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Photometric reverberation mapping of 3C120

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We report about a photometric campaing of the local active galactic nuclei (AGN) 3C120. The broad line region (BLR) size and the host-subtracted AGN luminosity were obtained through photometric reverberation mapping. The Hβ emission line responds to continuum variations with a rest frame lag of 23.6 ± 1.69 days. Using the flux variation gradient (FVG) method we determined the host galaxy subtracted rest frame 5100Å luminosity at the time of our monitoring campaign with an uncertainty of 10% ($L_{\rm AGN} = (6.94 \pm 0.71) \times 10^{43} erg\ s^{-1}$). Compared with recent spectroscopic reverberation results, 3C120 shifts in the R_{BLR} - L_{AGN} diagram remarkably close to the theoretically expected relation of $R \propto L^{0.5}$. This campaign is part of an ongoing photometric survey of Seyfert 1 galaxies conducted with robotic telescopes located near Cerro Armazones in Chile.

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1. Introduction

Reverberation mapping [4], where spectroscopic monitoring is used to measure the response delay τ of the broad emission lines to nuclear continuum variations, has proven to be a powerful tool to measure the average distance of the BLR clouds to the central source $R_{\rm BLR} = \tau \cdot c$. From theoretical considerations [15], the relationship $R_{\rm BLR} \propto L_{\rm AGN}^{\alpha}$, between H$\beta$ BLR size and nuclear luminosity (5100Å), should have $\alpha = 0.5$. This has been investigated intensively [12, 10, 11, 2, 3], with the latest observational result being $\alpha = 0.519^{+0.063}_{-0.066}$.

If constrained more tightly, the $R_{\rm BLR} \propto L_{\rm AGN}^{\alpha}$ relationship can be used as an alternative luminosity distance indicator. The intrinsic luminosity of the AGN ($L_{\rm AGN}$) can be inferred from the radius of the BLR ($R_{\rm BLR}$), resulting in the determination of the AGN distance. Moreover, due to the large luminosity and the extensive range of redshift at which the AGNs can be observed, the $R_{\rm BLR} - L_{\rm AGN}$ relationship offers the opportunity to discriminate between different cosmologies and to probe the dark energy [8, 22]. However, these methods require that the large scatter of the current $R_{\rm BLR} - L_{\rm AGN}$ relation can be reduced significantly, i.e. by factors up to 10, and that reverberation mapping of large samples can be performed efficiently.

Recently, Haas et al. [8] have revisited photometric reverberation mapping. They demonstrated for Ark120 and PG0003+199 (Mrk335) that this method is very efficient and even applicable using very small telescopes. Broad filters are used to measure the triggering continuum variations, while suitable narrow band filters catch the emission line response.

The estimation of the host-subtracted nuclear luminosity $L_{\rm AGN}$ is challenging as well. One may use high-resolution imaging data and model the host galaxy profile in order to disentangle the nuclear flux ([3], using HST imaging). An alternative approach is provided by the flux variation gradient method (FVG, [5, 25]). This method can be easily applied to monitoring data and does not require high spatial resolution.

3C120 is a nearby Seyfert 1 galaxy known to be strongly variable in the optical, characterized by short and long term variations with amplitudes of up to 2 mag on a timescale of 10 years [14, 23].

Here we present new measurements of the BLR size, host-subtracted AGN luminosity based on a well-sampled photometric reverberation mapping campaign, allowing us to revisit the position of 3C120 in the BLR size - luminosity relationship. As a lucky coincidence, Grier et al. [7] have carefully monitored 3C120 spectroscopically one year after our campaign allowing us to directly compare our photometric monitoring results with their spectroscopic results.

2. Observations

The photometric monitoring campaign was conducted between October 2009 and March 2010 using the robotic 15 cm VYSOS-6 telescope of the Universitätssternwarte Bochum, located near Cerro Armazones in Chile[1]. The images were reduced using IRAF[2] packages and custom written tools, following the standard procedures for image reduction.

[1]More information about the telescope and the instrument has been published by Haas et al. [8].

