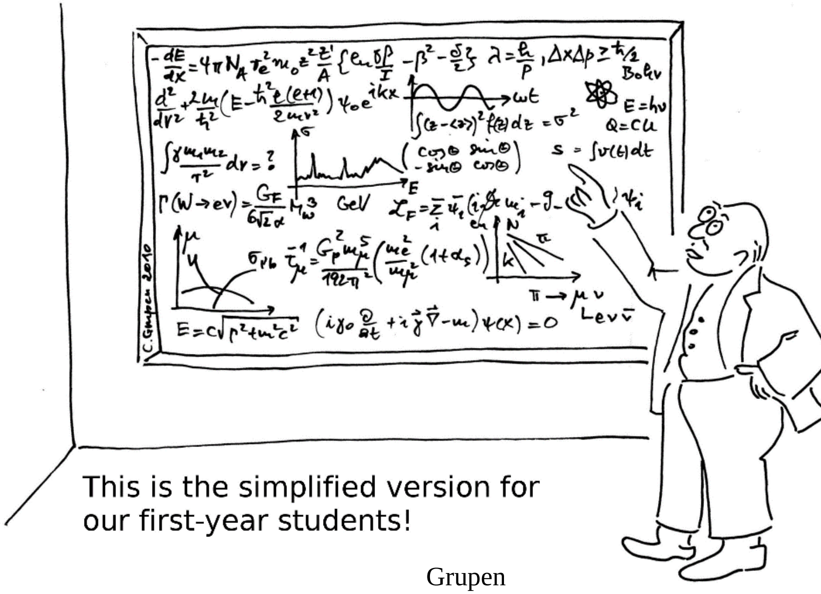
Life of Stars

Filling the intellectual Vacuum: Energy Production

- Contenders:
  - Gravitational contraction
  - Radioactivity (1903)
  - Annihilation ($E=mc^2$, 1905) of proton and electron
  - Hydrogen to helium nuclear fusion
- From early 1920s: probably fusion, but how?
  - Gamov 1928: QM tunneling can overcome electrostatic repulsion of protons

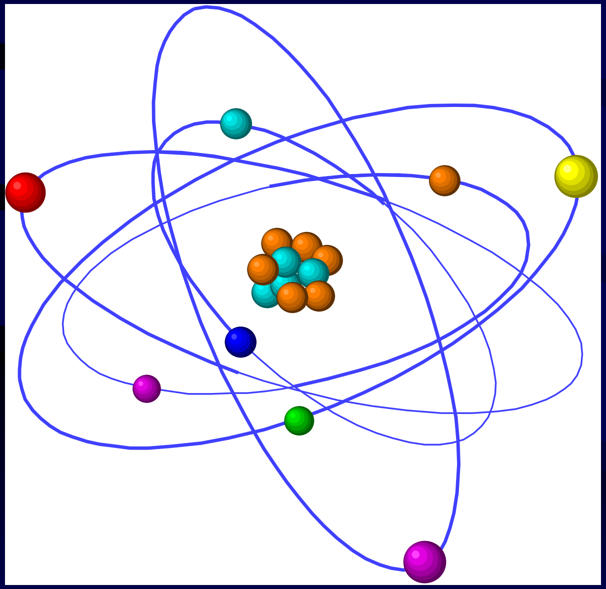
Bethe/Weizsäcker (1939)

- Worked out details of hydrogen fusion including latest nuclear physics results detailing probabilities and temperature dependence
- Two possibilities
  - CNO cycle (T^{16}, dominant in massive stars)
  - Proton-proton chain (T^{5}, Sun et al)



Grupen

Nuclear Fusion



- Atoms: electrons orbiting nuclei
- Chemistry deals only with electron orbits (electron exchange glues atoms together to from molecules)
- Nuclear power comes from the nucleus
- Nuclei are very small
  - If electrons would orbit the statehouse on I-270, the nucleus would be a soccer ball in Gov. Kasich's office
  - Nuclei: made out of protons (el. positive) and neutrons (neutral)

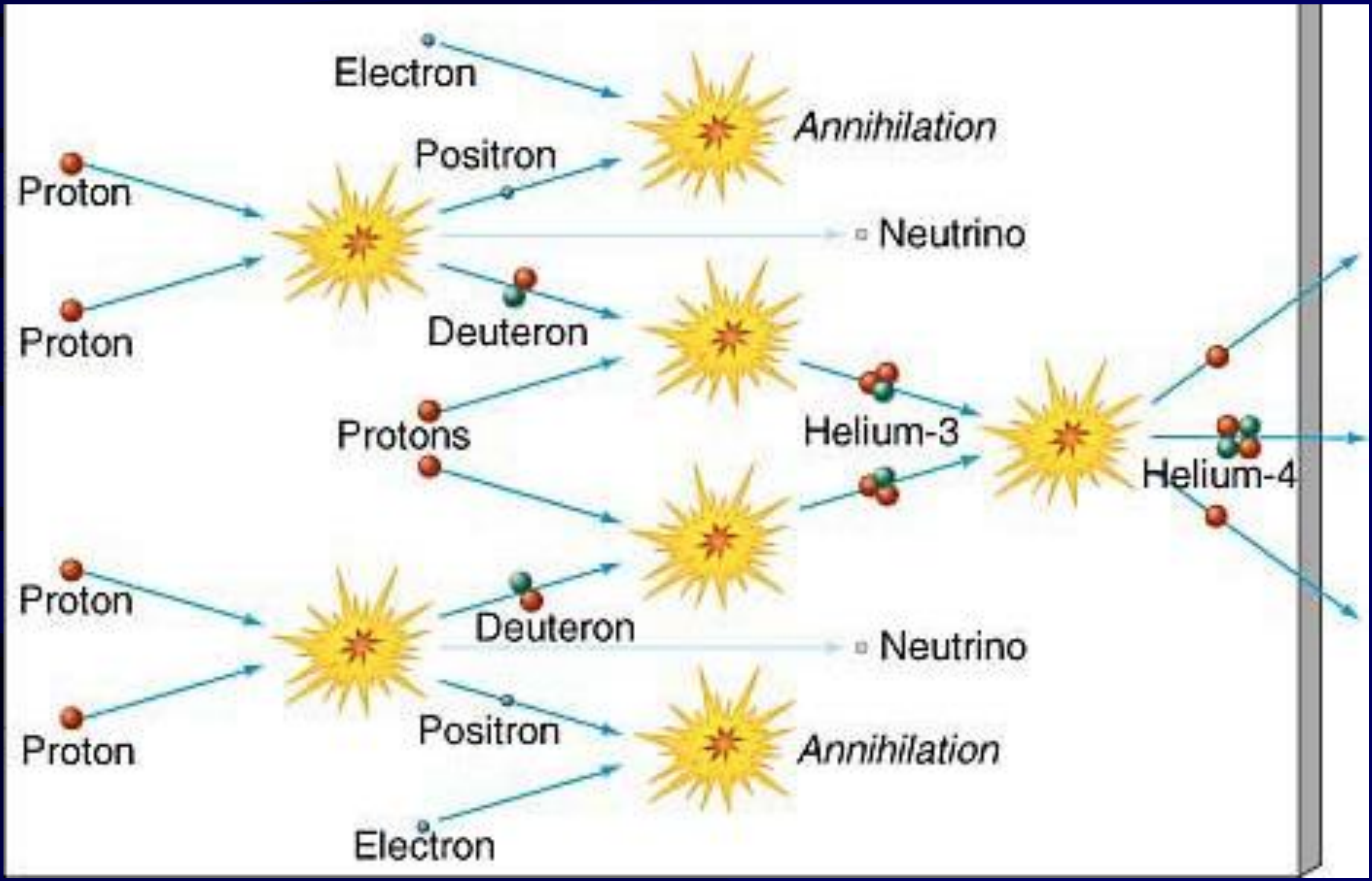
Nuclear fusion reaction

- In essence, 4 hydrogen nuclei combine (fuse) to form a helium nucleus, plus some byproducts (actually, a total of 6 nuclei are involved)
- Mass of products is less than the original mass
- The missing mass is emitted in the form of energy, according to Einstein's famous formulas:

$$E = mc^2$$

(the speed of light is very large, so there is a lot of energy in even a tiny mass)

