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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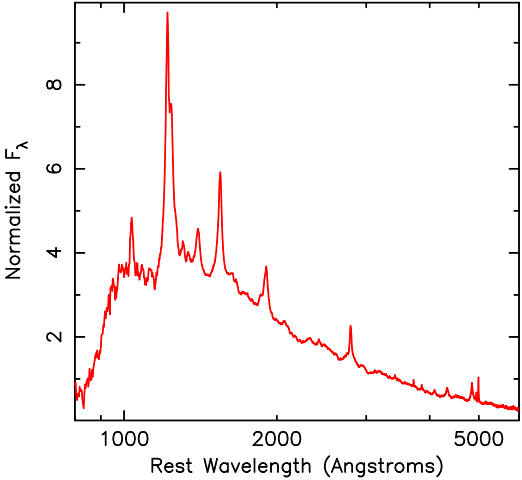
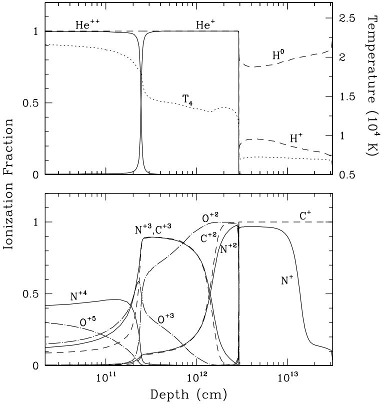
AGN Emission Lines

- 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



Photoionization Equilibrium

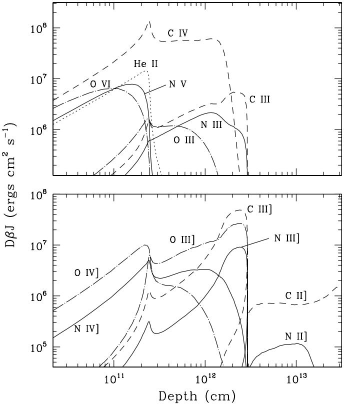
- Photons with energy greater than 13.6 eV will ionize hydrogen
- Photons ionize atoms according to their ionization potential
- Ions recombine with rates dependent on density
- Result depends on ionization parameter: U$= \phi/n_H c$



(Hamann et al. 2002)

Thermal Equilibrium

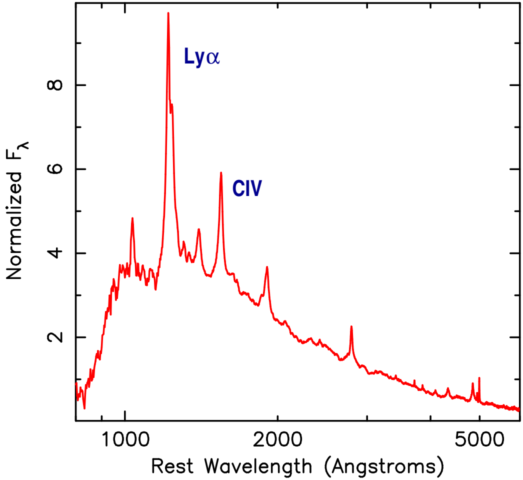
- Photoelectrons heat the gas
- Cooling by radiative recombination => H, He
- Cooling by collisional excitation of e.g., $C^{+}3$



(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.



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.

Outline

Early Photoionization Models

- 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 Lyα/Hβ 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 Lyα
- Densities were constrained to be less than $10^{10}\ \mathrm{cm}^{-3}$
- Shape of the ionizing continuum based on extrapolation of observed continuum, and HeII.
- The covering fraction 10% based on observed eqw of Lyα
- The column density $10^{23}\ \mathrm{cm}^{-2}$ based on truncating CII]/Lyα

Reverberation Mapping

- First large IUE and ground-based results mid 1980s (e.g. Peterson 1988)
- Short time lags for high-ionization lines ==> 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 $\propto 10^{11} cm^{-3}$

