Astronomy 350L

(Fall 2006)

The History and Philosophy of Astronomy

(Lecture 17: Birth of Astrophysics II)

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TA: Jarrett Johnson

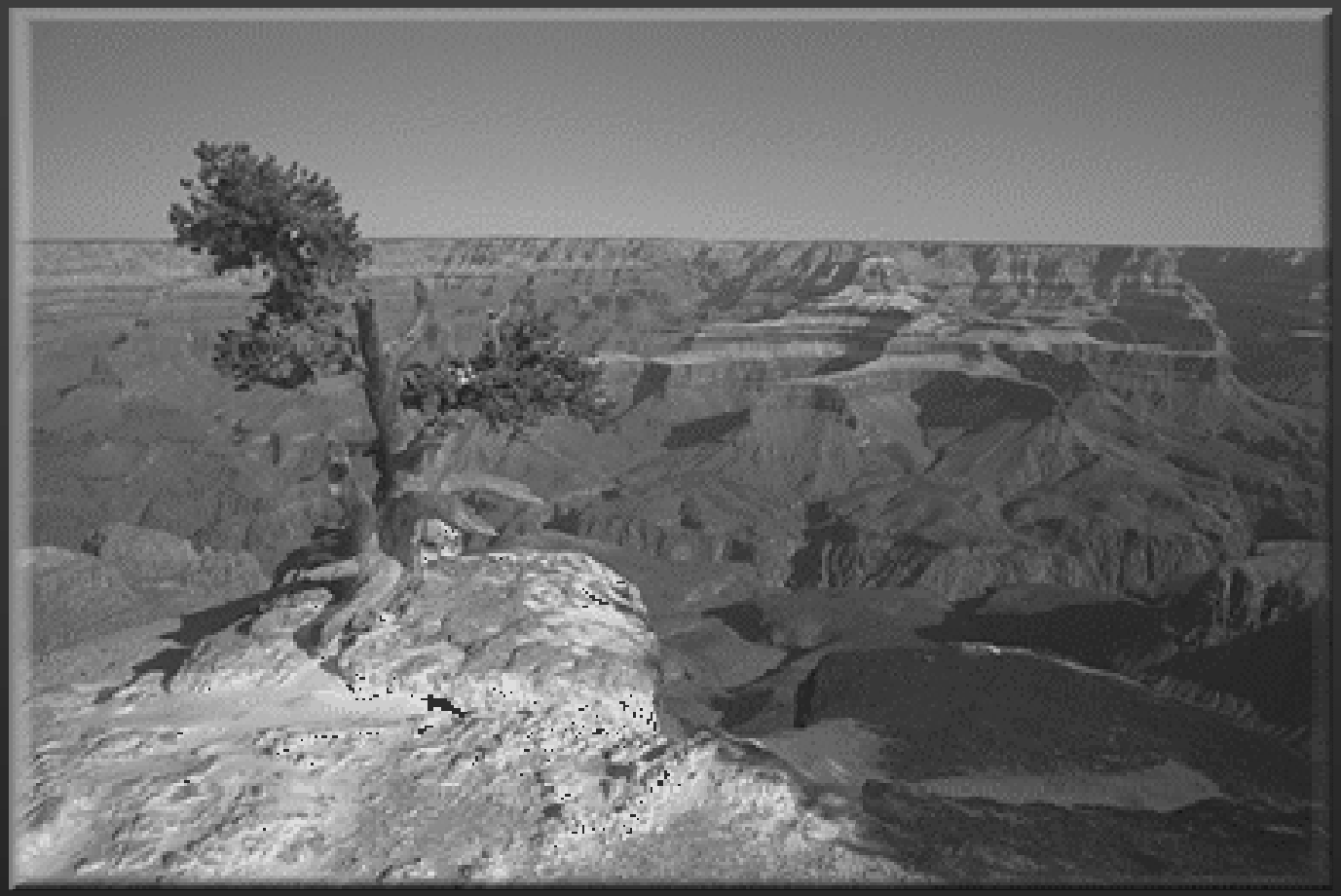
The University of Texas at Austin

- **Which questions would an astronomer have asked about the stars in the early 1800s?**
  - How far away are they (stellar distance scale)?
  - What are the stars made of (stellar composition)?
  - How massive are they?
  - How long do they live (stellar lifetimes)?
  - By what mechanism do they shine?
  - Is the Sun just a (nearby) star?
    A: Yes, already widely believed (Descartes, Newton)

The Great Age Controversy

- one of the biggest riddles of the 19th century!
  - Claim 1: Earth must be very old (billions of years):
    - geological time
    - biological (evolutionary) time
  - Claim 2: World cannot be so old:
    - Earth would have cooled too much by now!
    - Sun cannot shine for so long!

Geological Timescale



- Big Q: How was Grand Canyon created?
  A: in a single, catastrophic event (catastrophism)?
  B: slowly, over many eons (uniformitarianism)?

Catastrophism: A Young Earth

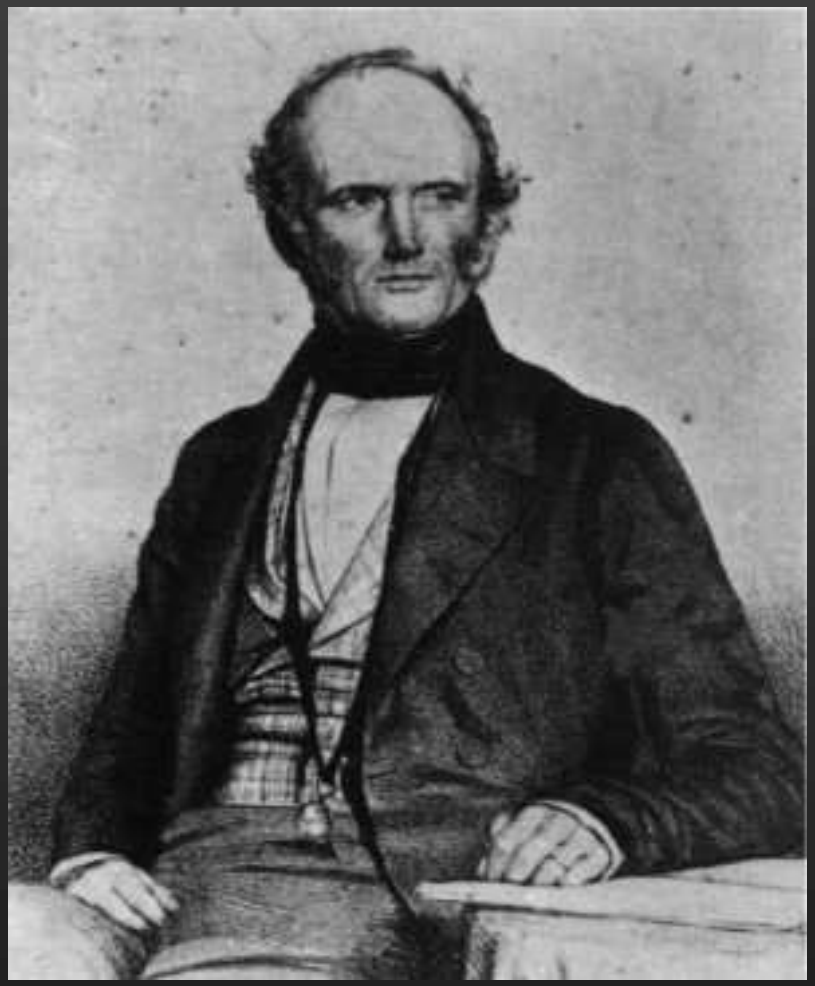
- James Ussher (Archbishop of Armagh, 1581-1656)

- calculated (using the Bible) when God created the universe:

Oct. 23rd, 4004 BC (Sunday, 8pm)

Age of Earth = few 1,000 years

Geological Timescale



- Charles Lyell (1797-1875)
- 1830: *Principles of Geology*

  - convincingly makes case for uniformitarianism
  - age of the Earth = few billion years

Geological Timescale

PRINCIPLES

OF

GEOLOGY,

BEING

AN ATTEMPT TO EXPLAIN THE FORMER CHANGES
OF THE EARTH'S SURFACE,

BY REFERENCE TO CAUSES NOW IN OPERATION.

BY

CHARLES LYELL, Esq., F.R.S.

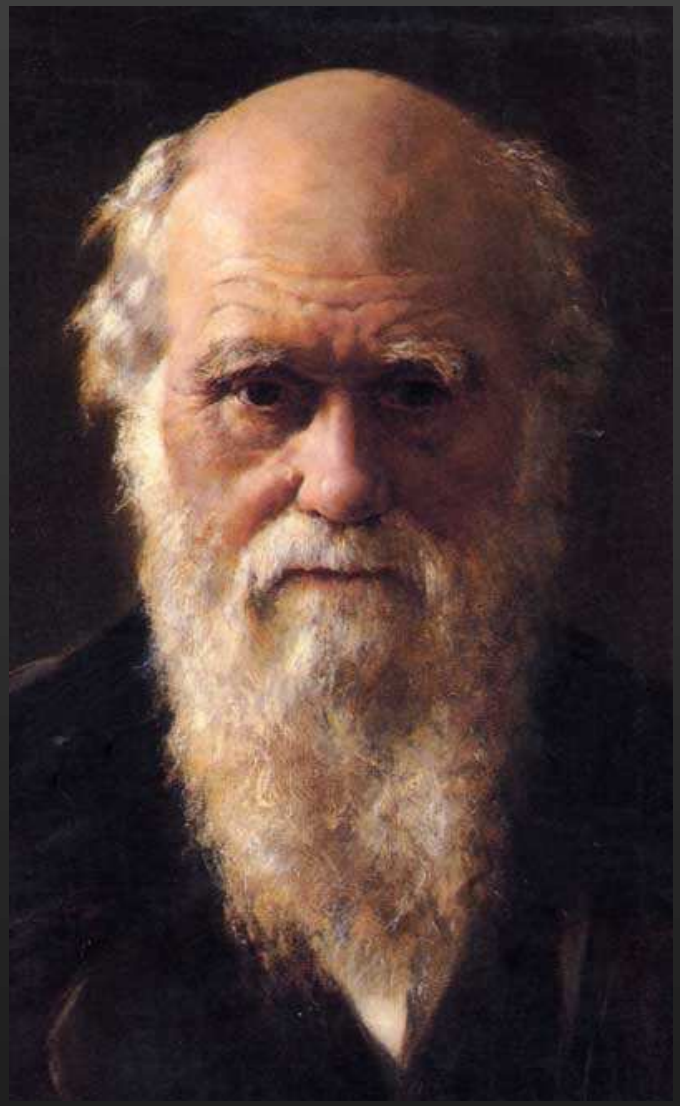
IN TWO VOLUMES.

