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Mapping the Broad-Line Region

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Abstract. The gas distribution in the broad-line region of active galaxies can be studied using photoionization models tuned to fit the observed light-curves in several recent reverberation campaigns. Old models of this type fall short of explaining the observations, in particular they fail to reproduce the simultaneous flux variation of several emission lines with different levels of ionization. Two recent attempts produce much better results. One (Kaspi & Netzer 1999) suggests a simple radial distribution of clouds and the other (Korista & Goad 2000) makes use of the LOC model. However, even the new improved models cannot explain the observed intensity of the Balmer lines, and other lines of low-ionization species. Part of the difficulty is due to inadequate transfer methods and part possibly due to improper modeling of the gas distribution.

The review describes the assumptions going into the more advanced calculations, as well as the likely reasons for the inadequate fits. It also addresses the fundamental issues of cloud confinement and the disk-BLR relationship.

1. Introduction

Broad emission line regions (BLRs) in active galactic nuclei (AGN) have been monitored, from the ground and space, for more than two decades. A major goal of the more recent campaigns (Peterson, these proceedings) has been the detailed mapping of the gas distribution in those regions, a goal that can only be achieved by reverberation mapping. Wide wavelength-band, long time-base observations are, by far, the best way to achieve this goal since they provide information about line intensity and line response to the varying ionizing continuum.

While some of the modern multi-wavelength campaigns have been very successful, and many detailed spectroscopic results are available, theoretical progress has lagged behind. There are a few firm results (e.g., that the BLR is stratified with the higher ionization species closer to the center), but no complete and detailed model has emerged. The sources of the difficulty are the complex nature of photoionization modeling and the unknown and probably complex gas distribution.

This review gives a short summary of the state-of-the-art mapping of AGN-BLRs with emphasis on results obtained in 1999 and 2000. It makes use of the best available data sets, mostly the multi-wavelength studies of NGC 5548, and addresses the difficulties and challenges facing the modelers. The review is arranged as follows: §2 gives the necessary background regarding the relevant, general, reverberation-mapping results. §2 addresses some of the fundamental issues regarding the BLR, in particular the notion of "clouds", and §4 emphasizes difficulties with present-day photoionization models. Finally, §5 shows a detailed example and the way it was calculated in two recent papers. The last section, §6, is about future prospects and the theoretical requirements to meet the challenges of new campaigns and, perhaps, dedicated reverberation missions like *Kronos*.

2. Reverberation-Mapping Results

Several successful reverberation-mapping campaigns have been carried out, resulting in a wealth of data on line and continuum variations (see Peterson, these proceedings). Regarding systematic studies of large samples, the most extensive results are given by Kaspi et al. (2000) who have combined earlier mass and size determinations for 17 low-luminosity AGN, with new results based on a seven-year monitoring of 17 PG quasars. The combined sample of 34 objects enables us to deduce the BLR size ($R_{\rm BLR}$) and the central black hole mass, over four orders of magnitude in luminosity (see Kaspi, these proceedings). The results can be summarized as follows:

- The BLR size, as determined by the lag of the Balmer lines relative to the optical continuum, assuming $L_{46} = 9 \times \lambda L_{\lambda}(5100\,\text{Å})$, where $L_{46} = L_{\rm Bolometric}/10^{46}$ ergs s^{-1}is

$$R_{\rm BLR}({\rm Balmer}) = 0.15 L_{46}^{0.7}\ {\rm pc} \qquad (1)$$

- The comparison of the Balmer-line lags and the high-ionization line lags, in low-luminosity AGN, suggests that all BLRs are stratified, with lines from higher-ionization species emitted preferentially closer to the ionizing source. The definition of $R_{\rm BLR}$ is thus ion-dependent. In particular,

$$R_{\rm BLR}({\rm He\,II}) \simeq 0.2 R_{\rm BLR}({\rm Balmer})\,. \qquad (2)$$

  This gives constraints on the level of ionization and, as shown later, also on the disk-BLR interaction.

