Constraining cosmological parameters with reverberation-measured AGN

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The Radius-Luminosity relation (RL) offers the possibility to estimate the distance to the AGN independently of the redshift, which is suitable for cosmological analysis. However, it seems that the accretion rate induces a departure on the RL relation, which after all can be corrected. In order to improve the previous corrections and get better cosmological results, it is explored the use of the width of the line ($\sigma_{\mathrm{rms,line}}$), measured in the RMS spectrum as a velocity field for estimating the black hole mass. Also, it is used a new bolometric correction for the Eddington ratio estimation. It is not possible to get a better correction, therefore the previous correction is used to constrain the cosmological parameters.

1 Introduction

The reverberation mapping (RM) method is based on the determination of the time in which emission lines response to the continuum variations (Peterson, 2006). When a photon of the continuum finds a cloud of the broad line region (BLR), it is photoionized and emission lines are produced. The time required is called time delay and it is given by $\tau_{\mathrm{BLR}} = \mathrm{R}_{\mathrm{BLR}}/c$, where $\mathrm{R}_{\mathrm{BLR}}$ is the size of the BLR. This powerful technique has provided a more realistic view of the BLR. For example, it has been demonstrated the ionization stratification of the BLR, i.e. high–ionization lines (e.g. CIV $\lambda1549$) are emitted closer to the continuum source than low–ionization lines (e.g. Hβ or MgII).

The most important results provided by the RM method is the relationship between the size of the BLR and the luminosity of the source, $\mathrm{R}_{\mathrm{BLR}} \propto L^{\alpha}$. It is called the Radius-Luminosity relation (RL), see Fig. 1 and Fig. 2. To get an accurate time delay long-time monitoring is required, therefore only a hundred of AGN with low redshift ($z < 1$) has been reverberation-mapped. In Fig. 1 and 2 are shown the largest sample for Hβ reverberation-mapped AGN. The most accepted optical RL relation (Bentz et al., 2013) is,

$$\log\left(\frac{R_{\mathrm{BLR}}}{1\ \mathrm{lt-day}}\right) = (1.527\,\pm\,0.31)\,+\,0.533^{+0.035}_{-0.033}\log\left(\frac{L_{5100}}{10^{44}\mathrm{L}_{\odot}}\right), \tag{1}$$

where R_{BLR} is in units of light-days (1 lt–day) and L_{5100} is the continuum luminosity at 5100Å. Then, knowing the luminosity of the source (L_{5100}) is possible to determine the size of the BLR and therefore the black hole mass for single-epoch observations.

Since the RL relation offers the possibility to estimate the luminosity independently of the redshift, the estimation of the distance to the source will be also independent. Additionally, the small scatter (0.13–0.19 dex, Bentz et al., 2013; Kilerci Eser et al., 2015), shown by the RL relation makes the RM results suitable for

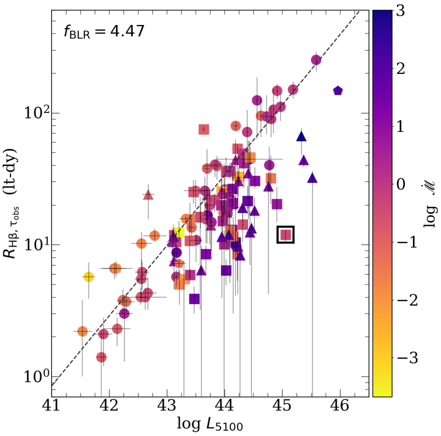

Fig. 1: Radius-Luminosity relation using a sample of Hβ reverberation-mapped AGN. Colors indicate the variation of the dimensionless accretion rate. The black square marks the position of J142052.

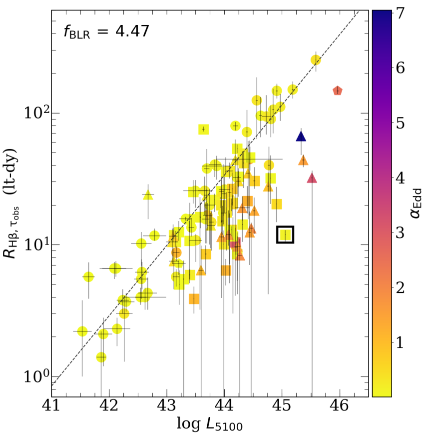

Fig. 2: Same as Fig. 1, but now colors indicate the variation of the Eddington ratio. The black square marks the position of J142052.

cosmological proofs (Watson et al. (2011); Haas et al. (2011); Czerny et al. (2013); King & Lasota (2014)).

