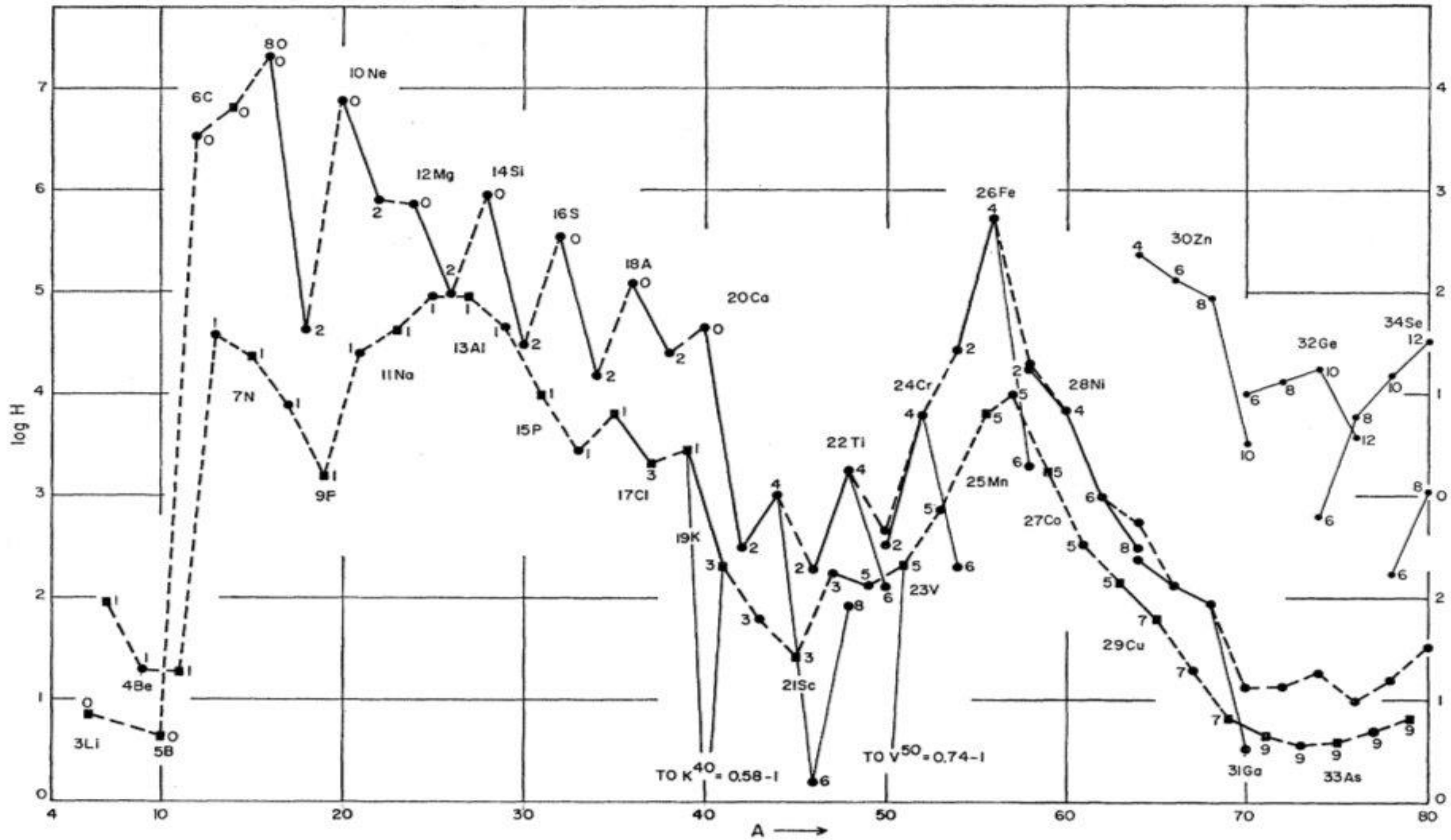
REVIEWS OF MODERN PHYSICS VOLUME 28, NUMBER 1 JANUARY, 1956

Abundances of the Elements*

HANS E. SUESS,† *U. S. Geological Survey, Washington, D. C.*

AND

HAROLD C. UREY, *Department of Chemistry and Enrico Fermi Institute for Nuclear St*
University of Chicago, Chicago, Illinois



