Masses are much harder than distance, luminosity, or temperature.

- Since we are only ever seeing a point source, it is hard to determine how much mass is contained.
  - If we could see another nearby object (another star maybe?) we could use the gravity between the objects as a measure of the mass.

Binary Stars to the Rescue!!

- Types of binary star systems:
  - Visual Binary
  - Eclipsing Binary
  - Spectroscopic Binary

About half of all stars are in binary systems.
**Visual Binary**

We can directly observe the orbital motions of these stars

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**Eclipsing Binary**

We see light from both A and B. We see light from all of B, some of A. We see light from both A and B. We see light only from A.

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**Spectroscopic Binary**

Star B spectrum at time 1: approaching, therefore blueshifted

1. approaching us

Star B spectrum at time 2: receding, therefore redshifted

2. receding from us

We determine the orbit by measuring Doppler shifts

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Animation from [http://www-astronomy.mps.ohio-state.edu/~pogge/Ast162/Movies/spanim.gif](http://www-astronomy.mps.ohio-state.edu/~pogge/Ast162/Movies/spanim.gif)
Newton's Laws of gravity provide the mass

Direct mass measurements are possible only for stars in binary star systems.

Once we know:
- \( p = \text{period} \)
- \( a = \text{average separation} \)

We can solve Newton's equations for mass (M).

Astronomer's Toolbox:

- Measure **Distance**:
  - parallax...good to nearby stars but not beyond

- Measure **Luminosity**:
  - measure apparent brightness and distance, infer luminosity

- Measure **Temperature**:
  - Wien's law, or, better yet, take spectra and use spectral classification.

- Measure **Mass**:
  - For stars in binary orbits, if we can get their orbital parameters, we can figure out their mass.

Wide range of luminosities, temperatures and masses.

Any **correlation** among these quantities?

The Hertzsprung Russell Diagram

- THIS IS AN IMPORTANT DIAGRAM TO UNDERSTAND.

- Basics:
  - Plots **Stellar Luminosity** (not apparent brightness) **Vs**
    - **Temperature** or **Color** or **Spectral Class**
Study this plot!

D. They DO show a relationship or relation between them!

Clicker Question

Are the variables plotted here related to each other?

A. Yes, they show a relationship
B. You can’t be sure – you don’t know what they are!
C. They are related to each other or else both are related to a third variable
D. Either A or C
E. None of the above

H-R diagram

Emitted power per unit area = \( \sigma T^4 \)
where \( \sigma = 5.67 \times 10^{-5} \text{ergK}^{-4} \text{cm}^{-2} \text{s}^{-1} \)

Total luminosity from a star of radius R:

\[ L = 4\pi R^2 \sigma T^4 \]

For the same temperature, more luminous stars have larger radii.
Main sequence stars

- Burning hydrogen in their cores
- Stellar masses decrease downward
- Temperatures are hotter for more massive stars (more gravitational pressure → higher T, remember Equation of State)
- More luminous (higher T → much higher emitted power)

Lifetimes on Main Sequence (MS)

- Stars spend 90% of their lives on MS
- Lifetime on MS = amount of time star fuses hydrogen (gradually) in its core
- For Sun (G), this is about 10 billion years
- For more massive stars (OBAF), lifetime is (much) shorter
- For less massive stars (KM), lifetime is longer

Stellar lifetimes along the main sequence

- Available hydrogen fuel is greater for the most massive stars...
- But luminosity (rate at which hydrogen is fused) is MUCH higher
- More massive (more luminous) main sequence stars run out of fuel sooner

Example: Most massive O star:

\[ M = 100 \, M_{\text{Sun}} \]
\[ L = 10^6 \, L_{\text{Sun}} \]
\[ \frac{M}{L} = 10^2 \frac{10^6}{10^3} = 10^4 \text{ of the Sun} \]
\[ \text{Life}_{\text{O-STAR}} = 10^{10} \text{ yrs} \times 10^{-4} = 10^6 \text{ yrs} \]

Main-Sequence Star Summary

High Mass:
- High Luminosity
- Short-Lived
- Large Radius
- Hot
- Blue

Low Mass:
- Low Luminosity
- Long-Lived
- Small Radius
- Cool
- Red
**Clicker Question**

George and Abe are two main sequence stars; George is an M star and Abe is a B star. Which is more massive? Which is redder in color?