Vol. I.

LONDON:

JOHN MURRAY, ALBEMARLE-STREET.

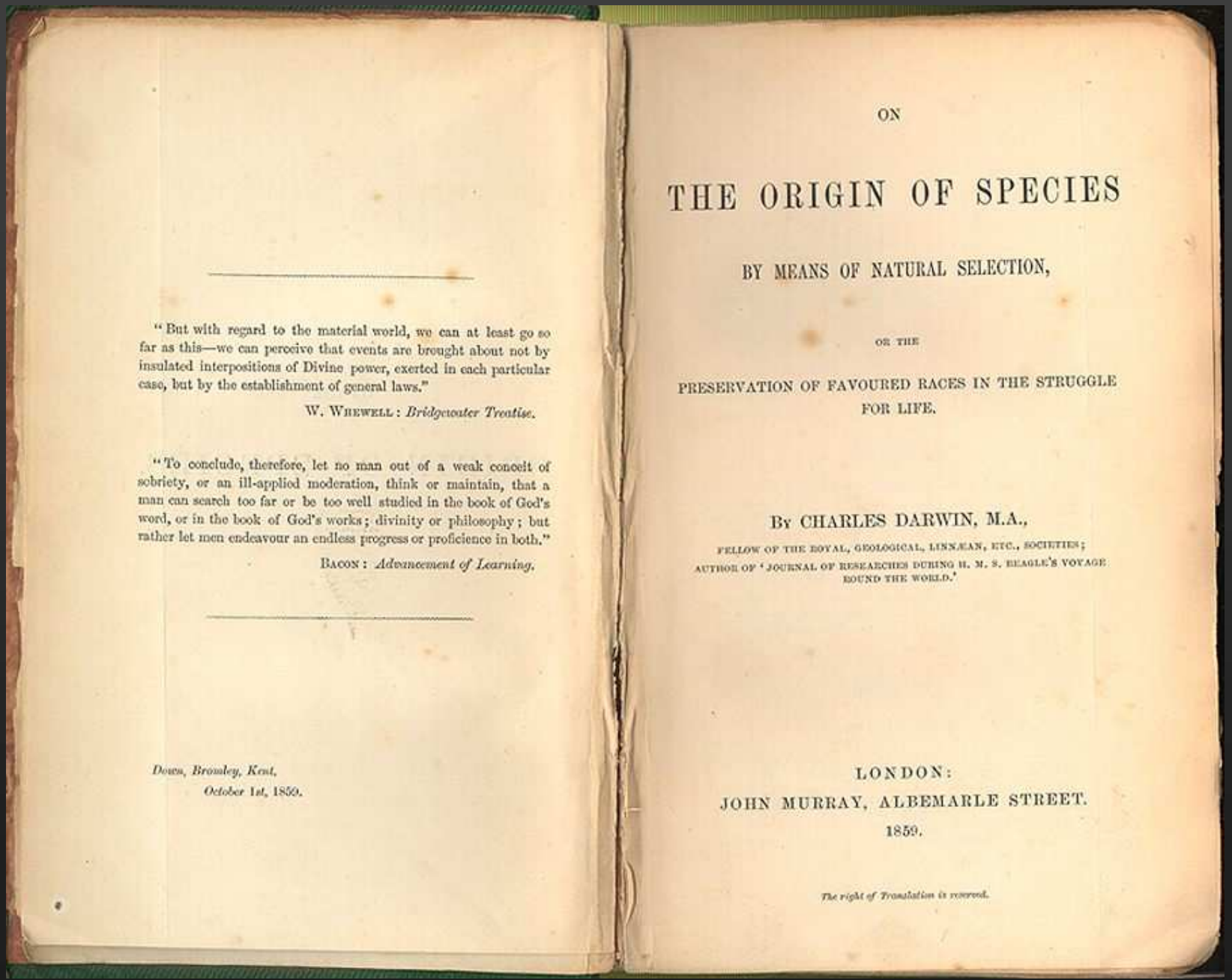
Biological Timescale



- Charles Darwin (1809-82)
- 1859: *Origin of Species*

  - theory of evolution:
    - random mutation
    - natural selection
  - age of the Earth =
    few billion years

Biological Timescale



"But with regard to the material world, we can at least go so far as this—we can perceive that events are brought about not by insulated interpositions of Divine power, exerted in each particular case, but by the establishment of general laws."

W. Whewell: *Bridgewater Treatise.*

"To conclude, therefore, let no man out of a weak conceit of sobriety, or an ill-applied moderation, think or maintain, that a man can search too far or be too well studied in the book of God's word, or in the book of God's works; divinity or philosophy; but rather let men endeavour an endless progress or proficience in both."

Bacon: *Advancement of Learning.*

Down, Bromley, Kent,
October 1st, 1859.

ON

THE ORIGIN OF SPECIES

BY MEANS OF NATURAL SELECTION,

OR THE

PRESERVATION OF FAVOURED RACES IN THE STRUGGLE FOR LIFE.

By CHARLES DARWIN, M.A.,

FELLOW OF THE ROYAL, GEOLOGICAL, LINNÆAN, ETC., SOCIETIES;
AUTHOR OF 'JOURNAL OF RESEARCHES DURING H. M. S. BEAGLE'S VOYAGE ROUND THE WORLD.'

LONDON:
JOHN MURRAY, ALBEMARLE STREET.
1859.

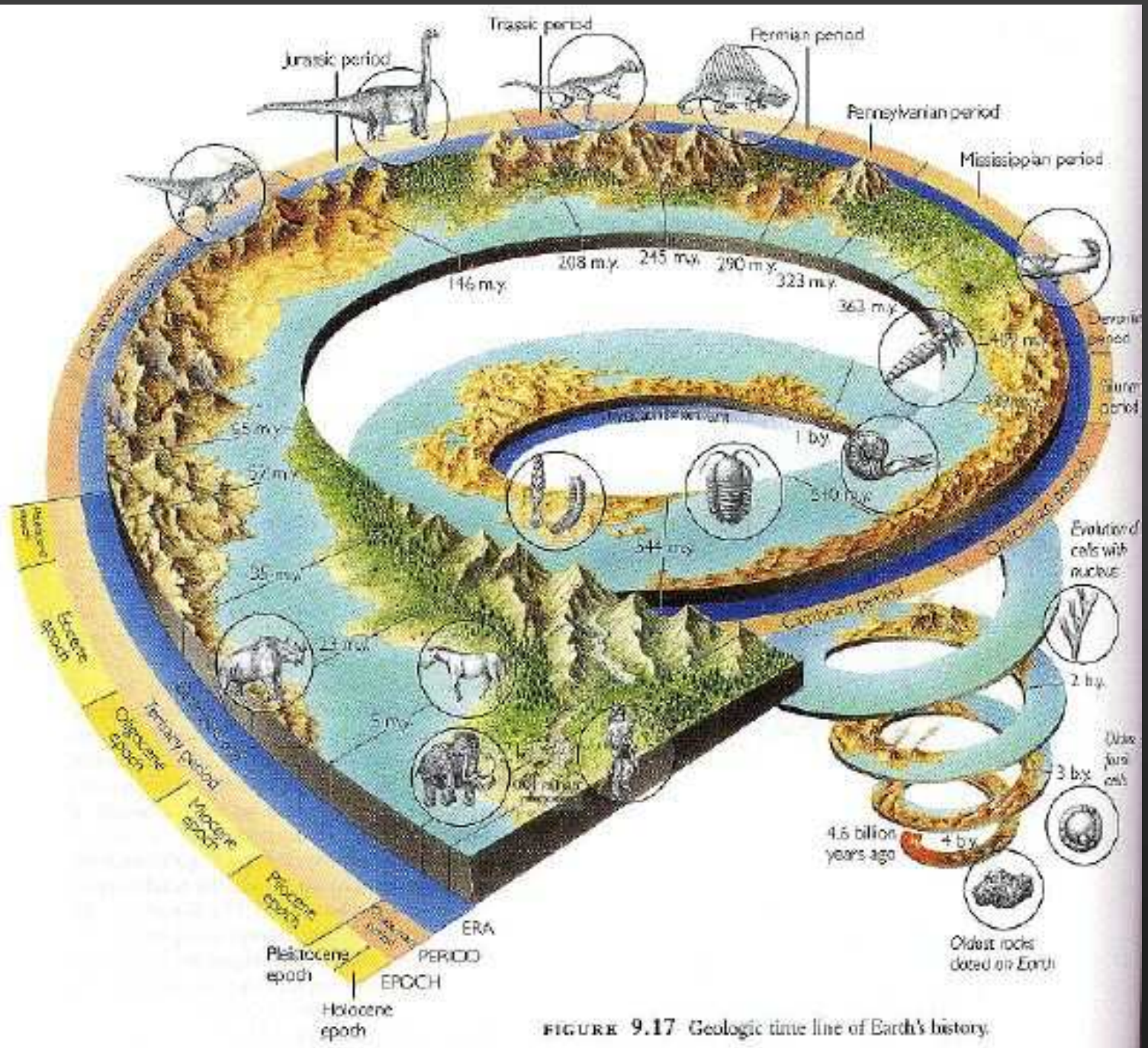
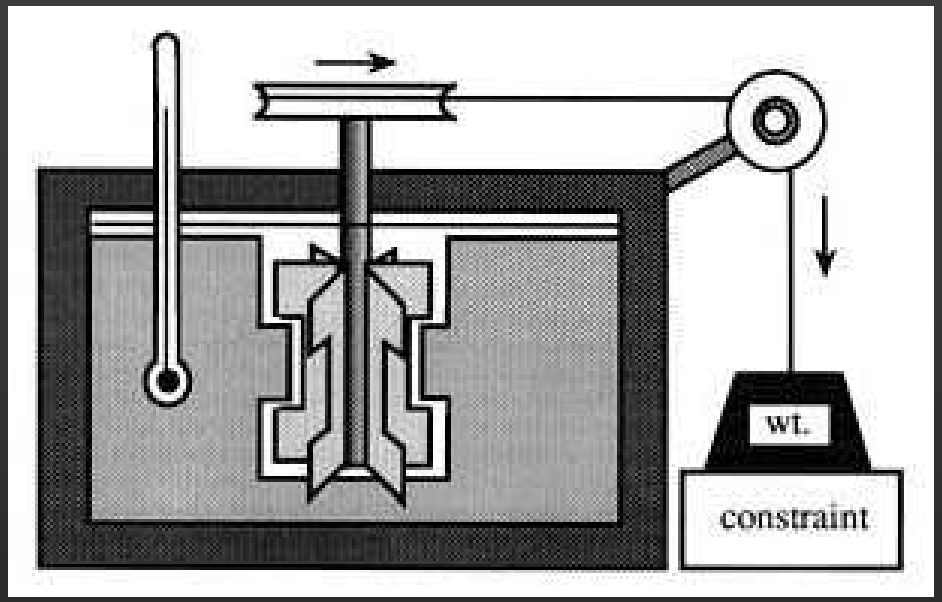


FIGURE 9.17 Geologic time line of Earth's history.

