Supermassive black holes and spectral emission lines

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Abstract. It is widely accepted that active galactic nuclei (AGN) are hosting a supermassive black hole in their center. The supermassive black hole is actively fueled by surrounding gas through an accretion disk, which produces a broad band continuum (from X-ray to radio emission). The hard photons from the accretion disk create the photoionized plasma around the central black hole, which emits a number of broad emission lines. Therefore, one of the signatures of the strong activity in galaxies is the emission of the broad spectral lines (line widths of several 1000 km/s), which are seen only in a fraction of AGN, so called Type 1 AGN. These broad emission lines often show very complex line profiles, usually strongly variable in time. Here we will describe the basic properties of the broad emission lines and how can we use them to derive the properties of the central supermassive black hole, i.e., the mass and spin, or see signatures of supermassive binary black holes.

1. Introduction

The X-ray, UV, optical, and IR broad emission lines (BELs) are seen in the spectra of some active galactic nuclei (AGN), the so-called Type 1 AGN. Their fluxes and profiles can give us the information about the geometry and physics of the region where they are forming, i.e., the broad-line region (BLR). The BLR is a photoionized gas heated by the radiation coming from the compact accretion disk which fuels the supermassive black hole in the center of an AGN, and produces the powerful radiation that makes AGN different from normal galaxies (see [1] for a review on AGN and their spectral properties).

One of the characteristics of AGN is a number of broad emission lines in a wide spectral range: from the X-ray to the infrared spectral range. In a number of AGN, the very broad spectral line Fe Kα in the X-ray spectrum has been observed (first time detected in MGC-6-30-15 by [2]). It was shown that this line originates in the innermost part of the accretion disk (see, e.g., [3]) and can give us the crucial facts about the supermassive black hole and the plasma conditions in its vicinity. The broad UV and optical lines are present in spectra of Type 1 AGN, and their width indicates a gravitationally bounded motion.

Nowadays it is of great importance to study the properties of the supermassive black holes, as it is believed that they evolve together with host galaxies, the so-called coevolution of galaxies and black holes, through mergers and accretion (for a review see [4]). It is crucial to determine the supermassive black hole masses to trace the coevolution across cosmic time. One of the powerful methods to obtain the mass is by reverberation mappings of the BLR in Type 1 AGN [5] and applying the virial theorem on the BLR properties assuming Keplerian motion (see, e.g., [6, 7, 8]). However, this method is still not precise enough, as the kinematics and structure of
the BLR have not yet been mapped directly (see, e.g., [9]), and is, thus, important to study in detail the broad emission lines in order to constrain the physics and kinematics of the BLR [10]. Another possible method that can be used for the estimates of the supermassive black hole mass, is based on the spectropolarimetric monitoring of broad emission lines [11], and was successfully applied in case of the Type 1 AGN Mrk 6 (see [11]). Finally, since massive galaxies grow through mergers, we should see the formation of supermassive binary black holes in the center of galaxies that have undergone major mergers [12]. We do not, however, observe them on small scales (see [19] for a recent review).

In this paper we give a short overview of the usage of the spectral lines (Fe Kα and UV/optical) for estimates of the black hole masses and spins. Mostly we will present the work from the Group for astrophysical spectroscopy at the Astronomical observatory in Belgrade [13, 14]. We will describe the basic properties of the broad emission lines and their application in determining the parameters of supermassive black holes, i.e., the mass and spin. Moreover, we will describe how can we see signatures of supermassive binary black holes in the broad emission lines.

