The properties of emission lines and their correlations in spectra of Active Galactic Nuclei

Jelena Kovačević and Luka Ć. Popović
Astronomical Observatory, Volgina 7, 11060 Belgrade, Serbia
E-mail: jkovacevic@aob.bg.ac.rs

Abstract. Active Galactic Nuclei (AGNs) are the most luminous objects in the Universe. It is assumed that an AGN consists of a supermassive black hole in the center, surrounded by accreting gas. In that process, a large amount of energy is produced, resulting in a very complex spectrum that shows a number of strong emission lines, which arise in the plasma located close to the supermassive black hole.

Here we analyse the line profile shapes, which are signature of the geometry, physical and kinematical properties of the AGN emission gas. Especially we analysed the optical Fe II lines, in order to answer to some unexplained questions about their origin. We found correlations between line properties which physical background is still not explained. Possible influence of starbursts to AGN spectral properties is discussed.

1. Introduction
It is estimated that about 5-10% of all galaxies have Active Galactic Nucleus (AGN) in their center. AGNs are the most luminous objects in the Universe and their luminosity may be a few thousands times higher than luminosity of nuclei of normal galaxies. It is assumed that an AGN consists of a supermassive black hole in the center, surrounded by accreting gas. In the process of accretion, a large amount of energy is produced which photoionize the gas in surrounding of the black hole. It results in rich and complex spectra, which consist of the continuum emission and strong broad and narrow emission lines.

The emission region closer to the black hole (<0.1 pc) is called the Broad Line Region (BLR), because it produces the broad emission lines. It has a higher density (10^8-10^11 cm^-3) than plasma which is further (<100 pc) from the black hole and accretion disk, which is called the Narrow Line Region (NLR). In this region, narrow lines arise and plasma has a very low density, in some cases even lower than the vacuum which is usually produced in laboratories. The density of the Narrow Line Region is assumed to be 10-1000 cm^-3, and temperatures of both regions are estimated to be: 10000-25000 K.

The densities of the Narrow and Broad Line Regions are estimated according the presence or absence of some forbidden or semi-forbidden lines. Namely, some lines which arise in the Narrow Line Region, and which are very strong in AGN spectra, could be strongly forbidden, and almost impossible to be produced in laboratory conditions. These lines (as [O III] λλ4959, 5007 Å, [S II] λλ6716, 6731 Å, [N II] λλ6548, 6583 Å, etc.) are collisionally excited and their ratios could be used for determination of the temperature and density in the NLR. These forbidden lines could be very strong in AGN spectra probably because of very low density of the NLR –
which allow the radiative deexcitation from metastable level, and presence of very large amount of the low density gas.

Figure 1. Example of an AGN spectrum (object SDSS 041210.17-051109.1), where the forbidden [O III]λλ4959, 5007 Å lines are very prominent.

The most prominent forbidden emission lines in AGN spectra are the [O III]λλ4959, 5007 Å lines which arise in magnetic dipole and partly in electric quadrupole transitions (see [1]). In some spectra, they may have higher intensity than allowed lines in the optical part. The example of strong [O III]λλ4959, 5007 Å lines is shown in Fig 1.

While the average width of narrow lines is FWHM ≈ 500 km/s, the broad lines have more complex shapes and larger widths. Namely, the BLR probably consists of different layers of the plasma, which have different kinematical properties. It results with complex and very broadened line profiles, which have an average FWHM ≈ 5000 km/s, but it may go up to 15000 km/s. The broad line profile composed from kinematically different components is shown in Fig 2. Also, the line emission from the accretion disk may contribute to the final line profile, as for example of an extreme case Hα line in spectrum of object SDSS J0942+0900 [3], for which FWHM Hα ≈ 40000 km/s (see Fig 3).

Shapes of the emission lines, their flux ratios, as well as their shifts and widths, are signature of the geometry, physical and kinematical properties of the emission gas. Therefore, we investigated relationships between different spectral properties in large AGN sample, in order to get better insight of AGN nature.