- The black-hole mass, as obtained from measuring the Balmer-line widths, and combining them with $R_{\rm BLR}$(Balmer) assuming Keplerian motions in a spherical cloud system, is

$$M = 1.9 \times 10^{8} L_{46}^{1/2}\ M_{\odot} \qquad (3)$$

- The mean "hydrogen-ionization parameter", $U_{\rm H}$ (i.e., the ionization parameter obtained by integrating over the hydrogen Lyman continuum), assuming that the gas density at the region emitting the Balmer lines and the spectral energy distribution (SED) do not depend on luminosity, is

$$U_{\rm H} \propto L_{46}^{-0.4}\,. \qquad (4)$$

While some of these assumptions cannot be fully justified (e.g., the one about the SED) or calibrated, and some of the suggested dependences not necessarily linear, as assumed here, they are nevertheless useful working assumptions and good starting points for future multi-line analysis.

3. Mass Distribution in the BLR

3.1. Clouds and Bloated Star Models

The nature and the properties of the broad-line region clouds are still open questions. Three types of so-called "clouds" and cloud distributions will be considered here.

"Standard clouds:" This assumes only one type of cloud at any location. The cloud density, shape, and column density are unique functions of the radial and azimuthal coordinates. Such models have been described, in great detail, by Netzer (1990) and have been recently revisited by, e.g., O'Brien, Goad, & Gondhalekar (1994), Goad & Koratkar (1998) and Kaspi & Netzer (1999).

Locally optimally emitting clouds (LOC): The LOC model (Baldwin et al. 1995; Korista & Goad 2000, and references therein) assumes numerous clouds, with a range of properties (density, column density, and covering fraction) at any given location. The main suggestion is that the local ionizing flux, and the gas density, produce a large range of ionization parameter at any given location. Lines from high and low ionization species are produced, with different efficiencies, at all radii, and the local spectrum reflects the range of physical properties. The $1/r^2$ flux variation is the main reason for the different contributions to the various emission lines at different locations. The general tendency is for lines of higher ionization and higher critical density to be emitted closer to the center, but there are important deviations from this simple behavior. The current version of the LOC model assumes power-law distributions in density and covering factor and constant column density (Korista & Goad 2000). Other distributions are likely too, and the model is still under development (e.g., Horne, Korista, & Goad 2000).

Bloated stars: This model was suggested by Edwards (1980), Mathews (1983), Penston (1988), Scoville & Norman (1989) and Kazanas (1989) and studied in greater detail by Alexander & Netzer (1994, 1997) and Alexander (1997). It proposes that the broad emission lines are emitted from the winds or the mass-loss envelopes of giant stars in the central cluster. The number of such "clouds" is smaller than in the other two models and the mass in each one (and hence the total BLR mass) is much larger.

A major theoretical problem with all cloud models is the confinement of the clouds. Earlier ideas (e.g., Krolik, McKee, & Tarter 1981), invoking a two-phase medium in pressure equilibrium, are problematic because of the low expected temperature of the inter-cloud gas (e.g., Mathews & Ferland 1987). Magnetic pressure confinement (e.g., Rees 1987) is a more likely possibility and models along this lines have been developed (see Emmering et al. 1992; Kónigl & Kartje 1994; Bottorff & Ferland 2000). Other alternatives (e.g., relativistic gas) have also been explored, but the problem is still unsolved.

Regardless of the nature of the external pressure, all confined cloud models assume local pressure equilibrium (i.e., the pressure is a unique function of the distance from the center). This favors homogeneous local cloud distributions (i.e., gas density which is varying with distance) and presents a real challenge to the LOC model because of the large pressure variations in clouds of different densities.

3.2. Other Models

Other BLR models have also been suggested. For example, Königl & Kartje (1994) discuss the idea of a continuous, magnetically driven flow from the central disk that breaks, eventually, into individual clouds. Pure wind solutions are unacceptable on grounds that the line-width analysis clearly indicates high and low ionization material in the same location. This would favor condensations or clouds rather than a continuous flow.

The term "clouds" used later on refers to all types of condensations that are likely to be present in the BLR.

