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SPECTRAL LINE STUDIES

"It is of course not unusual to conclude that all of these problems need further observational (and theoretical) investigation ..... "

- Beverley Wills (p.284)

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Suzy Collin-Souffrin

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A SURVEY OF QSO EMISSION LINES

Beverley J. Wills
McDonald Observatory and Department of Astronomy
University of Texas, RLM 15.308
Austin, Texas 78712
U.S.A.

ABSTRACT. "Standard" photoionization models of the broad line region (BLR) consist of numerous small optically thick clouds of identical ionization, density, temperature and optical depth, moving under the influence of the gravity and radiation field of a 10^{7-8} $M_\odot$ black hole and confined by a high temperature gas. Such models have provided a good description of observed line strengths and widths with only very minor modification. Although photoionization remains the most important heating mechanism in the BLR, new observations point to a wider range of physical conditions and to clues about the geometric and dynamic arrangement of the emitting gas. I want to highlight the observations that have led us to this view.

1. INTRODUCTION

I shall relate the properties of various classes of luminous QSO-like objects and present a global description of the emission line region. This is a dangerous (however convenient!) approach because there are important differences between high luminosity compact and extended radio QSOs, radio quiet QSOs and the lower luminosity active nuclei of broad line radio galaxies, Seyfert 1 and other galaxies, and it remains to be seen whether or not these differences are only of degree and can be encompassed in some "unified scheme." The volume "Astrophysics of Active Galaxies and Quasi-Stellar Objects" (Miller 1985) contains excellent reviews of the situation at the time of the 7th Santa Cruz Workshop on Astrophysics, held in July 1984. I will therefore emphasize the most recent work. In the following, AGN will refer to those lower luminosity active nuclei where the evidence for a surrounding galaxy is quite strong. QSO will refer to the higher luminosity objects, and a radio-loud QSO is a quasar.

1.1. The Standard Model

Excitation of narrow and broad lines is by photo-ionization. (For the most recent evidence for this, from the strong correlation between strengths of lines and non-thermal continuum, see de Robertis [1985] and Kinney *et al.* [1985]). Line ratios are primarily determined by the ionization parameter which is the ratio of ionizing photon density to electron density at the surface of the cloud or filament facing the central continuum radiation source. The highly ionized H^+ region produces the high ionization lines He II

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λ1640, CIV λ1549, and some Lyα. The depths of the BLR clouds, which can be very extended if X-rays and γ-radiation are strong, produce lower ionization species: Mg II λ2800, H I and Fe II lines. Most CIII] λ1909 is produced at intermediate depths. Abundances are solar or slightly higher (Gaskell *et al.* 1981, Uomoto 1983). For the history and details of the calculations see Davidson and Netzer (1979) and Netzer and Ferland (1984). Table I gives typical parameters of a "Standard Model".

TABLE I. Characteristics of the "Standard Model"

	Broad Line Region (BLR)	Narrow Line Region (NLR)
Overall dimensions	0.1 - 1 pc	> 1 Kpc
Ensemble FWHM	5000 km/s	500 km/s
Filling factor	10^{-8}	small
Covering factor	0.2	small
Individual clouds:		
Optical depth, τ(Lyc)	10^{5}	> 1
Density	$10^{9.5}$ cm^{-3}	10^{5} cm^{-3}
Ionization parameter, U	10^{-2}	$10^{-2.5}$
Temperature	10^{4} K	10^{4} K
Size	10^{12} cm	> 10^{12} cm

It has been recognized almost from the beginning that a higher ionization component is needed to explain the strengths of O VI and N V lines and that a hot (10^{8} K) intercloud gas is needed to pressure-confine the BLR clouds. Below we summarize recent observations indicating other ways in which the standard model must be modified.

