Line profile variations in selected Seyfert galaxies

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Abstract. Continua as well as the broad emission lines in Seyfert 1 galaxies vary in different galaxies with different amplitudes on typical timescales of days to years. We present the results of two independent variability campaigns taken with the Hobby-Eberly Telescope. We studied in detail the integrated line and continuum variations in the optical spectra of the narrow-line Seyfert galaxy Mrk 110 and the very broad-line Seyfert galaxy Mrk 926. The broad-line emitting region in Mrk 110 has radii of four to 33 light-days as a function of the ionization degree of the emission lines. The line-profile variations are matched by Keplerian disk models with some accretion disk wind. The broad-line region in Mrk 926 is very small showing an extension of two to three light-days only. We could detect a structure in the rms line-profiles as well as in the response of the line profile segments of Mrk 926 indicating the BLR is structured.

1. Introduction
Seyfert galaxies belong to the class of active galaxies or active galactic nuclei (AGN). They are emitting a nuclear nonthermal continuum emission that cannot be caused by stellar sources. Seyfert galaxies are less luminous than the quasars which show nearly identical emission line spectra. However, in most cases Seyfert galaxies are close-by and therefore they can be studied in more detail. All spiral and elliptical galaxies contain a supermassive black hole of the order of $10^6$ to $10^{10}$ solar masses in the center. The central luminosity in active galaxies is probably caused by accretion of material from the outer regions. Many details of the transformation process from kinetical energy into radiation energy are still not understood.

The line emitting black hole is surrounded by the broad emission-line region - the innermost line emitting region in AGN. The emission lines are caused by photoionization of the central nuclear region. The broad-line region (BLR) has an extension of light-days to light-months and can not be resolved spatially on direct images.

Studying the variability of the broad emission lines - caused by the central variable source - can give us information on the extension and structure of the broad-line region. This is based on the delayed response of the integrated line intensities with respect to the central ionizing source.

For a set of about 35 AGN reliable distances of the H/β line emitting regions exist [1]. Based on these distances in combination with assumptions regarding the rotation velocities of the broad-line clouds it is possible to derive the central black hole masses.

A study of the variations of the emission line profiles can give us information on the kinematics of the broad-line region: e.g. a faster response of the individual line wings gives us information on inflow or outflow motions. A comparison of the chronology of line-profile variations with theoretical model calculations gives us the possibility to discriminate between radial, turbulent...
or Keplerian motions. However, only excellent spectra with high signal/noise ratio can be used for this kind of study.

Detailed reverberation studies exist for a handful of galaxies only. Here we want to present line-profile studies of the narrow-line Seyfert 1 galaxy Mrk 110 and of the broad-line Seyfert galaxy Mrk 926.

2. Emission line variability in Mrk 110

Mrk 110 is a narrow-line Seyfert galaxy with a H$\beta$ line width of 1400 km/s. We studied their broad-line variability with the 10m Hobby-Eberly Telescope (HET) at McDonald Observatory over a period of 7 months ([2]) with a typical interval of 5 days. Fig. 1 shows some optical spectra of Mrk 110 taken with the 10m Hobby-Eberly Telescope at McDonald observatory.

Light curves we derived from our variability campaign of Mrk 110 are given in Fig. 2. Shown are the light curves of the continuum flux at 5135 Å (in units of $10^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$) and of the integrated emission line fluxes of H$\gamma$, H$\beta$, H$\alpha$, HeII$\lambda$4686, HeI$\lambda$5876, HeI$\lambda$5016, and HeI$\lambda$4471 (in units of $10^{-15}$ erg cm$^{-2}$ s$^{-1}$).

In a next step we calculated cross-correlation functions of the 5135 Å continuum light curve with the emission line light curves. The delays $\tau$ of the integrated HeII, HeI and Balmer lines with respect to continuum variations are presented in Table 1. The time lags can be interpreted as the light-travel time across the emission line region for the different broad emission lines. The size of the line emitting region corresponds to 4 to 33 light days for the individual lines (Table 1). To get some information about the velocity field of the line emitting region we derived the widths of the broad emission line profiles (FWHM) from the rms spectra of the variability campaign. The rms spectra are free of contamination from the superimposed narrow emission lines. These narrow emission lines originate at radii of 100 to 1000 pc from the center and remain constant over timescales of years. The time lags of the strongest Balmer and Helium lines in Mrk 110 are plotted as a function of their FWHM in Fig. 4.

The line widths and time lags are clearly correlated. One can interpret the light-travel time as the characteristic distance $R$ of the line emitting region and the FWHM of the rms emission line as the characteristic velocity $v$ of the line emitting clouds. Those emission lines that originate closer to the central black hole exhibit broader emission line widths.