[2]IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

Light curves were obtained with a median sampling of 2 days in the *B*-band (Johnson band pass = 4330 ± 500 Å), *V*-band (Johnson band pass = 5500 ± 500 Å) and the redshifted Hβ (NB = 5007 ± 30 Å) line. Photometry was performed using a 7.5" aperture. The light curves are calculated relative to $\sim$ 20 nearby non-variables reference stars located on the same field, having similar brightness as the AGN. The absolute calibration was obtained using the measured fluxes of reference stars from the SA095 field [13] observed on the same nights as the AGN.

Additionally, we obtained an single epoch spectrum[3] using the Calar Alto Faint Object Spectrograph (CAFOS) instrument at the 2.2 m telescope on Calar Alto observatory, Spain. The spectrograph's slit width was 1."54.

3C120 lies at redshift $z = 0.0331$ so that the Hβ line falls into the NB 5007±30 filter. The NB filter effectively covers the line between velocities -3800km/s and +2200km/s.

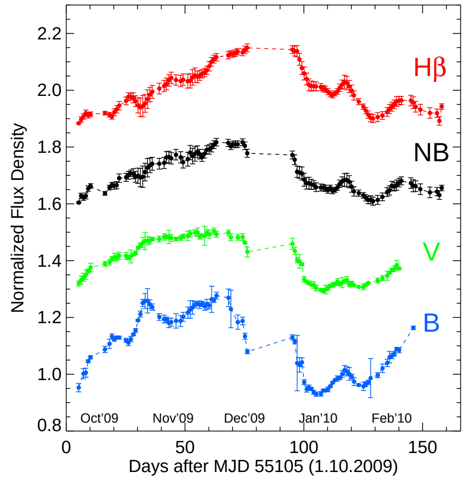

Figure 1: Observed light curves for 3C120 between Oct. 2009 and March 2010. The Hβ light curve is computed by subtracting a scaled *V* curve from the NB curve and re-normalizing it to mean = 1. The light curves are vertically shifted by multiples of 0.2 for clarity.

3. Results

3.1 Light curves and BLR size

The light curves of 3C120 are shown in Figure 1. The *V* band flux, on average, corresponds to $\sim$ 56% of the narrow band flux. Considering that the *V* flux comprises the contributions from the continuum, the Hβ and the OIII lines, we choose 50% continuum flux contribution in the NB filter. Thus, we computed a synthetic Hβ light curve by subtracting a scaled *V* curve from the NB curve, i.e. Hβ = NB − 0.5 *V*. We used the discrete correlation function (DCF, [6]) to cross correlate the light curves. The cross correlation of *B*-band and Hβ yields a time delay of 25.1 days defined by the centroid τ_{cent}. To determine the uncertainty in the time delay we applied the flux randomization and random subset selection method (FR/RSS, [17], [18]).

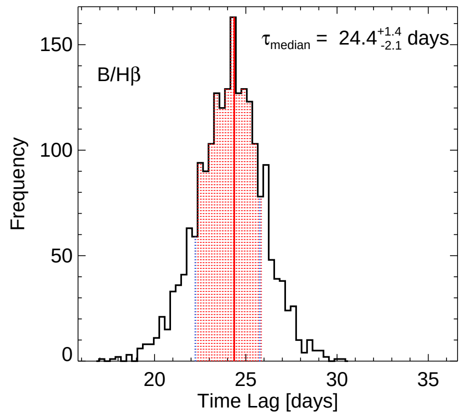

Figure 2: Results of the lag error analysis. Distribution of the centroid lag obtained by cross correlating 2000 FR/RSS subset light curves. The red area marks the 68% confidence range used to calculate the errors of the centroid.

[3]More information on the spectrum and black hole mass estimation can be found in Pozo et al. [19].

We calculated the discrete correlation function for 2000 pairs of subset light curves and the corresponding centroid (Fig. 2). This yields a median lag τ_{cent} = 24.4 $^{+1.4}_{-2.1}$ days. Correcting for the time dilation factor we obtain a rest frame lag τ_{rest} = 23.6 ±1.7 days.

