**Topics**

- **Stellar interiors**
  - equations of state
  - energy transport: radiation, convection, conduction
  - nucleosynthesis

- **Stellar photospheres**
  - radiative transfer
  - opacities
  - formation of spectral lines
Topics (cont.)

- Compact objects
  - white dwarfs, neutron stars, brown dwarfs
- Binary stars
  - evolution, significance
- Formation and evolution of stars
  - determination of stellar ages
- Formation and evolution of planetary systems
Prerequisites

- Advanced undergraduate-level:
  - classical mechanics
  - quantum mechanics
  - electrodynamics
  - thermodynamics
- No prior knowledge of astronomy expected
Texts

- required

- recommended

Stellar Interiors
Physical Principles, Structure, and Evolution
Second Edition

The Observation and Analysis of Stellar Photospheres
Third Edition
Course Organization

• **semi-weekly lectures**: TuTh 2:20–3:40pm
• **weekly readings**
  • textbooks + select articles
  • lecture notes available on website after lecture
• **bi-weekly homework assignments**
  • some programming will be necessary
  • co-operation encouraged
  • submit your own work
• **office hours**: Wed 1–2pm, ESS 452
Course Organization

- Need to re-schedule following lectures:
  - Sep 6, 8 (Tue, Thu)
  - Oct 13 (Thu)
  - Oct 18, 20 (Tue, Thu)

- Possible alternate class meeting times:
  - Mondays: decided on Mondays, 4–5:20pm
  - Tue between 5–8pm
  - Wednesdays between 10am–1pm
Grading

- 40% homework assignments
- 20% midterm (take-home)
- 40% final exam (take-home)
Astronomical and Stellar Phenomenology
Phenomenology

- Radiation, magnitudes
- Distances
- Detection of light, photometric system
- Stellar spectral classification
Blackbody Radiation

- **Planck’s law**
  - specific intensity
  - $[\text{erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sterad}^{-1}]$ or $[\text{Jy sterad}^{-1}]$
  - $1 \text{ Jy} = 10^{-23} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$

- **Wien displacement law**

- **Stefan-Boltzmann law**
  - energy flux density
  - $[\text{erg s}^{-1} \text{ cm}^{-2}]$

- **Stellar luminosity**
  - $[\text{erg s}^{-1}]$
  - $R_{\text{Sun}} = 6.96 \times 10^{10} \text{ cm}$
  - $L_{\text{Sun}} = 3.9 \times 10^{33} \text{ erg cm}^{-1}$

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

\[
T \lambda_{\text{max}} = 0.29 \text{ K cm}
\]

\[
F = \sigma T^4
\]

\[
\sigma = \frac{2\pi^5 k^4}{15c^2h^3} = 5.67 \times 10^{-5} \text{ erg cm}^{-2} \text{s}^{-1} \text{K}^{-4}
\]

\[
L_* = 4\pi R_*^2 \sigma T_{\text{eff}}^4
\]
Blackbody Radiation

$T_{\text{eff, Sun}} = 5777 \text{ K}$
Color of Blackbody Radiation
Astronomical Magnitudes

• Stefan-Boltzmann Law: \[ F = \sigma T^4 \quad [\text{erg s}^{-1} \text{ cm}^{-2}] \]

• apparent magnitude: \[ m = -2.5 \log \frac{F}{F_0} \]
  – \( m \) increases for fainter objects!
  – \( m = 0 \) for Vega; \( m \sim 6 \) mag for faintest naked-eye stars
  – faintest galaxies seen with Hubble: \( m \approx 30 \) mag
    • \( 10^{9.5} \) times fainter than faintest naked-eye stars
  – dependent on observing wavelength
    • \( m_V, m_B, m_J \), or simply \( V \) (550 nm), \( B \) (445 nm), \( J \) (1220 nm), etc

• bolometric magnitude (or luminosity): \( m_{\text{bol}} \) (or \( L_{\text{bol}} \))
  – integrated over all wavelengths
  – \( M_{\text{bol, Sun}} = +4.75 \) mag (absolute bolometric magnitude of the Sun)
Magnitudes and Colors

• bolometric correction:
  • $M_{bol} = M_V + BC$
  • $M_{V,Sun} = +4.82$ mag, so $BC_{Sun} = -0.07$ mag

