Outline: A brief history of Nuclear Astrophysics N. Prantzos

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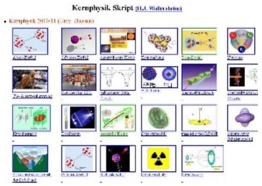
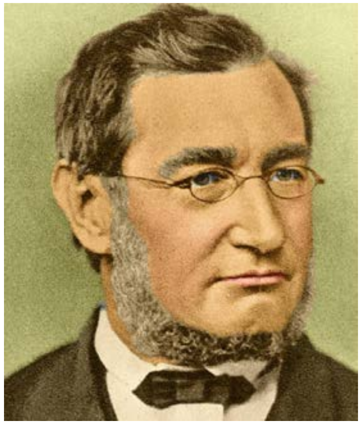


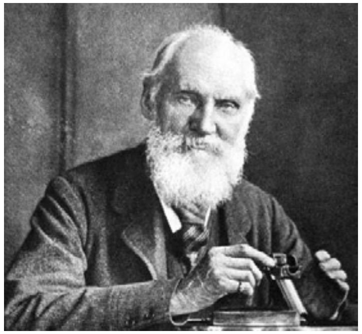
1. thermodynamics
2. subatomic physics
3. Sun´s energy
4. quantum-mechanical tunnel effect
5. CNO cycle (Hans Bethe)

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



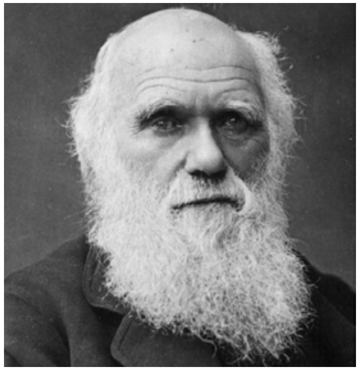
1847: Robert Julius von Mayer
Sun heated by fall of meteors

1854: Hermann von Helmholtz
Gravitational energy of Kant´s contracting protosolar nebula of gas and dust turns into kinetic energy
timescale ~ E_{Grav}/L_{Sun} ~ 30 My



1850s: William Thompson (Lord Kelvin)
Sun heated at formation from meteorite fall, now « an incandescent 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 (* 1100 feet high) in 300 My
Such large Earth ages also required by geologists, like Charles Lyell

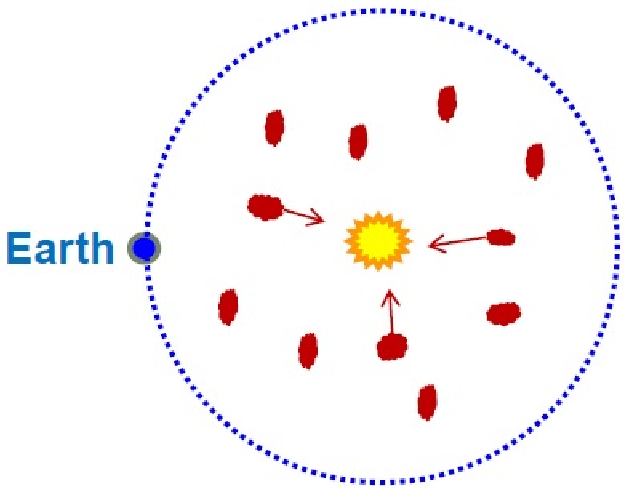


A gaseous, contracting and heating Sun

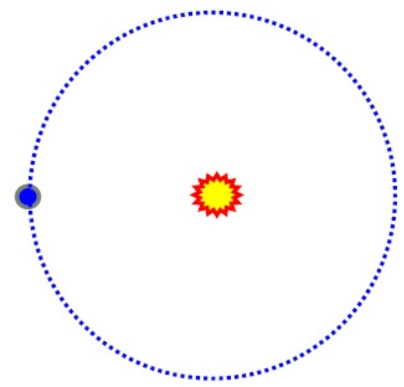
Mean solar density: $\rho = \frac{M}{\frac{4\pi}{3}R^3} \approx 1.35\ g/cm^3$ Sun liquid → incompressible

1870s: J. Homer Lane, 1880s: August Ritter : Sun gaseous → compressible

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



Mayer - Kelvin - Helmholtz



Helmholtz - Ritter

source of solar energy: gravitational contraction $energy \sim \frac{G \cdot M^2}{R}$

characteristic timescale of contraction: $T_{contraction} \cong \frac{energy}{luminosity} \sim 30\ My$

Kelvin – Helmholtz – Ritter timescale

The chemical composition and physical conditions of stellar surfaces

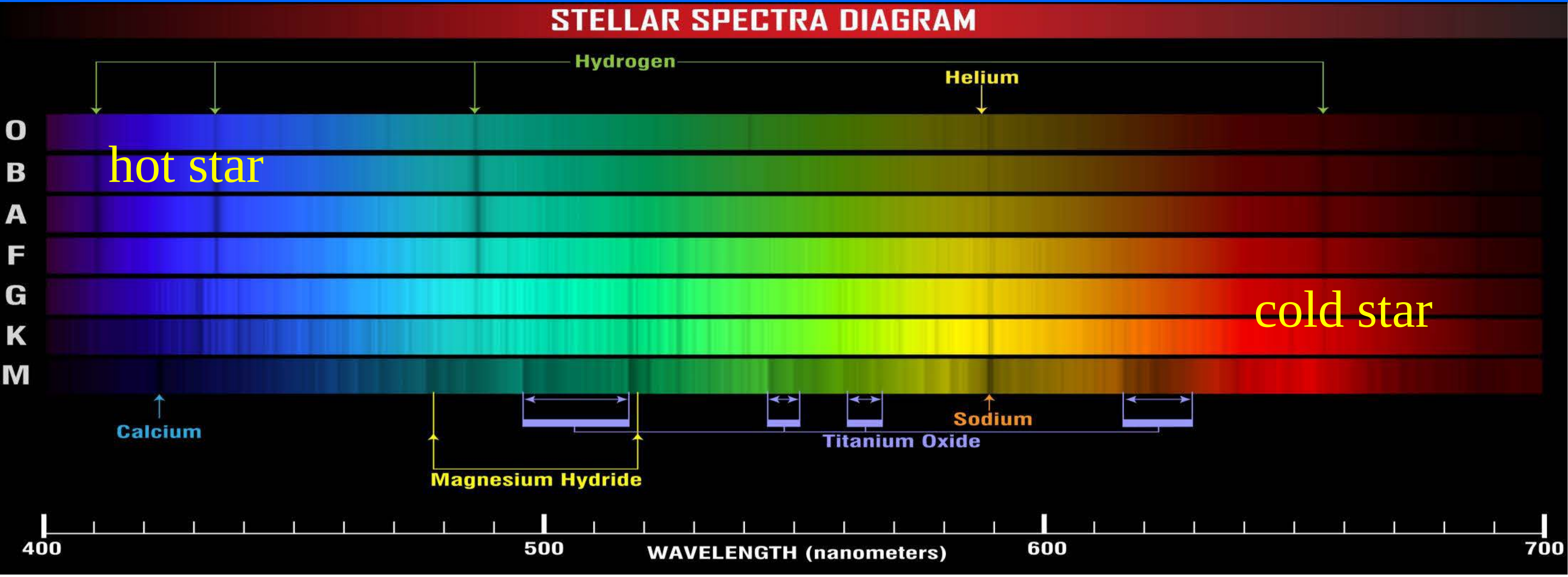
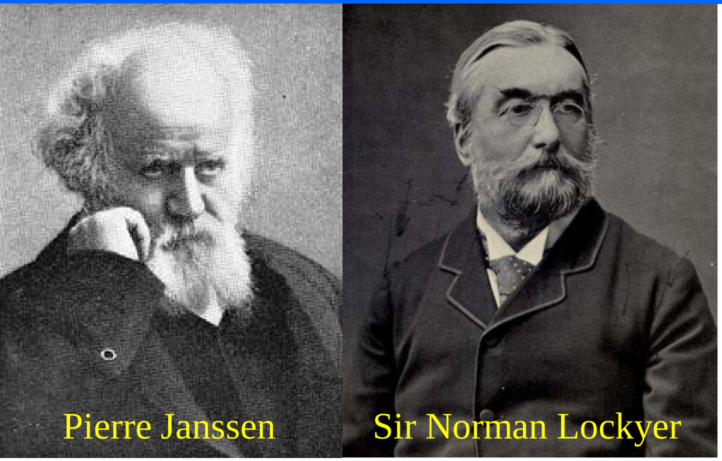


