Reading: Chapter 18, section 18.4, Chapter 22, Section 22.1-22.3
Chapter 21, through 21.3
OBAFGKM Contest: a better mnemonic for OBAFGKM?
• written (or e-mail) entries due Tuesday, February 27
• judging by an "independent" panel
• prizes!

Last time: Stellar Families, Masses and Luminosities
• H-RD reveals distinct groups - dominated by the Main Sequence
• Masses of stars can be found using binary star systems
• The Main Sequence is a sequence of Mass
• Mass and Luminosity correlate - the M-L relation as a consequence of fundamental physics

Today: Stellar lifetimes - how they evolve and how we know
• M-L relation tells us that massive stars ‘die’ sooner
• Stellar lifetimes are very long. But what happens when they ‘die?’
• Star clusters reveal what happens to stars as they age and die

The Vogt-Russell Theorem (1926):
Properties of ordinary stars are determined uniquely by mass and composition

• Mass+Composition -> position in H-R diagram
• on M.S., star burning hydrogen
• BUT: star is voluntarily changing its composition!
• V-R theorem demands:
  • star must leave M.S. when hydrogen is exhausted
  • so stars must move in the H-R diagram as they age
• “Stellar Evolution”

Life Expectancies for Main Sequence Stars
• available fuel supply \( \propto \) mass
• rate of fuel consumption \( \propto \) luminosity
• rate of consumption \( \times \) lifetime = total fuel consumed
  • so… luminosity \( \times \) lifetime \( \propto \) mass
  or lifetime \( \propto \) mass / luminosity
• combine with luminosity \( \propto \) mass\(^4\) to give
  \[ t_{\text{ms}} \propto \frac{1}{M^3} \]
  \[ t_{\text{ms}} = 10^{10} \text{ yr} \times (M/M_{\odot})^{-3} \]
• Massive Stars burn out faster

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<tr>
<th>Mass (x sun)</th>
<th>Lifetime [yr]</th>
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<td>10</td>
<td>10 million</td>
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<td>5</td>
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How do stars change over time?

- Stars evolve slowly!
  - we see stars as if they are frozen in time

- Stars in the sky have different ages:
  - Which stars are young?
  - Which are old?

- How do they evolve?
  - red giants $\rightarrow$ main sequence?
  - along the main sequence?
  - main sequence $\rightarrow$ white dwarfs?

- Ages needed of a bunch of stars to trace a stellar life cycle

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Key Objects: Star Clusters

- **Associations**
  - several dozen stars
  - 10-100 pc in diameter
  - lots of massive main sequence stars

- **Open Clusters** (i.e. Hyades, **Pleiades**, M67, ...)
  - 10s of parsecs in diameter
  - 100 - several thousand stars
  - found in Milky Way disk

- **Globular Clusters** (i.e. Omega Cen., **M80**)
  - 10,000 - 100,000+ stars
  - 10 - 50 pc across
  - found in the “halo” of the Milky Way
H-R (C-M) diagram for an Association

Open Clusters

M34

M67

H-R (C-M) diagram for an Open Cluster
Cluster C-M Diagrams

- **Associations**
  - nearly all stars on Main Sequence
  - includes O and B stars

- **Open Clusters**
  - O and B stars are missing from Main Sequence
  - a few red giants

- **Globular Clusters**
  - no main sequence O, B, A, or F stars
  - many red giants and other stars
  - only low-mass stars remain on Main Sequence

H-R (C-M) diagram for a Globular Cluster

H-R (C-M) diagram for an Association
Remember: \[ t_{	ext{ms}} = 10^{10} \text{ yr} \times (\frac{M}{M_{\odot}})^{-3} \]

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- **O stars in Associations**
  - younger than 10 million years
- **M.S. A Stars in Open Clusters**
  - older than 10^7 years and younger than 400 million years
  - O, B stars have become red giants
- **M.S. G Stars in Globular Clusters**
  - stars more massive than G stars have become red giants
  - age \sim 10 billion years

As a cluster ages:
- main sequence “peels down”
  - clusters do not change type as they age
- most massive remaining MS star gives age of cluster
Age of oldest clusters:
~12-14 billion years
Is this the age of the Universe?

- With star clusters as our guide, we can:
  - recreate life cycles of stars with different masses
    birth → middle age → old age → death
  - follow several generations of stars
  - trace history of the Universe from its creation to the distant future

What about the end game(s)?

- We now see the ‘main’ lifetime trajectory
  i.e. what stellar adulthood looks like

- How are stars born?
  - What happens before they start burning hydrogen in the core?

- How do stars “die?”
  - What happens when they run out of nuclear fuel?