

SPECTROSCOPY AND SPECTROPOLARIMETRY OF AGN: FROM OBSERVATIONS TO MODELLING

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Abstract. Active galactic nuclei (AGN) are one of the most luminous objects in the Universe, emitting powerful continuum and line emission across all wavelength bands. They represent an important link in the investigations of the galaxy evolution and cosmology. The resolving of the AGN inner structure is still a difficult task with current instruments, therefore the spectroscopy and spectropolarimetry are crucial tools to investigate these objects and their components, such as the properties of the supermassive black hole, the broad line region, and the dusty torus. In this review, we present the results of the project "Astrophysical spectroscopy of extragalactic objects", from the observations, data processing and analysis, to the modelling of different regions in AGN.

1. INTRODUCTION

Active galactic nuclei (AGN) are in the focus of the modern astrophysical investigation, since it is widely believed that all galaxies had at least one phase of high activity (AGN phase) in their life-time. Moreover, the AGN feed back huge amount of energy into surrounding medium, which may have influence on all scales, from the host galaxy to the intergalactic medium. Therefore, it is important to understand the structure of AGN and their radiation processes.

AGN host in their center super-massive black hole (SMBH) which is actively fueled by gas through the accretion disk. The accretion disk is emitting the X-ray continuum (and also Fe K α line) that is a powerful source of radiation which ionize the surrounding gas. The ionized gas that is very close to the central SMBH emits broad emission lines (with full width at half maximum - FWHM of $> 1000 \text{ km s}^{-1}$), that is

called the broad line region (BLR), whereas the ionized gas far from the center emits narrow lines ($\text{FWHM} < 1000 \text{ km s}^{-1}$), and consequently it is called the narrow line region (NLR). The BLR sometimes can be obscured by the dusty torus-like region, depending on the orientation of the system. Using the obscuration as a criterion, we can divide AGN into two classes: the type 1 AGN (the BLR is not obscured), which show the broad and narrow emission lines in the UV/optical/IR spectra, and type 2 (the BLR is obscured) AGN, which have only narrow emission lines. Even though we know the general model of these objects, there are still many open questions. Some important ones are: i) what is the structure and kinematics of the BLR; ii) how to estimate the mass of the central SMBH, iii) are there present and how to detect binary SMBH, iv) what is the structure of the dusty torus, and many others. In order to answer these, the spectroscopic and spectropolarimetric observations can give us great insight into these hidden regions.

The investigation the AGN structure using spectroscopy, spectropolarimetry and other methods/effects (simulations, gravitational milli- and micro-lensing, etc.) have been a subject of the project "Astrophysical spectroscopy of extragalactic objects" (P.I. L.Č. Popović), that was accepted in 2010, and has been funded (until the end of 2017) by the Ministry of Education, Science and Technological Development of Republic of Serbia. In our research we try to fix some questions given above and here we give an overview of recently obtained results.

2. LONG-TERM OPTICAL MONITORING OF AN AGN SAMPLE

AGN show high variability in their spectra, that can be used to probe the kinematics and physics of the BLR by comparing the variability of the continuum and broad emission line fluxes. Therefore we performed the long-term optical monitoring campaign of several type 1 AGN, whose broad emission lines have different spectral characteristics: Seyfert 1 galaxies (NGC 5548, NGC 4151, NGC 7469), Narrow-line Seyfert 1 galaxy - NLSy 1 (Ark 564), double-peaked line radio loud (3C 390.3) and radio quiet (Arp 102B) galaxy, and a luminous quasar (E1821+643). Additionally, we explore variability of two AGN in spectro-polarization: 3C390.3 and Mrk 6. The spectral observations were done with six telescopes based at four different observatories: the Special Astrophysical Observatory (SAO) of the Russian Academy of Science in Russia (1-m and 6-m telescopes), the Guillermo Haro Astrophysical Observatory in Mexico (2.1-m telescope), the Observatorio Astronomico Nacional at San Pedro Martir in Mexico (2.1-m telescope), and the Calar Alto Observatory in Spain (3.5-m and 2.2-m telescopes). The spectro-polarimetric observations were performed with 6m telescope of the SAO using the modified spectrograph SCORPIO.

