Constraint on the time variation of the fine-structure constant with the SDSS-III/BOSS DR12 quasar sample

Franco D. Albareti1*, Johan Comparat1, Carlos M. Gutiérrez2,3, Francisco Prada1,4,5, Isabelle Paris6, David Schlegel7, Martín López-Corredoira2,3, Donald P. Schneider8,9, Arturo Manchado2,3, D. A. García-Hernández2,3, Patrick Petitjean10 and Jian Ge11

1 Instituto de Física Teórica (UAM/CSIC), Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain
2 Instituto de Astrofísica de Canarias (IAC), E-38205 La Laguna, Tenerife, Spain
3 Departamento de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Tenerife, Spain
4 Campus of International Excellence UAM+CSIC, Cantoblanco, E-28049 Madrid, Spain
5 Instituto de Astrofísica de Andalucía (CSIC), Glorieta de la Astronomía, E-18080 Granada, Spain
6 INAF, Osservatorio Astronomico di Trieste, Via G. B. Tiepolo 11, 34131 Trieste, Italy
7 Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA, 94720, USA
8 Department of Astronomy and Astrophysics, The Pennsylvania State University, University Park, PA 16802, USA
9 Institute for Gravitation and the Cosmos, The Pennsylvania State University, University Park, PA 16802, USA
10 Institut d’Astrophysique de Paris, CNRS-UPMC, UMR7095, 98bis bd Arago, 75014 Paris, France
11 Department of Astronomy, University of Florida, Gainesville, FL 32611-2055, USA

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ABSTRACT

From the Sloan Digital Sky Survey Data Release 12, which covers the full Baryonic Oscillation Spectroscopic Survey (BOSS) footprint, we investigate the possible variation of the fine-structure constant over cosmological time scales. We analyze the largest quasar sample considered so far in the literature, which contains 10,363 spectra with $z < 1$. All the BOSS quasar spectra are selected from a visually inspected quasar catalog. We apply the emission line method on the $[\text{O} \, \text{iii}]$ doublet ($\lambda \lambda 4960, 5008$ Å) and obtain $\Delta \alpha/\alpha = (1.4 \pm 2.3) \times 10^{-5}$ for the relative variation of the fine-structure constant. We also investigate the possible sources of systematics: misidentification of the lines, sky OH lines, $\text{H}$β and broad line contamination, optimal wavelength range for the Gaussian fits, chosen polynomial order for the continuum spectrum, signal-to-noise ratio and good quality of the fits. The uncertainty of the measurement is dominated by the sky subtraction. The results presented in this work, being systematics limited, have sufficient statistics to constrain robustly the variation of the fine-structure constant in redshift bins ($\Delta z \approx 0.06$) over the last 7.9 Gyr. In addition, we study the $[\text{Ne} \, \text{iii}]$ doublet ($\lambda \lambda 3870, 3969$ Å) present in 462 quasar spectra; and discuss the systematic effects on using these emission lines to constrain the fine-structure constant variation. Better constraints on $\Delta \alpha/\alpha (< 10^{-6})$ using the emission line method would be possible with high resolution spectroscopy.

Key words: cosmology: observations – quasars: emission lines – surveys – line: profiles – large-scale structure of Universe.

1 INTRODUCTION

Since Dirac’s philosophical argument (Dirac 1937), several experiments have been performed to constrain possible variation on dimensionless constants of physical theories. Dirac’s idea is based on the unlikely fact that the most fundamental constants of the Universe have a certain fixed value (at a given energy) with no apparent relation with the real world. It is more likely that their present values are the result of a dynamical process which had yielded the fundamental constants as they are measured today. Therefore, they should be considered as characterizing the state of the Universe (Uzan 2003). There are many current theoretical frameworks which allow for such variation of the fundamental constants, for instance, string theory, modified gravity and theories with extra-dimensions. Moreover, the experimental bounds on their variation has become stronger...
a stringent test for those theoretical models (cf. Thompson 2013; Leal et al. 2014).

The most studied fundamental constants are the fine structure constant \( \alpha \), the Newton gravitational constant \( G \) and the electron-to-proton mass ratio \( \mu \) (Uzar 2003, 2011; García-Berro et al. 2007). In this article, we consider the possible variation of the fine structure constant as measured through astronomical observations. For this purpose, we use the complete dataset of quasar spectra collected by the Sloan Digital Sky Survey III (SDSS-III; Eisenstein et al. 2011) Baryonic Oscillation Spectroscopic Survey (BOSS, Dawson et al. 2013). All these spectra have been visually inspected and classified as quasars by the BOSS Collaboration and results are gathered in the SDSS-III/BOSS Data Release 12 Quasar catalog (DR12Q, see Páris et al. 2015).

The fine structure constant governs the electromagnetic coupling between photons and charged particles \( \alpha = e^2/(\hbar c) \). Current constraints on its relative variation \( \Delta \alpha/\alpha \) over geological time scales are \([\Delta \alpha/\alpha] < 7 \times 10^{-6}\) up to \( z \approx 0.15 \) (2 Gyrs ago), obtained from the Oklo phenomenon (Petrov et al. 2006); and \([\Delta \alpha/\alpha] < 3 \times 10^{-7}\) up to \( z \approx 0.45 \) (4.5 Gyrs ago) from meteorites (Olive et al. 2002), which also excludes possible variations on the scales of the solar system. By measuring fine-structure multiplets at different redshift in the absorption or emission spectra of galaxies and quasars, located in different directions of the Universe, we can measure an estimate of the variation of \( \alpha \) with time or space over cosmological scales.

The first measurements of the variation of \( \alpha \) from astronomical observations obtained an accuracy \( \Delta \alpha/\alpha \approx 10^{-2} = 10^{-4} \) (Savedoff 1954; Bahcall & Salpeter 1965; Bahcall et al. 1967). Since then, the methods and understanding of systematics have dramatically improved, and current measurements, using absorption multiplets along the line-of-sight of three quasars around redshift 1.5, observed with a spectral resolving power \( R = 60,000 \) at ESO-VLT and UVES, have reached the \( z \approx 5 \times 10^{-6} \) level (Evans et al. 2014). Using emission lines a \( z \approx 2 \times 10^{-3} \) level is achieved with about 1,500 \( z \approx 300 \) quasar spectra at \( z \approx 0.6 \) (Gutiérrez & López-Corredoira 2014; Rahmani et al. 2014); using the SDSS \( R \approx 2,000 \) spectrograph (Smee et al. 2013).

There exist several methods to measure the possible variations of the fine structure constant through astronomical observations. However, they can be divided in two general classes depending on whether emission or absorption lines are used. The measurements on absorption features on a quasar spectrum are currently limited by the precision in the wavelength calibration of the spectra, i.e., 50 to 200 m/s using spectra with \( R = 60,000 \) (Molaro et al. 2013; Evans et al. 2014; Whitmore & Murphy 2015). Furthermore, this method, although more precise, remains controversial as several assumptions are made.

In this article we use the method based on emission lines, first proposed by Bahcall & Salpeter (1965), which is less affected by systematics. With a large ensemble of quasars and/or using high resolution spectroscopy, the uncertainty can be reduced significantly, and will compete with the absorption method when using high-resolution spectroscopy.