However, the recent inclusion of reverberation-mapped sources with high accretion rates (Du et al., 2016, 2018, and references therein) has increase the scatter in the relation. This indicates that there is an effect of the accretion rate on the RL relation.

In this contribution, it is explored the use of the width of line ($\sigma_{\rm rms,line}$) in the RMS spectrum as a velocity field in the black hole mass estimation and a new the bolometric correction for the Eddington ratio estimation, in order to verify if the previous correction proposed can be improved (Section 2). In Section 3 it is explored the use of reverberation-mapped AGN for constraining cosmological parameters. In Section 4 are shown the conclusions.

2 Accretion rate effect on the RL relation

For a long time, the use of the RL relation has been the most popular method for estimating the size of the BLR and the black hole mass. However, the recent monitoring of super-Eddington sources performed by the SEAMBH (Super-Eddington Accretion in Massive Black Holes, Du et al. 2018, and references therein) team has opened new debates around the RL relation. Usually, the super-Eddington sources show the largest departures from the classical RL relation. This departure seems to be related to the level of the accretion rate, the largest departures are associated with the largest accretion rate while the low accretion rate sources follow the RL relation within uncertainties.

Along this contribution, the largest sample of Hβ reverberation-mapped AGN (117 objects) is used, which includes a collection of previous monitoring sources names as Bentz collection, the SEAMBH, and SDSS-RM samples. A description of

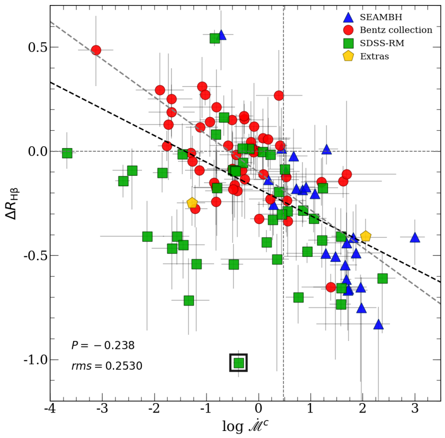

Fig. 3: Relation between the parameter ΔR and the dimensionless accretion rate, $\dot{M}$. The black and gray lines indicate the best orthogonal fit considering the full sample and excluding the SDSS-RM sample, respectively. The black square marks the position of J142052.

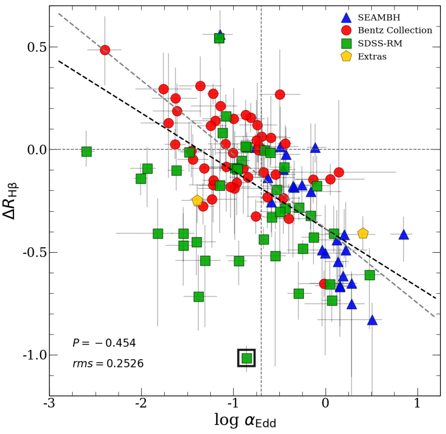

Fig. 4: Relation between the parameter ΔR and the Eddington ratio, $\alpha_{\rm Edd}$. The black and gray lines indicate the best orthogonal fit, considering the full sample and excluding the SDSS-RM sample, respectively. The black square marks the position of J142052.

the full sample is reported in Martínez-Aldama et al. (2019).

In order to estimate the black hole mass ($M_{\rm BH} = f_{\rm BLR}\frac{R_{\rm BLR}\,v^2}{G}$) we used the width of the line ($\sigma_{\rm rms,line}$) in the RMS spectrum as the velocity field, which according to Woo et al. (2015) is less affected by orientation effects than the FWHM of the line, with a proper virial factor of 4.47. The size of the BLR ($R_{\rm BLR}$) is estimated from the time delays, which are taken from Martínez-Aldama et al. (2019).

In order to estimate the accretion rate intensity the dimensionless accretion rate ($\dot{M}$[1]) Throughout the paper, it may be better to use $\dot{\mathscr{M}}$ instead of $\dot{M}$ for dimensionless accretion rate. and the Eddington ratio ($\alpha_{\rm Edd}$[2]) are used. The bolometric luminosity was estimated considering the new bolometric correction factor proposed by Netzer (2019). Figures 1 and 2 show the RL relation with the dimensionless accretion rate and Eddington ratio variations along the diagram.

