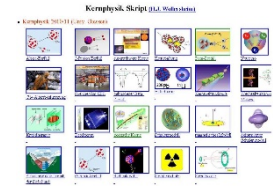


# Outline: A brief history of Nuclear Astrophysics N. Prantzos

Lecturer: Hans-Jürgen Wollersheim

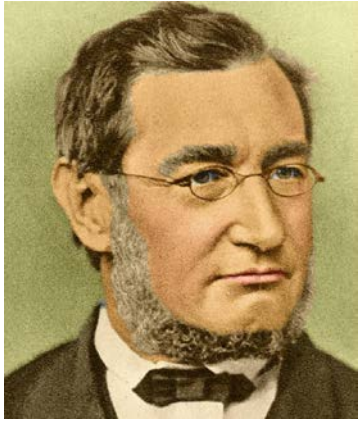
e-mail: [h.j.wollersheim@gsi.de](mailto:h.j.wollersheim@gsi.de)

web-page: <https://web-docs.gsi.de/~wolle/> and click on



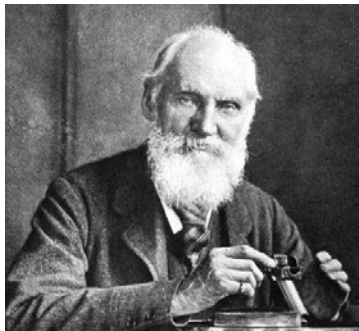
1. thermodynamics
2. subatomic physics
3. Sun's energy
4. quantum-mechanical tunnel effect
5. CNO cycle (Hans Bethe)

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



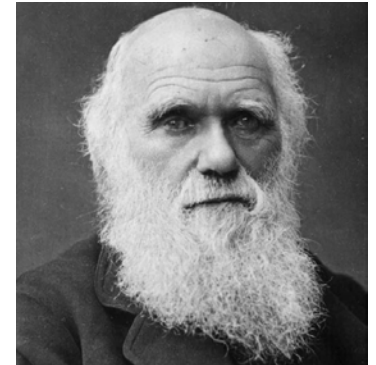
*1847: Robert Julius von Mayer*  
Sun heated by fall of meteors

*1854: Hermann von Helmholtz*  
Gravitational energy of Kant's  
contracting protosolar nebula of gas  
and dust turns into kinetic energy  
timescale  $\sim E_{\text{Grav}}/L_{\text{Sun}} \sim 30 \text{ My}$



*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 wide (\* 1100  
feet high) in 300 My  
*Such large Earth ages also required by  
geologists, like Charles Lyell*



# A gaseous, contracting and heating Sun

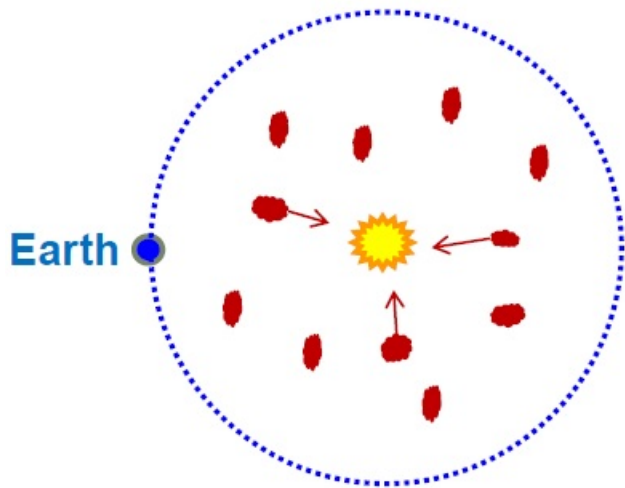
Mean solar density:  $\rho = \frac{M}{\frac{4\pi}{3}R^3} \approx 1.35 \text{ g/cm}^3$

Sun liquid  $\rightarrow$  incompressible

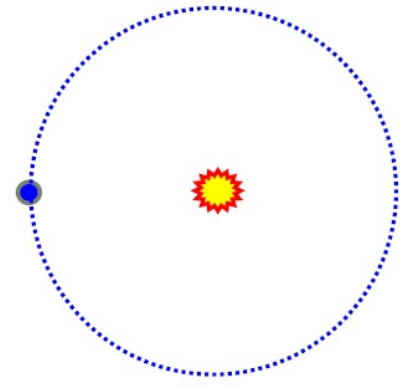
1870s: J. Homer Lane, 1880s: August Ritter :