3.3. The Number of BLR Clouds

Emission-line observations suggest that, in many objects, the line profiles are smooth over thousands of km/sec. In particular, the very detailed observations of low-luminosity sources like NGC 4151 clearly demonstrate that the deviation from a smooth flow or motion are extremely small (Arav et al. 1997; Arav et al. 1998). This has been used to argue that the standard cloud model, with thermal line widths for individual clouds, requires a huge number of clouds to explain the observed profiles. Monte-Carlo simulations suggest that the number can exceed 10^7 for sources like NGC 4151.

While the smooth line profiles are problematic for all cloud models, this is specifically noticeable in the bloated star model where the expected number of stars is relatively small ($\sim 10^4 - 10^5$; see Alexander & Netzer 1997). One possibility is that the internal motion in the clouds are super-sonic, reaching perhaps several hundred km/sec (Bottorff & Ferland 2000, and references therein). Alternatively, the cometary tails of bloated stars may cover a large velocity range. This helps to reduce the number of clouds, but introduces another difficulty regarding the cloud-stability. It is also related to the general optical-depth problem since large internal motions can dramatically decrease the line opacities.

4. Reliable and Unreliable Line Intensities

Any attempt to fit the observed, variable AGN emission lines by the results of standard photoionization models faces the difficulty that most strong emission lines are very optically thick. Such lines are normally treated by using an escape probability formalism which is local in nature, i.e., the emitted line photons are not allowed to interact with the material on their way out. Sophisticated, state of the art photoionization codes like CLOUDY (by G. Ferland), ION (Netzer 1996) or XSTAR (by T. Kallman) are limited in their ability to treat accurately some of the lines.

The local escape probability method is probably adequate for treating the high ionization lines like C IV $\lambda1549$ and N V $\lambda1240$, the recombination lines like He II $\lambda1640$, intercombination lines like C III] $\lambda1909$, and perhaps also Lyα. It is definitely inadequate for the hydrogen Balmer lines, and perhaps also for calculating the intensity of lines of low-ionization ions like Fe^+ and Mg^+. Moreover, it is not at all clear that the emission pattern of the large optical-depth clouds (i.e., the degree of anisotropy of the line emission), which is readily computed with escape probability based codes, is accurate. Full radiative transfer methods, combined with detailed ionization treatment like those in photoionization codes, must be used to verify the accuracy of the present calculations. Such codes are not yet available and meaningful tests of the mass distribution in the BLR, based on reverberation-mapping results, must be carried out avoiding the less reliable emission lines.

5. Case Study: NGC 5548

5.1. Early Works

There have been several attempts to explain the time-dependent spectrum of NGC 5548, the best studied AGN, starting with the work of Krolik et al. (1991). Most models assumed smooth radial spherical cloud distributions or multi-zone BLR. They have addressed the time-dependent intensity variations of several lines but did not take into account the additional constraints imposed by the time-dependent line intensity *ratios*. Models of this type are described in Ferland et al. (1992), O'Brien, Goad, & Gondhalekar (1994), Pérez, Robinson, & de la Funte (1992), Shields, Ferland, & Peterson (1995), Bottorrf et al. (1997), Dumont, Collin-Souffrin, & Nazarova (1998), and Goad & Koratkar (1998). More detailed modeling, including several emission lines and requiring that *all lines* fit the observations, are discussed by Kaspi & Netzer (1999) and by Korista & Goad (2000). Only these state-of-the-art models are discussed below.

5.2. Direct and Indirect Fitting Methods

Before describing the details of the models, a comment on the fitting procedure is in order. While a major aim of the earlier line-reverberation campaigns was to recover the transfer functions of individual lines, the results obtained so far limit the usefulness of this approach. Transfer functions like the ones presented in Krolik et al. (1991) are not unique. They allow a range of solutions, i.e. a range of possible mass distributions. Moreover, it is difficult to find a one-to-one correlation between the assumed emissivity maps (obtained from the calculated transfer functions) and the actual mass distribution in the source. The two are related by the emission efficiency which, in many cases, is a complicated, non-linear function of the gas distribution. These so-called "indirect" or "inversion" methods fall short of recovering the true source geometry (for additional information on the transfer function method see Horne, these proceedings).

Alternatively, one can guess the mass distribution and use photoionization models to calculate the time-dependent spectrum. The results of such calculations are then compared with the observations and a goodness of fit score is obtained. A better guess will result in a better fit. The present available data sets and theoretical line intensity uncertainties suggest that the number of possible gas distributions is rather limited. This "direct" or "forward" method is more time consuming, yet the results are more physically meaningful. The most successful models, so far, are both based on such forward methods.