Hydrogen fuses to Helium



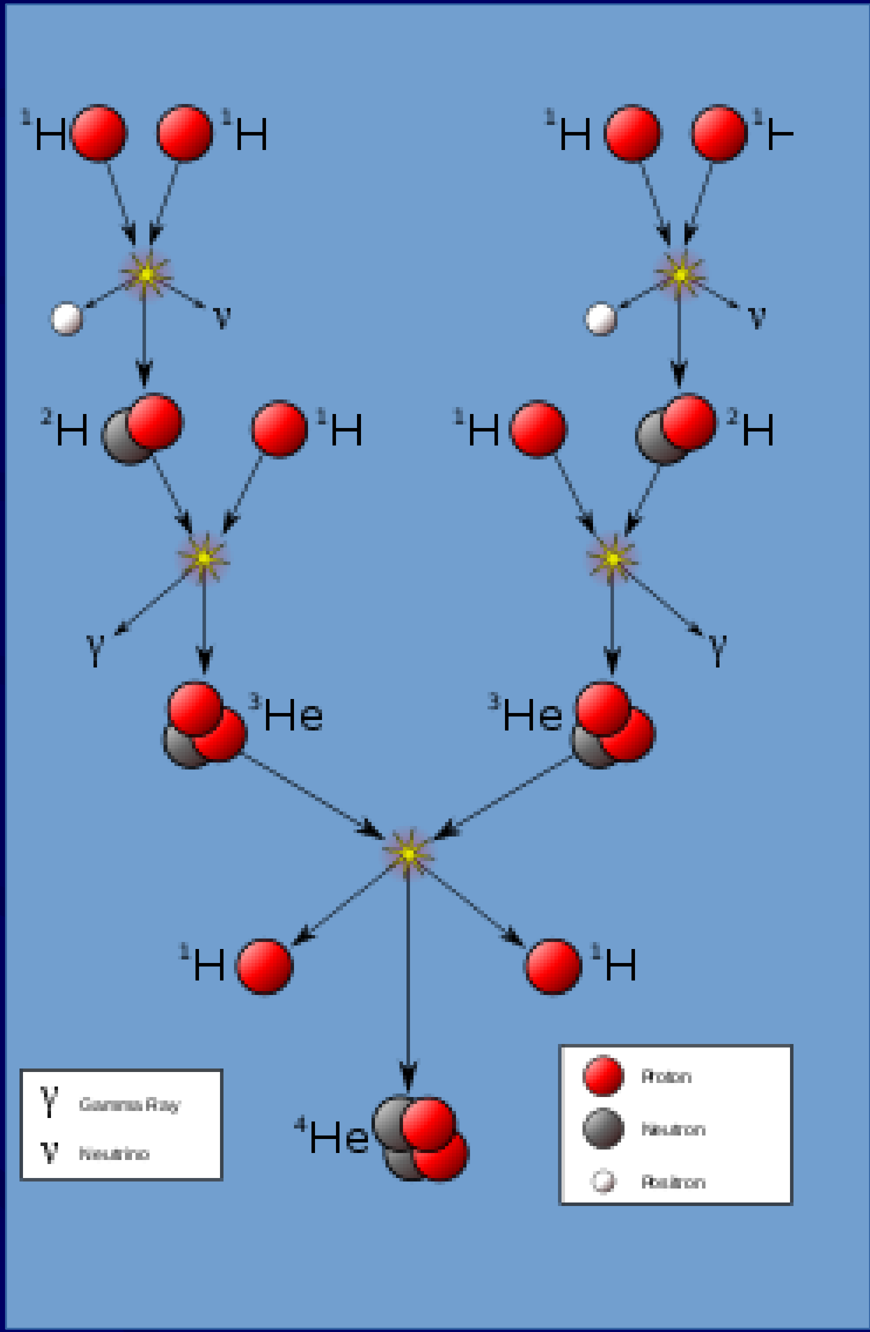
Start: 4 protons → **End:** Helium + neutrinos + energy

Hydrogen fuses to Helium

$E=(\Delta m)c^2$

4 Hydrogen nuclei (protons) have more mass than 1 He nucleus (Alpha particle) built from them

→ mass difference ("binding energy") is radiated away as energy



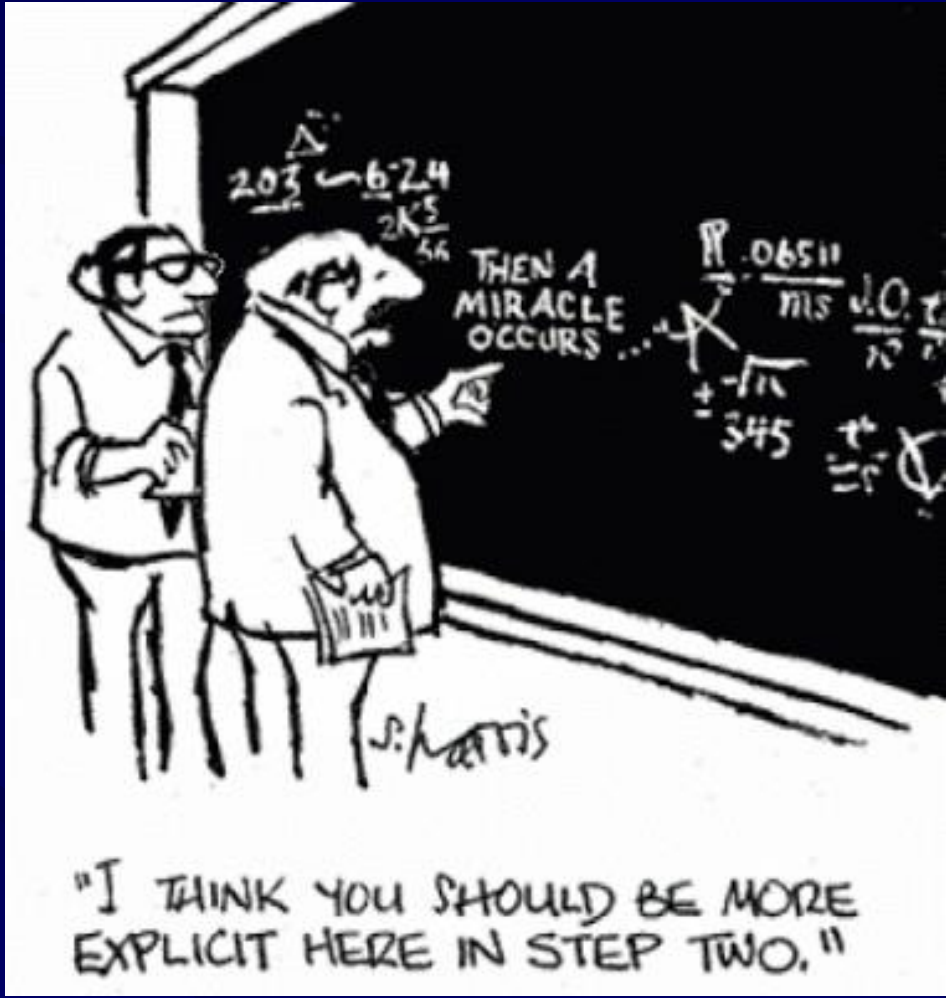
Everything is on the table now!