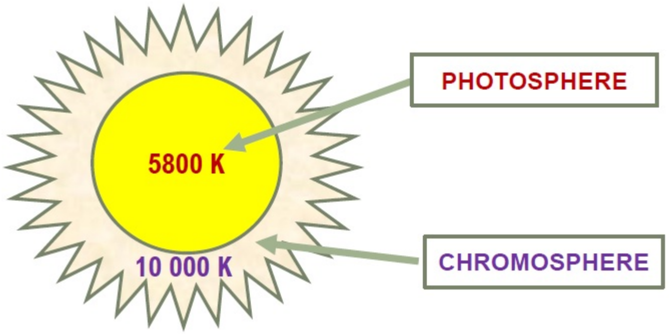
Table 2.1 Father Secchi's stellar classification of 1866

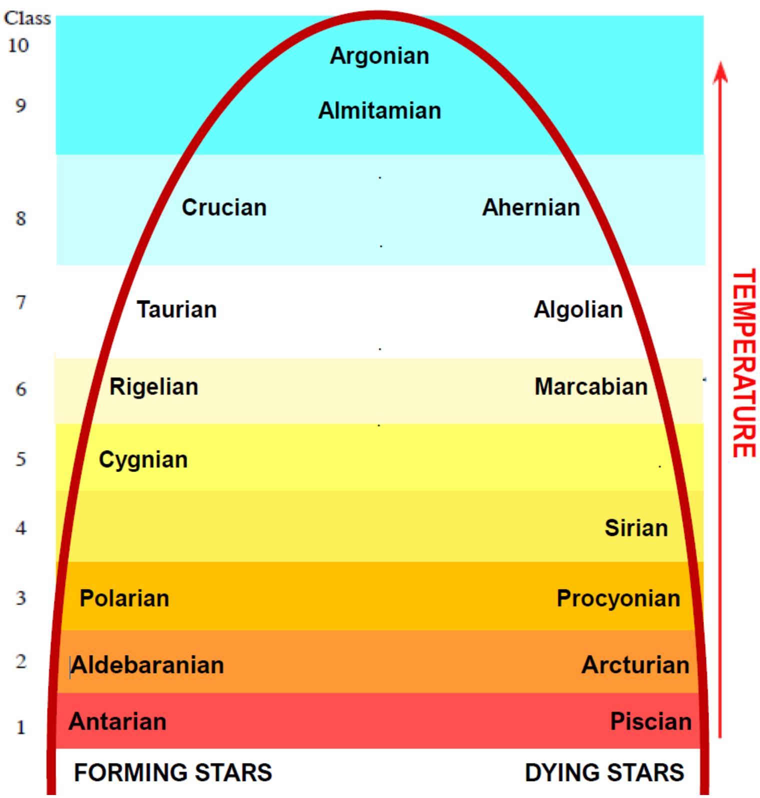
Class	Properties	Prototypes	Color
Type I	Strong hydrogen lines	Sirius, Vega	White–blue
Type II	Numerous metallic lines (Na, Ca, Fe), weak hydrogen lines	Sun, Capella, Arcturus	Yellow–orange
Type III	Bands of lines which get darker towards the blue (TiO_2), and metallic lines as in Type II above	Betelgeuse, Antares	Red
Type IV	Bands that shade in the other direction. Faint stars, few visible to naked eye		Deep red

Spectroscopy reveals Helium in the Sun



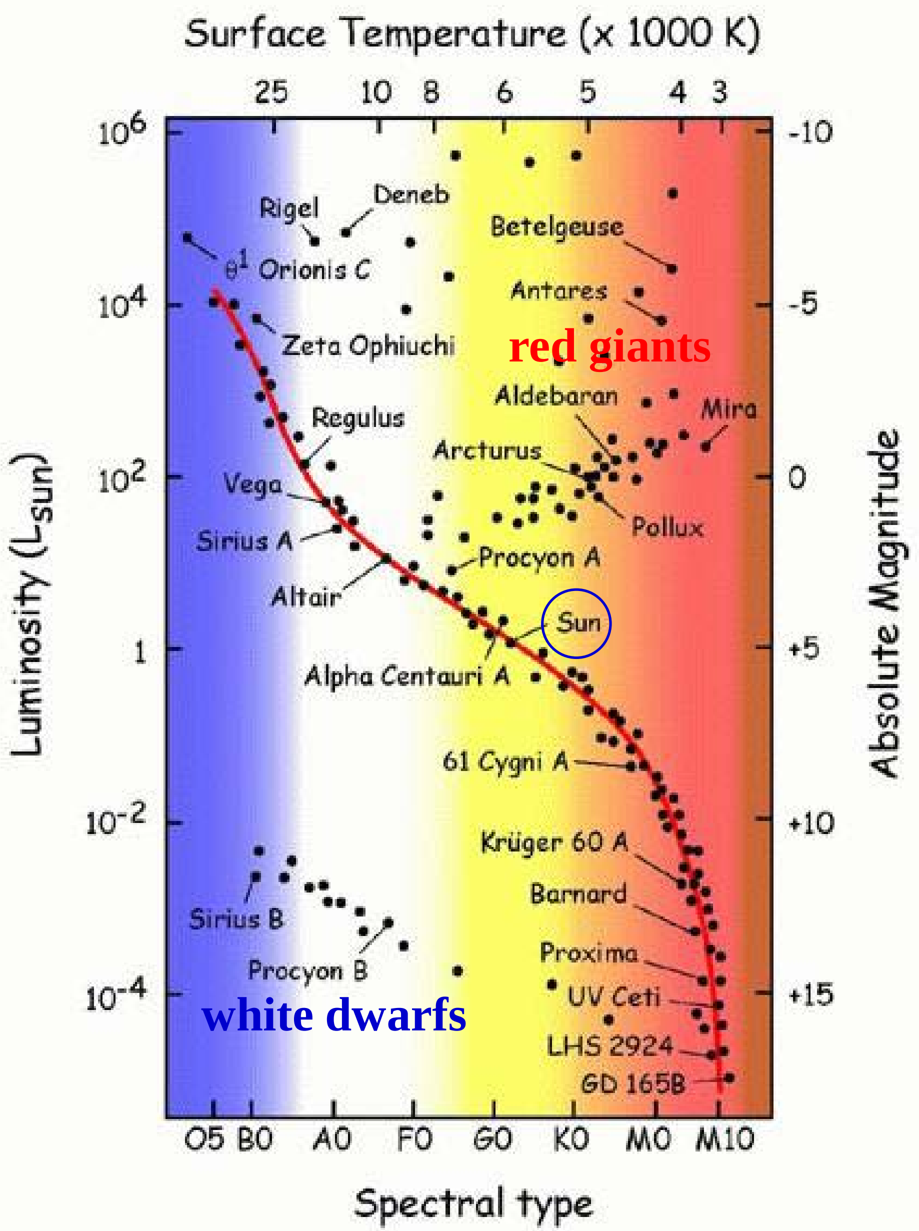
- 1868 co-discovery of Helium in the Sun´chromosphere during a solar eclipse

