The Broad Emission Line Regions of Quasars: Current Status and Future Prospects

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**Abstract.** The spectrum emitted by the Broad Emission Line Regions of Active Galactic Nuclei can measure the luminosity of the central object and the chemical composition of the interstellar medium in a very young galaxy, and so constrain the expansion of the universe and the first stages of the evolution of massive galaxies. Here I review some recent developments in our understanding of the nature of the clouds and the interpretation of their spectra.

1. **Introduction**

The high redshift Active Galactic Nuclei (AGN) allow us to study the spectrum of some of the earliest massive structures that formed. The emission lines formed in the Broad Emission Line Region (BELR) tell us of the matter that is most intimately associated with the innermost regions. The most fundamental questions we can ask of the BELR spectrum include the following: What is the composition of the emitting gas? What does it tell us about the evolution and age of the associated star cluster? Can the spectrum be used as to deduce the luminosity of a quasar, in turn allowing them to be used as cosmological probes? What is the physics of the energy generation, and what are the dynamics of the emitting gas? What is the mass of the central object, and nature of the accretion mechanisms?

Although there are many questions, two things we know for sure are that the emitting clouds are photoionized (line-continuum reverberation measurements show this; see the review by Peterson 1993), and that the SDSS will produce the most complete database of AGN spectra ever obtained. How can photoionization theory and the SDSS database be combined to gain insight into fundamental questions about AGN and the formation of the first massive structures in the redshift 5–10 universe?

Here I review what I consider to be the outstanding problems in quasar emission-line research. This focuses on the problems that I have found most interesting, and is not intended as a general review of AGN emission lines.

2. **Physics of a Photoionized Cloud**

I described the physics of a single BELR cloud in Ferland (1999, 2003a). I only review the critical points here. The emitting gas has a low density, by laboratory standards, and so is not in thermodynamic equilibrium. As a result the observed
spectrum is set by a host of microphysical processes, and large-scale numerical simulations are used to understand the message of the spectrum. The emitted spectrum is sensitive to these details, which is a complication, but is also why the lines reveal so much about the conditions within the gas.

Large-scale plasma simulations of the BELR were one of the first applications of computers to astrophysics (Bahcall & Kozslovsky 1969; see also the excellent review by Davidson & Netzer 1979). One immediate conclusion was that the emitted spectrum was very sensitive to cloud parameters. This led to the idea that some physical process had “fine-tuned” these parameters, since the ensemble of quasars have fairly similar emission-line spectra. This inhibited emission-line research since the agent governing this unknown process was itself unknown.

One popular model was the “hot-warm” pressure equilibrium picture of Krolik, McKee, & Tarter (1981). This assumed that the emission-line clouds, assumed to be discrete structures with constant gas pressure and temperatures near $10^4$ K, were in pressure equilibrium with a surrounding hot intercloud medium, presumed to be near the Compton temperature of the continuum, $\sim 10^7$ K. Although such confinement could explain why a warm cloud with a special pressure could survive, some problems were immediately noted. Mathews & Ferland (1987) pointed out that the hot intercloud medium would be optically thick in the soft x-ray regime. Further, the two-phase stability only occurs over a very limited range of gas densities (see Figure 2 of that paper), while the theory does not explain why only this narrow range of densities would be selected by most quasars.

3. The Modern Revolution

Two observations have dramatically revised our understanding of the nature of the emission-line regions. The first was reverberation mapping, which showed that the BELR was distributed over a broad range of radii (Peterson 1993). The “single parameter” models described above had placed the clouds at a single radius that was significantly larger than observed.

The second discovery was that the BELR profiles remained smooth far out in the line wings (Arav et al. 1998). The conventional picture was that the BELR was composed of discrete “clouds”, with each cloud having only thermal motions within it, $\sim 10$ km s$^{-1}$, for H in a 10,000 K gas. The observed line widths of $\sim 10^4$ km s$^{-1}$ were due to macroturbulence, some sort of bulk (perhaps orbital) motions of clouds, since non-thermal gas motion would not occur within a particular constant gas pressure cloud. If all clouds have the same emission-line spectrum then the observed profiles reflect the number of clouds at each observed velocity interval. Observations of the extreme line wings should detect single clouds, which would be seen as single sharp components.

The first measurements by Capriotti, Foltz, & Byard (1981) were inconclusive, but Keck observations of Arav et al. (1998) show that the line wings remain very smooth well into the extreme wings, to an extent that essentially rules out discrete constant-gas-pressure clouds.
4. A Modern Picture

In the remaining discussion the word “cloud” is used with the broadest possible meaning. It could be a magnetically confined coronal loop or a section of the outflowing wind above an accretion disk.