Reviews of Modern Physics 1957

Synthesis of the Elements in Stars*

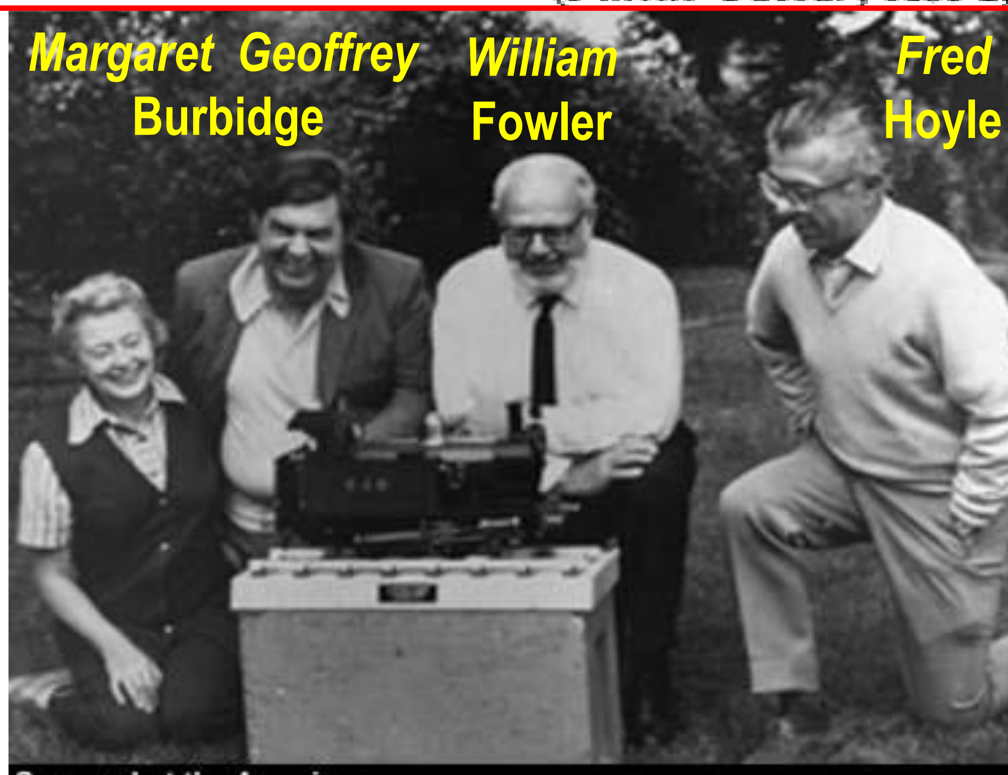
E. Margaret Burbidge, G. R. Burbidge, William A. Fowler, and F. Hoyle

Kellogg Radiation Laboratory, California Institute of Technology, and
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington,
California Institute of Technology, Pasadena, California