Sun gaseous  $\rightarrow$  compressible

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



Mayer - Kelvin - Helmholtz



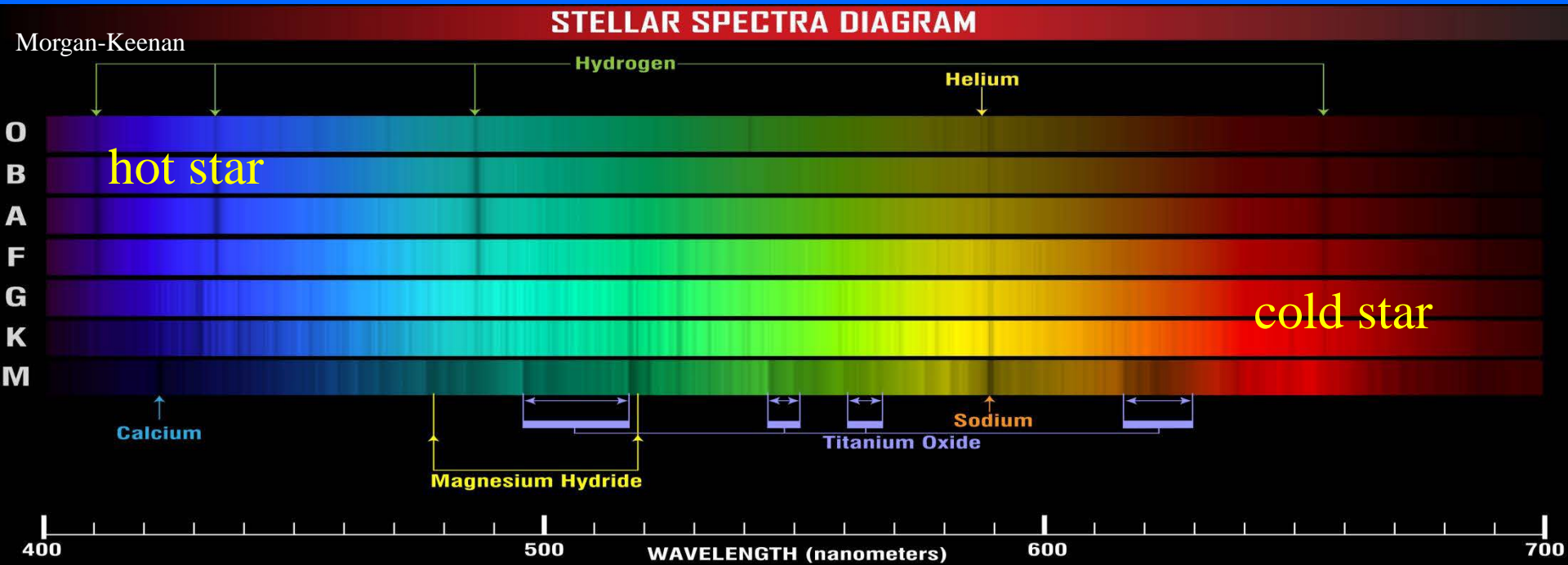
Helmholtz - Ritter

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

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

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 ( $\text{TiO}_2$ ), 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

# Spectral classification

Before astronomers knew much about stars, they classified them based on the strength of observed absorption lines.

Classification by line strength started as A, B, C, D, ....., but became:

O, B, A, F, G, K, M, (L)

**A temperature sequence!**

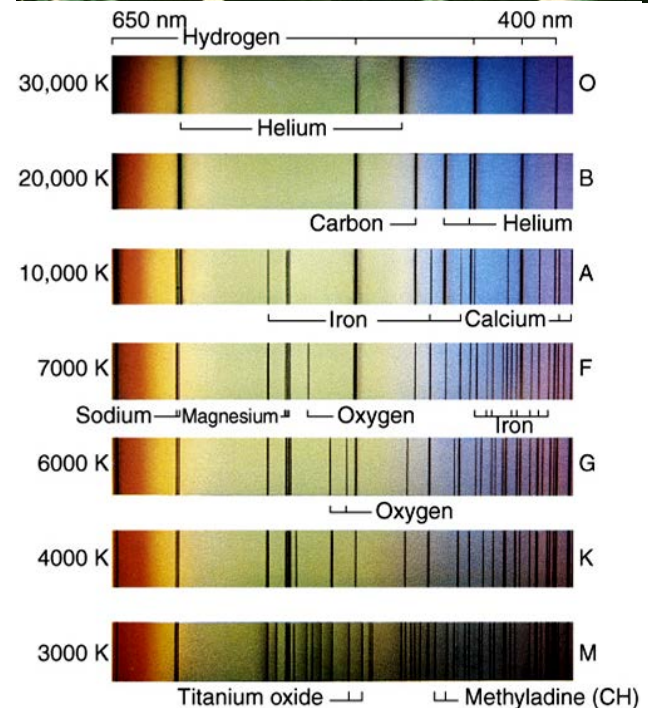
Cannon's system officially adopted in 1910

.

“Oh Be A Fine Girl/Guy Kiss Me”

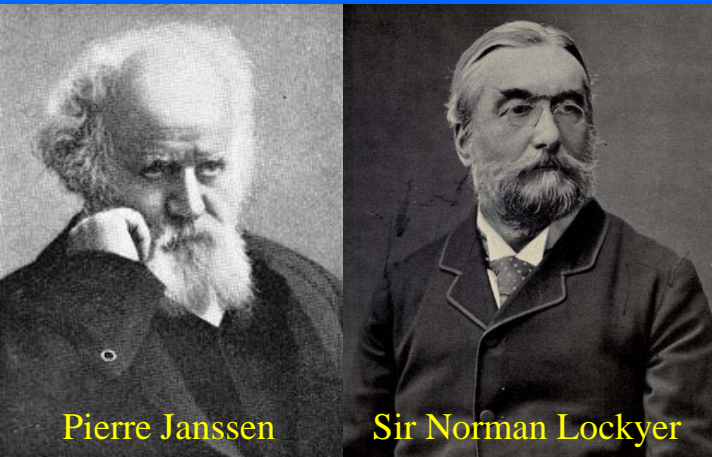


Annie Jump Cannon

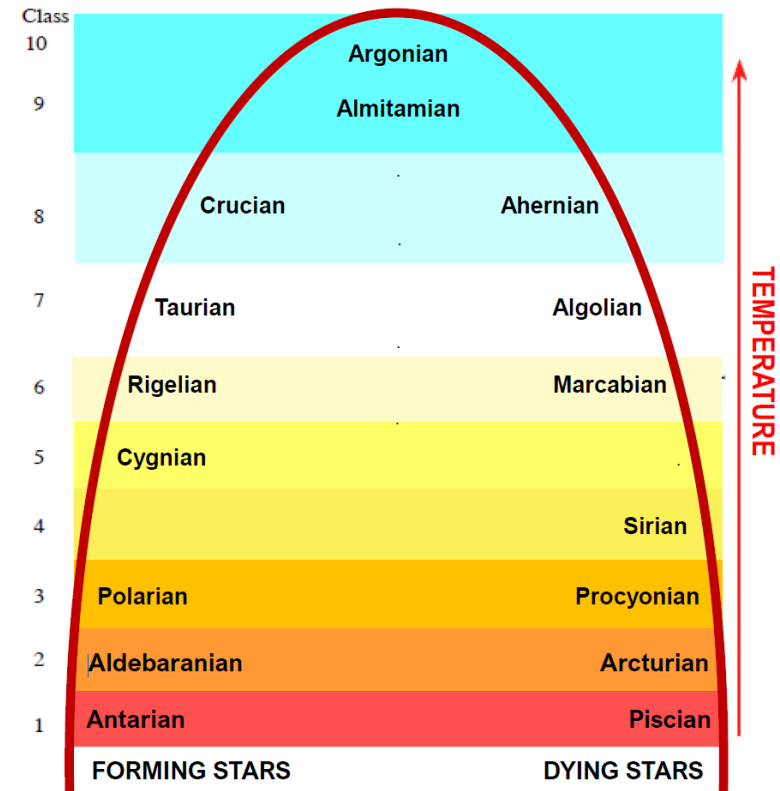
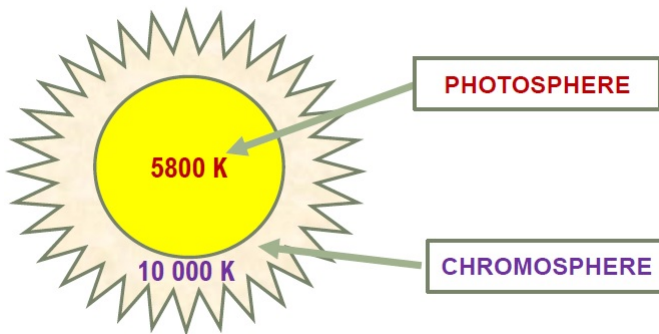