• magnitude differences:
  – relative brightness of two objects at the same wavelength
    $$V_1 - V_2 = -2.5 \log \frac{F_{V1}}{F_{V2}}$$
  • $\Delta m = 5$ mag approx. equivalent to $F_1/F_2 = 100$
  – relative brightness of the same object at different wavelengths (color)
    $$B - V = -2.5 \left( \log \frac{F_B}{F_V} - \log \frac{F_{B,Vega}}{F_{V,Vega}} \right)$$
    – by definition Vega has a color of 0 mag at all wavelengths, i.e.
    $$(B - V)_{Vega} = 0$$ mag
Extinction and Optical Depth

• Light passing through a medium can be:
  – transmitted, absorbed, scattered

• \(dI_\nu(s) = -\kappa_\nu \rho I_\nu \, ds = -I_\nu \, d\tau_\nu\)
  – medium opacity \(\kappa_\nu \) [cm\(^2\) g\(^{-1}\)]
  – optical depth \(\tau_\nu = \kappa_\nu \rho s\) [unitless]

• \(I_\nu = I_{\nu,0}e^{-\tau} = I_{\nu,0}e^{-\kappa\rho s} = I_{\nu,0}e^{-s/l}\)
  – photon mean free path: \(l_\nu = (\kappa_\nu \rho)^{-1} = s/\tau_\nu\) [cm]

• Extinction along the line of sight: apparent magnitude \(m_\nu\) is attenuated by
  \[A_\nu = 2.5 \log \left(\frac{F_\nu,0}{F_\nu}\right) = 2.5 \log(e)\tau_\nu = 0.43\tau_\nu\text{, mag}\]

  – reddening between two frequencies \((\nu1, \nu2)\) or wavelengths is defined as
  \[E_{\nu1,\nu2} = m_{\nu1} - m_{\nu2} - (m_{\nu1} - m_{\nu2})_0\text{ [mag]}\]

  – \((m_{\nu1} - m_{\nu2})_0\) is the intrinsic color of the star
  \[A_\nu / E(B-V) \approx 3.0\]
Interstellar Extinction Law

extinction is highest at ~100 nm = 0.1 µm
unimportant for >10 µm
Interstellar Extinction: Dust

visible (0.5 micron)  
mid-infrared (~20 micron)
Atmospheric Transmission Bands

Percent

Total Absorption and Scattering

Wavelength (μm)

Water Vapor
Carbon Dioxide
Oxygen and Ozone
Methane
Nitrous Oxide
Rayleigh Scattering
Absolute Magnitude and Distance Modulus

• The apparent magnitude of a star at 10 pc
  – used to compare absolute brightnesses of different stars
  \[ M = m + 2.5 \log \frac{F(r)}{F(10 \text{ pc})} \]

• Distance modulus (DM)
  – a proxy for distance
  \[ m - M = 5 \log \left( \frac{r}{10 \text{ pc}} \right) \]
  – DM = 0 mag for object at 10 pc
  – DM = –4.4 mag for Proxima Cen
  – DM = 14.5 mag to Galactic center
Measuring Distance: Trigonometric Parallax

- distance $d$ to nearby star is 1 parsec (pc) when angle $\theta = 1$ arc sec (1")
- $d = \frac{1 \text{ AU}}{\theta}$

- 1 pc = 3.26 ly = 2.06 AU = 3.09e18 cm
- Proxima Cen is at 1.3 pc ~ 4.3 ly

Stellar parallaxes need largest possible baseline.
The Bessell approximations to UBVRI passbands
Photometric Systems

- **UBVRI(ZY)** (visible)
  - Johnson, Bessel, Cousins, Kron, etc
- **ugriz** (visible)
  - Thuan-Gunn, Strömgren, Sloan Digital Sky Survey (SDSS), etc
- **JHKLM(NQ)** (infrared)
  - Johnson, 2-micron All-Sky Survey (2MASS), Mauna Kea Observatory (MKO), etc