5.3. A Comparison of the LOC and the Radial Distribution Models

Considering the recently published models, the Kaspi & Netzer (1999) work assumes the simplest, radial distribution of spherical, constant density clouds with seven parameters: the inner and outer radii, the radial density parameter s, given by

$$N(r) \propto r^{-s}, \tag{5}$$

the cloud number density parameter, p, given by

$$n_c(r) \propto r^{-p}, \tag{6}$$

the normalization of the density and column density at a given radius, and the global normalization of the covering factor (i.e., the total line emission). In practice, only 3 or 4 of the parameters are left free when looking for the best solution (s, p, the density normalization and, in some cases, the innermost radius $r_{\rm in}$). A modified version of the model includes also a variable-shape SED which adds one or two parameters.

In this radial-distribution model, the radial dependences of the column density, the cloud radius (or geometrical cross section), the ionization parameter and the covering factor are all related to s and p. The total line emission, E_l, is obtained by integrating over the single-cloud line emission $j_{c,l}(r, L_{\rm ion}) = \pi R_c^2 \epsilon_l(r, L_{\rm ion})$, i.e.,

$$E_l \propto \int_{r_{\rm in}}^{r_{\rm out}} n_c(r) j_{c,l}(r, L_{\rm ion})\ r^2 dr\ , \tag{7}$$

where $L_{\rm ion}$ is the ionizing luminosity and ϵ_l is the line flux (ergs s^{-1} cm^{-2}) as obtained from detailed photoionization calculations. Some results, for a particular choice of parameters, are shown in Fig. 1. The Kaspi & Netzer (1999) calculations do not attempt any fit of the Balmer-line light curve because of the above mentioned transfer uncertainty. Experimenting with a large number of models, Kaspi and Netzer concluded that various spherical cloud distributions give reasonable fits to the time-dependent intensities of four emission lines: Lyα, He II λ1640, C III] λ1909, and C IV λ1549. No model can reproduce the observed intensity of the strong Mg II λ2798 line. All successful models reproduce the relative intensity of the above four lines at all times, as well as their total flux. The best models are characterised by $\chi^2 \approx 2$. Some of the more specific results are:

- No constant ionization parameter model ($s = 2$) can explain the time-dependent spectrum of NGC 5548. The best fit models are those with $1 \lesssim s \lesssim 1.5$.
- Large column density clouds produce better fits. The lower limit on the column density, at a distance of 1 light-day (lt-day), is 10^{23} cm^{-2} .
- The models suggest a well-defined range of densities, translating to $10^{11} < N(r = 1\,{\rm lt-day}) < 10^{12.5}$ cm^{-3}.

