Reading: Chapter 18, section 18.4, Chapter 22, Section 22.1-22.3
Chapter 21, through 21.3

OBAFGKM mnemonics: small extra credit opportunity
better(?) mnemonics for OBAFGKM
see Discussions page on Canvas

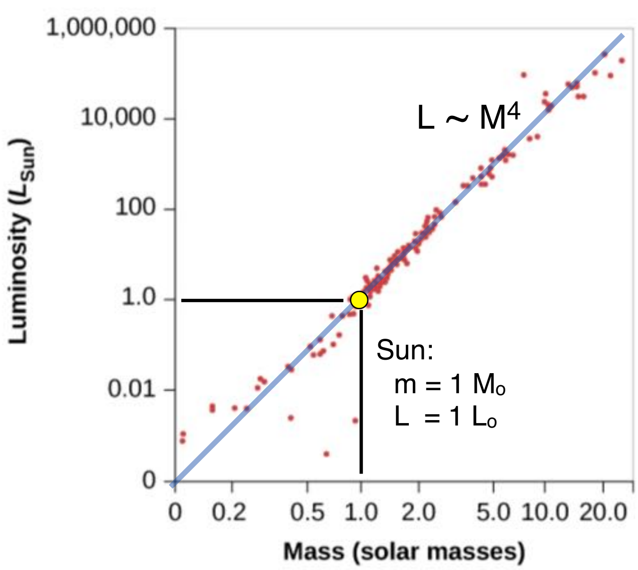
Last time: **Stellar Families, Masses and Luminosities**

- 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

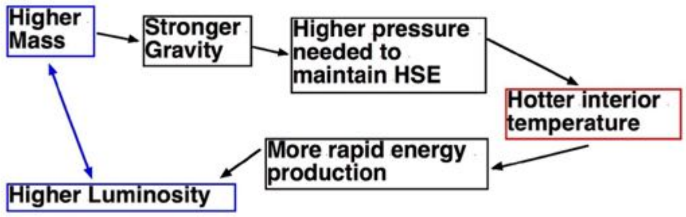
Today: **Stellar lifetimes - how they evolve and how we know**

- 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 Mass-Luminosity Relation



The Mass-Luminosity Relation



- Eddington (1926):
  $L \propto M^4$ for main sequence stars
- Main sequence is a sequence in MASS
  blue stars are more massive than red stars
- The Sun is a M.S. star = the Sun burns hydrogen in its core
- **all M.S. stars burn hydrogen in their cores**

The Vogt-Russell Theorem (1926):

Properties of ordinary stars are uniquely determined by mass and composition

- Mass+Composition —> position in H-R diagram
- on M.S., star burns 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 ∝ mass
- rate of fuel consumption ∝ luminosity
- rate of consumption x lifetime = total fuel consumed
  - so... luminosity x lifetime ∝ mass

    or lifetime ∝ mass / luminosity
  - combine with luminosity ∝ $mass^4$ to give

    $t_{ms} \propto 1/M^3$

    $t_{ms} = 10^{10}$ yr x $(M/M_{sun})^{-3}$
- **Massive Stars burn out faster**

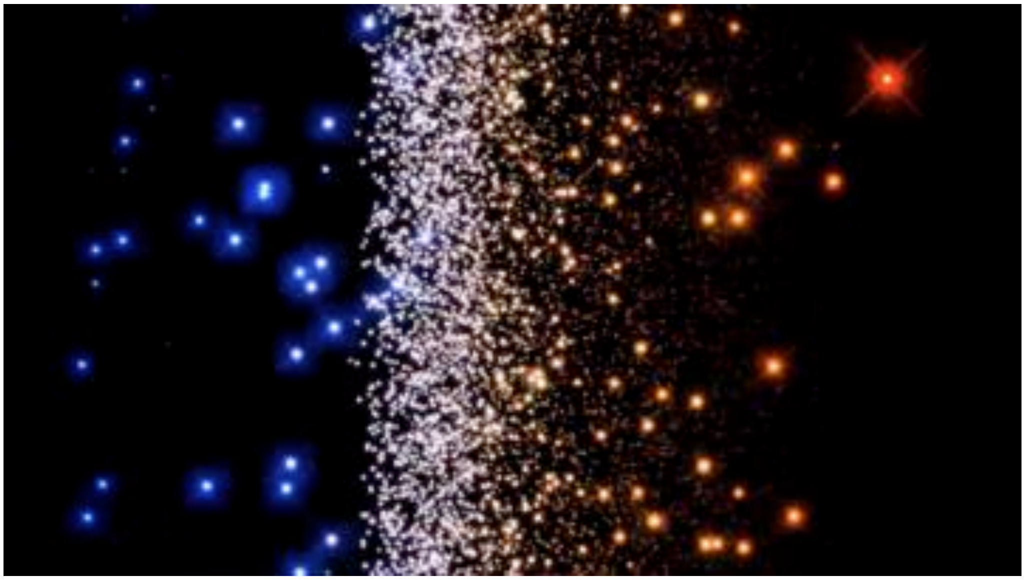
Mass (x sun)	Lifetime [yr]
10	10 million
5	80 million
3	370 million
2	1.3 billion
1	10 billion
0.8	20 billion

