## Course Overview

- **We want to understand the physics of stars**
- **Lecture schedule:**

<table>
<thead>
<tr>
<th>class meeting</th>
<th>topic</th>
<th>HKT Ch.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>general overview</td>
<td>A</td>
</tr>
<tr>
<td>2–3</td>
<td>preliminaries</td>
<td>1</td>
</tr>
<tr>
<td>4–5</td>
<td>stellar evolution overview</td>
<td>2.1–2.7, 2.9, 2.10</td>
</tr>
<tr>
<td>6–7</td>
<td>equation of state</td>
<td>3</td>
</tr>
<tr>
<td>8–9</td>
<td>radiative &amp; conductive transfer</td>
<td>4.1–4.6</td>
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<td>10–11</td>
<td>convection</td>
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<tr>
<td>12–13</td>
<td>stellar energy sources</td>
<td>6</td>
</tr>
<tr>
<td>14</td>
<td><strong>midterm</strong></td>
<td></td>
</tr>
<tr>
<td>15–18</td>
<td>stellar models</td>
<td>7 + MESA</td>
</tr>
<tr>
<td>19–20</td>
<td>structure and evolution of Sun</td>
<td>9</td>
</tr>
<tr>
<td>21</td>
<td>structure and evolution of WDs</td>
<td>10</td>
</tr>
<tr>
<td>22–24</td>
<td>things that go BOOM</td>
<td>2.8, 2.9, 2.13 + other</td>
</tr>
<tr>
<td>25–6</td>
<td>brown dwarfs, stellar formation, exoplanets</td>
<td>2.14 + other</td>
</tr>
<tr>
<td>27–28</td>
<td>class discussion</td>
<td></td>
</tr>
</tbody>
</table>
Course Overview

- Alternate text: *Stellar Physics*, by Brown
  - part of the Open Astrophysics Bookshelf: [http://open-astrophysics-bookshelf.github.io/](http://open-astrophysics-bookshelf.github.io/)
Course Overview

- Lectures will be a mix of chalkboard writing and slides
  - Slides will be posted online on the BlackBoard course webpage
- All students will give a brief (~20 minute) presentation on a topic of their choice
  - You should pick a topic that connects to one of the scheduled lectures
    - Alternately, you can do a short project with the MESA stellar evolution code and report what you learned
  - Recent research papers are a good place to look
  - Connect to the basic discussions we have in class
  - Ideally we'll have one presentation during a few lectures toward the end of the class
  - Topics should be finalized before the first midterm
Course Overview

- Homeworks will be a mix of analytic problems and short programming problems
  - ODE integration, root finding, basic linear algebra methods will be needed
  - Any programming language is fine (my solutions will be in Fortran and/or python)
- I'm shooting for 6 homework assignments (due in class on the date specified)

<table>
<thead>
<tr>
<th>#</th>
<th>topic</th>
<th>assigned</th>
<th>due</th>
<th>PDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>basics of stars</td>
<td>09-01-15</td>
<td>09-15-15</td>
<td>--</td>
</tr>
<tr>
<td>2</td>
<td>evolution &amp; equation of state</td>
<td>09-15-15</td>
<td>09-24-15</td>
<td>--</td>
</tr>
<tr>
<td>3</td>
<td>radiation &amp; convection</td>
<td>09-29-15</td>
<td>10-08-15</td>
<td>--</td>
</tr>
<tr>
<td>4</td>
<td>reactions and stellar models</td>
<td>10-29-15</td>
<td>11-10-15</td>
<td>--</td>
</tr>
<tr>
<td>5</td>
<td>the Sun and white dwarfs</td>
<td>11-10-15</td>
<td>11-19-15</td>
<td>--</td>
</tr>
<tr>
<td>6</td>
<td>explosions &amp; remaining topics</td>
<td>11-24-15</td>
<td>12-03-15</td>
<td>--</td>
</tr>
<tr>
<td>final</td>
<td>everything...</td>
<td>12-03-15</td>
<td>12-14-15</td>
<td>--</td>
</tr>
</tbody>
</table>
Course Overview

- Midterm exam is in class
- Final exam is take-home during finals week
  - It will be due at the start of the exam period scheduled by the Registrar for our class (date and time given on syllabus)
Class Business

