The flux ratio of the [OIII] $\lambda\lambda5007, 4959$ lines in AGN: Comparison with theoretical calculations

M. S. Dimitrijević1*, L. Č. Popović1, J. Kovačević1,2, M. Dačić1 and D. Ilić2
1 Astronomical Observatory, Volgina 7, 11160 Belgrade 7, Serbia
2 Department of Astronomy, Faculty of Mathematics, University of Belgrade, Studentski trg 16, 11000 Belgrade, Serbia

ABSTRACT
By taking into account relativistic corrections to the magnetic dipole operator, the theoretical [OIII] $5006.843/4958.511$ line intensity ratio of 2.98 is obtained. In order to check this new value using AGN spectra we present the measurements of the flux ratio of the [OIII] $\lambda\lambda4959, 5007$ emission lines for a sample of 62 AGN, obtained from the Sloan Digital Sky Survey (SDSS) Database and from published observations. We select only high signal-to-noise ratio spectra for which the line shapes of the [OIII] $\lambda\lambda4959, 5007$ lines are the same. We obtained an averaged flux ratio of 2.993 ± 0.014, which is in a good agreement with the theoretical one.

Key words: galaxies:active - quasars:emission lines - quasars:general

1 INTRODUCTION
The forbidden [OIII] $\lambda\lambda4958.911$ Å $(2s^22p^2^1D_2-2s^22p^2^3P_1)$ and $\lambda5006.843$ Å $(2s^22p^2^1D_2-2s^22p^2^3P_2)$ spectral lines are among the most prominent emission lines, not only in the spectra of photoionized nebulae, but also in the spectra of photoionized gas around Active Galactic Nuclei (AGN) due to the relatively high abundance of doubly charged oxygen ions. These lines are typical for AGN and originate from the ionized Narrow Line Region (NLR) gas surrounding the accreting super massive black hole in the centre (see Osterbrock [1989]). It should be emphasized that since they are located in the centre of the visible band they are very often observed in spectra of HII regions, photoionized nebulae and AGN. Because of observational and physical circumstances this pair of lines are suitable to: (a) test observationally the accuracy of theoretical calculations from atomic theory; (b) check the linearity of the detectors in use; (c) eventually test the assumptions on the target physics under extreme circumstances (optical thickness effects).

These two spectral lines are the result of magnetic dipole transitions with a small contribution of electric quadrupole radiation. The elaborate theoretical work of Galavis et al. [1997] provided the [OIII] $5006.843/4958.911$ intensity ratio value of 2.89. Storev & Zeippen [2000] checked this result by using photoionized gaseous nebulae spectra, where these lines can be observed with a very high signal-to-noise ratio. They found a small, but well-established, difference of 4-9 per cent between observations and theory. Namely Rosa [1985] deduced an intensity ratio of 3.03 ± 0.03, while measurements of Iye et al. [1987] provided a value of 3.17 ± 0.04, and that of Leisy [1996] the value of 3.00 ± 0.08.

In order to improve the agreement between observations and theory, Storev & Zeippen [2000] took into account the relativistic corrections to the magnetic dipole operator, demonstrating that they affect the transition probabilities for the [OIII] $\lambda\lambda5006.843$ Å and $\lambda4958.911$ Å lines. They obtained the A- value ratio of 3.01, implying a line intensity ratio of 2.98, which is only two percent or less different from the values Rosa [1985] and Leisy [1996] obtained from gaseous nebulae spectra, and 6 per cent different from the value Iye et al. [1987] obtained from the central region of starburst galaxy Tololo 1924-416 (H II regions). Iye et al. [1987] found a spatial variation of the forbidden line parameters, where the ratio is found to vary from 2.63 ± 0.15 to 3.33 ± 0.07 along the slit (see their table 3 and fig. 10) with a mean value of 3.17 ± 0.04, which significantly deviates from theoretical ratio Storev & Zeippen [2000]. The authors mentioned that such results might be caused by the detector’s nonlinearity.

Storev & Zeippen [2000] also underlined the necessity to additionally check their theoretical improvement of the line intensity ratio by the corresponding observation in photoionized gaseous nebulae spectra. However, due to instrumentational improvements the accuracy and resolution of observed spectra has increased to the point where we can now use AGN spectra for such purposes.

The [OIII] $\lambda\lambda4959, 5007$ lines originate in the NLR of an AGN, the region with conditions which differ from those...
in photoionized gaseous nebulae: i) the emission comes from a spatially very extended region, so that one can expect quite different physical and kinematical conditions in different parts of a NLR; ii) the dust on large spatial scales can result in orientation-dependent effects on NLR line fluxes. However, one can expect that the forbidden-line emission is isotropic since self-absorption in narrow lines is negligible. Therefore, due to the significance of this pair of lines, it is important to check whether their flux ratio is in agreement with theory. Only then can it be reliably used for different checks of theoretical assumptions concerning the physics of the NLR and photoionized gaseous nebulae.