# Spectroscopy reveals Helium in the Sun

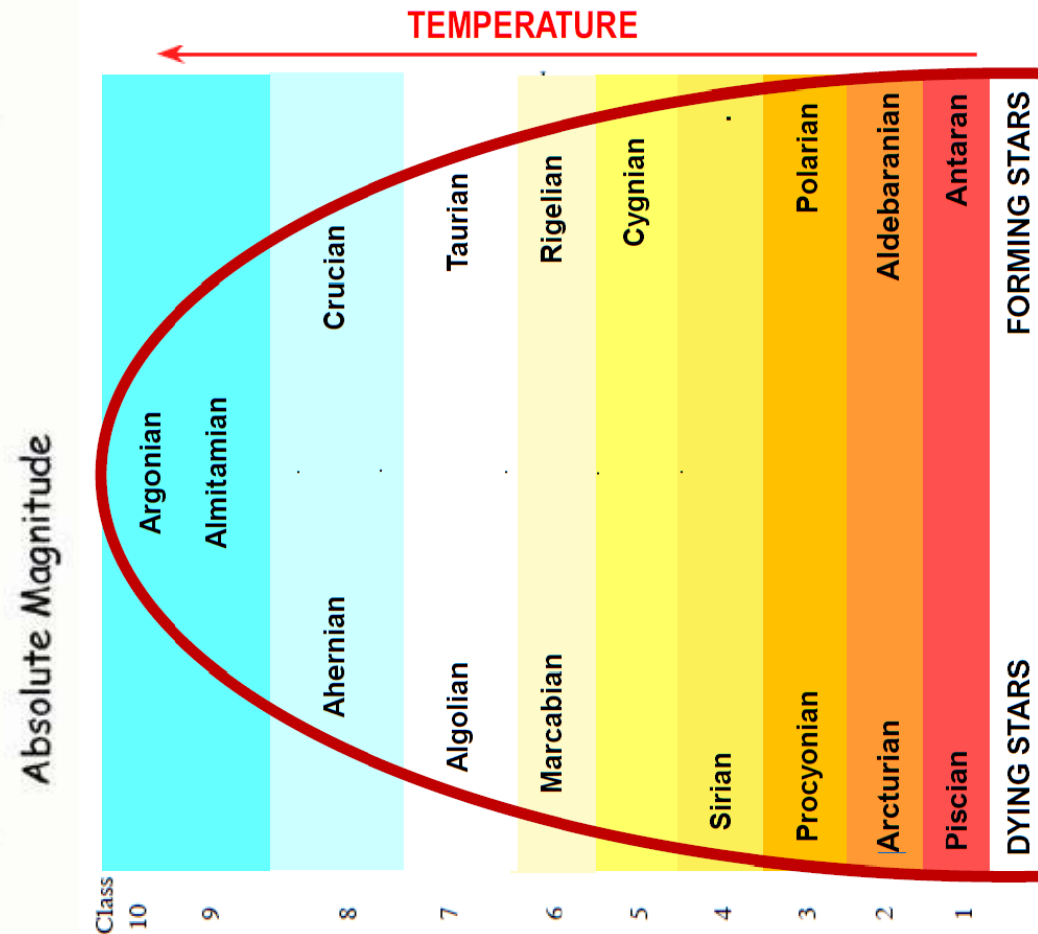
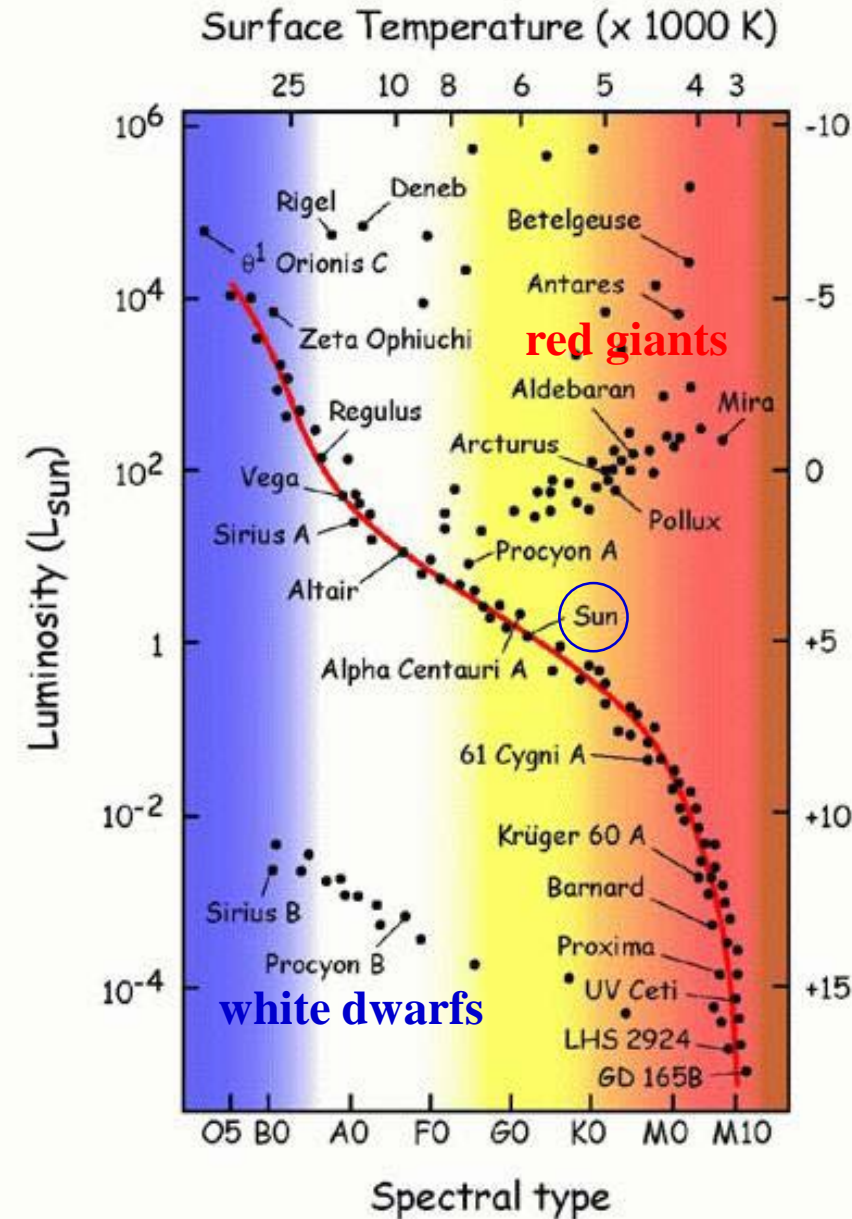