2. THE NARROW LINE REGION (NLR)

- For radio galaxies, with radio structure ~ 100 Kpc, the rotation axis of the narrow line gas is aligned with the direction of the radio "jet", but in general not with the stellar rotation axis (Heckman *et al.* 1985, Simkin 1979). There are also more complex motions. Narrow band and continuum imaging and spectroscopy of steep spectrum radio galaxies and QSOs suggest an external origin for the gas, perhaps disk gas captured during mergers of galaxies (e.g., Stockton and MacKenty 1984, Heckman *et al.* 1985, Spinrad and Djorgovski 1984).
- Narrow line profiles give information about the NLR closer to the nucleus: for Seyfert galaxies asymmetry is observed in the [OIII] λ5007 line (Whittle 1985a, Heckman *et al.* 1984, Vrtilek and Carleton 1985). The line peaks are at the galaxy systemic velocity, and asymmetry increases toward the base of the line, in the sense of there being more emission to the blue of the peak. This implies radial motions together with obscuration, either (i) infall with dust at the back of the narrow line clouds (away from the ionizing source) or (ii) outflow with pervasive obscuration or a central region hiding clouds on the far side. Unlike compact quasars and radio-quiet AGN, limited data for Kpc-scale radio emitting objects do not show systematic [OIII] asymmetry (Heckman *et al.* 1984).

These observations suggest that the rotating outer NLR knows about the central engine, and that radial motions and obscuration are important in the inner NLR. How does this relate to the BLR?

- The [OIII] line widths in AGN correlate with broad Hß widths and are independent of physical conditions in NLR, and optical non-thermal luminosity (Shuder 1984, Heckman *et al.* 1984, Whittle 1985b). This suggests an indirect link between NLR and BLR kinematics, such as related special geometries with a resulting similar dependence of projected velocities on inclination to the line of sight, e.g., disk geometry (see below). The relation may hold for QSOs but the scatter is large.
- [OIII] luminosity declines markedly with increasing broad line contribution, along the sequence Seyfert 2 - Seyfert 1.8, 1.5 - Seyfert 1, almost independent of physical conditions in the NLR. This suggests that the BLR is shielding the NLR from the central continuum, and if, as is believed, the BLR covering factor is small (0.1-0.2), the covering factor for the NLR must also be small. A flattened, coplanar system for both the BLR and NLR, e.g., a disk, is then a possible configuration (Cohen 1983).
- Osterbrock and colleagues have noted that high ionization narrow lines, present in broad line AGN, e.g., [Fe X], tend to be broader and blue-shifted compared with low ionization narrow lines. More detailed studies show, for some Liners and Seyfert 1s, correlations of increasing ionization potential and/or critical density with increasing narrow line width (e.g., Filippenko, this symposium, Filippenko and Halpern 1985, de Robertis and Osterbrock 1984, Whittle 1985c). These suggest higher ionization and densities with increasing velocity probably as the central ionizing source is approached. But the NLR is more complex than that: at least in some cases there is a range of densities for a given ionization level. In one well-studied case, NGC 3712, velocities (FWHM) range from a few hundred to 2000 km/s, with a corresponding range in density from 10^2 to $10^{7.5}$ cm^{-3} - approaching the densities and velocities of the BLR.

All this suggests co-planar disk-like structures and a physically merging (but distinct) NLR and BLR.

3. THE BROAD LINE REGION

Many new observations suggest a wider range of optical depths, densities and ionization parameter in the BLR, as a function of velocity and/or distance from the ionizing continuum.

3.1. Line Strengths

- Fe II emission is much stronger than previously thought (e.g., Wills *et al.* 1985). Typically, the intensity ratio Fe II/Lyα ~ 1-2. In two extreme Fe II emitters, Fe II/Lyα >30 (Wampler 1985, 1986)! Very high densities, > 10^{11} cm^{-3}, large optical depths (10^7) and/or low U (10^{-3}) can produce strong low ionization lines. This requires a separate optically thin emission region of high U to produce the high ionization lines. The intensity ratio Fe II/Mg II λ2798 ~ 8, compared with 1.5 - 4 from models. In Wampler's two strong Fe II emitters the ratio may be 50 to 100. Mechanisms other than photoionization have been suggested (see Joly, this symposium, Collin-Souffrin, this symposium). Is iron overabundant?
- Hydrogen Lines: Balmer, Paschen and Brackett line ratios require more than reddening, and high optical depths and densities are needed (Miller 1985). Balmer

continuum and high order Balmer lines are too strong, and extreme X-ray or γ-ray fluxes may be required (Wills *et al.* 1985). The intensity ratio Lyß/Lyα suggests that Lyα may come from an optically thin region (Wilkes 1984, 1985, Green *et al.* 1980). So perhaps there is more than one kind of BLR cloud. Wills *et al.* (1985) suggest that the Balmer continuum may come from a hot accretion disk.

