Photoionization Models

• How photoionization codes work (simplified)
• Calculating a specific model
• Additional complications/considerations
• Unresolved emission-line regions
• Cloudy
Photoionization Codes

Equations for calculating a model:

1) \[ \frac{dI_\nu}{ds} = -I_\nu \frac{d\tau_\nu}{ds} + j_\nu \] (radiative transfer)

where \[ \frac{d\tau_\nu}{ds} = \sum n_j a_{\nu j} \] (sum over all ions)

2) \[ n(X^i) \int_{\nu_i}^{\infty} \frac{4\pi J_\nu}{h\nu} a_\nu(X^i) d\nu = n(X^{i+1}) n_e \alpha(X^i, T) \] (ion. equil.)

where \[ \sum n(X^i) = n(X) \] and Abundance = \[ n(X)/n(H) \]

3) \[ G = L_R + L_{FF} + L_C \] (conservation of energy)
Procedure:

• Assume a geometry (spherical, plane-parallel, etc.)
• Determine the ionizing flux at the incident face of the cloud
  (PN – inner face of shell, filled H II region – surface of star,
  AGN – ionized face of discrete cloud (usually a slab))
• Divide the cloud into zones and calculate the reduction of photons as you move into the cloud
• Use the on-the-spot approximation (all diffuse ionizing photons are absorbed locally) in the first series of calculations to determine: temperature, ionization fractions, emissivities, and reduction of ionizing photons in each zone
• In subsequent iterations, determine the diffuse field as you go to deeper zones in the cloud
Calculating a Specific Model

• Estimate the initial input parameters:
  1) Geometry (sphere, shell, slab, other?)
  2) \( n_e \) (or \( n_H \)) - from [O II], [S II], critical densities, etc.
     - is density a function of distance: \( n(r) \) ?
  3) Ionizing spectrum (spectral energy distribution)
     - clues from type of source, Zanstra method, etc.
  4) Flux of ionizing source (star, AGN, etc.) at surface of cloud
  5) Abundances (normally assume solar to begin with)

• Calculate the model
• Compare model spectrum to observed spectrum
  (usually line ratios relative to H\(\beta\))
• Iterate
Additional Considerations

- Optical depth of cloud *(when to terminate the integration?)*
  
  Extremes:
  1) matter bounded – optically thin to ionizing radiation
  2) radiation bounded – optically thick to ionizing radiation

- Filling factor \((\varepsilon)\): percentage of volume that is filled
  – are there discrete clouds?

- Covering factor \((C)\): fraction of ionizing flux that is intercepted by the gas:
  \[ C = \frac{\Omega}{4\pi} \]

- Multicomponent models *(when one component just won’t do!)*
  
  Ex) Condensations in a diffuse medium (two densities)
  Ex) Two or more clouds at different distances from source

- Many other games you can play!
Unresolved Emission-Line Regions

- Ex) broad-line region (BLR) of AGN
- Problem: don’t know distance from source to cloud(s)
- Assume a slab (discrete cloud, large distance from source)
- Use the ionization parameter (U):

\[
U = \frac{\int_{v_0}^{\infty} \frac{L_v}{h\nu} dv}{4\pi r^2 c n_e} = \frac{\# \text{ ionizing photons} / \text{vol}}{\# \text{ electrons} / \text{vol}} \quad \text{at the incident face}
\]

From the ionization equilibrium equation:

\[
U = \frac{Q_{\text{ion}}}{4\pi r^2 c n_e} \approx \frac{\alpha(X^i, T) \cdot n(X^{i+1})}{a_v(X^i) \cdot c \cdot n(X^i)}
\]

\[\rightarrow U \text{ is a dimensionless parameter that specifies the ionization fractions}\]
\[\rightarrow U \text{ is the most important factor in determining line ratios}\]
\[\quad (n_e \text{ is next most important})\]
Emission-Line Ratios as a Function of $U$