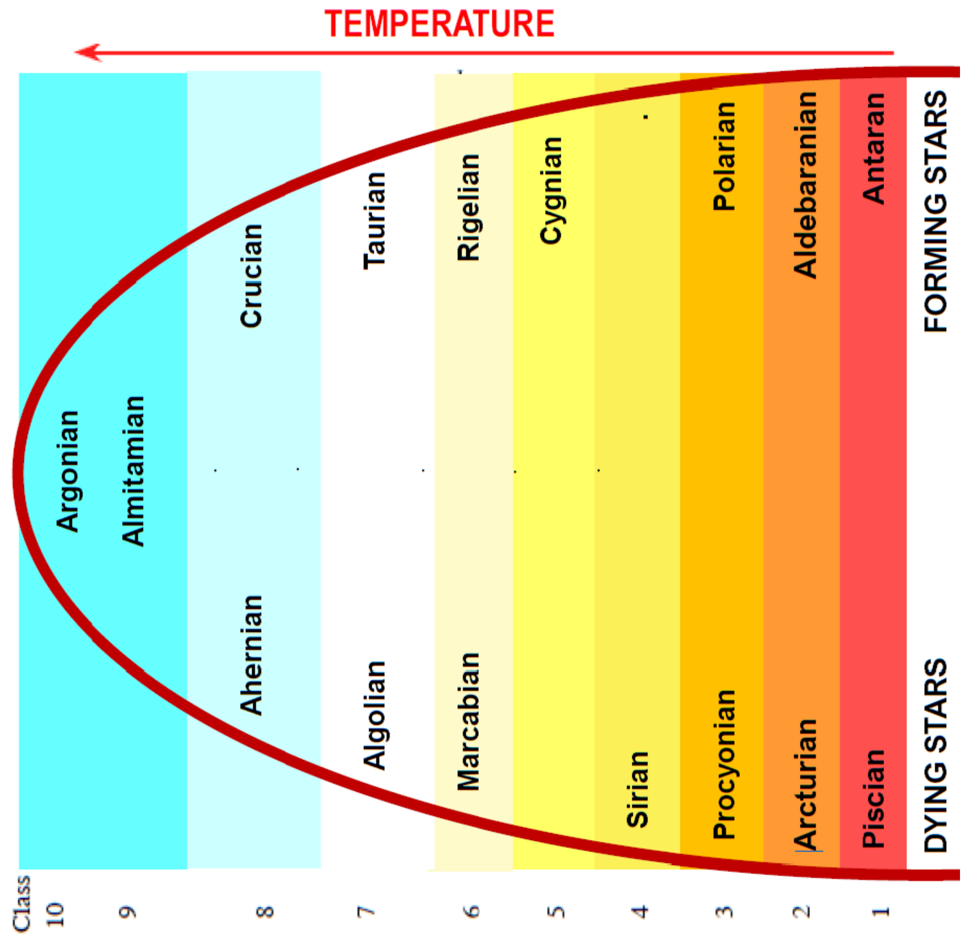




Lockyer´s theory of stellar evolution

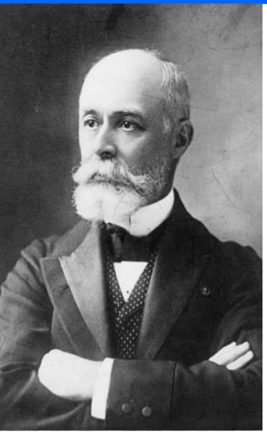
Hertzsprung-Russell diagram





Lockyer´s theory of stellar evolution:
running opposite to current

Subatomic physics

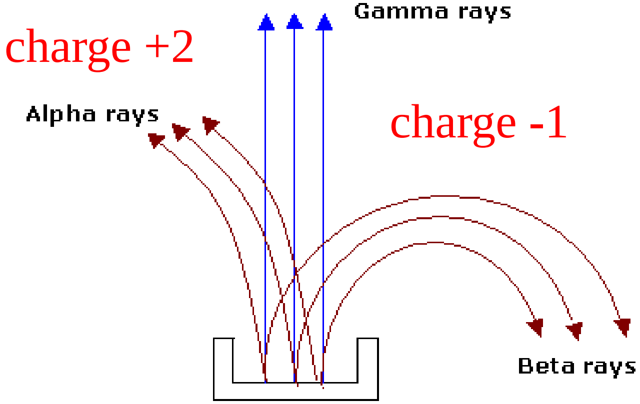


1896: discovery of **radioactivity** (Uranium)
by Henri Bequerel

1896-1897: identification of radioactive Po and Ra
by Pierre and Marie Curie

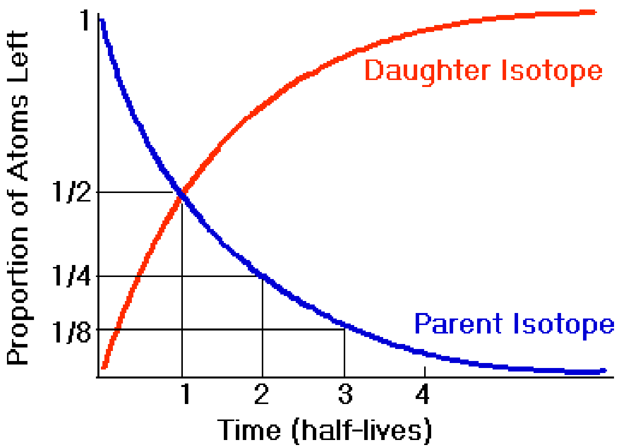
1897: discovery of the **electron**
by Joseph John Thomson