- ❖ 1868 co-discovery of Helium in the Sun's chromosphere during a solar eclipse



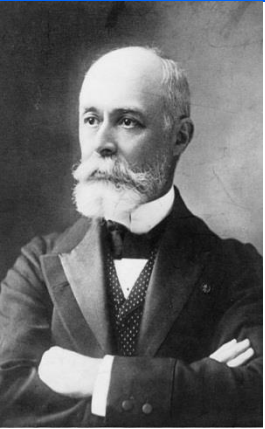
Lockyer's theory of stellar evolution

# Hertzsprung-Russell diagram



Lockyer's theory of stellar evolution:  
running **opposite** to current

# Subatomic physics



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

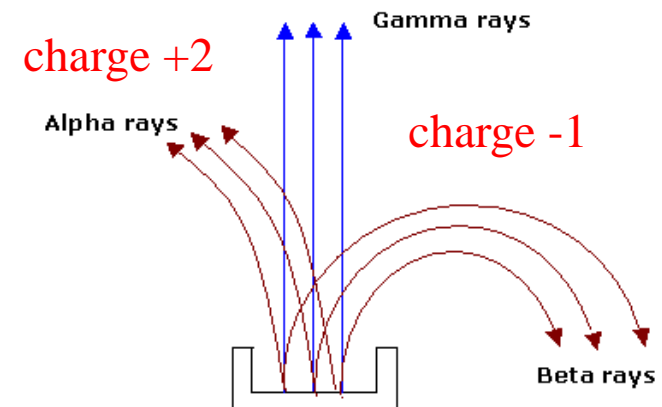
1896-1897: identification of radioactive Po and Ra  
by **Pierre and Marie Curie**



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



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



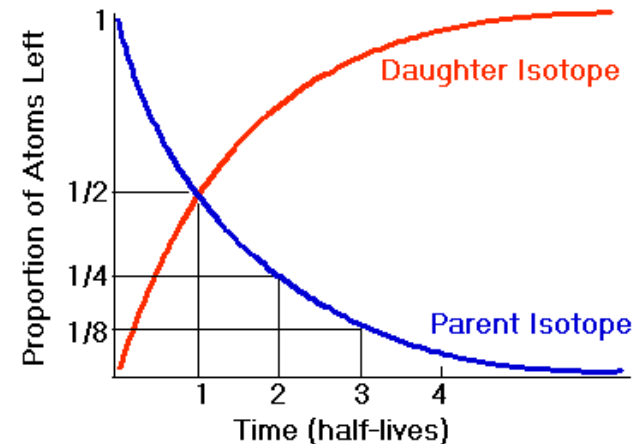


# Radioactivity dating of rocks and energy source



1902: Rutherford-Soddy's  
law of radioactive decay

$$N = N_0 \cdot \exp(-t/\tau)$$



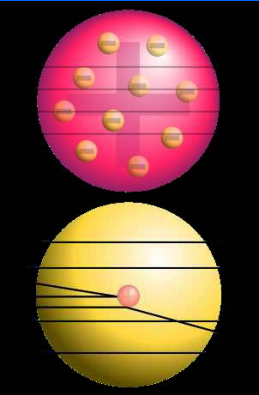
1902: Rutherford shows that **alpha** radiation is **Helium** nuclei  
suggests to use Uranium/Helium for dating

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.*

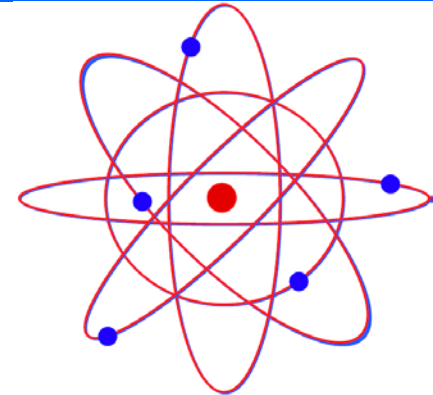
1907 Rutherford: Helium in the Sun results from radioactivity and so does solar energy  
But what makes substances radioactive and how is the energy put there?

# The atomic nucleus and the proton



1909: **Geiger-Marsden experiment**

strong deflection of some  $\alpha$  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  $\sim 10^{-15}$  m**

1919 **Rutherford** produces hydrogen nuclei bombarding nitrogen with  $\alpha$  particles



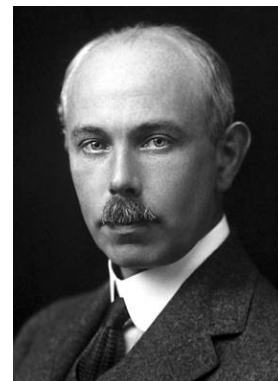
1920: Rutherford names the hydrogen nucleus **proton (charge +1)**

1910s: development of mass spectrograph

by **Francis William Aston**

identification of isotopes and measurements of their masses

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



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



1915: William Draper Harkins

First ideas (rather confused)

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  $L = 4 \cdot 10^{26}$  J/s

