THE NATURE OF THE BROAD LINE REGION:
OPTICAL/UV/X-RAY STUDIES

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ABSTRACT

The broad line region (BLR) is a complex ensemble of clouds with different physical conditions, location and kinematics. Recent progress has been made primarily on two components of the broad line region:

(1) the fastest moving gas which emits the rapidly varying wings of the highly ionized lines such as C IV λ1550. Detailed observations fail to reveal net radial motions of this gas and furthermore there is new evidence, at least in NGC 4151, that the spatial distribution of the gas changes in a few years.

(2) the very dense gas (probably assembled in an accretion disk) which emits the iron Kα fluorescence line and the low ionization lines such as the Balmer lines. The rest of the broad line region emitting the narrower components (FWHM ≤ 2500 km s⁻¹) and its transition to the narrow line region remain poorly understood.

1. X-RAY STUDIES

In the program of the conference, the title of this paper was “The Nature of the Broad Line Region: Optical/UV Studies”. However, with the new data on the X-ray spectrum and the iron Kα fluorescence line obtained by the X-ray satellites EXOSAT and Ginga the X-ray results must be included in discussions of the properties of the broad line region.

Considerations of the energy budget have led several authors to propose that the lines from the BLR emitted by ions in low ionization states — Balmer lines, Fe II multiplets — are emitted by cold dense gas heated by hard X-rays [1,2,3]. The intensity and profile of the low ionization lines might therefore provide information on the way the X-ray source illuminates the cold gas and modifies its temperature compared to what it would be without X-ray irradiation [3,8,18].

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NGC 4151 X-Ray and UV light curves

Figure 1. a) The 2–10 keV flux of NGC 4151 corrected for absorption as a function of epochs [21,22]. b) Same for the flux at 1455 Å [12]. Lines are drawn only to aid the eye. Abscissae: year minus 1900.0.
Figure 2. a) and b) Enlargements of figure 1 along the time axis, for selected episodes.
There is a second argument based on the results of EXOSAT and Ginga in the 2–30 keV range for part of the primary X-ray radiation to be reprocessed by cold matter (e.g. [4] and references therein). It has been shown that reprocessing produces a hardening of the spectrum at \( \sim 20 \) keV and a strong iron Kα fluorescence line at 6.4 keV [16,17]. Both of these signatures of reprocessing of hard X-rays by cold dense matter have now been detected in Seyfert galaxies [4,5,6,7].

How is the cold dense gas distributed? In a wide cone or in a disk? The intensity of the features produced by the reprocessing can be explained only if the cold gas intercepts a large fraction of the X-ray emission, a situation best explained if the cold gas is in a slab such as an accretion disk.

A third set of data suggests the importance of the effects of the irradiation of the disk by the X-ray source. In NGC 4151, NGC 5548 and 3C 273 [12,13,14], the IUE observations show that the time scale of the variations of the UV continuum is too short for these variations to be caused by variations of the accretion rate in standard thin disk models. Two phenomena (not exclusive) can cause such rapid UV variations: flares in the inner part of the disk or irradiation of the disk by the variable X-ray source [15]. This latter suggestion is strongly supported in the case of NGC 4151 by the good correlation observed between the UV flux and the X-ray flux (figure 1,2). This correlation is not seen in all of the few objects adequately observed (For example, it is not seen in 3C 273 [14], which suggests that a flare type activity also contributes to the rapid UV flux variations).

The expected intensity, wavelength and profile of the Kα line (figure 3) for different cases of illumination of the disk, and for various inclination angles of the disk on the line of sight have been extensively investigated [9,10,11]. The abundances can be obtained from the comparison of the intensity of the iron Kα line and the excess intensity that causes the hardening of the spectrum at 20 keV.

