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# Modelling photometric reverberation data of 3C120 - evidence for a disk-like broad line region

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We consider photometric reverberation mapping, where the nuclear continuum variations are monitored via a broad band filter and the echo of emission line clouds of the broad line region (BLR) is measured with a suitable narrow band (NB) filter. In the first part of this contribution we investigate how a incomplete emission line coverage by the NB filter influences the BLR size determination. This includes the two basic cases of 1) the symmetric cut of the blue and red part of the line wings and 2) the filter positioned asymmetrically to the line center so that essentially a complete half of the emission line is contained in the NB. We find that symmetric cutting of line wings may lead to an overestimate of the BLR size which is less than about 5%. The case of asymmetric line wing cutting, as for our data of the Seyfert-1 galaxy 3C120, yields the BLR size with less than 1% bias. In the second part of this contribution we model the BLR of 3C120. We use well sampled light curves with quite sharp features, which were provided by photometric reverberation mapping at the Universitätssternwarte Bochum in Chile. The aim is to determine the geometry type of the BLR. We find that a spherical BLR yields only a poor fit of the light curves, but a thin disk-like BLR with extension from 22 to 28 light days and nearly face-on inclination $i = 10^\circ \pm 5^\circ$ reproduces all of the features of the light curve with great significance. To summarise, any BLR size bias due to narrow-band line cut in photometric reverberation mapping is usually negligible. Thanks to the well sampled light curves efficiently obtained by photometric reverberation mapping it was possible to determine the BLR geometry for 3C120.

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## 1. Introduction

Reverberation mapping of Active Galactic Nuclei (AGN) is a powerful tool to get geometric information about the inner regions of AGNs which are too small to be resolved with imaging. Here we are interested in the size and geometry of the Broad-Line-Region (BLR). While spectroscopic reverberation mapping is already well established for measuring the average BLR sizes, taking spectra requires considerable observing time and resources.

Therefore (at the Universitätssternwarte Bochum) we perform photometric reverberation mapping. We use a B-Band filter to measure the continuum variations and a narrow band filter (NB) to catch the emission line echo (Haas et al. [1]). However, it may happen that the NB filter cuts parts of the emission line. The line wings correspond to BLR clouds with fastest line of sight velocities. For Keplerian motion these coulds populate the inner zones of the BLR. Thus, for photometric reverberation mapping, one must expect that cutting the line wings may result in an overestimate of the BLR size. Another constellation is that the line is not centered in the narrow band filter. Therefore, we here examine if this leads to a possible bias in the determination of the BLR size as well.

In the second part, we model photometric reverberation light curves of the Seyfert-1 galaxy 3C120, obtained in the *B*-band and a narrow-band containing the H$\beta$ line. The aim is to distinguish between a spherical and a disk-like BLR geometry.

## 2. Modelling method

We consider two simple geometrical models for the BLR, a hollow sphere and an inclined thin disk, parameterised by inner and outer radius ($R_{inn}$, $R_{out}$) and a $r^{-2}$ density profile. It turned out that the density profile plays a minor role. We assume that the BLR clouds move on Keplerian circular orbits and react almost instantly to flux variations arriving from the center. We calculate the time-delay function of the BLR for a range of parameters. In the calculations we did not consider N individual clouds, but used equations for a continuous BLR.

For a ring with inclination $i$ (0° = face on, 90° = edge-on) in polar coordinates the time-delay is

$$\Delta\tau = \frac{r}{c}(1 - cos\phi \cdot sini)$$

where r is the length of the vector, $\phi$ its angle and c is the speed of light.

For a hollow sphere using spherical coordinates the time-delay is:

$$\Delta\tau = \frac{r}{c}(1 + sin\phi \cdot cos\Theta)$$

where r is the length of the vector, $\phi$ and $\Theta$ its angles and c is the speed of light.

## 3. The effect of cutting the line wings on the measured lags

We focus on disk-like BLR geometries as worst cases, because disks have higher proportion of line wings (fast BLR clouds) than spherical BLRs, hence disks are more effected by line-cutting.