Time  $t = 4.5$  Gy  $= 1.35 \cdot 10^{17}$  s

Energy = Luminosity \* Time  $= 5 \cdot 10^{43}$  Joule

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

Sun's mass  $m = 2 \cdot 10^{30}$  kg

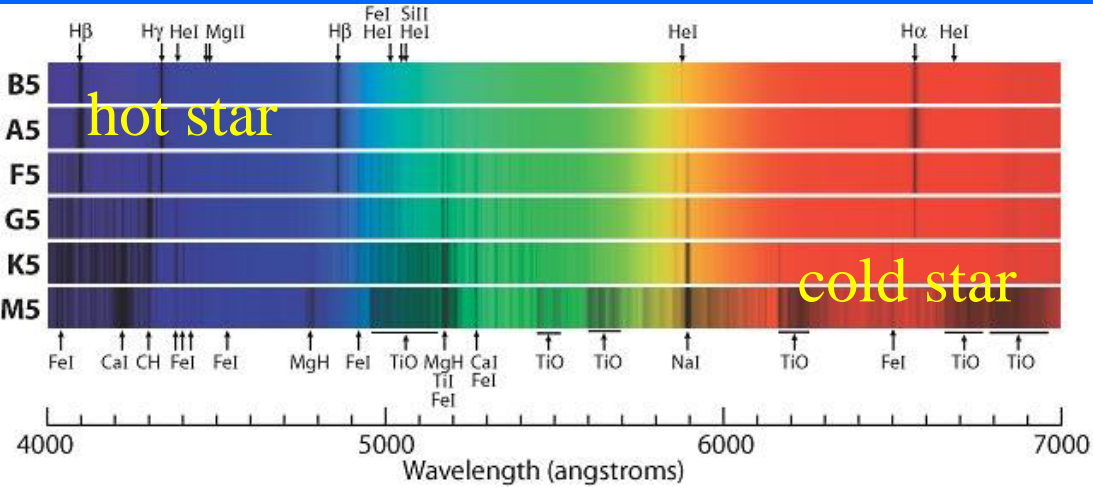
nuclear energy available  $E(\text{nuclear}) = \varepsilon \cdot f \cdot m \cdot c^2$

Fraction of Sun's mass (in hydrogen) which participated in nuclear reactions in the past  $t = 4.5$  Gy

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

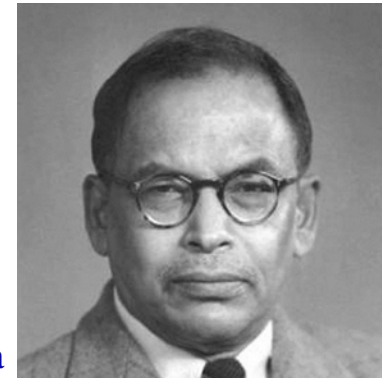
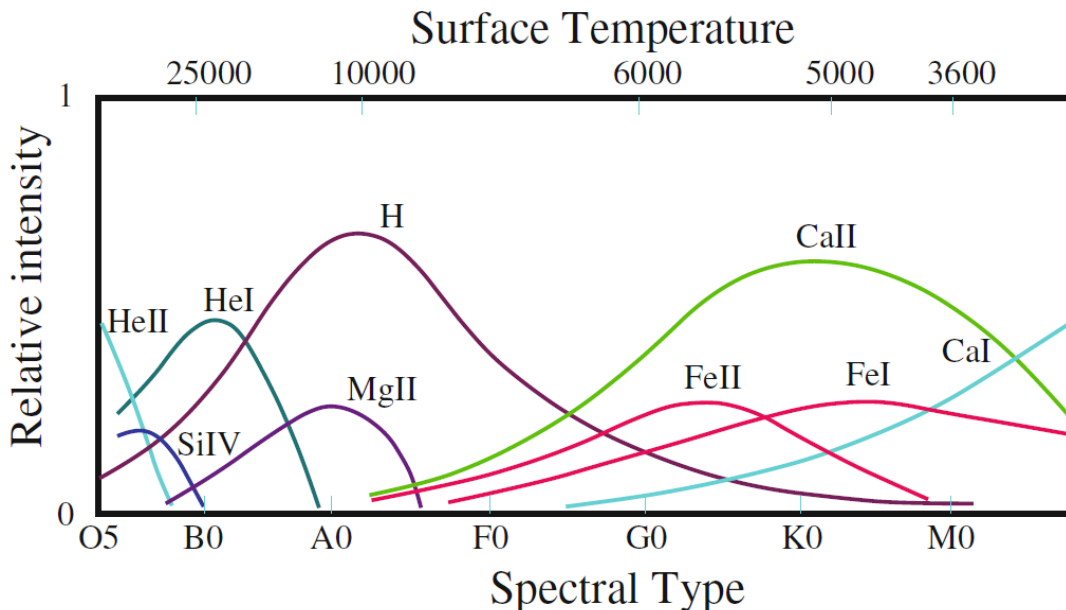
How much hydrogen is there in the Sun?

**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 <sup>+</sup>	12	20	Ca <sup>+</sup>	5.0
3	Li	0.0	22	Ti	4.1
6	C <sup>+</sup>	4.5	23	V	3.0
11	Na	5.2	24	Cr	3.9
12	Mg	5.6	25	Mn	4.6
12	Mg <sup>+</sup>	5.5	26	Fe	4.8
13	Al	5.0	30	Zn	4.2
14	Si	4.8	38	Sr	1.8
14	Si <sup>+</sup>	4.9	38	Sr <sup>+</sup>	1.5
14	Si <sup>+++</sup>	6.0	54	Ba <sup>+</sup>	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  $10^{11}$

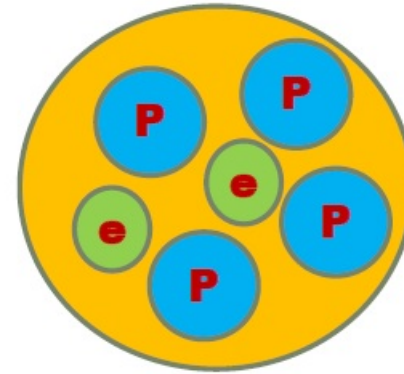
The outstanding discrepancies between the astrophysical and terrestrial abundances are displayed for hydrogen and helium. The enormous abundance derived for these elements in the stellar atmosphere is almost certainly not real. Probably the result may be considered, for hydrogen, as another aspect of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

