AGN – Physics of the Ionized Gas

- Physical conditions in the NLR
- Physical conditions in the BLR
- LINERs
- Emission-Line Diagnostics
- High-Energy Effects
Evidence for Photoionization

- continuum and Hβ luminosity correlated over a huge range

Emission-Line Diagnostics for Seyfert NLRs

- T = 10,000 – 20,000 K from [O III] lines $\rightarrow$ photoionization (shock heating gives temperatures $\approx$ 40,000 K)
- Emission lines span a wide range in ionization potential (IP):
  - IP needed to create [O I]: 0 eV, [Fe X IV]: 361 eV
  $\rightarrow$ Power-law SEDs with substantial X-ray contribution
- UV radiation forms a classic H II region on the “front face”
- X-rays penetrate deep into the cloud to create a “partially-ionized zone” (PIZ): \( \frac{N(\text{H II})}{N(\text{H I})} \approx 0.1 \) to 0.2
  - In the PIZ, elements are neutral or singly ionized
  - substantial emission from HI, [O I], [N II], [S II], Mg II
  $\rightarrow$ Large column densities ($N_H = 10^{19} - 10^{21}$ cm\(^{-2}\))
- HST resolved spectroscopy shows wide range in number density.
  $\rightarrow$ \( n_H = 10^2 - 10^6 \) cm\(^{-3}\) (from lines with a range in critical density)
Collisional Excitation of H Lines in the PIZ

• X-rays penetrate deep into the cloud to create high-energy ("suprathermal") electrons, which cause multiple ionizations in the mostly neutral gas.
• Suprathermal electrons also collisionally excite the $n = 1$ level in hydrogen:
  \[ 4\pi j_v = n_e n_{H^0} q_{12} h\nu_{L\alpha} \], where $q$ is the collision rate
• $L\alpha/H\beta$ can reach ~50 in the NLR, compared to recombination value of 33.
• $H\alpha$ is the next most collisionally enhanced line ($n = 1$ to $n = 3$)
• $H\alpha/H\beta$ can reach ~ 3.1 in the NLR, compared to the recombination value of 2.85
Results from NLR models

• Photoionization codes like CLOUDY contain all of the important physics (X-ray ionization of the PIZ, collisional excitation and ionization, Auger effect, charge exchange, etc.)

• Input parameters: U (or luminosity and distance for spatially resolved regions), continuum shape (SED), number density ($n_H$), abundances, column densities ($N_H$).

• Models indicate abundances are approximately solar
  – previous “low abundance” cases due to a high-density component, which suppresses the forbidden lines (CNO, etc.)

• Multiple components (with different $U$, $n_H$) are usually needed at each position.

• Power-law interpolation between UV and X-ray ($\alpha_\nu \approx 1.5$) works - no need for huge EUV bump (BBB)

• Dust within the clouds can suppress resonance lines (esp. Ly$\alpha$)
Ex) STIS Long-Slit Spectra of the NLR in NGC 4151
### Model Results from Two Regions

<table>
<thead>
<tr>
<th>Spectral Bin</th>
<th>Log U</th>
<th>$n_e$ (cm$^{-3}$)</th>
<th>$N_H$ (cm$^{-3}$)</th>
<th>% H$\beta$</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1-0.3 NE</td>
<td>-2.67</td>
<td>1.2 E4</td>
<td>1.6 E21</td>
<td>50%</td>
<td>RB</td>
</tr>
<tr>
<td></td>
<td>-3.0</td>
<td>1.0 E7</td>
<td>5.6 E19</td>
<td>25%</td>
<td>MB</td>
</tr>
<tr>
<td></td>
<td>-1.08</td>
<td>1.0 E5</td>
<td>5.6 E20</td>
<td>25%</td>
<td>MB</td>
</tr>
<tr>
<td>0.3-0.5 NE</td>
<td>-2.67</td>
<td>1.2 E4</td>
<td>1.6 E21</td>
<td>90%</td>
<td>RB</td>
</tr>
<tr>
<td></td>
<td>-1.36</td>
<td>6.0 E2</td>
<td>5.3 E20</td>
<td>10%</td>
<td>MB</td>
</tr>
</tbody>
</table>