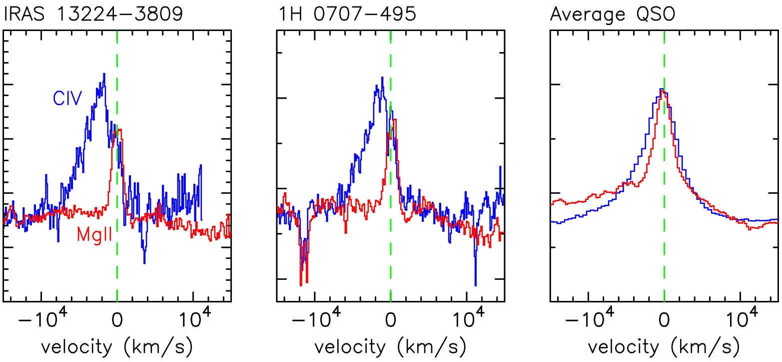
Reverberation Mapping

- 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

HIL and LIL

- 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
- ==> 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

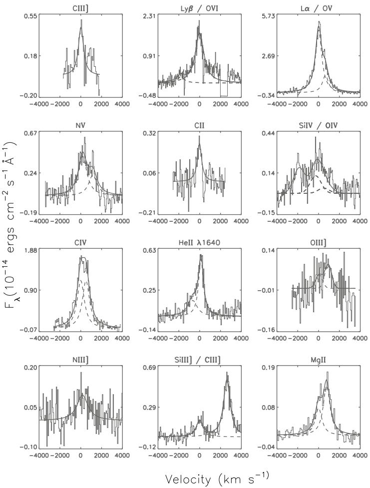
Observational Support



- Leighly & Moore (2004); also Gaskell 1982, Wilkes 1984, Marziani et al. 1996, Richards et al. 2002

Not Always true

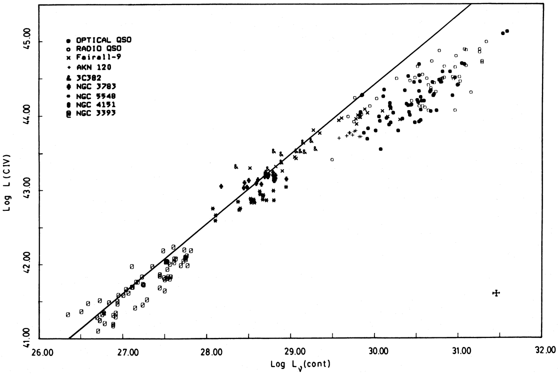
- Casebeer, Leighly & Baron (2006)



Outline

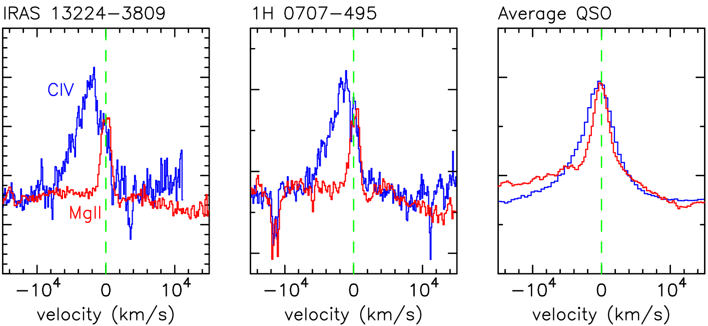
Optically Thin Gas

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



(Wamsteker & Colina 1986)

Optically Thin Gas



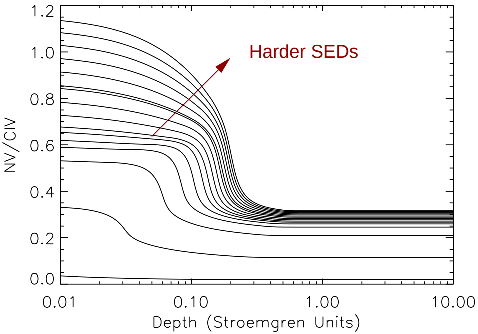
(Leighly & Moore 2004)

