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Kinematics in the central Broad Line Region of AGN

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Abstract. The broad emission lines in the spectra of Seyfert galaxies originate in the innermost line emitting region (BLR) that is surrounding the central supermassive black hole. The variability of the integrated emission lines with respect to the variable continuum gives us information on the distance of the line emitting region. Line profile variations contain information on geometry and kinematics of the broad line region. We present 2D-reverberation mapping studies of three Seyfert galaxies: Mrk 110, NGC 4593 and Mrk 926. There are strong indications for the existence of accretion disks in Mrk 110 and NGC 4593. Further velocity components might be overlaid in the BLR. In the case of Mrk 926 we could not resolve the BLR in detail because of its extreme small broad line region.

Key words. Galaxies: active – Galaxies: Seyfert – Galaxies: nuclei – Galaxies: individual – (Galaxies:) quasars: emission lines

1. Introduction

The central broad line region (BLR) in active galactic nuclei is the emitting region of the variable broad emission lines. This region is spatially unresolved on direct images. It is the innermost line emitting region in active galaxies. The region is located next to the central ionizing source surrounding a supermassive black hole. The BLR has a diameter of the order of light months to light years only.

The spectra of the BLR contain information on the energy emitted by the central ionizing source. Furthermore, the bulk motions in the BLR must be dominated by the central black hole. Studying the variable central ionizing source in the UV or optical continuum and the delayed response in the variable broad emission lines gives us information about size and structure of the broad emission line region. A detailed comparison of the process of line profile variations with theoretical models gives us the possibility to discriminate whether radial outflow or inflow, turbulent motions, or Keplerian orbits of the line emitting clouds are dominant in this region. By knowing correctly the geometry and kinematics of the broad line clouds one can estimate quite accurately the central black hole mass.

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2. Theoretical BLR kinematics

The mean distance of the broad line emitting regions with respect to the central ionizing source can be estimated by correlating the light curves of the integrated emission line intensities with the light curves of the variable continuum intensities.

