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)
Nuclear Fusion

- **Atoms**: electrons orbiting nuclei
- **Chemistry** deals only with electron orbits (electron exchange glues atoms together to form 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)
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  \rightarrow  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 equilibrium
- 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)
Reconstructing 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 $\sim 10^{-7}$ m, similar to the wavelength of visible light
  - Composition is not well known

- **Temperature depends on the proximity of stars, typically $\sim 100$ 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.

A 15 $M_\odot$ protostar takes about $10^5$ years to reach the main sequence...

...while a 1 $M_\odot$ protostar takes much longer, more than $10^7$ years.
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 $\rightarrow$ 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

<table>
<thead>
<tr>
<th>Mass (in solar masses)</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Suns</td>
<td>10,000 Suns</td>
</tr>
<tr>
<td>10 million yrs</td>
<td></td>
</tr>
<tr>
<td>4 Suns</td>
<td>100 Suns</td>
</tr>
<tr>
<td>400 million yrs</td>
<td></td>
</tr>
<tr>
<td>1 Sun</td>
<td>1 Sun</td>
</tr>
<tr>
<td>10 billion yrs</td>
<td></td>
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<tr>
<td>½ Sun</td>
<td>0.01 Sun</td>
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<tr>
<td>500 billion yrs</td>
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</table>
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
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”

- **Main-sequence turnoff**
- **Zero-age main sequence**
- **Time = 0**
- **Time = 10^7 yr**
- **Time = 10^8 yr**
- **Time = 10^9 yr**
- **Time = 10^10 yr**

Horizontal branch
Red-giant branch
Subgiant branch
White dwarfs
Main-sequence turnoff