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Broad-Line Profile Variability

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Abstract. Many years of monitoring a sample of 10 AGNs with a median sampling rate of about one spectrum per week yields strong evidence that broad-line *profile* variations are not induced by reverberation effects, but rather signify real changes in the structure of the continuum-source and broad-line region complex, contrary to line *flux* variations, which do respond to continuum variations. If the profile variations indeed trace internal changes in the BLR, then the BLR cannot consist of the billions of small clouds as the standard model of the BLR prescribes. Rather, small-number statistics are necessary. The sample of AGNs also indicates there are three preferred 'components' in the line profiles. These can be explained as geometrical projection effects due to an anisotropic continuum irradiating an otherwise spherical BLR.

1. Observations

Starting in 1989, Peterson and collaborators have carried out a program of long-term monitoring of ten active galactic nuclei (AGNs) using the 1.8 m Perkins Telescope at Lowell Observatory. Each week a full night is dedicated to this program for as long as the objects are visible during the season. Bad weather introduces gaps in the time series, but on average about 20 spectra are taken of each object per year. The spectra have a nominal resolution of about 10 Å and are centered at the broad He II λ4686 and Hβ emission lines. The spectra are internally calibrated with respect to each other using the narrow [O III] emission lines which are nonvariable in flux.

The spectral time series thus produced lends itself to studies of long-term trends in the variability characteristics of the broad-line profiles. The primary objects under study are NGC 5548 (Wanders & Peterson 1996), 3C 120, Akn 120, Mrk 79, Mrk 110, Mrk 335 (Kassebaum et al. 1997), Mrk 509, Mrk 590 (Peterson et al. 1993), Mrk 704, and Mrk 817.

In this contribution, the average and root-mean-square (RMS) profiles of the broad Hβ emission lines are discussed.

2. Average and RMS Profiles

For a long time series, the average emission-line profile $\Phi(v)$ is a measure of the time-delay integral of the transfer function (TF) $\Psi(v,\tau)$:

$$\Phi(v) \equiv \int \mathrm{d}\tau \, \Psi(v,\tau) \approx \frac{\langle L(v,t) \rangle}{\langle C(t) \rangle} \tag{1}$$

(Blandford & McKee 1982). Here, as well as elsewhere, angled brackets denote time average, and $L(v,t)$ and $C(t)$ are the emission-line profile and continuum flux at time t, respectively.

The interpretation of the average profile is quite straightforward; it represents the emission-line profile were the continuum flux constant in time. Because the TF depends upon the geometry and kinematics of the BLR, the average profile does so as well. If the BLR is in a steady state, i.e., if it does not change its internal structure, the TF and the average profile are time-independent.

The RMS profile $\sigma(v)$, which characterizes the line variations around the mean, can be defined as

$$\sigma^2(v) \equiv \langle [L(v,t) - \langle L(v,t) \rangle]^2 \rangle \,. \tag{2}$$

The RMS profile is more difficult to interpret than the average profile, because it depends upon the type of continuum variations. Obviously, if there are no variations, the RMS profile will be zero for all v. However, the RMS profile is a good tool to highlight the variable part of the emission-line profile. If, for example, the wing of an emission-line profile varies around the mean with a larger amplitude than the core, this will show up in the RMS profile as a stronger wing than the core. Any constant, nonvariable parts, such as the narrow emission lines, will not be present in the RMS profile.

3. NGC 5548: An Evolving BLR

Perry, van Groningen, & Wanders (1994) and Wanders & Peterson (1996) showed that emission-line profiles do not change their *shape* in response to continuum variations, which occur on a time scale of several weeks, but appear to change their shape on a longer time scale of several years, and in a more-or-less unpredictable way. The time scale of several years is comparable to the BLR crossing time of the gas, which suggests a link between the profile variations and internal gas motions within the BLR. In other words, changes in the shape of the emission-line profile probably trace structural changes in the BLR.

Figure 1 shows the normalized average and RMS profiles of NGC 5548 over a time span of five years (Wanders & Peterson 1996).