1850s: Conservation of Energy

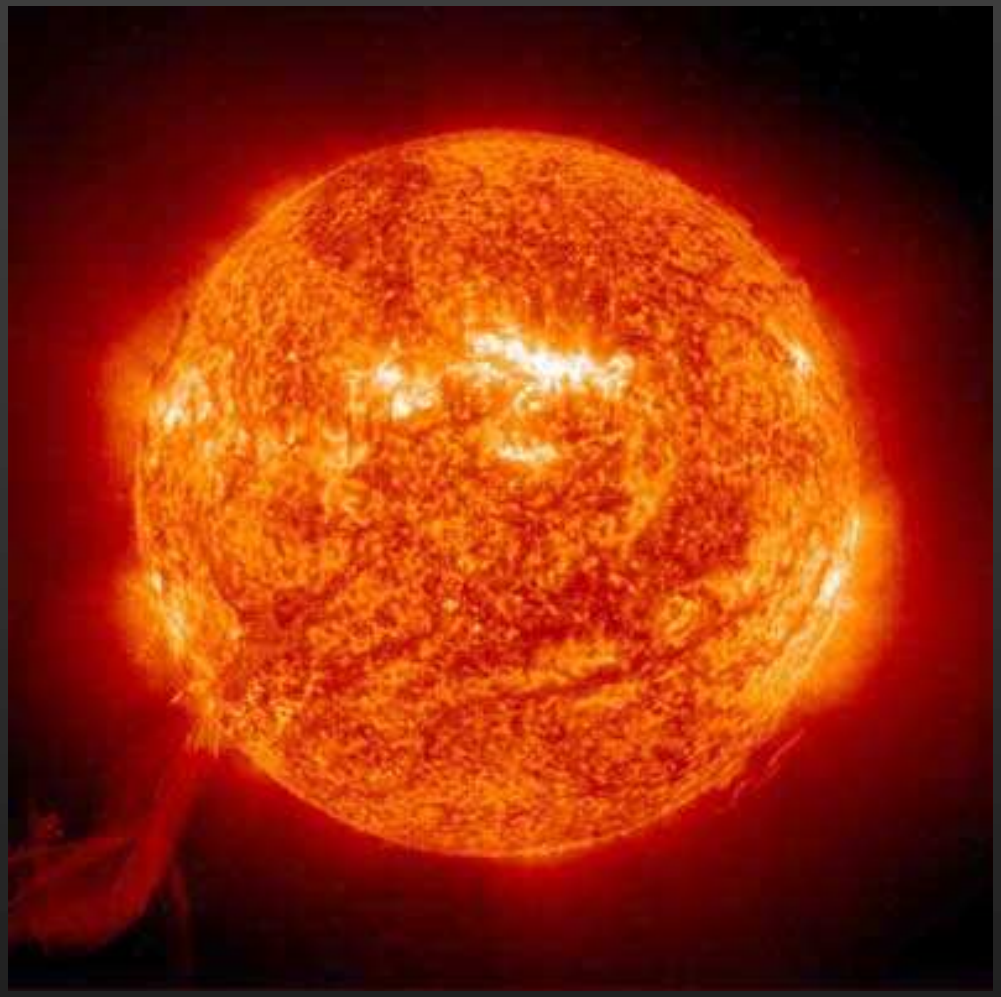
James Joule (1818-89)



- In a closed system (e.g., universe):

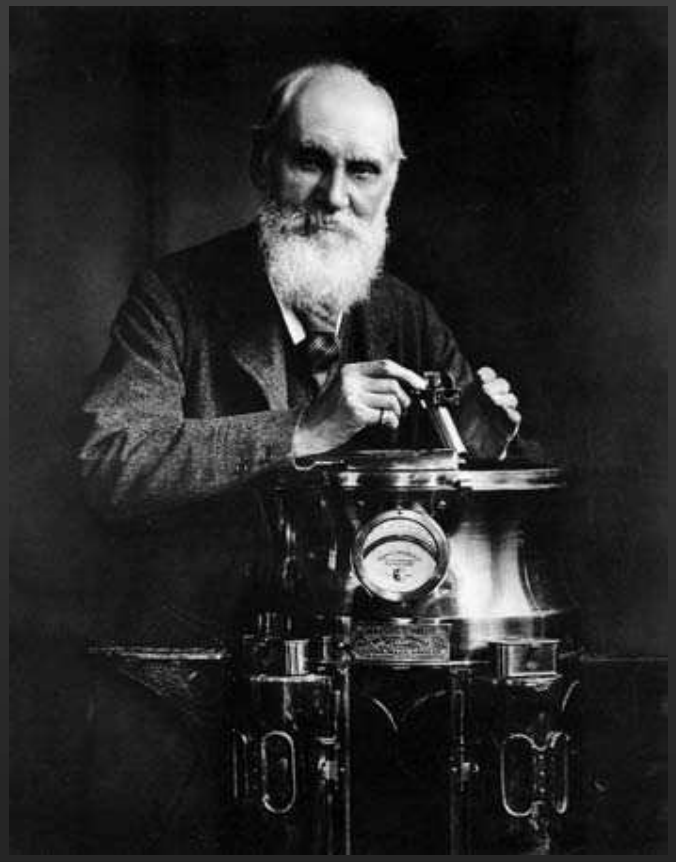
ENERGY=constant

How much Energy does the Sun contain?



- Sun's lifetime=
  total energy/luminosity
- Chemical energy
  - Sun made up of coal
  - age = few 1,000 years
- What powers the Sun (and the stars)???

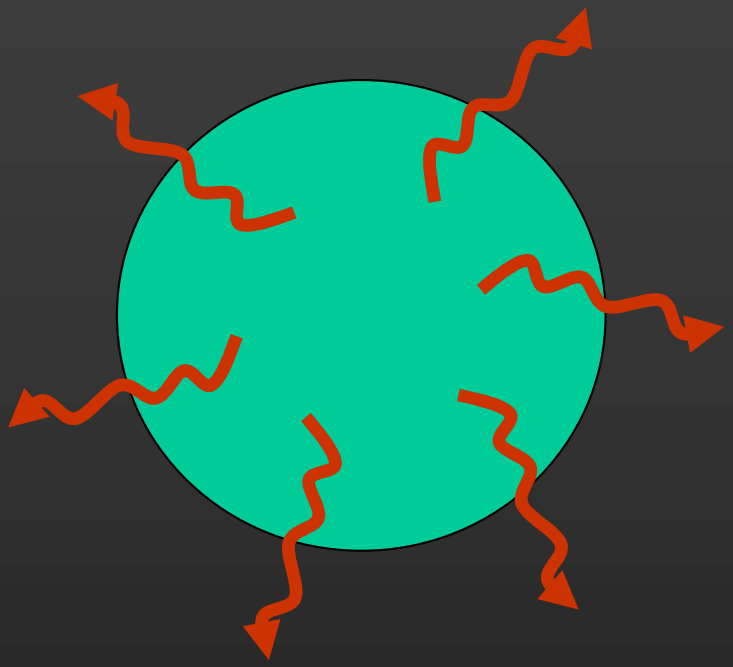
Powering the Sun: Gravitational Energy???



Lord Kelvin (1824-1907)

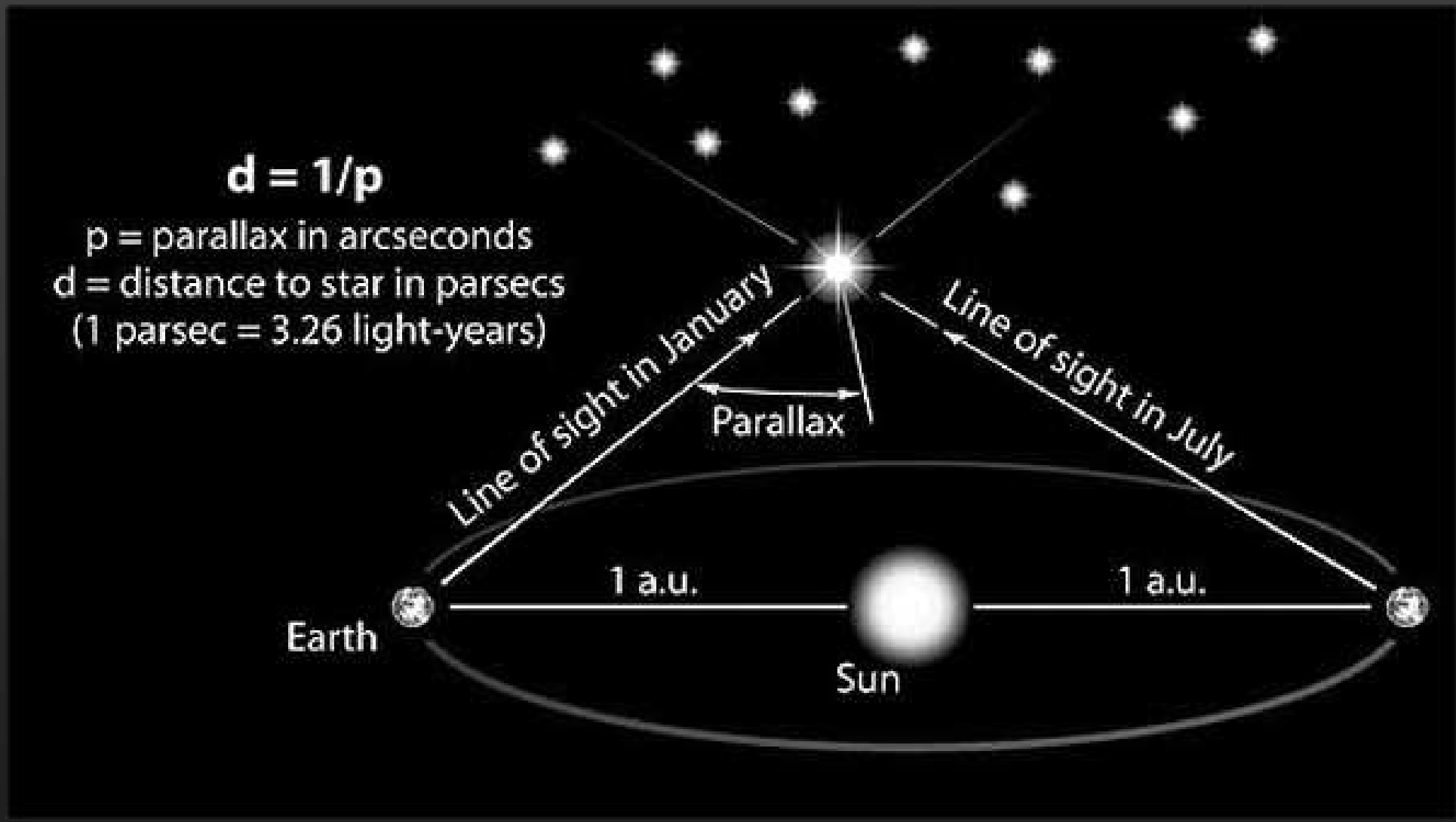
Hermann von Helmholtz (1821-94)

Powering the Sun: Gravitational Energy???