4.1. The LOC Model

We developed the “locally optimally-emitting cloud” (LOC) model of the BELR to account for the distribution of cloud distances derived from reverberation measurements (Baldwin et al. 1995). Gas exists over a broad span of radii, and at each radius has a wide range of densities. Selection effects, largely introduced by the atomic physics, ensure that the ensemble of clouds produces the observed spectrum (see also Baldwin 1997).

The most important conclusion of the LOC picture is that the observed spectrum, being dominated by selection effects, is not determined by detailed cloud properties or parameters. It is possible to avoid questions of the cloud origins and move straight on to using the spectrum to measure fundamental quasar properties that are of broad interest. Some examples include the metallicity of the emitting gas, what that says about the nuclear evolution of the central star cluster, the shape of the energizing continuum that strikes clouds, and the total mass in clouds. The key to using the BELR to measure these properties is to first employ large-scale numerical plasma simulations to identify the line ratios that are reliable diagnostics of important quantities, despite the almost certain presence of inhomogeneities and other complexities. This approach is discussed in Ferland (2003b).

Some conclusions, not reviewed here, are that the metallicity of the gas is at or above solar, even at redshift $z > 5$, and that it correlates with luminosity (Hamann & Ferland 1999). This suggests that the luminous quasar phase occurs only after stellar evolution has proceeded long enough to increase the metallicity of the interstellar medium to high values, and says something about the time scales for formation of the deep potential well in which the quasar resides. The mass associated with these clouds is substantial. Large reservoirs of neutral or molecular gas, not emitting in the optical or UV, must exist within the BELR if the properties of the emitting clouds are to be stable – for example a hydrogen ionization front must be free to move across the cloud as the luminosity varies, so neutral gas must exist. So a star cluster with a mass of order a galactic bulge is responsible for the BELR if the gas is produced by normal stellar evolution (Baldwin et al. 2003). For luminous quasars the total mass in the BELR must be $\sim 10^4$–$10^5 M_\odot$.

4.2. A Turbulent or Windy BELR

The Arav et al. (1998) observation that line profiles do not break up into distinct components rules out most forms of the discrete cloud model. In a series of papers we investigated the possibility that distinct clouds do exist, but that they are highly turbulent. This added turbulence would make lines broader and so smear out the spectrum.

Rees (1987) had suggested that BELR clouds may be magnetically confined. Non-dissipative magnetohydrodynamic (MHD) waves are usually associated with
a magnetic field in the ISM (Myers & Goodman 1988) and could provide an
effective line broadening mechanism. In the simplest form the magnetic
energy density, $B^2/8\pi$, would equal the kinetic energy in MHD waves, $\frac{1}{2}\rho u^2$,
($\rho$ is the gas density and $u$ the turbulent velocity) and would be of order the
gravitational energy density $GM\rho/r$. This MHD turbulence would constitute
microturbulence, a velocity field that adds in quadrature with thermal velocities
in affecting line widths. In a series of papers Mark Bottorff and I investigated
the effects that such turbulence, or the fractal cloud distribution that is argued
to be an inevitable consequence of it, would have on the observed spectrum
(Bottorff & Ferland 2000, 2001, 2002). The conclusion was that the observed
spectrum is consistent with very large microturbulence velocities (Bottorff et al.
2000).

Another possibility is that the BELR is actually a wind, perhaps above an
accretion disk. Several models have been worked out, including magnetically ac-
celerated clouds (Bottorff, Korista, Shlosman, & Blandford 1997), models where
the velocity gradient focuses line escape (Chiang & Murray 1996), and the wind
models of Königl & Kartje (1994). This family of models also appears capable
of reproducing the observed spectrum.

The lesson in all this is that the physics that governs the spectrum intro-
duces the strong selection effects inherent in the LOC picture, and so it is not
too hard to reproduce the observed spectrum if clouds are present with a wide
variety of densities and separations from the central object. This is a disappoint-
ment — the spectrum is not strongly sensitive to the origin of the gas. However,
it is also a Good Thing — we can skip over these uncertainties and go straight
to more fundamental questions about the quasar.

Although the detailed nature of the clouds remains a mystery, the observa-
tions of smooth line profiles does show, conclusively, that non-thermal motions
must be present within BELR clouds. This has an important implication for
the cloud equation of state. When non-thermal motions (microturbulence) are
present the total pressure (neglecting radiation pressure) is given by the sum
of gas ($nkT$) and ram ($\frac{1}{2}\rho u^2$) pressures. If the gas motions are supersonic, as
required by the Arav et al. observations, then ram pressure dominates over gas
pressure by a large amount. This conclusion, which follows directly from observa-
tions, is important, since it rules out the entire family of two-phase equilibrium
models. We are left with either a fractal/MHD/ISM-like or windy model for the
regions.