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

Optically Thin Gas

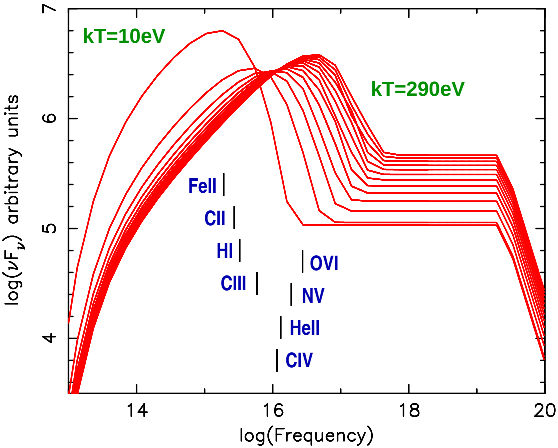
- Investigated in detail by Shields et al. 1995
- Can explain saturation behavior of CIV
- May also explain UV absorption lines
- May also explain X-ray warm absorber

Optically Thin Gas



- line ratios can be very sensitive to optically thin gas.

Spectral Energy Distribution

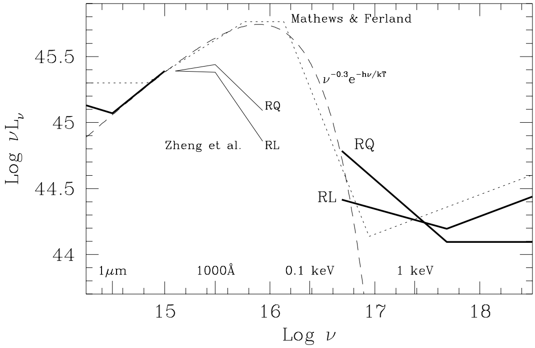


EUV Bump

- 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

EUV Bump

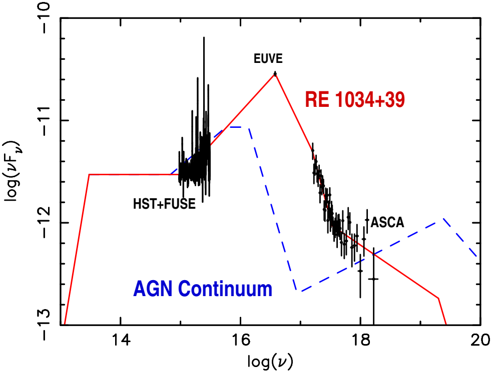
- Krolik & Kallman 1988 -
- Korista et al. 1996 - HeII emission



(Laor et al. 1997)

Emission Lines in RE 1034+39

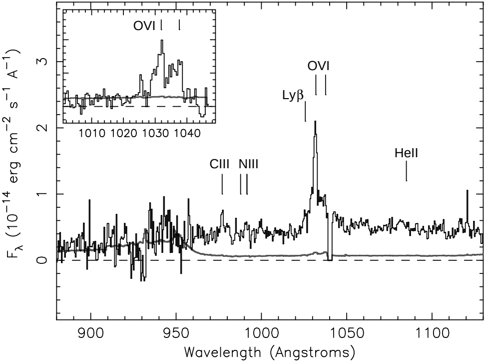
- RE 1034+39 is a low-luminosity NLS1 known for its hard (X-ray dominant SED)
- Coordinated FUSE, EUVE and ASCA observations.