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

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

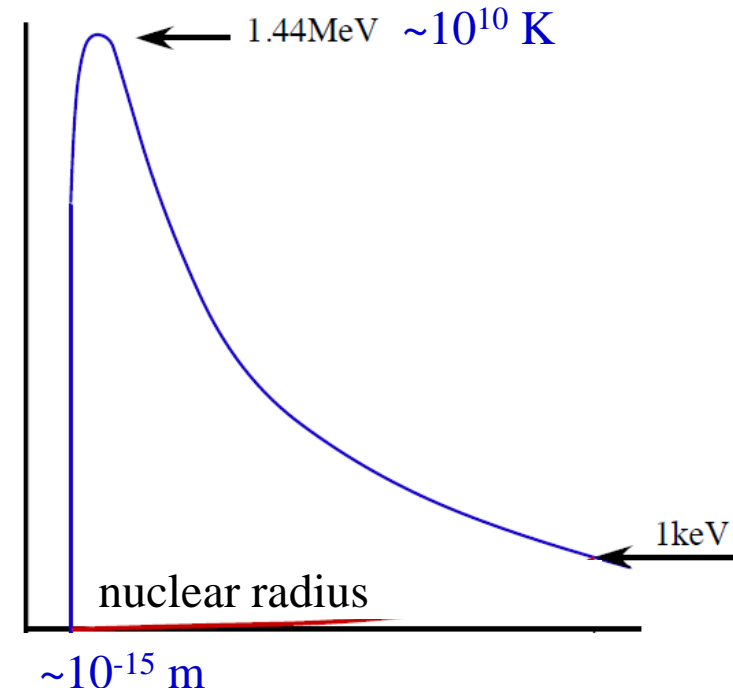


## Problem 2: How to bring just 2 protons together?

Enormous temperatures ( $T > 10^{10}$  K)  
are required, so that particles have enough  
kinetic energy  $E \sim kT$  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*

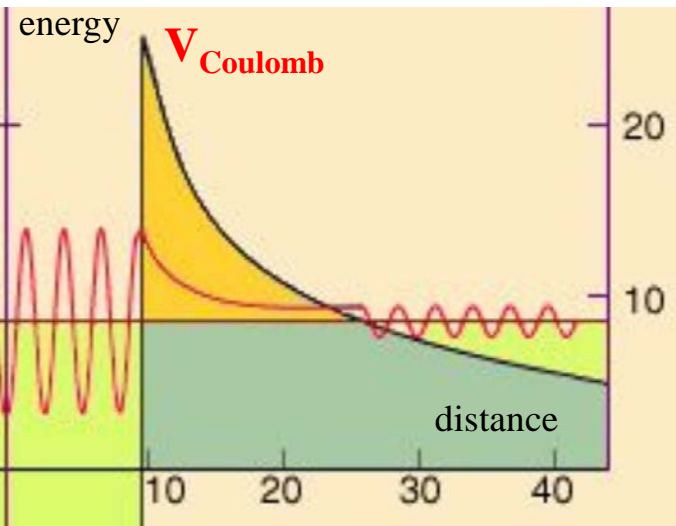


# George Gamow light at the end of the tunnel

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



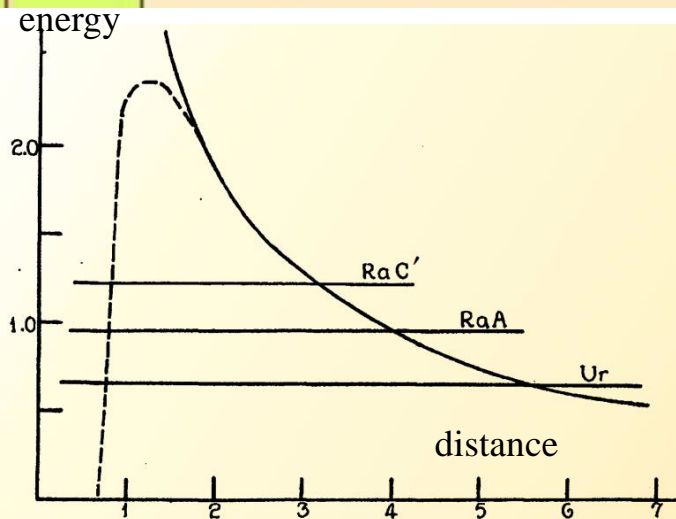
George Gamow



quantum-mechanical tunnel effect (1928):

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

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



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



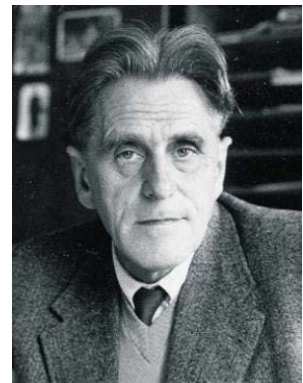
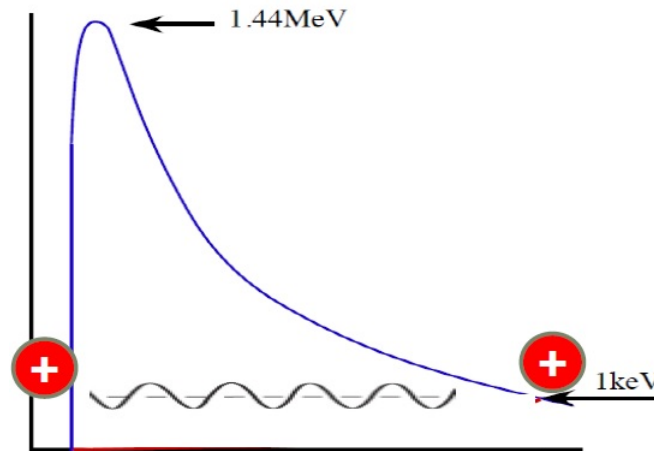
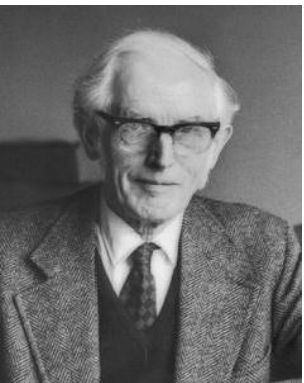
Edward Condon

# 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-



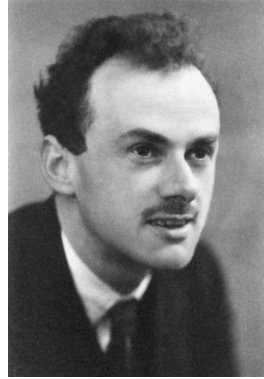
Proton fusion may indeed occur in temperatures at the center of the Sun, thanks to the tunnel effect