$[\text{O III}]$ 5007, $[\text{O II}]$ 3727, $[\text{N II}]$ 6584, $[\text{O I}]$ 6300, $[\text{S II}]$ 6731, $[\text{N I}]$ 5200, $\text{C III}^\ast$ 1909, $\text{C IV}$ 1549, $\text{He I}$ 5876, $\text{He II}$ 4686
• So for AGN models, the typical input parameters are:
  1) $U$ – Guess from ratios: C IV/C III, etc.
  2) $n_H$ – presence of lines with certain critical densities
     Ex) [O III] not present in BLR, so $n_H > 10^8 \text{ cm}^{-3}$
  3) SED – from X-ray, UV, and optical observations (don’t know EUV!)
  4) $N_H$ – integrate model until lines that form deep in cloud are matched – usually very optically thick
  5) Abundances (last resort!)

• Usually, at least 2 components with different $U$, $n_e$ needed
• Can derive distances of clouds from $U$, $n_e$
Cloudy - State of the Art

• Main web page (downloads, documentation, discussion, etc.): http://www.nublado.org/

• Current status of numerical simulations of photoionized gas: Ferland, G.J. 2003, ARAA, 41, 517

Ex) HST/STIS Spectra of the Narrow-Line Region in NGC 1068 (Seyfert 2 Galaxy)

WFPC 2 image
blue - stellar
red  -  Hα
green - [O III]
NGC 1068: NLR – [O III] Image

continuum “hot spot”

hidden nucleus

4.0"
(290 pc)
STIS Raw UV Spectrum

hot spot
NGC 1068 - Hot Spot
STIS Spectrum of NLR

Huge range in ionization:
- Low: O I, Mg II, C II
- High: C IV, [O III], etc.
- Coronal: [Fe XI], [Fe XIV], [S XII] (IP_C = 504 eV)
Redshift vs. Ionization Potential

- kinematic evidence for distinct components

$r_s = -0.65, P_r << 0.001$
NLR Photoionization Models – 3 components

1) LOWION: $U = 10^{-3.2}$, $n_H = 3 \times 10^4 \text{ cm}^{-3}$, $N_H = 1 \times 10^{21} \text{ cm}^{-2}$

2) HIGHTON: $U = 10^{-1.5}$, $n_H = 6 \times 10^4 \text{ cm}^{-3}$, $N_H = 1 \times 10^{21} \text{ cm}^{-2}$

3) CORONAL: $U = 10^{0.2}$, $n_H = 7 \times 10^2 \text{ cm}^{-3}$, $N_H = 4 \times 10^{22} \text{ cm}^{-2}$ (?)

Constrained to be ~25 pc from nucleus
Intrinsic and Filtered Continua (for LOWION)

