Characterizing Stars
Guiding Questions

1. How far away are the stars?
2. What evidence do astronomers have that the Sun is a typical star?
3. What is meant by a “first-magnitude” or “second magnitude” star?
4. Why are some stars red and others blue?
5. What are the stars made of?
6. As stars go, is our Sun especially large or small?
7. What are giant, supergiant, and white dwarf stars?
8. How do we know the distances to remote stars?
9. Why are binary star systems important in astronomy?
10. How can a star’s spectrum show whether it is actually a binary star system?
11. What do astronomers learn from stars that eclipse each other?
Parallax

When you are at position B, the tree appears to be in front of this mountain.

When you are at position A, the tree appears to be in front of this mountain.

Position A  Position B
In January, the nearby star appears to be here.

In July, the nearby star appears to be here.

Parallax of a nearby star
The closer the star, the more its apparent position shifts as seen from Earth.

Parallax of an even closer star
Careful measurements of the parallaxes of stars reveal their distances

Relation between a star’s distance and its parallax

\[ d = \frac{1}{p} \]

- Distance to a star, in parsecs
- \( p \) = parallax angle of that star, in arcseconds

- Distances to the nearer stars can be determined by parallax, the apparent shift of a star against the background stars observed as the Earth moves along its orbit.
- Parallax measurements made from orbit, above the blurring effects of the atmosphere, are much more accurate than those made with Earth-based telescopes.
- Stellar parallaxes can only be measured for stars within a few hundred parsecs.
Barnard’s star has a parallax of 0.54 arcsec

\[ d = \frac{1}{p} = \frac{1}{0.547} = 1.83 \text{ pc} \]

Because 1 parsec is 3.26 light-years, this can also be expressed as

\[ d = 1.83 \text{ pc} \times \frac{3.26 \text{ ly}}{1 \text{ pc}} = 5.96 \text{ ly} \]
With greater distance from the star, its light is spread over a larger area and its apparent brightness is less.
If a star’s distance is known, its luminosity can be determined from its brightness

Inverse-square law relating apparent brightness and luminosity

\[ b = \frac{L}{4\pi d^2} \]

- \( b \) = apparent brightness of a star’s light, in W/m²
- \( L \) = star’s luminosity, in W
- \( d \) = distance to star, in meters

- A star’s luminosity (total light output), apparent brightness, and distance from the Earth are related by the inverse-square law
- If any two of these quantities are known, the third can be calculated
Determining a star’s luminosity from its apparent brightness

\[
\frac{L}{L_\odot} = \left( \frac{d}{d_\odot} \right)^2 \frac{b}{b_\odot}
\]

\( L/L_\odot \) = ratio of the star’s luminosity to the Sun’s luminosity

\( d/d_\odot \) = ratio of the star’s distance to the Earth-Sun distance

\( b/b_\odot \) = ratio of the star’s apparent brightness to the Sun’s apparent brightness
The Population of Stars

- Stars of relatively low luminosity are more common than more luminous stars.
- Our own Sun is a rather average star of intermediate luminosity.
Stellar Motions

\[ v = \text{the star's space velocity} \]
\[ v_r = \text{the star's radial velocity} \]
\[ v_t = \text{the star's tangential velocity} \]

\[ d = \text{distance from Earth to the star} \]
Astronomers often use the magnitude scale to denote brightness – a scale that was introduced by the ancient Greeks about 300 BC.

- The apparent magnitude scale is an alternative way to measure a star’s apparent brightness.
- The absolute magnitude of a star is the apparent magnitude it would have if viewed from a distance of 10 parsecs.
Apparent magnitudes of stars in the Pleiades
A star’s color depends on its surface temperature - recall Wien’s Law

(a) A cool star with surface temperature 3000 K emits much more red light than blue light, and so appears red.

(b) A warmer star with surface temperature 5500 K emits roughly equal amounts of all visible wavelengths, and so appears yellow-white.