1897: identification of **alpha** and **beta** rays
by Ernest Rutherford



Radioactivity dating of rocks and energy source

1902: Rutherford-Soddy´s
law of radioactive decay
$N = N_0 \cdot exp(-t/\tau)$



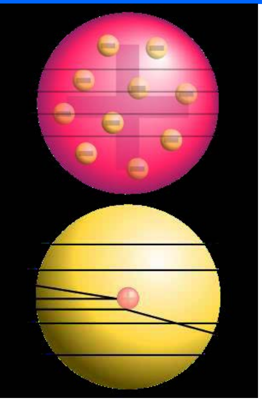
1902: Rutherford shows that **alpha** radiation is **Helium** nuclei
suggests to use Uranium/Helium for dating

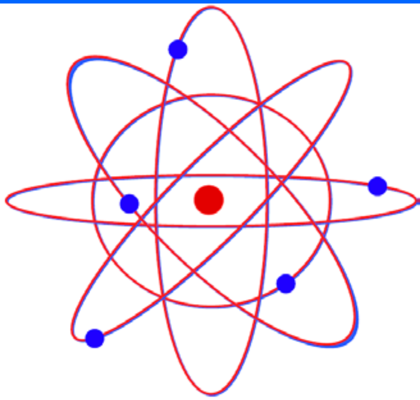
1907: Bertram Boltwood old rocks are 400 My to 2 Gy old, the Earth is even older

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.

1907 Rutherford: Helium in the Sun results from radioactivity and so does solar energy
But what makes substances radioactive and how is the energy put there?

The atomic nucleus and the proton





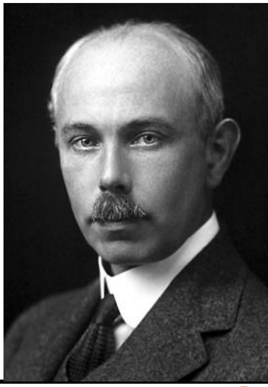
1909: Geiger-Marsden experiment
strong deflection of some α particles bombarding a foil of gold

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^{-15} m

1919 Rutherford produces hydrogen nuclei bombarding nitrogen with α particles

$$^{14}N + \alpha \rightarrow {}^{17}O + H$$

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



1910s: development of mass spectrograph
by Francis William Aston
identification of isotopes and measurements of their masses

1919: mass (^{4}He) = mass (4 protons) * (1-0.007)

Sun´s energy conversion of H to He: $E=\Delta m \cdot c^2$

First ideas (rather confused)

1915: William Draper Harkins

1919: Jean Perrin

1920: Sir Arthur Stanley Eddington

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 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.

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 = $4\cdot10^{26}$ J/s

Time t = 4.5 Gy = $1.35\cdot10^{17}$ s

Energy = Luminosity * Time = $5\cdot10^{43}$ Joule

efficiency of transformation of mass to energy through $4p \rightarrow\ ^4He:\ \varepsilon = 0.007$

Sun´s mass m = $2\cdot10^{30}$ kg

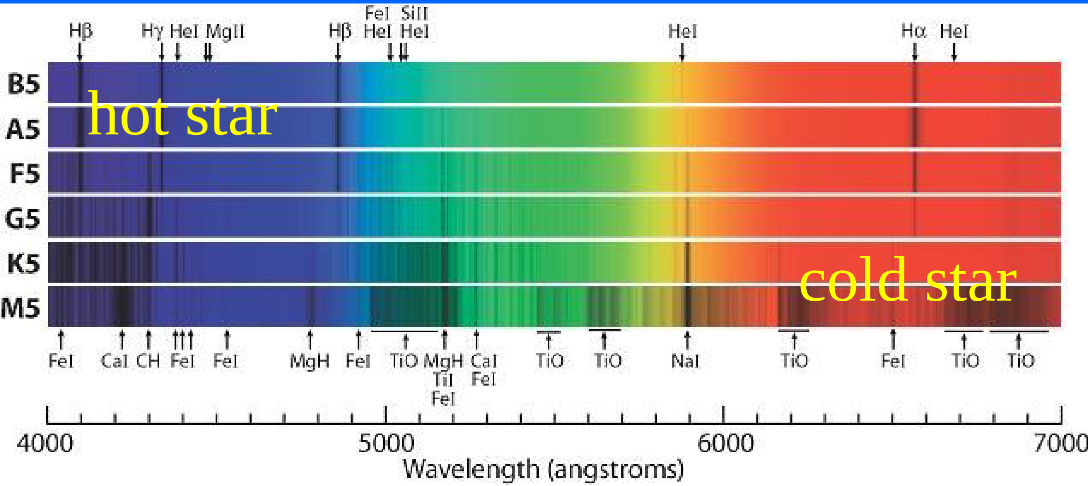
nuclear energy available $E(nuclear) = \epsilon \cdot f \cdot m \cdot c^2$

Fraction of Sun´s mass (in hydrogen) which participated in nuclear reactions in the past t = 4.5 Gy

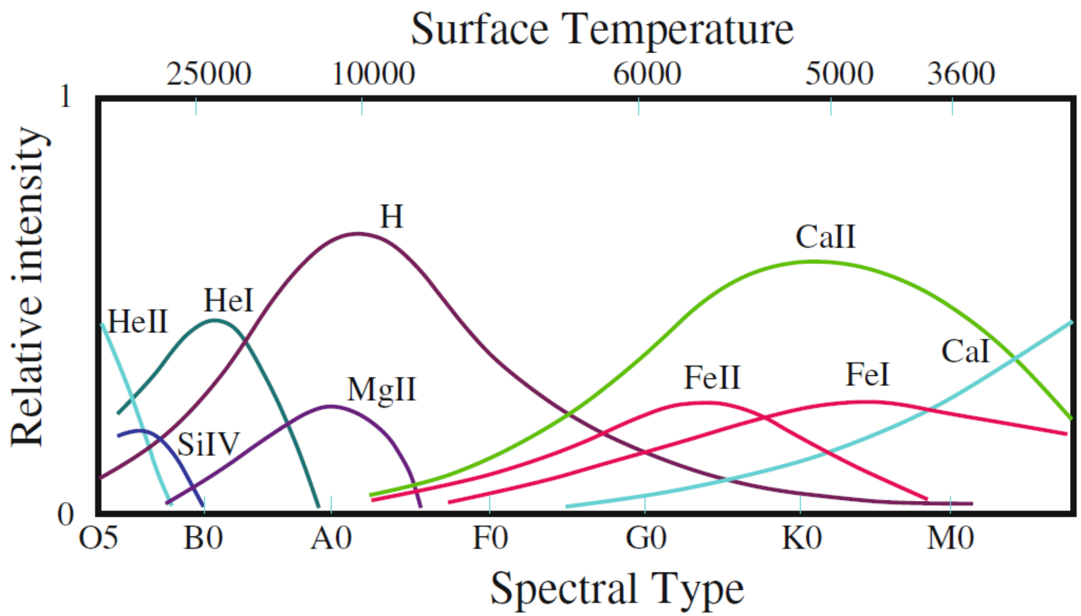
$$f \sim \frac{L \cdot t}{\varepsilon \cdot m \cdot c^2} \sim 0.05$$

How much hydrogen is there in the Sun?