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 → main sequence?
  - along the main sequence?
  - main sequence → white dwarfs?
- Ages needed of a bunch of stars to trace a stellar life cycle

Mass (x sun)	Lifetime [yr]
10	10 million
5	80 million
3	370 million
2	1.3 billion
1	10 billion
0.8	20 billion

Key Objects: Star Clusters



Key Objects: Star Clusters

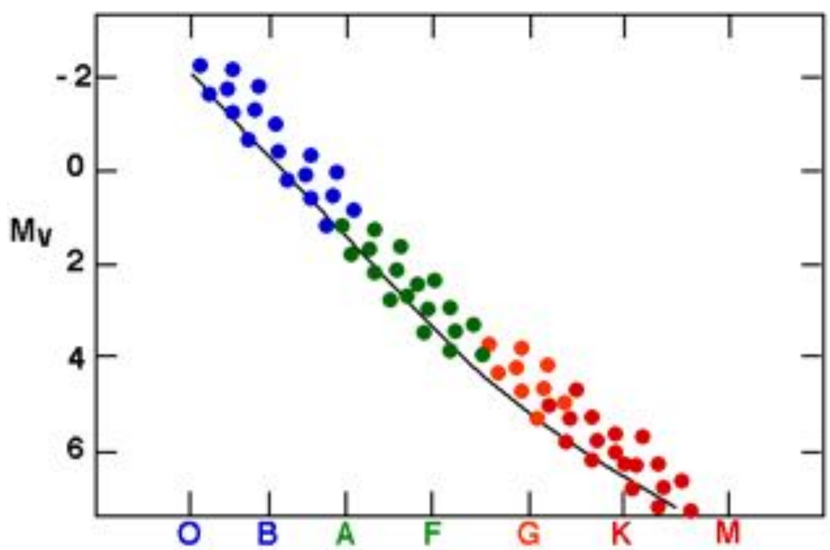
- **Associations**
  - several dozen stars
  - 10-100 pc in diameter
  - lots of massive main sequence stars

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

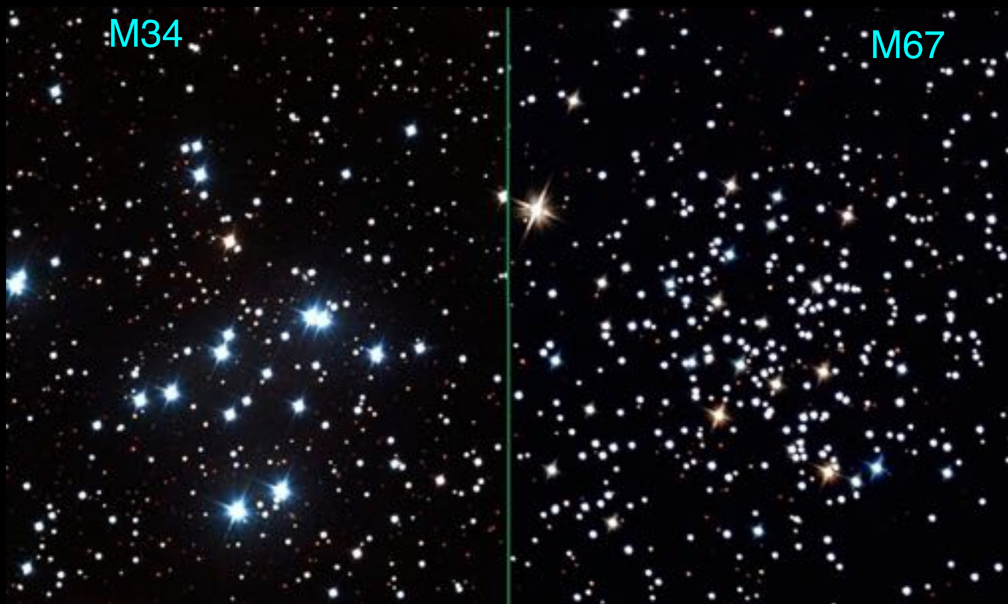
- **Globular Clusters** (i.e. Omega Cen., **M80**)
  - 10,000 - 100,000+ stars
  - 10 - 50 pc across
  - found in the “halo” of the Milky Way