3.1. The Average Profile

Clearly, the average profile of NGC 5548 changes in a smooth fashion over these 5 years. Since the initial condition in 1989, a shoulder appears and disappears on the blue wing ($v \approx -2500\,\mathrm{km\,s^{-1}}$) and is strongest during 1991. In 1993, a shoulder develops on the red wing ($v \approx +2500\,\mathrm{km\,s^{-1}}$). These profile changes in

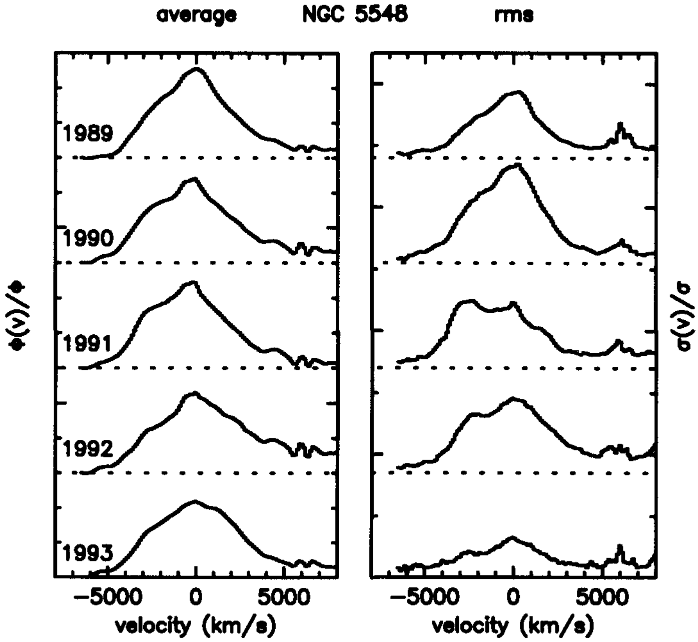

Figure 1. NGC 5548 average $\Phi(v)$ and RMS $\sigma(v)$ profiles (from Wanders & Peterson 1996).

the average profile are strong evidence that the observed BLR (as characterized by the TF) is *not* in a steady state.

The standard model for the BLR assumes the presence of a huge number ($\gtrsim 10^8$) of small, optically thick clouds. If these were distributed randomly in the BLR, the stochastic variations in the cloud distribution would not be discernible and the BLR would be in a steady state. Hence, the fact that we *do* observe changes in the BLR implies that the number of clouds in the BLR is not very large, but rather limited to ~1000–10 000 in order to provide a clumpy BLR. Note that one reaches the same conclusion of small number statistics if the continuum source (CS), instead of the BLR, is the component that changes its structure and illuminates different parts of the BLR differently over the course of time.

There arise obvious problems which need to be solved when only a small number of clouds are imposed on the BLR. For example, they need to be large in order to cover enough of the CS to explain the observed line fluxes. At the same time, the column densities may not be too large for each cloud (Peterson 1994). Also, small cloud numbers require large intrinsic velocity dispersions ($\sim 1000\,\mathrm{km\,s^{-1}}$, compared to a thermal width of $\sim 10\,\mathrm{km\,s^{-1}}$) of the clouds in order to produce a smooth emission-line profile. This, as well as the longevity of the clouds, indicates they are bound to objects like stars (perhaps extended atmospheres [cf. Alexander, these proceedings] or winds resulting in comet tails coming off of stars) or are shocks that survive for at least a few years.

3.2. The RMS Profile

The RMS profiles of NGC 5548 make clearer what is already observable in the average profiles: there are three preferred variable 'components' to the emission-line profile, a core component, and a red- and blue-wing component (at $v \approx \pm 2500\,\mathrm{km\,s^{-1}}$). These vary independently of one another and during some years one component can be stronger than the other. For example, during 1991 all three components are visible, with the blue wing dominating the profile variations. Independent of which of the components dominates, there are no significant time-lag differences between the core and wing components, as previous studies of NGC 5548 have shown (Korista et al. 1995; Wanders & Peterson 1996). Hence, radial motions are not dominant in the BLR.