The spectral resolution of EXOSAT and Ginga is insufficient to obtain the profile of the iron line but data on the position and equivalent width have been obtained for \( \sim 20 \) Seyferts/quasars. These are in general agreement, statistically, with the model of illumination of an accretion disk by a central compact primary X-ray source [e.g. 4,10]. Specifically, the centroid of the iron line is always measured to be consistent with the rest energy of 6.4 keV with an error of 0.1 keV; this is in agreement with the model prediction that for about 70% of the objects (for a random distribution of inclination) the shift of the centroid of the iron line would be less than 0.1 keV from its rest energy value. Similarly the equivalent width of the iron line is predicted to be between 90 and 160 eV for 80% of the objects, with a mean value of 120 eV, also in agreement with the observed distribution of equivalent width which peaks in the range 100–150 eV with a mean of 140 ± 10 eV [10].

On the other hand, the agreement is not perfect. In the model of Matt et al. [10] which is the most complete so far, the main discrepancy involves objects at high inclination. Firstly in a group of randomly oriented objects about 15% of them (the ones seen at highest inclination) should have a line centroid redshifted by \( \gtrsim 0.2 \) keV; such large redshifts, however, are not observed. It is possible that such objects are hidden from our view by an external ring of absorbing matter.
Figure 3. The line profiles of the iron Kα fluorescence line in the model of ref. [10]. For 3 values of \( \cos \theta \), where \( \theta \) is the inclination angle of the disk along the line of sight and 2 values of the outer radius, \( 10^2 \) and \( 10^4 \) gravitational radii in upper and lower panel respectively.

Figure 4. The asymmetry ratio B/R of the C IV line in function of \( f_\lambda \) (|v| > 3870 km s\(^{-1}\)) after 1984.5 in NGC 4151. The loops corresponding to the different campaigns fall at distinctly separate places on the diagram.
This would explain why they do not appear among the observed objects. Secondly, large equivalent widths (between 160 and 260 ev) are observed in about 30% of the objects. Such large values are expected to be observed for disks seen almost edge-on. The origin of such large equivalent widths is not understood. It may imply that the X-ray source illuminating the disk is diffuse (corona) or if it is a compact source it is located at least at 20 gravitational radii above the disk [10].

2. PROPERTIES OF AGN/QUASARS FROM STUDIES OF THE VARIABILITY

a) Historical remarks

The first AGN for which modelling of emission line ratios has been attempted are high luminosity quasars ($z > 2$). At the time of the first photoionization models it was thought that the various emission lines such as CIV $\lambda$1550, CIII] $\lambda$1909, MgII $\lambda$2800, Ly$\alpha$ had nearly the same profile. As a consequence, it was believed that all the gas or gas clouds in the BLR had the same physical properties i.e. same density, ionization parameter and even distance from photon source.

The first IUE spectra of nearby Seyfert 1 galaxies showed this assumption not to be correct for low luminosity AGNs. A single snapshot [20] showed that among the brightest lines CIV was the widest followed by MgII, then by CIII]. This implies that the highest velocity clouds are the most highly ionized and/or have higher electron densities, and that Seyfert 1 are not exact scaled down versions of quasars.

Shortly afterward, the first variability studies of low luminosity AGN, in particular NGC 4151, showed that the broadest component of the emission lines varied the fastest. The broad line region is, therefore, geometrically thick and its dimension cannot be characterized by only one number. There is a range of distances from center associated to different velocities and line ratios. In other words there is stratification.

b) Recent results

As is often the case in science much information comes from the in depth study of (hopefully) typical objects.