### 4.3. The Ionizing Continuum

Mathews & Ferland (1987; MF87) derived the mean shape of the ionizing con-
tinuum of a typical quasar. We used direct observations where possible, and the
He II $\lambda1640$ recombination line to measure the unobservable continuum near
4 Ryd. This line, the $n=3$ to $n=2$ transition of He$^+$, is formed by Case B
radiative recombination even in the quasar environment. This is because res-
onance lines of He II are destroyed before they undergo very many scatterings
due to absorption by H$^0$ and other species. As a result, substantial populations
of excited levels, the effect that complicates H I lines in this environment, do
not occur. This essential simplicity was first argued by MacAlpine (1981) and
later confirmed by extensive calculations (Bottorff et al. 2002). There are 0.57
λ1640 photons produced per He$^{+2}$ recombination. Since the number of He$^{+2}$ recombinations per unit volume is equal to the number of He$^+$ ionizations, the number of 4 Ryd photons striking gas is $1/0.57 = 1.7$ times the number of λ1640 photons observed. The λ1640 line directly measures the continuum near 200Å.

The gas covering factor $\Omega/4\pi$ is the fraction of the central object’s ionizing photons that actually strikes emission-line clouds, or, equivalent, the fraction of the sky as seen by the central object that is covered by clouds. It must be significantly less than unity since BELR clouds are never seen along the line of sight to the continuum source (except possibly in BAL quasars). Then, the total luminosity of the continuum source at 4 Ryd is simply $\nu L_\nu(4\text{Ryd}) \approx 1.7L(\lambda1640) \times (\Omega/4\pi)^{-1}$. Using this argument MF87 found a continuum shape that peaked at an energy near 4 Ryd.

Zheng et al. (1997) directly measured the ionizing continuum in a sample of high redshift quasars and found it to be surprisingly softer than the MF87 continuum. The directly measured continuum shape is not energetic enough to account for the observed high-energy lines when a realistic covering factor is assumed (Korista et al. 1997). This is evocative of the case in the Seyfert 2 galaxies where we do not observe the same continuum as the emission line clouds (Antonucci 1993). So it seems likely that the ionizing continuum is beamed, and that the continuum seen by BELR clouds is harder than what we observe directly.

5. Some Mysteries, and the Future

What types of questions can a large data base like that produced by SDSS answer? Here are some ideas. But first an observation.

The idea that the BELR is emitted by distinct clouds, perhaps in pressure equilibrium with a hot phase, has been around for some time. As outlined above, this model has very serious problems, most notably its inability to account for the smoothness of the emission lines in the far wings. Arav’s article in these proceedings reaches similar conclusions from his study of broad absorption lines. Windy and turbulent models were almost exclusively discussed at this meeting. This represents a major shift in the cloud paradigm.

What might be done with a large data base such as the SDSS? The basic questions that the emission lines can answer center on the evolutionary state of the stellar and gas systems and their use as cosmological probes.

The kinematic state of the BELR is still a mystery. Gaskell (1982) and Wilkes & Carswell (1982; see also Espey et al. 1989) discovered that the low and high ionization emission lines do not have the same redshift. Corbin (1992) investigated several implications of this. The nature of this line shift is not now well understood. SDSS has already investigated aspects of this (Richards et al. 2002). Does the extent of this shift correlate with emission line relative intensities in any way? A crucial but often overlooked constraint is that Ly$\alpha$ is beamed back towards the continuum source in a photoionized cloud (Ferland & Netzer 1979). This means that we only see the far side of the BELR in this line, unlike nearly all other lines, which are radiated less anisotropically. The fact that the profiles agree to the extent that they do is surprising.
If a quasar’s luminosity could be determined from its spectrum then they could be used as cosmological probes (see the conference proceedings edited by Ferland & Baldwin 1999). The Baldwin Effect (BE; Baldwin 1977) is an inverse correlation between a line’s equivalent width (the strength of a line relative to the nearby continuum) and a quasar’s luminosity. This was discovered using the CIV $\lambda$1549 line, although many lines show the correlation. Korista, Baldwin, & Ferland (1998) present a model of the BE that is based on correlated changes between the continuum shape, the gas metallicity, and luminosity.

Although line-to-continuum correlations like the BE have been well-studied for some time, line to line correlations have been elusive. This is the opposite from what is expected from photoionization theory. The intrinsic emission-line spectrum of a single cloud is set by the continuum shape, the metallicity, and the selection effects described by the LOC. The relative intensities of a pair of emission lines should be set entirely by these three quantities. But the equivalent width of a line is affected by these three things plus the gas covering factor and whatever differences exist between the continuum we see at in the UV and the ionizing continuum seen by the clouds. So the expectation is that line-to-line correlations should be both simpler and cleaner than line to continuum correlations.