For estimating the departure from the RL relation we used the parameter ΔR, which is the difference between the value estimated from the observed time delay and the expected one from the RL relation, $\Delta R = R_{\rm obs}/R_{\rm R-L}$. Figures 3 and 4 show the relations between ΔR, $\dot{M}$ and $\alpha_{\rm Edd}$, respectively. According to the Pearson coefficient, the correlation for $\dot{M}$ is weak ($P_{\dot{\rm M}} = -0.238$), while for $\alpha_{\rm Edd}$ is stronger ($P_{\alpha_{\rm Edd}} = -0.454$). An orthogonal fit was performed to estimate the trend of the relations, in both cases the *rms* value is similar and there is not a preference in any case.

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[1] $\dot{M} = 20.1\left(\frac{l_{44}}{\cos\theta}\right)^{3/2} m_7^{-2}$, where l_{44} is the luminosity at 5100 Å in units of 10^{44} erg s^{-1}, θ is 0.75, and m_7 is the black hole mass in units of 10^7 M$_\odot$ (Du et al., 2016)

[2] $\alpha_{\rm Edd} = L_{\rm bol}/L^{\rm c}_{\rm Edd}$, where $L_{\rm Edd} = 1.5\times10^{38}\left(\frac{M_{BH}}{{\rm M}_\odot}\right)$ and $L_{\rm bol} = 1\times10^{10}\,{L_{5100}}^{0.8}$

Excluding the SDSS-RM sample, it seems that both Bentz and SEAMBH samples show a stronger relation between ΔR and $\dot{M}$ (and $\alpha_{\rm Edd}$), which is confirmed by the Pearson coefficient estimation ($P_{\dot{\rm M}} = -0.299$ and $P_{\alpha_{\rm Edd}} = -0.573$). Both samples occupy a different space in the diagram which is related to the accretion rate level, but this behavior is continuous within the samples. The majority of the Bentz objects show a low accretion rate, contrary to the selection criteria of the SEAMBH sample. However, this trend disappears when the SDSS-RM sample is included. Some of the sources seem to follow the relation of the rest of the objects, but other ones are spread to the lowest accretion rates direction. This behavior can be associated with short monitoring of the sample.

As it is shown in the Appendix of Martínez-Aldama et al. (2019), the short cadence of the SDSS-RM sample could affect the determination of the time delay, and then the black hole mass and accretion rate estimations. The object J142052 is the most luminous object in the sample and it shows a spectrum similar to the expected for the highest accretors (e.g. Negrete et al., 2018), then a high accretion rate is expected. However, estimated accretion rate is smaller. It is clearly identified in Fig. 3 and 4. Therefore, the determination of the time delay in some objects is also probably affected by the short-time monitoring.

On the other hand, previously Martínez-Aldama et al. (2019) found that the best relationship is given by the dimensionless accretion rate using a virial factor anti-correlated with the FWHM of the line (Mejía-Restrepo et al., 2018; Yu et al., 2019), which is correct in some sense the orientation effects. As it is stressed in that paper, the correlation between ΔR and the accretion rate level strongly depends on the expression used for model the accretion rate level and the virial factor. The main difference with the exercise shown in this paper is the selection of the $\sigma_{\rm rms,line}$ as a velocity field and their corresponding virial factor (4.47). For modeling $\sigma_{\rm rms,line}$ the majority of the sources of the Bentz collection and a NLS1 sample, which mimics the behavior of the SEAMBH, was used. It probably explains the *correct* behavior of both samples in Fig. 3 and 4. However, SDSS-RM sample points to an unknown direction, where the time monitoring affects particularly for the highest luminous objects.

Recently, Fonseca Alvarez et al. (2019) made a similar analysis with the SDSS-RM sample and found similar results to the ones shown in this contribution. They also stress that the correlation is strong in the previous analysis, like Martínez-Aldama et al. (2019), because the parameter ΔR and $\dot{M}$ (and $\alpha_{\rm Edd}$) are not completely independent, since both depend on the black hole mass. This could be the explanation of the stronger relation shows by $\alpha_{\rm Edd}$ in this contribution, since the bolometric correction factor depends on the luminosity.

Therefore, a new independent method to estimate the black hole mass is required, in order to calibrate the results provided by the RM method and clarify a real dependence between the parameters. Additionally, long-time monitoring, a clear view of the dynamics of the BLR (which solve the virial factor and the orientation effect problems), high redshift sources are still required to understand the physics behind the RL relation.