**MB** – matter bounded (optically thin)
**RB** – radiation bounded (optically thick)
Comparison of Models and Observations

Model Ratio/Dereddened Ratio

Line ID

0.3'' – 0.5'' NE

0.1'' – 0.3'' NE
Physical Diagnostics of the BLR

- No forbidden lines, some semi-forbidden lines:
  - No broad [O III] $\lambda\lambda 4959, 5007 \rightarrow n_H \geq 10^8$ cm$^{-3}$
  - Broad C III] $\lambda 1909: \rightarrow n_H \leq 10^{11}$ cm$^{-3}$

- Cooling is primarily done by recombination lines (H and He) and collisional excitation of permitted lines (e.g., C IV, N V in UV; Fe II in UV and optical)
- X-ray ionization (also important in NLR)
  - ejected outer shell (suprathermal) electrons causes $\sim$6 collisional ionizations
  - Auger effect: X-ray photon can eject multiple electrons

Ex) $O^{+2}(1s^2 2s^2 2p^2 \, 3P) + h\nu \rightarrow O^{+3}(1s \, 2s^2 2p^2 \, 2P) + e^-$
- leaves $O^{+3}$ in excited state

  $O^{+3}(1s \, 2s^2 2p^2 \, 2P) \rightarrow O^{+4}(1s^2 2s^2 \, 1S) + e^-$ (autoionization)

- Fe II, Mg II, C I, and O I are enhanced in the PIZ $\rightarrow N_H = 10^{22} - 10^{23}$ cm$^{-2}$
- BLR is not resolved: $U = 10^{-2}$ to $10^{-1}$ from photoionization models
- Dust cannot survive in the BLR. Seyferts have “normal” abundances
The “Lα/Hβ” Problem

- Baldwin (1977) discovered the “Lα/Hβ” problem by piecing together spectra of QSOs at different redshifts
  - Lα/Hβ ≈ 5 – 10 for the BLR, whereas recombination gives ~33
  - What’s going on?

- BLR clouds have large column and number densities.
- Lα scatters throughout the PIZ in BLR clouds, populating the n = 2 level
- Hβ (and Hα) are collisionally excited in the PIZ, and therefore enhanced by factors of 3 – 6 over recombination values
- Lα is further reduced by ionization of electrons in n = 2 level
- Currently, there is still an “Fe II” problem: models underpredict the amount of Fe II emission
  - huge number of levels, so radiative transfer (radiative pumping, resonance fluorescence, and transition coincidences) and collisional excitations are complicated
Fe II Partial Grotrian Diagram
BLR “Cloud” Photoionization Model

(Osterbrock & Ferland, p. 364)
BLR Line Ratios

<table>
<thead>
<tr>
<th>Ion</th>
<th>( \lambda ) (Å)</th>
<th>Observed(^a)</th>
<th>( U = 10^{-1.5} )</th>
<th>Multi-component Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>O VI</td>
<td>1034</td>
<td>0.1–0.3</td>
<td>0.019</td>
<td>0.16</td>
</tr>
<tr>
<td>( \text{L} \alpha )</td>
<td>1216</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>N V</td>
<td>1240</td>
<td>0.1–0.3</td>
<td>0.039</td>
<td>0.04</td>
</tr>
<tr>
<td>Si IV + O IV</td>
<td>( \sim 1400 )</td>
<td>0.08–0.24</td>
<td>0.091</td>
<td>0.06</td>
</tr>
<tr>
<td>C IV</td>
<td>1549</td>
<td>0.4–0.6</td>
<td>0.77</td>
<td>0.57</td>
</tr>
<tr>
<td>He II + O III</td>
<td>1666</td>
<td>0.09–0.2</td>
<td>0.13</td>
<td>0.14</td>
</tr>
<tr>
<td>C III + Si III</td>
<td>1909</td>
<td>0.15–0.3</td>
<td>0.077</td>
<td>0.12</td>
</tr>
<tr>
<td>Mg II</td>
<td>2798</td>
<td>0.15–0.3</td>
<td>0.16</td>
<td>0.34</td>
</tr>
<tr>
<td>H( \beta )</td>
<td>4861</td>
<td>0.07–0.2</td>
<td>0.045</td>
<td>0.09</td>
</tr>
</tbody>
</table>