It has been very hard to identify line to line correlations. Espey & Andreadis (1999) show that the slope of the BE depends on the ionization potential of the species. The eigenvector analyses described by Todd Boroson and Bev Wills in these proceedings detects subtle changes in the spectrum. These must be, at some level, a correlation between relative emission line intensities. However, up to now these hints at underlying correlations have been bedeviled by insufficient data and selection effects.

With a complete enough data set the question could perhaps be inverted—what are the sources of scatter in the observed correlations and could corrections to this scatter be introduced? Examples of possible sources of noise include beaming of emission lines, chemical inhomogeneities across the BELR, or if clouds only exist in portions of the density—incident continuum flux plane. Understanding the scatter would be a step to making quasars valuable cosmological probes.

These mysteries can be solved by going at this with the large SDSS samples with their uniform and well-understood selection procedures. For instance, photoionization theory predicts that the spectrum is strongly affected by the shape of the ionizing continuum. Does the line spectrum show any correlation with the slope of the UV continuum, as expected by theory? Many avenues of research are possible.

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References

Antonucci, R. 1993, ARA&A, 31, 473
Arav N., Barlow, T. A., Laor, A., Sargent, W. L. W., & Blandford, R. D. 1998, MNRAS 297, 990
Bahcall, J. H., & Kozlovsky, B.-Z. 1969, ApJ, 155, 1077
Baldwin, J. A. 1977, ApJ, 214, 679
Baldwin, J. A. 1997, in Emission Lines in Active Galaxies: New Methods and Techniques, ed. B. M. Peterson, F. Cheng, & A. S. Wilson (San Francisco: ASP), 80
Baldwin, J. A., Ferland, G. J., Korista K. T., & Verner, D. 1995, ApJ, 455, L119
Baldwin, J. A., Ferland, G. J., Korista, K. T., Hamann, F., & Dietrich, M. 2003, ApJ, 582, 590
Bottorff, M. C., Baldwin, J. A., Ferland, G. J., Ferguson, J. W., & Korista, K. T. 2002, ApJ, 581, 932
Bottorff, M., & Ferland, G. J. 2000, MNRAS, 316, 103
Bottorff, M., & Ferland, G. J. 2001, ApJ, 549, 118
Bottorff, M., & Ferland, G. J. 2002, ApJ, 568, 581
Bottorff, M., Ferland, G. J., Baldwin, J., & Korista, K. 2000, ApJ, 542, 644
Bottorff, M., Korista, K. T., Shlosman, I., & Blandford, R. 1997, ApJ, 479, 200
Capriotti, E. R., Foltz, C., & Byard, P. 1981, ApJ, 245, 396
Chiang, J., & Murray, N. 1996, ApJ, 466, 704
Corbin, M. R. 1992, ApJ, 391, 577
Davidson, K., & Netzer, H. 1979, Rep. Prog. in Physics, 51, 715
Espey, B. & Andreadis, S. 1999, in Quasars and Cosmology, ed. G. Ferland & J. Baldwin (San Francisco: ASP), 351
Espey, B. R., Carswell, R. F., Bailey, J. A., Smith, M. G., & Ward, M. J. 1989, ApJ, 342, 666
Ferland, G. J. 1999a, in Quasars and Cosmology, ed. G. Ferland & J. Baldwin (San Francisco: ASP), 147 (astro-ph/0307450)
Ferland, G. J. 2003a, in Star Formation Through Time, ed. E. Pérez, R. M. González Delgado, & G. Tenorio-Tagle (San Francisco: ASP), 69
Ferland, G. J. 2003b, ARA&A, 41, 517
Ferland, G. J., & Baldwin, J. 1999, Quasars and Cosmology, ASP 162
Ferland, G. J., & Netzer, H. 1979, ApJ, 229, 274
Gaskell, C. M. 1982, ApJ, 263, 79
Hamann, F., & Ferland, G. J. 1999, ARAA, 37, 487
Königl, A., & Kartje, J. F. 1994, ApJ, 434, 446
Korista, K., Ferland, G. & Baldwin, J. 1997, ApJ, 487, 555
Korista, K., Baldwin, J., & Ferland, G. 1998, ApJ, 507, 24
Krolik, J., McKee, C. M., & Tarter, C. B. 1981, ApJ, 249, 422
MacAlpine, G. M. 1981, ApJ, 251, 465
Mathews, W. G., & Ferland, G. J. 1987, ApJ, 323, 456
Myers, P. C., & Goodman, A. A. 1988, ApJ, 329, 392
Peterson, B. M. 1993, PASP, 105, 247
Rees, M. J. 1987, MNRAS, 228, 47
Richards, G. T., et al. 2002, AJ, 124, 1
Zheng, W., Kriss, G. A., Telfer, R. C., Grimes, J. P. & Davidsen, A. F. 1997, ApJ, 475, 469
Wilkes, B. J., & Carswell, R. F. 1982, MNRAS, 201, 645