Announcements

Homework 2 is due next Thursday (Feb. 4)

Other than my office hours, homework help is also available Fridays 12-1pm (Ismael Mireles); https://physics.unm.edu/pandaweb/undergraduate/tutoring.php
Overall structure

ANATOMY OF THE SUN

Core

Radiative Zone

Convection Zone

Corona

Chromosphere

Photosphere
The Sun’s atmosphere

- Photosphere: yellowish color. The part we see, T=5800 K.
- The Sun is a giant sphere or gas - so it doesn't have a well defined surface.
- Talking about the surface: we mean the photosphere.
- The point where atmosphere becomes completely opaque is the photosphere (defines diameter of the Sun).
Limb darkening

- Outer portions of photosphere being cooler
- Photons travel about the same path length

Dimmer light comes from higher, relatively cool layer within the photosphere.

Bright light comes from low-lying, hot layer within the photosphere.
Granulation

- Photosphere is lowest of 3 atmospheric layers
- Granulation due to convection

This picture shows blobs ~1000 km across
Chromosphere

- Middle layer, characterized by Hα emission: red color.
- The gas is very rarefied (10^{-4} density of photosphere).
- Also featured are gas plumes jutting upward.
H alpha image showing chromospheric activity. Photo taken through filter which lets through only light of wavelength of H-alpha (656 nm).

Spectrum of chromosphere is dominated by emission lines – what does this say about temperature compared to photosphere?
Corona

1999 total solar eclipse

2017 total solar eclipse

Image credit: Luc Viatour/Diliff

Ejects mass into space -> solar wind

Shapes of streamers vary on timescales as short as days!
Next total solar eclipse: April 8, 2024
Thermal Profile of the Sun

- Photosphere
- Chromosphere
- Transition region
- Low corona

<table>
<thead>
<tr>
<th>Height (km)</th>
<th>Temperature (K)</th>
<th>Height (km)</th>
<th>Temperature (K)</th>
<th>Height (km)</th>
<th>Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2000</td>
<td>$1 \times 10^6$</td>
<td>3000-6000</td>
<td>$1.5 \times 10^6$</td>
<td>7500-10000</td>
<td>$2 \times 10^6$</td>
</tr>
<tr>
<td>2000-3000</td>
<td>$8600$</td>
<td>6000-9000</td>
<td>$28000$</td>
<td>10000-15000</td>
<td>$75000$</td>
</tr>
</tbody>
</table>

Temperature minimum region
The nature of the stars
What are stars?

Are they all alike?
Is the Sun typical?

How can we describe/classify stars?

- Temperature
- Luminosity (total energy output)
- Mass (orbital motion)
- Physical sizes
- True motion in space

To estimate those parameters, we need to know the distance!
Two dimensions are easy – use photograph for angular position. Distance not so easy, the only direct means is by parallax.

*Parallax is the apparent angular shift of an object due to a change in an observer’s point of view.*
The parallax formula for distance

- $d = 1/p$ where $p$ is the parallax angle and $d$ is the distance in pc.
- Distance units: $1 \text{ pc} = 3.26 \text{ ly} = 3.09 \times 10^{16} \text{ m} = 206,265 \text{ AU}$
- It took us until 1838 to measure stellar parallaxes since the stars are so far away => small parallax angles

Limitations

- Until recently we only knew accurate (0.01") parallaxes for a few hundred stars ($\Rightarrow d \sim 100 \text{pc}$)
- In the 1990's the ESA satellite Hipparcos measured over 100,000 parallaxes with an accuracy of 0.001"
- Gaia has measured over a billion stars to 2 kpc
Proper motion

- Caused by physical movement of a star with respect to our Solar system

- This is in contrast to parallax which is an apparent motion of the star due to the motion of the Earth

- Proper motion is the angle a star moves per year (angular motion on the sky), and it is a linear drift

- The superposition of this linear drift and the elliptical motion from the parallax effect leads to a 'wavy' path on the sky

This star moved 4' over this time - a huge proper motion of 10¨.9/yr.
Tangential velocity

\[ v_t = 4.74 \mu d, \] where \( \mu \) is the proper motion [”/yr] and \( d \) is the distance [pc]; this choice of constants gives \( v_t \) in the units of km/s.

Radial velocity

Given by Doppler shift:

\[ v_r = \left[ \frac{\lambda_{\text{observed}} - \lambda_{\text{emitted}}}{\lambda_{\text{emitted}}} \right] c \]

Dependent on distance

Independent on distance
Space Velocity

Speed and direction of star. From Pythagorean theorem

\[ V = \sqrt{V_t^2 + V_r^2} = \sqrt{(4.74 \mu d)^2 + V_r^2} \]

Typical stellar space velocities are 20-100 km/s.