\(^a\) The observed intensities from a sample of intermediate (\( z \approx 2 \)) redshift quasars.

(Osterbrock & Ferland, p. 365)

- note: no prediction of Fe II emission … hmmm
BLR Parameters from Photoionization Models

- Sizes: typically ~10 light days (in diameter) for Seyfert 1s
  1) Reverberation mapping – use time lag (τ) of emission lines with respect to continuum variations: r = cτ
  2) Photoionization models: Determine ionization parameter and density from models. Determine $Q_{\text{ion}}$ from luminosity and SED.

$$U = \frac{Q_{\text{ion}}}{4\pi r^2 c n_e} \rightarrow \text{solve for } r. \quad \text{To 1st order, } r \propto \sqrt{L}$$

- Mass of ionized gas in BLR:

$$L(\text{Hβ}) = n_e n_p \alpha_{\text{Hβ}}^{\text{eff}} h \nu_{\text{Hβ}} V \varepsilon \quad \text{where } \varepsilon = \text{filling factor}$$

$$M_{\text{BLR}} \approx V \varepsilon n_p m_p = \frac{L(\text{Hβ}) m_p}{n_e \alpha_{\text{Hβ}}^{\text{eff}} h \nu_{\text{Hβ}}} \approx 0.7 \text{ } L_{42}(\text{Hβ}) \frac{10^{10} \text{ cm}^{-3}}{n_e} M_{\odot}$$

- Filling factor $\varepsilon$: assume a spherical BLR ($V = \frac{4}{3} \pi r^3$)

From above: $\varepsilon = \frac{L(\text{Hβ})}{n_e n_p \alpha_{\text{Hβ}}^{\text{eff}} h \nu_{\text{Hβ}} V} \approx 0.01 - 0.1$
• Covering factor – fraction of sky covered by BLR clouds
  - assume all ionizing photons are absorbed and use predicted equivalent width of emission line \( W(H\beta) \)

\[
L_{H\beta} = h\nu_{H\beta} \frac{\alpha_{\text{eff}}^{H\beta}(H^0, T)}{\alpha_B(H^0, T)} \int_{\nu_0}^{\infty} \frac{L_{\nu}}{h\nu} \, d\nu
\]

\[
L_{H\beta} = L_\lambda(\lambda 4861)W_\lambda(H\beta) = L_\nu(\lambda 4861) \frac{d\nu}{d\lambda} W_\lambda(H\beta)
\]

Assume power-law continuum: \( L_\nu = Cv^{-n} \)

Then \( W_\lambda(H\beta) = \frac{\lambda_{H\beta} \alpha_{\text{eff}}^{H\beta}(H^0, T)}{n \alpha_B(H^0, T)} \left( \frac{\nu_0}{v_{H\beta}} \right)^{-n} = \frac{568}{n} (5.33)^{-n} \)

( for a covering factor of 1)

So for \( n = 1 \), the predicted EW is \( W_\lambda(H\beta) \approx 106 \) Ang.

