Ionized Gas: Line Emission

Lecture 1

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Topics

- Introduction
  - HII regions & Planetary Nebulae
- Recombination Line Emission
  - HI, HeI
- Collisionally Excited Line Emission
  - Abundances
  - Atomic Structure
  - Density limits / Critical density
- Some sample Spitzer galaxy spectra
Examples

- Gas ionized by an energetic radiation field
  - Lots of photons with $h\nu > 13.6$ eV
- Examples -

<table>
<thead>
<tr>
<th></th>
<th>$T_{\text{star}}$ ($10^4$ K)</th>
<th>$N_{H}$ (cm$^{-3}$)</th>
<th>$T_{\text{electron}}$ ($10^4$ K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HII regions</td>
<td>30 - 50</td>
<td>10 - 10$^5$</td>
<td>0.5 - 1.0</td>
</tr>
<tr>
<td>PNe</td>
<td>80 - 600</td>
<td>10$^3$ - 10$^7$</td>
<td>1.0 - 1.5</td>
</tr>
<tr>
<td>AGNs</td>
<td>$\nu^1$ - $\nu^2$</td>
<td>$\sim 5 \times 10^3$</td>
<td>1.0 - 2.0</td>
</tr>
</tbody>
</table>

HII Regions

Molecular cloud collapses, forming stars.

Ionized Hydrogen (HII) regions surrounding newly formed stars.

Note – these regions have lots of structure and are very clumpy (see images that follow).
Planetary Nebulae

Outer layers of red giant are ejected into ISM. Hot core ionized gas surrounding star.

Again – clump structure is evident (see images that follow).

Helix Nebula (NGC 7293)

Spitzer APOD: 01/12/2006
Some handy numbers

- Ionization thresholds:
  - HI 13.6 eV  912 Å  3.29 × 10^{15} Hz
  - HeI 24.5 eV  506 Å  5.92 × 10^{15} Hz
  - HeII 54.4 eV  228 Å  13.2 × 10^{15} Hz

- For peak of BB to be at ~912 Å
  - T ~ 32,000 K
  - Implies a rough lower mass cut-off for HII regions

- Conversions:
  - \( \lambda(\text{Å}) = 12,398 / E(\text{eV}) \)  
    (1 eV = 1.602 × 10^{-12} ergs)
  - \( \nu(10^{15}\text{Hz}) = 0.2418 \text{ eV} \)
Photoionization cross-sections

$$a_\nu \left(10^{-18} \text{ cm}^2\right)$$ vs $$\nu \left(10^{15} \text{ Hz}\right)$$

Kurucz model atmospheres

$$H_\nu \left(\text{ergs/cm}^2/\text{s}/\text{Hz}\right)$$ vs $$\lambda \ (\text{nm})$$

Log g = 4.5

Temperature:
- T = 50000
- T = 45000
- T = 40000
- T = 35000
- T = 30000
### Sizes of HII regions

<table>
<thead>
<tr>
<th>Type</th>
<th>T* (K)</th>
<th>log(N_{Lyc})</th>
<th>r_s (pc)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>N=1</td>
</tr>
<tr>
<td>O5</td>
<td>48,000</td>
<td>49.67</td>
<td>108</td>
</tr>
<tr>
<td>O6</td>
<td>40,000</td>
<td>49.23</td>
<td>74</td>
</tr>
<tr>
<td>O7</td>
<td>35,000</td>
<td>48.84</td>
<td>56</td>
</tr>
<tr>
<td>O9.5</td>
<td>31,000</td>
<td>47.95</td>
<td>29</td>
</tr>
<tr>
<td>B0.5</td>
<td>26,200</td>
<td>46.83</td>
<td>12</td>
</tr>
</tbody>
</table>

\[ N_{Lyc} = \frac{4}{3} \pi r_s^3 N_H^2 \alpha_B \]

\[ r_s \equiv r_{HII} \]

\[ \alpha_B = \alpha_A - \alpha_I \]

- \( N_{Lyc} \) = the number of Lyman continuum photons emitted per second by the star,
- \( r_s \equiv r_{HII} \) is called the Strömgren radius,
- \( \alpha_B = \alpha_A - \alpha_I \) is the recombination coefficient to \( n = 2 \)

### Schematic HII/HeII regions

- \( H^+ \), \( He^0 \)
- \( H^0 \)
- \( H^+ \), \( He^+ \)

