# Class Schedule (full details on website)

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<td>Draine Ch 6 &amp; 7</td>
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<td>Draine Ch 8 &amp; 9</td>
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<td>Draine Ch 12, 13 &amp; parts of Ch 14</td>
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<td><strong>5.</strong> Photoionization and HII regions</td>
<td>Draine Ch 15 (parts)</td>
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<td>Draine Ch 17 &amp; parts of Ch 18</td>
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<td>Draine Ch 5 (parts) &amp; 19</td>
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<td>Draine Ch 31 (parts) &amp; 32</td>
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<td><strong>11.</strong> Shocks, supernova remnants and the 3-phase ISM model</td>
<td>Parts of Draine Ch 35, 36 &amp; 39</td>
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Today’s Lecture

- HII regions
- Strömgren spheres
- Corresponding textbook material: Draine Ch. 15
Recombination lines result from the downward cascade following recombination in ionized gas

Recombination to the ground-state lead to ionizing photons; these immediately lead to ionization (“on-the-spot” approximation)

In Galactic conditions, case B recombination is valid: Lyman lines (all lines connecting to the ground state) optically thick, all other lines optically thin

Recombination spectrum (line ratios) for $n << 100$ is independent of density (spontaneous decay more rapid than collisions); temperature comes in through $T$-dependence of recombination coefficient $\alpha$; but $T$ of HII regions fairly uniform 5000-10000 K; so only weak $T$-dependence

High $n$ (radio recombination lines) much more complicated: density dependence and stimulated emission

Recombination lines measure Star Formation Rate
Recombination Coefficients for H

Using the definitions

\[ \alpha_A = \alpha = \sum_{n=1}^{\infty} \alpha_n(T) \]

\[ \alpha_B = \sum_{n=2}^{\infty} \alpha_n(T) = \alpha_A(T) - \alpha_1(T) \]

\[ \approx 2.6 \times 10^{-13} \left( \frac{10^4}{T} \right)^{0.85} \]

**TABLE 2.1**
Recombination coefficients\(^a\) \(\alpha_n \, 2_L\) for \(H\)

<table>
<thead>
<tr>
<th>(\alpha_n , 2_L)</th>
<th>(T)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5000° K</td>
</tr>
<tr>
<td>(\alpha_1 , 2_S)</td>
<td>2.28 \times 10^{-13}</td>
</tr>
<tr>
<td>(\alpha_2 , 2_S)</td>
<td>3.37 \times 10^{-14}</td>
</tr>
<tr>
<td>(\alpha_2 , 2_P)</td>
<td>8.33 \times 10^{-14}</td>
</tr>
<tr>
<td>(\alpha_3 , 2_S)</td>
<td>1.13 \times 10^{-14}</td>
</tr>
<tr>
<td>(\alpha_3 , 2_P)</td>
<td>3.17 \times 10^{-14}</td>
</tr>
<tr>
<td>(\alpha_3 , 2_D)</td>
<td>3.03 \times 10^{-14}</td>
</tr>
<tr>
<td>(\alpha_4 , 2_S)</td>
<td>5.23 \times 10^{-15}</td>
</tr>
<tr>
<td>(\alpha_4 , 2_P)</td>
<td>1.51 \times 10^{-14}</td>
</tr>
<tr>
<td>(\alpha_4 , 2_D)</td>
<td>1.90 \times 10^{-14}</td>
</tr>
<tr>
<td>(\alpha_4 , 2_F)</td>
<td>1.09 \times 10^{-14}</td>
</tr>
<tr>
<td>(\alpha_{10} , 2_S)</td>
<td>4.33 \times 10^{-16}</td>
</tr>
<tr>
<td>(\alpha_{10} , 2_G)</td>
<td>2.02 \times 10^{-15}</td>
</tr>
<tr>
<td>(\alpha_{10} , 2_M)</td>
<td>2.7 \times 10^{-17}</td>
</tr>
<tr>
<td>(\alpha_A)</td>
<td>6.82 \times 10^{-13}</td>
</tr>
<tr>
<td>(\alpha_B)</td>
<td>4.54 \times 10^{-13}</td>
</tr>
</tbody>
</table>

\(^a\) In \(\text{cm}^3\ \text{sec}^{-1}\).
Radio recombination lines

G35.194 – 1.75
A E B r

Channels

Antenna Temperature (mK)

C92α  He92α  H92α

40 channels
1 MHz
25 km/s

92α

91α + 92α

91α

C91α  He91α  H91α  H154ε

-100 mK
Photoionization of pure H nebula

Q: how many hydrogen atoms can be ionized by UV photons from star?