- Broad [OIII] is suspected in some Seyfert 1 nuclei and QSOs (van Groningen and de Bruyn 1985, Meyers and Peterson 1985, Wills *et al.* 1985). This suggests the existence of BLR densities near the [OIII] critical density of ~ 10^6 cm^{-3}. So BLR densities overlap with those of the NLR.
- A feature at 1909 Å may not be all CIII]. If confirmed this provides further evidence that in some QSOs CIII] λ1909 may have been collisionally suppressed and there could be densities of $10^{10.5}$ cm^{-3} and higher (Wampler 1986, Hartig and Baldwin 1985, see also Gaskell *et al.* 1981).

All these observations indicate a range of physical conditions in clouds giving rise to the broad lines, perhaps more than one kind of heating mechanism and even weird abundances.

3.2. Broad Line Profiles

- Quasars do not have "narrow" broad lines. The FWHM always exceeds 2000 km/s (Wills and Browne 1986).
- FWHM (Hß) is inversely correlated with R, the ratio of radio flux in the compact core to that in the extended lobes. In the relativistic beaming model, R measures inclination, so this correlation may be explained by a disk-like BLR with its axis parallel to the radio axis (Wills and Browne 1986, see also Wills and Wills, this symposium).
- High ionization lines are (statistically) blue-shifted with respect to low ionization lines, and with respect to the narrow lines, e.g., Lyα and CIV λ1549 are blue-shifted ~1000 km/s with respect to OI λ1304 and CII λ1335, and Mg II is blue-shifted by ~600 km/s with respect to the NLR (Gaskell 1982, Uomoto 1984, Wilkes 1985).

More detailed profile studies show:

- He I λ5876 and Hß are broader than Hα in Seyfert 1s (Osterbrock and Shuder 1982) suggesting that U and electron density increase with increasing velocity (inwards). But this effect is smaller in high luminosity AGN and not detected in QSOs (Shuder 1984). In QSOs Balmer lines are probably narrower than He II λ4686 (Wills *et al.* 1985). OI and CII may be narrower than CIV and Lα (Wilkes and Carswell 1982) and Mg II and Hß narrower than CIV (in Seyferts and QSOs, Mathews and Wampler 1985, Joly *et al.* 1985). That is, lower ionization lines are narrower.
- Broad Hß is quite symmetric, very similar in shape (but not width) from one object to another and also similar in shape to the narrow lines in high-ionization Seyfert 1s. So a unique acceleration mechanism (or geometry, or both) may operate in all NLR and BLR (de Robertis 1985).
- Lyα and C IV are very symmetric in most cases, and profiles are logarithmic. The symmetry of Lyα is consistent with radial motions only if the emitting region is optically thin (e.g. Wilkes 1984, Wilkes and Carswell 1982). But in the standard model asymmetry is expected; Lyα is from an optically thick region and escapes only from the side of the cloud facing the continuum source. An optically thin Lyα region may also be indicated by Lyß/Lyα ~0.006 (Wilkes 1984).

As in the case of the line strengths, the profile results suggest a range of physical conditions and in addition show that clouds of different densities, ionization parameter, optical depth etc. have different kinematic properties.

3.3 Broad Line Variability

Line variability is probably ubiquitous among Seyfert 1 nuclei, and recently more data have become available on profile variability and the response of various UV and optical lines to changes in the continuum, with some surprising results. Probably the most extreme are for the well-studied cases of NGC 4151 (Ulrich *et al.* 1984 and Antonucci and Cohen 1983) and Akn 120 (Peterson *et al.* 1985), where BLR radii of a few light days are deduced. As an example of recent trends, in Table II I reproduce results from a re-analysis of earlier data by Gaskell and Sparke (1985).