(Casebeer, Leighly & Baron 2006)

FUSE Spectra

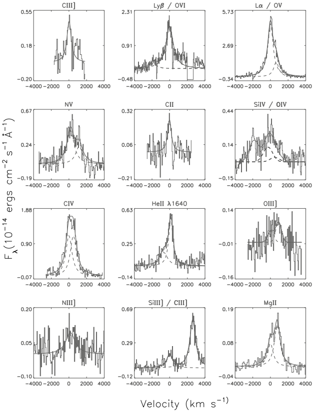
- Strong high-ionization line emission (e.g., OVI)
- Narrow and symmetric lines - no wind.
- Weak low-ionization line emission



(Casebeer, Leighly & Baron 2006)

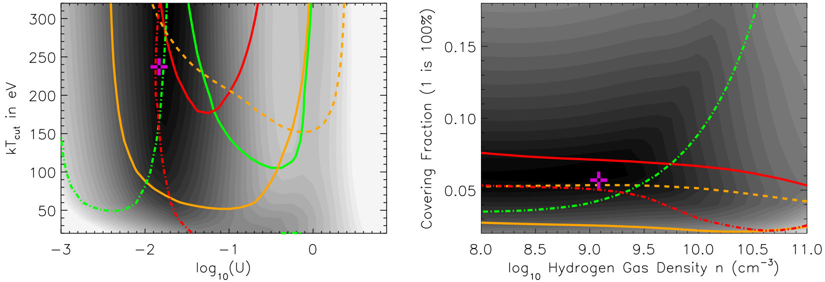
Narrow, Symmetric Emission Lines

- All the lines are narrow and symmetric - no wind is present.



(Casebeer, Leighly & Baron 2006)

Cloudy Models

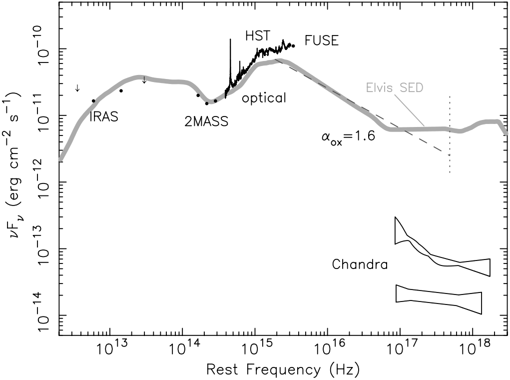


(Casebeer, Leighly & Baron 2006)

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

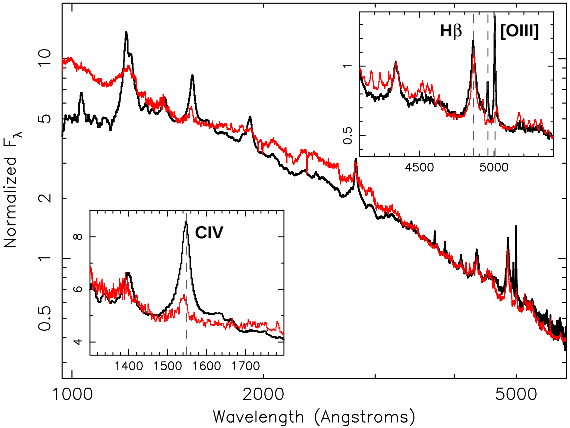
PHL 1811

- 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)

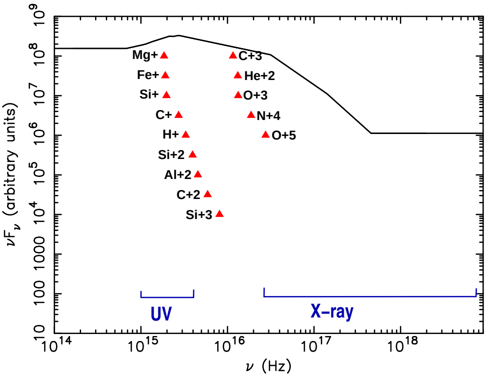
PHL 1811 vs Francis Composite



(Leighly et al. 2006 submitted)

Wind-Filtered Continua

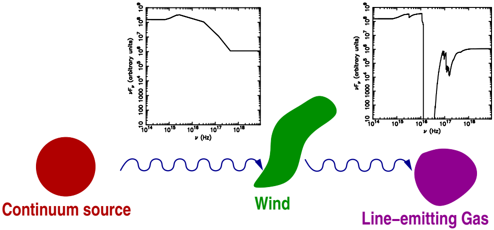
- Objects with blue-shifted high-ionization lines have strong low-ionization lines (e.g., SiII, FeII).
- Implies emission very far from the black hole, unless....