- Hydrostatic equilibrium
- Thermal equilibium
- Chemical composition: about

  90% H, 9% He, 1% “metals”
- Convective core, radiative layer, convective zone
- Nuclear fusion as energy source with known temperature and density and composition dependence

Perfecting the model – Towards the Stellar Lifecycle

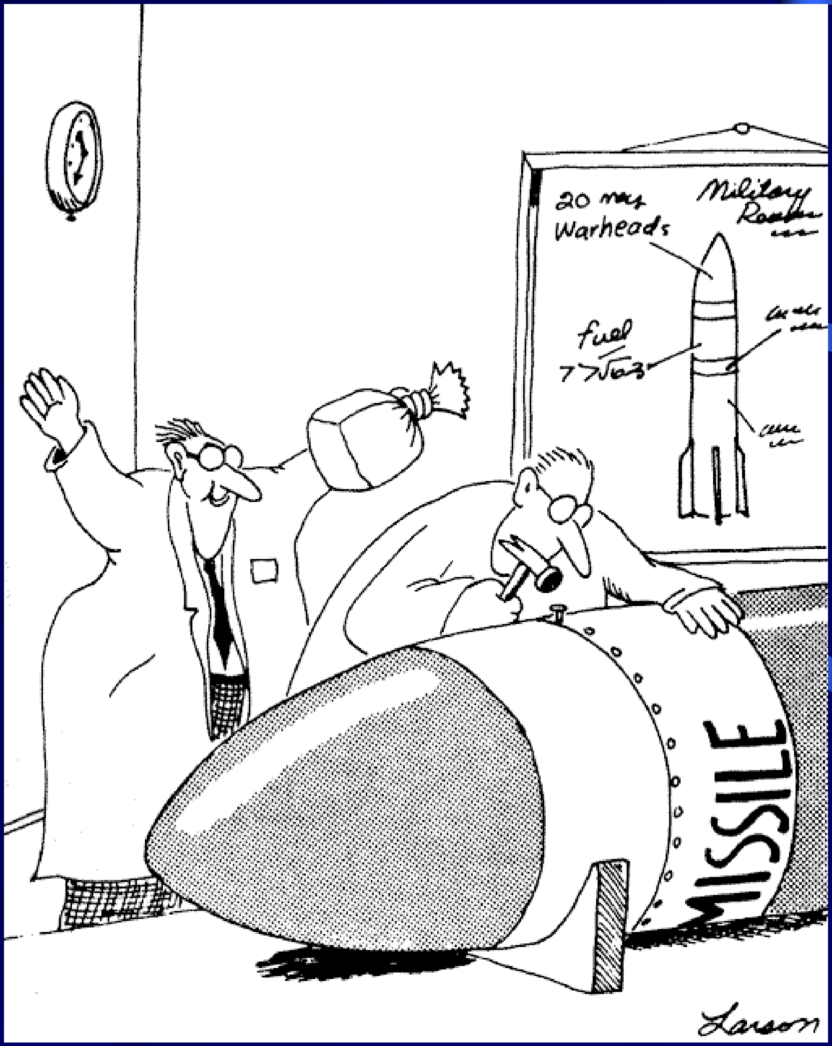
- Problem: How are the 4 HRD groups of stars related if at all?
- Standard Model explains only Main Sequence



Stellar (Model) Evolution

- Strömgren 1932: as hydrogen is used up, stars become brighter, cooler
- Öpik 1938: Red Giants might fuse Helium

→ All stars in HRD can be explained by the same physics?!

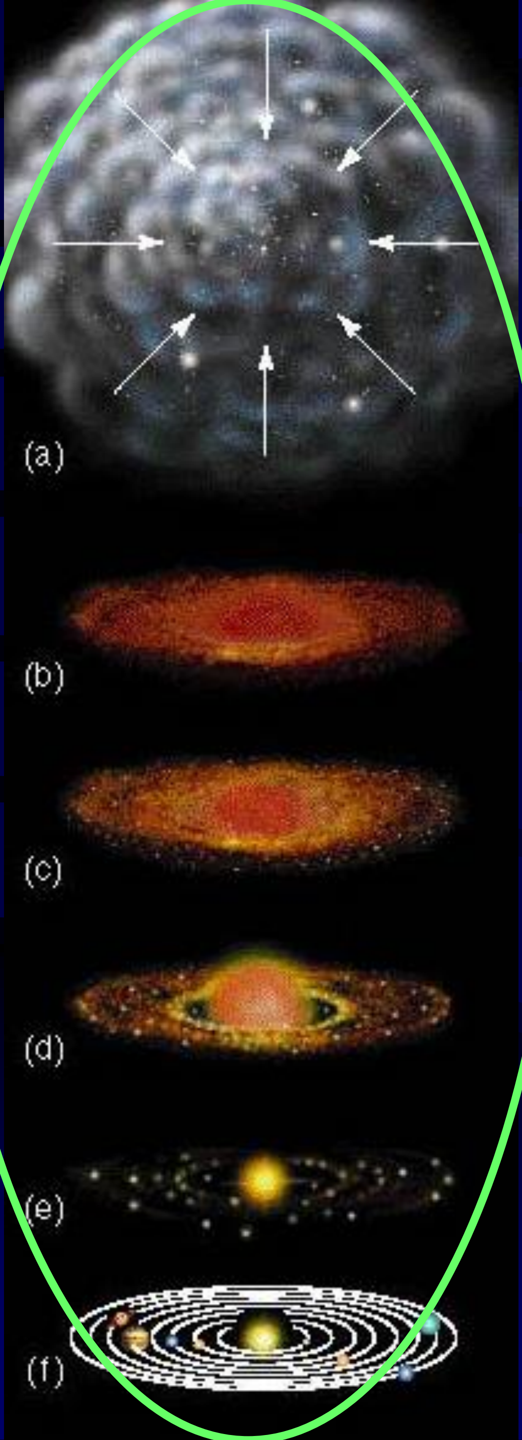


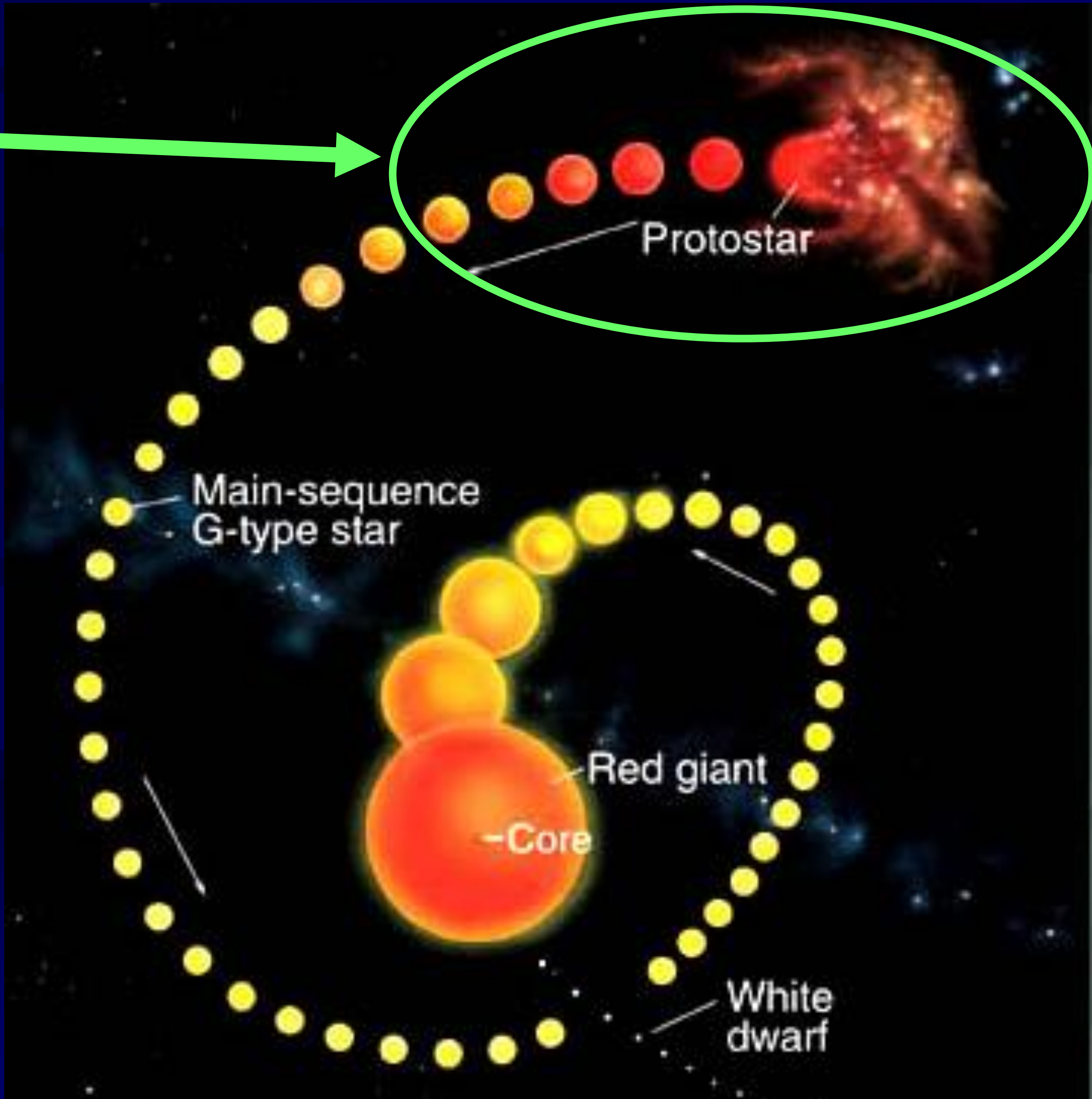
Start Number Crunching to model Stars: Solve Differential Equations with boundary Conditions