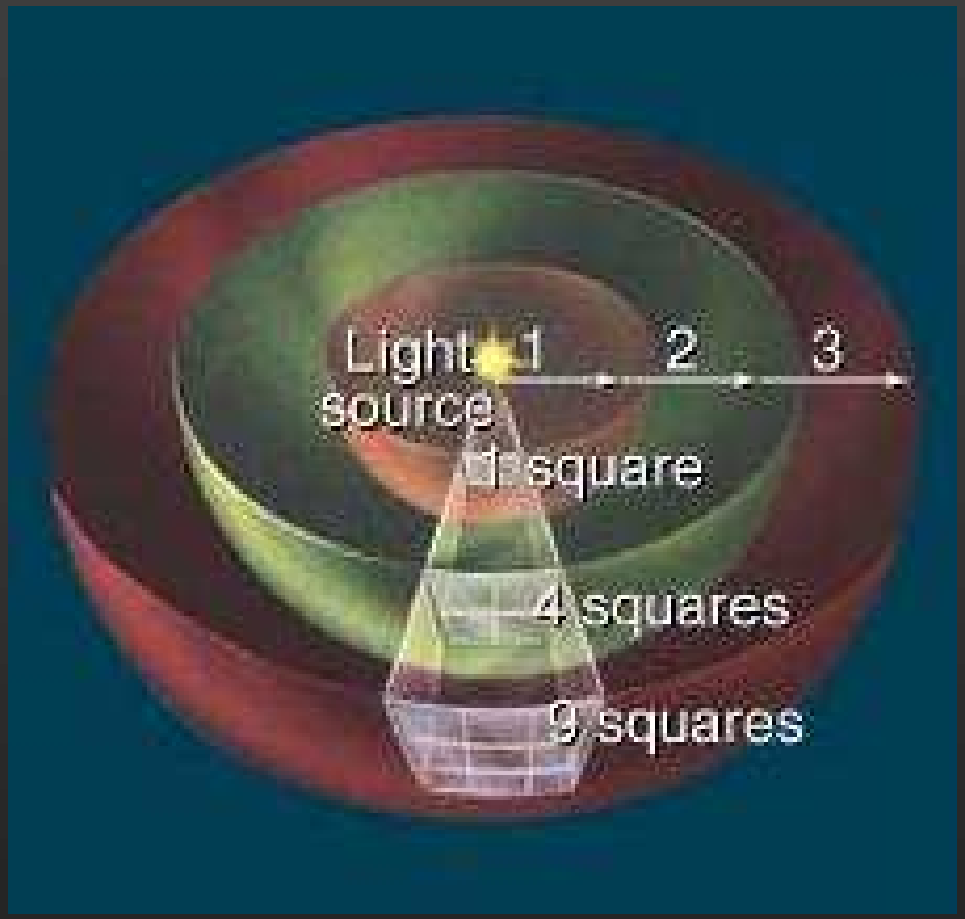


- Kelvin-Helmholtz contraction:
  - for the Sun: age = few million years
    (compared to billions of years required)
  - need even more efficient energy source!

Stellar Distances: From Parallax!



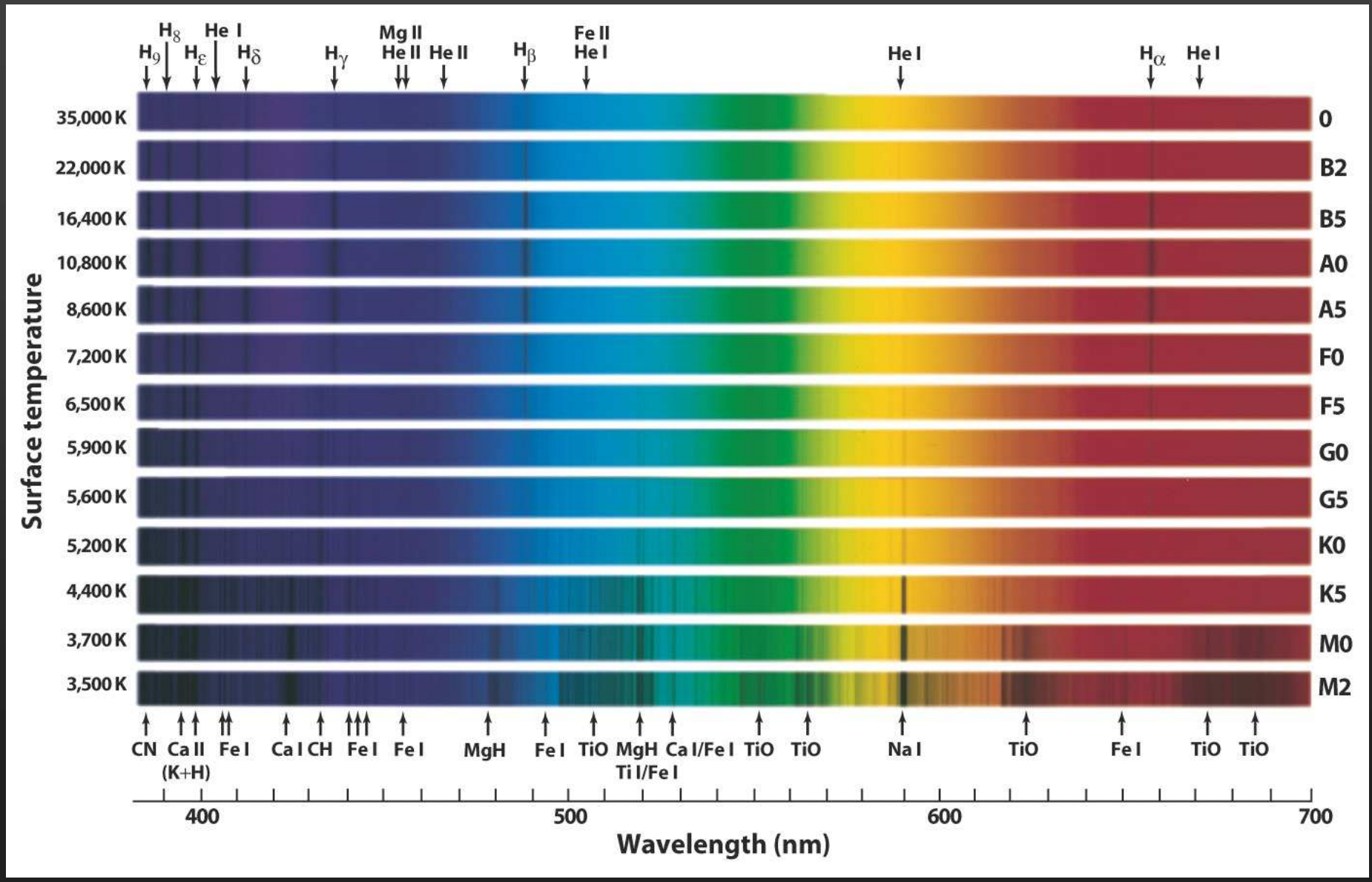
Stellar Luminosities: From Inverse-square Law



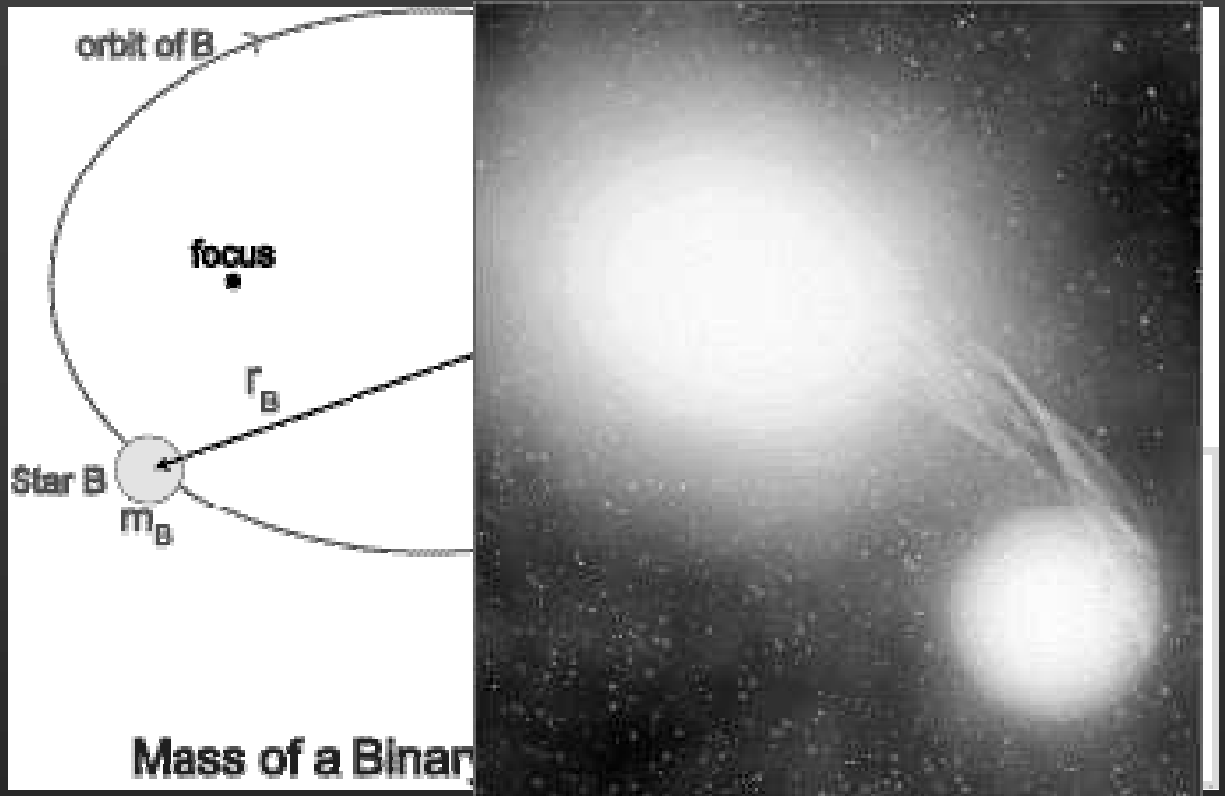
- what we measure:
  flux = energy/area
  (`apparent brightness')
- if distance (d) to star is known, can figure out true (intrinsic) brightness
  = Luminosity (L)

- $L = 4 \times \pi \times d^2 \times \text{flux}$ ("inverse-square law")

Stellar Surface Temperatures: From Spectra



Stellar Masses: From Orbits of Binary Stars



- Kepler's Law:

$$M_A + M_B = \frac{a^3}{P^2}$$

How do the Stars work?