To study AGN, we use reverberation mapping that uses temporal fluctuations of the central continuum source, and the subsequent response of the BLR emission. The time delay between the continuum and the broad line fluctuations provides an estimate of the size of the BLR, and can also be used to estimate the black hole mass. Our reverberation mapping measurements of the radius of the BLR are based on the Z-transformed Discrete Correlation Function and procedures that model the statistically likely behavior of the light curves in the gaps between observations (e. g. JAVELIN, Gaussian process regression-GP). These procedures were applied on the continuum and line flux light-curves of our objects. We used either observed or simulated light-curves to get the most reliable result (see Kovačević *et al.* 2014b,

2015). Our reverberation measurements are included in the AGN Black Hole Mass Database (<http://www.astro.gsu.edu/AGNmass/>) hosted at Georgia State University, USA. It contains all AGN with published spectroscopic reverberation mapping results in the refereed journals.

Any tool describing the AGN variability has to handle irregular sampling and measurement errors in observed light curves, in order to produce physical results. Since AGN light curves are too sparsely sampled to resolve day variability, using simple linear interpolation between data points are impossible. Linear interpolation also incorrectly assumes that there is no uncertainty associated with the interpolation process or the measurements. For these reasons, we model the AGN continuum light curve using a stochastic model of AGN variability, such as Gaussian process (GP) regression, allowing us to evaluate the light curve at arbitrarily small timescales. The ability of GP is demonstrated in Fig. 1 (see Shapovalova et al. 2016 for details) where the flares become clearer in the GP light curves than in the observed curves alone. We also introduced GP for determination of periodicity in AGN light curves (Kovačević et al. 2017).

The spectral data have been presented and analyzed in Shapovalova et al. (2001, 2004, 2008, 2010a, 2010b, 2012, 2013, 2016, 2017), Popović et al. (2008, 2011, 2014) and Afanasiev (2014, 2015). Some of the important results in this part are: i) published online spectral data (line and continuum fluxes obtained using uniform procedures) from several decades of monitoring for seven type 1 AGN; ii) estimated the size of the BLR and the mass of the SMBH; iii) the BLR is probably of a disk-like shape, but with complex structure, in the sense that the single geometry cannot explain the whole BLR (e.g. outflows or hot-spots are present, etc.). Also, the BLR is mainly heated by the photoionization from the central source, but other mechanisms may be present, which is seen in the lack of correlation between line and continuum fluxes; iv) it seems that polarization region in AGN is smaller than we expected. A short review of these investigations and a comparative analysis of the results are given in Ilić et al. (2015, 2017).

One important part of these investigations was the analysis of the long-term light curves of different emission lines and continuum searching for periodicities (Bon et al. 2012, 2016, Kovačević et al. 2017).

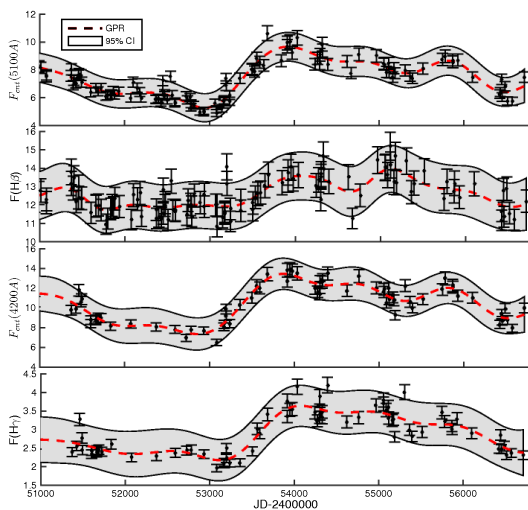


Figure 1: GP best fit (dashed line) to the observed light curves (dots with error bars) of the continuum at 5100 Å, H β , continuum at 4200 Å and H γ (from top to bottom) in quasar E1821+643. The shaded band represents the 95% confidence interval (CI) for the GP predicted curve (Shapovalova et al. 2016).