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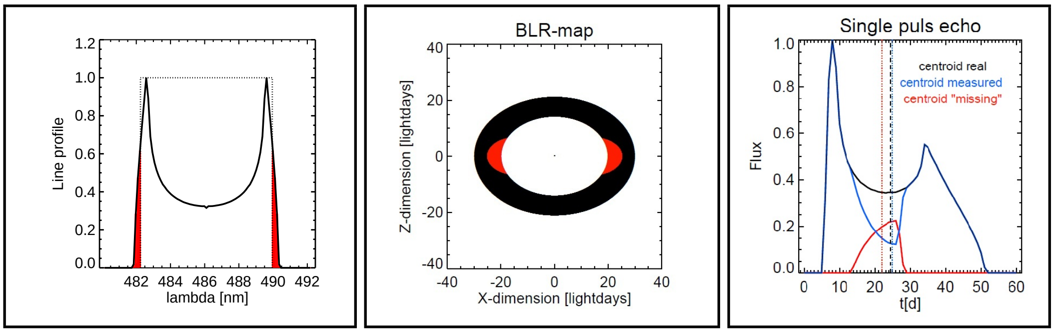


**Figure 1:** Illustration of the symmetric case for a disk-like BLR ($i = 45°$, $R_{inn} = 20$ *light days*, $R_{out} = 30$ *light days*, $v_{max} = 3700\ km/s$). Left: rectangular filter symmetrically centered on the spectral line. The parts of the line which are cut off by the filter are shaded in red. Middle: BLR areas inside (black) and outside (red) of the filter. Right: The solid curves show the time delay function of the entire BLR (black), the BLR part outside of the filter (red), and the BLR part inside of the filter (blue). The vertical dotted lines give the centroid of the respective solid curves.

### 3.1 The symmetric case for a rectangular band pass

We start with the case of an inclined disk-like BLR and a rectangular filter centred on the emission line as illustrated in Figure 1. That part of the BLR which is missed due to the NB is shaded in red. Already by eye one can see that the average echo of these innermost clouds must arrive earlier than the echo of the complete disk. The echo of an isotropic light pulse from the (point-like) central accretion disk is calculated as shown on the right panel of Figure 1. The first echo peaks lags the continuum pulse by about 7 days. It originates from the front side of the ring which is tilted towards the observer. The latest echo from the back side arrives about 40 – 50 days later than the continuum pulse.

In order to compare with observations, we measure the mean lag by the centroid of the time delay function, which corresponds to the centroid of the cross correlation of two light curves. The mean true lag of the entire BLR is 24.5 days. The BLR part missed by the narrow band filter is that with the highest line-of-sight velocity (red shaded). The echo of this region has a mean lag of 22 days. Nevertheless, for the BLR covered by the narrow band the measured echo has a mean lag of 25 days. This is only 2% larger than the true mean BLR size. The reason for the remarkably small deviation between measured and true BLR size is that the loss is taking place close to the centroid, while the outer parts remain untouched. (see Figure 1, right)

Further simulations of a range of BLR geometries and extensions show that – except for extremely broad emission lines – the bias in overestimating the mean BLR size is clearly smaller than 5%, hence smaller than other BLR size errors (C. Bruckmann [1]).

### 3.2 The asymmetric case as for 3C120

The symmetric case of a line being centred in the narrow band is rather the exception than the rule. The question is. Would an asymmetric positioned filter make the situation worse?

3C120 lies at redshift $z = 0.033$ so that the H$\beta$ line is shifted from 486.1 nm to 502.1 nm. Thus, H$\beta$ falls roughly into the OIII filter (500.7 nm, FWHM 5 nm) although neither symmetrically

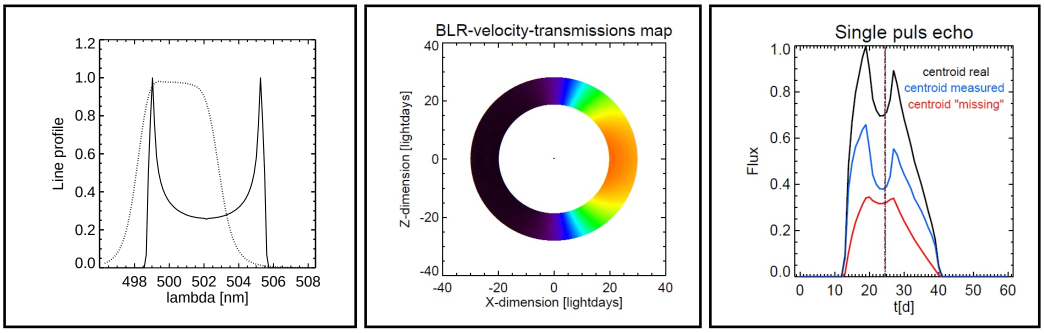


**Figure 2:** Illustration of the asymmetric case for a disk-like BLR as for 3C120 ($i = 10^\circ$, $R_{inn} = 22$ *light days*, $R_{out} = 28$ *light days*, $v_{max} = 2850\ km/s$). Left: Position of the H$\beta$ line relative to the used OIII filter. Middle: BLR areas inside (black) and outside (colored) of the filter. Right: The solid curves show the time delay function of the entire BLR (black), the BLR part outside of the filter (red), and the BLR part inside of the filter (blue). The centroids of the respective solid curves are plotted by the vertical dotted lines, which virtually coincide.

nor completely, as illustrated on the left panel of Figure 2. Remarkably, the H$\beta$ line has quite a symmetric profile and nearly the complete blue half of the line falls into the OIII narrow band.