3.1.1 Host-subtracted AGN luminosity

In order to determine the pure AGN luminosity, commonly at 5100Å, the contribution of the host galaxy to the nuclear flux has to be subtracted. The contribution of the host galaxy to the nuclear flux of 3C120 has been studied by Bentz et al. [2, 3] using high resolution HST imaging as well as by Winkler et al. [24, 25], and Sakata et al. [20] using the so-called flux variation gradient method, which was originally proposed by Choloniewski et al. [5]. We here apply the FVG method to our 3C120 data and compare our results with the previous ones. A detailed description of the FVG method is presented in Pozo et al. [19]. Figure 3 shows the B and V fluxes obtained during the same nights and through the same aperture in a flux-flux diagram. The host color range is taken from [20] and drawn from the origin of ordinates (dashed lines).

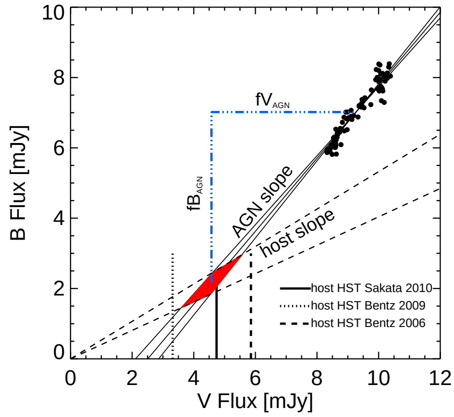

Figure 3: Flux variation gradient diagram of 3C120. The solid lines delineate the bisector regression model yielding the range of the AGN slope. The dashed lines indicate the range of host slopes determined by Sakata et al. [20] for 11 nearby AGN. The intersection between the host galaxy and AGN slope (red area) gives the host galaxy flux in both bands. The two vertical dotted and dashed lines show the host flux determined by Bentz et al. [2, 3] . The solid line shows the host flux obtained by Sakata et al. [20]. The dash-dotted blue lines represent the range of the AGN flux in both filters.

Flux Variations Gradients (FVGs) were evaluated by fitting a linear slope with the OLS bisector method, described in Isobe et al. [9]. It yields a linear gradient of $\Gamma_{BV} = 1.12 \pm 0.04$. The results are consistent with $\Gamma_{BV} = 1.11 \pm 0.02$ determined by Sakata et al. [20] and $\Gamma_{BV} = 1.02 \pm 0.07$ obtained by Winkler et al. [25]. Averaging over the intersection area between the AGN and the host galaxy slopes, we obtain a mean host galaxy flux of (2.17 ± 0.33) mJy in B and (4.58 ± 0.40) mJy in V. Our host galaxy flux derived with the FVG method is consistent with the values $f_B \approx 2.10$ mJy and $f_V \approx 4.73$ mJy obtained by Sakata et al. [20]. Note that one has to coadd the values of Tables 5 and 8 of Sakata et al. [20], in order to include the flux contribution of the narrow lines ([OIII]λ4959, 5007, Hβ, Hγ) to each filter.

The difference between the two results by Bentz et al. [2, 3] lies mainly in the type of model used for the decomposition of the galaxy. The first study considered a general Sersic function for modeling bulges [2]. The second study performed the modeling with variations and improvements to the original profile [3]. Our value ($fV_{host} = 4.58 mJy$) falls exactly in the middle between both values, simply suggesting that our determination is consistent, within the error margins. The rest frame flux at 5100Å was interpolated from the host-subtracted AGN fluxes in both bands, adopting for the interpolation that the AGN has a power law SED ($F_\nu \propto \nu^\alpha$) with a spectral index $\alpha = \log(fB_{AGN}/fV_{AGN})/\log(\nu_B/\nu_V)$, where ν_B and ν_V are the effective frequencies in the B and V bands, respectively. The error was determined by interpolation between the ranges of the AGN fluxes $\pm\sigma$ in both filters, respectively. All flux values are listed in Pozo et al. [19].

To determine the mean AGN luminosity during our campaign, we used the distance of 145 Mpc [3]. This yields $L_{\rm AGN} = (6.94 \pm 0.71) \times 10^{43} ergs^{-1}$.