(Leighly 2004)

Wind-Filtered Continua

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



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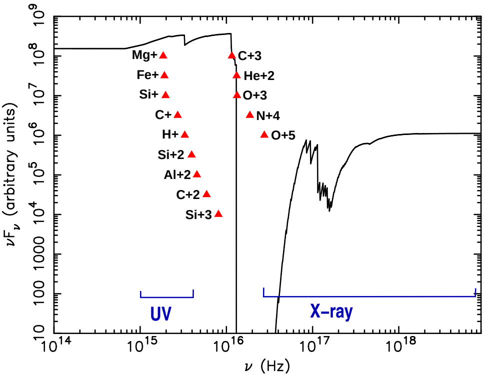


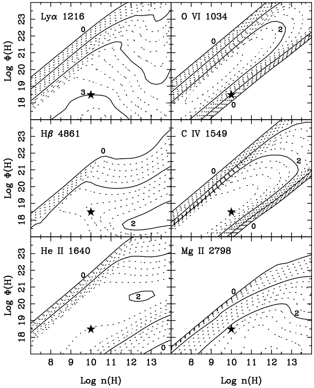
(Leighly 2004)

LOC model: Motivation

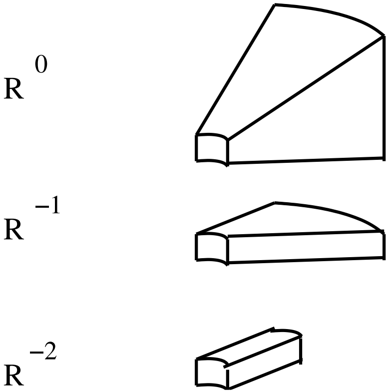
- Emission lines in the same object may have different profiles
- Emission lines response to changes in continuum luminosity have different time lags

Background of Locally Optimally Emitting Cloud Models

- First introduced by Baldwin (1995)



Different Radial Distributions



Locally Optimally Emitting Cloud Models Baldwin (1995)

TABLE 1

OBSERVED AND PREDICTED LINE INTENSITIES

Emission Line (1)	Observed Intensity[a] (2)	Maximum Reprocessing (3)	LOC Integration[b] (4)
O VI λ1034+Ly$\beta\lambda$1026	0.1–0.3	0.28	0.16
Lyα λ1216	1.00	1.00	1.00
N V λ1240	0.1–0.3	0.06	0.04
Si IV λ1397+O IV] λ1402	0.08–0.24	0.08	0.06
C IV λ1549	0.4–0.6	0.54	0.57
He II λ1640 + O III] λ1666	0.09–0.2	0.11	0.14
C III]+Si III]+Al III λ1900	0.15–0.3	0.28	0.12
Mg II λ2798	0.15–0.3	0.38	0.34
Hβ λ4861	0.07–0.2	0.08	0.09

(Baldwin et al. 1995)

[a] Intensity relative to Lyα λ1216, 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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OBSERVED AND PREDICTED LINE INTENSITIES

Emission Line (1)	LOC Integration (2)	RE1034 LOC (3)	RE1034 measured (4)	PHL1811 measured (5)
O VI λ1034+Lyβ λ1026	0.16	0.52	0.51	*a*
Lyα λ1216	1.00	1.00	1.00	1.00
N V λ1240	0.04	0.18	0.18	1.4
C IV λ1549	0.57	1.11	0.54	0.77
He II λ1640 + O III] λ1666	0.14	0.25	0.11	0.12
Mg II λ2798	0.34	0.47	0.11	0.18