Stellar spectroscopy reveals the chemical composition and physical conditions



The intensity and width of spectral lines depends not only on the abundances of the elements, but also on the conditions (temperature, pressure and ionization) of the stellar atmosphere



Quantum mechanical models are required to infer true abundances, through the Saha ionization equation (1925)

Meghnad Saha

Abundances in stellar atmospheres

❖ 1925: H and He are the most abundant elements in stellar atmospheres

Cecilia Payne

Table 3.2 The first table of relative abundances in stellar atmospheres

Z	Atom	[A]	Z	Atom	[A]
1	H	11	19	K	3.5
2	He	8.3	20	Ca	4.8
2	He^+	12	20	Ca^+	5.0
3	Li	0.0	22	Ti	4.1
6	C^+	4.5	23	V	3.0
11	Na	5.2	24	Cr	3.9
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 $[A] \equiv \text{Log}\,A$. All abundances are relative to hydrogen, which is 10^{11}

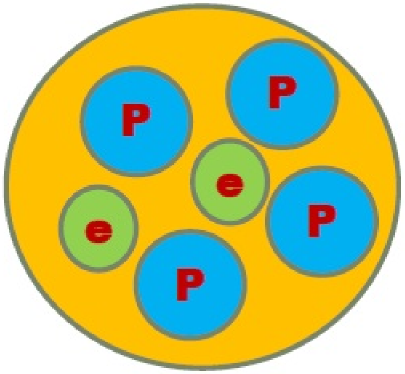
The outstanding discrepancies between the astrophysical and terrestrial abundances are displayed for hydrogen and helium. The enormous abundance derived for these elements in the stellar atmosphere is almost certainly not real. Probably the result may be considered, for hydrogen, as another aspect of 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

From H to He an impossible reaction?

Problem 1: How to make an α-particle?

(mass = $4 \cdot m_p$ charge = 2+)

4 protons + 2 electrons should be brought together
(neutrons unknown then)

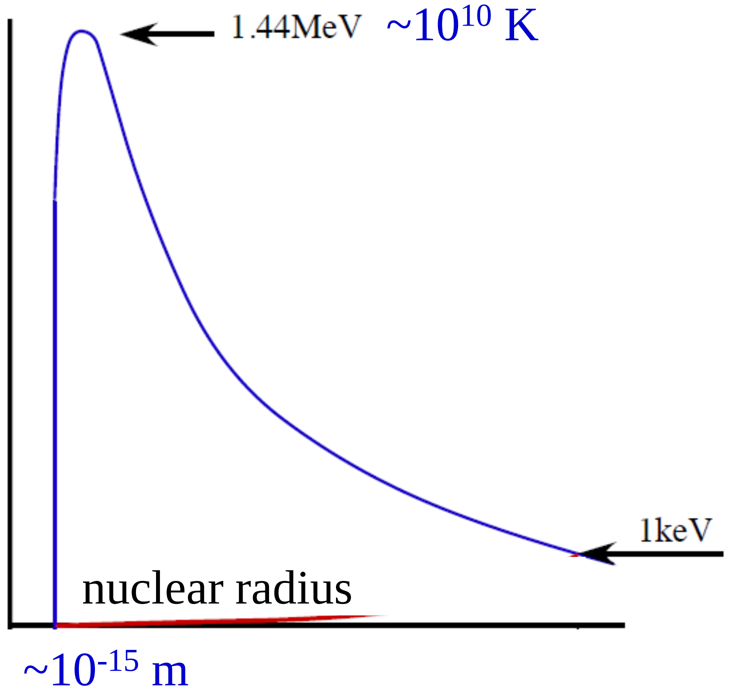


Problem 2: How to bring just 2 protons together?

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 $T \sim 10^7$ K

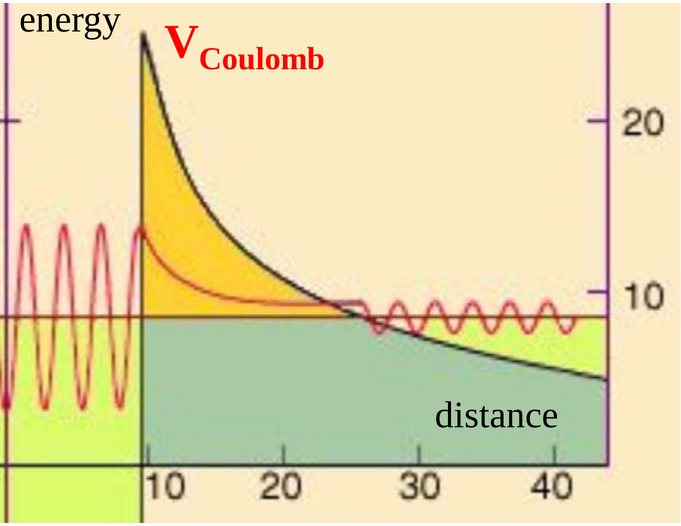
We do not argue with the critic who urges that the stars are not hot enough for this process; we tell him to go and find a hotter place



George Gamow light at the end of the tunnel

- How do emitted α-particle get out of the potential well of radioactive nuclei?
- Why their observed energies are smaller than the Coulomb barrier of those nuclei?

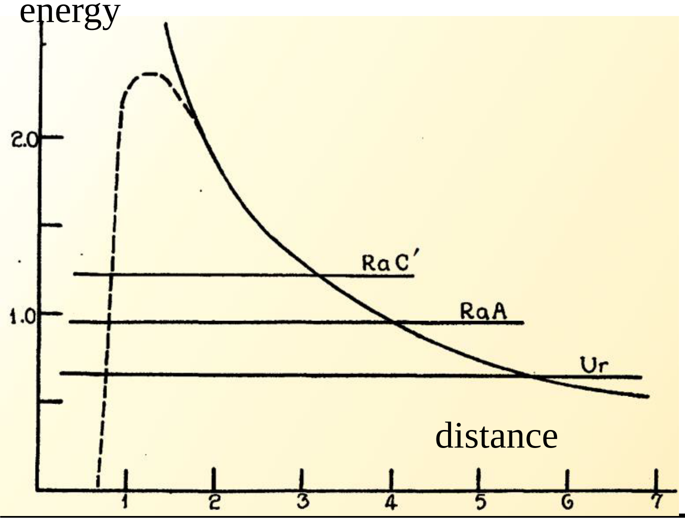
George Gamow



quantum-mechanical tunnel effect (1928):

particles with $E < V_{Coulomb}$ have a finite probability to escape

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



It also explains quantitatively why nuclei with larger half-lives eject α-particles with smaller energies (R. Gurney & E. Condon 1928-1929)