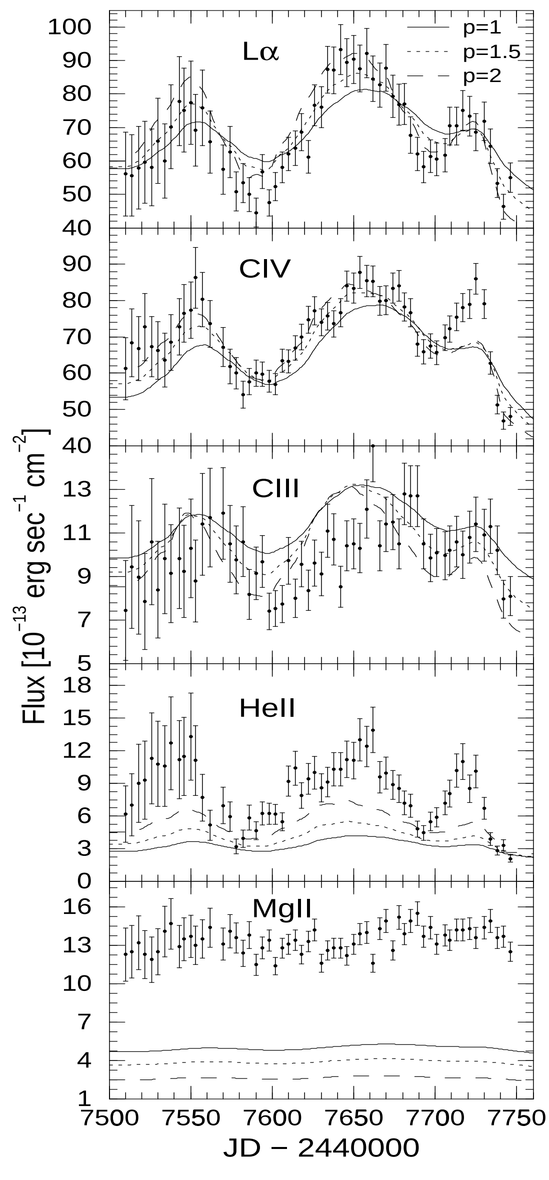

Figure 1. Simulated light curved for five strong emission lines observed in the spectrum of NGC 5548. The normalization is such that the density at 1 lt-day is $10^{11.4}$ cm^{-3}, the column density at 1 lt-day is 10^{24} cm^{-2}, $r_{\rm in} = 3$ lt-day and $r_{\rm out} = 100$ lt-day The density parameter is $s = 1$ and the number of clouds parameter p is allowed to change, as marked. For more information see Kaspi & Netzer (1999).

- The covering fraction (or the number density of clouds) is a strongly decreasing function of radius. The best fits require $p \lesssim 1.5$. The total covering fraction, as obtained from the simultaneous fitting of the above four lines, is ~ 0.3.

- There are some indications that the UV spectrum gets harder when the source is brighter.

- Various amounts of reddening, and/or different compositions, do not make a significant change in the fit.

The Korista & Goad (2000) modeling of the observed NGC 5548 light curves is tuned to fit the mean spectrum of the 1993 HST UV spectrum of the source (Korista et al. 1995). The model requires eight parameters for a given SED: three for the density (minimum density, maximum density, and the density power-law index), two for the covering fraction (power-law index and normalization), two for the radius ($r_{\rm in}$ and $r_{\rm out}$), and one for the column density. Only three of the parameters were allowed to very when fitting the observations. The model fits reasonably well the observed time-dependent fluxes of the four lines modelled by Kaspi & Netzer (1999), and fails, like the other model, to explain the Mg IIλ2798 line intensity. The χ^2 score for the four light curves is not given in the paper. The Korista & Goad (2000) computed light curves are shown in Fig. 2. A superficial comparison of Fig. 1 and Fig. 2 suggest that the result of the two methods are comparible. A more detailed inspection clearly show that some of the theoretical light curves computed by both models, are far from explaining the observations.

6. Future Prospects and the Disk–BLR Interaction

There are several ways to proceed both in observations and in modelling. Better modelling of the low-ionization lines, and the Balmer lines is definitely required since no present-day model can successfully explain the observed intensities of these lines. Full radiative-transfer codes, combined with detailed calculations of the micro-physics, are required. The lack of such models implies that the outer regions of the BLR is only poorly understood.

Both the LOC and the radial-distribution models can be improved and perhaps merged to produce more realistic mass distributions. A range of properties at any given location is a desirable property, although cloud confinement (i.e., the requirement that the pressure has a simple radial dependence) may present fundamental difficulties.

An interesting question is the scaling of the dimension of the cloud system with luminosity. The Kaspi et al. (2000) relationships, if confirmed, suggest that the ionization parameter scales with luminosity (eq. 4). It remains to be seen whether any of the above distributions can explain this result. The simplest version of the LOC model suggests the same ionization parameter for all sources with similar SED. However, some of the parameters of the model (e.g., the density power-law index) may depend on the source luminosity. Obviously, the possible change of SED with source luminosity must also be considered.