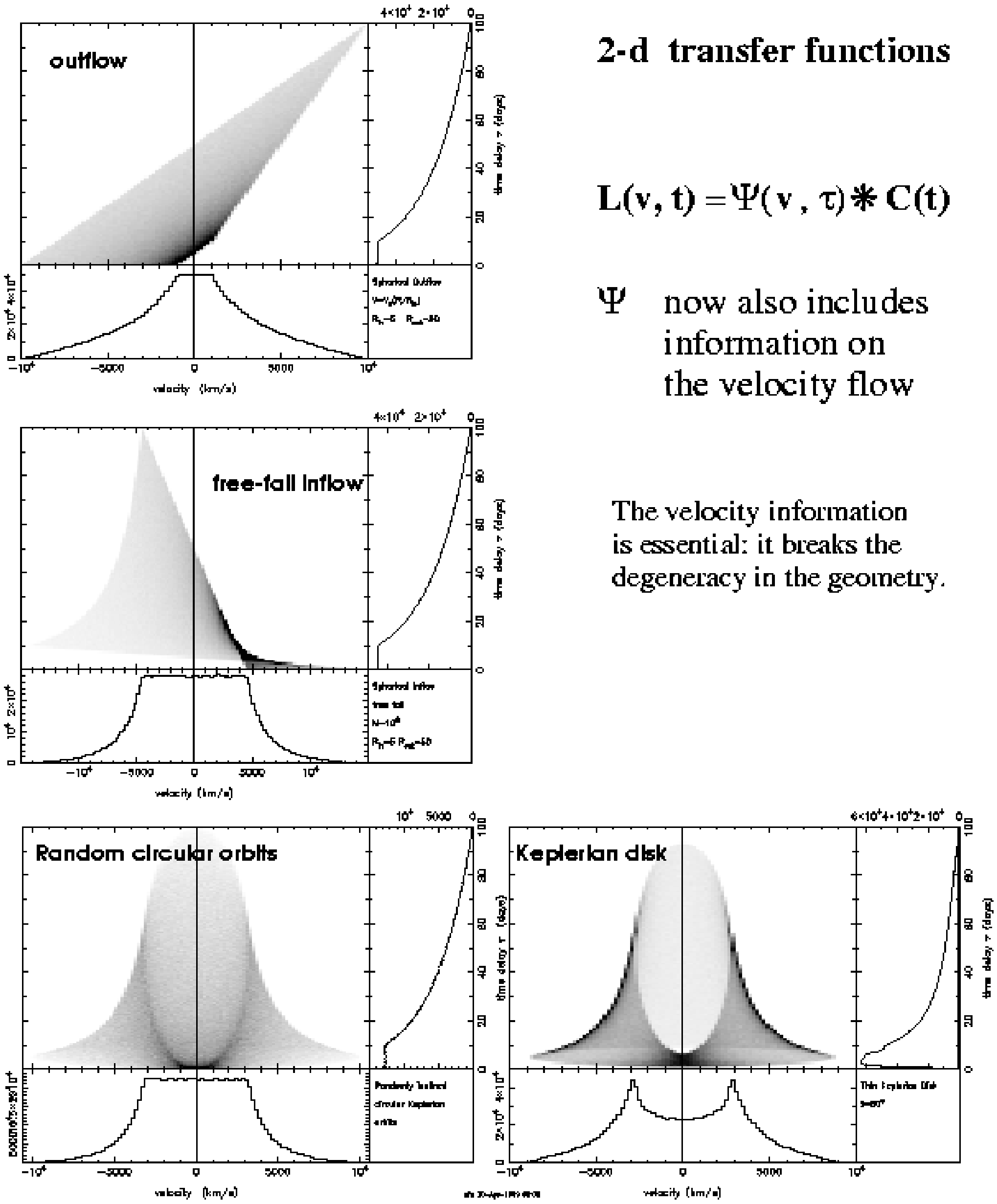

Fig. 1. Theoretical velocity-delay maps for different motions in the BLR (Welsh & Horne 1991).

Two dimensional echo images include line profile informations too and are sensitive to both the geometry and the velocity of the Broad Line Region. Welsh & Horne (1991) were among the first authors who developed two-dimensional echo images i.e. transfer functions that map continuum variations to emission line variations at each velocity

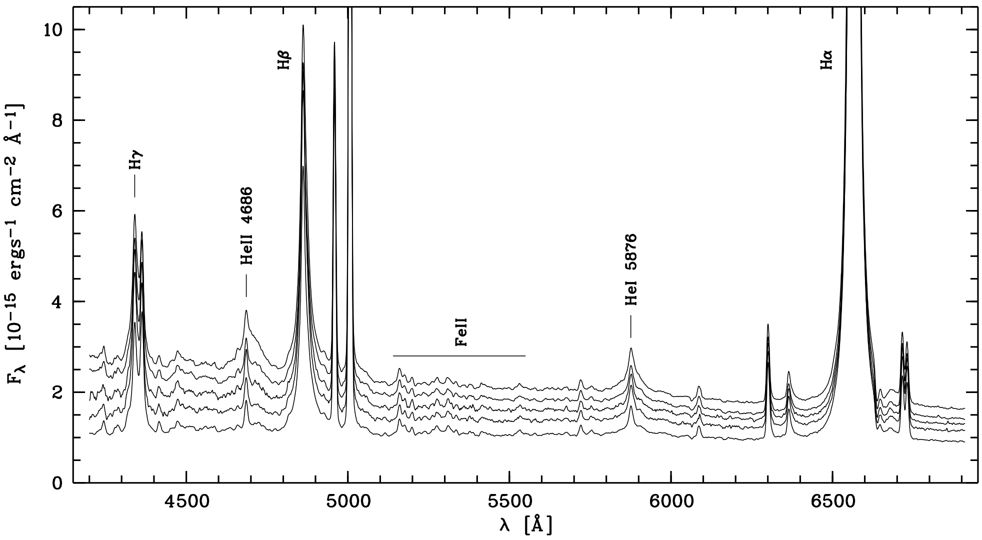

Fig. 2. Spectra of Mrk 110 taken with the 10m Hobby-Eberly Telescope at five epochs with a typical time interval of one month (from Kollatschny et al. 2001).

bin across an emission line. They described methods for constructing echo images from given BLR models and they presented echo images for spherical accelerated outflows, spherical free-fall inflows, circular Keplerian orbits at random orientations and Keplerian disk models at various inclinations. Fig. 1 shows some theoretical velocity-delay maps for different motions in the BLR. These theoretical velocity-delay maps can be compared with observed velocity-delay pattern in variable Seyfert 1 galaxies for constraining the geometry and kinematics of their BLR.