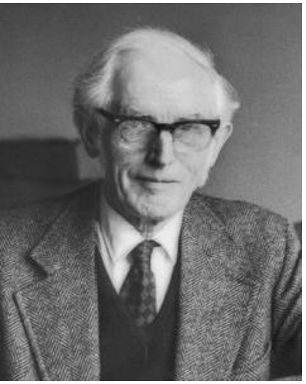
Edward Condon

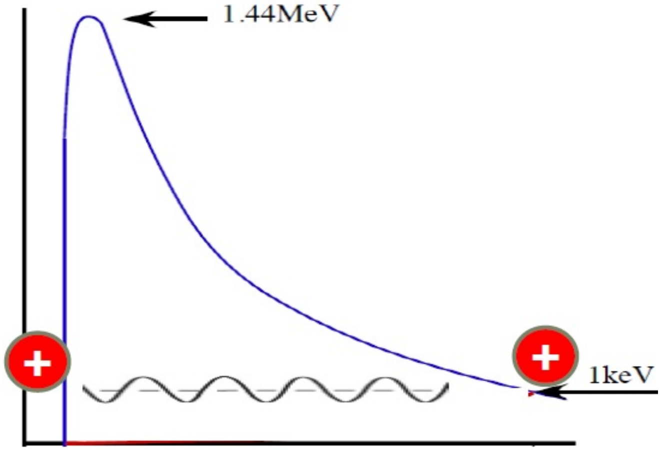
Zur Frage der Aufbaumöglichkeit der Elemente in Sternen.

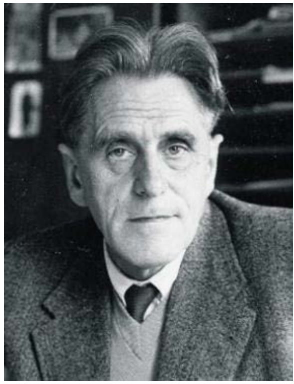
Von **R. d'E. Atkinson** und **F. G. Houtermans** in Berlin-Charlottenburg.

(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-





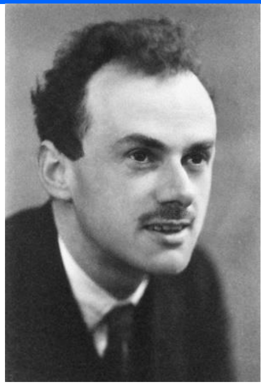


Proton fusion may indeed occur in temperatures at the center of the Sun, thanks to the tunnel effect

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

Particle discoveries in the 1930s

1930: prediction of the Neutrino
Wolfgang Pauli



1931: prediction of Positron
P.A.M. Dirac

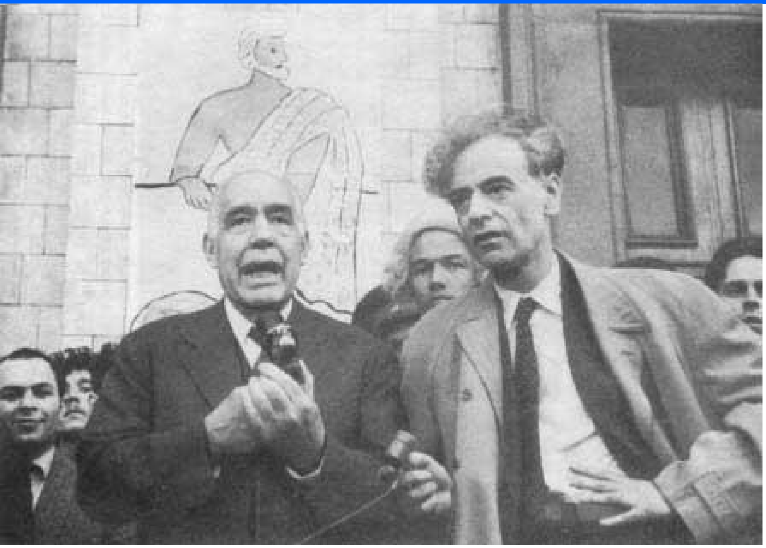
1931: discovery of Deuterium (heavy hydrogen ~ $2 \cdot m_p$)
Harold Urey

1932: discovery of Neutron (mass ~ m_p, charge = 0
James Cadwick

1932: discovery of Positron (mass ~ m_e, charge +1)
Carl Anderson

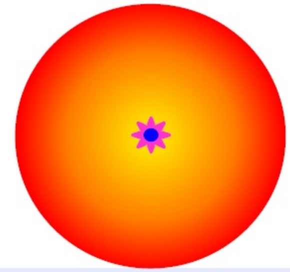
1934: development of the theory of β-decay
Enrico Fermi

Neutron star

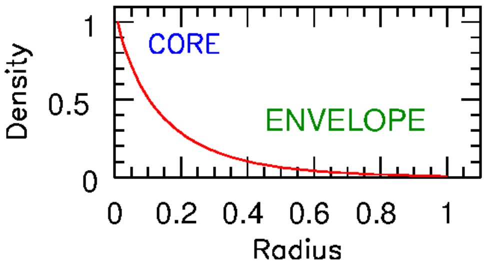


Niels Bohr & Lev Landau

Accretion of inner layers onto a small neutron star found in the stellar core

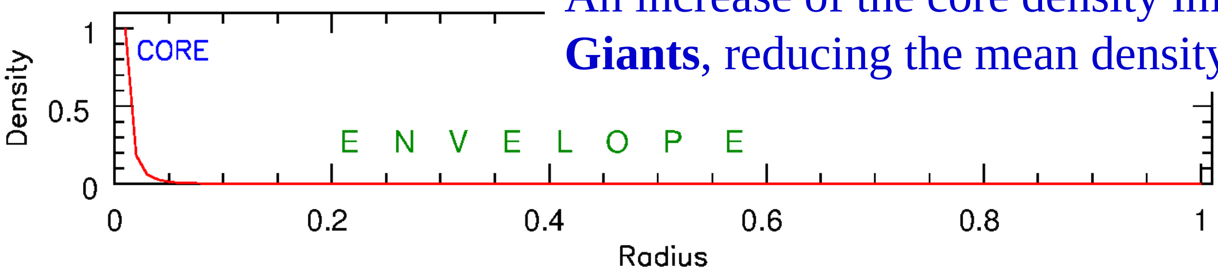


Thus we can regard a star as a body which has a neutronic core the steady growth of which liberates the energy which maintains the star at its high temperature ; the condition at the boundary between the two phases is as usual the equality of chemical potentials. The detailed investigation of such a model should make possible the construction of a consistent theory of stars.