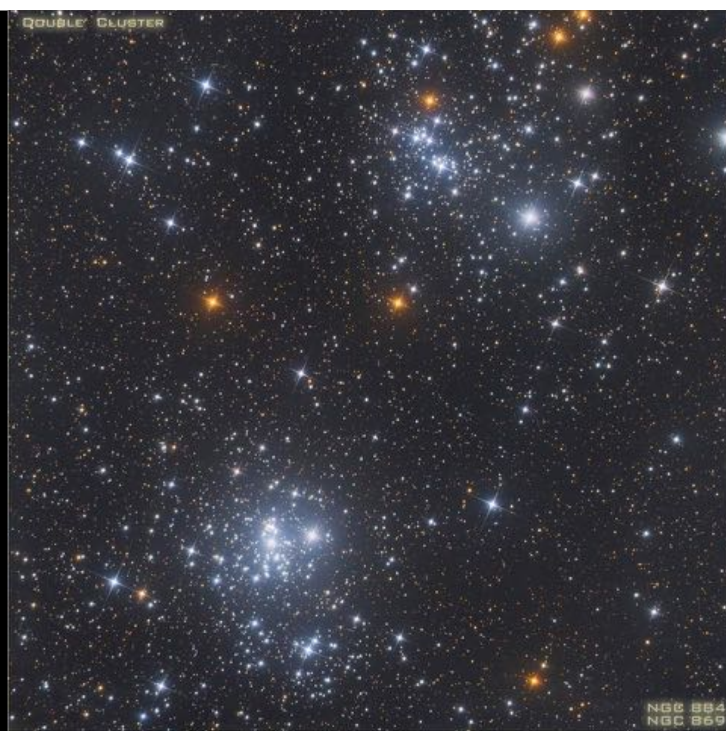
Associations

H-R (C-M) diagram for an Association

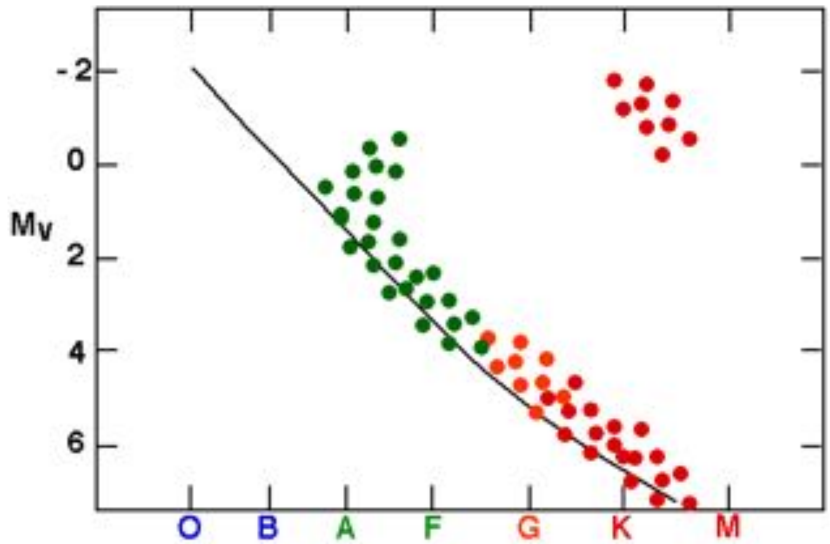


Open Clusters

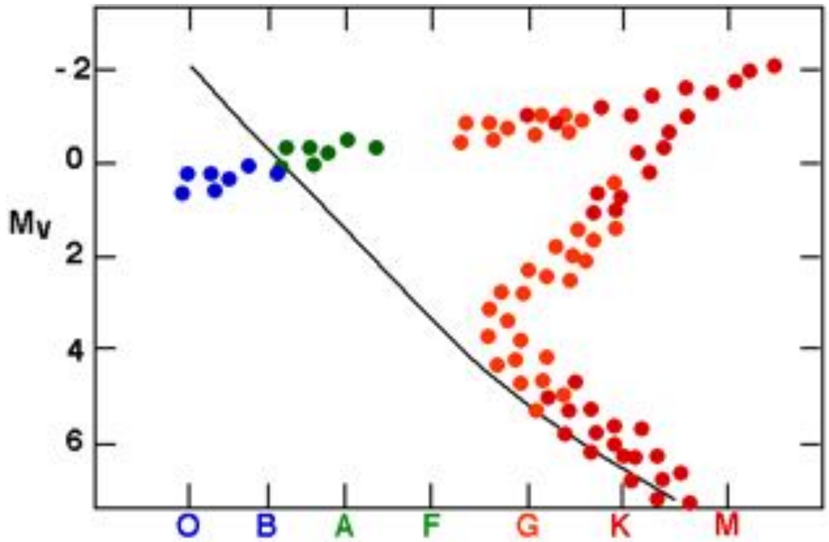




H-R (C-M) diagram for an Open Cluster

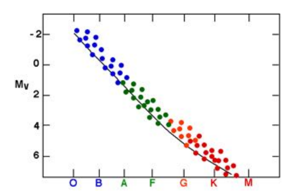


H-R (C-M) diagram for a Globular Cluster

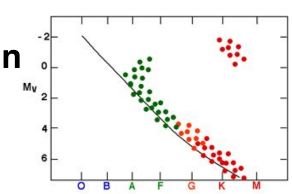


Cluster C-M Diagrams

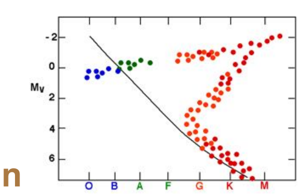
- **Associations**