**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  $\sim 2 \cdot m_p$ )  
Harold Urey



1932: discovery of Neutron (mass  $\sim m_p$ , charge = 0)  
James Chadwick



1932: discovery of Positron (mass  $\sim m_e$ , charge +1)  
Carl Anderson



1934: development of the theory of  $\beta$ -decay  
Enrico Fermi

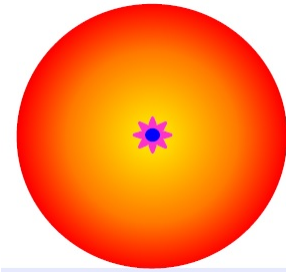


# Neutron star



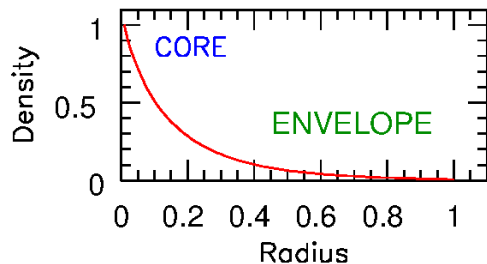
Niels Bohr & Lev Landau

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

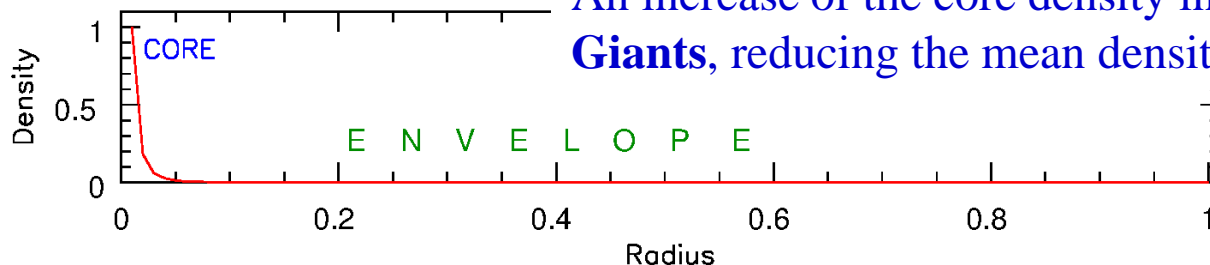


Thus we can regard a star as a body which has a neutronic core the steady growth of which liberates the energy which maintains the star at its high temperature ; the condition at the boundary between the two phases is as usual the equality of chemical potentials. The detailed investigation of such a 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]*

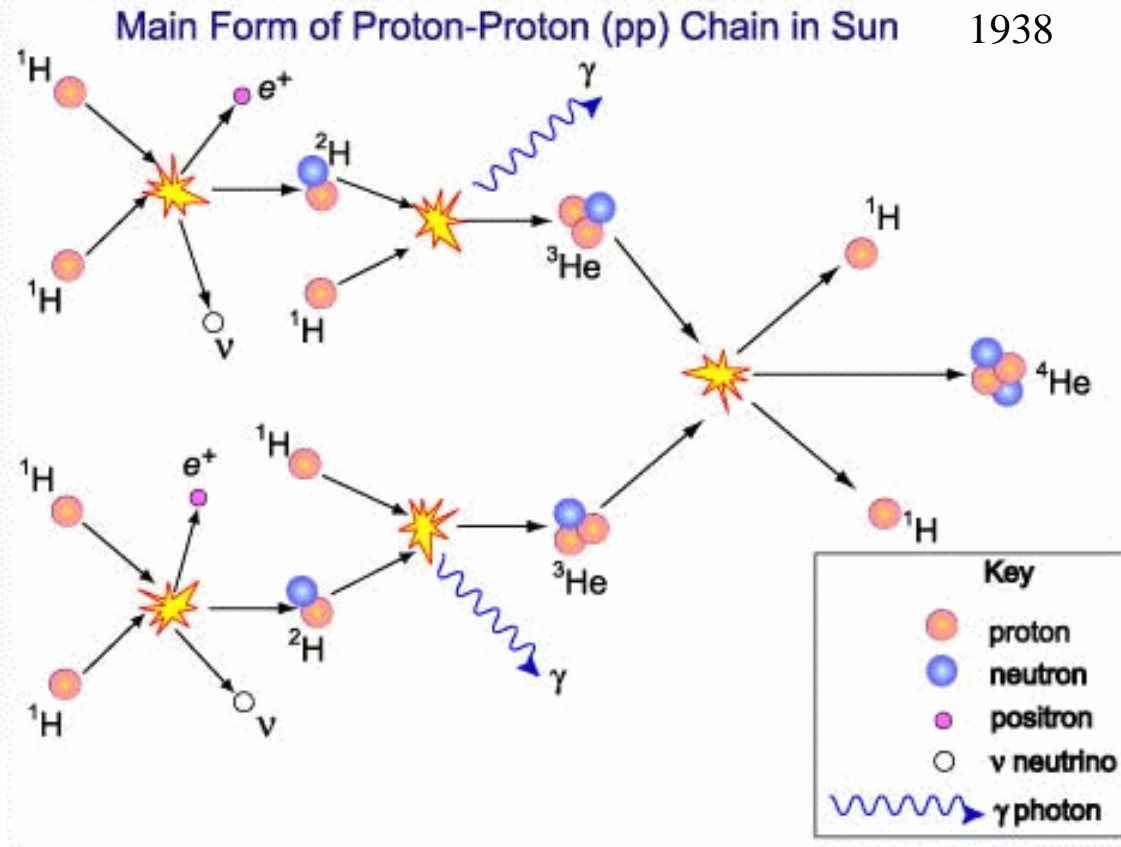
As another possibility the reaction  ${}^1_1\text{H} + {}^1_1\text{H} \rightarrow {}^2_1\text{H} + \beta^+$  was suggested. It seems that the rate of such a reaction under the conditions in stellar interiors would be just enough to account for the radiation of the sun, though for stars much brighter than the sun other more effective sources of energy are required.