The beginning of the SDSS survey opened a new era of precision, allowing us to use big samples of quasars; thus, reducing the statistical uncertainty of the measurement (see Table 1). Bahcall et al. (2004) analyzed a quasar sample drawn from the SDSS-Early Data Release 6 (SDSS-DR6, Stoughton et al. 2002). They obtained a value of

\[
\frac{\Delta \alpha}{\alpha} = (0.7 \pm 1.4) \times 10^{-4}
\]

for a sample of 42 quasars with redshifts \( z < 0.8 \), this period covers the last 7 Gyrs. With 1,568 spectra in the same redshift interval, Gutiérrez & López-Corredoira (2010) reported a more precise value using the SDSS Data Release 6 (SDSS-DR6, Adelman-McCarthy et al. 2008), i.e.

\[
\frac{\Delta \alpha}{\alpha} = (2.4 \pm 2.5) \times 10^{-5}
\]

Recently Rahmani et al. (2014) used the SDSS-DR7 (Abazajian et al. 2009) and measured

\[
\frac{\Delta \alpha}{\alpha} = (-2.1 \pm 1.6) \times 10^{-5}
\]

for 2,347 quasars, where the quoted error for this measurement is the standard deviation of the results weighted by errors estimated from Monte Carlo simulations.

Here, we extend these works by using the SDSS-III/BOSS Data Release 12 (SDSS-DR12, Alam et al. 2015), which covers the full BOSS survey footprint with an area coverage of 10,000 square degrees (see Fig. 1). In contrast to these previous investigations, we use spectra obtained with the current BOSS spectrograph (Smee et al. 2013) instead of the previous SDSS-II/III instrument, making our sample totally independent from the previous works. Moreover, the spectral range of the BOSS spectrograph allows an extension of the redshift interval for the [O III] doublet from \( z = 0.8 \) to \( z = 1 \). We increase the number of quasar spectra by a factor of four with respect to SDSS-DR7.

There are additional emission doublets, in addition to the [O III], that can be used to measure \( \Delta \alpha/\alpha \) as noted by Bahcall et al. (2004) and first used by Gruepe et al. (2005). Gutiérrez & López-Corredoira (2010) analyze different doublets

### Table 1: Summary of the results obtained by recent works based on the [O III] emission line method for the possible variation of the fine structure constant.

| Reference | # Quasar spectra | SDSS Release | \( z_{\text{min}} \) | \( z_{\text{max}} \) | Time ago (Gyrs)[(a)] | \( \Delta \alpha/\alpha \times 10^{-5} \) |
|-----------|------------------|--------------|--------------------|--------------------|----------------------|----------------------------------|
| Bahcall et al. (2004) | 42 | EDR | 0.16 | 0.80 | 7.0 | 7 ± 14 |
| Gutiérrez & López-Corredoira (2010) | 1,568 | DR6 | 0.00 | 0.80 | 7.0 | 2.4 ± 2.5 |
| Rahmani et al. (2014) | 2,347 | DR7 | 0.02 | 0.74 | 6.7 | –2.1 ± 1.6 |
| This work (2015) | 10,363 | DR12 | 0.00 | 1.00 | 7.9 | 1.4 ± 2.3[(b)] |

[(a)] For a \( \Lambda \)CDM cosmology with \( H_0 = 67.8 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_m = 0.31 \) and \( \Omega_\Lambda = 0.69 \) from Planck+WMAP-9+BAO (see Planck Collaboration et al. 2014).

[(b)] Based on SDSS-III/BOSS spectra (all the other analyses use SDSS-I and SDSS-II spectra). This makes our sample the largest sample used today, being almost independent from the ones of previous works. Note: Since we have a sample six times bigger than Gutiérrez & López-Corredoira (2010), we expect a factor \( \approx 2.5 \) of improvement in the error just from purely statistical reasons. In Fig. 1 and Fig. 2 it is shown that the error is dominated by the SDSS sky subtraction algorithm, which suggests that the performed analysis have reached the maximum precision with the available data.
and find that the [Ne ii] and [Si ii] doublets appear in the quasar spectra with sufficient frequency to have a meaningful sample. The results for [Si ii] are compatible with zero, although the uncertainty is an order of magnitude bigger than for [O iii]. However, they obtain a positive variation of the fine structure constant when the [Ne ii] lines are used. No explanation was found for this non-zero positive variation. In this work, we also analyze the [Ne ii] lines to check whether the same effect is present in our BOSS quasar sample.

There are also investigations which use Si iv absorption lines ($\lambda\lambda$ 1394, 1403 Å) to obtain a precision of $4 \times 10^{-6}$ (Chand et al. 2005). However, since the separation between both lines is $\approx 9$ Å, the precision needed in the laboratory value for the separation between both wavelengths is five times higher than with [O iii] lines. Nevertheless, these constraints apply to the redshift interval $1.59 < z < 2.92$ which does not overlap with our range, thus they are complementary to the ones reported in this paper.

The paper is organized as follows. First, in Sec. 2, we describe the dataset used for our analysis. Next, in Sec. 3, the methodology is presented, the emission line method is explained, and the code and simulations to analyze the spectra are described. In Sec. 4, we study several samples to check for systematics. Then, our results are presented in Sec. 5. Finally, we provide in Sec. 6 a summary of the main conclusions achieved with this research project.

2 SAMPLE DESCRIPTION

All the spectra used in this investigation were downloaded from the Sloan Digital Sky Survey Database. This survey (York et al. 2000), which began taking observations in 1998, consists of a massive collection of optical images and spectra from astronomical objects including stars, galaxies, and quasars. For this purpose, there is a dedicated 2.5-m wide-angle optical telescope at Apache Point Observatory in New Mexico (USA) (for more details, see Gunn et al. 2004). The third phase of this project (SDSS-III, Eisenstein et al. 2011) includes the Baryon Oscillation Spectroscopic Survey (BOSS, Dawson et al. 2013) among its four main surveys. The data analyzed in this research were provided by BOSS and it is used for measuring $\\Delta \alpha/\alpha$ for the first time. The SDSS-III/BOSS pipeline (Bolton et al. 2012) classifies the objects as quasars depending on some properties of the object. However, there is also a visually-inspected quasar catalog. In particular, our sample is obtained from the DR12Q catalog version Páris et al. 2015.

The wavelength coverage of the SDSS-III/BOSS spectrograph is 3600-10400 Å and that of the SDSS-II spectrograph is 3800-9200 AL; whether our sample is constructed from BOSS quasar spectra. The sample is homogeneous since all the spectra have been obtained with the same instrument; and it is independent from previous investigations. The wider coverage of the new spectra allows consideration of higher redshifts (up to $z = 1$, for [O iii] doublet) than in previous analysis based on the same method (see Table 1).

The BOSS spectrograph has two channels (blue and red) whose wavelength coverage is 3600-6350 Å and 5650-10400 Å respectively. The resolving power ranges from 1560 at 3700 Å to 2270 at 6000 Å (blue channel), and from 1850 at 6000 Å to 2650 at 9000 Å (red channel). Our sample falls almost entirely in the red channel. More complete information about the SDSS-II and BOSS spectrographs can be found in Smee et al. (2013). The number of pixels of each spectrum is about 4600. The pixel spacing is uniform in log-wavelengths ($\Delta \log \lambda = 10^{-4}$ dex).

2.1 Data Selection

The DR12Q catalog contains 297,301 objects. In Fig. 1(left panel) we show the quasar distribution in the sky. We summarize below the main selection criteria in order to define our fiducial sample.

