A Review of Photoionization Models for The Broad Line Region of QSOs

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Quasar Broad Lines

Why Study Quasar Broad Lines?

- Strong optical and UV emission lines
- Reflect the quasar central engine, its evolution, its environment.
  - Eigenvector 1
  - Spectral Energy Distribution
  - Probe of chemical evolution
Outline

1. Introduction

2. Early photoionization models => standard model
   - Radial stratification - reverberation mapping
   - Ionization stratification - HIL & LIL

3. More Recent Advances
   - Optically Thin Gas
   - Spectral Energy Distribution
   - Locally Optimally Emitting Cloud Model
   - Metallicity
   - Turbulence

4. Summary

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AGN Emission Lines

- Observed primarily in the optical and UV
- Doppler broadened by motion in the gravitational field of the black hole
- Powered by photoionization
- A broad range of widths and ionizations are observed
Photons with energy greater than 13.6 eV will ionize hydrogen.

Photons ionize atoms according to their ionization potential.

Ions recombine with rates dependent on density.

Result depends on ionization parameter: \( U = \frac{\phi}{n_H c} \)

(Hamann et al. 2002)
Thermal Equilibrium

- Photoelectrons heat the gas
- Cooling by radiative recombination => H, He
- Cooling by collisional excitation of e.g., C$^+3$

(Hamann et al. 2002)
AGN Emission Lines

- Under normal circumstances, recombination lines Lyalpha and CIV (and other lines from lithium-like ions) are expected to be strong.

![Normalized Intensity vs Wavelength for AGN Emission Lines]

- Lyα
- CIV

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Broad Line Region
Cloudy

- Created/maintained by Gary Ferland.
- Input continuum properties: ionizing photon flux, spectral energy distribution.
- Input gas properties: density, thickness.
- Output: predicted emission-line fluxes.
- Compare with observed emission-line fluxes.
Introduction

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Summary
Early photoionization models based on models applied to nebulae in our Galaxy

Poor signal-to-noise ratios and poor resolution hampered early models.

Important developments:

- separation of NLR and BLR
- discovery of the partially-ionized zone which required multi-level hydrogen atoms
- Able to explain low Ly$\alpha$/H$\beta$ due to large optical depth
The Standard Model

- One zone - consistency of line profile
- Ionization parameter $-2.8 \leq \log(U) \leq -1.5$ from CIV, CIII] and Ly[\alpha]
- Densities were constrained to be less than $10^{10}$ cm$^{-3}$
- Shape of the ionizing continuum based on extrapolation of observed continuum, and HeII.
- The covering fraction 10% based on observed eqw of Ly[\alpha]
- The column density $10^{23}$ cm$^{-2}$ based on truncating CIII]/Ly[\alpha]
Reverberation Mapping

- First large IUE and ground-based results mid 1980s (e.g. Peterson 1988)
- Short time lags for high-ionization lines $\Rightarrow$ 10x smaller radius
- Emission lines could see fainter continuum than direct observer, for example a flattened distribution
- Or $U$ is unchanged requiring a much higher density $\propto 10^{11} \text{cm}^{-3}$
Reverberation Mapping

- What was the effect on photoionization models of the BLR?
  - Density too high for CIII]
- Rees, Netzer & Ferland 1989: emission of high density clouds
  - Rule out high density don’t see (free-free, Balmer, Paschen)
- Ferland et al. 1992: stratification
  - Highest densities only required for high ionization lines
In 1980’s, S. Collin & collaborators pointed out that simultaneously producing high- and low-ionization lines in the same cloud is difficult.

- Low-ionization lines require high covering fractions
- Must be out of our line of sight
- \( \Rightarrow \) Low-ionization lines produced in accretion disk
- In addition, other sources of heat may increase low-ionization line flux
- CII] mainly emitted in partially ionized zone
- High columns are therefore not ruled out
Observational Support

Casebeer, Leighly & Baron (2006)
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Optically Thin Gas

- Is the high-ionization line-emitting gas optically thin to the Lyman continuum?
- Saturation of CIV at high continuum luminosities (Wamsteker & Colina 1986)
Optically Thin Gas

profile studies show low-ionization lines are narrow and symmetric. (Leighly & Moore 2004; Ferland et al. 1996)
Optically Thin Gas

- Investigated in detail by Shields et al. 1995
- Can explain saturation behavior of CIV
- May also explain UV absorption lines
- May also explain X-ray warm absorber
line ratios can be very sensitive to optically thin gas.
Spectral Energy Distribution

- FeII
- CII
- CIII
- CIV
- HeII
- NV
- OVI

kT=290eV

kT=10eV

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Broad Line Region
EUV Bump

- Emission lines should be able to determine shape of EUV
- Krolik and Kallman (1988) did this with 3 SED
- Korista et al. investigated effect of no BBB
- Zheng et al. (1997) produced HST composite spectrum
- They found a turnover towards shorter wavelength
- Laor et al. (1997) found soft excess pointed towards UV
Krolik & Kallman 1988 -
Korista et al. 1996 - Hell emission

(Laor et al. 1997)
RE 1034+39 is a low-luminosity NLS1 known for its hard (X-ray dominant SED)

Coordinated FUSE, EUVE and ASCA observations.

(Casebeer, Leighly & Baron 2006)
Strong high-ionization line emission (e.g., OVI)
Narrow and symmetric lines - no wind.
Weak low-ionization line emission

(Casebeer, Leighly & Baron 2006)
All the lines are narrow and symmetric - no wind is present.