3. SUPER-MASSIVE BINARY BLACK HOLES

Long term observations can indicate some type of variability in the continuum and line flux which has quasi-periodical (see Shapovalova et al. 2010b), or periodical behavior (see Bon et al. 2012, 2016, Shapovalova et al. 2016, Kovačević et al. 2017). This periodicity can be caused by perturbations in the emission line region (see e.g. Jovanović et al. 2010), but also may indicate a presence of the SMBH binary system in the center of an AGN (for a review see Popović 2012).

The binary SMBH are expected to be in the center of some galaxies (Begerman et al. 1980, Gaskell 1983), and since they are a result of galactic mergers, they are probably surrounded by gas, therefore one can expect that one or both black holes in the system are accreting matter producing radiation similar to the AGN emission (Popović 2012). The observations of the binary SMBH is possible on kpc-scale (see e.g. Woo 2014), however on the distances between components of order smaller than pc it is not possible to resolve the components by available telescopes. Therefore the spectroscopy is the only way to detect the SMBH binary candidates.

Our investigations of the sub-pc SMBH binaries using spectroscopy have been performed in two directions: i) modeling the sub-pc SMBH binary systems in order to detect specific feature in the spectral lines and their shifts (Popović et al. 2000, Jovanović et al. 2014, Smailagić & Bon 2015, Simić & Popović 2016), and ii) exploring the long-term variability in the line shapes (Bon et al. 2012, 2016, Shapovalova et al. 2016; Kovačević et al. 2017). Note here that we made a discovery of the first spectroscopically resolved sub-parsec orbit of a SMBH binary (see Bon et al. 2012) that was obtained by investigating the long term monitoring spectra of NGC 4151. This investigations continued with a series of papers where many other AGN appeared to show periodicity in their light curves (Bon et al. 2017, Kovačević et al. 2017, Marziani et al. 2017, etc.).

The main results that we obtained in this investigation are: i) there are indications in spectral variation (periodicity and line shape variations) that in some AGN a SMBH binary can be present, especially in NGC 4151 where spectral variability can be explained by SMBH binary dynamics; ii) from modeling of the SMBH binaries, taking different parameters of a SMBH binary system, we concluded that the line shapes and shifts can indicate a SMBH binary, but the dynamical effect of a binary system can be hidden by other processes in the BLR.

4. AGN SPECTRAL CHARACTERISTICS: FROM THE UV TO THE MIR

As it was noted in the Introduction, basically AGN can be divided in type 1 (with broad lines) and type 2 (without broad lines). However, the spectral properties in a wide spectral range from the ultraviolet (UV) to the mid-infrared (MIR) can be quite different in type 1 AGN. As an obvious case is a difference between the narrow line and broad line Seyfert 1.

The investigation of the type 1 AGN spectral characteristics is important from two reasons: first is that the correlations between different spectral properties indicate some physical processes (Boroson & Green 1992); and second is to find some constraints and relationships between spectral characteristics and luminosity, in order to use quasars as standard candles (see e.g. Lusso & Risaliti 2017).

In our research of AGN spectral characteristics we started from the optical, exploring the relationships between the broad Balmer lines (mostly $H\beta$ and $H\alpha$) and Fe II features around the $H\beta$ (Kovačević et al. 2010, Popović & Kovačević 2011) as well between the ratios of Balmer lines and connection with the continuum (Ilić et al. 2012, Rafanelli et al. 2014, Rakić et al. 2017). The next step was to connect the spectral characteristics in the optical and UV (Kovačević et al. 2014a, Kovačević-Dojčinović & Popović 2015, Jonić et al. 2016, Kovačević-Dojčinović et al. 2017) and then to connect the spectral properties between the optical and MIR (Lakićević et al. 2017).

One of very important tasks in this part was to find the stellar population influence on AGN spectra. With this goal we developed a code for full spectrum fitting of AGN spectra (Bon et al. 2014, Bon et al. 2016) using ULYSS code (Koleva et al. 2009) - the code for stellar population analysis, that enable us to analyse simultaneously complex emission line models, Fe II pseudo continuum, AGN continuum and host galaxy. Using this code we investigated properties of Type 2 (see Bon et al. 2014) and some Type 1 AGN as well (see Bon et al. 2016, Marziani et al. 2017a).