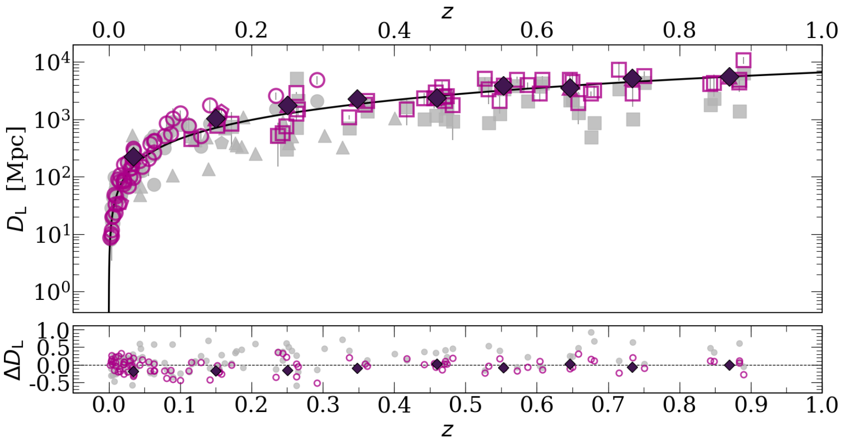

Fig. 5: Top panel: Hubble diagram. The black line corresponds to the ΛCDM model. Grey symbols mark the RM results before the correction by the accretion rate, while open symbols correspond to the ones after the correction by the accretion, respectively. Black diamonds correspond to the average values for the Luminosity distance considering redshift bins of $\Delta z = 0.1$. Bottom panel: the difference between the expected luminosity distance and the observed one. Color and symbols are the same as the top panel.

3 The use of the RL relation in cosmology

The low scatter in the RL relation offers the opportunity to determinate the luminosity distance independent of redshift and foregrounds the RM results to the cosmological analysis. However, the inclusion of the super-Eddington sources moves the RM results away from this purpose. Martínez-Aldama et al. (2019) tried to correct the scatter proposing a correction depending on the accretion rate level. In this contribution, we have repeated the same exercise, but considering $\sigma_{\rm rms,line}$ as a velocity field. However, the correction does not improve. Statistically, the previous results considering a dimensionless accretion rate and a virial factor anticorrelated with the FWHM of the line (Martínez-Aldama et al., 2019) are best. In this section is reviewed the process to obtain the cosmological parameters considering the results of Martínez-Aldama et al. (2019).

Since the luminosity can be determine from the RL relation, it is only required the flux, and then it is possible to determinate the distance to the source or the luminosity distance, $D_{\rm L} = \left(\frac{L_{5100}}{4\,\pi\,F_{5100}}\right)^{1/2}$. Then, it is possible to build a Hubble diagram and get the cosmological parameters. In Fig. 5 is hown the Hubble diagram, where the black line indicates the ΛCDM model (Planck Collaboration, 2018), which is the most accepted cosmological model nowadays. For comparison, it is included $D_{\rm L}$ after (open symbols) and before (gray symbols) the correction by the accretion rate effect. It is clear that the estimations after the correction show a better agreement with the ΔCDM, while the estimations before tends to be below. It is reflected in the bottom panel, where the difference between the expected luminosity (from ΔCDM) and the observed ones are smaller in the first case. As a visual representation, we also show the luminosity distance considering redshift bins of $\Delta z = 0.1$ (black symbols), however, it does not have any statistical relevance.

However, the estimation of the cosmological parameters indicates an agreement with the standard cosmological model, but with large errors (within 1σ confidence level). Previous results using other techniques give smaller errors (Risaliti & Lusso, 2019). Therefore, an increment in the sample and larger redshift ranges are required to improve the measurements.

4 Conclusions

In the present contribution we considered the $\sigma_{\rm rms,line}$ of the rms spectrum to try to improve the accretion rate effect, which induces a departure in the RL relation. However, there is not an improvement with respect to the previous results proposed by Martínez-Aldama et al. (2019). The use of $\sigma_{\rm rms,line}$ does not ensure better cosmological constraints. In order to decrease the uncertainties, many aspects have to be improved: virial factor, long-time monitoring of the sources, large RM samples, high redshift ranges, orientation effects, etc. In the near future, new surveys like LSST (Ivezić et al., 2019) or oz-DES (King et al., 2015) will use the RM technique to monitor a big number of sources. Then, many of the previous problems will be solved, but some effect like the accretion rate one must be considered.

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