4. Nine More AGNs: The 'Three-Component' BLR

Figure 2 presents the average and RMS profiles of nine more AGNs, monitored over 5–7 years. Most of these show single-peaked profiles, but Mrk 704 shows a double-peaked RMS profile, whereas Akn 120 shows a triple-peaked one, similar to the 1991 year of NGC 5548. Note also that Mrk 79 (red wing) and Mrk 509 (blue wing) show signs of a shoulder on the RMS profiles. We thus see there is more evidence for the three 'components' of the broad lines, whose relative strength can be anything from core-dominated (single-peaked) to wing-dominated (double-peaked) and in between (shoulders or triple-peaked). (cf. Gaskell & Snedden, these proceedings.)

5. A Simple Model

A model for the BLR must be able to account for the variability characteristics of the BLR, and hence must be able to fulfill the conditions:

1. that there are no significant bulk radial motions in the BLR as the simultaneity of the red- and blue-wing flux responses to continuum variations show (Korista et al. 1995; Wanders & Peterson 1996); and
2. that there are three variable 'components' (one core, two wing) to the broad Hβ emission line.

Wanders et al. (1995) introduced a simple model of a spherical BLR, extended in radius, in which the gas moves along randomly inclined circular orbits, illuminated by an *anisotropic* continuum source. This model is consistent with the observed TF of the C IV emission line in NGC 5548 (Wanders et al. 1995; Done & Krolik 1996). Its main property is that the *observed* BLR is biconical, without any significant radial motions. Biconical BLRs are known to be able to produce double-peaked profiles (O'Brien, Goad, & Gondhalekar 1994).

An anisotropic CS is expected from a standard accretion disk (Netzer 1987) and anisotropic radiation structures are observed on larger scales than the BLR