(Absorber: $U = 10^{-1.0}$, $N_H = 7 \times 10^{22} \text{ cm}^{-2}$)
<table>
<thead>
<tr>
<th>Emission Line</th>
<th>HIGHION$^a$</th>
<th>LOWION$^b$$^c$</th>
<th>Composite$^d$</th>
<th>Observed$^e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C II $\lambda$4267</td>
<td>(1.47)</td>
<td>(1.48)</td>
<td>(1.37)</td>
<td>...</td>
</tr>
<tr>
<td>N III $\lambda$4600</td>
<td>(0.84)</td>
<td>(0.78)</td>
<td>(0.68)</td>
<td>...</td>
</tr>
<tr>
<td>Ly α $\lambda$1216</td>
<td>34.18</td>
<td>40.44</td>
<td>35.74</td>
<td>30.17 ± 5.65</td>
</tr>
<tr>
<td>N V $\lambda$1240</td>
<td>3.33</td>
<td>0.00</td>
<td>2.50</td>
<td>18.19 ± 2.86</td>
</tr>
<tr>
<td>C II $\lambda$1355</td>
<td>0.03</td>
<td>0.09 (4.02)</td>
<td>1.01</td>
<td>0.95 ± 0.19</td>
</tr>
<tr>
<td>O IV $\lambda$1402 + Si IV $\lambda$1398</td>
<td>4.74</td>
<td>0.00</td>
<td>3.56</td>
<td>4.99 ± 0.19</td>
</tr>
<tr>
<td>N IV $\lambda$1486</td>
<td>2.99</td>
<td>0.00</td>
<td>2.24</td>
<td>0.76 ± 0.13</td>
</tr>
<tr>
<td>C IV $\lambda$1550</td>
<td>12.52</td>
<td>0.03</td>
<td>24.40</td>
<td>19.83 ± 2.53</td>
</tr>
<tr>
<td>He II $\lambda$1640</td>
<td>5.30</td>
<td>1.29</td>
<td>5.05</td>
<td>4.34 ± 0.57</td>
</tr>
<tr>
<td>O III $\lambda$1667</td>
<td>1.71</td>
<td>0.69</td>
<td>1.31</td>
<td>...</td>
</tr>
<tr>
<td>N II $\lambda$1750</td>
<td>0.81</td>
<td>0.65</td>
<td>0.62</td>
<td>...</td>
</tr>
<tr>
<td>C IV $\lambda$1909 + Si IV $\lambda$1883, 1892</td>
<td>6.64</td>
<td>1.04</td>
<td>5.25</td>
<td>7.16 ± 0.96</td>
</tr>
<tr>
<td>C II $\lambda$2326 + O III $\lambda$1342</td>
<td>0.24</td>
<td>1.36</td>
<td>0.57</td>
<td>0.47 ± 0.09</td>
</tr>
<tr>
<td>[Ne IV] $\lambda$2372</td>
<td>1.62</td>
<td>0.01</td>
<td>1.22</td>
<td>1.44 ± 0.20</td>
</tr>
<tr>
<td>[O IV] $\lambda$2370</td>
<td>0.00</td>
<td>0.77</td>
<td>0.19</td>
<td>...</td>
</tr>
<tr>
<td>Mg II $\lambda$2800</td>
<td>0.00</td>
<td>3.05 (8.54)</td>
<td>2.13</td>
<td>1.91 ± 0.21</td>
</tr>
<tr>
<td>He II $\lambda$2304</td>
<td>0.36</td>
<td>0.08</td>
<td>0.29</td>
<td>0.89 ± 0.21</td>
</tr>
<tr>
<td>[Ne VII] $\lambda$3346</td>
<td>1.83</td>
<td>0.00</td>
<td>1.38</td>
<td>1.74 ± 0.17</td>
</tr>
<tr>
<td>[O V] $\lambda$3426</td>
<td>4.99</td>
<td>0.00</td>
<td>3.74</td>
<td>4.94 ± 0.30</td>
</tr>
<tr>
<td>[Fe VII] $\lambda$3558</td>
<td>0.46</td>
<td>0.00</td>
<td>0.34</td>
<td>0.44 ± 0.07</td>
</tr>
<tr>
<td>[O III] $\lambda$3727</td>
<td>0.00</td>
<td>2.81</td>
<td>0.70</td>
<td>0.56 ± 0.08</td>
</tr>
<tr>
<td>[Fe VII] $\lambda$3760</td>
<td>0.65</td>
<td>0.00</td>
<td>0.48</td>
<td>0.83 ± 0.07</td>
</tr>
<tr>
<td>[Ne III] $\lambda$3869</td>
<td>1.12</td>
<td>1.67</td>
<td>1.26</td>
<td>2.35 ± 0.19</td>