Ejnar Hertzsprung (1873-1967)

Henry Norris Russell (1877-1957)

The Hertzsprung-Russell (HR) Diagram

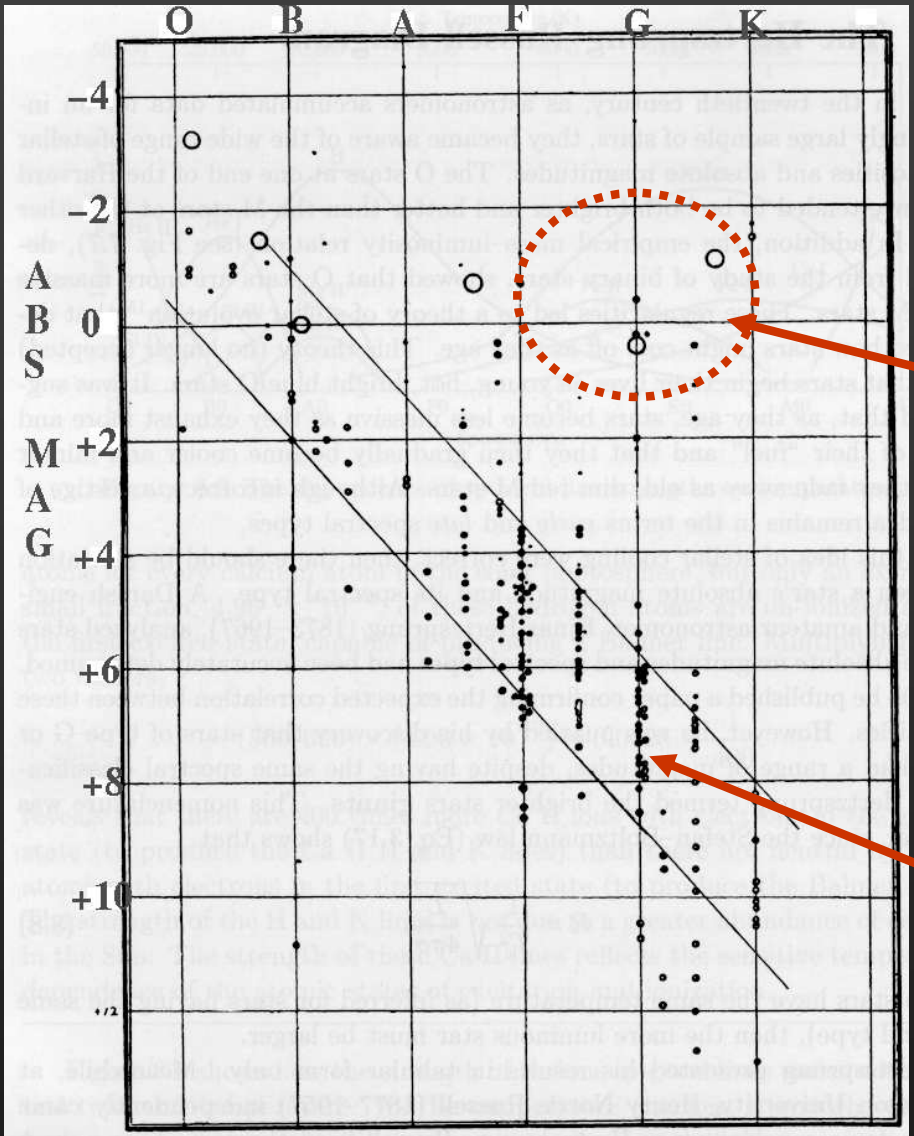
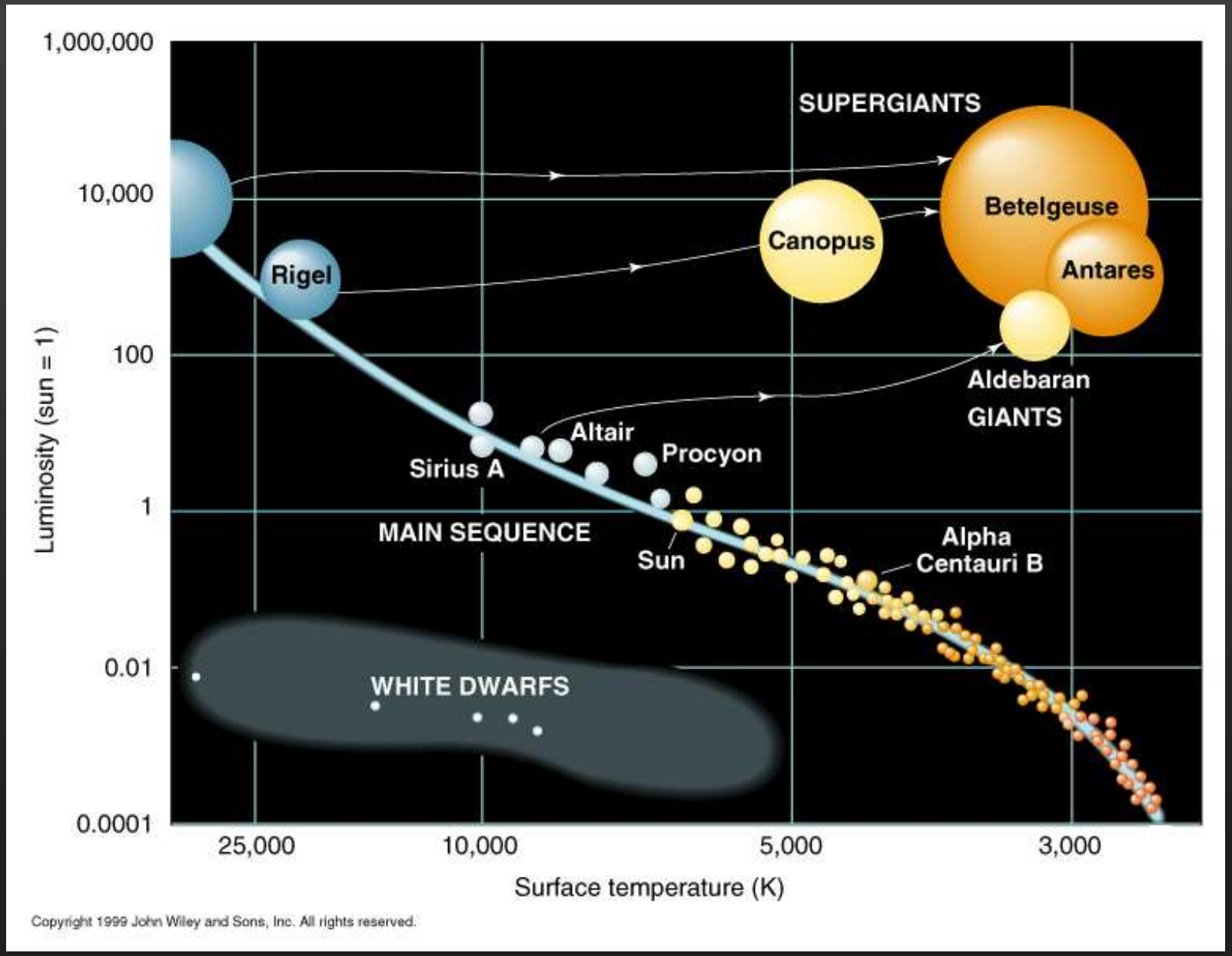


Figure 8.10 Henry Norris Russell's first diagram, with spectral types listed along the top and absolute magnitudes on the left-hand side. (Figure from Russell, *Nature*, *93*, 252, 1914.)