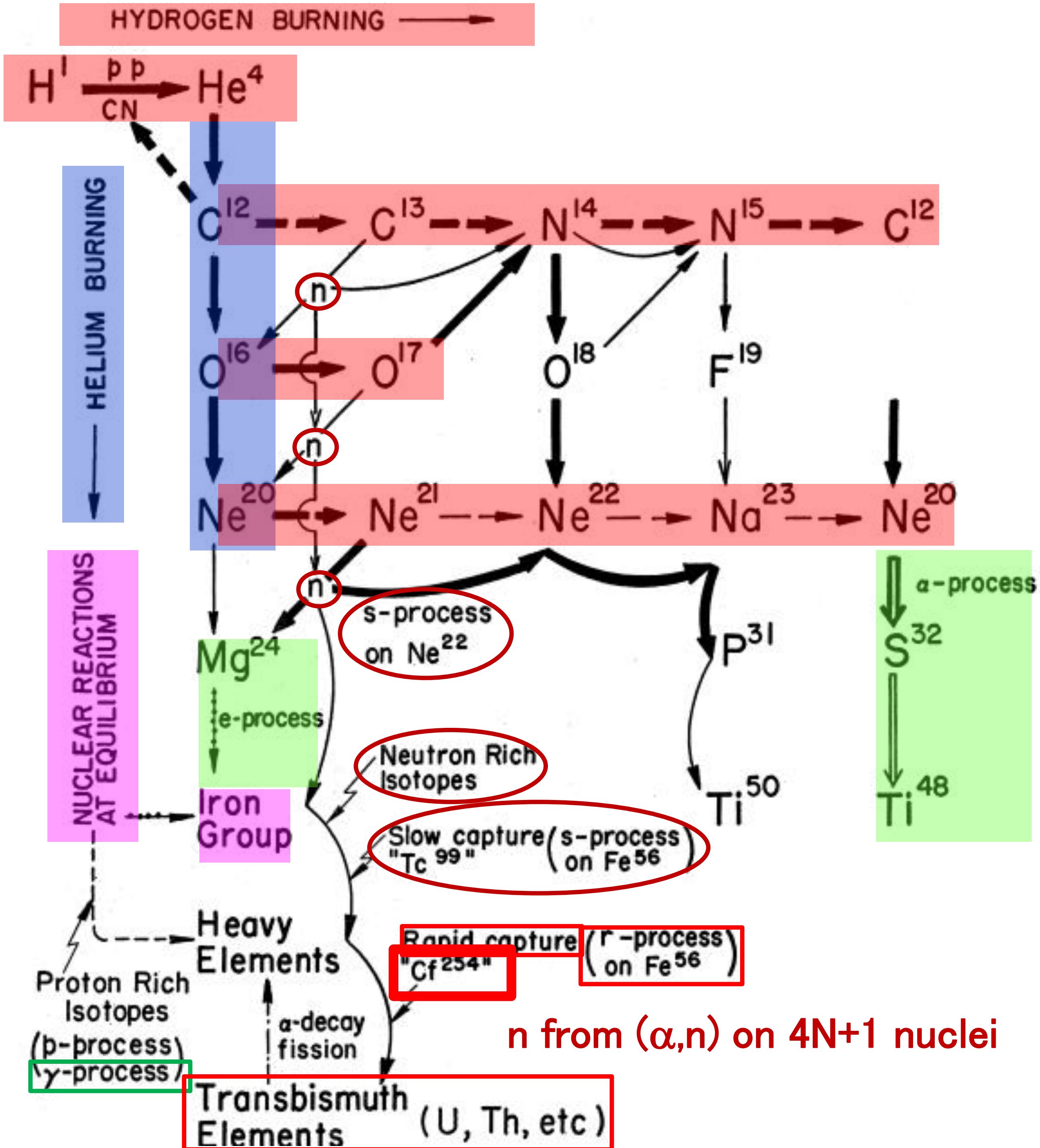
"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