Hydrostatic equilibrium dictates the density profile of a **normal star**

An increase of the core density inflates the envelope as in **Red Giants**, reducing the mean density



The problem of stellar energy

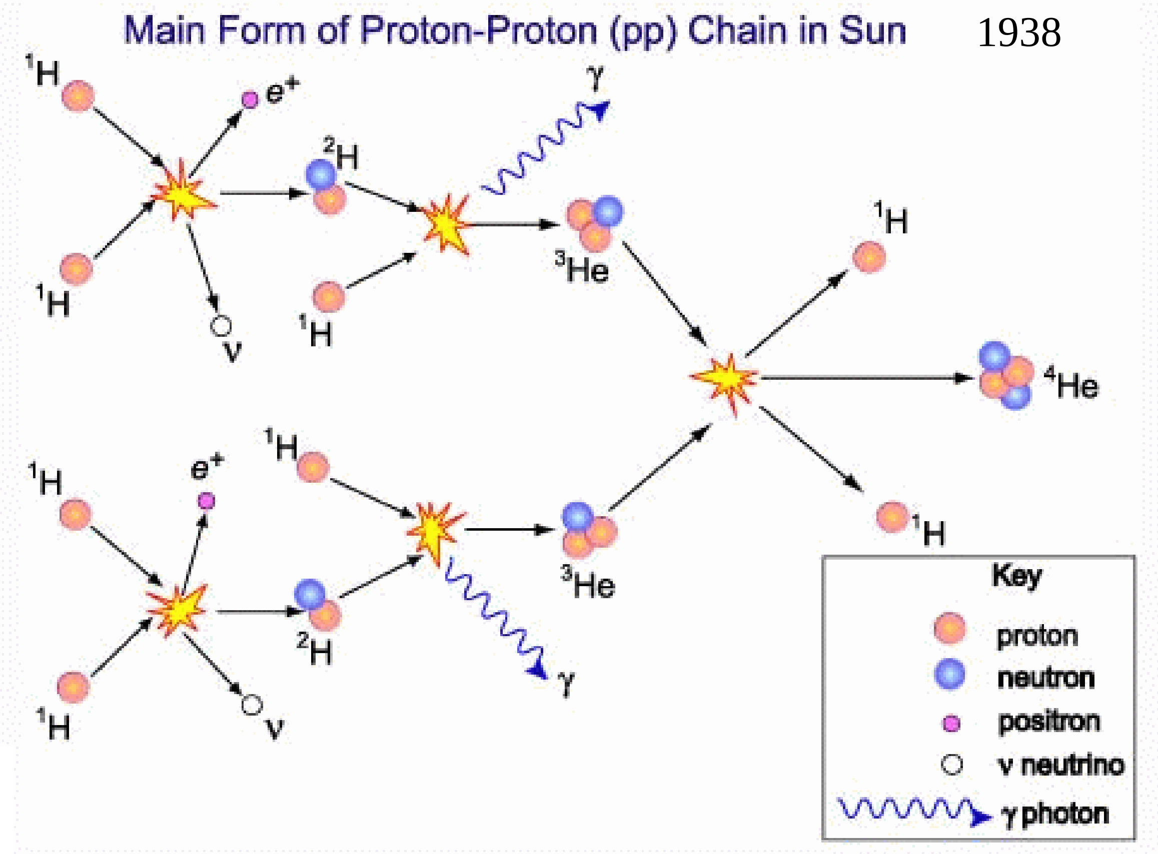
The problem of stellar energy was the subject of discussion of the Fourth Annual Conference on Theoretical Physics sponsored by the George Washington University and the Carnegie Institution of Washington, and held in Washington, D.C., on March 21-23. The Conference was attended by astrophysicists studying the internal constitution of the stars (S. Chandrasekhar, B. Stromgren, 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).

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....... **It was therefore concluded that stellar models with a concentrated nuclear core cannot represent real stars.** *[idea explored by Thorne+Zytkow 1975, 1977]*

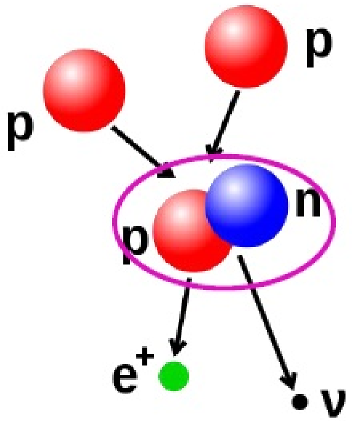
As another possibility the reaction $^1_1H + ^1_1H \rightarrow ^2_1H + \beta^+$ was suggested. It seems that the rate of such a reaction under the conditions in stellar interiors would be just enough to account for the radiation of the sun, though for stars much brighter than the sun other more effective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