Statistical equilibrium: photoionization = recombination

Strömgren sphere
Stellar fluxes
Calculated properties of Strömgren spheres

<table>
<thead>
<tr>
<th>Spectral type</th>
<th>$M_v$</th>
<th>$T_*(^\circ K)$</th>
<th>Log $Q(H^0)$ (photons/sec)</th>
<th>Log $N_e N_p r_1^3$ ($N$ in cm$^{-3}$; $r_1$ in pc)</th>
<th>$r_1$ (pc) ($N_e = N_p = 1$ cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O5</td>
<td>-5.6</td>
<td>48,000</td>
<td>49.67</td>
<td>6.07</td>
<td>108</td>
</tr>
<tr>
<td>O6</td>
<td>-5.5</td>
<td>40,000</td>
<td>49.23</td>
<td>5.63</td>
<td>74</td>
</tr>
<tr>
<td>O7</td>
<td>-5.4</td>
<td>35,000</td>
<td>48.84</td>
<td>5.24</td>
<td>56</td>
</tr>
<tr>
<td>O8</td>
<td>-5.2</td>
<td>33,500</td>
<td>48.60</td>
<td>5.00</td>
<td>51</td>
</tr>
<tr>
<td>O9</td>
<td>-4.8</td>
<td>32,000</td>
<td>48.24</td>
<td>4.64</td>
<td>34</td>
</tr>
<tr>
<td>O9.5</td>
<td>-4.6</td>
<td>31,000</td>
<td>47.95</td>
<td>4.35</td>
<td>29</td>
</tr>
<tr>
<td>B0</td>
<td>-4.4</td>
<td>30,000</td>
<td>47.67</td>
<td>4.07</td>
<td>23</td>
</tr>
<tr>
<td>B0.5</td>
<td>-4.2</td>
<td>26,200</td>
<td>46.83</td>
<td>3.23</td>
<td>12</td>
</tr>
</tbody>
</table>

NOTE: $T = 7500^\circ$ K assumed for calculating $\alpha_B$. 
Ionization structure of a pure hydrogen H II region

Note sharp transition at edge of Strömgren sphere
SFR from recombination lines

- Recombination lines (non-radio) measure $Q_0$, with small uncertainty due to temperature; extinction can be a problem.
- $Q_0$ can be turned into a massive star formation rate assuming a star formation history (burst, continuous,...) – major source of uncertainty.
- This can be turned into a total star formation rate assuming an initial mass function – major uncertainty.
HII region spectra

Spectrophotometry of the giant H II region NGC 604
Galaxy spectra

NGC 4889
E4

NGC 2775
Sa

NGC 6181
S0

NGC 4449
Sm/Im
Photoionization of nebula with H and He

- Ionization potentials:
  - H: 13.6 eV (912 Å)
  - He: 24.6 eV (504 Å)
  - He⁺: 54.4 eV (228 Å)
- Hotter stars are needed to ionize He
- Ionization potential of He⁺ too high for O stars ($T_\star > 50,000$ K)
  $\Rightarrow$ He++ does not occur in H II regions, only in planetary nebulae

*Presence of He II recombination line(s) in spectra indicates a very high effective temperature of the central star*
Photoionization of nebula with H and He

- Ionization potentials:
  - H: 13.6 eV (912Å)
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  \(\Rightarrow\) He\(^{++}\) does not occur in H II regions, only in planetary nebulae

*Presence of He II recombination line(s) in spectra indicates a very high effective temperature of the central star*
## Ionization Potentials