- I've activated the class BlackBoard page—it will only be used for the grade book.
- Remember: homework schedule is posted online.
  - I will briefly review some basics of numerical methods as needed.
- As we go through our lectures, think about what you might want to do your presentation on.
  - Some presentations will be done during the regular sequence of lectures, and the remaining will be done at the end of the semester.
Overview of Stellar Properties

- Read HKT Appendix A
Measuring Stellar Properties

- What properties do you think that we can measure?
  - Mass
  - Surface temperature
  - Composition
  - Radius
  - Energy output
  - Distance from us
The Sun

- The Sun is the closest star:

Fe XII at 195 angstroms imaged by the EIT instrument on SOHO
Properties of the Sun

- **Mass** = $2.0 \times 10^{33}$ g (333,000 Earth masses)
- **Diameter** = $1.4 \times 10^9$ cm (109 Earth Diameters)
- **Average Density** = (Mass/Volume) = $1.4$ g / cm$^3$
- **Luminosity** (i.e., total power output) = $4 \times 10^{33}$ erg/s
- **Surface Temperature** = 5800 K
- **Rotation Period** (at equator) = 25 days
- **Distance from Earth** = 1 AU = $1.5 \times 10^{13}$ cm

The Sun is an average star in almost every way
Distances

- Direct measurement: parallax
  - Look at apparent shift in foreground star as earth orbits the Sun
  - parsec: distance at which the earth-Sun separation subtends 1"
  - Hipparcos satellite measured parallaxes to 0.001”—over 120,000 stars
Stellar Motions

- Stars have relative motions wrt one another
- Proper motion is the speed across the sky (typically < arcseconds/year)
  - Barnard's star has a proper motion of 10.3" per year.
Other Distance Measures

- More indirect—rely on calibration with parallax
- Many based on the idea of a standard candle:
  - Measure apparent brightness of an object with known luminosity
  - Spectroscopic parallax: use known brightnesses of different types of stars
  - Cephids: variable stars with known period-luminosity relation
  - Type Ia supernovae: brightness correlates with the time it takes to fade
Coordinate Systems

- Your “backyard” reference: altitude-azimuth

- Equatorial system (think “earth-centered” celestial sphere)
  - Right ascension (analogous to longitude)
  - Declination (analogous to latitude)

Any point in the sky can be specified by its altitude (degrees above the horizon) and azimuth (degrees from North along the horizon).
Coordinate Systems

- Equitorial coordinates do not change with rotation of earth or time of year
  - Slow precession of earth's axis

(Carroll and Ostlie)
Coordinate Systems

- Galactic coordinates reference the center of the galaxy (from our vantage point)
Magnitudes

Chart 9: RA 4h to 8h, Declination +20° to -20°

Magnitude: 0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0

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Magnitudes

- Look at the night sky: some stars are brighter than others
- Greek astronomers created the magnitude system.
  - Stars assigned brightness on a scale of 1 to 6
    - 1 = brightest, 6 = faintest.
  - Standardized: difference in 5 magnitudes = factor of 100 in brightness
    - Logarithmic scale—our eye's response to light is also logarithmic
      \[
      \frac{f_1}{f_2} = 100^{(m_2 - m_1)/5}, \quad m_2 - m_1 = 2.5 \log \left( \frac{f_1}{f_2} \right)
      \]
- By brightness, we really mean flux—energy/area/second
- Remember: the brighter the object, the smaller the magnitude
Magnitude Example

- Consider 2 stars (one m=1 one m=2) that are unresolved—what combined magnitude would you measure?
Magnitudes

Today:
- Large telescopes see down to magnitude 30 and below
- Brightest stars have negative magnitudes

Apparent magnitude: measure of how bright something appears when viewed from earth

Absolute magnitude: measure of how bright something would appear if it were 10 pc from earth.