- Hot Star
- Hotter Star
Effects of He

- He competes for ionizing photons with H.
  - $a_\nu$(HeI) $> a_\nu$(HI) for $\nu > 24.6$ eV
- Opacity is increased.
- Supplies electrons
  - $\sim$10% contributions
- Recombinations that for HeI contribution to the diffuse radiation field.
  - Recombinations to $n=1$ can ionized both He and H.
  - Recombinations that populate $n=2$ can result in photons that can ionize H.
- See (AGN)$^2$ for further details on including He.
Hel energy level diagram

Energy (eV)

<table>
<thead>
<tr>
<th>Energy (eV)</th>
<th>Line (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>2.058 µm</td>
</tr>
<tr>
<td>20</td>
<td>584 Å</td>
</tr>
<tr>
<td>10830</td>
<td>10830 Å</td>
</tr>
<tr>
<td>628</td>
<td>628 Å</td>
</tr>
</tbody>
</table>

What ions have lines?

- What ions are present?
  - The most abundant species are most important
  - Expect ionic states of C, N, O
- Ionization potentials (in eV):

<table>
<thead>
<tr>
<th>Ion</th>
<th>I -&gt; II</th>
<th>II -&gt; III</th>
<th>III -&gt; IV</th>
<th>IV -&gt; V</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>11.256</td>
<td>24.376</td>
<td>47.871</td>
<td>64.476</td>
</tr>
<tr>
<td>N</td>
<td>14.53</td>
<td>29.593</td>
<td>47.426</td>
<td>77.45</td>
</tr>
<tr>
<td>O</td>
<td>13.614</td>
<td>35.108</td>
<td>54.886</td>
<td>77.394</td>
</tr>
</tbody>
</table>
For multi-electron atoms, transition can occur from various energy levels to the continuum.
Outer electron configurations of neutral atoms in their ground states are shown.
LS fine-structure splitting (p²)

Unperturbed State

Spin-

Spin

Residual Electrostatic

Spin-

Orbit

Not Allowed

Allowed

\( S = 0 \)

\( S = 1 \)

Unperturbed State

Spin-

Spin

Residual Electrostatic

Spin-

Orbit

Allowed

Not Allowed

\( ^1S_0 \)

\( ^1P_1 \)

\( ^1D_2 \)

\( ^3S_1 \)

\( ^3P_{0,1,2} \)

\( ^3D_{1,2,3} \)

\( ^2P_{3/2} \)

\( ^3P_2 \)

\( ^3P_0 \)

\( ^3P_1 \)

\( ^3P_2 \)

\( ^2P_{1/2} \)

\( ^4P_{3/2} \)

\( ^2P_{3/2} \)

\( ^1S_0 \)

\( ^2P \)

\( ^1S_0 \)

\( ^1D_2 \)

\( ^2D \)

\( ^1D_2 \)

\( ^3P_2 \)

\( ^3P_1 \)

\( ^3P_0 \)

\( ^2P_{1/2} \)

\( ^3P_2 \)

\( ^2P_{3/2} \)

p₁

p₂

p³

p⁴

p⁵

(see R&L, Ch. 9.4)
### p-electron ions

<table>
<thead>
<tr>
<th>p&lt;sup&gt;1&lt;/sup&gt;</th>
<th>p&lt;sup&gt;2&lt;/sup&gt;</th>
<th>p&lt;sup&gt;3&lt;/sup&gt;</th>
<th>p&lt;sup&gt;4&lt;/sup&gt;</th>
<th>p&lt;sup&gt;5&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>CII</td>
<td>CI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NIII</td>
<td>NII</td>
<td>NI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OIV</td>
<td>OIII</td>
<td>OII</td>
<td>OI</td>
<td></td>
</tr>
<tr>
<td>SIV</td>
<td>SIII</td>
<td>SII</td>
<td>SI</td>
<td></td>
</tr>
<tr>
<td>NeVI</td>
<td>NeV</td>
<td>NeIV</td>
<td>NeIII</td>
<td>NeII</td>
</tr>
<tr>
<td>ArVI</td>
<td>ArV</td>
<td>ArIV</td>
<td>ArIII</td>
<td>ArII</td>
</tr>
</tbody>
</table>