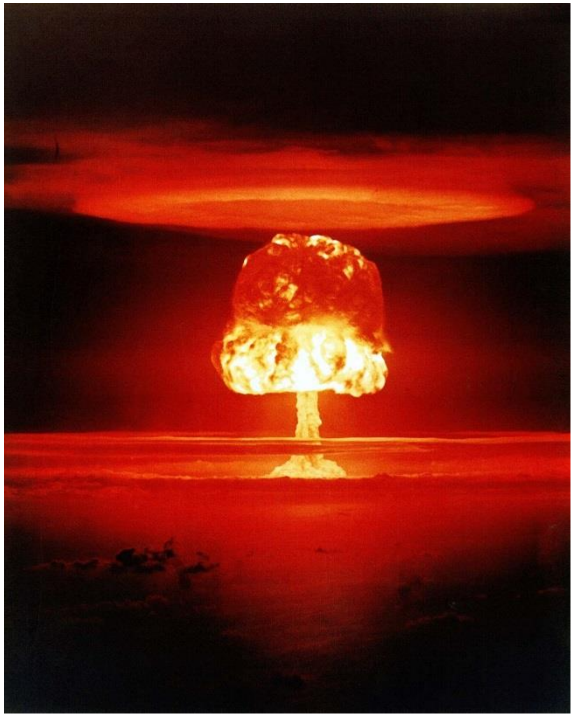
but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)



Data on neutron capture cross-sections and yields from the first H-bomb test in Bikini island (1954)





1957 : B2FH

The recent analysis of the atomic abundances (Su56) has enabled us to separate the isotopes in a reasonable scheme depending on which mode of synthesis is demanded. In particular, the identification of the *r*-process peaks was followed by the separation of the heavy isotopes beyond iron into the *s*-, *r*-, and *p*-process isotopes, and has enabled us to bring some order into the chaos of details of the abundance curve in this region. The identification of Cf^{254} in the Bikini test and then in the supernova in IC 4182 first suggested that here was the seat of the *r*-process production. Whether this finally turns out to be correct will depend both on further work on the Cf^{254} fission half-life and on further studies of supernova light curves, but that a stellar explosion of some sort is the seat of *r*-process production there seems to be little doubt.

1957 : Alastair G. W. Cameron

Nuclear reactions in stars and nucleogenesis

(Chalk River report)

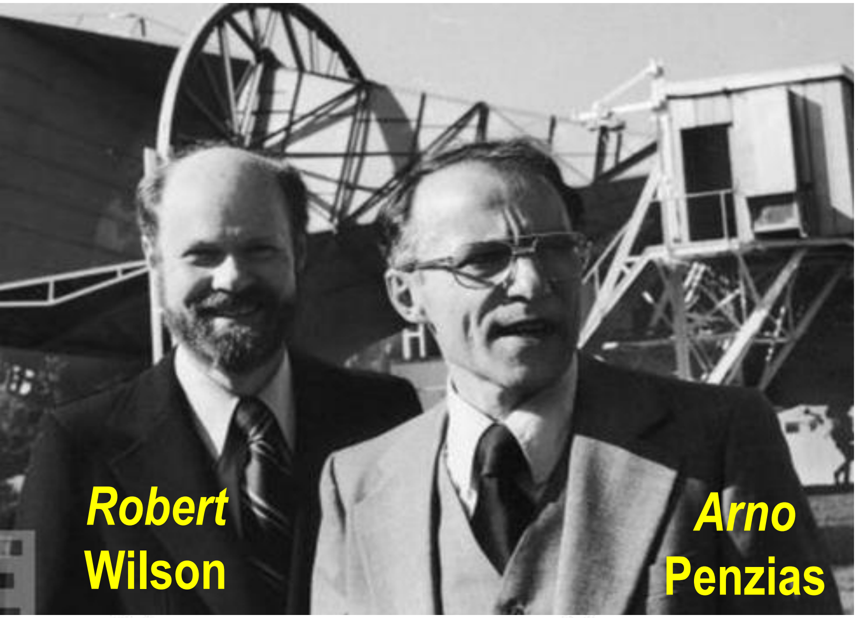
Elements	Method of Formation
D, Li, Be, B	Not formed in stellar interiors. Possibly made by nuclear reactions in stellar atmospheres
He, C, N, O, F, Ne	Hydrogen and helium thermonuclear reactions in orderly evolution of stellar interiors
Ne to Ca	1. Heavy-ion thermonuclear reactions in orderly evolution of stellar interiors 2. Neutron capture on slow time scale 3. Hydrogen and helium thermonuclear reactions in supernova explosions
Fe peak	Statistical equilibrium in pre-supernovae and in supernovae
Heavy elements :	
(*a*) Unshielded	Neutron capture on fast time scale in Type I supernovae
(*b*) Shielded	Neutron capture on slow time scale in orderly evolution of stellar interiors
(*c*) Excluded	1. Proton capture and photonuclear reactions in Type II supernovae 2. Photonuclear reactions on slow time scale in orderly evolution of stellar interiors
(*d*) Trans-bismuth	Neutron capture on fast time scale in Type I supernovae