Giant Branch

Main sequence

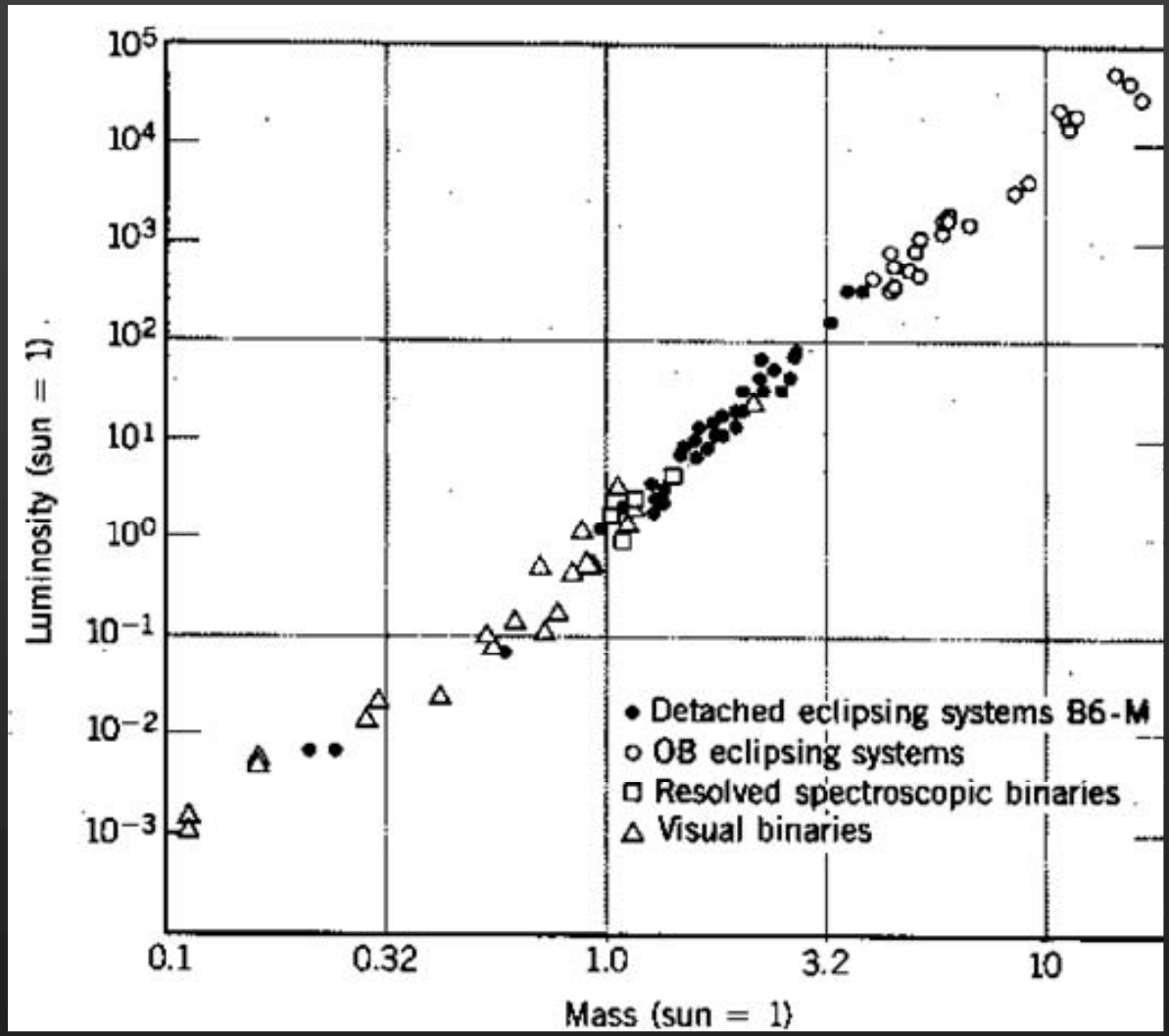
The Hertzsprung-Russell (HR) Diagram



The Mystery of the Main-Sequence

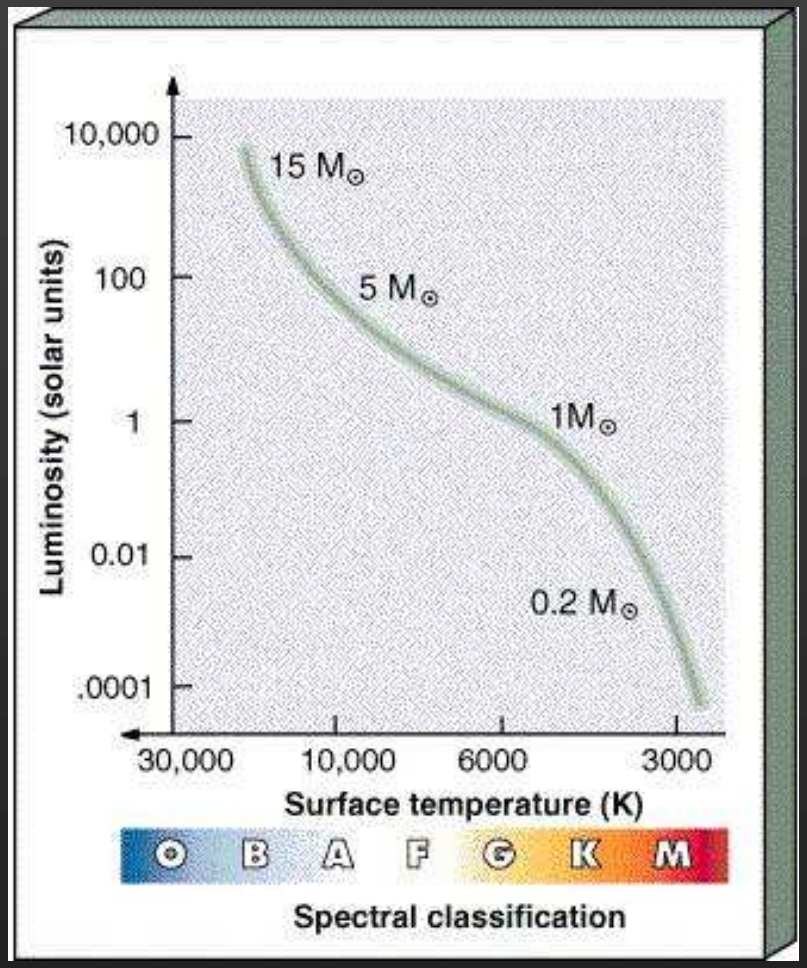
- Arthur Stanley Eddington (1882-1944)
- proved Einstein's GR theory (1919 eclipse expedition)
- *The Internal Constitution of the Stars* (1926)
  - the Laws of Stellar Structure

The Mystery of the Main-Sequence



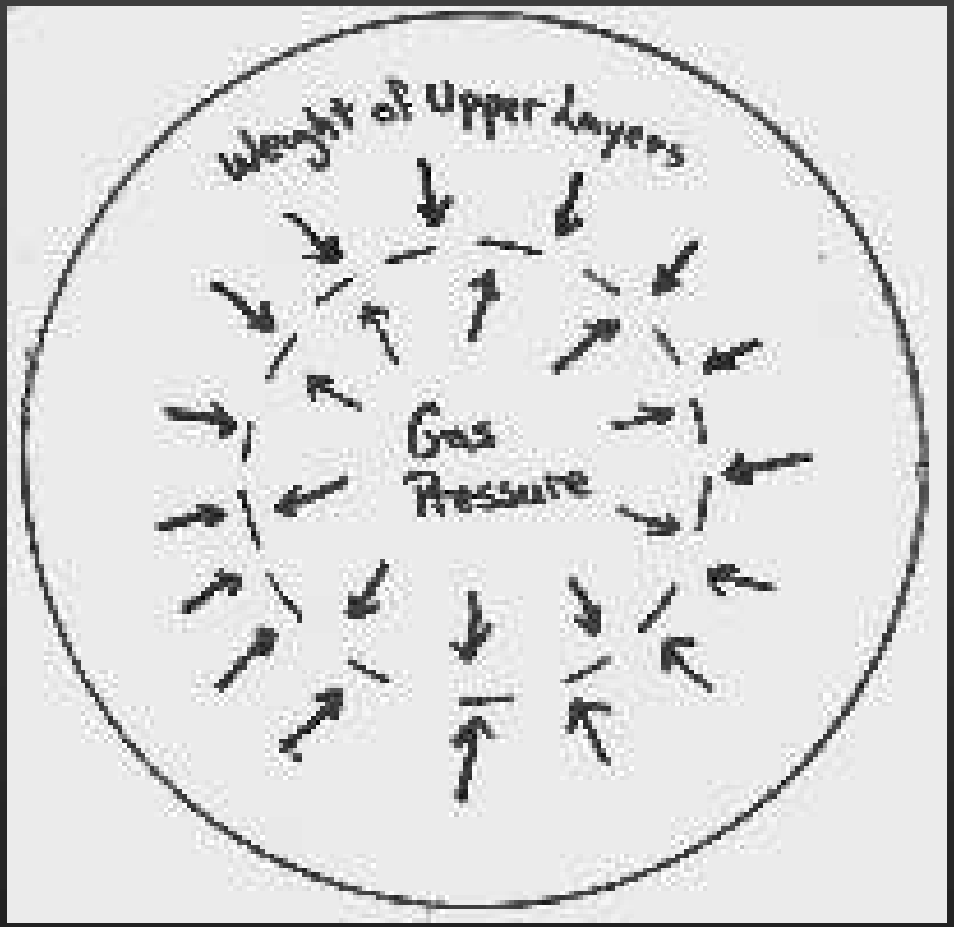
- Mass-luminosity relation (high M → high luminosity)

The Mystery of the Main-Sequence



- Mass-luminosity relation (high M → high luminosity)

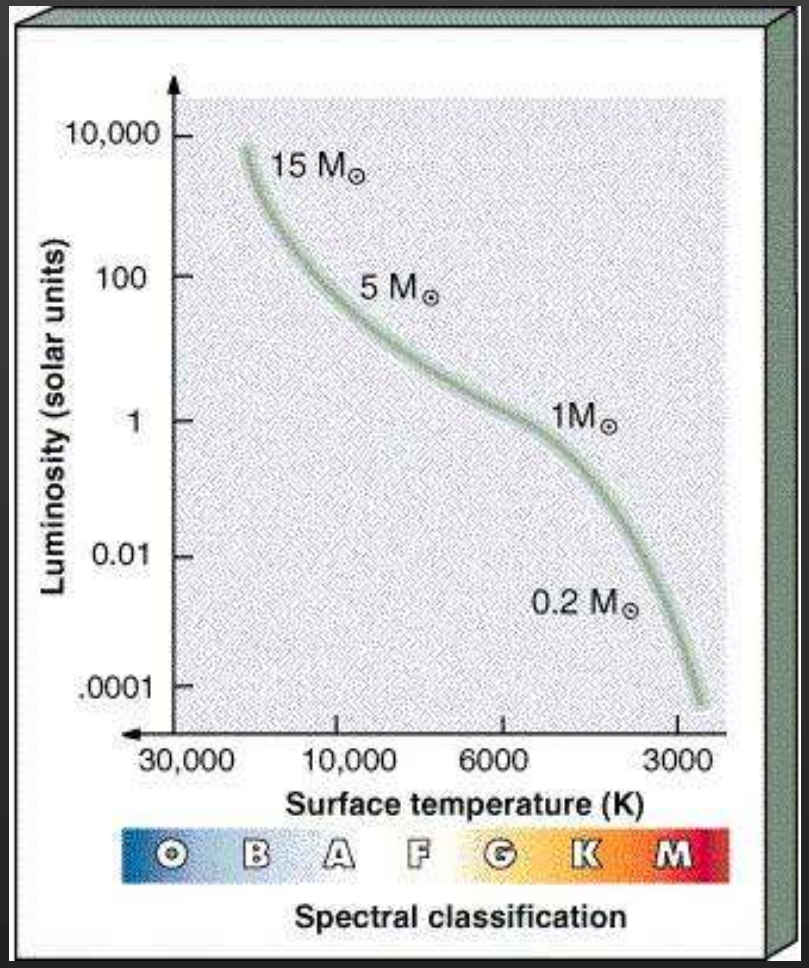
Eddington explains the M-L Relation:



- Law of Stellar Structure:
  - gravity = pressure
  - pressure = stellar heat
  - stellar heat = stellar luminosity

- gravity (M) ~ stellar luminosity (L)