Additionally, in type 1 AGN we can extract broad line profiles which are important for investigation of the BLR structure, especially an accretion disk contribution to broad emission line profiles (see e.g. Popović et al. 2004, Bon et al. 2006, Bon et al. 2009a, 2009b). We investigated the contribution of accretion disk emission using Hamburg-ESO (HE) sample of intermediate to high redshift quasars, that are some of the most luminous quasars known, hosting very massive black holes. We matched simulated relativistic ray tracing accretion disk profiles (see Jovanović 2012), with the optical emission $H\beta$ broad emission line profiles from HE sample, selected to have centroids of line widths measured at 1/4 of maximum line intensity significantly shifted to the red, in order to investigate gravitational redshift in these spectra (see Bon et al. 2015).

The most important obtained results in this part are: i) we constructed a unique Fe II template in the optical and UV part of AGN spectra (an online program for Fe II fitting is available on SerVO site, see <http://servo.aob.rs/FeIIAGN/>); ii) we proposed a model for Balmer quasi-continuum in the UV part of AGN spectra and also find that the nature of the optical Fe II lines is different than the UV Fe II ones; iii) using polycyclic aromatic hydrocarbons (PAH) in the MIR we found that the division between type 1 and type 2 AGN using optical criteria does not follow the MIR characteristics; iv) we developed a code for fitting the stellar population simultaneously with the spectrum of an AGN (type 1 and type 2) that can be used in investigation of the characteristics of AGN emission and host stellar population.

5. EXPLORING AGN STRUCTURE: MODELING AND GRAVITATIONAL LENSING

One of the important way to explore the structure of AGN is by modeling their emission regions. In this part we developed a model of relativistic accretion disk around SMBH, and simulated its X-ray radiation in the Fe $K\alpha$ line (see Jovanović 2012, and references therein). Comparisons between the simulated and observed Fe $K\alpha$ line profiles were then used to determine the parameters of the relativistic accretion disk, such as inclination, emissivity, inner and outer radius, as well as the spin of the central SMBH (see e.g. Jovanović et al. 2011, 2016).

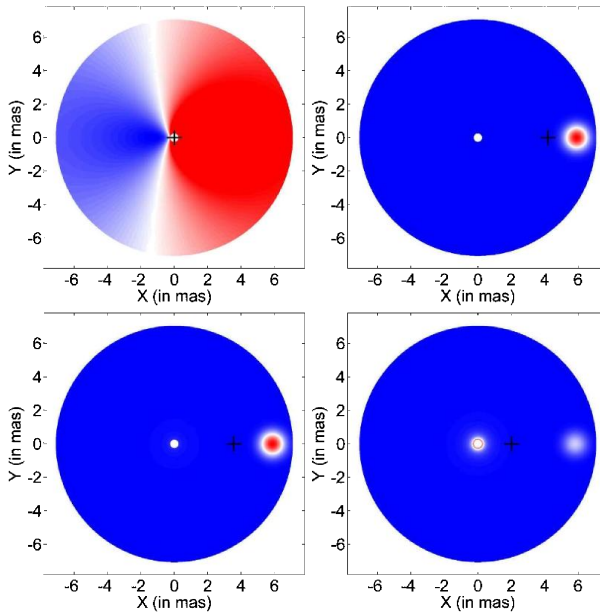


Figure 2: Photocenter positions (crosses) in the case of an accretion disk without (top left) and with perturbation (next three panels) for three different values of emissivity index (Popović et al. 2012).

The accretion disk model can be applied to the optical line emission, and comparing the observations and disk-models we demonstrated that the variability in broad line shapes can be explained by the hot-spot motion in the disk (Jovanović et al. 2010).

On the other hand, we also constructed a model for the dusty torus that was developed within SKIRT code, a state-of-the-art radiative transfer code based on Monte Carlo technique (Stalevski et al. 2011, Stalevski et al. 2012a), and explore the emission of the dusty torus with different physical parameters. More recently, dust emission models were used to study the relation between the ratio of the torus and AGN luminosities and the dust covering factor. This study (Stalevski et al. 2016) found that the observed luminosity ratio very often under- or overestimates the actual covering factor and provided a novel way to correct it and obtain the true values. In another recent study, the detailed modeling of the dust emission of the archetypal type 2 AGN in Circinus galaxy was performed, showing that contrary to the expectations, a major part of the dust emission is coming from the polar region, in a form of cone-like outflows (Stalevski et al. 2017).