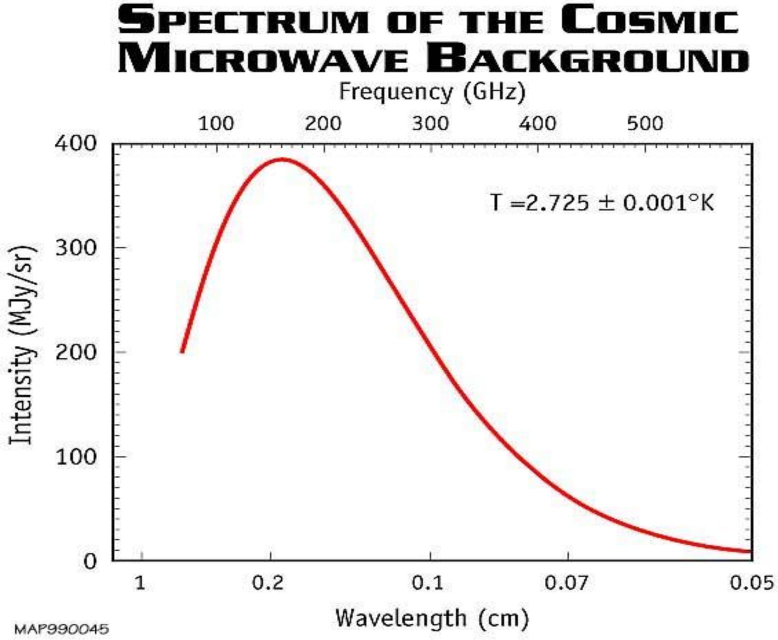
THE MYSTERY OF THE COSMIC HELIUM ABUNDANCE

By Prof. F. HOYLE, F.R.S., and Dr. R. J. TAYLER
University of Cambridge

This brings us back to our opening remarks. There has always been difficulty in explaining the high helium content of cosmic material in terms of ordinary stellar processes. The mean luminosities of galaxies come out appreciably too high on such a hypothesis. The arguments presented here make it clear, we believe, that the helium was produced in a far more dramatic way. Either the Universe has had at least one high-temperature, high-density phase, or massive objects must play (or have played) a larger part in astrophysical evolution than has hitherto been supposed. Clearly the approximate calculations of this present article must be repeated more accurately, but we would stress two general points: (1) the weak interaction cross-sections turn out to be just of the right order of magnitude for interesting effects to occur in the time-scale available; (2) for a wide range of physical conditions (for example, nucleon density) roughly the observed amount of helium is produced.

1965 : discovery of the Cosmic Microwave Background





*This lecture was delivered December 8, 1978, on the occasion of the presentation of the 1978 Nobel Prizes in Physics.

The origin of the elements*

Arno A. Penzias

Communications Sciences Division, Bell Laboratories, 4E–605,

Throughout most of recorded history, matter was thought to be composed of various combinations of four basic elements; earth, air, fire, and water. Modern science has replaced this list with a considerably longer one; the known chemical elements now number well over one hundred. Most of these, the oxygen we breathe, the iron in our blood, the uranium in our reactors, were formed during the fiery lifetimes and explosive deaths of stars in the heavens around us. A few of the elements were formed before the stars even existed, during the birth of the universe itself.