3. Observations and kinematics

We studied the variable line profiles of bright nearby Seyfert galaxies in different observing campaigns. These campaigns lasted six to twelve months. We took the spectra of our target galaxies every few days.

Here we will present results for three Seyfert galaxies having different broad line widths.

3.1. Mrk 110

Mrk 110 is a narrow-line Seyfert 1 galaxy with respect to their widths of the Balmer lines. These lines have widths of 1400 km/s. We investigated the spectral variablity of Mrk 110 with the 9.2-m Hobby-Eberly Telescope (HET) at McDonald Observatory over a period of 7 months (Kollatschny et al. 2001). The average interval between the observations was 7.3 days and the median interval was only 3.0 days. Fig. 1 shows some of our spectra we obtained during the campaign.

We correlated the integrated Balmer and Helium emission line intensity variations with respect to the continuum variations. An ionization stratification of the BLR could be verified considering the delays of the Balmer lines (20 to 30 light days) and Helium lines (4 to 15 light days). We determined a central black hole mass of $M = 1.83^{+0.54}_{-0.30} \times 10^7 M_\odot$ from the radial distances of different emission lines and their line widths. The calculated central masses derived from the different emission lines agree within of 20%.

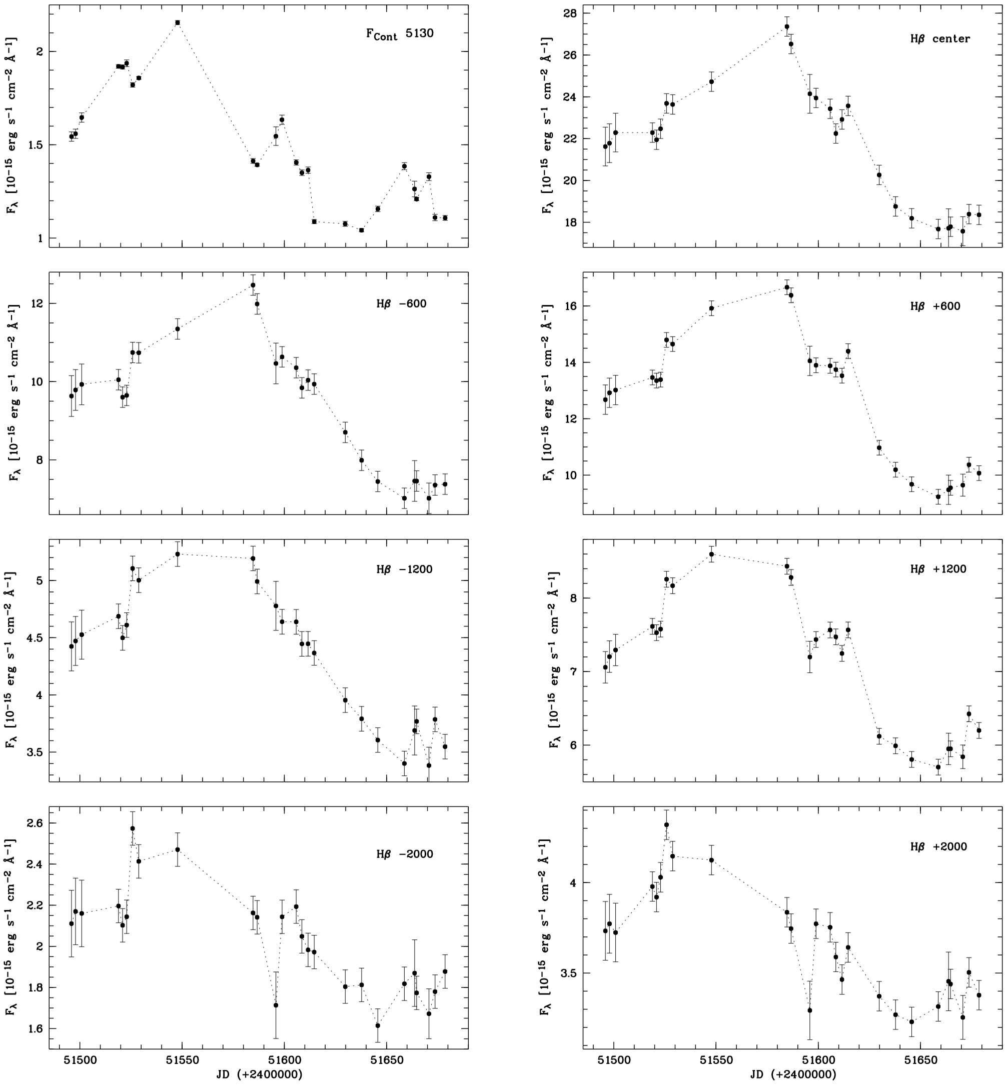

Fig. 3. Light curves of the continuum, of the Hβ line center as well as of different blue and red Hβ line wing segments ($v = \pm$ 600, 1200, 2000 km/s, Δv = 200 km/s) derived from our HET variability campaign of Mrk 110 (Kollatschny & Bischoff 2002).

Afterwards, we sliced the broad line profiles of Mrk 110 in segments of Δv = 400 km/s. The light curves of the optical continuum and of selected Hβ segments are shown in Fig. 3 (the Hβ line center, as well as the blue and red Hβ line wing segments). The light curves of the individual line segments are noteworthy different. However, light curves of the corresponding red and blue line segments are different to a lesser degree.

