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The flux ratio of the [O III] λλ5007, 4959 lines in AGN: comparison with theoretical calculations

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ABSTRACT

By taking into account the relativistic corrections to the magnetic dipole operator, the theoretical [O III] 5006.843/4958.911 line intensity ratio of 2.98 is obtained. In order to check this new value using the active galactic nuclei (AGN) spectra, we present the measurements of the flux ratio of the [O III] λλ4959, 5007 emission lines for a sample of 62 AGN, obtained from the Sloan Digital Sky Survey (SDSS) data base and the published observations. We select only the high signal-to-noise ratio spectra for which the line shapes of the [O III] λλ4959,5007 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 [O III] λ4958.911 Å ($2s^22p^2\ ^1D_2 - 2s^22p^2\ ^3P_1$) and λ5006.843 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 the spectra of H II regions, photoionized nebulae and AGN. Because of observational and physical circumstances this pair of lines are suitable to: (i) test observationally the accuracy of theoretical calculations from atomic theory; (ii) check the linearity of the detectors in use and (iii) 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 Galavís, Mendoza & Zeippen (1997) provided the [O III] 5006.843/4958.911 intensity ratio of 2.89. Storey & 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 (S/N). 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 the measurements of Iye, Ulrich & Peimbert (1987) provided a value of 3.17 ± 0.04, and that of Leisy & Dennefeld (1996) the value of 3.00 ± 0.08.

In order to improve the agreement between observations and theory, Storey & Zeippen (2000) took into account the relativistic corrections to the magnetic dipole operator, demonstrating that they affect the transition probabilities for the [O III] λ5006.843 and λ4958.911 Å lines. They obtained a ratio of the value of 3.01, implying a line intensity ratio of 2.98, which is only two per cent or less different from the values of Rosa (1985) and Leisy & Dennefeld (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 ratios (Storey & Zeippen 2000). The authors mentioned that such results might be caused by the detector's non-linearity.

Storey & 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 the resolution of observed spectra have increased to the point where we can now use the AGN spectra for such purposes.

The [O III] λλ4959,5007 lines originate in the NLR of an AGN, the region with conditions which differ from those in photoionized gaseous nebulae are the following: (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,[1]

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[1] Note here that the [O III] lines observed in AGN very often show a blue asymmetry and substructure in shapes (see e.g. Leipski & Bennert 2006).

(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 the theory. Only then can it be reliably used for the 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 [O III] 5006.843/4958.911 line intensity ratio (Storey & Zeippen 2000). Additionally, we want to investigate the usability of the AGN [O III] 5006.843/4958.911 emission-line flux ratio for the checks of various theoretical assumptions and the linearity of detectors in use. In order to do so, we will measure the considered flux ratio of the [O III] lines in a large sample of AGN. Moreover, we will derive some explicitly or implicitly given flux ratios of the [O III] λλ5007, 4959 lines in the existing literature (Nazarova, O'Brien & Ward 1996; Bahcall, Steinhardt & Schlegel 2004; Dietrich, Crenshaw & Kraemer 2005), obtained for galaxies and quasars in order to compare them with the Storey & Zeippen (2000) [O III] 5006.843/4958.911 line intensity ratio and our results.

2 THE SAMPLE AND MEASUREMENTS

We selected our AGN sample, choosing the spectra with high S/N, from Data Release Four (DR4) of the SDSS data base and the observations described in the paper of Marziani et al. (2003). The SDSS spectra cover the wavelength region 3800–9200 Å. It was shown that the flux calibration is a few per cent on average, which is impressive for a fibre-fed spectrograph (Tremonti, Heckman & Kauffmann 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 the scales of 500 Å, which has a negligible effect on our flux measurements that are obtained using an interval of less than 100 Å. Consequently, we exclude the effects of non-linearity of the detector on the measured [O III] line ratio.

In our analysis, we first subtracted the continuum by using DIPSO software package. In some spectra the H_β and Fe II emission lines, which contaminate the [O III] λλ4959, 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 λ4959 emission line into the stronger λ5007 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 line intensity peak ratios yield identical results. Examples of the maximal difference in the line wings and the central part of the profiles are shown in Figs 2 and 3, respectively. In these examples the observed spectra, the lines without continuum, contaminating Fe II and H_β emission and the profile of λ4959 scaled into the profile of λ5007 are presented. Our initial sample of 62 AGN was selected using the criterion that the shapes of the both lines are same or 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 [O III] λλ4959, 5007 line shapes (Figs 2 and 3). The final sample of 34 AGN has the best matching of the [O III] λλ 4959, 5007 line profiles (Fig. 1). We measured the