### Broad band photometric systems

<table>
<thead>
<tr>
<th>System</th>
<th>Band</th>
<th>(\lambda_{\text{eff}}) nm</th>
<th>FWHM nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>UBVRI</td>
<td>U</td>
<td>365</td>
<td>66</td>
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<tr>
<td></td>
<td>B</td>
<td>445</td>
<td>94</td>
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<tr>
<td></td>
<td>V</td>
<td>545</td>
<td>88</td>
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<tr>
<td></td>
<td>R</td>
<td>658</td>
<td>138</td>
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<tr>
<td></td>
<td>I</td>
<td>806</td>
<td>149</td>
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<tr>
<td></td>
<td>J</td>
<td>1220</td>
<td>213</td>
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<tr>
<td></td>
<td>H</td>
<td>1630</td>
<td>307</td>
</tr>
<tr>
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<td>K</td>
<td>2190</td>
<td>390</td>
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<td></td>
<td>L</td>
<td>3450</td>
<td>472</td>
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<tr>
<td></td>
<td>M</td>
<td>4750</td>
<td>460</td>
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<td>Hipparcos Tycho</td>
<td>Hp</td>
<td>550</td>
<td>225</td>
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<td></td>
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<td>420</td>
<td>75</td>
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<tr>
<td></td>
<td>Vt</td>
<td>640</td>
<td>100</td>
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<td>Thuan-Gunn</td>
<td>g</td>
<td>512</td>
<td>120</td>
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<td>r</td>
<td>668</td>
<td>100</td>
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<td>792</td>
<td>150</td>
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<td>912</td>
<td>140</td>
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<td>SDSS</td>
<td>u'</td>
<td>352</td>
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<td></td>
<td>g'</td>
<td>480</td>
<td>141</td>
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<td></td>
<td>r'</td>
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<td>154</td>
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<tr>
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<td>z'</td>
<td>911</td>
<td>141</td>
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### Intermediate band photometric systems

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<td></td>
<td>v</td>
<td>411</td>
<td>19</td>
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<tr>
<td></td>
<td>b</td>
<td>467</td>
<td>18</td>
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<tr>
<td></td>
<td>y</td>
<td>547</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>(\beta w)</td>
<td>489</td>
<td>15</td>
</tr>
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<td></td>
<td>(\beta n)</td>
<td>486</td>
<td>3</td>
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<td>DDO</td>
<td>45</td>
<td>451.7</td>
<td>7.6</td>
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<td>42</td>
<td>425.7</td>
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<td></td>
<td>41</td>
<td>416.6</td>
<td>8.3</td>
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<tr>
<td></td>
<td>38</td>
<td>390</td>
<td>17.2</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>349</td>
<td>37</td>
</tr>
</tbody>
</table>
Detection of Light

Quantum efficiencies of the 4 CCD chips on the Hubble WFPC2 camera

A charge-coupled device (CCD) converts photons to electrons
Detection of Light:
The Sloan Digital Sky Survey (SDSS)

SDSS 2.5 m telescope at Apache Point, NM

Ritchey-Chretien design (Cassegrain-like)
Detection of Light: The Sloan Digital Sky Survey (SDSS)
Detection of Light: The Sloan Digital Sky Survey (SDSS)
Phenomenology

- Radiation, magnitudes
- Distances
- Detection of light, photometric system
- Stellar spectral classification
A Spectrograph

telescope focus

A Schematic Diagram of a Slit Spectrograph
species with higher ionization potentials
Spectral Classification: Temperature