The aim of this paper is to check, with the help of a large sample of AGN spectra, the improved theoretical value of the [OIII] $\lambda\lambda$ 5006.843/4958.511 line intensity ratio (Storey & Zeippen 2000). Additionally, we want to investigate the usability of the AGN [OIII] $\lambda\lambda$ 5006.843/4958.511 emission line flux ratio for checks of various theoretical assumptions and for checks of linearity of detectors in use. In order to do so we will measure the considered flux ratio of the [OIII] lines in a large sample of AGN. Moreover, we will derive some explicitly or implicitly given flux ratios of the [OIII] $\lambda\lambda$ 5007, 4959 lines in the existing literature (Nazarova et al. 1996; Bahcall et al. 2004; Dietrich et al. 2005), obtained for galaxies and quasars in order to compare them with the Storey & Zeippen (2000) [OIII] 5006.843/4958.511 line intensity ratio and with our results.

2 THE SAMPLE AND MEASUREMENTS

We selected our AGN sample, choosing the spectra with high signal-to-noise ratio, from Data Release Four (DR4) of the SDSS Database and from the observations described in the paper of Marziani et al. (2003). The SDSS spectra cover the wavelength region 3800 Å - 9200 Å. It was shown that the flux-calibration is a few percent on average, which is impressive for a fibre-fed spectrograph (Tremonti et al. 2004). Tremonti et al. (2004) found that 1σ error in the synthetic colours is 5 per cent in g(4700Å)-(r(6200Å)). The remaining (small) flux-calibration residuals are coherent on scales of 500 Å, which has negligible effect on our flux measurements that are obtained using an interval of less than 100 Å. Consequently, we exclude the effects of nonlinearity of the detector on the measured [OIII] line ratio.

In our analysis, we first subtracted the continuum by using DIPSO software package. In some spectra the Hβ and Fe II emission lines, which contaminate the [OIII] $\lambda\lambda$ 4959, 5007, lines, were subtracted.

In order to arrive at a clean sample we defined the following selection criterion: when scaling the profile of the weaker $\lambda$4959 emission line into the stronger $\lambda$5007 emission line profile, the line profiles of the two lines in question should differ insignificantly in the given spectrum (Fig. 1). This assures that the measurements of flux ratios and of line intensity peak ratios yield identical results. Examples of the maximal difference in the line wings and in the central part of the profiles are shown in Fig. 2 and Fig. 3, respectively. In these examples the observed spectra, the lines without Fe II and Hβ emission, and the profile of $\lambda$4959 scaled into the profile of $\lambda$5007 are presented. Our initial sample of 62 AGN was selected using the criterion that the shapes of the both lines are same or that the difference is negligible as shown in Figs (1-3).

Following the criterion outlined above, from the initial sample of 62 AGN, we selected 56, then 40 and finally 34 spectra, discarding spectra with slightly different [OIII] $\lambda\lambda$ 4959, 5007 line shapes (Figs. 2, 3). The final sample of 34 AGN has the best matching of the [OIII] $\lambda\lambda$ 4959, 5007 line profiles (Fig. 1). We measured the flux ratio for each sample and we present here histograms of the flux ratio values of the initial sample of 62 AGN (Fig. 4) and of the final sample of 34 AGN (Fig. 5).

3 RESULTS AND DISCUSSION

3.1 The flux ratio of the [OIII] $\lambda\lambda$ 4959, 5007 lines in spectra of active galaxies and quasars

The [OIII] 5006.843 Å and $\lambda$4958.911 Å both originate from the same lower and slightly different upper energy level and both have a negligible optical depth since the transitions are strongly forbidden, therefore both may be scaled to exactly the same emission-line profile. Moreover, Bahcall et al. (2004) have shown that the effect of differential reddening on the line splitting is of the order of 10$^{-8}$, i.e. negligible. If there are multiple clouds that contribute to the emission, the observed emission-line profiles are composed of the same mixture of individual cloud complexes (Bahcall et al. 2004).

| Number of AGN in the sample | $R$       |
|-----------------------------|----------|
| 62                          | 2.992 ± 0.014 |
| 56                          | 2.986 ± 0.012 |
| 40                          | 2.994 ± 0.014 |
| 34                          | 2.993 ± 0.014 |

| Object          | $R$       |
|----------------|----------|
| Mrk 705        | 3.00     |
| Mrk 1239       | 2.90     |
| Mrk 734        | 2.92     |
| NGC 4748       | 2.99     |
| Mrk 783        | 2.92     |
| IRAS 13224-3809| 2.94     |
| CTS J13.12     | 3.02     |
| IRAS 15091-2107| 2.93     |
| Mrk 291        | 2.95     |
| RXS J20002-5417| 2.94     |
| ESO 399-IG 20  | 3.04     |
| Mrk 896        | 2.88     |
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Despite the fact that spectra of galaxies and quasars have not been used to explicitly check the theoretical flux ratio of the [OIII] $\lambda\lambda$5007, 4959 lines, there are examples where such ratios were obtained as a by-product or could be derived from published results [Nazarova et al. 1996; Bahcall et al. 2004; Dietrich et al. 2005].