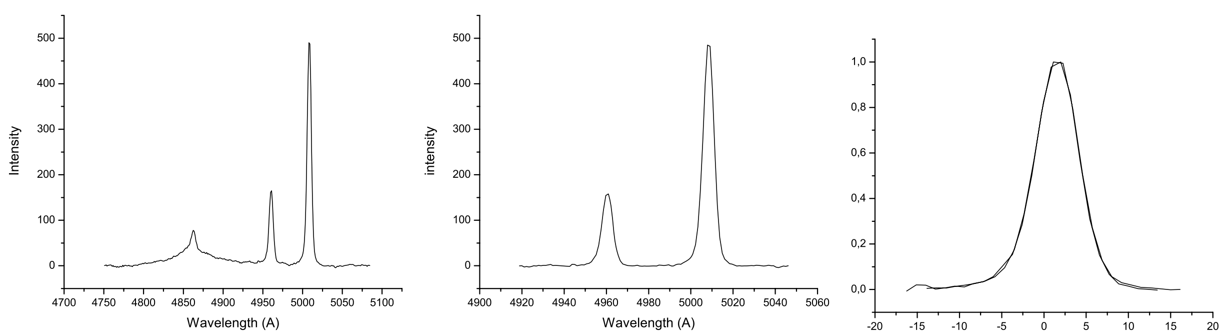

Figure 1. Example of the selected spectrum (SDSS J082308.29+42252000.00) with the same shapes of the [O III] λ 5007 and λ4959 lines. Left-hand panel: observed spectrum, middle panel: lines without continuum and contaminating emission and right-hand panel: the profile of λ4959 line scaled to the profile of λ5007 line.

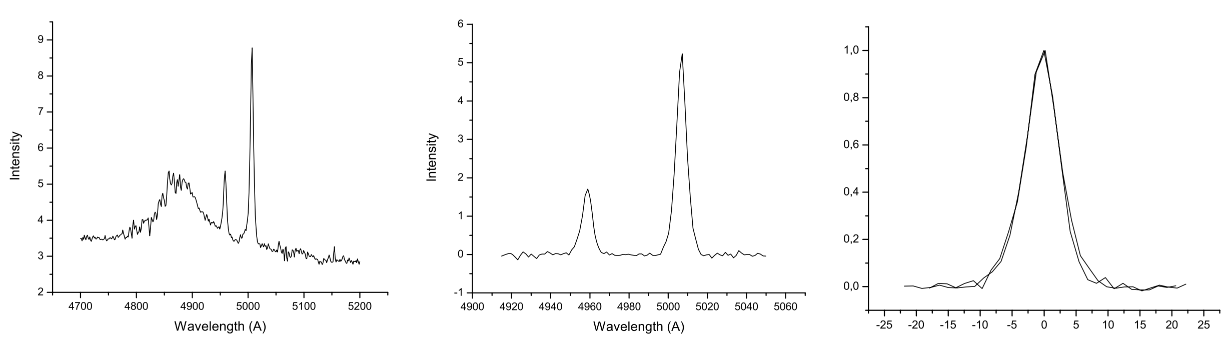

Figure 2. Example of the spectrum (PKS 2135−14) where the line shapes are slightly different in the line wings.

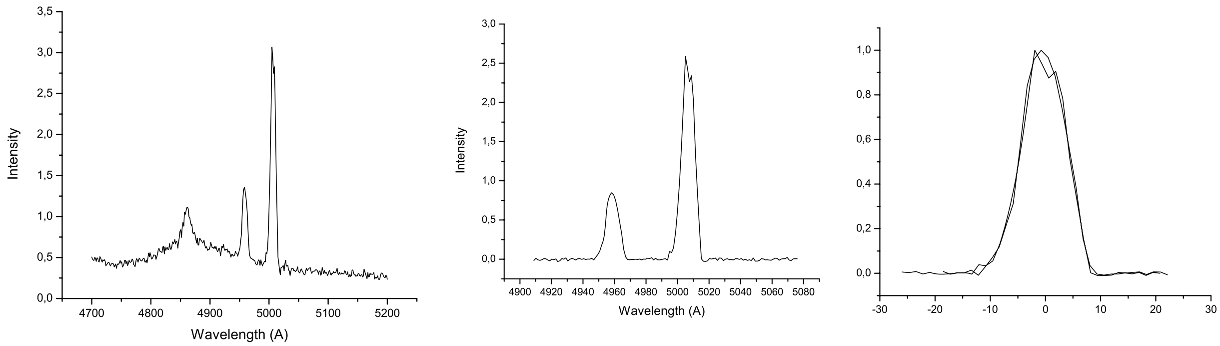

Figure 3. Example of the spectrum (PKS 2300−68) where the line shapes are slightly different in the central part.

flux ratio for each sample and present here the histograms of the flux ratio values of the initial sample of 62 AGN (Fig. 4) and the final sample of 34 AGN (Fig. 5).