TABLE II. Results from the Variability of NGC 4151

Line	Radius of BLR (light-days) (approximate)
He II	2 - close to ionizing continuum?
CIV, Hα, Hß	6
Mg II	>12 perhaps to > 100

The smallest time scales imply high densities of 10^{10} to > 10^{12} cm^{-3}, and similar results are derived for other Seyfert 1 nuclei. For QSOs the time scales are probably longer, but the trends may be similar (Gondhalekar, this symposium) i.e., emission line regions lie closer to the continuum source and are of higher density than in the standard model. Of note is the case of 3C 446: the strength of CIII] varies in proportion to continuum strength with a lag < 30 days and CIV does not vary (Stephens and Miller 1985)! Lyα varies with the continuum with a lag less than a few months (Bregman *et al.* 1985). These results certainly cannot be explained on the standard model!

3.4 Line Polarization

Results mainly from the work of Antonucci (1984) and Rudy *et al.* (1983) show some clear trends:

- In AGN, position angles of optical continuum polarization are often perpendicular to the Kpc scale radio structure, but nearly always parallel in higher luminosity BLRGs. (Compare with the earlier results of Stockman, Angel and Miley (1979) who found that continuum linear polarization for low polarization quasars tends to be aligned with extended radio structure.)
- In at least some AGN and QSOs the polarization appears to be wavelength independent.
- The position angle of broad line polarization is the same as for the continuum (tentatively for QSOs too).

The mechanism for line polarization must be electron or dust scattering. With respect to the distant observer the regions emitting the lines and continuum see the same scattering geometry. The standard model does not account for this. The geometry of the BLR, continuum, and/or scatterers must know about the central engine. (This also resurrects the idea that electron scattering could contribute to line broadening). It will be important for models, to compare the polarization for low and high ionization broad lines, since these may arise predominantly at somewhat different distances from the ionizing continuum.

4. SUMMARY - A POSSIBLE PICTURE FOR THE EMISSION LINE REGIONS

The NLR and at least the low ionization BLR are in a flattened disk-like configuration with the axis aligned with the axis of the central engine. The evidence comes from rotation curves for the outer NLR, apparent shielding of the NLR by the BLR, correlation of broad and narrow line widths, correlation of broad line width with apparent inclination of the radio axis, and the alignment of line and continuum polarization with the radio axis. This picture is also supported by the similarity of NLR and BLR line shapes and other evidence for the merging of the NLR and BLR.

There is accumulating evidence for different clouds with a range of properties in both the NLR and BLR, which also points to a merging of the NLR and BLR. Densities in the NLR and BLR range from a few hundred to $> 10^{11}$ cm^{-3}; velocities (FWHM) from a few hundred to 10^4 km/s. Probably density, ionization and velocity increase toward the central ionizing source. But the situation is more complicated than that. Some emitting regions of high ionization in the BLR are optically thin (as also previously suggested for N V etc.), and some of low ionization in the NLR are optically thick. Higher ionization lines are broader and blue-shifted relative to low ionization lines in both the NLR and BLR, which points to a stratified emission line region (as does the existence of a distinct NLR and BLR in the standard model) with radial motions and some obscuration, even in the higher luminosity objects. Seyfert 1 line variability results lend further support to a stratified model and suggest distances of the BLR from the continuum in AGN ranging from a few light days for high ionization material to hundreds of light days for low ionization line-emitting regions, perhaps even merging into an accretion disk.

This picture is far too simple and there are so many missing pieces in the puzzle that we have had to make big assumptions about the basic similarity of different classes of object. It is of course not unusual to conclude that all of these problems need further observational (and theoretical) investigation, but I believe that a comparison of different classes of AGN and QSOs is especially important.

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DISCUSSION

Hutchings : You mentioned velocity differences between high and low ionisation lines. Is this due to asymmetry or a shift of the entire profile ?

Wills : Velocity shift is just a first order measure of profile difference, and most broad line data cannot stand more detailed analysis. The highest signal to noise data suitable for comparison of high and low ionization is that obtained by Wilkes and Carswell (1982) and Wilkes (1985), but the low ionization OI and CII lines are weak.

For narrow lines, at least [OIII], the shift does appear to be due to increasing asymmetry from the peak to the baseline, the peak being at the systemic velocity. (See also the paper by Filippenko in this proceeding).