In a next step we computed cross-correlation functions (CCF) of all Hβ line segment light curves with respect to the 5100Å continuum light curve. The derived a delay map from the cross-correlation functions of all Hβ line segments (Δv = 400 km/s) is shown in

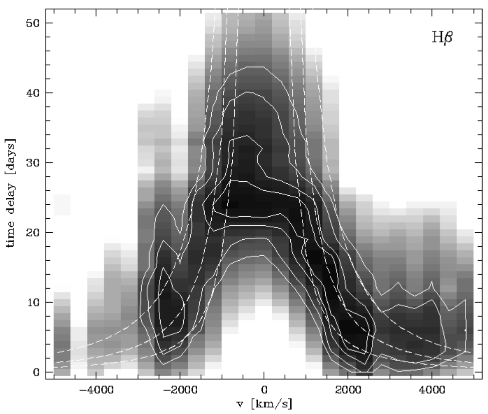

Fig. 4. The 2-D CCF(τ,v) of Mrk 110 shows the correlation of the Hβ line profile with continuum variations as a function of velocity and time delay (grey scale). Contours of the correlation coefficient are overplotted at levels of .85, .88, .91, .925 (solid lines). The dashed curves show computed escape velocities for central masses of 0.5, 1.0, 2.0 $\times$ $10^7 M_\odot$. (from bottom to top) (Kollatschny & Bischoff 2002).

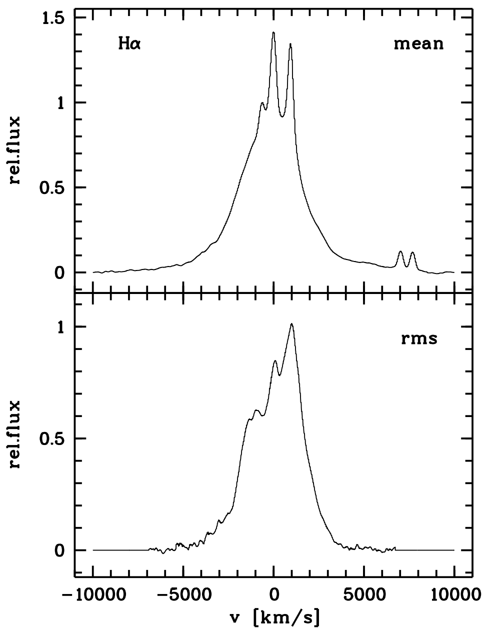

Fig. 5. Mean and rms profiles of Hα in NGC 4593 (Kollatschny & Dietrich 1997).

Fig. 4 in gray scale. The contours of the correlation coefficient are overplotted. The light curve of the central line region shows the longest delay: about 30 to 40 light days. The outer line wings segments respond much faster to continuum variations when compared to the inner ones with a delay of less than five days.

When comparing the observed velocity-delay pattern with model calculations of e.g. Welsh & Horne (1991) one can rule out a lot of 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. However, a Keplerian disk BLR model fulfills exactly the observed velocity-delay pattern of a faster response of both line wings compared to the center. A slightly faster and stronger response of the red line wing compared to the blue wing - as seen in Fig. 4 - is predicted in the disk-wind model of the BLR of Chiang & Murray (1996).