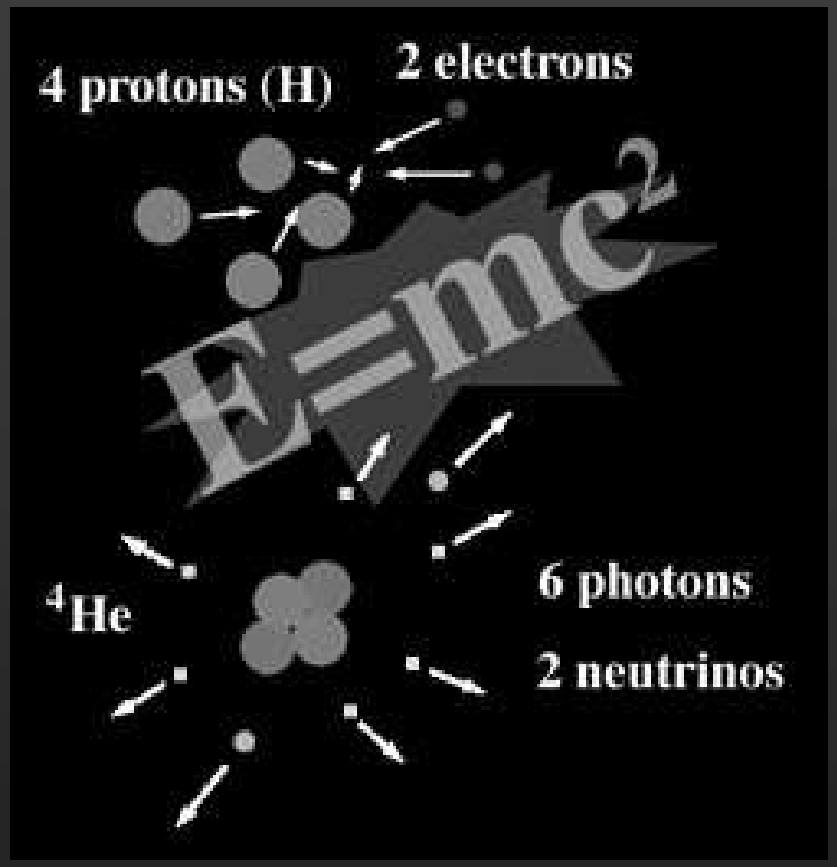
The Mystery of the Main-Sequence



- a stellar thermostat:
  - Central T~ ten million K
  - almost independent of mass!!!

- central temperature in star = almost constant!

Eddington's Conjecture for Stellar Energy Source:



- nuclear fusion:
  4 protons (H)
  à 1 helium (He) nucleus
- He nucleus has a bit less mass than sum of 4 protons (mass defect)
- missing mass = energy (Einstein's $E=m\,c^2$)

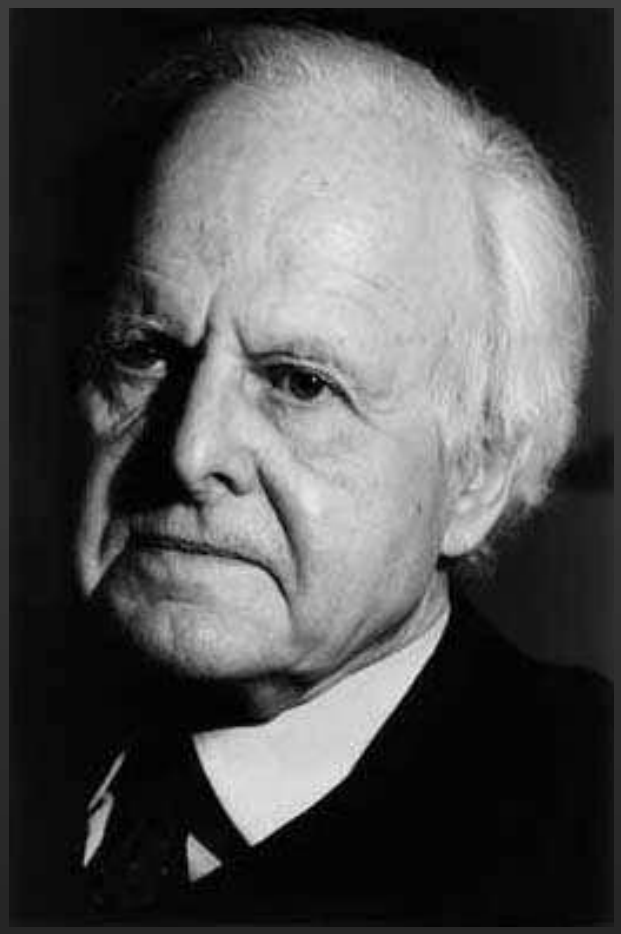
- **But how does this really work???**

Chemical Composition of the Stars

- Cecilia Payne-Gaposhkin (1900-79)
- Harvard PhD 1925
- hydrogen and helium are most abundant elements in the universe!

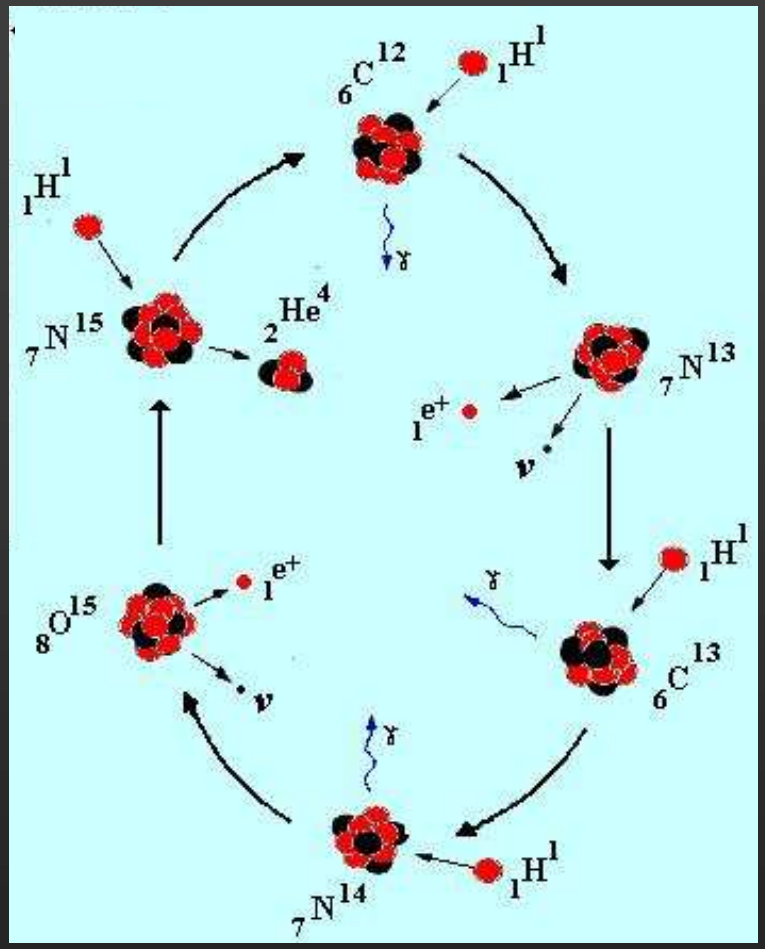
What makes the Stars Shine?

Hans Bethe (1906-2005)



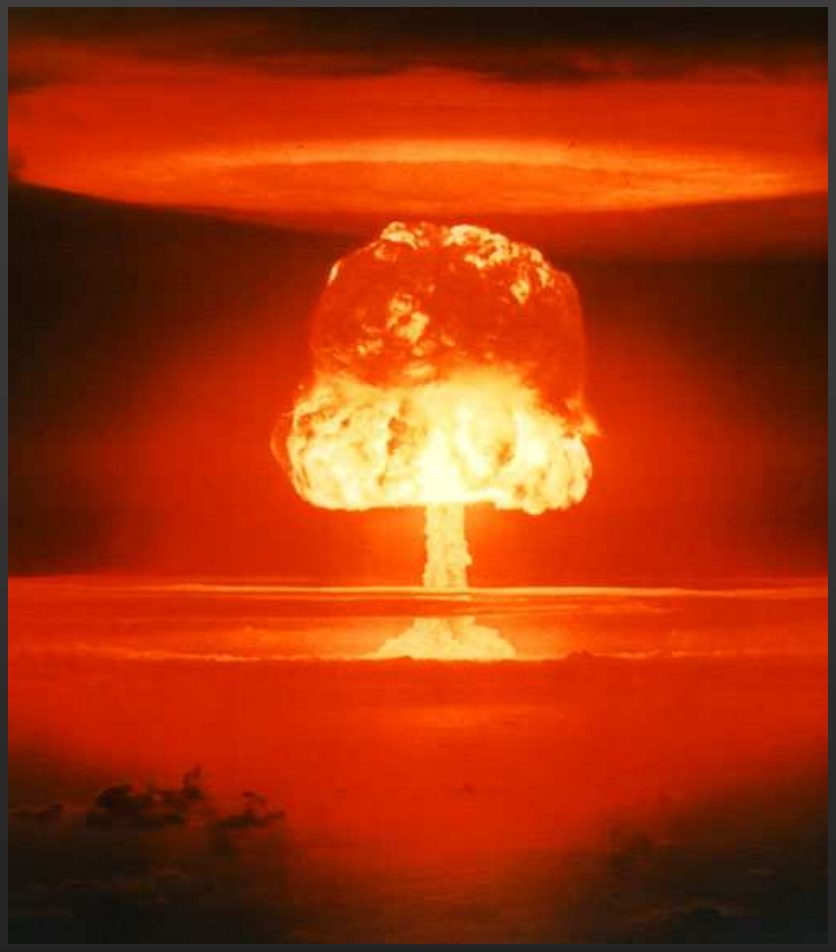
Carl Friedrich von Weizsaecker (born 1912)

What makes the Stars Shine?