\[ m - M = 5 \log \left( \frac{d}{10 \text{ pc}} \right) \]
## Magnitudes

### Apparent Magnitudes of Known Celestial Objects

<table>
<thead>
<tr>
<th>App. Mag.</th>
<th>Celestial Object</th>
</tr>
</thead>
<tbody>
<tr>
<td>−26.73</td>
<td>Sun</td>
</tr>
<tr>
<td>−12.6</td>
<td>Full Moon</td>
</tr>
<tr>
<td>−9.5</td>
<td>Maximum brightness of an Iridium Flare</td>
</tr>
<tr>
<td>−4.7</td>
<td>Maximum brightness of Venus</td>
</tr>
<tr>
<td>−3.9</td>
<td>Faintest objects observable during the day with naked eye</td>
</tr>
<tr>
<td>−2.9</td>
<td>Maximum brightness of Mars</td>
</tr>
<tr>
<td>−2.8</td>
<td>Maximum brightness of Jupiter</td>
</tr>
<tr>
<td>−1.9</td>
<td>Maximum brightness of Mercury</td>
</tr>
<tr>
<td>−1.5</td>
<td>Brightest star (except for the sun) at visible wavelengths: Sirius</td>
</tr>
<tr>
<td>−0.7</td>
<td>Second brightest star: Canopus</td>
</tr>
<tr>
<td>0</td>
<td>The zero point by definition: This used to be Vega (see references for modern zero point)</td>
</tr>
<tr>
<td>0.7</td>
<td>Maximum brightness of Saturn</td>
</tr>
<tr>
<td>3</td>
<td>Faintest stars visible in an urban neighborhood with naked eye</td>
</tr>
<tr>
<td>4.6</td>
<td>Maximum brightness of Ganymede</td>
</tr>
<tr>
<td>5.5</td>
<td>Maximum brightness of Uranus</td>
</tr>
<tr>
<td>6</td>
<td>Faintest stars observable with naked eye</td>
</tr>
<tr>
<td>7.7</td>
<td>Maximum brightness of Neptune</td>
</tr>
<tr>
<td>12.6</td>
<td>Brightest quasar</td>
</tr>
<tr>
<td>13</td>
<td>Maximum brightness of Pluto</td>
</tr>
<tr>
<td>27</td>
<td>Faintest objects observable in visible light with 8m ground-based telescopes</td>
</tr>
<tr>
<td>30</td>
<td>Faintest objects observable in visible light with Hubble Space Telescope</td>
</tr>
<tr>
<td>38</td>
<td>Faintest objects observable in visible light with planned OWL (2020)</td>
</tr>
</tbody>
</table>

(see also List of brightest stars)
• We only see the outer part of the star (the atmosphere)
• Color tells us about the temperature
• So far our magnitudes have been bolometric (the entire EM spectrum)
• We observe through filters
Colors

- Flux through B filter: $f_B$
- Flux through V filter: $f_V$
- Magnitude difference:

$$m_B - m_V = 2.5 \log \left( \frac{f_V}{f_B} \right)$$

- Usually just written as B-V
- Measure of the color of a star—a also directly related to temperature
- As T increases, $f_B/f_V$ increases, so $B - V$ decreases
Colors

- Spectra consist of a smooth continuum absorption lines)
- Tells us composition, temperature, ionization state information

(Jodrell Bank Observatory; based on Pickles 1988)
Blackbody Radiation

- Stars are very good blackbodies
  - Thermal equilibrium: emission = absorption
  - Emission spectrum is well known
    - Function of T only (unpolarized and isotropic)
    - Emission spectrum can be different than absorption spectrum—only need net energy gain to be 0

http://coolcosmos.ipac.caltech.edu/cosmic_kids/learn_ir/index.html

(Fir0002/Wikipedia)
Blackbody Radiation

- Blackbody intensity:

\[ I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1} \]

\[ I(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1} \]

\[ dE = I_\nu \cos \theta dA d\Omega dt d\nu = I_\lambda \cos \theta dA d\Omega dt d\lambda \]
Intensity

\[ I(\nu) d\nu = \text{energy/unit time/unit surface area in the frequency range } \nu \text{ to } \nu + d\nu \text{ being emitted into a cone of solid angle } d\Omega \]

Radiation moves through a small area \(dA\) into the cone described by \(d\Omega\)

Energy moving through this area into the solid angle \(d\Omega\) is

\[ dE = I_\nu \cos \theta dA d\nu d\Omega dt \]

Intensity is measured in units of \(\text{erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ ster}^{-1}\)
Blackbody Radiation
Blackbody Radiation

- Flux at the surface of a star

\[ f = \int \frac{dE}{dA dt} = \int I_\nu \cos \theta d\Omega d\nu = \sigma T^4 \]

\[ \sigma = 5.67 \times 10^{-5} \text{ erg cm}^{-2} \text{ K}^{-4} \text{ s}^{-1} \quad \text{Stefan-Boltzmann constant} \]

- Luminosity of a star:

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

- Wien's law:

\[ \lambda_{\text{max}} T = 0.29 \text{ cm K} = 2.9 \times 10^6 \text{ nm K} \]

Hotter stars have spectra that peak at shorter wavelengths
Flux vs. Luminosity

- Intensity has a direction, i.e. it is the energy/time/area/frequency emitted per unit solid angle in a specific direction.