(i) $\text{Redshift} < 1$. This limitation is imposed by the wavelength range of the BOSS optical spectrograph and the position of the [O iii] lines. This criterion decreases the sample to 45,802 quasars.

(ii) $S/N[S\text{[O iii]}] > 10$. We impose a mild constraint on the signal-to-noise ratio of the stronger [O iii] line (5008 Å) in order to preserve a large number of spectra. Constraints on the expected width and amplitudes of the lines help in avoiding misidentifications of the [O iii] doublet (see Sec. 4). This selection reduces the sample from 45,802 to 13,023 objects.

(iii) Non-converging fits. Since we analyze spectra with low $S/N$, there are some cases where the Gaussian fit to the lines does not converge. All these spectra are discarded. This amounts to drop 1,244, leaving us with 11,779 spectra.

Figure 1. Left panel: Sky distribution of the full SDSS-III/BOSS DR12Q quasars (297,301) in J2000 equatorial coordinates. Right panel: Number of quasars with [O iii] emission lines in our fiducial sample (10,363 quasars) in $\Delta z = 0.05$ bins. Black solid line shows the number of spectra with $S/N[S\text{[O iii]}] > 10$ (10,363 quasars), blue dashed line for $S/N[S\text{[O iii]}] > 25$ (4,015 quasars) and red dotted line for $S/N[S\text{[O iii]}] > 50$ (1,498 quasars).

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Sky emission lines. Strong atmospheric lines, for instance the O i 5578 Å line, are poorly or not completely removed by the SDSS sky subtraction algorithm. This may lead to a wrong identification of the [O iii] lines and an introduction of low S/N [O iii] spectra (Gutiérrez & López-Corredoira 2010). We try to use the SDSS sky mask (see Delubac et al. 2014 for more details) to remove spectra whose [O iii] lines lie within a particular distance from the strongest sky lines. Even though we vary the distance [O iii] – sky lines, use different set of sky lines, or evaluate other conditions (S/N, fit errors, ...) to remove the outliers, we typically eliminate 3-5 good spectra for each outlier. Thus, these tests decrease significantly the number of quasar while not being very effective: typically 50% of the outliers were not removed. Thus, we decided to eliminate all spectra for which the separation between both lines differ by more than 1 Å from the local value (see last paragraph in Sec. 3). Fig. 2 (left panel) shows the distribution of these outliers, and they are correlated with a typical sky spectrum. From a visual inspection, it is observed that these spectra have low S/N and they are in fact contaminated by sky emission line subtractions (see right panel of Fig. 2). This effect causes us to discard 1,416 spectra (12%). Finally, we have 10,363 spectra (fiducial sample) after applying all these selection criteria.

The presence of broad Hβ emission line (4861 Å) near the weak [O iii] line 4960 Å could produce a blueshift in the determination of the [O iii] line position. This leads to a positive bias in the measured centroid. Thus, in principle, the larger the difference between the measured line separation at redshift z in rest frame and the local one, the larger the difference between the measured and true line position. This leads to a positive contamination of Hβ lines. However, we do not restrict the Hβ line in our initial sample. We compute a weighted mean for ∆α/α as weights the uncertainty in ∆α/α computed with the standard errors for the position of the lines derived from the Gaussian fits. The contamination of Hβ is automatically taken into account. For instance, a broad Hβ line near the [O iii] line 4960 Å means a bad Gaussian fit, then we obtain larger errors in the position of the line centroids and bigger error in ∆α/α. This Hβ contamination has little weight on the final value. However, in Sec. 4 we analyze several samples where the S/N is constrained and see how this affects our results.

The selection criteria described above produce our fiducial sample of 10,363 quasars. The distribution of quasars in redshift according to their S/N [O iii] 5008 is plotted in Fig. 1 (right panel). In Fig. 3 (left panel), we show a composite image built with all our high S/N [O iii] spectra sorted by redshift. The right panel shows the [O iii] doublet in rest frame. An electronic table is published along with the paper which contains all the information of each spectrum for our fiducial sample (see Appendix 2).

3 METHODOLOGY
3.1 Measurement method
To first order, the difference between the energy levels of an atom is proportional to α². Transitions between energy levels of the same atom at a given ionization level, with the same principal quantum number and different total angular momentum J, have an energy difference proportional to α². These groups of transitions are called fine-structure multiplets. Savedoff (1956) first realized that the fine structure of these energy levels could be used to break the degeneracy between the redshift effect and a possible variation of α.

The value of the fine structure constant can be measured through the separation between the fine structure of absorption or emission lines in the spectra of distant quasars (Lizarraga 2003) as

\[
\frac{\Delta \alpha}{\alpha} (z) = \frac{1}{2} \left\{ \frac{(\lambda_2 - \lambda_1)}{[(\lambda_2 - \lambda_1)_0]/(\lambda_2 - \lambda_1)_0] - 1} \right\},
\]

where \(\lambda_1, \lambda_2 > \lambda_0\) are the wavelengths of the transitions and subscript 0 and z stand for their value at redshift zero (theoretical/laboratory values) and z, respectively. For illustrative purposes, expression 4 can be approximated by

\[
\frac{\Delta \alpha}{\alpha} \approx \frac{\epsilon}{2 \delta \lambda_0},
\]

where \(\delta \lambda_0 = [\lambda_2 - \lambda_1]_0\) is the local z = 0 separation between both wavelengths, and \(\epsilon = \delta \lambda_0/(1 + z) - \delta \lambda_0\) is the difference between the measured line separation at redshift z in rest frame and the local one. Thus, in principle, the larger the difference between the
pair of lines, the better the precision for $\Delta \alpha/\alpha$. However, in practice, systematics in the wavelength calibration over a larger interval dominate.

Concerning emission lines, the most suitable pair of lines is the [O III] doublet, which is often present in quasar spectra with relatively high signal-to-noise ratio ($S/N$). The vacuum values for the [O III] doublet wavelengths are

$$\lambda_{[\text{O III}]}^1 = 4960.295 \text{ Å}, \quad \lambda_{[\text{O III}]}^2 = 5008.240 \text{ Å},$$

(6)

$$\delta \lambda_{[\text{O III}]} = 47.945 \text{ Å},$$

(7)

which are published in the NIST Atomic Spectra Database\(^1\). These transitions are forbidden (they correspond to magnetic dipole and electric quadrupole transitions). The wavelength experimental values are obtained indirectly by first computing the energy levels from observed wavelengths using a theta-pinch discharge Pettersson 1982. The wavelength separation has directly been measured from HII regions using a ballon-borne telescope and Michelson interferometer Moorwood et al. 1980. Both measurements are in perfect agreement. From equation (5), a determination of $\epsilon$ with a precision of 1 Å allows for an uncertainty of $10^{-2}$ in $\Delta \alpha/\alpha$ when using the [O III] doublet. The precision from the NIST atomic data allows for a determination of $\Delta \alpha/\alpha$ up to $10^{-5}$, which is a bit less than the uncertainty in our result. One could perform a blind analysis in order to search for a possible variation on $\alpha$, where the absolute wavelength values are not required, if one had a large enough sample distributed in redshift. However, the precision on the absolute wavelengths limits the usefulness of high resolution spectroscopy until better measurements of the [O III] lines (or its separation) are available.