### OIII example

<table>
<thead>
<tr>
<th>Transition</th>
<th>A(s&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>¹S&lt;sub&gt;0&lt;/sub&gt; - ¹D&lt;sub&gt;2&lt;/sub&gt;</td>
<td>1.8</td>
<td>4363.2 Å</td>
</tr>
<tr>
<td>³P&lt;sub&gt;0&lt;/sub&gt; - ¹S&lt;sub&gt;0&lt;/sub&gt;</td>
<td>7.8×10&lt;sup&gt;-4&lt;/sup&gt;</td>
<td>2331.4 Å</td>
</tr>
<tr>
<td>³P&lt;sub&gt;1&lt;/sub&gt; - ¹S&lt;sub&gt;0&lt;/sub&gt;</td>
<td>2.2×10&lt;sup&gt;-1&lt;/sup&gt;</td>
<td>2321.0 Å</td>
</tr>
<tr>
<td>³P&lt;sub&gt;2&lt;/sub&gt; - ¹D&lt;sub&gt;2&lt;/sub&gt;</td>
<td>2.0×10&lt;sup&gt;-2&lt;/sup&gt;</td>
<td>5006.9 Å</td>
</tr>
<tr>
<td>³P&lt;sub&gt;1&lt;/sub&gt; - ¹D&lt;sub&gt;2&lt;/sub&gt;</td>
<td>6.7×10&lt;sup&gt;-3&lt;/sup&gt;</td>
<td>4958.9 Å</td>
</tr>
<tr>
<td>³P&lt;sub&gt;0&lt;/sub&gt; - ¹D&lt;sub&gt;2&lt;/sub&gt;</td>
<td>2.7×10&lt;sup&gt;-6&lt;/sup&gt;</td>
<td>4931.0 Å</td>
</tr>
<tr>
<td>³P&lt;sub&gt;1&lt;/sub&gt; - ³P&lt;sub&gt;2&lt;/sub&gt;</td>
<td>9.8×10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>51.8 μm</td>
</tr>
<tr>
<td>³P&lt;sub&gt;0&lt;/sub&gt; - ³P&lt;sub&gt;2&lt;/sub&gt;</td>
<td>3.0×10&lt;sup&gt;-11&lt;/sup&gt;</td>
<td>32.7 μm</td>
</tr>
<tr>
<td>³P&lt;sub&gt;0&lt;/sub&gt; - ³P&lt;sub&gt;1&lt;/sub&gt;</td>
<td>2.6×10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>88.4 μm</td>
</tr>
</tbody>
</table>
**Level populations**

- In order to estimate the emission, we need to know the populations of the various levels in each ion.
- Population to a given level can occur via
  - collisional transfer of an electron from another level
  - a radiative transition into the state
- Depopulation can occur in the same manner
  - collisional transfer of the electron out of the level
  - a radiative transition into another state
- In equilibrium, population and depopulation of a level must be the same.
Two level atom

$N_2 A_{21} + N_2 N_e q_{21} = N_1 N_e q_{12}$

$N_1 + N_2 = N_i$

- $q_{21}$ is the collision coefficient for moving an electron from level 2 to 1 (see Osterbrock, p50-51).

$$q_{21} = \int_0^\infty \nu \sigma_{21}(\nu) f(\nu) d\nu = \left( \frac{2\pi}{kT} \right)^{1/2} \frac{\hbar^2}{4\pi^2 m^{3/2}} \frac{\Omega(1,2)}{g_2}$$

$$\Omega(1,2) = \int_0^\infty \Omega(1,2; E) e^{-E/kT} d\left(\frac{E}{kT}\right)$$

Ignoring stimulated processes

Two level atom (cont’d)

- $\Omega(1,2)$ is the collision strength (of order unity, 0.2-7), calculated quantum mechanically.

- Via detailed balance arguments

$$\frac{q_{12}}{q_{21}} = \frac{g_2}{g_1} e^{-h\nu/kT}$$

- Solving for the population level 2

$$N_2 = \frac{N_i N_e q_{12}}{A_{21} + N_e q_{12} + N_e q_{21}}$$
$j$ for 2-level atom

- Which yields for the emissivity

$$j = \frac{h \nu_{21}}{4\pi} N_2 A_{21}$$

$$= \frac{h \nu_{21}}{4\pi} A_{21} \frac{N_i N_e q_{12}}{A_{21} + N_e q_{12} + N_e q_{21}}$$

- Limit for $N_e \to 0$.

$$j \to \frac{h \nu_{21}}{4\pi} N_i N_e q_{12}$$

So that every collision results in a photon.

---

$j$ for 2-level atom ($N_e$ limits)

- Limit for $N_e \to \infty$.

$$j = \frac{h \nu_{21}}{4\pi} A_{21} N_i \frac{q_{12}}{q_{21} + q_{12}}$$

$$= \frac{h \nu_{21}}{4\pi} A_{21} N_i \frac{g_2 e^{-h \nu/kT}}{g_1 + g_2 e^{-h \nu/kT}}$$

- Note that the levels are Boltzmann populated in this case, and $j \propto N_i$ (no $N_e$!).