To explore the effects of this line/filter constellation, we here use the parameters for the BLR of 3C120 which were found as best solution in the simulation below adopting circular Keplerian orbits. The middle panel of Figure 2 shows the part of the BLR entirely covered by the NB (black), and those parts which are missed (red) or only partly contained (blue/green/yellow) in the NB. The right panel of Figure 2 shows the echo of an isotropic light pulse from the (point-like) central accretion disk. The solid curves stand for the entire BLR (black), the missing part of the BLR (red) and the part contained in the NB (blue), weighted with the transmission. Notably, the centroids of the light echoes nicely agree, demonstrating that any bias is negligible.

## 4. BLR geometry of 3C120 from light curve modelling

The photometric reverberation data of 3C120 were obtained in the *B*-band and a narrow-band containing the H$\beta$ line (Pozo et al. [2], see also Pozo et al. this proceeding). Here, the aim is to distinguish between a spherical and a disk-like BLR geometry by means of light curve modelling. Figure 3 shows the *B* and H$\beta$ light curves. The light curves are well sampled and feature rich.

The *B* light curve has been corrected for host-galaxy contributions, hence represents essentially the pure AGN light curve, used in the modelling as triggering input. The H$\beta$ light curve has been constructed from the NB light curve corrected for continuum contributions derived from the *V* band curve. Nevertheless the H$\beta$ light curve may still contain non-variable contributions, for instance from the narrow line region. In order to use the H$\beta$ light curve as tracer for the BLR echo such contributions need to be removed. To determine the potential non-variable contribution to the H$\beta$ light curve, we performed a long trend analysis. Because the BLR size is in the order of 25 light days, on longer times scales ($<$100 days) both *B* and H$\beta$ should show the same long term trend, which is not the case in the original data. However, after subtraction of a suitably scaled non-variable contribution ($\sim$25%) from the H$\beta$ light curve and subsequent re-normalisation the long term trends agree excellently. We use this rectified H$\beta$ light curve as echo for the modelling.

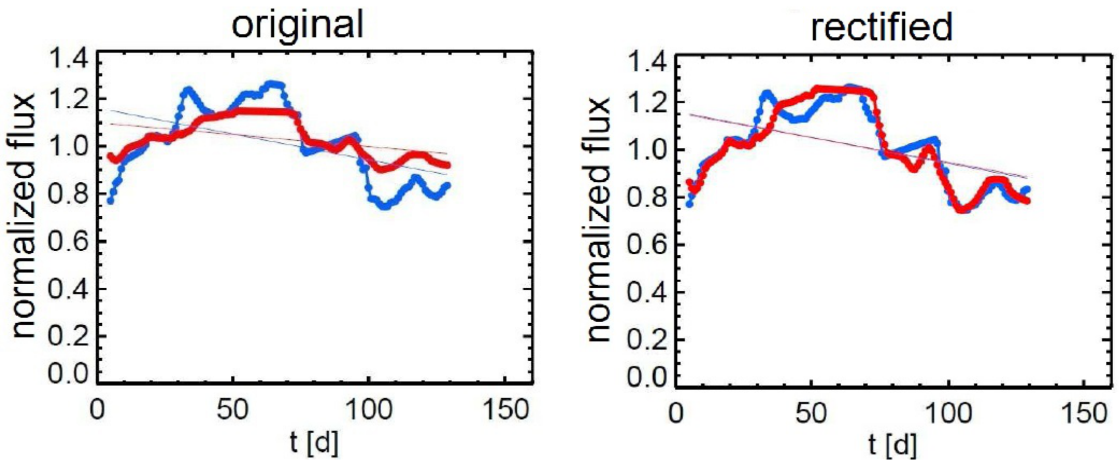


**Figure 3:** Light curves of 3C120 in $B$ (blue) and $H\beta$ (red), normalized to their mean. The $H\beta$ light curve is shifted back by the estimated time lag of 25 days. The thin lines represent the long term trend quantified by a linear fit to the light curves. Left: Original light curves; the long term trends of $B$ and $H\beta$ appear to differ. This is due to a non-variable flux contribution in the $H\beta$ light curve. Right: After determination and subtraction of the non-variable flux in the $H\beta$ light curve and re-normalisation the long term trends agree.