- Goal: “reach” all parts of the HR diagram
- How does a MS star turn into a giant?
  - Hydrogen shell burning
- Problem until 1950s: computing power
  - Need to integrate differential eqns “by hand”
  - Progress: M. Schwarzschild et al (1957)

Recontructing the Stellar Lifecycle

(Compare: Solar System Formation)



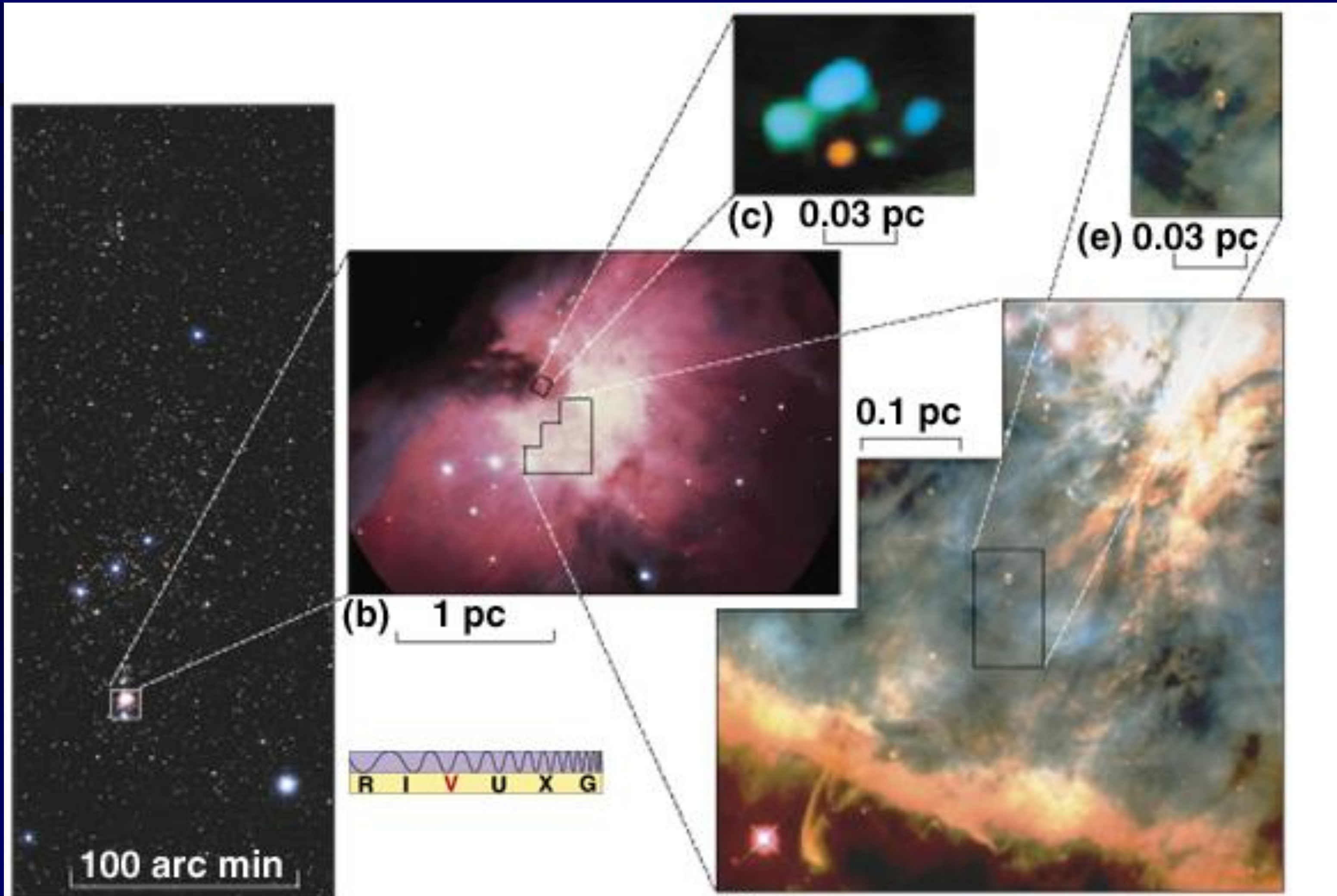


Where Stars come from: the Interstellar Medium

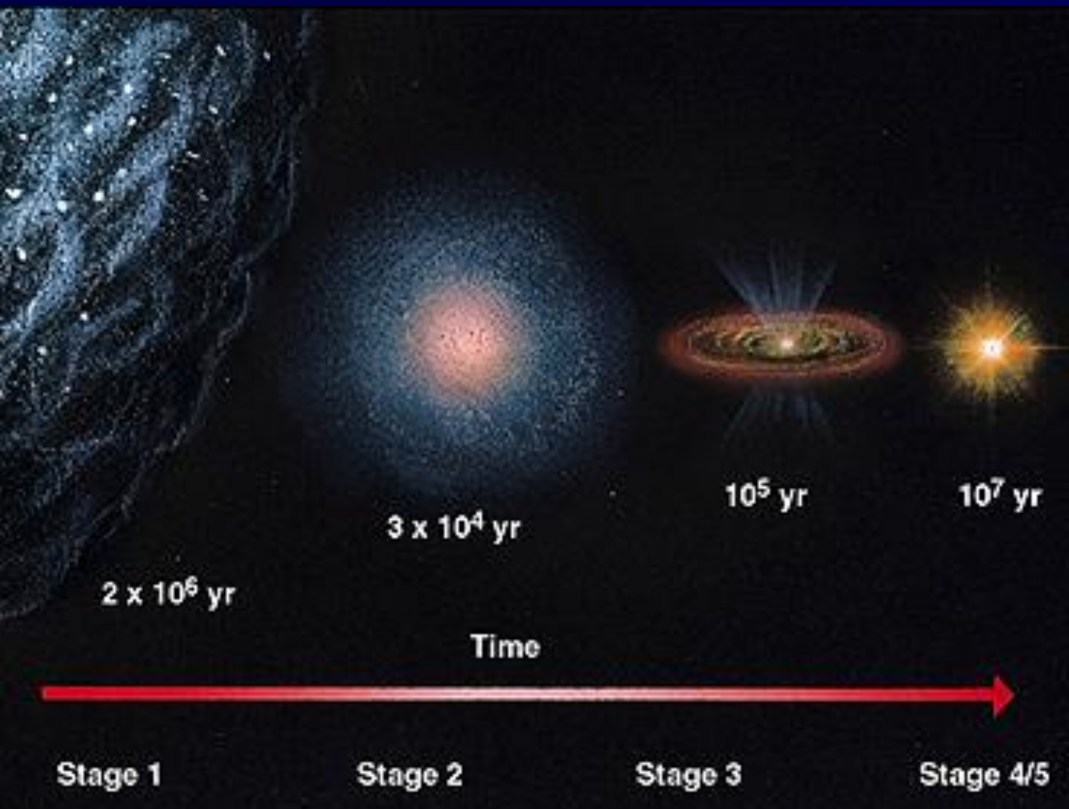
- Gas
  - Single atoms and molecules
  - Mostly hydrogen (90%), 9% helium; deficient in heavier elements
- Dust
  - Microscopic clumps of atoms/molecules
  - Size ~ 10^{-7} m, similar to the wavelength of visible light
  - Composition is not well known
- Temperature depends on the proximity of stars, typically ~100 K
- Density is very low!
  - Gas: about 1 atom/cm^3 D;   Dust: even less dense