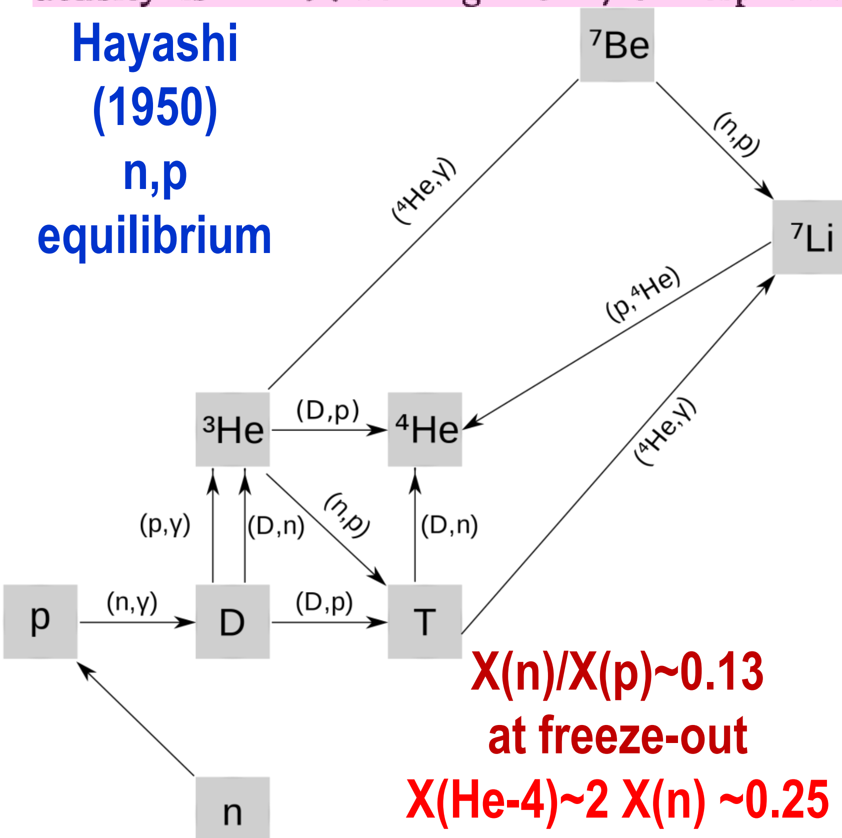
ON THE SYNTHESIS OF ELEMENTS AT VERY HIGH TEMPERATURES*

Robert V. Wagoner, William A. Fowler, and F. Hoyle
California Institute of Technology, Pasadena, California, and Cambridge University
Received September 1, 1966