### 3.2 Implementation

The code developed for the analysis of the quasar spectra follows the one described in Gutiérrez & López-Corredoira 2010, although there are some modifications and more information has been extracted from the analysis. We describe the main characteristic of our code below.

#### 3.2.1 Wavelength sampling

We consider only the experimental data together with their errors as processed by the SDSS pipeline to obtain the constraint on the possible variation of $\alpha$. We do not resample the wavelength range by using an interpolation method. Since the pixel spacing is uniform in log-wavelengths, a certain range of wavelengths in rest frame ($\lambda - \lambda + \lambda$) has the same number of pixels $N$, i.e.

$$N \propto \int_{\lambda - \lambda (1+z)}^{\lambda + \lambda (1+z)} d (\log \lambda) = \frac{\lambda (1+z)}{\lambda (1+z)} - \frac{\lambda (1+z)}{\lambda (1+z)} = \log \frac{\lambda (1+z)}{\lambda (1+z)},$$

(8)

independent of the redshift of the object. All the wavelength intervals with the same width in rest frame will have the same number of experimental points.

#### 3.2.2 Fit of the continuum spectrum

First, we fit a seventh-order polynomial to subtract the continuum spectrum while masking regions where strong and wide emission lines are present ($H\alpha$, $H\beta$, $H\gamma$, $H\delta$, MgII and the [O III] doublet). Our method differs from Gutiérrez & López-Corredoira 2010 in

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\(^1\) http://physics.nist.gov/PhysRefData/ASD/lines_form.html
that they use a cubic local spline to fit the continuum masking strong emission lines. The chosen order of the polynomial provides enough degrees of freedom to reproduce different continuum features. In Sec 3 we test how our measurement for $\Delta z/\alpha$ is affected by changing the polynomial order. Hundreds of continuum spectra fits were checked by eye. The residuals from the fits are smaller than the errors on the flux densities. Fig. 2 shows three different spectra with their continuum fit and residuals.

3.2.3 Signal-to-noise ratio

We follow Gutiérrez & López-Corredoira (2013) for the determination of the signal-to-noise ratio ($S/N$). Hence, we compute the standard deviation of the flux between 5040 (1 + $z$) Å and 5100 (1 + $z$) Å where there are no strong emission or absorption lines. Then, we search for the maximum of the [O iii] 5008 line, and determine $S/N_{[O\text{ iii}] 5008}$ as the ratio between the maximum of the line and the previously computed standard deviation. Although for a more reliable determination of the $S/N$ it is better to use a Gaussian fit to the line, this procedure avoids possible issues related when fitting data with very low $S/N$.

3.2.4 Measurement of the emission line wavelengths

To measure the wavelengths of the [O iii] doublet, our fitting code needs as input an accurate estimate of the redshift of the quasar, at least with an error $\Delta z < 3 \times 10^{-3}$. This allows a search for the emission lines in a 15 Å region around the expected location of the [O iii] lines. The SDSS pipeline provides a determination of the redshift based on a χ-squared fit to different templates; we refer to Bolton et al. (2012) for more details. These redshift estimates have errors between $10^{-4}$ and $10^{-5}$, which are sufficient for our purposes. Moreover, there is also a visual redshift estimation which can be found in the quasar catalog DR12Q (Paris et al. 2015). The difference between both redshift estimates (if any) is usually $|z_{\text{vis}} - z_{\text{spec}}| \approx 5 \times 10^{-4}$. We decided to adopt the visual redshifts since they are more reliable for our application. The centroid position of the [O iii] and [Ne iii] emission lines is determined by three different methods:

(i) Gaussian fit method:

First, we search for the maximum flux value in a ~ 15 (1 + $z$) Å window around the expected position of the line (according to the redshift provided by the DR12Q catalog). This procedure automatically erases any bias produced by the redshift value. Then, we make an initial Gaussian fit around the position of the maximum flux value using a fixed width of ~ 10 (1 + $z$) Å. From this first fit, we obtain a new position for the line centroid and a Gaussian width. These values are used as initial parameters for the final fit of the lines; namely, the wavelength range considered to perform the final fit is centred around the position of the line centroid, and it is four times the Gaussian width of the lines. This approach means that we consider pixels up to 2σ away from the center of the line. Hence, some lines are fitted using ~4-5 pixels while others with ~15-20 pixels depending on the line width. The fit takes into account the flux errors for each pixel, i.e., we use the $\text{ivar}$ column found in each spectrum as weights for the fit. Our final centroid measurement for each of lines considered corresponds to the centroid of the Gaussian fit done in the last step of the adopted procedure. We also derive an error for $\Delta \alpha/\alpha$ using the standard errors for the centre position of the Gaussians. In Fig. 3 we depict the [O iii] and [Ne iii] lines for the same quasar spectrum to illustrate the Gaussian fit method. This is our main method for measuring $\alpha$.

(ii) Integration method:

Here, the centroids of the lines are obtained by integrating around 1σ of the position of the fitted Gaussian from the previous method. This technique provides important indications of some features of the analyzed sample, for instance if there is Hβ contamination.

(iii) Modified Bahcall method:

In Bahcall et al. (2004) the authors used a different approach to compute the line positions. They performed a third-order spline interpolation to the stronger [O iii] 5008 line, then fitted this interpolation to the weaker 4960 line by adjusting the amplitude and separation of the profile. We have modified this method by using a Gaussian fit to the stronger line rather than a third-order spline.

Although we have described three different methods, the main results presented in this work are based on the Gaussian fit method,
while the other two are used only for comparison (see Sec. 3). All values quoted for $\Delta \alpha/\alpha$ in this paper come from the Gaussian fit method unless explicitly stated.

Finally, our final result for $\Delta \alpha/\alpha$ and its error is obtained in the same way as in Chand et al. (2005), namely we compute a weighted mean and a weighted standard deviation, where the error for $\Delta \alpha/\alpha$ of each spectrum is used as the weight.

3.3 Simulated spectra

In order to test the robustness and accuracy of our measurement method, we generate realizations of quasar spectra using as noise a normal distribution centred at the flux value, and taking the error in each pixel as the standard deviation. From our fiducial sample (10,363 quasars), we simulate 100 realizations for each spectrum. The estimated error derived from the simulations $(\Delta \alpha/\alpha)_{\text{sim}}$ includes

$$\Delta (\Delta \alpha/\alpha)_{\text{sim}}^2 = \Delta (\Delta \alpha/\alpha)_{\text{fit}}^2 + \Delta (\Delta \alpha/\alpha)_{\text{continuum}}^2 + \Delta (\Delta \alpha/\alpha)_{\text{code}}^2 ,$$

(9)

where $\Delta \alpha/\alpha_{\text{fit}}$ is the error derived from the Gaussian fit, which is our error estimate for each real spectrum. $\Delta \alpha/\alpha_{\text{continuum}}$ is the error from different continuum subtraction due to the Gaussian noise and $\Delta \alpha/\alpha_{\text{code}}$ is the systematic error of our code. Then, we expect $\Delta \alpha/\alpha_{\text{sim}} > \Delta \alpha/\alpha_{\text{fit}}$ and their difference will be an indication of the continuum and systematic errors. In Fig. 6 (left panel), we show the correlation between the error in $\Delta \alpha/\alpha$ from the Gaussian fits of each real spectrum and the standard deviation for $\Delta \alpha/\alpha$ of its 100 realizations. Almost all the standard deviations from the simulations are within a factor 0.5-2 of the standard error from the fits. This shows that our code and the continuum subtraction do not introduce small systematic errors compared to the Gaussian fitting.