The formation of Deuterons by proton combination

Hans Bethe

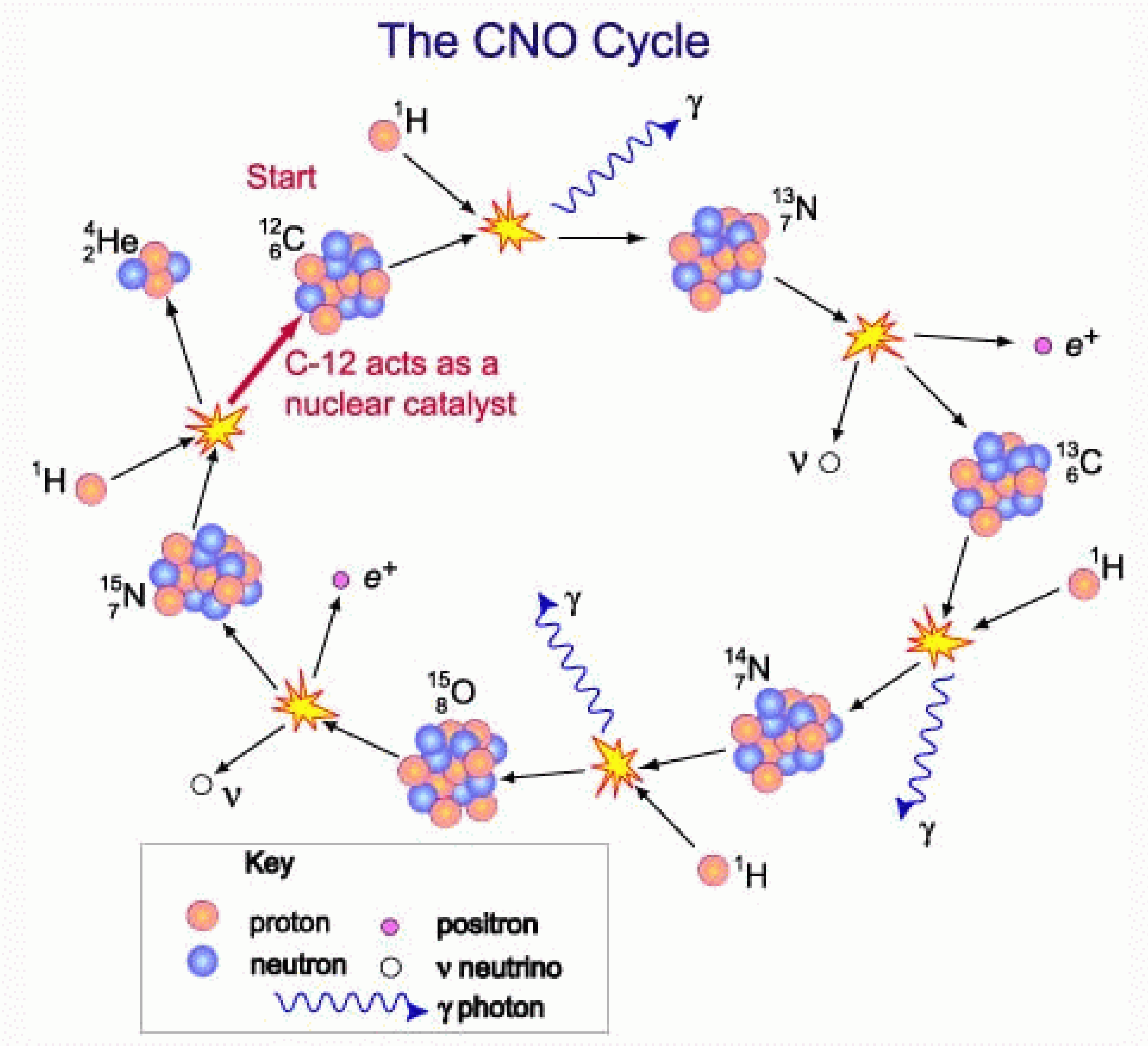


Charles Critchfield

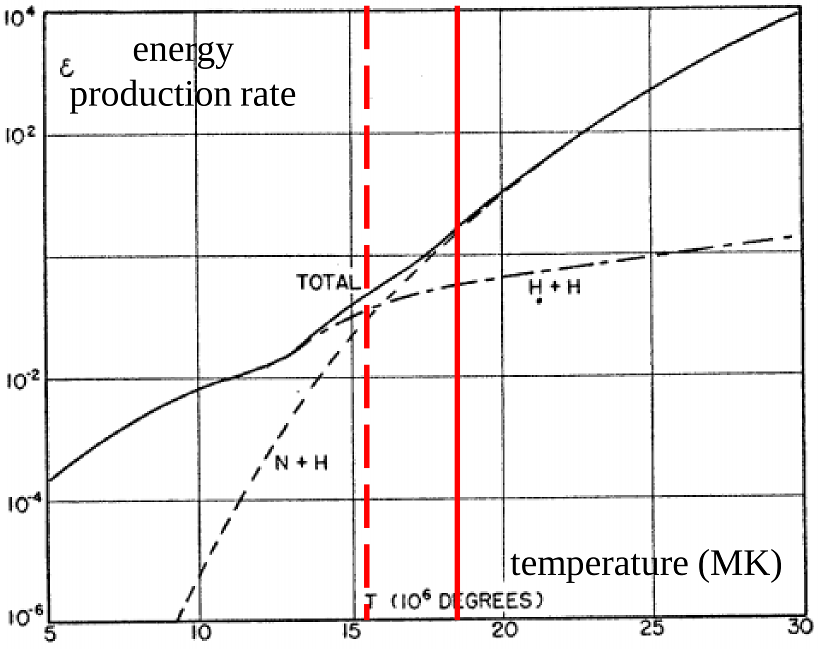


The probability of the astrophysically important reaction $H+H=D+\epsilon^+$ is calculated. For the probability of positron emission, Fermi's theory is used. The penetration of the protons through their mutual potential barrier, and the transition probability to the deuteron state, can be calculated exactly, using the known interaction between two protons. The energy evolution due to the reaction is about 2 ergs per gram per second under the conditions prevailing at the center of the sun (density 80, hydrogen content 35 percent by weight, temperature $2\cdot 10^7$ degrees). This is almost but not quite sufficient to explain the observed average energy evolution of the sun (2 ergs/g sec.) because only a small part of the sun has high temperature and

Energy production in stars 1939



Hans Bethe



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?

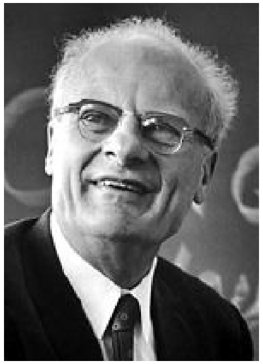
Because it is hot
and it is hot because it is massive

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 gravitational wave source
Nuclear weapons, the arm 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 ^{235}U

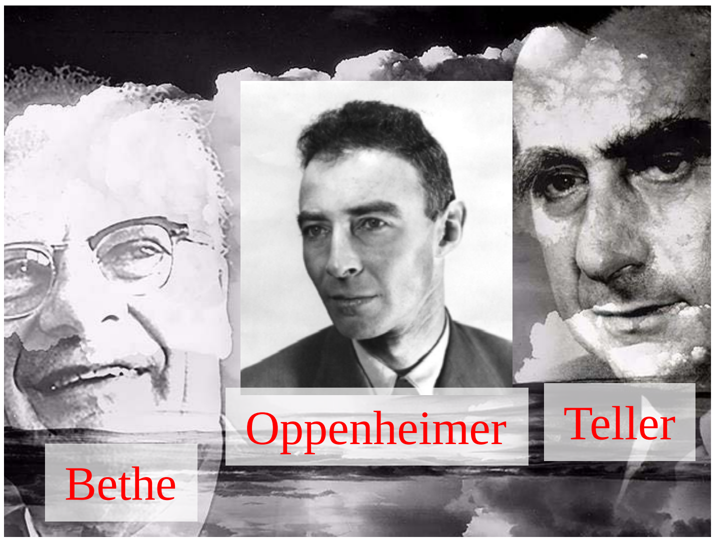
Formula for atomic bomb´s explosive yield
(with Richard Feynman)


Bethe


Fermi


Teller


Feynman



Bethe vs Teller in Oppenheimer affair (1955)

President´s Science Advisory Committee (1956-59)
Member, US Delegation to discussion
discontinuance and nuclear weapons test, 1958-59
scientists movement against the project of
anti-ballistic missiles (1960s) and star wars (1980s)

« 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 (1943) that a nuclear explosion would not ignite a chain reaction of atmospheric Nitrogen

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IGNITION OF THE ATMOSPHERE BY NUCLEAR BOMBS

E. Konopinski
C. Marvin
E. Teller

ABSTRACT

It is shown that, whatever the temperature to which a section of the atmosphere may be heated, no self-propagating chain of nuclear reactions is likely to be started. The energy losses to radiation always overcompensate the gains due to the reactions. This is true even with rather extravagant assumptions concerning the reactivity of the nitrogen nuclei of the air. The only disquieting feature is that the "safety factor", i.e. the ratio of losses to gains of energy, decreases rapidly with initial temperature, and descends to a value of only about 1.6 just beyond a 10-Mev temperature. It is impossible to reach such temperatures unless fission bombs or thermonuclear bombs are used which greatly exceed the bombs now under consideration. But even if bombs of the required volume (i.e., greater than 1000 cubic meters) are employed, energy transfer from electrons to light quanta by Compton scattering will provide a further safety factor and will make a chain reaction in air impossible.