(c) A hot star with surface temperature 10,000 K emits much more blue light than red light, and so appears blue.
<table>
<thead>
<tr>
<th>Star</th>
<th>Surface temperature (K)</th>
<th>$b_V/b_B$</th>
<th>$b_B/b_U$</th>
<th>Apparent color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bellatrix ($\gamma$ Orionis)</td>
<td>21,500</td>
<td>0.81</td>
<td>0.45</td>
<td>Blue</td>
</tr>
<tr>
<td>Regulus ($\alpha$ Leonis)</td>
<td>12,000</td>
<td>0.90</td>
<td>0.72</td>
<td>Blue-white</td>
</tr>
<tr>
<td>Sirius ($\alpha$ Canis Majoris)</td>
<td>9400</td>
<td>1.00</td>
<td>0.96</td>
<td>Blue-white</td>
</tr>
<tr>
<td>Megrez ($\delta$ Ursae Majoris)</td>
<td>8630</td>
<td>1.07</td>
<td>1.07</td>
<td>White</td>
</tr>
<tr>
<td>Altair ($\alpha$ Aquilae)</td>
<td>7800</td>
<td>1.23</td>
<td>1.08</td>
<td>Yellow-white</td>
</tr>
<tr>
<td>Sun</td>
<td>5800</td>
<td>1.87</td>
<td>1.17</td>
<td>Yellow-white</td>
</tr>
<tr>
<td>Aldebaran ($\alpha$ Tauri)</td>
<td>4000</td>
<td>4.12</td>
<td>5.76</td>
<td>Orange</td>
</tr>
<tr>
<td>Betelgeuse ($\alpha$ Orionis)</td>
<td>3500</td>
<td>5.55</td>
<td>6.66</td>
<td>Red</td>
</tr>
</tbody>
</table>

Source: J.-C. Mermilliod, B. Hauck, and M. Mermilliod, University of Lausanne.
Photometry and Color Ratios

- Photometry measures the apparent brightness of a star.
- The color ratios of a star are the ratios of brightness values obtained through different standard filters, such as the U, B, and V filters.
- The color ratios are a measure of the star’s surface temperature.
The spectra of stars reveal their chemical compositions as well as surface temperatures

- Stars are classified into spectral types
  - divisions of the spectral classes
    - O, B, A, F, G, K, and M
  - Subclasses
    - 0, 1, 2, 3, 4, 5, 6, 7, 8, 9

- The original letter classifications originated from the late 1800s and early 1900s
• The spectral class of a star is directly related to its surface temperature
  – O stars are the hottest
  – M stars are the coolest
Brown dwarfs are in even cooler spectral classes now called L and T.

- Unlike true stars, brown dwarfs are too small to sustain thermonuclear fusion.
Full Spectral Typing
Spectral Class and Luminosity Class

• The Sun
  – Classified as a G2 V

• Luminosity classes (use Roman numerals)
  – I – Giant
  – II – Giant
  – III – Giant
  – IV – Sub-giant
  – V – Main Sequence
Relationship between a star’s luminosity, radius, and surface temperature

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

- \( L \) = star’s luminosity, in watts
- \( R \) = star’s radius, in meters
- \( \sigma \) = Stefan-Boltzmann constant = \( 5.67 \times 10^{-8} \) W m\(^{-2}\) K\(^{-4}\)
- \( T \) = star’s surface temperature, in kelvins

- Stars come in a wide variety of sizes
- Recall Stefan-Boltzmann Law
Flowchart of Key Stellar Parameters

Parallax ($p$)

\[ d = \frac{1}{p} \]

Distance ($d$)

Apparent brightness ($b$)

\[ L = 4\pi d^2 b \]

Luminosity ($L$)

Spectrum

Spectral type

Surface temperature ($T$)

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

Radius ($R$)

Chemical composition
The Hertzsprung-Russell (H-R) Diagram

- The H-R diagram is a graph plotting the absolute magnitudes of stars against their spectral types—or, equivalently, their luminosities against surface temperatures.
- The positions on the H-R diagram of most stars are along the main sequence, a band that extends from high luminosity and high surface temperature to low luminosity and low surface temperature.
On the H-R diagram, giant and supergiant stars lie above the main sequence, while white dwarfs are below the main sequence.
By carefully examining a star’s spectral lines, astronomers can determine whether that star is a main-sequence star, giant, supergiant, or white dwarf.