- At high densities cooling (per ion per electron) is not as efficient because of collisional de-excitation.
Critical density

- Critical density -
  - The rough transition density from the low density to the high density regime.
  - Collisional depopulations equal radiative depopulations

\[ N_2 A_{21} = N_2 N_e q_{21} \quad \Rightarrow \quad N_c = \frac{A_{21}}{q_{21}} \]

- If there are multiple paths we must sum over all of them.

### Critical Densities

**Table 3.15**

Critical densities for collisional deexcitation

<table>
<thead>
<tr>
<th>Ion</th>
<th>Level</th>
<th>(n_e) (cm(^{-3}))</th>
<th>Ion</th>
<th>Level</th>
<th>(n_e) (cm(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>C II</td>
<td>(^2P_{3/2}^o)</td>
<td>5.0 \times 10^1</td>
<td>O III</td>
<td>(^1D_2)</td>
<td>6.8 \times 10^5</td>
</tr>
<tr>
<td>C III</td>
<td>(^3P_{2}^o)</td>
<td>5.1 \times 10^5</td>
<td>O III</td>
<td>(^3P_{2})</td>
<td>3.6 \times 10^3</td>
</tr>
<tr>
<td>N II</td>
<td>(^1D_2)</td>
<td>6.6 \times 10^4</td>
<td>O III</td>
<td>(^1P_{1})</td>
<td>5.1 \times 10^2</td>
</tr>
<tr>
<td>N II</td>
<td>(^3P_{1})</td>
<td>3.1 \times 10^2</td>
<td>Ne II</td>
<td>(^2P_{1/2})</td>
<td>7.1 \times 10^5</td>
</tr>
<tr>
<td>N II</td>
<td>(^3P_{1})</td>
<td>8.0 \times 10^1</td>
<td>Ne III</td>
<td>(^1D_2)</td>
<td>9.5 \times 10^6</td>
</tr>
<tr>
<td>N III</td>
<td>(^2P_{3/2}^o)</td>
<td>1.5 \times 10^3</td>
<td>Ne III</td>
<td>(^3P_{0})</td>
<td>3.1 \times 10^4</td>
</tr>
<tr>
<td>N IV</td>
<td>(^3P_{2})</td>
<td>1.1 \times 10^6</td>
<td>Ne III</td>
<td>(^3P_{1})</td>
<td>2.1 \times 10^5</td>
</tr>
<tr>
<td>O II</td>
<td>(^2D_{5/2}^o)</td>
<td>1.5 \times 10^4</td>
<td>Ne V</td>
<td>(^1D_2)</td>
<td>1.3 \times 10^7</td>
</tr>
<tr>
<td>O II</td>
<td>(^2D_{5/2}^o)</td>
<td>3.4 \times 10^3</td>
<td>Ne V</td>
<td>(^3P_{2})</td>
<td>3.5 \times 10^4</td>
</tr>
</tbody>
</table>

**NOTE:** All values are calculated for \(T = 10,000\) K.

From Osterbrock & Ferland
Multiple level atom

- The previous discussion is easily extended to atoms with more than two levels.
- For any level $m$ in an ion
  \[
  \sum_{k > m} N_k A_{km} + \sum_{k \neq m} N_k N_e q_{km} = N_m \sum_{k < m} A_{mk} + N_m \sum_{k = m} N_e q_{mk}
  \]
- We have the constraint that
  \[
  \sum_k N_k = N_i
  \]
- Where $N_i$ is the total number of ion of type $i$. 

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[SIII] 33.5/18.7 µm ratio

Similar plot for [OIII] 88/52 µm ratio
NGC 7714: Pure Starburst?

- Part of interacting system, $z = 0.00933$
- $L = 5.6 \times 10^{10} \ L_{\odot}$
- This is a relatively low extinction galaxy.
- Note dominance of PAH emission features in the spectrum.
- And presence of numerous emission lines.

7”

20 kpc

6450 A

NGC 7715

$z = 0.00924$

Densities and Temperatures

Figure from Osterbrock & Ferland

Ionized Gas Emission
Mrk 463 = UGC 8850

- Galaxy at $z = 0.050$
- $L = 6.0 \times 10^{11} \, L_{\odot}$
- Merging, twin Seyfert 2 nuclei. Mrk 463e dominates in IR
- Silicate absorption feature and line emission prominent.

Mrk 1014

- Quasar at $z = 0.163$
- $L = 4.1 \times 10^{12} \, L_{\odot}$
- Radio quiet, broad-line, dusty QSO with twin tidal tails.
- No obvious silicate emission, but ..
- Numerous emission lines and a number of PAH features seen.