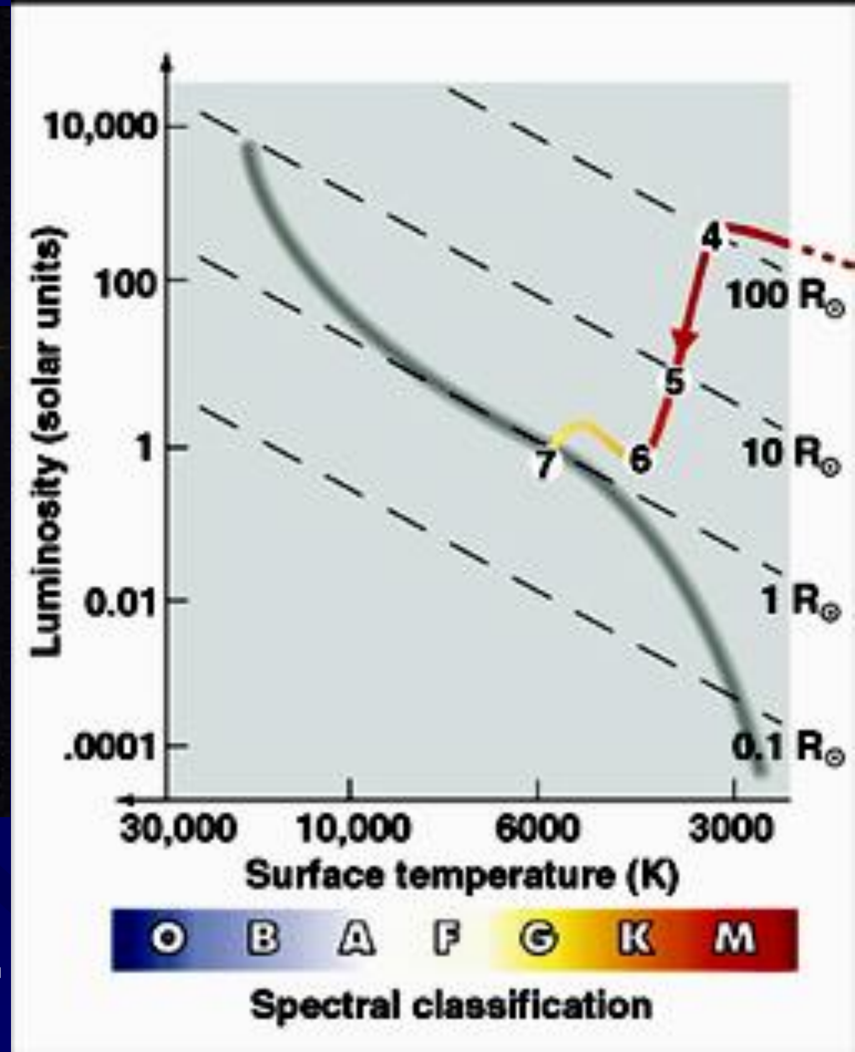
Example: Orion Nebula

- Orion Nebula is a place where stars are being born



Path in the Hertzsprung-Russell Diagram

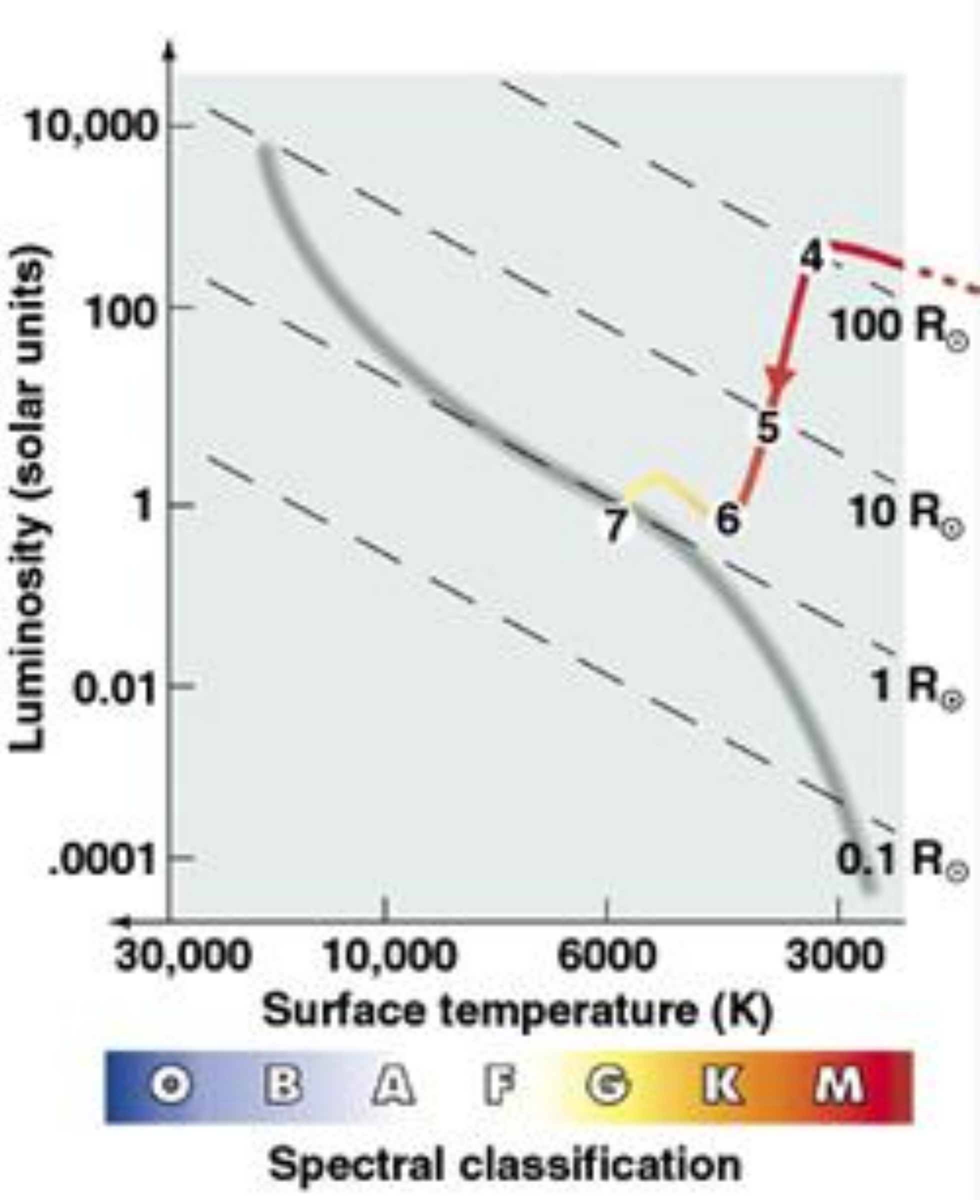




Gas cloud becomes smaller, flatter, denser, hotter → Star

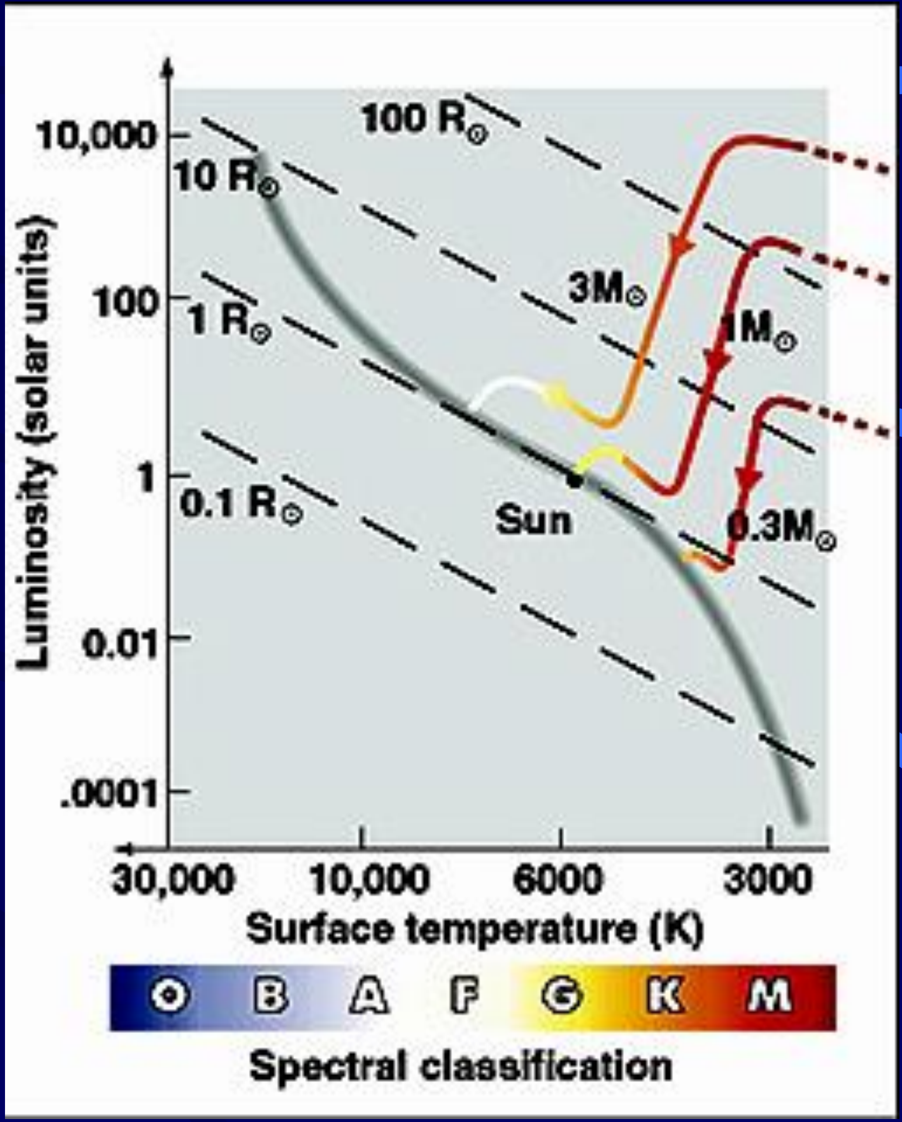
A Newborn Star

- Main-sequence star; pressure from nuclear fusion and gravity are in balance
  - Duration ~ **10 billion years** (much longer than all other stages combined)