(Casebeer, Leighly & Baron 2006)
Cloudy Models

(Casebeer, Leighly & Baron 2006)

- Cloudy modeling shows that emission-line strengths and ratios are best produced by hard SED.
PHL 1811

- Optically the second brightest quasar beyond $z = 0.1 (m_B = 14.4, z = 0.192)$.
- Undetected in ROSAT All Sky Survey
- Coordinated HST & Chandra observations
- Anomalously X-ray weak in 7 observations between 1990 and 2004

(Leighly et al. submitted)
PHL 1811 vs Francis Composite

Leighly et al. 2006 submitted
Objects with blue-shifted high-ionization lines have strong low-ionization lines (e.g., SiII, FeII).

Implies emission very far from the black hole, unless....

(Leighly 2004)
Wind-Filtered Continua

Filtering continuum through the wind softens it, leading to strong low-ionization lines.

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(Leighly 2004)
LOC model: Motivation

- Emission lines in the same object may have different profiles
- Emission lines response to changes in continuum luminosity have different time lags
Background of Locally Optimally Emitting Cloud Models

- First introduced by Baldwin (1995)
Different Radial Distributions

- $R^0$
- $R^{-1}$
- $R^{-2}$

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Broad Line Region

### TABLE 1

**Observed and Predicted Line Intensities**

<table>
<thead>
<tr>
<th>Emission Line (1)</th>
<th>Observed Intensity$^a$ (2)</th>
<th>Maximum Reprocessing (3)</th>
<th>LOC Integration$^b$ (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O VI $\lambda 1034 + Ly\beta \lambda 1026$</td>
<td>0.1–0.3</td>
<td>0.28</td>
<td>0.16</td>
</tr>
<tr>
<td>Ly$\alpha \lambda 1216$</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>N V $\lambda 1240$</td>
<td>0.1–0.3</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td>Si IV $\lambda 1397 + O IV \lambda 1402$</td>
<td>0.08–0.24</td>
<td>0.08</td>
<td>0.06</td>
</tr>
<tr>
<td>C IV $\lambda 1549$</td>
<td>0.4–0.6</td>
<td>0.54</td>
<td>0.57</td>
</tr>
<tr>
<td>He II $\lambda 1640 + O III \lambda 1666$</td>
<td>0.09–0.2</td>
<td>0.11</td>
<td>0.14</td>
</tr>
<tr>
<td>C III]+Si III]+Al III $\lambda 1900$</td>
<td>0.15–0.3</td>
<td>0.28</td>
<td>0.12</td>
</tr>
<tr>
<td>Mg II $\lambda 2798$</td>
<td>0.15–0.3</td>
<td>0.38</td>
<td>0.34</td>
</tr>
<tr>
<td>H$\beta \lambda 4861$</td>
<td>0.07–0.2</td>
<td>0.08</td>
<td>0.09</td>
</tr>
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(Baldwin et al. 1995)

$^a$Intensity relative to Ly$\alpha \lambda 1216$, combining data from Baldwin, Wampler, & Gaskell (1989), Boyle (1990), Cristiani & Vio (1990), Francis et al. (1991), Laor et al. 1995, Netzer et al. (1995), and Weymann et al. (1991).

$^b$Co-addition of emission from clouds as described in the text.
RE1034 and PHL1811

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<td>O VI $\lambda 1034 + \text{Ly} \beta \lambda 1026$</td>
<td>0.16</td>
<td>0.52</td>
<td>0.51</td>
<td>a</td>
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<tr>
<td>Ly$\alpha$ $\lambda 1216$</td>
<td>1.00</td>
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<tr>
<td>N V $\lambda 1240$</td>
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<td>1.4</td>
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a not measured in PHL1811
# RE1034 and PHL1811

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<td><strong>O VI λ1034+Lyβλ1026</strong></td>
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Metallicity in Quasars

- Quasars can be seen a long distance; their emission lines are amenable to chemical evolution studies.
- Nitrogen is a sensitive probe of metallicity:
  \[ \frac{N}{H} \propto \left( \frac{O}{H} \right)^2 \propto \left( \frac{Z}{Z_{\odot}} \right)^2 \]
- \( \text{FeII}/MgII \) may be a probe of the onset of the first star formation in the universe.
Hamann et al. (2002)

Best line ratios are close together in ionization potential and excitation potential, and critical density

Should not be important coolants

\[ \text{best is } [\text{NIII}] / [\text{OIII}] \]

Quasar metallicity solar or higher
Fell/MgII

- Fell/MgII doesn’t change appreciably to z=6 (Dietrich et al. 2003)
- But Fell is an important coolant
- Evidence that Fell has multiple excitation mechanisms

(Leighly & Moore 2006)
The abundances will change the cooling and structure in the gas (Ferland et al. 1996; Snedden & Gaskell 1999; Leighly 2004).

(Ferland et al. 1996)
Leighly (2004) found this cooling allowed her to explain weak CIV

- Major coolents hardly change, minor coolents OIV] increase
Microturbulence

- Microturbulence may be present and may be responsible for smooth line profiles
- Can strongly affect line fluxes and ratios
Microturbulence

- Lines escape more easily due to reduced opacity.
- FUV lines predominantly excited by continuum pumping strongly affected.
- Semiforbidden lines influenced the least.
- More effective on lines that are not important coolants.

(Bottorff et al. 2000)
Summary

- Cloudy is the current state of the art
- In some cases BLR clouds are optically thin
- The spectral energy distribution is important
- LOC models can replicate some observations
- More may need to be done for metallicity at high Z
- Turbulence may be important for the BLR