- Detectors measure the **energy flux** \((\text{erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1})\) hitting the detector.
  - Records energy hitting the detector area from all directions.
  - Frequency dependent—monochromatic flux.

- Integrate over all frequencies \(\rightarrow\) total flux \((\text{erg s}^{-1} \text{ cm}^{-2})\).

- We've now talked about flux in 2 different contexts

  - **Flux at the surface of a star:** \(f = \sigma T^4\)
    - Blackbody,

  - **Flux received from some distant star:**
    - \(f = L / (4\pi r^2)\), where \(r\) is the distance to the star.
    - This is the flux that enters into the magnitude equation.
Ex: Surface Temperature of Earth

- What would you expect the surface temperature of the Earth to be, based on its distance from the Sun?
Astronomy and the EM Spectrum

- We observe across the entire EM spectrum
- Our atmosphere is not transparent at all wavelengths

(NASA/JPL; http://gallery.spitzer.caltech.edu/Imagegallery/image.php?image_name=bg005)
Spectral Types

- Stars are grouped into spectral types, depending on the appearance of their spectral lines
  - Originally ordered by strength of H lines (A stars had strongest, then B, ...)
  - Now we order based on surface temperature (hottest to coolest)
  - O B A F G K M
Balmer Lines

- H and He are the most abundant elements in the Universe
  - Everything else is called a metal (< 2% by mass)

- The H Balmer lines are the transitions that end at \( n = 2 \)—these are the only visible lines in H spectrum
  - Strength of lines depends on balance of excitation and ionization
Originally it was thought that stars cool with age, so O stars are called “early” and M stars are called “late”.

Numbers further subdivide.
Spectral Types

- **M stars:**
  - Coolest end of spectrum, $T < 3500$ K
  - No $H\alpha$ absorption, some neutral metals
  - Molecules can form (CN, TiO, ...)

- **K stars:**
  - $T$ between 3500 and 5000 K
  - Neutral lines dominate

- **G stars (sun is G2):**
  - $T$ between 5000 and 6000 K
  - H lines are stronger than in K stars.
  - Ionized metal lines appear (e.g. Ca II)

- **F stars:**
  - $T$ between 6000 and 7500 K.
  - Ionized metal lines stronger.
Spectral Types

- **A stars:**
  - \( T \sim 7500 \) to \( 10000 \) K—white-blue.
  - \( H \) lines strongest in A stars.
  - Some ionized metal lines still present.
  - Vega = A0.
  - A0: \( M_{\text{bol}} = 0, B - V = 0 \)

- **B stars:**
  - \( T \) between 10000 and 30000 K (blue)
  - \( H \) lines weaker (ionization)
  - He I and He II lines appear

- **O stars:**
  - Hottest, \( T > 30000 \) K
  - Very few observed
  - Very few lines in visible spectrum

Notice where Balmer lines peak

\( H_\gamma \)
\( H_\beta \)
\( H_\alpha \)

**Relative Flux**

**Wavelength (\( \AA \))**
H-R Diagram

Horizontal axis: spectral class, B – V, or T (increasing to left).

Vertical axis: Luminosity or absolute magnitude.

main sequence: diagonal line running through all the spectral classes.

Some T-L combinations not realized in nature.

Wide range in L for stars of the same T.

Low L population: white dwarfs.
Life on the Main Sequence

PHY 521: Stars
Luminosity Class

- Vertical position in the H-R diagram—the luminosity class
- Main sequence stars are luminosity class V (Sun = G2 V)
- Sub-giants denoted IV
- Giants denoted III
- Supergiants I (sometimes Ia and Ib)

Spectral type G star with luminosity 10 000x higher main sequence must be larger (why?)—giants and supergiants.
B-V