ABSTRACT

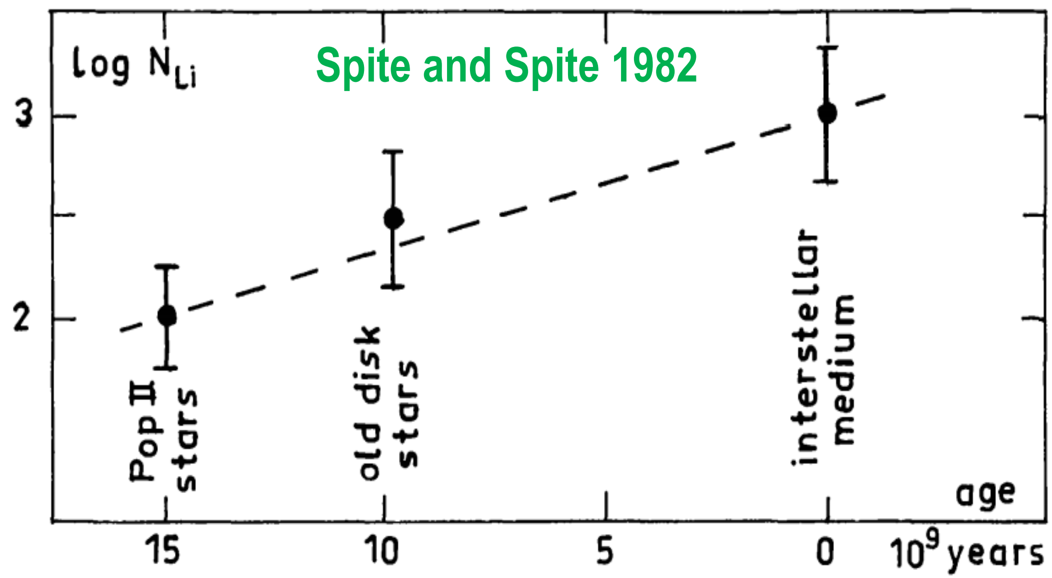
A detailed calculation of element production in the early stages of a homogeneous and isotropic expanding universe as well as within imploding-exploding supermassive stars has been made. If the recently measured microwave background radiation is due to primeval photons, then significant quantities of only D, He^3, He^4, and Li^7 can be produced in the universal fireball. Reasonable agreement with solar-system abundances for these nuclei is obtained if the present temperature is 3° K and if the present density is $\sim 2 \times 10^{-31}$ gm cm³, corresponding to a deceleration parameter $q_0 \approx 5 \times 10^{-3}$. However,