  - Temperature ~ 15 million K at core, 6000 K at surface
  - Size ~ Sun



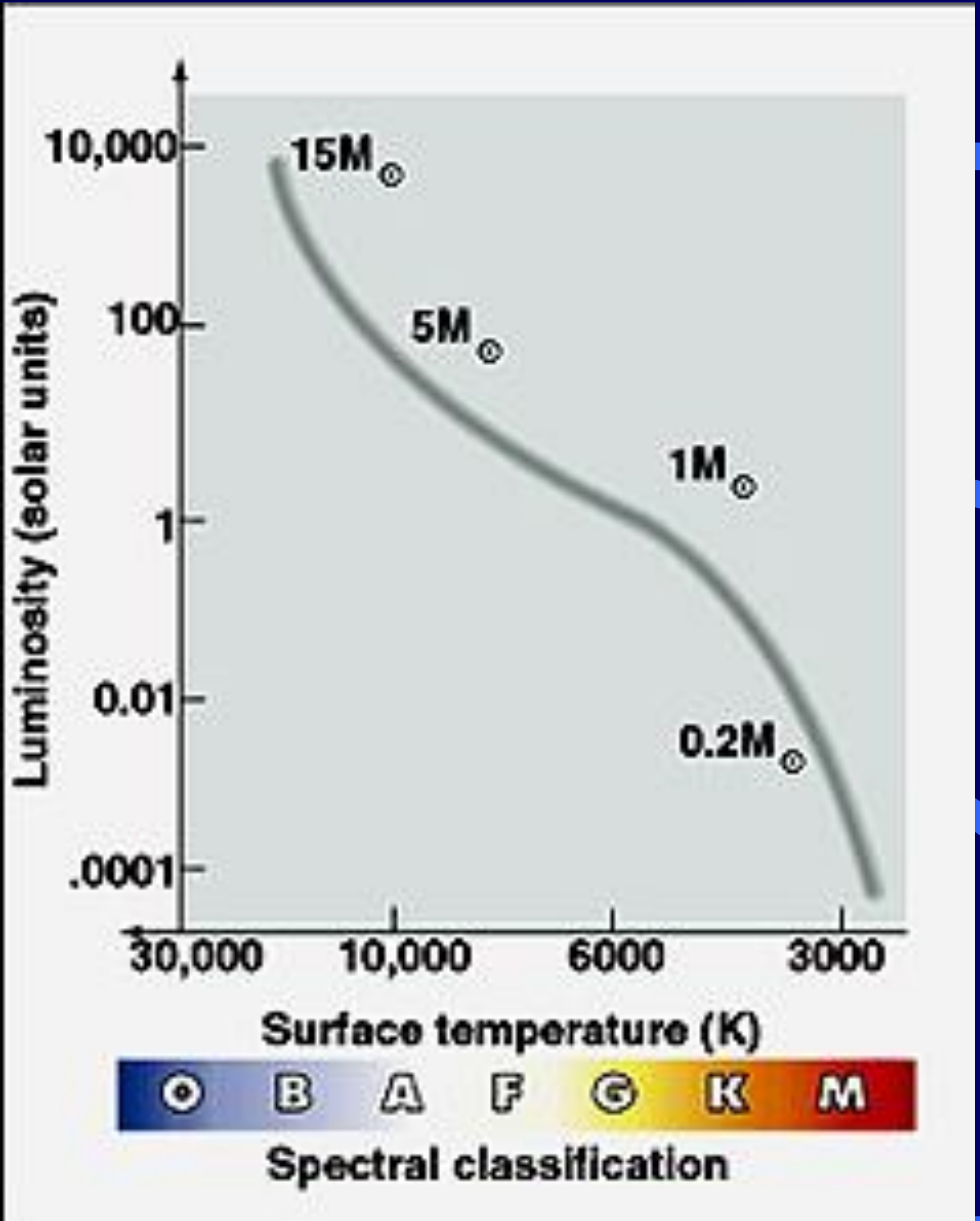
Mass Matters

- Larger masses
  - higher surface temperatures
  - higher luminosities
  - take less time to form
  - have shorter main sequence lifetimes
- Smaller masses
  - lower surface temperatures
  - lower luminosities
  - take longer to form
  - have longer main sequence lifetimes