It is possible to determine the central black hole mass under the assumption of Keplerian
orbits of the line emitting clouds:

\[ M_{\text{orbital}} = f v^2 G^{-1} R. \]

Here is \( v \) the characteristic emission-line velocity (rms line width), \( G \) the gravitational constant, and \( R = \tau c \) the distance of the line emitting region from the center (\( \tau \) = calculated cross-correlation lag of line emitting region).

From all the emission lines we calculated a mean black hole mass of \( 1.8 \cdot 10^7 M_\odot \) in Mrk 110 (Table 1, [2]).
Table 1. Rms line widths (FWHM) of the strongest emission lines: H\textalpha, H\textbeta, HeI\lambda5876, and HeII\lambda4686; cross-correlation lags \(\tau\) and virial mass estimations \(M\) of the central black hole on Mrk 110

| Line    | FWHM (rms) \([\text{km s}^{-1}]\) | \(\tau\) \([\text{days}]\) | \(M\) \([10^7 \text{M}_\odot]\) |
|---------|-------------------------------|----------------|------------------|
| HeII    | 4444 ± 200                    | 3.9 ± 2      | 2.25 ± 3         |
| HeI     | 2404 ± 100                    | 10.7 ± 6     | 1.81 ± 4         |
| H\textbeta | 1515 ± 100                   | 24.2 ± 4     | 1.63 ± 4         |
| H\textalpha | 1315 ± 100               | 32.3 ± 5     | 1.64 ± 5         |

Figure 3. Normalized Balmer, HeI and HeII lines of Mrk 110 in velocity space (from [3]).

Figure 4. Distance of the Balmer and Helium emitting line regions from the central ionizing source in Mrk 110 as a function of FWHM derived from their rms line profiles. The dotted and dashed lines are model calculations for central masses of 0.8, 1.5, 1.8, 2.2, and 2.9 \(\cdot 10^7 \text{M}_\odot\) (from bottom to top) (from [3]).

The relation between radius and velocity for different black hole masses is shown in Fig. 4. The dotted and dashed lines correspond to virial masses of 0.8, 1.5, 1.8, 2.2, and 2.9 \(\cdot 10^7 \text{M}_\odot\) (from bottom to top).

In a next step we sliced the broad line profiles of Mrk 110 in segments of \(\Delta v = 400\ \text{km/s}\). This corresponds to the spectral resolution. Then we computed cross-correlation functions (CCF) of all segment light curves of the Balmer and Helium lines with respect to the 5100\AA continuum light curve. The 2-D CCF give the correlations of the H\textbeta and HeI\lambda5876 line-profile segments with continuum variations as a function of radial velocity and time delay (gray scale) (Figs. 5 and 6). The contours of the correlation coefficient are overplotted.

The light curve of the central line region in H\textbeta shows the longest delay: about 30 to 40 light days. The outer line wings segments respond much faster to continuum variations when
Figure 5. This 2-D CCF gives the correlation of H$\beta$ line-profile segments with continuum variations as a function of radial velocity and time delay (gray scale). Contours of the correlation coefficient are overplotted at levels of 0.85 to 0.93 (solid lines). The dashed curves show computed escape velocities for central masses of 0.5, 1.0, and 2.0 $10^7 M_\odot$ (from bottom to top) ([3]).

Figure 6. This 2-D CCF gives the correlation of HeI$\lambda$5876 line-profile segments with continuum variations as a function of radial velocity and time delay (gray scale). Contours of the correlation coefficient are overplotted at levels of 0.85 to 0.93 (solid lines). The dashed curves show computed escape velocities for central masses of 0.5, 1.0, and 2.0 $10^7 M_\odot$ (from bottom to top) ([3]).

compared to the inner ones with a delay of less than five days.

The same trend of the velocity-delay pattern is to be seen in the HeI$\lambda$5876 line. However the delays of the HeI$\lambda$5876 segments are only half of the H$\beta$ delays as has been noted before for the integrated lines.

If one compares the observed velocity-delay pattern with model calculations [4] one can make some statements about the dominant velocity field in the broad-line region. One can rule out some simple kinematical models for the BLR in Mrk 110: the line wings show the shortest delay with respect to the continuum and react nearly simultaneously. Therefore we can rule out radial inflow or (biconical) outflow motions as the dominant motions. A Keplerian disk BLR model fulfills the observed velocity-delay pattern of a faster response of both line wings compared to the center. In addition one can see in Figs. 5 and 6 that the red line wing shows a slightly faster and stronger response compared to the blue wing. This is an indication for an additional accretion disk-wind in the BLR (see [5]).