3.2. NGC 4593

NGC 4593 is a nearby Seyfert 1 galaxy with normal Balmer line widths of the order of 3500 km/s. This galaxy has been one of the key objects of a five months line profile variability monitoring campaign (Lovers of Active Galaxies: LAG) of six Seyfert galaxies and two quasars. Typically once per week high signal to noise spectra were taken at La Palma, Spain. These spectra were taken at the 4.2 m William Herschel Telescope (WHT) and at the 2.5 m Isaac Newton Telescope (INT).

Mean and rms Balmer line profiles have been calculated from all available spectra. Normalized Hα profiles are plotted in Fig. 5. The rms profile is steeper than the mean profile (Kollatschny & Dietrich 1997).

We divided the broad Hα profile in 7 segments with respect to the shape of the rms profile. The core segment contains the central component only. The inner wing components include the strong line components at (v_{rel} = $\pm$1000 km s^{-1}) and the remaining parts of the line wings have been divided in two fur-

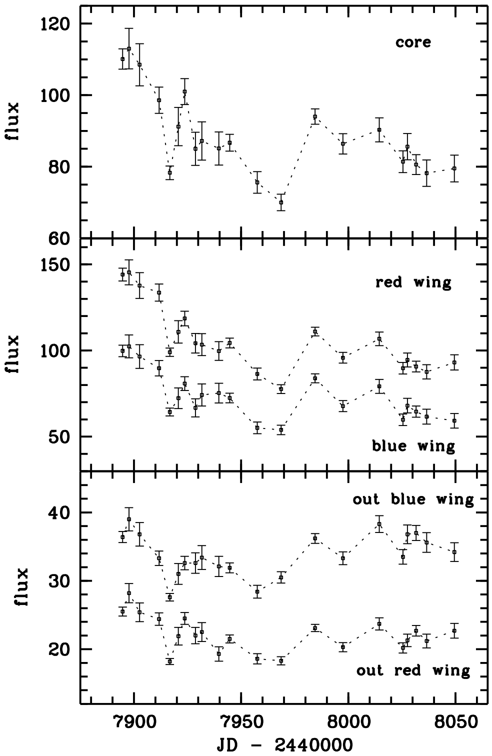

Fig. 6. Light curves of the Hα line core, of the integrated inner and middle wings (blue wing shifted by -30 flux units) as well as of the outer wings (blue wing shifted by 5 flux units) in NGC 4593. The points are connected by a dotted line to aid the eye (Kollatschny & Dietrich 1997).

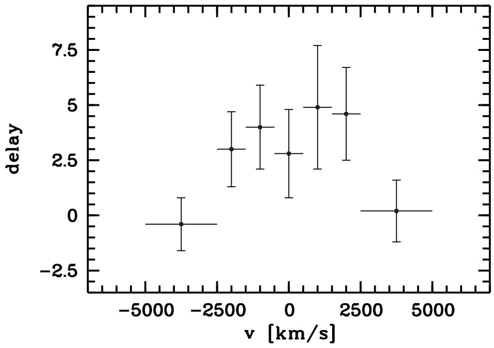

Fig. 7. Results of the CCF analysis of the Hα emission line sections vs. the optical continuum light curve in units of days in NGC 4593 (Kollatschny & Dietrich 1997).

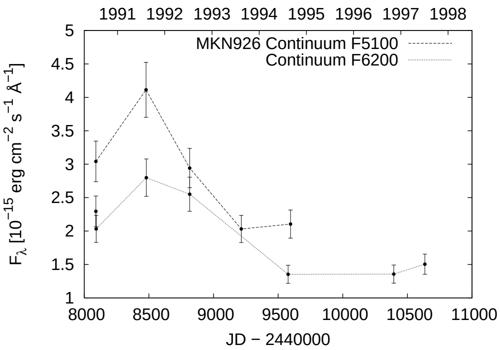

Fig. 8. Long term light curves of the continuum flux at 5100 Å (and at 6200 Å for Mrk 926) (in units of 10^{-15} erg cm^{-2} s^{-1} Å^{-1}). The points in the light curves are connected by a dotted line to aid the eye (Kollatschny et al. 2006).

ther segments. The individual light curves of the line core, of the integrated inner and middle wings as well as of the outer line wings are given in Fig. 6. One can see in NGC 4593 the same effect that has been found in Mrk 110: The light curves of line segments are different while the light curves of the corresponding red and blue line segments are similar.