3 RESULTS AND DISCUSSION

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

Both the [O III] λ5006.843 and λ4958.911 Å lines originate from the same lower and slightly different upper energy level and 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 $10^{-8}\ \tau_{5007}$, 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).

Despite the fact that spectra of galaxies and quasars have not been used to explicitly check the theoretical flux ratio of the [O III] $\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 Mrk 79 with long-slit spectroscopy, using the intensity ratio of the [O III] $\lambda\lambda$4959, 5007 lines to check the accuracy of the flux measurements along the slit. Their fig. 2 shows the measured ratios of [O III] $\lambda\lambda$4959, 5007 lines plotted against the position 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, we excluded them from present considerations.

Bahcall et al. (2004) used these [O III] 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 [O III] $\lambda\lambda$5007, 4959 lines is 2.99 ± 0.02. We note that this result obtained from the 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_β line for 12 narrow-line Seyfert 1 (NLS1) galaxies. Using the [O III] 4959/H_β and [O III] 5007/H_β flux ratios given in Dietrich et al. (2005), we derived the flux ratio of the [O III] $\lambda\lambda$5007, 4959 lines for these 12 NLS1 galaxies. The results are given in Table 1. The average value for the ratio of observed fluxes corrected for internal reddening is 2.953 ± 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 2 and Figs 4 and 5. As one can see from Table 2 and Figs 4 and 5, discarding line profiles with slightly lower quality does not significantly influence the result.

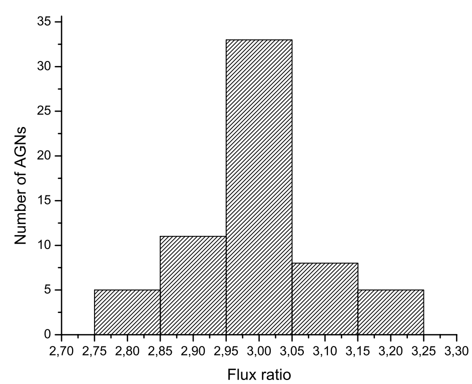

Figure 4. Histogram showing the distribution of the measured flux ratio for the initial 62 AGN sample.

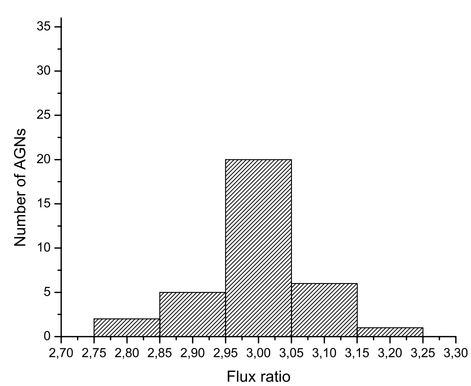

Figure 5. Histogram showing the distribution of the measured flux ratio for the final 34 AGN sample.

Table 1. The flux ratio R of the [O III] λ λ4959, 5007 lines of 12 NLS1 galaxies, derived on the basis of Dietrich et al. (2005).

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
The average value	2.953 ± 0.014

Table 2. The flux ratio R of the [O III] $\lambda\lambda$5007, 4959 lines of 62 AGN. The initial sample of 62 AGN is successively reduced to 34 by discarding the line profiles of lower quality.

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

The obtained flux ratio of 2.993 ± 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 H II region observations, which led to the previously mentioned theoretical reworking (Rosa 1985 – 3.03; Iye et al. 1987 – 3.17; Leisy & Dennefeld 1996 – 3.00). We should note here that the measurements given in Rosa (1985) and Iye et al. (1987) were performed in the 1980s and these differences are probably due to the observational equipment.

4 CONCLUSIONS

In order to check the improved theoretical value of the intensity ratio of the [O III] $\lambda\lambda$5007, 4959 lines, we measured the corresponding flux ratio in a sample of 62 AGN with a high-S/N spectra taken from the SDSS data base (DR4) and the observations described in Marziani et al. (2003). Also, from the existing literature we compiled the 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 H II region spectra. This is probably not caused by different physics, but by technological advances and the better instrumentation used in the observations of AGN spectra.

(iii) Despite the fact that the [O III] 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 [O III] $\lambda\lambda$4959, 5007 emission lines in AGN spectra (not only in photoionized gaseous nebulae and H II region spectra) may be used to test observationally the accuracy of theoretical calculations and check the linearity of the detectors.

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