As a further proof, we consider the results of the simulations for the 1,416 dropped spectra because of sky emission lines (criterion iv, see Sec. 2). We found that more than 80% of the spectra show standard deviations greater than $10$ Å in the relative separation between the lines, which confirm that these spectra have very low $S/N$. Fig. 6 (right panel) shows the error from the simulations as a function of redshift. The error are distributed in two clouds of points, and it is observed that the cloud with bigger errors mimic the sky spectrum.

4 SYSTEMATICS

In this section, we examine the possible unnoticed systematic errors by analyzing different quasar samples. Table 2 summarizes all the samples considered together with their mean redshifts and the measured value for $\Delta \alpha/\alpha$.

We consider the following sources of systematic errors:

(i) Misidentification of the lines. The expected line widths and amplitudes are useful to avoid misidentification of the [O iii] emission lines. a) Line widths: Since both lines originate on the same upper energy level, their width must coincide. We check that this is the case by considering quasars whose [O iii] line widths are the same within a relative fraction. It is seen that more than 3,000 quasars have line widths which differ by less than a 5% (see
Table 2). b) Amplitude ratio: Atomic physics states that the amplitude ratio between the \([\text{O}III] 5008\) and \([\text{O}III] 4960\) lines is 2.98 (Storey & Zeippen 2000) (as quoted in Sec. 5, we obtain \(\Delta \alpha/\alpha \) for our fiducial sample (10,363). The solid line represent a one-to-one correspondence, while the dashed lines have slopes of 2 and 0.5. Right panel: Error estimated from the simulations as a function of redshift.

(ii) Wavelength interval for the Gaussian fits. We use a wavelength range of \(2\sigma\) around each \([\text{O}III]\) line in order to obtain the final Gaussian fit to the line profiles. We study how our results depend on this choice. By considering a larger wavelength interval the results are more affected by the \(\text{H}\beta\) contamination and possible asymmetries on the line wings. The differences in the number of spectra for these samples (which are obtained by applying the selection criteria ii-iv) discussed in Sec. 3.1) arise because of the criteria concerning the non-converging fits and the outlier points described in the previous section.

(iii) \(\text{H}\beta\) contamination. We analyze samples where the ratio between \(S/N_{\text{H}\beta}\) and \(S/N_{[\text{O}III] 4960}\) is constrained. Despite the fact that the value for \(\Delta \alpha/\alpha\) decreases as we place more stringent constraints on \(\text{H}\beta\), it is always compatible with zero within the error. This analysis demonstrates that the contamination from \(\text{H}\beta\) line is already taken into account when a weighted mean is used.

(iv) Continuum subtraction. We use a seventh-order polynomial to subtract the continuum spectrum. We examine if the polynomial order has important effects on our measurements. Our value for \(\Delta \alpha/\alpha\) and their error is only slightly affected by the chosen polynomial order.

(v) Goodness of Gaussian fits. We quantify the quality of the Gaussian fits by the \(R^2\) coefficient. All the considered samples show values for \(\Delta \alpha/\alpha\) compatible with zero.

(vi) Different methods for measuring the \([\text{O}III]\) lines position. We compare the results obtained by the methods to measure the position of the \([\text{O}III]\) lines described in Sec. 3.2.4. Since not all the methods provide an error for the measurement, we cannot calculate a weighted mean and it is necessary to select a more restricted sample. Then, we consider a sample where the difference between the widths of the lines is less than 25%, the amplitude ratio is cons-
Table 2. Results for $\Delta \alpha/\alpha$ considering several samples with different constraints. The number of quasar spectra, the mean and standard deviation of the redshift and the value for $\Delta \alpha/\alpha$ are shown.

| $\sigma_{9450}/\sigma_{3008} - 1$ | # Quasar spectra | redshift | $\Delta \alpha/\alpha \times 10^{-5}$ |
|----------------------------------|------------------|----------|-------------------------------------|
| < 50%                            | 10,028           | 0.56 ± 0.21 | 1.6 ± 2.3                          |
| < 25%                            | 8,877            | 0.56 ± 0.21 | 1.9 ± 2.3                          |
| < 10%                            | 5,846            | 0.56 ± 0.21 | 1.7 ± 2.5                          |
| < 5%                             | 3,458            | 0.54 ± 0.22 | −0.9 ± 3.0                         |

$\langle F_2 \times \sigma \rangle_{9808/9450}$ # Quasar spectra redshift $\Delta \alpha/\alpha \times 10^{-5}$

| 2.98 ± 0.50                      | 8,327            | 0.56 ± 0.21 | 1.8 ± 2.4                          |
| 2.98 ± 0.25                      | 5,761            | 0.55 ± 0.21 | −0.4 ± 2.6                         |
| 2.98 ± 0.10                      | 2,658            | 0.54 ± 0.21 | 0.0 ± 3.4                          |
| 2.98 ± 0.05                      | 1,411            | 0.52 ± 0.22 | 5.2 ± 4.6                          |

Fit width # Quasar spectra redshift $\Delta \alpha/\alpha \times 10^{-5}$

| 2$\sigma$                        | 10,363           | 0.56 ± 0.21 | 1.4 ± 2.3                          |
| 3$\sigma$                        | 10,252           | 0.59 ± 0.20 | 5.5 ± 2.5                          |
| 4$\sigma$                        | 9,978            | 0.59 ± 0.20 | 7.1 ± 2.7                          |
| 5$\sigma$                        | 9,726            | 0.59 ± 0.20 | 5.3 ± 2.6                          |

$S/N_{\text{H}I}/[\text{O} \text{III}]$ # Quasar spectra redshift $\Delta \alpha/\alpha \times 10^{-5}$

| < 5                             | 10,338           | 0.57 ± 0.21 | 1.4 ± 2.3                          |
| < 2                             | 9,831            | 0.57 ± 0.21 | 0.6 ± 2.3                          |
| < 1                             | 8,162            | 0.57 ± 0.21 | 0.1 ± 2.5                          |
| < 0.5                           | 5,831            | 0.58 ± 0.21 | −0.7 ± 2.8                         |

Pol. order (cont.) # Quasar spectra redshift $\Delta \alpha/\alpha \times 10^{-5}$

| 3                               | 10,528           | 0.57 ± 0.21 | 1.0 ± 2.3                          |
| 5                               | 10,550           | 0.57 ± 0.21 | 1.3 ± 2.3                          |
| 7                               | 10,363           | 0.56 ± 0.21 | 1.4 ± 2.3                          |
| 9                               | 10,471           | 0.56 ± 0.21 | −1.1 ± 2.3                         |

$R^2$ (both fits) # Quasar spectra redshift $\Delta \alpha/\alpha \times 10^{-5}$

| > 0.9                           | 9,254            | 0.56 ± 0.21 | 1.5 ± 2.4                          |
| > 0.97                          | 6,045            | 0.56 ± 0.21 | 2.8 ± 2.7                          |
| > 0.99                          | 2,301            | 0.54 ± 0.21 | 2.0 ± 3.5                          |
| > 0.995                         | 845              | 0.51 ± 0.22 | −0.4 ± 4.8                         |