2. The sample and analysis
For this investigation we use the sample of 302 Type 1 AGNs (with the broad and narrow emission lines), selected with criteria described in paper [4]. The spectra are taken from Sloan Digital Sky Survey (SDSS) database.

Basic assumptions we made are: 1) that emission lines arise by superposition of the radiation from different emission regions, which have different physical and kinematical properties. These regions are: the Narrow Line Region, Broad Line Region and Intermediate Line Region (ILR) – which is between these two. 2) The complex profiles of emission lines may be described by a sum of Gaussians, which represents emission from different emission regions. Their widths, shifts and intensities reflect the physical and kinematical properties of emission regions.

The detailed procedure of fitting of spectra is described in [4]. All Balmer lines are fitted with three Gaussians, which represent the emission from the NLR, BLR and ILR. We assume
Figure 2. Example of complex shape of H\beta line in AGN spectra. It is caused by kinematical properties of emitting gas [2].

Figure 3. Extreme example of very broad emission line: H\alpha line from spectrum of object SDSS J0942+0900 [3]. H\alpha \approx 40000 \text{ km/s}.

that all narrow lines originate from the same emission region, and consequently they have the same widths and shifts. The iron lines within 4400 – 5500 Å range are fitted with calculated template given in [4]. Example of a fit is shown in Fig 4.

Figure 4. Example of the fit of an AGN spectrum in range 4400 – 5500 Å.

There are some indications that evolution of AGNs is probably related with starburst regions (see [5], [6], [7]). Namely, it is possible that AGNs in an earlier phase of their evolution are composed of starburst (star-forming) regions and the central engine - accretion disk and supermassive black hole ([6], [8], [9]). In order to investigate the influence of starbursts to AGN spectra, we separated the total sample to two subsamples: pure AGNs - objects in which radiation from AGN dominates, and starburst dominant subsample, which are probably objects with composite structure (AGN associated with starbursts). For separation of the sample we accepted a criteria of \( R = \log(\text{[O III]}/\text{H\beta NLR}) = 0.5 \) (see [10]), where pure AGNs are with \( R > 0.5 \), and starburst dominant objects with \( R < 0.5 \).
3. Results
After we found all line parameters from the best fit of spectra, we performed correlations between measured spectral properties for the total sample and for two subsamples. We focus our investigation to: find the place in the AGN structure where the Fe II lines arise, to analyse the influence of starbursts to AGN spectra and to investigate Baldwin effect correlations, which physical cause is still unknown.

3.1. Location of the Fe II emitting region in AGNs
The iron lines in AGN spectra are very interesting for investigation, because there are still many open questions connected to them and they are assumed to be related with the AGN evolution. The complex iron ion in the AGN gas produces many lines, which overlap and make irregular features in AGN spectra. Therefore, the line identification, as well as calculation of the relative intensities of the Fe II lines are very difficult. Namely, it seems that mechanism of excitation of all Fe II lines is still unknown because the observed lines can not be well explained with simple photoionization models, and therefore some additional mechanisms are requested. Also, many correlations are observed between the Fe II lines and other spectra properties, which do not have physical explanation yet.

![Figure 5. The correlation between the width of Fe II and Hβ ILR component.](image)

![Figure 6. The same, but for the Hα ILR component.](image)

![Figure 7. The same, but for the Hα BLR component.](image)

In this investigation we try to find the place in the AGN structure where the Fe II lines are produced, which is still open problem. There are many propositions by different authors: accretion disk, BLR, ILR, or partly in the BLR and partly in the NLR (see references in [4]).
We compared the widths of the Fe II optical lines and the widths of different components of Balmer lines, which are coming from different emission regions (NLR, ILR, BLR). Since the widths of the line components reflect the kinematical properties of the emission regions, the correlation between them imply the kinematical connection.