For example, Nazarova et al. (1996) investigated the Seyfert 1.2 galaxy Mkn 79 with long-slit spectroscopy, using the intensity ratio of the [OIII] $\lambda\lambda$4959, 5007 lines to check the accuracy of the flux measurements along the slit. They report that the ratio is very close to the value of 2.94, but due to the scatter of results and error bars given in their figure, they excluded them from present considerations.

Bahcall et al. (2004) used these [OIII] lines of quasars with $0.16 < z < 0.80$, obtained from the SDSS Early Data release, to test whether the fine-structure constant depends on cosmic time. As a by-product, they found that the ratio of transition probabilities corresponding to the [OIII] $\lambda\lambda$5007, 4959 lines is $2.99 \pm 0.02$. We note that this result obtained from spectra of quasars is in agreement with the theoretical value given by Storey & Zeippen (2000). Storey & Zeippen (2000) obtained a theoretical ratio of transition probabilities of 3.01, which is within the given error bars of the observationally derived value.

Dietrich et al. (2005) measured the NLR emission-line flux ratios relative to the flux of the $H_{\beta}$ line for 12 Narrow-Line Seyfert 1 (NLS1) galaxies. Using the [OIII] $4959/H_{\beta}$ and [OIII] $5007/H_{\beta}$ flux ratios given in Dietrich et al. (2005), we derived the flux ratio of the [OIII] $\lambda\lambda$5007, 4959 lines for these 12 NLS1 galaxies. The results are given in Table 2. The average value for the ratio of observed fluxes corrected for internal reddening is $2.953 \pm 0.014$, which also supports the theoretical improvement of Storey & Zeippen (2000).

3.2 Our measurements

The results of our measurements for these three mentioned samples are given in Table 1 and in Figs. 4 and 5. As one can see from Table 1 and Figs. 4 and 5, discarding line profiles with slightly lower quality does not significantly influence the result.

The obtained flux ratio of $2.993 \pm 0.014$ is in agreement with the theoretical improvement of Storey & Zeippen (2000), who obtained the intensity ratio of 2.98. This is better than some of the earlier values derived from photoionized gaseous planetary nebulae and HII regions observations, which led to the previously mentioned theoretical reworking (Rosa 1983) - 3.03; Iye et al. 1983 - 3.17; Leiss 1987 - 3.00. We should note here that measurements given in Rosa (1983) and Iye et al. (1987) were performed in the 1980s and these differences are probably due to the observational equipment.
Figure 3. Example of the spectrum (PKS 2300-68) where the line shapes are slightly different in the central part.

Figure 4. Histogram showing the distribution of the measured flux ratio for the initial 62 AGN sample.

Figure 5. Histogram showing the distribution of the measured flux ratio for the final 34 AGN sample.

4 CONCLUSIONS

In order to check the improved theoretical value of the intensity ratio of the [OIII] λλ 5007, 4959 lines we measured the corresponding flux ratio in a sample of 62 AGN with a high signal-to-noise ratio spectra taken from SDSS database (DR4) and from the observations described in Marziani et al. (2003). Also, from existing literature we compiled measurements of the intensity ratio in AGN spectra obtained as a by-product. On the basis of our investigation we give the following conclusions:

i) The flux ratio (2.993 ± 0.014) obtained from our measurements is in good agreement with the theoretical improvement obtained by Storey & Zeippen (2000), who derived an intensity ratio of 2.98. Our observational result supports the introduction of theoretical relativistic corrections to the magnetic dipole operator in the calculation of the corresponding line intensity ratio.

ii) Our measured flux ratio obtained from AGN spectra is in better agreement with the theoretical one compared to the same ratio measured from photoionized gaseous planetary nebulae and HII regions spectra. This is probably not caused by different physics, but by technological advances and the better instrumentation used in observations of AGN spectra.

iii) Despite the fact that the [OIII] lines in spectra of AGN may have very complex line profiles, they can be used to check sophisticated theoretical calculations. Also, we have demonstrated that, with the development of instrumentation, the flux ratio of the [OIII] λ4959, 5007 emission lines in AGN spectra (not only in photoionized gaseous nebulae and HII regions spectra) may be used to test observationally the accuracy of theoretical calculations and to check the linearity of the detectors.

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