Method # Quasar spectra redshift $\Delta \alpha/\alpha \times 10^{-5}$

| Gaussian (weighted)             | 4,537            | 0.58 ± 0.20 | −0.4 ± 2.8                         |
| Gaussian                        | 4,537            | 0.58 ± 0.20 | 1.2 ± 4.5                          |
| Integration                     | 4,537            | 0.58 ± 0.20 | 3.6 ± 4.8                          |
| Modified Bahcall                | 4,537            | 0.58 ± 0.20 | 0.8 ± 4.4                          |
| Median                          | 4,537            | 0.58 ± 0.20 | 1.8 ± 1.4                          |

$[\text{O} \text{ III}]$ # Quasar spectra redshift $\Delta \alpha/\alpha \times 10^{-5}$

| < 1000                          | 10,353           | 0.56 ± 0.21 | 1.4 ± 2.3                          |
| < 500                           | 8,990            | 0.56 ± 0.21 | 0.2 ± 2.4                          |
| < 300                           | 2,798            | 0.52 ± 0.22 | −0.8 ± 3.9                         |
| < 200                           | 150              | 0.52 ± 0.24 | 21 ± 18                            |

strained to differ from 3.00 by less than 0.5 and the $S/N_{\text{H}I}$ is half the $S/N_{\text{[O} III\text{]}}$.

(vii) Broad lines. We also study samples where the width of both lines is less than a certain value (in km s$^{-1}$). These samples are compatible with except for the sample with $\Delta \alpha/\alpha$ = 0.25), with 5 points non-overlapped and the standard deviation of the $\Delta \alpha/\alpha$ measurement in each bin (bottom red line). The quasar sample (10,363 spectra) is our fiducial sample obtained by applying the selection criteria described in Sec. 2.

$\Delta \alpha/\alpha$ (upper blue line) derived from the Gaussian fits (also in over-lapping bins) and a typical sky spectrum. Even though we have imposed a constraint on our initial sample based on the sky emission lines, the standard deviation and errors still correlate with the sky. In particular, for the standard deviation correlation, this means that the precision in our measurement of $\Delta \alpha/\alpha$ along the whole redshift interval is limited by the SDSS sky subtraction algorithm.

5 RESULTS

We used a total of 10,363 quasar spectra, drawn from the SDSS-III/BOSS DR12Q catalog, after applying the selection criteria i–iv) (see Sec. 2), to measure the possible variation of the fine-structure constant and the following measurement is reported below as a final result of this investigation

$$
\frac{\Delta \alpha}{\alpha} = (1.4 \pm 2.3) \times 10^{-5}.
$$

This value does not indicate any time variation in $\alpha$ and it is compatible with previous results obtained in different investigations based on the same method by Bahcall et al. (2004), Gutierrez & Lopez-Corredoira (2010) and Rahmani et al. (2014). The redshift dependence of the measurements is shown in Fig. 8 (left panel), where several bins have been made taking into account the redshift intervals affected by the sky (shaded zones). In the right panel, we show the results obtained from the simulations described in Sec. 4 using the same redshifts intervals for the bins. It is observed that the main difference between the real results and the simulations are in the regions where there are strong sky lines (shaded regions), while being in agreement in the remaining zones. Detailed information about each bin for the real data can be found in Table 2.

Our results are little affected by the specific constraints imposed in our sample as discussed in Sec. 4. For instance, we vary the width for the Gaussian fits, the contamination of H$\beta$, the polynomial order used to fit the continuum spectrum, the quality of the
Figure 9. Left panel: $\Delta \alpha/\alpha$ vs. redshift (real data). Details about each bin are listed in Table 3. Right panel: $\Delta \alpha/\alpha$ vs. redshift measurements and their errors, from the simulations. A typical sky spectrum and shadowed regions where the sky contamination is expected to be large, are shown as reference.

Figure 10. $\Delta \alpha/\alpha$ vs $S/N_{[O\text{ III}]}$ 5008 (solid symbols) with the mean error (black lines) in linear-log scale for the initial sample (10,363 quasars) described in Sec. 2. The deviation of $\Delta \alpha/\alpha$ from zero steadily decreases as the $S/N$ increases. The mean error is computed as the mean of the error in $\Delta \alpha/\alpha$ (from the fits) using overlapping bins (200 spectra per bin, 1 non-overlapped).

Table 3. Detailed information about the bins in Fig. 9

| Redshift interval | # Quasar spectra | Redshift | $\Delta \alpha/\alpha \times 10^{-5}$ |
|-------------------|-----------------|----------|-------------------------------|
| 0.390 – 0.460     | 817             | 0.42 ± 0.02 | −5.2 ± 6.8           |
| 0.460 – 0.520     | 723             | 0.49 ± 0.02 | 5.5 ± 8.9            |
| 0.520 – 0.580     | 757             | 0.55 ± 0.02 | 0.4 ± 9.2            |
| 0.625 – 0.675     | 988             | 0.65 ± 0.01 | −3.5 ± 7.4           |
| 0.715 – 0.765     | 1,177           | 0.74 ± 0.01 | 1.7 ± 7.1            |
| 0.820 – 0.880     | 644             | 0.84 ± 0.02 | 4.7 ± 9.2            |

Gaussian fits and test different methods to measure $\Delta \alpha/\alpha$. The most important effect found is that by considering broader widths for the Gaussian fits, the results are more affected by the contamination from Hβ and possible asymmetries in the line wings. We have also checked for possible misidentifications of the [O III] emission lines using their expected widths and amplitude ratio.

Table 4 contains the results for $\Delta \alpha/\alpha$ when the lower bound on the $S/N_{[O\text{ III}]}$ 5008 is increased. All the results remain compatible with zero. In Fig. 10 the measured $\Delta \alpha/\alpha$ for our fiducial sample (10,363 quasars) as a function of the $S/N_{[O\text{ III}]}$ 5008 of the spectrum is plotted. Recently, there has been a report on a significant deviation for $\alpha$ from being a constant as a function of space (King et al. 2012). Table 5 contains the results for each galactic hemisphere, and no statistical meaningful difference is found to claim for a spatial variation (a more detailed analysis will be presented somewhere else).

We are inclined to parametrize the possible variation of $\alpha$ through a dependence on redshift $z$. This is justified since any possible variation on $\alpha$ must be dominated by the local geometry of space-time (at least if we consider the dynamics of the Universe as the main reason for such variation). Therefore, one is led to consider the possible variation of $\alpha$ as a function of redshift ($z = 1/a(t) - 1$) or the Ricci scalar $R(t) = 6H(t)^2[1 - q(t)]$, where $a(t)$ is the scale factor, $H(t)$ the Hubble parameter and $q(t)$ is the deceleration parameter. Since the Ricci scalar is not known for each quasar, it is straightforward to consider a possible variation with redshift. In contrast, for a time parametrized model of the variation of $\alpha$ the analysis depends on the particular cosmology considered. Since there is no significant clear dependence we use a linear model in redshift. Then, for

| $S/N_{[O\text{ III}]}$ 5008 | # Quasar spectra | Redshift | $\Delta \alpha/\alpha \times 10^{-5}$ |
|--------------------------|-----------------|----------|-------------------------------|
| > 10                     | 10,363          | 0.56 ± 0.21 | 1.4 ± 2.3           |
| > 20                     | 5,270           | 0.53 ± 0.21 | −0.5 ± 2.5           |
| > 50                     | 1,498           | 0.47 ± 0.20 | −3.4 ± 3.1           |
| > 100                    | 451             | 0.41 ± 0.19 | −2.0 ± 3.6           |
| > 500                    | 12              | 0.24 ± 0.19 | 6 ± 12              |