The models of accretion disk (which emits in X-ray and optical) and dusty torus are used to explore some variability that can be seen in quasars, which is important for the Gaia reference frame (Popović et al. 2012). As an example of the photo-center variability we illustrate in Fig. 2 the displacement of disk's photo-center as a function of the bright spot emissivity.

The AGN central part model (disk+torus, described above) allowed us to explore gravitational lensing effects on the spectra of lensed quasars. Additionally we modeled milli- and micro-lens maps, and simulate the lens transition across the inner part of

an AGN, modeling the spectral variations (Simić et al. 2011, Stalevski et al. 2012b, Popović & Simić 2013, Simić & Popović 2014). Also we performed observations of several lensed quasars with 6m SAO telescope in order to compare our models with observations (Popović et al. 2010)

In this part we can outline the following results: i) we developed a unique model for the AGN torus (note here that paper of Stalevski et al. 2012 has been cited more than 100 times); and a library of emission models of the AGN dusty torus is available online (<https://sites.google.com/site/skirtorus/>); ii) we give prediction for variation in the quasar position using the models from accretion disk to torus that is very useful for the Gaia reference frame; iii) we give predictions in spectral variation due to microlensing that can be used in the separation between the intrinsic quasar variation (see Section 2) and a microlensing event.

6. BLACK HOLE MASSES - MEASUREMENT AND VIRIALIZATION

As noted in the Introduction, it seems that the central SMBH has influence on the structure of host galaxy and its evolution. Therefore the measurement of SMBH masses in center of galaxies is a very important task in astronomy today. In difference with "normal" galaxies, galaxies with AGN in the center give us possibility to measure the mass of central black hole exploring the gas motion in the BLR. There are several direct and indirect methods for the black hole measurement (see review of Peterson 2014), among them the reverberation is one of the direct methods, but it is also telescope time consuming.

In this part, we worked in two directions: i) exploring the geometry and structure of the BLR using variability (see references in Section 2) and comparing virialization in different broad lines (Mg II and H β , see Jonić et al. 2016), and ii) exploring polarization in broad lines as a tool to measure the SMBH mass (Afanasiev et al. 2014, Afanasiev & Popović 2015, Savić et al. 2017).

To measure SMBH masses using polarization in the emission line we performed observations of a number of AGN with 6-m SAO telescope and we explore observed data to find black hole masses. Additionally, we did simulations using STOKES code (Goosmann et al. 2013) and find that the proposed method can give very good results (Savić et al. 2017).

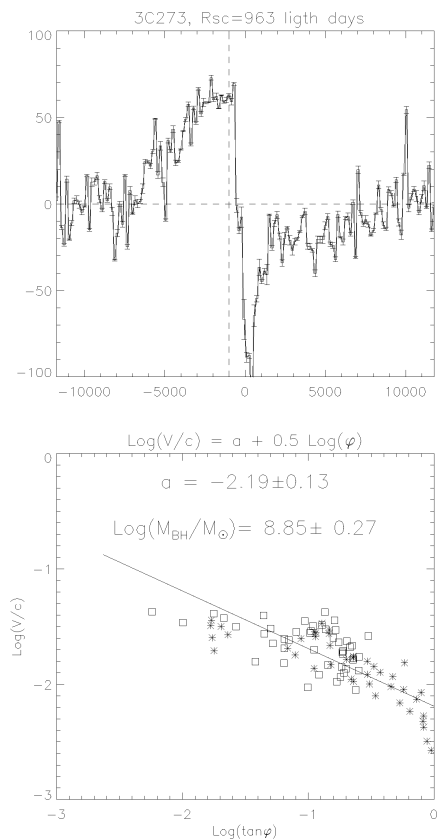


Figure 3: The polarization angle - PA observed in quasar 3C 273 (upper panel), and estimation of the black hole mass of quasar (bottom panel) as given in Afanasiev & Popović (2015).