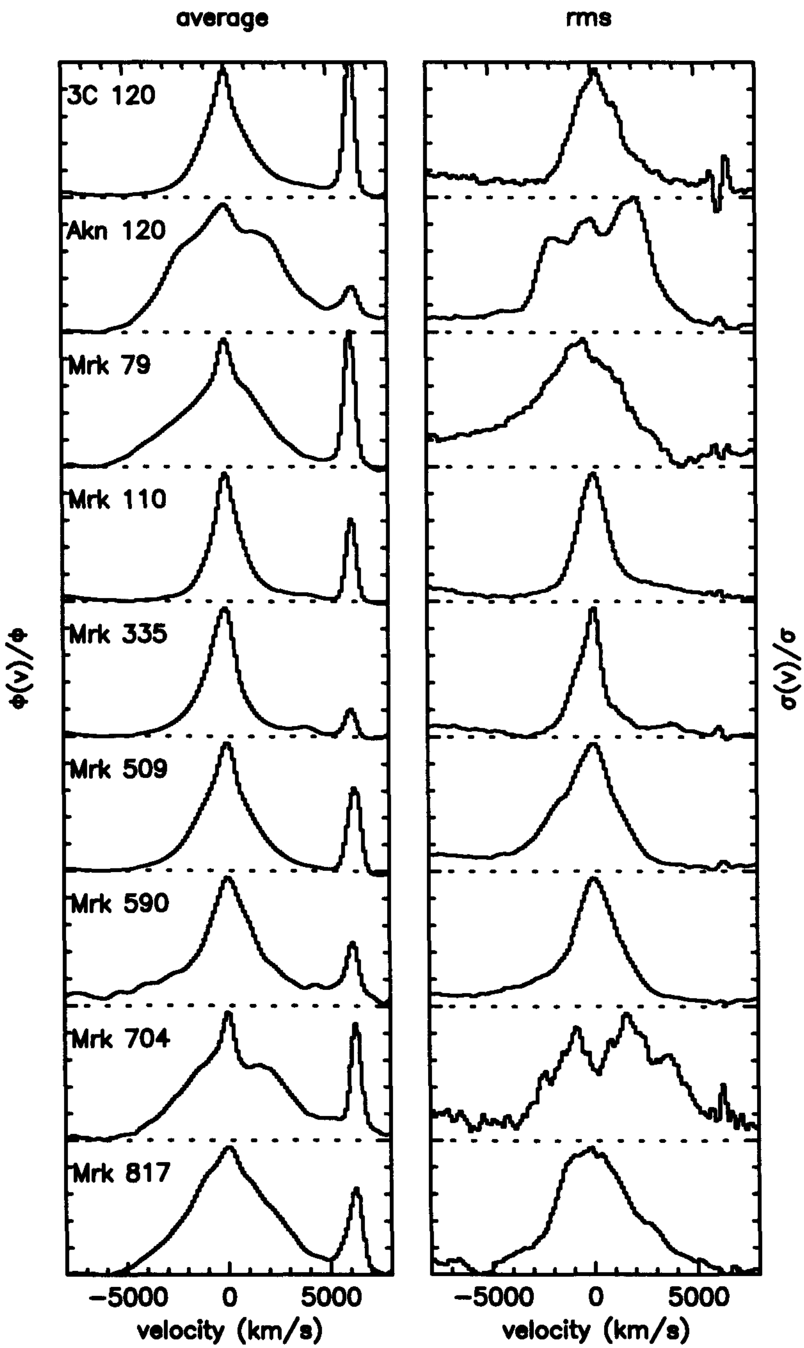

Figure 2. Average and RMS profiles of nine more AGNs.

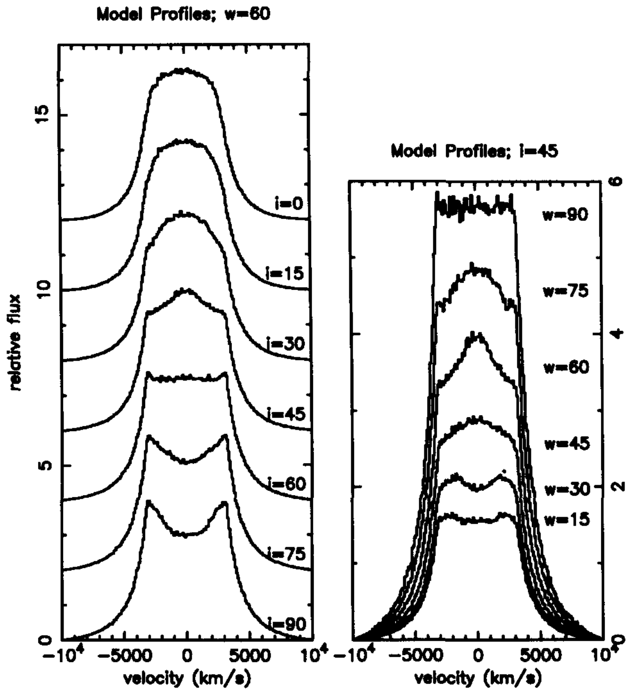

Figure 3. Example line profiles resulting from an anisotropic CS with an inclination of 0°, 15°, 30°, 45°, 60°, 75° and 90° and a fixed semi-opening angle of $w = 60°$ (left), and a semi-opening angle of 15°, 30°, 45°, 60°, 75°, and 90° (isotropic CS) and inclination $i = 45°$ (right)

(e.g., Wilson, these proceedings; Robinson, these proceedings). It is thus not far-fetched to pose the existence of an anisotropic continuum radiation field at the scale of the BLR as well.

Goad & Wanders (1996) examined the emission-line profiles that would be observed from such an anisotropic model. Figure 3 presents examples of average emission-line profiles. These profiles are due to a beamed continuum component three times the strength of an underlying isotropic component. The left plot shows how the profiles vary as a function of inclination with a constant effective continuum-beam semi-opening angle $w = 60°$, whereas the right plot shows the variation as a function of semi-opening angle at constant inclination $i = 45°$.