Table 5. Results for the North and South galactic hemispheres.

| Galaxy hemisphere | # Quasar spectra | Redshift | $\Delta \alpha/\alpha \times 10^{-5}$ |
|-------------------|-----------------|----------|-------------------------------|
| North             | 8,069           | 0.56 ± 0.21 | 2.6 ± 2.6           |
| South             | 2,294           | 0.59 ± 0.20 | −3.1 ± 4.9           |
which do not show any dependence of \( \Delta \alpha / \alpha \) with redshift. From this sample, we also obtain a value for the line ratio \( [\text{Ne } \text{ iii}] \alpha / [\text{O } \text{ ii}] \alpha \approx 2.96 \pm 0.02 \text{sys} \), where \( F_2 \) is the maximum flux density of the line and \( \sigma \) is the Gaussian width. The value reported is a weighted mean where the \( S/N \) \([\text{ Ne }\text{ iii}] \) at 5008 Å is used as weights. The quoted systematic error is computed from the analysis of samples with different polynomial orders for the continuum fit and different fit widths (see Table 6), since this quantity is more affected by these two parameters of the analysis. The value we obtain is in agreement with the best current theoretical value (2.98, Storey & Zeippen 2000).

Finally, we measure from 462 quasar spectra with \([\text{ Ne } \text{ iii}]\) emission lines \( \Delta \alpha / \alpha [\text{ Ne } \text{ iii}] = (34 \pm 1) \times 10^{-4} \), compared to \( \Delta \alpha / \alpha [\text{ Ne } \text{ iii}] = (36 \pm 1) \times 10^{-4} \) obtained by Gutiérrez & López-Corredoira (2010). The analysis of the \([\text{ Ne } \text{ iii}]\) lines reveals the same systematic effect previously observed, namely a clear tendency for a positive variation of \( \alpha \). Fig. 11 compares the results obtained for \( \Delta \alpha / \alpha \) for spectra where both \([\text{ O } \text{ ii}]\) and \([\text{ Ne } \text{ iii}]\) lines are present. To account for this effect, an error on the wavelengths for the \([\text{ Ne } \text{ iii}]\) lines or a wrong wavelength spectral calibration of \( \sim 0.6 \) Å is necessary. There are experimental (Bowen 1955) and indirect (Kramida & Nave 2006) values for the wavelengths of the \([\text{ Ne } \text{ iii}]\) lines which are in agreement with errors \( \approx 3 \times 10^{-2} \) Å. We use the NIST values for the \([\text{ Ne } \text{ iii}]\) lines

\[
[\text{ Ne } \text{ iii}] 1455.49 \text{ Å} \\
[\text{ Ne } \text{ iii}] 1457.72 \text{ Å} \\
[\text{ Ne } \text{ iii}] 1459.84 \text{ Å}
\]

Moreover, the results for the \([\text{ O } \text{ ii}]\) doublet guarantee the good calibration of the SDSS spectra (and many more independent scientific results based on the SDSS spectra). In the appendix, we have measured the \([\text{ Ne } \text{ iii}]\) lines using a high-resolution spectrum from the planetary nebula IC418 obtained with the FIES spectrograph at the NOT telescope (see Diaz-Luis et al. 2014 for more observational details). The difference between the \([\text{ Ne } \text{ iii}]\) lines quoted by NIST and our measurement account for a variation on \( \Delta \alpha / \alpha < 10^{-6} \), a thousand times smaller than the discrepancy observed. However, we find that the weak \([\text{ Ne } \text{ iii}]\) lines is blended with He which explains the systematic effect observed when using the \([\text{ Ne } \text{ iii}]\) doublet (see Appendix 1).

6 SUMMARY

The main conclusions of this work are:

(i) From 45,802 objects at \( z < 1 \) classified as quasars, we have extracted a sample of 10,363 quasars with \([\text{ O } \text{ ii}]\) emission lines.

(ii) With this fiducial sample, we have estimated a value for the possible variation of the fine structure constant \( \Delta \alpha / \alpha \approx (1.4 \pm 2.3) \times 10^{-5} \), which represents the most accurate result obtained with this methodology.

(iii) After analyzing more than 30 different testing samples, we conclude that our results are quite robust and are compatible with no variation of the fine structure constant.

(iv) Systematic effects have been studied such as misidentification of the lines, \( \text{H}/ \text{H} \) contamination, broad lines, width for the Gaussian fits, polynomial order for the continuum spectrum, \( S/N \) and the goodness of the fits. We have also compared the results with the ones obtained by using the different methods described in Sec. 3 to measure the position of the \([\text{ O } \text{ ii}]\) lines and they are shown to be consistent.

(v) We have determined the ratio of the \([\text{ O } \text{ ii}]\) transition lines to be \( 2.96 \pm 0.02 \text{sys} \), which is in good agreement with previous experimental and theoretical values.

(vi) From over 1,000 simulated realizations of quasar spectra, we conclude that the precision of our emission line method is dominated by the error from the Gaussian fits. Hence, the error from the continuum subtraction and any possible systematics from our code are small.

(vii) The standard deviation of the results as a function of redshift correlates with the sky. This result suggests that our main source of uncertainty is determined by the SDSS sky subtraction algorithm.

Table 6. Results for the line ratio when polynomials of different orders are used to subtract the continuum and different range for the Gaussian fits are used. For each sample, the number of quasar spectra, the mean redshift together with its standard deviation and the value for \( F_2 \times \sigma \) shown.\[ F_2 \times \sigma \]

| Pol. order | # Quasar spectra | redshift | \( F_2 \times \sigma \) |
|-----------|-----------------|----------|------------------|
| 2         | 10,528          | 0.57 ± 0.21 | 2.96             |
| 3         | 10,550          | 0.57 ± 0.21 | 2.94             |
| 4         | 10,363          | 0.56 ± 0.21 | 2.96             |
| 5         | 10,471          | 0.56 ± 0.21 | 2.98             |

The main conclusions of this work are:

(i) From 45,802 objects at \( z < 1 \) classified as quasars in the SDSS-III/BOSS DR12 quasar catalog, we have extracted a sample of 10,363 quasars with \([\text{ O } \text{ ii}]\) emission lines.

(ii) With this fiducial sample, we have estimated a value for the possible variation of the fine structure constant \( \Delta \alpha / \alpha = (1.4 \pm 2.3) \times 10^{-5} \), which represents the most accurate result obtained with this methodology.

(iii) After analyzing more than 30 different testing samples, we conclude that our results are quite robust and are compatible with no variation of the fine structure constant.

(iv) Systematic effects have been studied such as misidentification of the lines, \( \text{H}/ \text{H} \) contamination, broad lines, width for the Gaussian fits, polynomial order for the continuum spectrum, \( S/N \) and the goodness of the fits. We have also compared the results with the ones obtained by using the different methods described in Sec. 3 to measure the position of the \([\text{ O } \text{ ii}]\) lines and they are shown to be consistent.

(v) We have determined the ratio of the \([\text{ O } \text{ ii}]\) transition lines to be \( 2.96 \pm 0.02 \text{sys} \), which is in good agreement with previous experimental and theoretical values.