A. George is more massive and redder
B. Abe is more massive and redder
C. George is more massive; Abe is redder
D. Abe is more massive; George is redder
E. They are both main sequence, they’re the same mass and same color.

**Clicker Question**

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What about the other objects on the H-R diagram?

- Top end of main sequence starts to “peel off”
- Pleiades star cluster shown → no more O and B stars

As stars run out of hydrogen fuel their properties change (generally they turn into red giants- more on why later)
Main-sequence turnoff point of a cluster tells us its age.

How do we measure the age of a stellar cluster?

A. Use binary stars to measure the age of stars in the cluster.
B. Use the spectral types of the most numerous stars in the cluster to infer their temperatures, and thus, the age of the cluster.
C. Find stars in the instability strip and use their variability period to measure their age.
D. Look for the age of stars at the main-sequence turnoff point.
E. Determine if the cluster is an open cluster or globular cluster and use the average age of those types of clusters.

Main sequence A-stars have masses about 3 times that of the Sun, and luminosities about 30 times that of the Sun. What is the age of a cluster which has a “turnoff” at A-stars? (Remember: The Sun’s lifetime ~ 10 billion years)

A) 100 thousand years
B) 100 million years
C) 1 billion years
D) 10 billion years
E) 100 billion years

Clicker Question
Main sequence A-stars have masses about 3 times that of the Sun, and luminosities about 30 times that of the Sun. What is the age of a cluster which has a “turnoff” at A-stars? (Remember: The Sun’s lifetime ~ 10 billion years)

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D) 10 billion years
E) 100 billion years

Where we see this best: Star Clusters

1. Open Clusters
- Loose groups of 1000’s of stars
- This is where most stars in the Galaxy are born

Pleiades: an “open cluster” of stars about 100 million years old
- Compare with Sun’s age of about 4.6 BILLION years old

Groups of 100’s to millions of stars
- All about the same distance (apparent brightness tracks luminosity well)
- All formed about the same time (i.e. all are same age)
- Range of different mass stars!
2.) Globular Clusters

- Generally much older - up to 13 BILLION years
- ~millions of stars, densely packed
- Intense gravitational interactions

Cepheid Variable Stars

- Some stars vary in brightness because they cannot achieve proper balance between power welling up from the core and power radiated from the surface
- Most pulsating variable stars inhabit an instability strip on the H-R diagram
- The most luminous ones are known as Cepheid variables: important for distance measurements

Temperature

Which star is most like our Sun?

Luminosity

Clicker question

Temperature

Which star is most like our Sun?

Clicker question
Which of these stars will have changed the least 10 billion years from now?

A  
B  
C  
D  

Clicker question

Which of these stars can be no more than 10 million years old?

A  
B  
C  
D  

Clicker question
Stellar Properties Review

**Luminosity:** from brightness and distance

\[ (0.08 \, M_{\text{Sun}}) \quad 10^{-4} \, L_{\text{Sun}} \sim 10^{6} \, L_{\text{Sun}} \quad (100 \, M_{\text{Sun}}) \]

**Temperature:** from color and spectral type

\[ (0.08 \, M_{\text{Sun}}) \quad 3,000 \, \text{K} \sim 50,000 \, \text{K} \quad (100 \, M_{\text{Sun}}) \]

**Mass:** from period (p) and average separation (a) of binary-star orbit

\[ 0.08 \, M_{\text{Sun}} \sim 100 \, M_{\text{Sun}} \]

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The H-R Diagram review

_So far:_

Stars on Main Sequence (MS)

_Next:_

- Pre MS (Star Birth)
- Post MS: Giants, Super Giants, White dwarfs