3.1.2 The BLR size - luminosity relationship

Figure 4 shows the $R_{\rm BLR}$ and L_{AGN} values obtained by Bentz et al. [3], the result for 3C120 obtained by Grier et al. [7] and the two objects Ark120 and PG0003 studied with well sampled photometric reverberation mapping by Haas et al. [8]. While the relationship appears to be well defined, many objects have large uncertainties yet and/or lie quite off the regression line. Part of this may simply be due to the fact that AGN are complex objects, but part of the dispersion may be due to sparse sampling of early reverberation data.

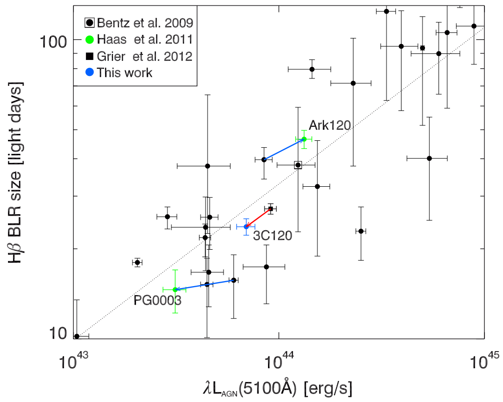

Figure 4: $R_{BLR} - L$ relationship from data of Bentz et al. [3] (black dots) with a fitted slope $\alpha = 0.519$ (dotted line). The diagram is zoomed to contain the objects of this work (3C120, blue dot) and Haas et al. [8] (Ark120 and PG0003, green dots). The blue arrows show the positional shift of the new measurements with respect to the previous ones from Bentz et al. [3]. The red arrow shows the shift of 3C120 between our result and that obtained by Grier et al. [7]. The slope α of this shift is remarkably close to the theoretically expected value of $\alpha = 0.5$. The original position of 3C120 by Bentz et al. [3] is in the center of the plot and marked by the square surrounding the fat dot.

For 3C120 we have now three positions in the R-L diagram: one from Peterson et al. [16], quite on the regression line but having large uncertainties presumably due to sparse sampling; one from the spectroscopic monitoring campaign in 2010/2011 by Grier et al. [7]; and one from our photometric monitoring campaign in 2009/2010. The last two campaigns both have a good time sampling and small uncertainties. The striking result from these two campaigns is that the slope between these positions of 3C120 is $\alpha = 0.504$, hence according to intrinsic brightness changes, 3C120 moves parallel to the theoretically expected slope (red arrow in Fig. 4). With increasing luminosity the BLR size grows proportional to the square root of the luminosity, and these changes appear to occur rather quickly, i.e. within days or weeks. Note that this does not represent physical in- or outwards movements of the clouds, rather the locally optimally emitting clouds are found at a different position [1].

4. Summary

Using a robotic 15 cm telescope located at an excellent site, we have performed a five months monitoring campaign for the Seyfert 1 galaxy 3C120. We determined the broad line region size, the virial black hole mass and the host-subtracted AGN luminosity. The results are:

1. The time lag τ_{rest} = 23.6 $\pm$1.69 days, obtained from cross correlation of the Hβ emission line with the optical continuum light curve, has changed over one year, but the physical relation $R_{\rm BLR} \propto L^{1/2}_{{\rm AGN},\lambda 5100}$ still holds. The small uncertainty in our measurements (7%) is presumably due to the well sampled photometric reverberation data.

2. Using the flux variation gradient method (FVG) and a conservatively limited host galaxy color range, it is possible to find the host galaxy subtracted AGN luminosity of 3C120 at the time of our monitoring campaign to be $L_{\rm AGN} = (6.94 \pm 0.71) \times 10^{43} ergs^{-1}$.

The new results obtained for the BLR size and AGN luminosity of 3C120 fit well into the BLR size-luminosity diagram. We conclude that photometric reverberation mapping is an attractive method with the advantage to efficiently measure the BLR and the host-subtracted luminosities for large samples of quasars and AGNs. Not only applicable with small telescopes, photometric AGN reverberation mapping could become a key tool for the upcoming large monitoring campaigns, for instance with the Large Synoptic Survey Telescope (LSST). This could be an important step forward in order to constrain cosmologial parameters from the $R_{\rm BLR} \propto L^{1/2}_{{\rm AGN},\lambda 5100}$ relationship in order to determine quasar distances and to probe the dark energy ([8, 22]) as well as to enlarge the current statistics for black hole masses.

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