3. Emission line variability in Mrk 926

Mrk 926 is a very broad-line Seyfert galaxy. The Balmer and Helium lines have width of about 10000 km s$^{-1}$. We are monitoring Mrk 926 since many years ([6]). Here we present results of a variability campaign taken with the Hobby-Eberly Telescope in the years 2004 and 2005 ([7]). Fig. 7 shows 15 spectra of Mrk 926 that have been taken between August and December 2005. Fig. 8 shows the continuum light curves at 4600 and 5180 Å (in units of $10^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$) and the lightcurves of the integrated emission line fluxes of H$\beta$ and H$\alpha$ (in units of $10^{-15}$ erg cm$^{-2}$ s$^{-1}$) for the year 2005. Fig. 9 gives the mean spectrum of Mrk926 for both campaigns in 2004 and 2005. The rms spectrum is shown at the bottom with two different vertical scalings. It has additionally been scaled by a factor of 6 to enhance weaker line structures. The rms spectrum shows the variable part of the line profiles: In the H$\alpha$ and H$\beta$ rms spectra are an inner double-
Peaked structure as well as two further outer blue and red components visible. Normalized mean and rms line profiles of Hα and Hβ in velocity space are presented in Figs. 10 to 12. The rms profiles of Hα and Hβ show detailed subcomponents while the mean profiles does not show these details. There is a narrow central component in the Balmer rms spectra \((v \leq \pm 600 \text{ km s}^{-1})\) and two broad inner \((v \leq \pm 6000 \text{ km s}^{-1})\) as well as outer \((v \geq \pm 6000 \text{ km s}^{-1})\) line components. Comparing the mean and rms spectra with each other one can see that these broad outer and inner line segments varied with different amplitudes.

The radius of the BLR is very small with an upper limit of 2 light-days. This is the result of the cross-correlation functions CCF(τ) of the continuum light curve at 5180 Å with the Hβ and
Hα light curves (Fig. 13). We derived an upper limit of the central black hole mass in Mrk 926 of \( M = 11.2 \times 10^7 M_\odot \) based on the delays and line-widths ([7]).

Again we sliced the Hα and Hβ velocity profiles of Mrk 926 into velocity segments of widths \( \Delta v = 400 \) km s\(^{-1}\). Then we measured the intensities of all subsequent velocity segments from \( v = -15,000 \) until \(+15,000\) km s\(^{-1}\) and compiled their light curves. The light curves of all line segments including the light curves of the continuum at 5180 Å look similar. There were no clear-cut differences between the outer and inner segments or between the red and blue wings as seen in Mrk 110 ([3]) . Subsequently we computed cross-correlation functions (CCFs) of all line segment (\( \Delta v = 400 \) km s\(^{-1}\)) light curves with the 5180 Å continuum light curve.

The derived delays of the Hα line segments with respect to the 5180 Å continuum light curve are given in Figs 14 as a function of distance to the line center. The thin solid line in Fig. 14 delineates the contour lines of the correlation coefficient at levels of 0.85, 0.75, and 0.65 for Hα. The heavy dashed line connects the centers of all cross-correlation functions for the different line profile segments. The time delay of the line segment light curves was calculated from the uppermost 10 percent of the cross-correlation functions. One can see that all segments show a
Figure 12. Normalized rms line profiles of Hα (dashed line) and Hβ (solid line) in velocity space ([7]).

Figure 13. Cross-correlation functions CCF(τ) of the continuum light curve at 5180 Å with the Hβ and Hα light curves as well as the Hβ autocorrelation function ([7]).

Figure 14. The 2-D CCF(τ,v) of Mrk 926 shows the correlation of the Hα line segment light curves with the continuum light curve at 5180 Å as a function of velocity and time delay (grey scale). Contours of the correlation coefficient are overplotted at levels of 0.85, 0.75, and 0.65 (solid lines). The heavy dashed line connects the centers of all individual cross-correlation functions ([7]).

Figure 15. Maximum response of the correlation functions of the Hα (solid line, filled square) and Hβ (dashed line, open circle) line segment light curves with the continuum light curve at 5180 Å as well as their normalized rms profiles. The response curves are shifted by 0.5 to avoid strong overlap of the curves ([7]).

more or less constant delay of two to three days. Further details regarding the delay could not be resolved with our sampling rate.

Fig. 15 shows the maximum response of the Hα and Hβ line segment cross-correlation functions. It is surprising that the characteristics of the Hα and Hβ line segment responses have the same pattern. The response is independent of the intensity of the line segments. There
are two pronounced outer minima at -6 000 and +7 600 km s\(^{-1}\) in the response distribution as well as two central minima at -400 and +800 km s\(^{-1}\). It is interesting that the double structure in the H\(\alpha\) and H\(\beta\) response curves which contains two separate inner and outer components has been found before in the rms profiles. The same pattern was derived in a completely different way. The structured response may be considered as an independent evidence of a structured BLR in addition to the structure found in the rms profiles.

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