2. Broad emission lines and supermassive black holes

Broad emission lines are an important tool to study the properties of the BLR in AGN (see, e.g., [9, 15, 10]). However, one should note the observed fact that the BLR is a complex region showing multiple components (e.g., [9, 16]), thus the broad line properties show contributions from different regions with different kinematics [17]. For example, the X-ray Fe Kα line arise within a few gravitational radii of the center of supermassive black hole in the accretion disk [3], while the UV/optical broad lines originate further away in the accretion disk (e.g., broad double-peaked Hα and Hβ lines in 3C390.3, [18]) or complex geometry of the accretion disk with the additional component [16] or outflowing material [17]. Moreover, complex broad line profiles (e.g., asymmetric or showing two displaced peaks) could indicate a supermassive black hole binary and complex BLR [19]. Finally, the broad emission lines of AGNs often exhibit variability, which is probably caused by variation in the ionizing continuum strength and by dynamic evolution of the BLR gas. Studying the variability of the broad lines (fluxes, widths, profiles, asymmetries) we can find the size, geometry and physical properties of the BLR [10].

2.1. Fe Kα line - spin of the supermassive black holes

The fluorescent/recombination iron Kα line is produced when the hard X-ray radiation cause the ejection of the K-shell electrons of an iron atom/ion following the photoelectric absorption of an X-ray [20]. For the neutral iron, the Fe Kα line energy is 6.4 keV and is usually a narrow line, but if it originates from a relativistic accretion disk of AGN it becomes wider and changes its profile due to kinematical effects: Doppler boosting and gravitational redshift, and that kind of line broadening is often observed in spectra of Seyfert galaxies [3]. Black holes have three measurable parameters: charge, mass and angular momentum (or spin), where in the case of supermassive black holes of AGN, only the latter two are of important as they are responsible for several observational effects detected in the observed Fe Kα line profile [21, 22, 23]. Figure 1 demonstrates the difference in the line emitting regions and the corresponding line profile in the case of the non-rotating (Schwarzschild metric) and rotating black hole (Kerr metric). It is clearly seen in Figure 1 (bottom panels), that for almost maximally rotating black hole, the red peak of the Fe Kα line is more intensive and the red wing is much more extended (see [23] for review). However, the angular momentum of the supermassive black hole has significant influence on the broad line profile and thus by comparing the observed and modeled Fe Kα line profiles some essential information about the spin of the supermassive black hole can be
Figure 1. Illustrations of accretion disk (left panels) and the corresponding Fe Kα line profiles (right panels) in the case of Schwarzschild metric (upper panels) and Kerr metric with angular momentum $a = 0.998$ (bottom panels). The parameters of the disk in both cases are: inclination $i = 35^\circ$, inner radius $R_{in} = R_{ms}$, and outer radius $R_{out} = 20 R_g$ (figure from [22]).

retrieved [21, 22, 23]. There are several more works in which the attempts to estimate the spin of the supermassive black hole using the observed Fe Kα were made (see, e.g., [24] for review).

2.2. UV/optical broad emission lines - mass of the supermassive black holes

The UV/optical broad emission lines are variable in most of AGN. A long-term monitoring of these lines, has revealed that changes in the broad lines fluxes are lagged to flux changes in the continuum (see, e.g., [25, 26, 27]). This is illustrated in Figure 2, which shows the cross correlation function between the light curves of the continuum and broad Hβ emission line fluxes for two AGN: 3C 390.3 and NGC 5548 (see [28] for details on the analysis). The objects have been monitored for more than a decade in [29, 30]. The time lag gives directly the distance of the BLR $R_{BLR}$, which together with the gas velocity $V$, obtained from the line widths, gives the mass of the supermassive black hole $M_{BH}$, with the assumption that the BLR gas is virialized (see [31] for review):

$$M_{BH} = f \frac{R_{BLR} V^2}{G},$$
Figure 2. The Z-transformed discrete correlation function applied to the light curves of the continuum and H\text{\textbeta} emission line for 3C 390.3 and NGC 5548. The horizontal and vertical error bars correspond to 1\sigma uncertainties for a normal distribution (for details see [28]).