(vi) From over 1,000 simulated realizations of quasar spectra, we conclude that the precision of our emission line method is dominated by the error from the Gaussian fits. Hence, the error from the continuum subtraction and any possible systematics from our code are small.

(vii) The standard deviation of the results as a function of redshift correlates with the sky. This result suggests that our main source of uncertainty is determined by the SDSS sky subtraction algorithm.

Figure 11. Comparison between \([\text{ Ne } \text{ iii}]\) and \([\text{ O } \text{ ii}]\) measurements for \( \Delta \alpha / \alpha \). Empty symbols stand for spectra with \( S/N \) \([\text{ Ne } \text{ iii}] \approx 35 \) and solid squares represent spectra with \( S/N \) \([\text{ Ne } \text{ iii}] \approx 35 \). \([\text{ Ne } \text{ iii}]\) measurements have a clear tendency to a positive variation of \( \alpha \), which is due to a systematic effect affecting the \([\text{ Ne } \text{ iii}]\) measurement. This same effect has already been noticed by Gutiérrez & López-Corredoira (2010).
(viii) The same systematic effect previously noticed by Gutiérrez & López-Corredoira (2010) has been found on the [Ne iii] lines measurement. Incorrect measurement for the separation of the [Ne iii] has been excluded as a possible reason, and a blending of the He and the [Ne iii] 3969 is identified as the source of this effect (see Appendix 1).

(ix) The measurement of $\Delta \alpha/\alpha$ using SDSS-III/BOSS spectra has reached the maximum precision unless better sky subtraction algorithms are developed; to obtain better constraints ($< 10^{-6}$) using the emission line method, high resolution spectroscopy ($R \approx 100,000$) is mandatory.

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APPENDIX 1

As discussed in Sec. [3] the measurements for $\Delta \alpha/\alpha$ using the [Ne iii] emission lines show a positive variation of $\alpha$ of the order $10^{-5}$. To exclude the possibility of a wrong value of the standard wavelength separation between the [Ne iii] lines, we use a high-resolution spectrum ($R \approx 25,000$) of the planetary nebula IC 418. The IC 418 optical spectrum (3600-7200 Å) was taken under service time at the Nordic Optical Telescope (NOT; Roque de los Muchachos, La Palma) in March 2013 with the FIES spectrograph.

We used FIES in the low-resolution mode ($R \approx 25,000$) with the 2.5’ fibre (centred at the central star of IC 418). Three exposures of 1200 s each were combined into a final IC 418 spectrum, reaching a S/N (in the stellar continuum) of 60 at 4000 Å and in excess of 150 at wavelengths longer than 5000 Å (see Diaz-Luis et al. [2014]) for more observational details). To measure $\Delta \alpha/\alpha$ we need to know the ratio $R = (\lambda_2 - \lambda_1) / (\lambda_2 + \lambda_1)$, which is independent of the peculiar velocity of the planetary nebula. From our data we obtain

\[
R = (1259561 \pm 4) \times 10^{-8},
\]

compared to the one using NIST values for the wavelengths $R_{\text{NIST}} = 1259560 \times 10^{-8}$.

The difference between the two values translates into a variation on $\Delta \alpha/\alpha < 10^{-6}$. Thus, the measured wavelength separation for the [Ne iii] doublet does not account for the positive variation on $\alpha$ observed using these lines. Fig. [A1] shows the Gaussian fit to the [Ne iii] line profiles present in the IC 418 spectrum.

The IC 418 spectrum shows two different lines near the [Ne iii] 3969 Å line (see Fig. [A2]). One (3971 Å) is He i, the other one is He i (3965 Å). Hence, we search for a possible blending of the [Ne iii] line 3969 with these two lines in our much lower spectral resolution quasar spectra. In Fig. [A3] we show stack quasar spectra with narrow emission lines. It can be seen that the weak [Ne iii] line is blended. This explains the systematics observed in the [Ne iii] measurements of the fine structure constant. To quantify the displacement produced by the blending with He i line, we do a Gaussian convolution of the Planetary Nebula spectrum to lower the resolution down to $R \approx 2000$. Since the line intensity ratio of [Ne iii] and He may differ in the quasar narrow emission line region and the Planetary Nebula, we show in Fig. [A4] the shift produced by the He i line as a function of the ratio [Ne iii]/He i.

APPENDIX 2

We publish along with the paper an electronic table with the fiducial sample (10,363 quasars) from which all the subsamples considered...
Table A1. Description of the electronic table with the fiducial sample (10,363 quasars) published along with the paper.

| Column | Name            | Format    | Description                                                                 |
|--------|-----------------|-----------|-----------------------------------------------------------------------------|
| 1      | SDSS_NAME       | STRING    | SDSS-DR10 designation hhmmss.ss+ddmms.s (J2000)                            |
| 2      | RA              | DOUBLE    | Right Ascension in decimal degrees (J2000)                                 |
| 3      | DEC             | DOUBLE    | Declination in decimal degrees (J2000)                                     |
| 4      | THING_ID        | INT32     | Thing_ID                                                                    |
| 5      | PLATE           | INT32     | Spectroscopic Plate number                                                 |
| 6      | MJD             | INT32     | Spectroscopic MJD                                                          |
| 7      | FIBER           | INT32     | Spectroscopic Fiber number                                                 |
| 8      | Z_VI            | DOUBLE    | Redshift from visual inspection                                            |
| 9      | Z_PIPE          | DOUBLE    | Redshift from BOSS pipeline                                                |
| 10     | ERR_ZPIPE       | DOUBLE    | Error on BOSS pipeline redshift                                            |
| 11     | ALPHA           | FLOAT     | $\Delta \alpha/\alpha$ from the Gaussian fits                              |
| 12     | ERR_ALPHA       | FLOAT     | Standard error for $\Delta \alpha/\alpha$ from the Gaussian fits          |
| 13     | SN_01           | FLOAT     | $S/N$ for the [O III] 4960 line                                            |
| 14     | SN_02           | FLOAT     | $S/N$ for the [O III] 5008 line                                            |
| 15     | 01_FIT          | FLOAT     | Line centroid for the [O III] 4960 line                                    |
| 16     | 02_FIT          | FLOAT     | Line centroid for the [O III] 5008 line                                    |
| 17     | ERR_01          | FLOAT     | Error on the line centroid for the [O III] 4960 line                       |
| 18     | ERR_02          | FLOAT     | Error on the line centroid for the [O III] 5008 line                       |
| 19     | 01_FLUX         | FLOAT     | Gaussian amplitude at the centre for the [O III] 4960 line                 |
| 20     | 02_FLUX         | FLOAT     | Gaussian amplitude at the centre for the [O III] 5008 line                 |
| 21     | 01_WIDTH        | FLOAT     | Gaussian width for the [O III] 4960 line                                   |
| 22     | 02_WIDTH        | FLOAT     | Gaussian width for the [O III] 5008 line                                   |
| 23     | FILE_NAME       | STRING    | File name to download from the SDSS server                                 |

Figure A2. IC 418 spectrum centred at [Ne III] 3968 line. The two close lines are He (3971 Å) and He i (3965 Å).

in the paper are drawn. Table A1 describes the information and format of each column.

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Figure A4. Shift produced by the He line in the $[\text{Ne III}]$ 3969 line as a function of the line-intensity ratio of both lines as measured from the Planetary Nebula convolved spectrum.

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