We found significant correlations between the widths of the Fe II and ILR components of Balmer lines, and trend with BLR components of Balmer lines. Correlations are shown in Figs 5, 6 and 7. No correlation is found between the widths of NLR components and Fe II. This imply that optical iron lines probably arise in the ILR region, and partly in the BLR [4].

3.2. Contribution of starbursts to AGN spectra (in type 1 AGNs)

We performed correlations between spectral properties (continuum luminosity, broad and narrow line widths, equivalent widths of lines) for two subsamples (pure AGN and starburst dominant) and found significant differences in some correlations. We found that the width of the broad H\(\beta\) is in a significant correlation with the FWHM of narrow [O III] lines (see Fig 8), as well as with continuum luminosity (\(L_{5100}\)) (see Fig 9), but only for the starburst dominant subsample. There are no any correlations between these parameters for the AGN dominant subsample (see [10]). One of the possible explanations may be influence of the starburst to the emission, not only narrow emission lines, but also partly broad ones.

![Figure 8](image1.png)

Figure 8. FWHMs of the broad H\(\beta\) vs. the narrow [O III] lines. Filled circles denote the starburst dominant subsample, and open circles, pure AGNs.

![Figure 9](image2.png)

Figure 9. Correlations between the continuum luminosity and FWHM H\(\beta\) for starburst dominant (left) and AGN dominant subsample (right).
3.3. Baldwin effect correlations

Anticorrelations between EWs (equivalent widths) of the emission lines and continuum luminosity are commonly called the Baldwin effect (see [11]), and their physical cause is still unclear, because they can not be explained by a simple photoionization model. Here, we investigated the Baldwin effect correlations for different line components, and we perform these correlations also separately to the pure AGN and starburst dominant subsample.

We found that different components of the same line (for example H$\beta$), have different relationships with the continuum luminosity (as the continuum luminosity increases, EW H$\beta$ NLR decreases, but with broad H$\beta$ no correlation!).

From the other hand, when we analyse separately different subsamples, we find correlation between the EW of H$\beta$ broad and $L_{5100}$ for the starburst dominant subsample ($r=0.56$, $P=9\times10^{-9}$), while there is no correlation for the AGN dominant subsample ($r=-0.03$, $P=0.67$). It is even more interesting that for the starburst dominant subsample, EW of the broad H$\beta$ increases, as continuum luminosity increases, which is Inverse Baldwin effect.

The previous results imply that Baldwin effect correlations depend on dominant source of ionization in a sample (accretion disc in pure AGN or starburst).

Future work is needed to explain physical background of observed correlations.

4. References

[1] Dimitrijević M S, Popović L Č, Kovačević J, Dačić M, Ilić D 2007 Monthly Notices of the Royal Astronomical Society 374 118
[2] Gaskell C M, Snedden S A 1997 Emission Lines in Active Galaxies: New Methods and Techniques; Astronomical Society of the Pacific Conference Series; San Francisco: edited by Bradley M. Peterson, Fu-zhen Cheng, and Andrew S. Wilson 113 193
[3] Wang T-G, Dong X-D, Zhang X-G, Zhou H-Y, Wang J-X & Lu, Y-J 2005 Astrophysical Journal Letters 625 35.
[4] Kovačević J, Popović L Č, Dimitrijević M S 2010 Astrophysical Journal Supplement 189 15
[5] Lipari S L & Terlevich R J 2006 Monthly Notices of the Royal Astronomical Society 368 1001
[6] Mao Y-F, Wang J, Wei J-Y 2009 Astronomy & Astrophysics 9 529
[7] Sani E, Lutz D, Risaliti G, Netzer H, Gallo L C, Trakhtenbrot B, Sturm E, Boller T 2010 Monthly Notices of the Royal Astronomical Society 403 1246
[8] Wang J, Wei J 2006 Astrophysical Journal 648 158
[9] Wang J, Wei J. 2008 Astrophysical Journal 679 86
[10] Popović L Č, Kovačević J 2011 Astrophysical Journal 738 68
[11] Baldwin J A 1977 Astrophysical Journal 214 679