- **Nuclear Fusion via the CNO Cycle**
  (Bethe and Weizsaecker 1938)

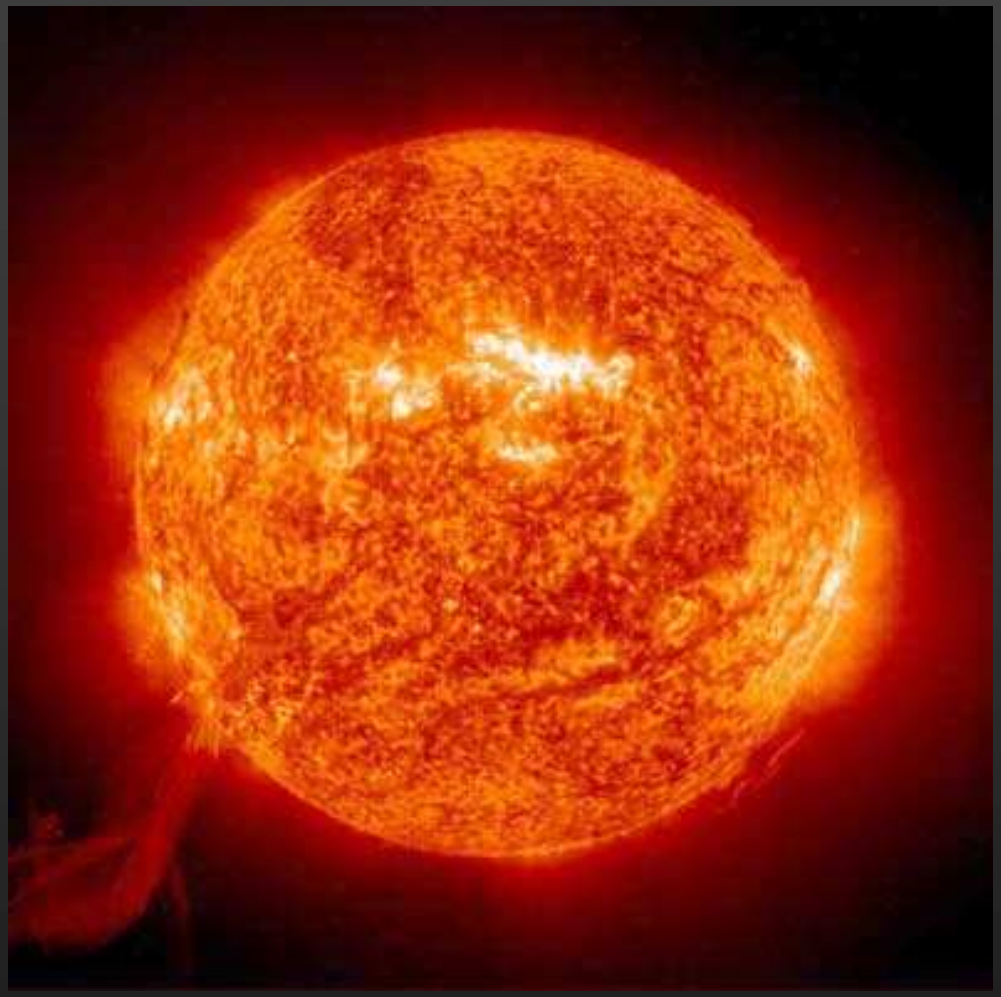
Astrophysics and the Bomb



- **Both worked on bomb during WWII:**

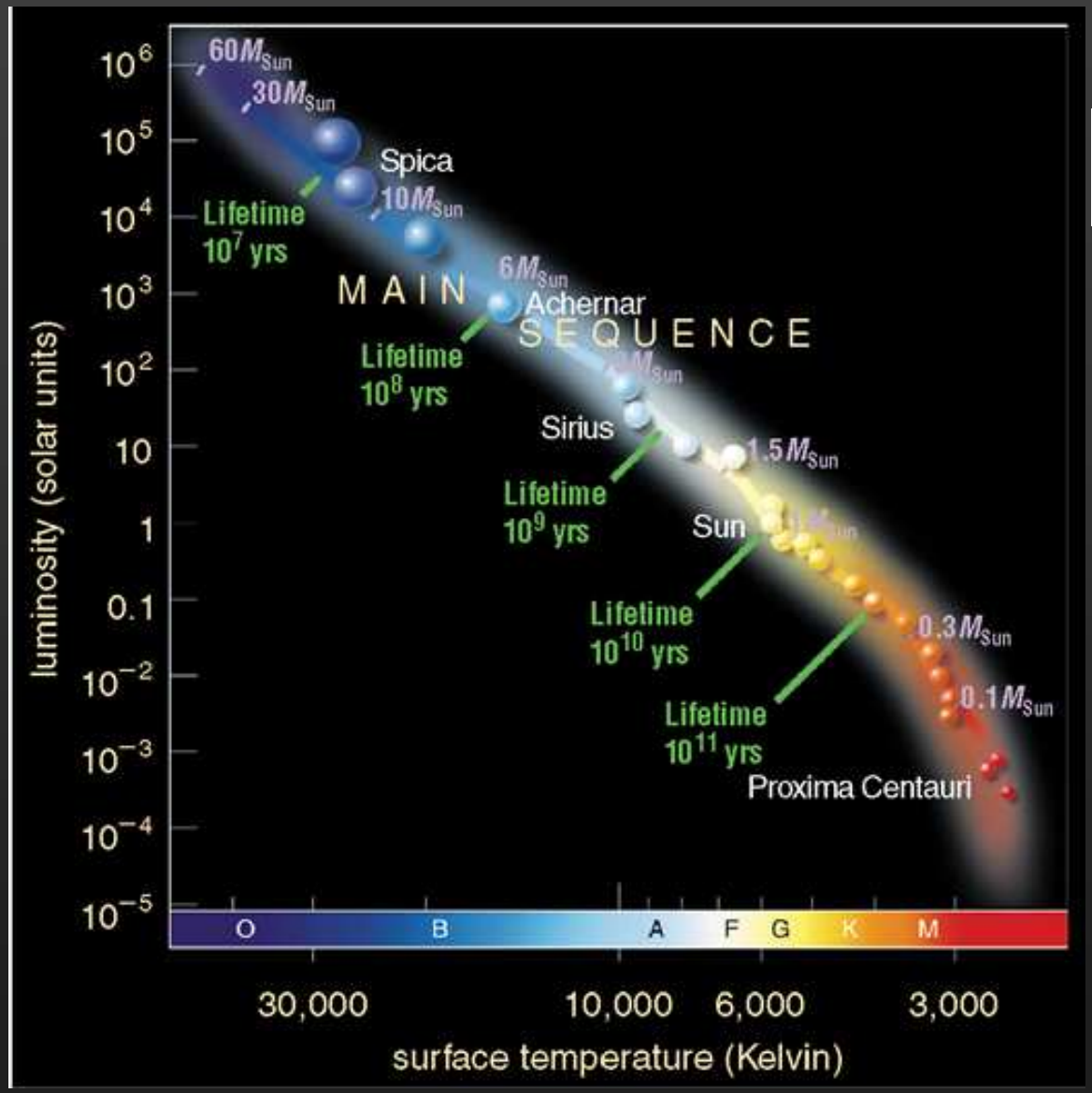
  Bethe (Manhattan Project, USA); Weizsaecker (Nazi bomb project à thwarted!?)

How much Energy does the Sun contain?



- Sun's lifetime=
  total energy/luminosity
- Nuclear energy
  - Sun made up of H/He
  - age = few billion years
- Age crisis resolved!

How long do the Stars live?

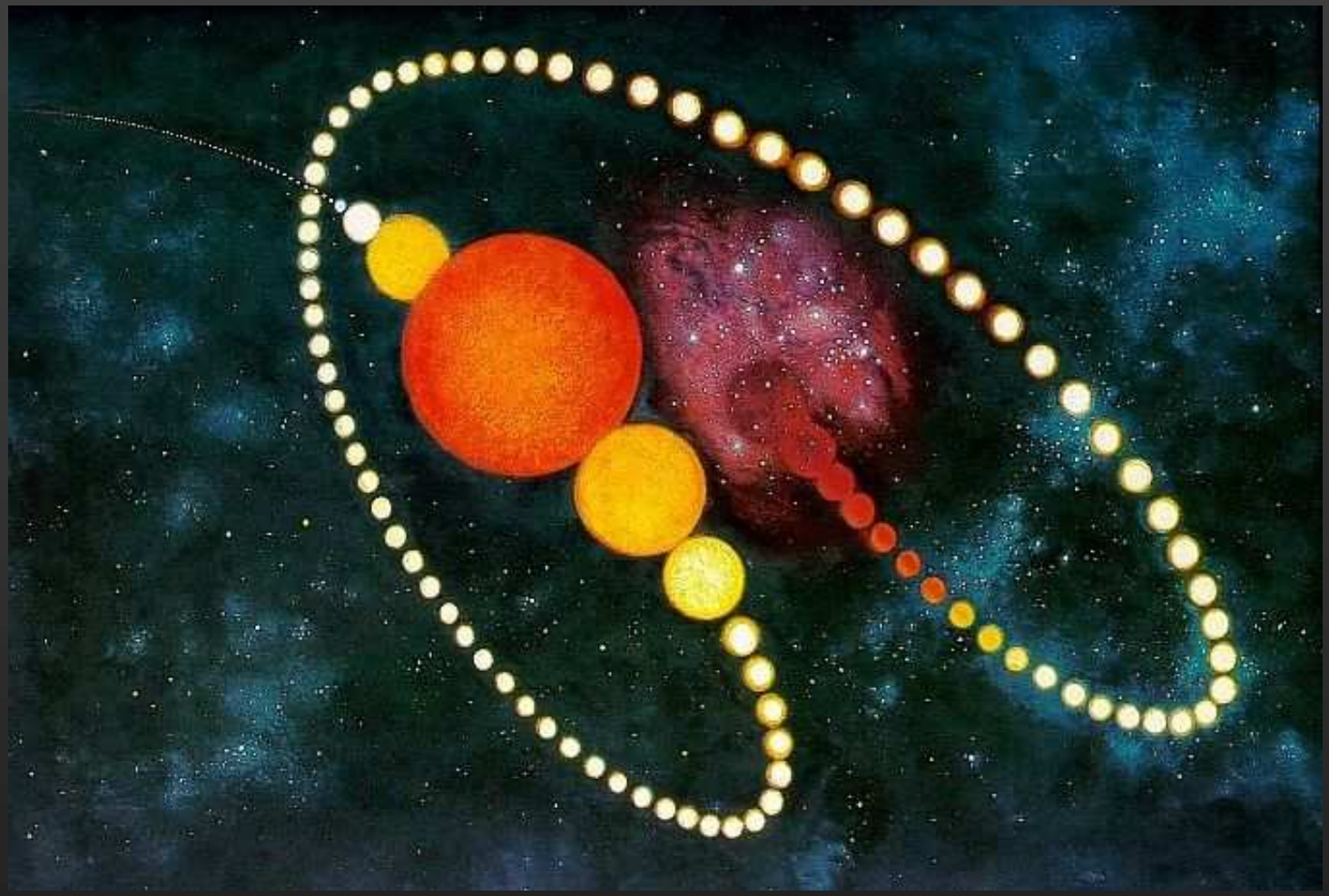


$$\text{stellar lifetime} \propto \frac{\text{stellar mass}}{\text{stellar luminosity}}$$

$$\text{stellar lifetime} \propto \frac{1}{(\text{stellar mass})^2}$$

- a huge range of stellar lifetimes !

All stars (and the Sun) evolve!



- Sun’s Life: from molecular cloud to white dwarf (~10 billion years)

Birth of Astrophysics (part 2)

- Figuring out the energy source of the stars:
  - "Age crisis" of 19th century: How to reconcile the long timescales of geology and biology (billions of years) with estimated lifetime of the Sun, then estimated to be only few million years)???
  - gravitational energy NOT sufficient!
  - Need nuclear (fusion) energy!

- Pioneers of astrophysics:
  - Kelvin-Helmholtz (gravitational energy)
  - Hertzsprung-Russell diagram
  - Arthur Eddington explains the main-sequence
  - Bethe and Weizsaecker figure out stellar fusion energy