Hutchings : Could you comment on the very asymmetrical or double-peaked broad lines that Gaskell has picked out in the past.

Wills : Gaskell has advocated the gravitational influence of binary black holes to explain some apparent double-peaked and complex line profiles (Nature, 1985, 315, 386). This fits in nicely with ideas on the formation of activity in nuclei through galaxy mergers.

Bregman : I and coworkers (Huggins, Glassgold, and Kinney) have seen $L\alpha$ line variation in 3C 446 (z=1.404) in 2 months. If the lines are symmetric about the central source, then $n \geq 10^{14}$ cm^{-3} is implied. Instead, we argue that the density is lower, which implies that the clouds are distributed anisotropically. A significant amount of ionizing gas probably lies near our line of sight and at several light years from the ionizing source.

Wills : I think this is a possible explanation but would feel uneasy about applying it if the same phenomenon were to be observed in many more QSOs. I think other more generally applicable geometries may be possible, but whatever explanation is preferred the CIV λ1549 emission is unlikely to be emitted in predominantly the same region as the CIII] 1909 or $L\alpha$.

Gondhalekar : Comment : We have studied QSOs up to $z \sim 1$ with IUE and we find variability of emission lines in most objects.
Question : In how many objects do you see symmetric and irregular $L\alpha$

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profiles ? In UV spectra we find a large incidence of irregular Lα profile.

Wills : Only the highest signal-to-nosie observations where one can subtract the influence of blended lines and possible absorption, seem to be suitable for Lα profile studies (e.g. Wilkes and Carswell 1982). Some QSOs had symmetric lines and not others, but the sample was very small.

Filippenko : It is true that many Lα profiles appear to be much more symmetrical than one would expect from a model in which optically thick clouds are moving radially. However, Kallman and Krolik have recently proposed a model in which the optical depth to electron scattering in the hot confining medium is approximately 0.1; in this case, the back sides of clouds are ionized to a fairly great extent, and the line profiles become more symmetrical. This optical depth to electron scattering is not high enough to wipe out continuum variability.

Wills : This model seems to require a fairly specific set of conditions, and I think it remains to be seen whether all this is theoretically reasonable.

De Bruyn : You mentioned the presence of broad [OIII] emission in some Seyfert 1's and said this was evidence for densities less than $10^6 cm^{-3}$ in the BLR. Ernst van Groningen and I have strong evidence for broad [OIII] emission in many Seyferts (there is a late poster on these results) and conclude that densities between 10^6 and 10^7 are called for. We believe this emission to come from a region distinct from the proper NLR and BLR rather than the BLR itself. Could you comment on this ?

Wills : I think this supports the idea that the whole emission line region is more complex than we thought-different regions and/or clouds or filaments of different physical properties.

Khachikian : What is your opinion about variations of [OIII] lines in NGC 1275 during some days ?

Wills : I have not thought much about that. Perhaps it is possible in lower luminosity objects to have some [OIII] in a very small region ? There is another example in a paper by Antonucci (Ap.J.) where the narrow line appears to disapper completely.

Malkan : You mentioned that some AGN's (e.g. Mrk 486) have the same polarization position angle in their continua and broad emission lines. These all turn out to be reddened, dusty AGN's, so the dust-scattering explanation of polarization looks fine. However, there are many less dusty AGN's (e.g. NGC 4151, 5548, MKn509) which have polarized continua, but essentially unpolarized Balmer emission lines. It's possible that many AGN's may have this sort of polarization, and it may require a different explanation (i.e. not based on dust scattering).

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Wills : I was really referring to the higher luminosity broad line radio galaxies and possibly QSOs where Antonucci favours electron scattering and Rudy and colleagues favour dust. One must explain the observations where line polarization is observed. Where it is not observed it may not exist or may be below the sensitivity of the observations.

Kundt : Talking of split emission lines is in low-luminosity objects : didn't Cyril Hazard report on split emission lines in (high-luminosity) high-redshift objects ?

Turnshek : The object was 1011+09, also studied by Foltz et.al. (1983, P.A.S.P.). This object is a BAL QSO and Foltz et.al showed that the reported splitting is probably due to absorption.