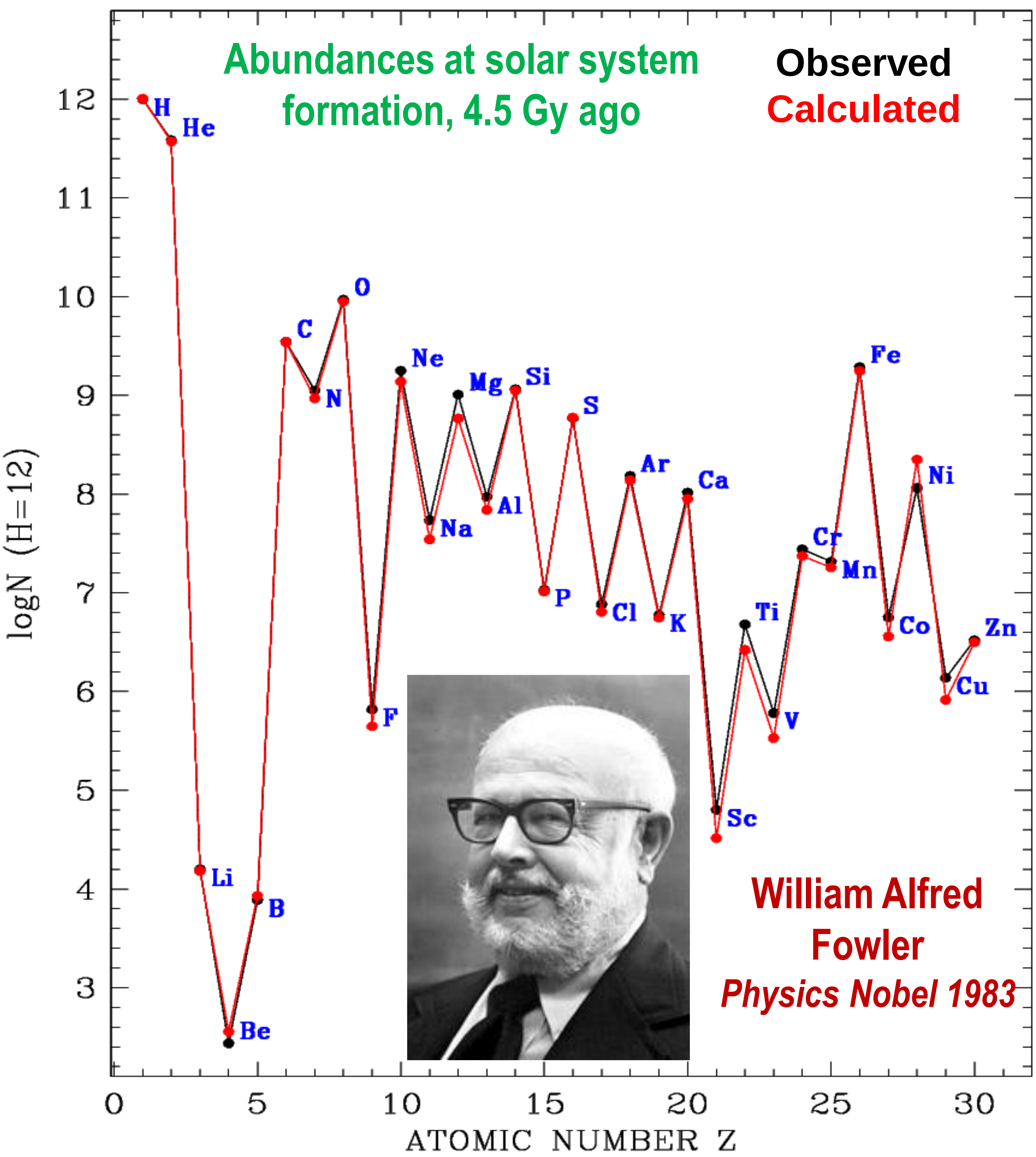
Hayashi (1950)
n,p equilibrium

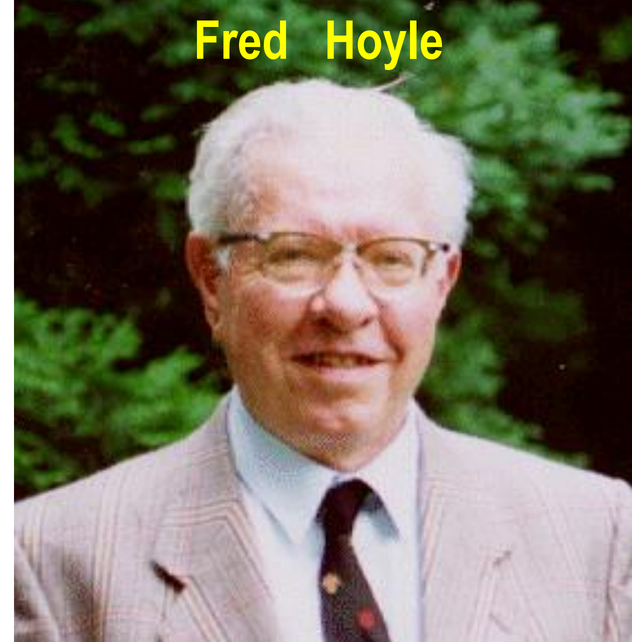


X(n)/X(p)~0.13 at freeze-out
X(He-4)~2 X(n) ~0.25

- Only way to produce so much He4 (~25 % by mass)
- Only way to produce Deuterium (destroyed in stars)
- Only way to produce so much early Li7




Abundances at solar system
formation, 4.5 Gy ago
Observed
Calculated
logN (H=12)
ATOMIC NUMBER Z
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
William Alfred
Fowler
Physics Nobel 1983


Fred Hoyle

Q. Jl R. astr. Soc. (1986) **27**, 445–453

Personal Comments on the History

Sir Fred Hoyle
Dockray, Ullswater, Cumbria

'In 1926 it was possible for people who were not very good to solve important problems, but now people who *are* very good cannot find important problems to solve.' **P.A.M. Dirac**

My story today is at an end. By 1966, nuclear astrophysics was changing quickly from being an interesting by-way in astronomy to becoming a popular thoroughfare. Since it happens to be my personal philosophy that not too much that is interesting lies waiting to be discovered in the realms of the orthodox, as nuclear astrophysics had now become, I decided to spend my efforts elsewhere, with what success or otherwise I will be glad to tell you 30 years from now.