Three quantities need to be measured - distance is the most difficult one.
Why care about stellar motions?

- A tool to study structure of our Galaxy
  - Motion of the Sun (~ 20km/s)
  - Rotation of the Galactic Plane (local)
  - Odd phenomena/stars that might indicate special events
  - Past merger events
How bright is a star?

- Luminosity ($L$, intrinsic property): the total energy output, a physical property of the star. Doesn't depend on distance.

- Apparent brightness ($F$, or $b$): measures how bright a star appears to be on a distance. Does depend on distance!

- The brightness, or intensity, of light diminishes as the inverse square of the distance.

$$ F = \frac{L}{4\pi d^2} $$

Same amount of radiation from a star must illuminate a bigger area as distance from star increases. The area increases as the square of the distance.
Apparent magnitudes

- Measurement of brightness of stars as they seem from Earth.

- Smaller magnitudes mean brighter stars and defined such that 5 magnitude differences implies a factor of 100 in brightness.

- Magnitude difference related to brightness ratio:

\[ m_2 - m_1 = 2.5 \log \left( \frac{b_1}{b_2} \right) \]

- Also note: if \( \frac{b_1}{b_2} = 100 \), then \( 2.5 \log \left( \frac{b_1}{b_2} \right) = 5 \)

- This is a logarithmic scale - no zero point is defined. Done by defining certain stars to have zero magnitude.
A factor of 2.512 difference in brightness per magnitude. Box 17-3.

<table>
<thead>
<tr>
<th>Apparent magnitude difference ((m_2 - m_1))</th>
<th>Ratio of apparent brightness ((b_1/b_2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.512</td>
</tr>
<tr>
<td>2</td>
<td>((2.512)^2 = 6.31)</td>
</tr>
<tr>
<td>3</td>
<td>((2.512)^3 = 15.85)</td>
</tr>
<tr>
<td>4</td>
<td>((2.512)^4 = 39.82)</td>
</tr>
<tr>
<td>5</td>
<td>((2.512)^5 = 100)</td>
</tr>
<tr>
<td>10</td>
<td>((2.512)^{10} = 10^4)</td>
</tr>
<tr>
<td>15</td>
<td>((2.512)^{15} = 10^6)</td>
</tr>
<tr>
<td>20</td>
<td>((2.512)^{20} = 10^8)</td>
</tr>
</tbody>
</table>

A simple equation relates the difference between two stars’ apparent magnitudes to the ratio of their brightnesses:

Magnitude difference related to brightness ratio

\[
m_2 - m_1 = 2.5 \log \left( \frac{b_1}{b_2} \right)
\]
• The apparent magnitude scale - some examples:

- Sun (-26.7)
- Full moon (-12.6)
- Venus (at brightest) (-4.4)
- Sirius (brightest star) (-1.4)
- Naked eye limit (+6.0)
- Binocular limit (+10.0)
- Pluto (+15.1)
- Large telescope (visual limit) (+21.0)
- Hubble Space Telescope and large Earth-based telescopes (photographic limit) (+30.0)
Caution:
Apparent magnitude is NOT power output! A star may have bright (small) apparent magnitude because it is close to us, or it might have a bright (small) magnitude because it produces a huge amount of light.

As scientists, we want a brightness scale that takes distance into account and measures the total energy output of the star.

Absolute magnitude:
Definition: the apparent magnitude a star would have if it were precisely 10 pc away from us

\[ m - M = 5 \log(d) - 5 \]

\( m \) is apparent magnitude (measured)
\( d \) is distance (calculated from parallax)
\( M \) is absolute magnitude
Derivation

This comes from the definition of magnitude (a magnitude difference of 5 equals a factor 100 in brightness):

\[ m_2 - m_1 = 2.5 \log \left( \frac{F_2}{F_1} \right) \]

Now assume star 1 is at a distance \( d \) with an apparent magnitude \( m_1 = m \), and star 2 is at the distance of 10 pc with apparent magnitude \( m_2 = M \):

\[ \frac{F_{10 \text{ pc}}}{F_d} = 100^{(m-M)/5} \]