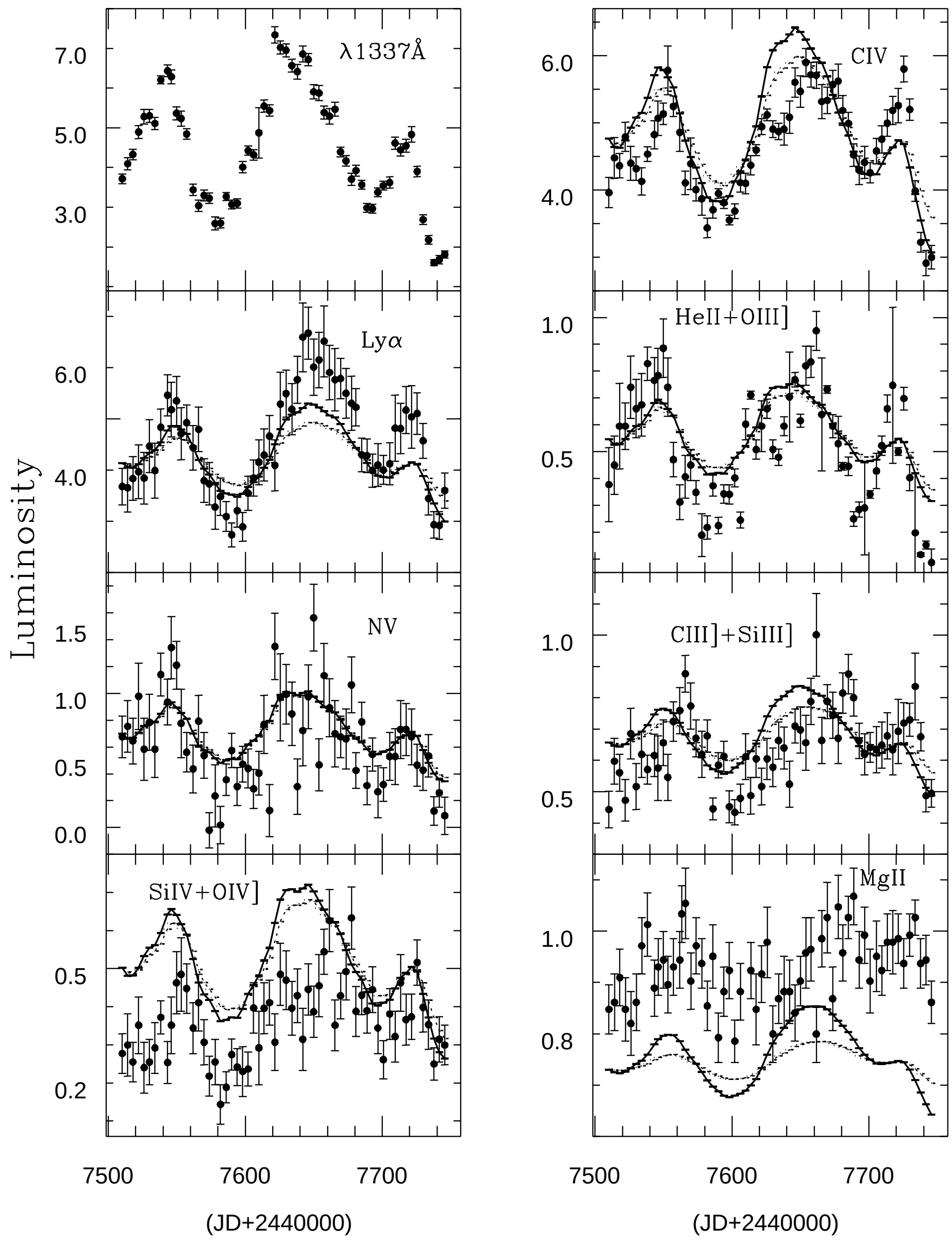

Figure 2. LOC model fit to the observations of NGC 5548, showing the UV continuum (upper left panel) and various emission line light curves. For more information see Korista & Goad (2000).

Finally, it is interesting to note that the radial-distribution cloud model, as well as the LOC model, require that much of the high-ionization material is located close to the center. In particular, using the M-L relationship (eq. 3), we find that the so called $R_{\rm BLR}$(He II) is emitted within $\sim$ 1000 gravitational radii, at least in the lower-luminosity sources. It is therefore conceivable that the hot disk corona and the inner BLR co-exist in the same volume. This may shed new light onto the confinement problem as well as the long term survival of BLR clouds. A detailed discussion of these ideas is beyond the scope of this review.

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