<table>
<thead>
<tr>
<th>Element</th>
<th>Ion. Pot. [eV]</th>
<th>Element</th>
<th>Ion. Pot. [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>13.598</td>
<td>Al</td>
<td>5.99</td>
</tr>
<tr>
<td>C</td>
<td>11.26</td>
<td>Si</td>
<td>8.15</td>
</tr>
<tr>
<td>O</td>
<td>13.618</td>
<td>S</td>
<td>10.36</td>
</tr>
<tr>
<td>N</td>
<td>14.54</td>
<td>Ca</td>
<td>6.11</td>
</tr>
<tr>
<td>Na</td>
<td>5.14</td>
<td>Ca&lt;sup&gt;+&lt;/sup&gt;</td>
<td>11.87</td>
</tr>
<tr>
<td>Mg</td>
<td>7.65</td>
<td>Fe</td>
<td>7.87</td>
</tr>
</tbody>
</table>

*O and N cannot be ionized in general ISM*
Photoionization of nebula with H and He

- Ionization potentials:
  - H: 13.6 eV (912Å)
  - He: 24.6 eV (504Å)
  - He\(^+\): 54.4 eV (228Å)

- Hotter stars are needed to ionize He

- Ionization potential of He\(^+\) too high for O stars \((T_\star > 50,000 \text{ K})\)
  \(\Rightarrow\) He\(^{++}\) does not occur in H II regions, only in planetary nebulae

*Presence of He II recombination line(s) in spectra indicates a very high effective temperature of the central star*
Visible spectroscopy

Planetary nebula

Note He II recombination lines $\rightarrow$ hot star
Ionization by O and B stars

Case 1: Spectrum of star peaks at ≈13.6 eV

Lots of photons with $13.6 \text{ eV} < h\nu < 24.6 \text{ eV}$, few photons with $h\nu > 24.6 \text{ eV}$

→ Two Strömgren spheres,

small central $\text{He}^+$ zone surrounded by large $\text{H}^+$ region

Case 2: Spectrum of star peaks at $>24.6 \text{ eV}$

Lots of photons with $h\nu > 24.6 \text{ eV}$

$\text{H}^+$ and $\text{He}^+$ zones coincide
Ionization structure H and He in model H II regions

Case 1

Case 2
He\(^+\) / H\(^+\) radius as function of \(T\)
Photoionization of nebulae with heavy elements

- Same analysis as for He
- Ionization potential of O$^{++}$ and He$^+$ are nearly identical $\rightarrow$ O$^{+++}$ zone coincides with He$^{++}$ zone (for $T_\star \approx 100,000$ K)
- Structure of nebulae can be somewhat affected by charge transfer reactions

$$X^{(m+1)+} + H \rightarrow X^{m+} + H^+$$

For $m \geq 2$, this process is usually fast
Ionization structure of H, He and O for planetary nebula
Ring nebula (M57, NGC 6720)

$T_\star = 120,000$ K

Blue: He recombination
Green: [O III]
Red: [N II]

Note stratification
Planetary Nebula NGC 6543

- Red: Hα λ6563
- Green: [N II] λ6584
Real HII regions

- HII regions gradually expand due to thermal pressure. Very young HII regions, born in very dense molecular clouds are very small and dense: ultracompact HII regions (UCHRs).

- Due to the expansion, a dense layer builds up at the ionization front

- Radiation pressure may be a dominant force close to the central star
Real HII regions

- Real HII regions are not uniform but clumpy; since almost all emission scales with EM, all probes are strongly biased towards dense regions.

- Ionization goes with $n$, recombination with $n^2$; therefore denser regions “cost” more ionizing photons.

- Due to the expansion of the HII region, the region near the ionization front (IF) is dense and therefore bright.
Orion Bright Bar Ionization Front
Real HII regions

- Strömgren spheres are **ionization bounded**, i.e., nebula absorbs all ionizing photons from star (there is more gas than can be ionized); some HII regions (including planetary nebulae) are **density bounded** so that some UV photons escape the nebula (there are photons left when you are out of gas)

- Some UV photons are absorbed by dust. In UCHRs this can be dominant. This partially suppresses emission lines, radio continuum, radius, etc.
Real HII regions can have central stellar wind cavities
The Rosette nebula
(red=H\textalpha,  
green=[OIII],  
blue=[SII])
Composite Hα map compiled by Finkbeiner from WHAM, VTSS & SHASSA.