infrared spectra

visible spectra
### Spectral Classification: Temperature

<table>
<thead>
<tr>
<th>Spectral Type</th>
<th>Atmospheric Temperature (K)</th>
<th>Hydrogen (Balmer) Features</th>
<th>Other Features</th>
<th>M/M$_\odot$</th>
<th>R/R$_\odot$</th>
<th>L/L$_\odot$</th>
<th>Main Sequence Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>&gt;33,000 K</td>
<td>weak</td>
<td>Ionized Helium (He$^+$) features sometimes in emission Strong UV continuum</td>
<td>20-60</td>
<td>9-15</td>
<td>90,000-800,000</td>
<td>10-1 Myr</td>
</tr>
<tr>
<td>B</td>
<td>10,500-30,000 K</td>
<td>medium</td>
<td>Neutral He absorption</td>
<td>3-18</td>
<td>3.0-8.4</td>
<td>95-52,000</td>
<td>400-11 Myr</td>
</tr>
<tr>
<td>A</td>
<td>7,500-10,000 K</td>
<td>strong</td>
<td>H features maximum at A0 Some features of heavy elements, eg Ca$^+$</td>
<td>2.0-3.0</td>
<td>1.7-2.7</td>
<td>8-55</td>
<td>3 Gyr - 440 Myr</td>
</tr>
<tr>
<td>F</td>
<td>6,000-7,200 K</td>
<td>medium</td>
<td>Weak Ca$^+$</td>
<td>1.1-1.6</td>
<td>1.2-1.6</td>
<td>2.0-6.5</td>
<td>7-3 Gyr</td>
</tr>
<tr>
<td>G</td>
<td>5,500-6,000 K</td>
<td>weak</td>
<td>Ca$^+$ H&amp;K, Na &quot;D&quot; Sun is G2V</td>
<td>0.9-1.05</td>
<td>0.85-1.1</td>
<td>0.66-1.5</td>
<td>15-8 Gy</td>
</tr>
<tr>
<td>K</td>
<td>4,000-5,250 K</td>
<td>v. weak</td>
<td>Ca$^+$, Fe, Strong molecules, eg CH, CN</td>
<td>0.6-0.8</td>
<td>0.65-0.80</td>
<td>0.10-0.42</td>
<td>17 Gy</td>
</tr>
<tr>
<td>M</td>
<td>2,600-3,850 K</td>
<td>v. weak</td>
<td>Molecules, eg TiO Very red continuum</td>
<td>0.08-0.5</td>
<td>0.17-0.63</td>
<td>0.001-0.08</td>
<td>56 Gyr</td>
</tr>
<tr>
<td>L</td>
<td>1,400–2,500 K</td>
<td>none</td>
<td>Molecules: H$_2$O, hydrides reddest star-like objects</td>
<td>&lt;0.08</td>
<td>~ 0.1</td>
<td>10$^{-5}$–10$^{-3}$</td>
<td>&gt;100 Gyr</td>
</tr>
<tr>
<td>T</td>
<td>400–1,400 K</td>
<td>none</td>
<td>Molecules: H$_2$O, CH$_4$</td>
<td>&lt;0.08</td>
<td>~ 0.1</td>
<td>10$^{-6}$–10$^{-5}$</td>
<td>N/A</td>
</tr>
<tr>
<td>Y</td>
<td>&lt;400 K</td>
<td>none</td>
<td>Molecules: H$_2$O, CH$_4$, NH$_3$</td>
<td>&lt;0.08</td>
<td>~ 0.1</td>
<td>&lt;10$^{-6}$</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Stellar Classification: Temperature

- Sun
- M dwarf
- L dwarf
- T dwarf
- Jupiter
- brown dwarfs
- planets

5700 K

5700 K ~3500 K ~2000 K ~1000 K 160 K
Spectral Classification: Luminosity

• luminosity, radius, surface gravity, and surface pressure are mutually related

\[ L = 4\pi R^2 \sigma T_{\text{eff}}^4, \quad g = GM/R^2, \quad P = \rho l \] (\(l\) is photon m.f.p.)

• define “luminosity spectral class”

  V: dwarfs, \(\log g \approx 4.5\) [cgs units]
  IV: subgiants, \(\log g \approx 3\) (approximately as on Earth)
  III: giants, \(\log g \approx 1.5\)
  II: (bright) giants, \(\log g \approx 0.5\)
  I: supergiants, \(\log g \approx -0.5\)

• Sun: G2 V star (\(T_{\text{eff}} = 5777\)K, \(\log g = 4.43\))
Luminosity Effects at A0

(figure from D. Gray)
Hertzsprung-Russell (H-R) Diagram

- \( \log L \) vs. \( \log T_{\text{eff}} \)

- main sequence:
  - locus of most stars
  - bulk of stellar lifetimes
  - \( L \propto M^{3.8} \)
  - \( \tau_{\text{MS}} \approx 10^{10} \text{ yr} (M/M_{\odot})^{-2.8} \)
Color-Magnitude Diagram (CMD)

- proxy for the \((T_{\text{eff}}-L)\) Hertzsprung-Russell diagram
- e.g., \(B-V\) vs. \(M_V\), \(J-K\) vs. \(M_K\), etc.
Stellar Abundances

• derived from spectral lines
• compared to the Sun or to abundance of hydrogen (H) in star—or both
• a.k.a., “metallicity”
• “metal-poor” stars, a.k.a. “subdwarfs” are hotter than dwarfs of same luminosity

\[ [\text{Fe/H}] = \log \left[ \frac{n(\text{Fe})}{n(\text{H})} \right] \text{Sun} - \log \left[ \frac{n(\text{Fe})}{n(\text{H})} \right] \]
Stellar Populations

- **Population I:**
  - low galactic scale heights, rotate with galactic disk, similar composition to Sun

- **Population II:**
  - large scale heights, high space velocities, low mass: *old stars*
Star Clusters

- globular clusters (e.g., M80): Pop II stars, gravitationally bound, dense
- open clusters (e.g., Pleiades): Pop I stars, gravitationally bound, < 2 Gyr
- “O-B” associations: loose, not gravitationally bound, < 20 Myr