- Colors of the various spectral/luminosity types

Table 9.2. **Spectral type, color, and effective temperature.**

<table>
<thead>
<tr>
<th>Spectral type</th>
<th>Main sequence</th>
<th>Giants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$B - V$</td>
<td>$T_e$ (K)</td>
</tr>
<tr>
<td>O5</td>
<td>-0.45</td>
<td>35,000</td>
</tr>
<tr>
<td>B0</td>
<td>-0.31</td>
<td>21,000</td>
</tr>
<tr>
<td>B5</td>
<td>-0.17</td>
<td>13,500</td>
</tr>
<tr>
<td>A0</td>
<td>0.00</td>
<td>9,700</td>
</tr>
<tr>
<td>A5</td>
<td>0.16</td>
<td>8,100</td>
</tr>
<tr>
<td>F0</td>
<td>0.30</td>
<td>7,200</td>
</tr>
<tr>
<td>F5</td>
<td>0.45</td>
<td>6,500</td>
</tr>
<tr>
<td>G0</td>
<td>0.57</td>
<td>6,000</td>
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<tr>
<td>G5</td>
<td>0.70</td>
<td>5,400</td>
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<tr>
<td>K0</td>
<td>0.84</td>
<td>4,700</td>
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<tr>
<td>K5</td>
<td>1.11</td>
<td>4,000</td>
</tr>
<tr>
<td>M0</td>
<td>1.24</td>
<td>3,300</td>
</tr>
<tr>
<td>M5</td>
<td>1.61</td>
<td>2,600</td>
</tr>
</tbody>
</table>

*a Adapted from C. W., Allen, *Astrophysical Quantities.*

(Shu)
Stellar Populations

- Normal stars initially contain about 70% H, 28% He, and 2-3% heavier elements (metals) by mass.

- **Population I** stars:
  - rich in metals (like the Sun)
  - later generation of stars (formed from the ashes of previous stars)

- **Population II** stars:
  - poor in metals (ex. stars in old globular clusters)
  - some stars with metalicity $1/100000^{th}$ of the Sun are known

- **Population III** stars:
  - zero metalicity—very first stars to form
  - none known
Stellar Populations

Spectra of Stars with Different Metal Content

- **Sun:**
  - Fe/H = 1/31,000

- **CD -38 245:**
  - Fe/H = 1/310,000,000

- **HE 0107-5240:**
  - Fe/H = 1/6,800,000,000

- **Population III:**
  - Fe/H = 0
The Milky Way

- **Halo:**
  - Spherically symmetric distribution of older stars.
  - Density falls off with distance from galactic center

- **Disk:**
  - Distribution of stars orbiting the galactic center in the thin plane

- **Bulge:**
  - Spherical distribution surrounding the galactic center.

(from Bennett et al.)
The Scale of the Universe

- For the most part, we will use the CGS system of measurements in this class (centimeters, grams, seconds).

\[
384,000 \text{ km} = 3.84 \times 10^{10} \text{ cm}
\]

- Some measurements are so common that we give them names. The average distance between the Earth and the Sun is called the **astronomical unit** (or **AU**). \(1 \text{ AU} = 1.5 \times 10^{13} \text{ cm} \).
The Scale of the Universe

- We will focus on stars—these come in a wide variety of sizes

The Sun viewed in the extreme ultraviolet (SOHO/NASA)

Betelgeuse, a red supergiant star

Note: we defined a new unit of length—the solar radius

\[ 7 \times 10^{10} \text{ cm} = 1 R_\odot \]

\[ 650 R_\odot \]
The Scale of the Universe

- At the small end are compact objects

The white dwarf companion to Sirius A has a radius of 0.008 $R_\odot$.

An isolated neutron star. The radius is ~10 km.
The Scale of the Universe

- In between is the interstellar medium—gas a dust enriched in metals from previous stellar explosions.

Another new unit of length, the light year, $\text{ly} = 9.46 \times 10^{17}$ cm.

The Orion Nebula and the Crab Nebula—a supernova remnant.

# of seconds in yr $\approx \pi \times 10^7$. 

(Images: The Orion Nebula and The Crab Nebula)
The Scale of the Universe

- About 1/2 of the stars in the sky are in binary systems or groups/clusters

- The Pleiades cluster—an open cluster of stars

- Albireo—a multiple star system

- The globular cluster M3 contains ~500,000 stars
The Scale of the Universe

- Stars are the luminous component of galaxies

The Andromeda galaxy—a galaxy a bit bigger than our own, containing $\sim 10^{12}$ stars

The Coma cluster, a large cluster of galaxies.

[Images of galaxies and clusters with scale indicators]
The Hubble Ultra Deep Field—every point of light you see here is a galaxy, more than 10,000 of them.