The two Seyferts which have been the best studied are NGC 5548 and NGC 4151. The two sets of data are of the same quality but differ by the way they were accumulated. NGC 5548 was observed in one long single campaign [19]. NGC 4151 was observed during a number of campaigns over 12 years resulting in a larger number of observations than for NGC 5548. The campaign on NGC 5548 is a natural continuation of the observations of NGC 4151 and is aimed at better quantifying the results obtained from NGC 4151. Keith Horne, in the next talk, will present the results on NGC 5548. The larger data set of NGC 4151 offers a different perspective and allows one to investigate changes from a few days to a few years [12]. The results relative to the emission lines are summarized as follows:
Figure 5. The light curves of the blue wing and the red wing of C IV shown separately in NGC 4151. The two wings have similar behavior at some epochs and different behavior at others.
Figure 6. Examples of long and short term variations of the C IV lines in NGC 4151. Variations within days are shown on each panel. One can appreciate the variations on time scales of years by comparing the two panels and considering that between 1985 and 1990, the C IV line passed through a stage of near perfect symmetry (during the 1988 November - 1989 January campaign).
1 - No evidence for net radial motions of the fast moving gas. We have studied in detail the response of the blue wing and the red wing using of C IV in the velocity range $|3700 - 10000|$ km s$^{-1}$. In principle, when the continuum flux varies one expects that the blue wing and the red wing will respond differently if the gas emitting the wings is inflowing, outflowing or has no radial motions. The point representing the intensity ratio of the blue wing to the red one (B/R) would describe loops of characteristic orientations in the B/R vs continuum flux diagram depending on whether the gas has net radial motions, is inflowing or is outflowing. Figure 4 shows B/R for 3 IUE campaigns during which several minima and maxima were followed with an appropriate time sampling (3 to 4 days). We note that the trajectories of the point B/R vs $f_\lambda$ do not overlap even for overlapping ranges of $f_\lambda$.

For $f_\lambda > 5 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ there is no systematic increase or decrease of B/R with changes of the continuum level nor the reverse. This is not consistent with radial motions. It has been suggested that the gas clouds are therefore in chaotic motions, i.e. they move along open trajectories in the gravitational field of the central objects. Similarly, the extensive campaign on NGC 5548 has brought no evidence for radial motions. For $f_\lambda \leq 5 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ B/R increases when the continuum flux decreases. This is due to a weak residual blue wing which persists even when the continuum is low and the red wing has faded.

Remark on the trajectories of the fast moving gas clouds. Chaotic motions imply that the trajectories would cross the plane of the accretion disk. However, it is easy to show that the accretion disk cannot be crossed by the fast moving clouds. The fast moving clouds therefore are formed on one or the other side of the disk and, thereafter, remain on the side of the disk where they were formed. The gravitational field of the central mass is not the only force influencing their motions. Other forces such as radiation pressure or magnetic forces must play an important role.

3 - Changes in the distribution of the broad line gas on a time scale of years. A comparison of the temporal behavior of the wings of C IV in NGC 4151 at different epochs provides some evidence for changes in the distribution of the broad line gas: During the decrease and increase branches of the deep minimum of 1988 November 29 - 1989 January 30 the C IV line maintains a high degree of symmetry. In contrast during other campaigns the blue and red wings respond differently to the continuum variations and there are in general large changes in the C IV wings intensity ratio from campaign to campaign (figures 5,6). The near perfect symmetry maintained by the line in 29 November 1988 - 30 January 1989 implies a symmetric distribution of the emitting matter with respect to the center + absence of radial motions. The asymmetries in preceding and following campaigns can best be explained as due to non-symmetric distribution of the emitting matter. This is consistent with a redistribution or rearrangement of the fast moving gas on a time scale of one to a few years, probably in the form of the arrival of a new gas cloud in the inner part of the broad line region. These gas clouds could be detached from stars of from the accretion disk itself.
3. CONCLUSIONS

It is clear that the broad line region cannot be investigated independently of the X-ray emission. The X-ray emission is the main source of energy of the low ionization lines and its effects on the temperature of the disk translate directly into observable properties of the lines such as profile and equivalent width of the Balmer lines and of the iron Kα fluorescence line. Future work should aim at global interpretation of the UV/optical and X-ray properties of the continuum and line intensities and profiles [see ref. 18 for a first effort in this direction]. Recent observations of the fastest moving gas reveal no radial motions (case of NGC 4151 and NGC 5548) and in NGC 4151 suggest that the spatial distribution of the gas changes on a time scale of one to a few years. Furthermore, it is likely that the fastest moving gas clouds cannot cross the disk. The gravitational field of the central mass is not the only force influencing their motions. Other forces such as radiation pressure or magnetic forces must play an important role [23].

REFERENCES