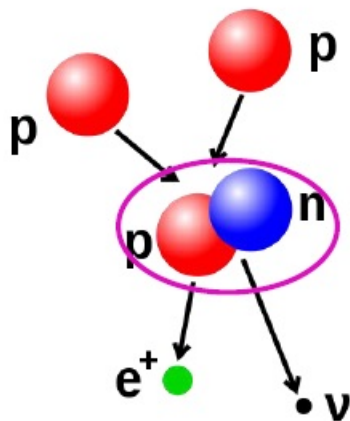
# The formation of Deuterons by proton combination



Hans Bethe

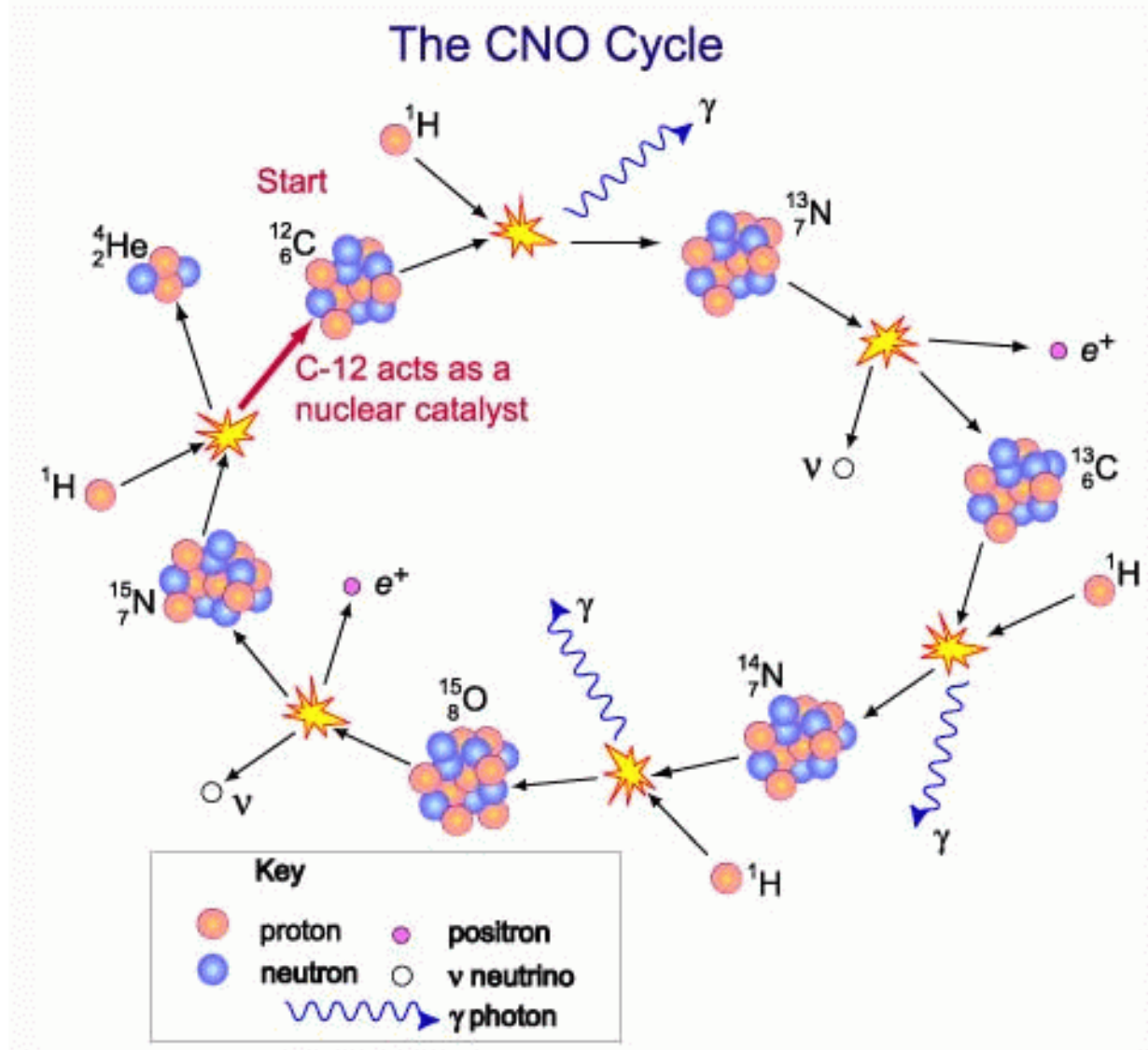


Charles Critchfield

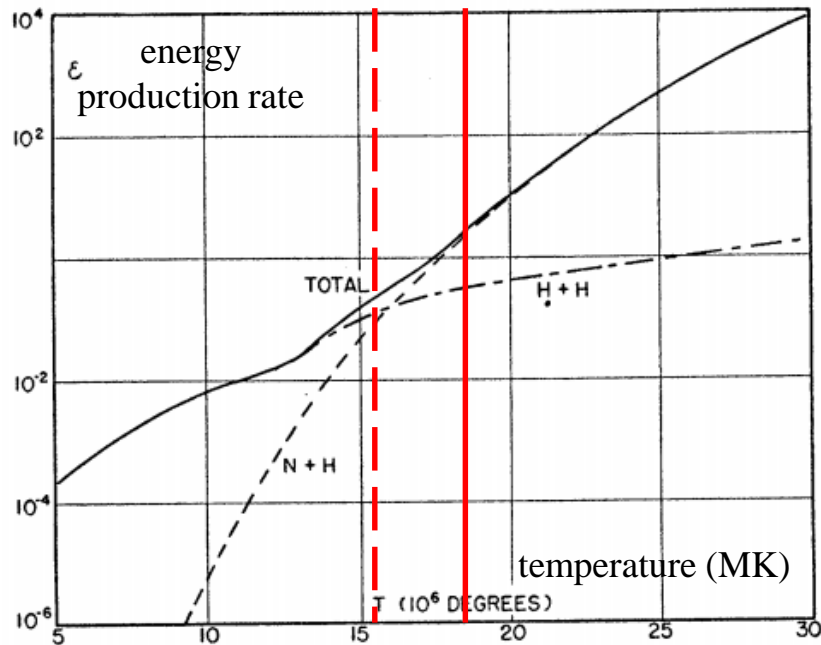


The probability of the astrophysically important reaction  $H+H=D+\epsilon^+$  is calculated. For the probability of positron emission, Fermi's theory is used. The penetration of the protons through their mutual potential barrier, and the transition probability to the deuteron state, can be calculated 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 ( $\alpha$ -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  $^{235}\text{U}$

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.