  - **nearly all stars on Main Sequence**
  - includes O and B stars



- **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**



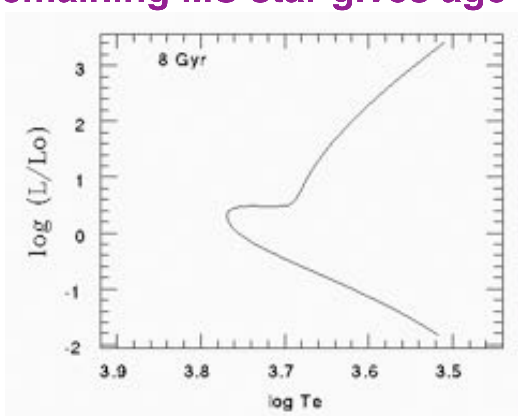
Remember: $t_{ms} = 10^{10}$ yr x $(M/M_{sun})^{-3}$

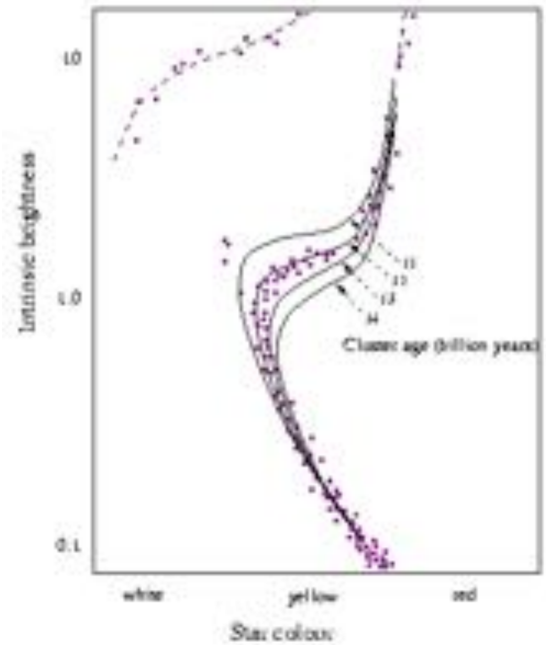
Type	Mass (x sun)	MS Lifetime [yr]
O	10	10 million
A	3	370 million
G	1	10 billion
K	0.8	20 billion

- **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 ~ 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?