Next we use the relation \( F = L/4\pi d^2 \) or, equivalently \( b = L/4\pi d^2 \):

\[ \frac{F_{10 \text{ pc}}}{F_d} = \frac{L}{4\pi (10 \text{ pc})^2} \frac{4\pi d^2}{L} = \frac{d^2}{100 \text{ pc}^2} \]
Thus,

\[
\frac{d^2}{100 \text{ pc}^2} = 100^{(m-M)/5} \rightarrow d^2 = 100 \times 100^{(m-M)/5} = 100^{5/5} \times 100^{(m-M)/5} = 100^{(m-M+5)/5}
\]

Taking the log of this then yields

\[
2 \log(d) = \frac{m-M+5}{5} \log(100) = \frac{m-M+5}{5} \cdot 2
\]

\[
m - M + 5 = 5 \log(d) \rightarrow m - M = 5 \log(d) - 5
\]

where \(d\) must be in units of parsecs.
The absolute magnitude is a more useful measure of a star’s power output (Luminosity).

Examples:

<table>
<thead>
<tr>
<th>M</th>
<th>Star</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5</td>
<td>Betelgeuse</td>
</tr>
<tr>
<td>-1.5</td>
<td>Sirius</td>
</tr>
<tr>
<td>+5</td>
<td>Sun</td>
</tr>
<tr>
<td>+10</td>
<td>Sirius B</td>
</tr>
</tbody>
</table>
• Since $L = 4\pi d^2 b$, we can compare any star’s luminosity to the Sun’s by a ratio:

\[
\frac{L_*}{L_{\text{Sun}}} = \frac{4\pi d_*^2 b_*}{4\pi d_{\text{Sun}}^2 b_{\text{Sun}}} = \left(\frac{d_*}{d_{\text{Sun}}}\right)^2 \frac{b_*}{b_{\text{Sun}}}
\]

• Knowing relative distance and brightness, we know the star’s relative luminosity. Finally, you can show that

\[
M_{\odot} - M_* = 2.5 \log \frac{L_*}{L_{\odot}}
\]
Luminosity function

- Describes the relative numbers of stars with different luminosities
- There are more faint stars than bright
- Note the enormous range in luminosity

![Graph showing the luminosity function](image)
Are you seeing neighbor stars, or highly luminous (but distant) stars?

Recall that 1 pc is 3.26 ly. E.g. Betelgeuse is about 160 pc away.
Colors of stars

- From Wien's law $\lambda_{\text{max}} = \frac{0.0029}{T}$ we expect hotter objects to be bluer.
To measure colors

- A set of filters can be used to determine the colors of stars

- In fact, we don't need distances - apparent magnitudes in each filter works

- If a B magnitude is small, does that mean that the star is very blue?
  - Not necessarily, the V and R magnitudes might be even smaller. Then the star is brighter in redder filters.
To quantify color: color index

- Need brightness measurements through at least 2 filters to determine color
- Example: B-V color index

\[ Cl = B - V = 2.5 \log \left( \frac{b_V}{b_B} \right) + const \]

- The constant is chosen so that a star at 10^4 K has a B-V = 0.0

<table>
<thead>
<tr>
<th>Star</th>
<th>Surface temperature (K)</th>
<th>( \frac{b_V}{b_B} )</th>
<th>( \frac{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) Ursa 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.
Temperature, color and color ratio

- The $b_v/b_B$ color ratio is small for hot stars, and large for cool stars.
Binary stars

Tatooine
1. Visual binaries - can see both stars. Binaries (any type) always orbit around the mutual center of mass.
• Can plot orbit of either star around the other, treated as stationary.

Period = 87.7 years
\[ a_1 M_1 = a_2 M_2 \]

where \( a \) = semimajor axis, \( M \) = mass

Recall semimajor axis = half of the long axis of ellipse
Visual binaries allow direct calculation of stellar masses. Use Kepler's third law:

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

\( M_1, M_2 \) are masses of the two stars (in M\(_\odot\))
\( a = \) semimajor axis of one star's orbit around the other (in units of Earth-Sun distance, AU)
\( P = \) orbital period (in years)
• Gives the sum of the masses, not individual masses. Need another equation: Use fact that the more massive star will be closer to center of mass:

\[
\frac{a_2}{a_1} = \frac{M_1}{M_2}
\]

• Two equations in two unknowns => can solve for individual masses.
2. Spectroscopic binaries - even if you can't see both stars, might infer binary from spectrum.
3. **Eclipsing binaries** - stars periodically eclipse each other.
3. Eclipsing binaries - stars periodically eclipse each other. Can tell it's binary from "light curve" - plot of brightness vs. time.
4. Astrometric binaries - one star can be seen, the other can't. The unseen companion makes the visible star "wiggle" on the sky.