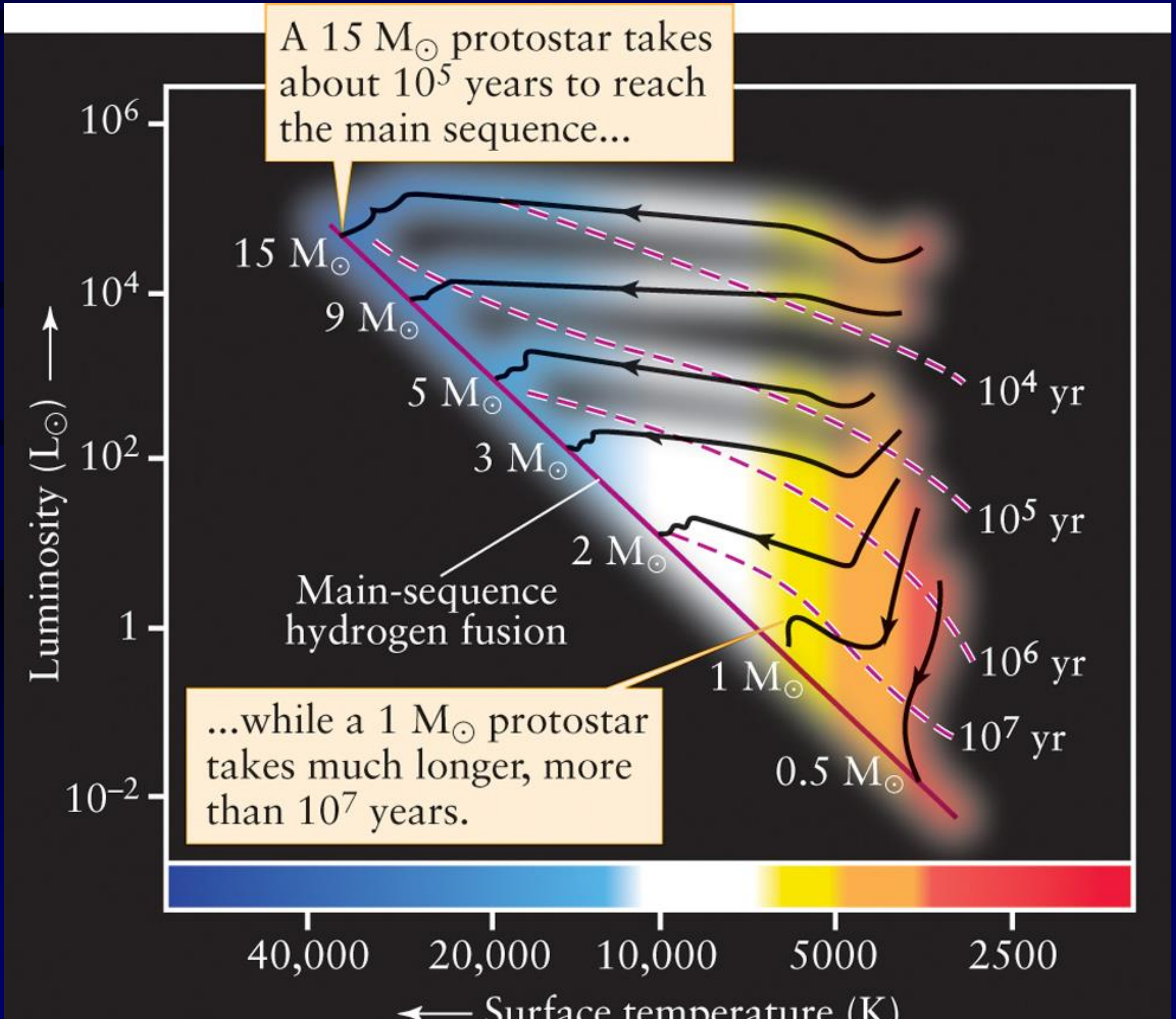


Mass and the Main Sequence

- The position of a star in the main sequence is determined by its mass
  - →All we need to know to predict luminosity and temperature!
- Both radius and luminosity increase with mass

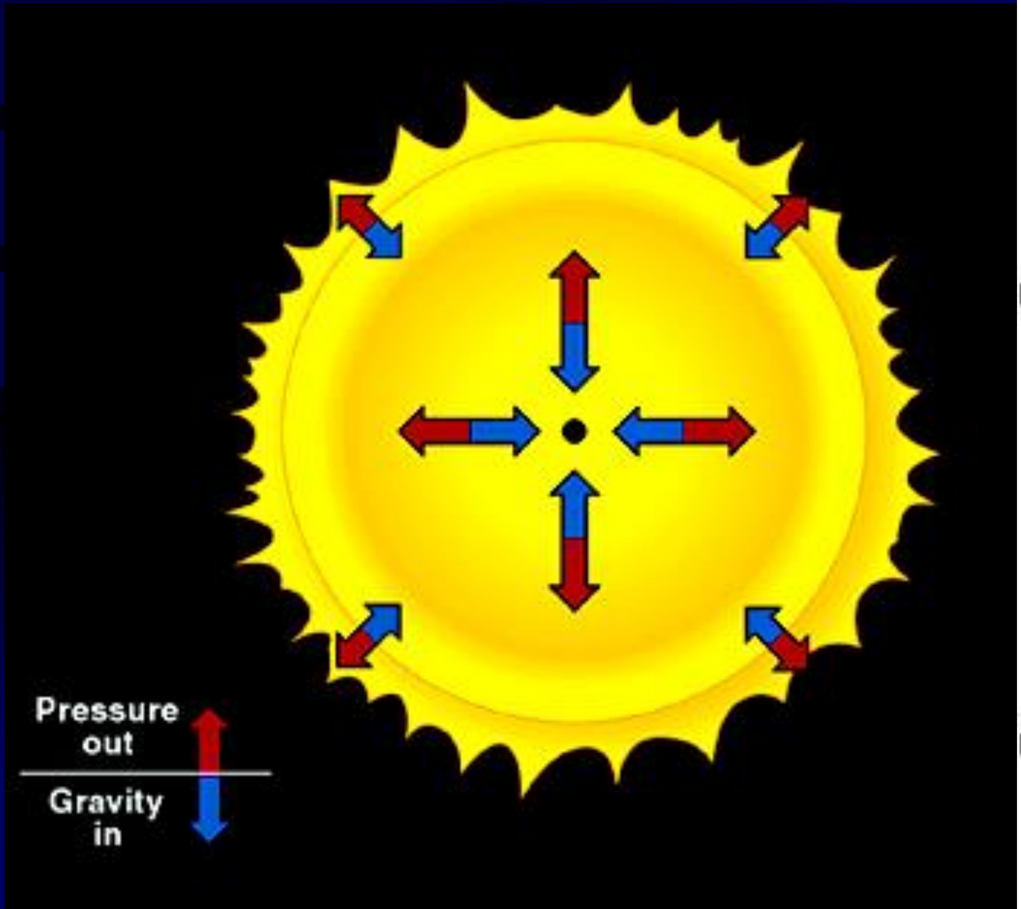


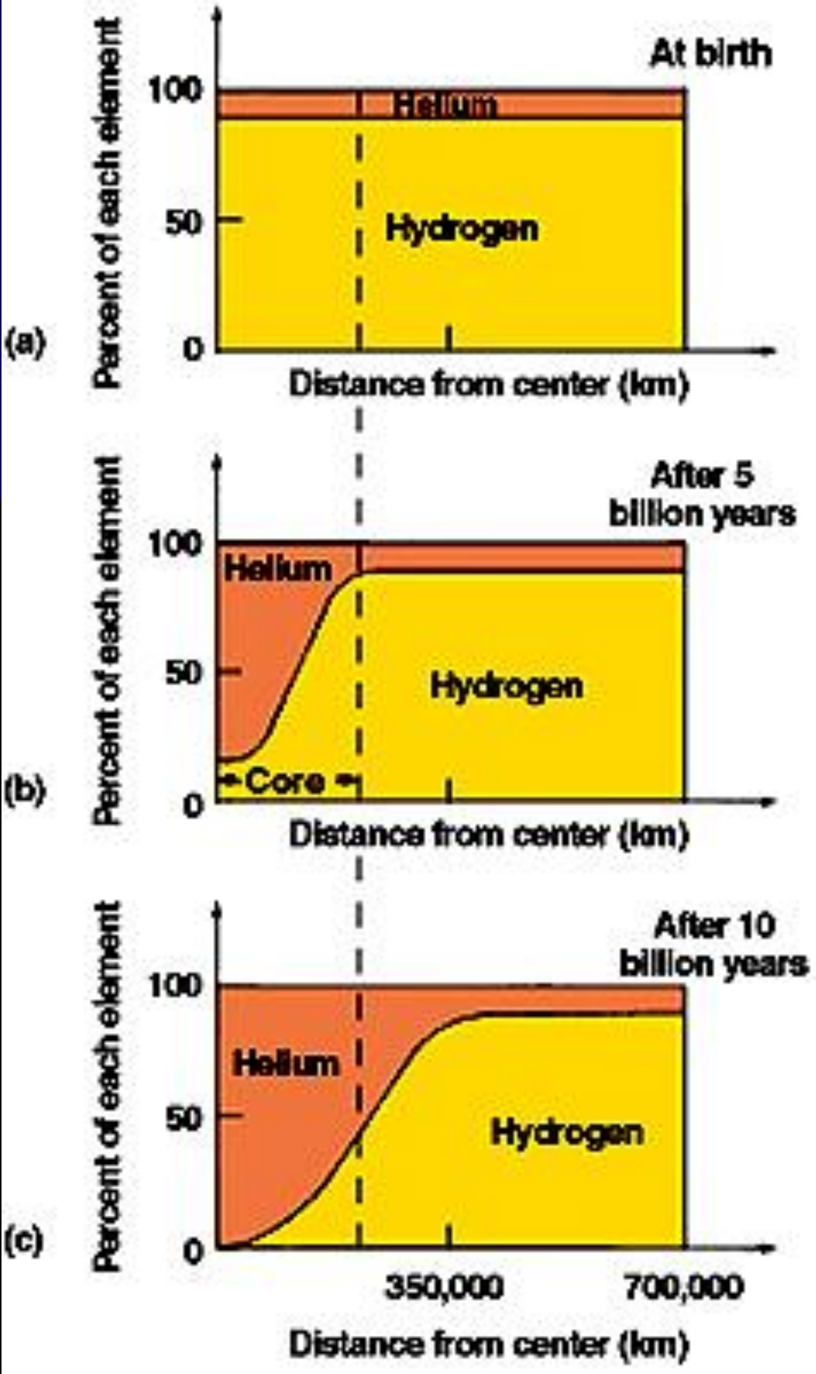
Mass determines how fast a star is born and how luminous it is



Why Do Stars Leave the Main Sequence?