</tr>
<tr>
<td>[O III] $\lambda$4367 + He</td>
<td>0.50</td>
<td>0.68</td>
<td>0.55</td>
<td>0.56 ± 0.10</td>
</tr>
<tr>
<td>[Sr II] $\lambda$4072</td>
<td>0.00</td>
<td>0.87</td>
<td>0.22</td>
<td>0.33 ± 0.05</td>
</tr>
<tr>
<td>H$\beta$ $\lambda$4100</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.33 ± 0.05</td>
</tr>
<tr>
<td>H$\gamma$ $\lambda$4340</td>
<td>0.47</td>
<td>0.47</td>
<td>0.47</td>
<td>0.66 ± 0.06</td>
</tr>
<tr>
<td>[O II] $\lambda$4363</td>
<td>0.63</td>
<td>0.07</td>
<td>0.49</td>
<td>0.43 ± 0.05</td>
</tr>
<tr>
<td>He II $\lambda$4686</td>
<td>0.87</td>
<td>0.19</td>
<td>0.70</td>
<td>0.60 ± 0.05</td>
</tr>
<tr>
<td>H$\beta$</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>[O III] $\lambda$4959</td>
<td>6.60</td>
<td>2.85</td>
<td>5.66</td>
<td>4.96 ± 0.38</td>
</tr>
<tr>
<td>[O III] $\lambda$5007</td>
<td>19.80</td>
<td>8.36</td>
<td>16.99</td>
<td>15.12 ± 0.98</td>
</tr>
<tr>
<td>[Fe VII] $\lambda$5030</td>
<td>0.79</td>
<td>0.00</td>
<td>0.60</td>
<td>0.83 ± 0.07</td>
</tr>
<tr>
<td>He I $\lambda$5016</td>
<td>0.02</td>
<td>0.13</td>
<td>0.05</td>
<td>0.25 ± 0.12</td>
</tr>
<tr>
<td>[Fe VII] $\lambda$6563</td>
<td>1.18</td>
<td>0.00</td>
<td>0.85</td>
<td>1.08 ± 0.10</td>
</tr>
<tr>
<td>[O VII] $\lambda$6300 + [S III] $\lambda$6312</td>
<td>0.00</td>
<td>2.29</td>
<td>0.57</td>
<td>0.27 ± 0.03</td>
</tr>
<tr>
<td>[O I] $\lambda$6300 + [Fe II] $\lambda$6304</td>
<td>1.17</td>
<td>0.71</td>
<td>1.08</td>
<td>0.80 ± 0.07</td>
</tr>
<tr>
<td>[N V] $\lambda$6548</td>
<td>0.00</td>
<td>2.65</td>
<td>0.66</td>
<td>0.98 ± 0.22</td>
</tr>
<tr>
<td>[Ne III] $\lambda$6563</td>
<td>2.78</td>
<td>2.94</td>
<td>2.82</td>
<td>2.81 ± 0.51</td>
</tr>
<tr>
<td>[N II] $\lambda$6584</td>
<td>0.00</td>
<td>7.65</td>
<td>1.91</td>
<td>2.94 ± 0.66</td>
</tr>
<tr>
<td>[S II] $\lambda$6716</td>
<td>0.00</td>
<td>1.03</td>
<td>0.26</td>
<td>0.17 ± 0.03</td>
</tr>
<tr>
<td>[S II] $\lambda$6731</td>
<td>0.00</td>
<td>1.22</td>
<td>0.30</td>
<td>0.21 ± 0.04</td>
</tr>
<tr>
<td>[O III] $\lambda$7325</td>
<td>0.00</td>
<td>0.98</td>
<td>0.24</td>
<td>0.24 ± 0.04</td>
</tr>
<tr>
<td>[S II] $\lambda$7069</td>
<td>0.00</td>
<td>1.17</td>
<td>0.30</td>
<td>0.51 ± 0.09</td>
</tr>
<tr>
<td>[S II] $\lambda$9532</td>
<td>0.01</td>
<td>3.08</td>
<td>0.72</td>
<td>1.28 ± 0.17</td>
</tr>
</tbody>
</table>
“CORONAL” Model

Atomic Data Needed

- “Toy model” generated to match the ionization states seen
- To get a real model of the emission lines, we need:
  1) Collision strengths for these intermediate ionization states
  2) Accurate dielectronic recombination rates
     (over a temperature range 40,000 – 100,000 °K)