The important results we obtained in this part is that we give a new method for AGN black hole mass measurements using the polarization in broad lines (illustrated in Fig. 3). The method can explore virialization in the BLR, and can be applied on the one-epoch observations (see Afanasiev & Popović 2015 for more details).

7. AGN GAMMA RAY EMISSION, GAMMA RAY BURSTS AND THEIR IMPACT ON THE LOW IONOSPHERE

The gamma ray radiation can be observed in objects with jets, as e.g. blazars, but also can be produced by exotic objects (as e.g. black hole collisions) which emit enormous gamma ray flux, known as gamma ray bursts (GRBs). Gamma ray emission is mostly connected with violent processes in the Universe, and has been the subject of investigation for the last several decades (after the launching of gamma ray telescopes).

In this part we investigate the gamma-ray emission in blazars. First we explore the extraordinary gamma-ray activity of the gravitationally lensed blazar PKS 1830-211 (Donnarumma *et al.* 2011), finding also that this variability can be caused by microlensing (since the source of gamma radiation is very compact), that was a direct application of our AGN and lens models (see Section 5). Second, we explore flare-like variability of the Mg II emission line in the gamma-ray blazar 3C 454.3 (León-Tavares *et al.* 2013), connecting the Mg II emission variability and variability in gamma ray emission. It was interesting that we found a good correlation between gamma-ray and Mg II variability, indicating that Mg II originates from the jet.

To explore the origin of the gamma-rays in shock-waves, we developed a shock wave model and fit 30 GRBs (Simić & Popović 2012). We found some characteristics of GRBs, and divide them in two groups - short and long lasting GRBs.

A GRB emits the huge amount of energy that impacts the upper parts of Earth atmosphere, and this opens a question: how much a GRB can affect the Earth atmosphere, especially the low ionosphere? This was a subject of our research (Nina *et al.* 2015), and we found that GRBs perturb the low ionosphere, and its reaction is significant in a short period of several seconds after the GRB has been detected by satellites.

The most important results in these investigations are: i) we found that gamma ray emission in some AGN correlates with the broad Mg II line, this indicates that in some cases broad Mg II line is originated in the jet-like region, that it is not connected with the classical BLR – this should be taken into account when Mg II line is used for black hole mass measurements; ii) we found statistical significance that GRBs have influence on the ionosphere, since we found that reaction of ionosphere is several seconds after the GRB detection by satellites (this discovery was noted as 'research spotlight' in March, 2016, see <https://eos.org/research-spotlights/gamma-ray-bursts-leave-their-mark-in-the-low-ionosphere>).

8. SUMMARY AND FUTURE PLANS

Here we present the most important results of the spectro-polarimetric observations and modeling of different parts of AGN (accretion disk, BLR, dusty torus), obtained in the last several years. We also note, that beside the scientific part, the project was a base for worldwide collaboration and some research subjects were PhD and master thesis for several students. Additionally, we organized several workshops (see

<http://servo.aob.rs/eeditons/Workshops.php>) and spectral line shapes conferences (see <http://servo.aob.rs/scslsa11/>).

Probably the project will finish at the end of this year or during the next one, but we are going to continue our activities in the field of spectroscopy of extragalactic objects. We are going to: i) continue with the monitoring of several broad line AGN in order to find the geometry and size of the BLRs and estimate SMBH masses; ii) continue with spectropolarimetric observations of several type 1 AGN in order to measure masses and find the inclination of the BLR; iii) develop models of AGN central part and gravitational lenses in order to explore the influence of milli- and micro-lensing to the spectra of lensed quasars; iv) explore spectral properties of type 1 AGN, including also X-ray emission, in order to find some relationships which can be used for cosmological investigations.

At the end let us note that we are included in the Large Synoptic Survey Telescope - LSST project (in scientific part for AGN investigation), that will give us opportunity to extend our investigations. Also, we are going to provide low resolution spectrograph which can be installed at 1.4m telescope Milanković, and can be actively involved in AGN monitoring campaign.

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