(a) A supergiant star has a low-density, low-pressure atmosphere: its spectrum has narrow absorption lines.

(b) A main-sequence star has a denser, higher-pressure atmosphere: its spectrum has broad absorption lines.
Using the H-R diagram and the inverse square law, the star’s luminosity and distance can be found without measuring its stellar parallax.
Pathway to Spectroscopic Parallax

Apparent brightness ($b$) → Spectrum → Luminosity class → H–R diagram → Luminosity ($L$) → Distance ($d$)

Luminosity class → Spectral type → Surface temperature ($T$) → $L = 4\pi d^2 b$

H–R diagram → $L = 4\pi R^2 \sigma T^4$ → Radius ($R$)

Chemical composition
Binary Stars

• Binary Stars
  – Two stars held in orbit around each other by their mutual gravitational attraction
    • Surprisingly common

• Visual Binary
  – Those binary star systems that can be resolved into two distinct star images by an Earth-based telescope are called visual binaries

• Each of the two stars in a binary system moves in an elliptical orbit about the center of mass of the system
Sample Binary Star System

Period = 87.7 years
Binary Star System Analogy

The center of mass of the system of two children is nearer to the more massive child.

A “binary system” of two children
The center of mass of the binary star system is nearer to the more massive star.
Binary Star Systems and Stellar Masses

• Binary stars are important because they allow astronomers to determine the masses of the two stars in a binary system.

• The masses can be computed from measurements of the orbital period and orbital dimensions of the system.

\[ M_1 + M_2 = \frac{a^3}{P^2} \]

- \( M_1, M_2 \) = masses of two stars in binary system, in solar masses
- \( a \) = semimajor axis of one star’s orbit around the other, in AU
- \( P \) = orbital period, in years
Main sequence stars are stars like the Sun but with different masses.

The mass-luminosity relation expresses a direct correlation between mass and luminosity for main-sequence stars.

The greater the mass of a main-sequence star, the greater its luminosity (and also the greater its radius and surface temperature).
For a main-sequence star, high mass means high luminosity...

...while low mass means low luminosity.

Sun
The H-R Diagram
View of the Main Sequence

For a main-sequence star, high mass means high luminosity, high surface temperature, and a large radius...

...while low mass means low luminosity, low surface temperature, and a small radius.
Spectroscopy makes it possible to study binary systems in which the two stars are close together

- Some binary star systems can be detected and analyzed even though the system may be so distant, or the two stars so close together, that the two star images cannot be resolved.
- A spectroscopic binary appears to be a single star but has a spectrum with the absorption lines for two distinctly different spectral types of stars.
- A spectroscopic binary has spectral lines that shift back and forth in wavelength. This is caused by the Doppler effect, as the orbits of the stars carry them first toward then away from the Earth.
When one of the stars in a spectroscopic binary is moving toward us and the other is receding from us, we see two sets of spectral lines due to the Doppler shift.

When both stars are moving perpendicular to our line of sight, there is no Doppler splitting and we see a single set of spectral lines.
Light curves of eclipsing binaries provide detailed information about the two stars

- An eclipsing binary is a system whose orbits are viewed nearly edge-on from the Earth, so that one star periodically eclipses the other.
- Detailed information about the stars in an eclipsing binary can be obtained from a study of the binary’s radial velocity curve and its light curve.
Eclipse of a binary star
Jargon

- absolute magnitude
- apparent brightness
- apparent magnitude
- binary star (binary)
- brown dwarf
- center of mass
- color ratio
- distance modulus
- double star
- eclipsing binary
- giant
- Hertzsprung-Russell diagram
- H-R diagram
- inverse-square law
- light curve
- luminosity
- luminosity class
- luminosity function
- magnitude scale
- main sequence
- main-sequence star
- mass-luminosity relation

- metals
- OBAFGKM
- optical double star
- parallax
- parsec
- photometry
- proper motion
- radial velocity
- radial velocity curve
- red giant
- space velocity
- spectral classes
- spectral types
- spectroscopic binary
- spectroscopic parallax
- spectrum binary
- stellar parallax
- supergiant
- tangential velocity
- UBV photometry
- visual binary
- white dwarf