The covering factor is: \( C_f = \frac{W_{\text{obs}}(H\beta)}{W_p(H\beta)} = \frac{20}{106} \approx 0.2 \)
LINERs

- \([\text{O III}]/H\beta < 3\) (like galaxies with H II nuclei)
- \([\text{O I}]/H\alpha > 0.05\) (like the NLR in Seyferts)
- Original suggestion: shock heating or hot stars
- However, subsequent evidence indicates photoionization by AGN continuum (including X-rays) is likely for most
- \(U = 10^{-3}\) to \(10^{-5}\) for LINERs (rather than \(10^{-1}\) to \(10^{-2}\) for Seyferts)
- Probably due to low luminosity of continuum source, rather than higher density or greater distance

\[
U = \frac{Q_{\text{ion}}}{4\pi r^2 cn_e}
\]

- Further evidence for AGN: \(\sim20\%\) of LINERs show a mini BLR (type 1 LINERs)
- Transition objects: may be combination of starburst and AGN
Emission-Line Diagnostics (BPT Diagram)

- x - H II galaxy
- ■ - Seyfert NLR
- ○ - “pure” LINER
- ○ - transition object (H II + LINER)

(Ho, Filippenko, & Sargent, 1997, ApJS 112, 315)
High Energy Processes/ X-ray Spectra of AGN

- X-ray spectra of AGN show evidence for hot photoionized gas (T = 30,000 - 100,000 K; U = 1 - 10)
- Heating:
  - Photoionization of inner and outer shell electrons
  - Collisional ionization from ejected outer-shell (suprathermal) electrons
- Cooling:
  - Recombination lines: dominant in X-ray spectra (transitions to inner shells: n = 1,2,3 corresponding to K, L, M)
  - Fluorescence after ejection of inner-shell electrons: competes with Auger effect
  - Radiative recombination continuum (RRC), e.g., Lyman continuum (LC): narrow, since kT << I.P.
  - Two-photon: significant, since critical density for 2s in H-like heavy elements is > 10^{14} \text{ cm}^{-3}.
  - Photoexcitation important due to many lines in spectra.
  - Collisional excitation: not so important in X-ray spectra: kT << \chi
If seen in absorption, we can see the effects of absorption edges and scattering on the ionizing continuum: $\tau_\nu = a_\nu N_{ion}$

The gas starts to become “Compton thick” at $N_e \sim 1/a_\nu \sim 10^{24} \text{ cm}^{-2}$
Chandra images reveal extended X-ray gas in the NLR of NGC 1068
Chandra spectra reveal emission lines - mostly H and He-like.
Observed lines can be matched by photoionization models with $U \approx 1 - 10$
He-like Triplet Lines (rif): O VII

(Morales 2002)

- Triplet lines are sensitive to density, since the intercombination and forbidden lines can be collisionally de-excited.
- Unfortunately, the critical densities are rather high: $n_e \approx 10^{10} \text{ cm}^{-3}$, so not much help for the NLR (useful for higher density gas).
High-Energy Processes - Inner Shell Ionization

- Inner shell ionization - vacancy filled by ejection of electrons (Auger effect) and/or fluorescent emission
- Yield = probability of filling K-shell vacancy by emission of K$\alpha$ line.
- Fe ($Z = 26$) is abundant and has a high yield: Fe K$\alpha$ is strong in hard X-ray region.

(Osterbrock & Ferland, p. 280)
• Energy of Fe Kα increases with ionization state, as there is less “screening” of nucleus by outer electrons with non-zero wave functions close in.
• With high-resolution spectroscopy, one can determine ionization state of gas from Fe peak (Fe XVIII and lower often known as “cold iron” by X-ray astronomers).

(Osterbrock & Ferland, p. 282)
Fe Kα Emission from MCG-6-30-15

- Relativistic disk fit to Fe Kα profile, velocity up to $\sim 0.4c$
- Rest-frame line center at 6.4 keV - consistent with emission from cold accretion disk.
- Peak slightly blueshifted due to Doppler boosting of approaching gas.
- Long red tail due to GR: can measure BH mass and spin.

(Osterbrock & Ferland, p. 349)