Figure 3 shows that single-peaked, double-peaked, and 'shouldered' profiles can arise as a function of viewing angle and/or semi-opening angle only. Actually, as Goad & Wanders (1996) show, even triple-peaked profiles occur (with large semi-opening angles, $w \approx 75°$, and intermediate inclinations $i \approx 45°$). We find that this simple model is consistent with

1. the observed non-radial motions in the BLR (Korista et al. 1995);
2. the observed TF of the BLR (Wanders et al. 1995; Done & Krolik 1996);

3. the three 'components' of the broad emission lines.[1]

The number of free parameters in the full model is large, but the simplest case discussed here already produces a wealth of profile shapes (and TFs) sufficient to explain the observations.

We are left with the problem of line asymmetries. As with most BLR models, asymmetries are second-order effects. One can speculate that the asymmetries are due to small number of cloud statistics. Depending upon the position of the cloud within the BLR, one or another 'component' of the emission line is enhanced with respect to the others. These changes occur on the dynamical time scale of the gas (the moving in and out of the beamed continuum source), whereas on the small time scales of several weeks reverberation effects play an important role. It is clear that in an anisotropic environment, the interpretation of the TF is not a straightforward task.

6. Conclusions

In this paper I have tried to point out that the Hβ profile variations are not induced by the variations in the continuum source. Line profile variations are therefore, in contrast to line flux variations, not reverberation effects.

Profile variations, as evidenced by the changes in the normalized average profile of, amongst others, the AGN NGC 5548, occur on time scales of several years, comparable to the BLR crossing time. This suggests the profile variations actually trace changes in the observed distribution of the BLR gas.

If profile variations indeed trace internal changes in the observed gas distribution, then this implies the number of BLR 'clouds' is not very large, as the standard model of the BLR prescribes, but rather on the order of 1000–10 000, such that stochastic variations in the cloud distribution are observable.

Profile variations seem to take place predominantly in three specific positions of the emission line, suggestive of a 'three-component' structure: a central core component, and a red- and blue-wing component, approximately symmetrical around the core. The position of these 'components' in the line profile is seemingly stable in time over many years.

A simple model of an anisotropic continuum source irradiating a spherical BLR, in which the clouds move along randomly inclined circular Keplerian orbits, is capable of explaining the three-component profiles as the results of projection effects and viewing angles. Anisotropy of the continuum source may thus be very important for interpreting line profiles and their variations.

In conclusion:

1. Basic profile structures like single peaks, shoulders, double peaks, are explainable as projection effects due to an anisotropically illuminated BLR.

2. Flux variability *within* the profile structures are explainable as stochastic variations in the cloud distribution with small numbers of clouds.

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[1] Note that these components are not physical components but are due to geometrical projections!

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References

Blandford, R. D., & McKee, C. F. 1982, ApJ, 255, 419.

Done, C., & Krolik, J. H. 1996, ApJ, 463, 144.

Goad, M. R., & Wanders, I. 1996, ApJ, 468, in press.

Kassebaum, T. M., Peterson, B. M., Wanders, I., Pogge, R. W., Bertram, R., & Wagner, R. M. 1997, ApJ, submitted.

Korista, K. T., et al. 1995, ApJS, 97, 285.

Netzer, H. 1987, MNRAS, 225, 55.

O'Brien, P. T., Goad, M. R., & Gondhalekar, P. M., 1994, MNRAS, 268, 845.

Perry, J. J., van Groningen, E., Wanders, I. 1994, MNRAS, 271, 561.

Peterson, B. M. 1994, in Reverberation Mapping of the Broad-Line Region in Active Galactic Nuclei, ASP Conf. Ser. Vol. 69, p. 1.

Peterson, B. M., Ali, B., Horne, K., Bertram, R., Lame, N. J., Pogge, R. W., & Wagner, R. M., 1993, ApJ, 402, 469.

Wanders, I., & Peterson, B.M. 1996, ApJ, 466, 174.

Wanders, I., Goad, M. R., Korista, K. T., Peterson, B. M., Horne, K., Ferland, G. J., Koratkar, A. P., Pogge, R. W., & Shields, J. C. 1995, ApJ, 453, L87.