- Running out of fuel





Simple Energy Bookkeeping determines the Life Expectancy of Stars

- Stars radiate energy
- This energy comes from $E=mc^2$, so their mass is their fuel
- The more mass, the more gravity, the more power they radiate → the faster they run out of fuel

Simple Math

- More mass – longer life
- More luminosity – shorter life
- Hence: (life expectancy) = (mass) / (luminosity)
  - Sun has life expectancy of about 10 billion years
  - Sirius is 25x more luminous and has twice the mass
    ➔ Sun will live 25/2 =13.5 times longer than Sirius

Main Sequence Lifetimes

Mass (in solar masses) **Lifetime**	**Luminosity**
10 Suns **10 million yrs**	**10,000 Suns**
4 Suns **400 million yrs**	**100 Suns**
1 Sun **10 billion yrs**	**1 Sun**
½ Sun **500 billion yrs**	**0.01 Sun**

Observing Stellar Evolution by studying Globular Cluster HR diagrams

- Plot stars in globular clusters in Hertzsprung-Russell diagram
- Different clusters have different age
- Observe stellar evolution by looking at stars of same age but different mass
- Deduce age of cluster by noticing which stars have left main sequence already

Lessons from Star Clusters
(M3: Sandage/Arp 1953)

- Idea: All stars in a cluster are same age, composition, distance!
- As stars age, they leave the Main Sequence and climb into the giant branch

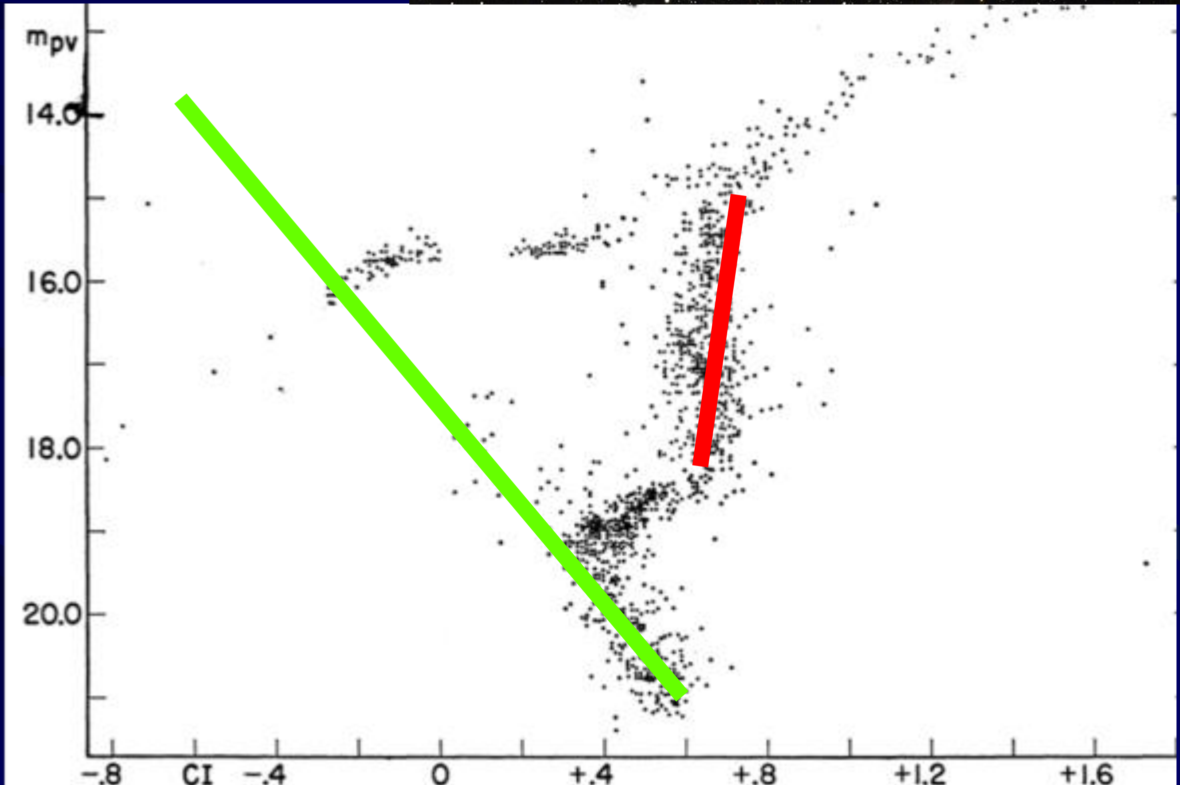
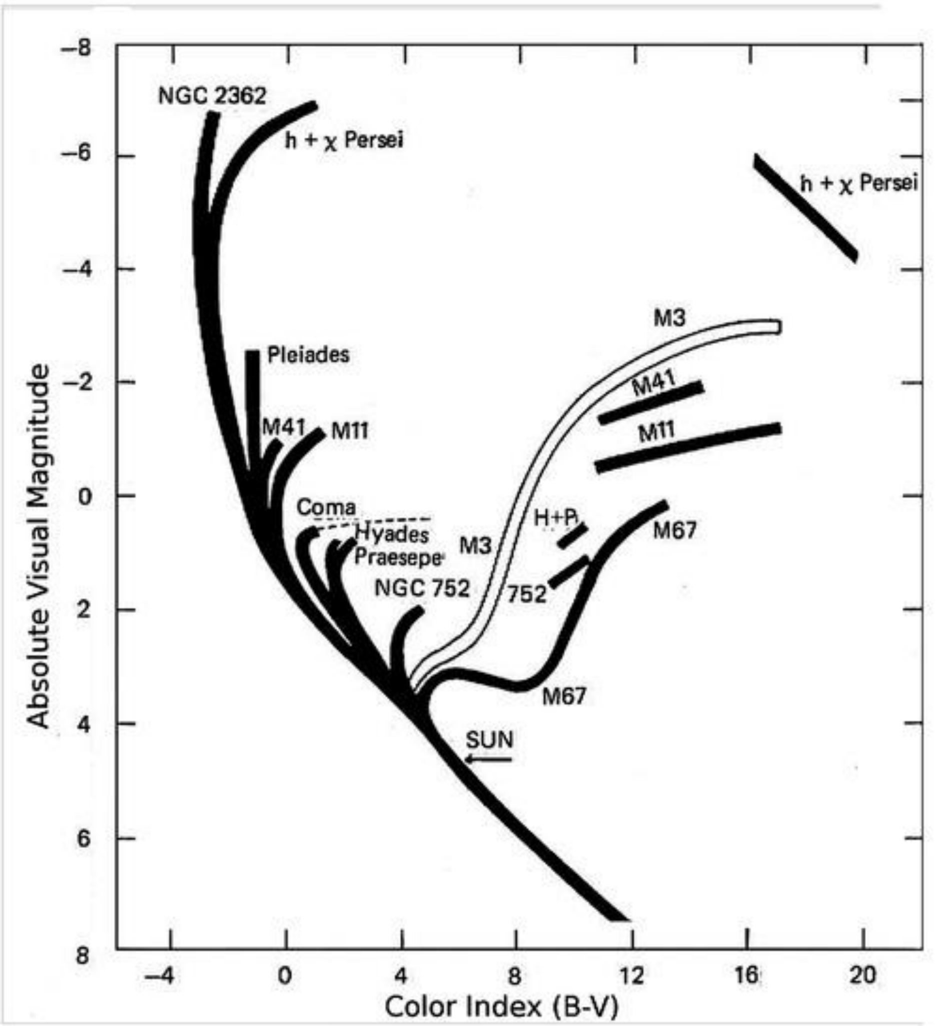


Figure 1. The color-magnitude diagram for M3. All known variable stars were excluded from the photometry. ordinate and abscissa are on the magnitude and color system of the photographic materials. The transformation to the *P* and *V* system of Stebbins, Whitford, and Johnson may be made by use of the color equations 1, 2, and 3 given in the text. The diagram does not represent a homogeneous sample. The density of points does not, therefore, give a relat luminosity function.

Open Clusters: Watching Young Stars age in time lapse



- Sandage 1957

  (M3 is the globular cluster from the last slide)

- Hot stars are massive, live and die fast

Catching Stellar Evolution “red-handed”