The delays of the Hα segments with respect to the variable continuum are shown in Fig. 7 as function of location in velocity space. The outer Hα wings show no detectable delay within of one day with respect to the optical continuum. Therefore they originate very close to the ionizing continuum source. The cross-correlations results of the inner line wings and of the line core show that these segments originate at distances of three to five light days. Again this BLR seems to be dominated by rotational motions of a disk as in the case of Mrk 110. However, the additional indications for an outflow are less clear.

3.3. Mrk 926

Mrk 926 is another galaxy we selected for a detailed spectroscopic variability study with the 9.2m Hobby-Eberly Telescope (HET). Mrk 926 is a Seyfert 1 galaxy with very broad emission lines: the line widths (FWHM) of the Balmer and Helium lines are broader than

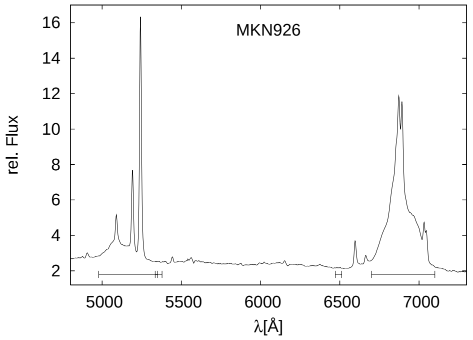

Fig. 9. Mean AGN spectrum of Mrk 926. (Kollatschny et al. 2006).

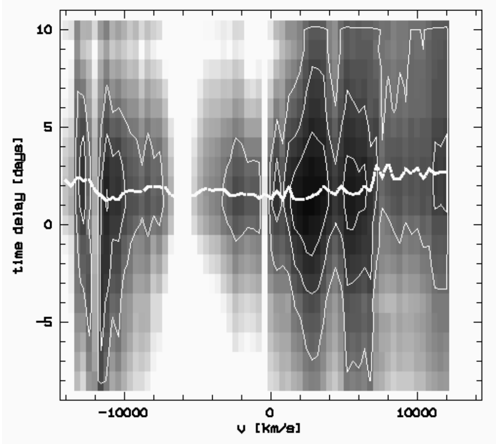

Fig. 10. The 2-D CCF(τ,v) of Mrk 926 shows the correlation of the Hα line segment light curves with the continuum light curve at 5180 Å as a function of velocity and time delay (grey scale). Contours of the correlation coefficient are overplotted at levels of 0.85, 0.75, and 0.65 (solid lines). The heavy dashed line connects the centers of all individual cross-correlation functions (Kollatschny & Zetzl 2009).

10 000 km s^{-1}. We could demonstrate in a first study on long-term variability of very broad-line AGNs (Kollatschny et al. 2006) that Mrk 926 showed strong Hβ line variability amplitudes. Fig. 8 shows the continuum variations in Mrk 926 over a period of 8 years. A mean spectrum of Mrk 926 is given in Fig. 9 demonstrating the very broad and asymmetric Balmer line profiles. We took high S/N spectra of Mrk 926 with the 9.2m Hobby-Eberly Telescope (HET) on two observing campaigns in the years 2004 and 2005. We derived mean and rms Balmer line profiles as well as light cuves of the continuum and of the Balmer lines from these data. The Balmer lines showed delays of less than five light days with respect to the ionizing continuum. Finally, we sliced the broad lines in segments of Δv = 400 km/s and correlated the individual light curves of the segments with the continuum light curve (Kollatschny & Zetzl 2009) in the same way as it has been presented before for Mrk 110. Fig. 10 shows the 2-D CCF(τ,v) 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). The delays of the individual line segments of Hα as well as of Hβ with respect to the continuum variability at 5180 Å are very short (0 to 3 light-days only) and they are more or less constant over the entire line profile. The observed uniformity of the line-segment delays of Mrk 926 is different to what has been observed in Mrk 110 before. However, an existing pattern in the 2-D CCFs of Mrk 926 might be hidden in our data due to the very small BLR. The temporal sampling of the HET campaign was insufficient to detect any detailed structures on timescales of less than four light-days.

4. Conclusions

In all three investigated Seyfert galaxies we found indications for accretion disks on basis of 2D-reverberation mapping studies while the situation is less clear in the case of Mrk 926 because of its extreme small broad line region. Furthermore there are indications that other velocity components might be overlaid in the BLR. Similar results have been found in a recent preprint by Bentz et al. (2009).

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