[a] not measured in PHL1811

RE1034 and PHL1811

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Metallicity in Quasars

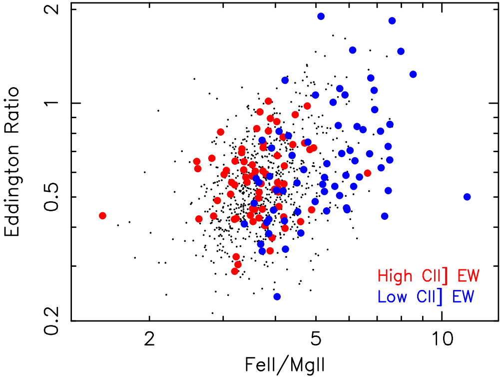
- Quasars can be seen a long distance; their emission lines are amenable to chemical evolution studies
- Nitrogen is a sensitive probe of metallicity $[N/H] \propto [O/H]^2 \propto [Z/Z_{\odot}]^2$
- $FeII/MgII$ may be a probe of the onset of the first star formation in the universe.

Metallicity Studies

- Hamann et al. (2002)
- Best line ratios are close together in ionization potential and excitation potential, and critical density
- Should not be important coolants
- $==>$ best is $[NIII]/[OIII]$
- Quasar metallicity   solar or higher

FeII/MgII

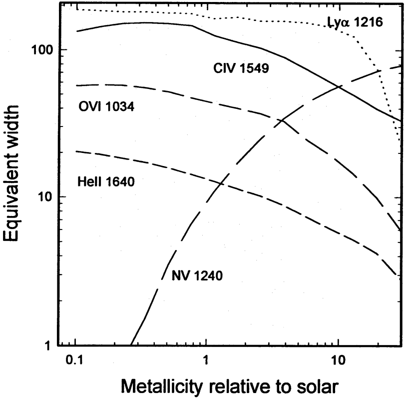
- FeII/MgII doesn't change appreciably to z=6 (Dietrich et al. 2003)
- But FeII is an important coolant
- Evidence that FeII has multiple excitation mechanisms



(Leighly & Moore 2006)

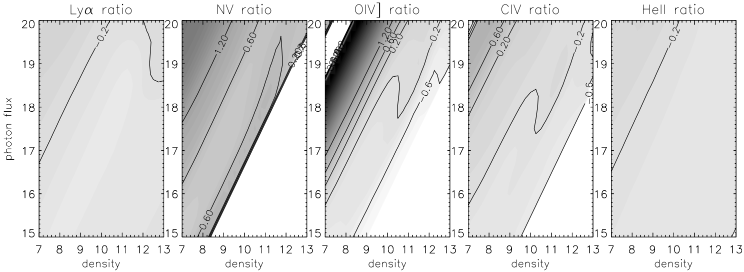
Metallicity and Cooling

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



(Ferland et al. 1996)

Metallicity and Cooling



(Leighly 2004)

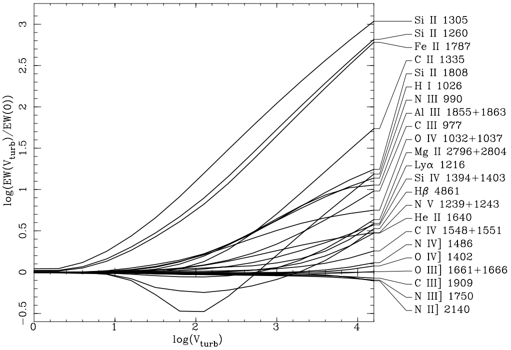
- Leighly (2004) found this cooling allowed her to explain weak CIV
- Major coolents hardly change, minor coolents OIV] increase

Microturbulance

- 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)

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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