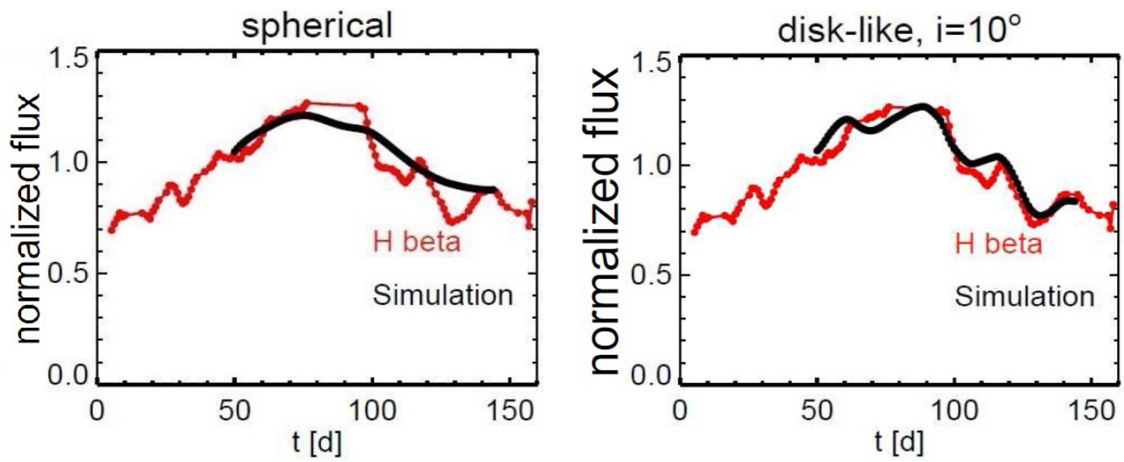


**Figure 4:** $H\beta$ light curve (red) and best modelling results (black) for a spherical (left) and a disk-like (right) BLR. The model results are shown only after the inital settle-down phase (~50 days), to account for the unknown continuum light curve before day zero.

By combining the time-delay function for a range of spherical and disk-like BLR parameters with the triggering light curve of the AGN continuum, we created echo light curves and compared them with the $H\beta$ light curve. Figure 4 shows the best simulation results for a spherical and a disk-like BLR. Of special importance are the pronounced sharp features in the $H\beta$ light curve, for instance the sudden declines at day ~70 and ~90. Even the best spherical fit does not well reproduce the sharp features, questioning a spherical BLR for 3C120. However, the best disk like model with an inclination of 10° well reproduces the features of the $H\beta$ light curve, providing strong evidence in favour of a disk-like BLR in 3C120.

Based on detailed spectroscopic reverberation mapping and velocity-delay maps of 3C120, Grier et al. ([3]) find also evidence for a disk-like BLR. Remarkably, our results have been obtained without explicit velocity information, but under the assumption that the BLR is essentially virialised. Actually, the light curves do not depend on the velocity of the BLR clouds, but on the location of the clouds, hence the BLR shape. This explains why it is possible – under favourable conditions as in our case of 3C120 – to infer the BLR shape even from photometric reverberation data.

## 5. Summary

We have investigated two topics with regard to the efficient technique of photometric reverberation mapping.

Firstly the question is examined, how the determination of the BLR size is affected, if the broad emission line is not fully covered by the chosen narrow band filter. By modelling a range of configurations, we find that possible biases for the BLR size are smaller than a few percent. Asymmetric cutting of emission line by the filter has even smaller effects. Thus, BLR sizes from narrow-band photometric reverberation mapping are quite reliable.

Secondly motivated by these positive results, we modelled the feature rich photometric reverberation light curves of 3C120 to determine the basic geometry of the BLR, whether it is spherical or disk-like. To this end we developed a consistent solution for the amplitude problem, that is the proper absolute scaling of the AGN continuum and echo light curves. While a spherical BLR-model does not fit the observation, a disk-like BLR model with extension from 22 to 28 light days and inclination $i = 10^\circ \pm 5^\circ$ provides an excellent reproduction of the H$\beta$ light curve of 3C120.

## References

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