where \( f \) is the dimensionless parameter, so-called virial coefficient, and \( G \) is the gravitational constant. These are the basis of the reverberation mapping method (see, e.g., [5, 6, 7, 8]). It was also shown that the BLR distance \( R_{BLR} \) scales with the nuclear continuum luminosity \( L \) (see, e.g., [32, 33, 34, 35, 36]). This RL relationship gives a mass scaling relation that allows us to obtain an estimate of the mass of the supermassive black hole from an individual (i.e., single-epoch) spectrum of the AGN using the parameters of continuum and broad emission line (many different broad emission lines can be used, but the main one are H\text{\textbeta}, Mg II and C IV). This has been widely applied on different and large samples of data (e.g., [32, 33, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47], and many others), even on very distant quasars \( z > 5.5 \) (e.g., [48]). Nevertheless, this method has many difficulties and is still not accurate (see, e.g., [49] for a review). First of all, the factor \( f \) depends on the BLR geometry that is still not known, and mostly the statistical values for \( f \) are used (e.g., [50, 51, 52]). Secondly, there are many systematic errors in the time lag determinations (see, e.g., [53, 49]), such as low data quality or undersampling of data, etc. Therefore, intensive and well-coordinate optical monitoring campaigns of Type 1 AGN are needed to investigate the structure (especially the geometry) of the BLR (such as presented in [54, 29, 55, 30, 56, 57]).

2.3. Broad emission lines and supermassive binary black holes

There are only several examples where supermassive binary black holes have been detected on spatially resolved imaging or/and spectroscopy (see [19] for a recent review). One possibility of a binary BLR detection (thus the supermassive binary black holes system detection) is by using the broad optical lines, even if the lines are single-peaked with some peculiar line profile. Recently, [58] analyzed the broad H\textalpha line profile and flux variability during a period of more than 20 years of NGC 4151, one of the best studied Seyfert galaxy. They presented evidence for the first spectroscopically resolved subparsec orbit (with a 15.9 year period) of supermassive binary black holes. Moreover, [59] found 88 candidates for subparsec supermassive black hole binaries among Sloan Digital Sky Survey quasars, by searching for the broad H\textbeta emission lines that are displaced from the quasar rest-frame, since this would be expected if one of the two black holes accretes at a much higher rate than the other and carries with it the only BLR of the system.

In general, in case of the supermassive black hole binary system, we can have either one
emitting region around two black holes, or two emitting regions clearly separated around each black hole. Thus the models of the binary BLRs around two supermassive black holes [60] give large diversity of line profiles, as shown in Figure 3. The left panel presents the case where both supermassive black holes have the BLR (as a Roche lobe around each of them), where the orbit is edge-on to the observer. The right panel presents the case when only one component has the BLR. The line profile is composite from emission of both regions in the case of binary BLR (Figure 3, left panel), but in some cases the line profile can show only one peak, e.g., if only one BLR is present (Figure 3, right panel). Even in the case of binary BLR, the line profile depends strongly on the orbital phase and may change from a very asymmetric (double peaked and highly shifted) to the symmetric profile (see Figure 4. in [19]). Thus, the variability in the line profile is expected to be detected.

3. Conclusions
Here we briefly presented the possibility to use broad emission lines in AGN to find the parameters of the central supermassive black hole. The main conclusion is that broad emission lines of Type 1 AGN and their properties (flux, profile, variability) can be used to obtain the properties of the BLR gas near the supermassive black hole. Using the parameters for the BLR (dimension and velocity field) we are able to determine the mass of the central supermassive black hole. On the other hand, the shape of the X-ray Fe Kα line can be used to find the spin of the central supermassive black hole. At the end, the complex and variable broad lines can indicate a presence of the supermassive binary black holes at sub-parsec scales. Therefore, the investigation of the spectral line shapes in general can help us to understand the structure of the most mysterious objects, as in this case of supermassive black holes in the center of AGN.

Acknowledgments
This work was supported by the Ministry of Education, Science and Technological Development of Republic of Serbia through the project Astrophysical Spectroscopy of Extragalactic Objects (176001).
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