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The ratio of the C IV $\lambda\lambda$1548,1550 rest-wavelengths from high-redshift QSO absorption lines*

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Abstract. We use very high quality VLT-UVES quasar spectra obtained in the course of the ESO Large Programme "Cosmic evolution of the Intergalactic Medium", to show that the ratio of the C IV doublet rest-wavelengths published in the literature and widely used is not consistent with high-redshift observations. From the analysis of 106 C IV systems we obtain: λ_2/λ_1 = 1.00166228 ± 0.13 × 10^{-6}. A similar analysis on 28 Si IV systems shows that the observed ratio is consistent with the well known Si IV$\lambda\lambda$1393,1402 wavelengths. Using Si IV lines to calibrate the C IV lines in 11 systems, we find $\lambda_{1,2}$ = 1548.2049 and 1550.7785 ± 0.0012 Å which is consistent with the Griesmann & Kling (2000) laboratory wavelengths. The precision on the doublet ratio is better because of the large number of C IV systems available for the measurement. This shows that it is possible to perform atomic physics measurements using high redshift astrophysical data.

Key words. cosmology: observations – galaxies: intergalactic medium – galaxies: halos – galaxies: quasars: absorption lines

1. Introduction

The resonance transitions $2s^2S_{1/2}$–$2p^2P_{1/2,3/2}$ near 1550 Å for C IV and $3s^2S_{1/2}$–$3p^2P_{1/2,3/2}$ near 1400 Å for Si IV are among the most important transitions for optical plasma diagnostics in the interstellar medium, the intergalactic medium and stellar atmospheres. They are widely observed in the ultraviolet with HST but also in the optical and infrared wavelength ranges when redshifted. The rest wavelengths of these transitions have been measured experimentally by Griesmann & Kling (2000). These measurements are very important as the energy of the atomic transitions depend on the electromagnetic coupling constant α that has been claimed recently to vary with cosmic time (Murphy et al. 2003; see however Srianand et al. 2004 and Chand et al. 2004). Indeed, the possible time variation of α is registered in the absorption line spectra seen toward high-z QSOs (Savedoff 1956) and several attempts to measure the variation in α were based on measuring at high redshift the wavelengths of alkali doublets like the Si IV doublet (Cowie & Songaila 1995; Varshalovich et al. 1996; Murphy et al. 2001b). The C IV doublet could be used as well if the rest wavelengths were known with better accuracy. In addition, C IV is one of the species most frequently detected in the gas at high redshift. The ratio of the two wavelengths in the doublet is therefore of great interest to anyone interested in fitting the C IV absorption lines at high-z (e.g., Rauch et al. 1996; Pichon et al. 2003).

The laboratory measurements of the doublet wavelengths by Griesmann & Kling (2000) are more accurate for Si IV than for C IV. In the present paper we show that we can measure the ratio of the two wavelengths in the C IV doublet with even better accuracy using high redshift data the calibration of which is ascertain by the Si IV doublet.

2. Data

The data used in this study have been obtained with the Ultraviolet and Visible Echelle Spectrograph (UVES) mounted on the ESO KUEYEN 8.2 m telescope at the Paranal observatory for the ESO-VLT Large Programme "Cosmic evolution of the intergalactic medium" (PI: Jacqueline Bergeron). This survey gives a homogeneous sample of 20 QSO lines of sight suitable for studying various properties of the inter-galactic medium over a redshift range 1.7−4.5. All the quasars were observed in good seeing conditions (better than 0.8 arcsec) with 1 arcsec slit width. The data were reduced using an improved version of the UVES pipeline, a set of procedures implemented in a dedicated context of MIDAS, the ESO data reduction package (Aracil et al. in preparation). The main characteristics of the pipeline is to perform a precise inter-order background subtraction for science frames and master flat-fields, and to allow

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for an optimal extraction of the object signal rejecting cosmic ray impacts and performing sky-subtraction at the same time. The reduction is checked step by step. Wavelengths are corrected to vacuum-heliocentric values and individual 1D spectra are combined together. As the error spectrum is very important for our analysis care was taken while combining the error spectrum of individual exposures. In all cases spectra were obtained covering the observed wavelength range of 3000−10 000 Å. In this study we use only absorption lines that are redshifted to the red of the Lyman-α emission line. A typical *S/N* ratio of ∼50−80 per pixel is achieved in the whole wavelength range of interest and spectral resolution is ≥45 000. This is approximately a factor two improvement on *S/N* at similar resolution compared to earlier studies.

Possible systematic effects leading to wavelength mis-calibration have been discussed by Murphy et al. (2001a) and we specify here a few technical points. Wavelength calibration has been extensively checked using the ThAr lamps. Errors measured from the lamp spectra are typically ∼2 mÅ. Air-vacuum wavelength conversion has been made using Edlén (1966) formula at 15°C. A shift in the wavelength scale can be introduced if the Thorium-Argon lamp and the science spectra are taken at systematically different temperatures. In the case of the Large Programme, most of the lamp spectra have been taken just before or after the science exposures. In any case, the temperature variations measured over one night in UVES are smaller than 0.5 K (see Dekker et al. 2000). Heliocentric correction is done using Stumpff (1980) formula. In addition, all exposures have been taken with the slit alined with the parallactic angle so that atmospheric dispersion has little effect on our measurements. Therefore, as discussed by Murphy et al. (2001a), uncertainties due to these effects are neligible. Note that in any case, in this study we mainly discuss the ratio of the C IV$\lambda\lambda$1548,1550 wavelengths which are separated by ∼4−6 Å only (Sect. 3). On these scales, relative calibration is even more accurate.

3. The wavelength ratio

3.1. Inaccuracy in the C IV wavelengths

We have searched the 20 QSO lines of sight for C IV systems and fitted them automatically with Voigt profiles (see Pichon et al. 2003). In the course of this exercize, we noticed that for a number of systems, apparently not particularly blended, the two absorption lines were slightly shifted in the wavelength direction one relative to the other. Looking carefully at these systems led us to the conclusion that the wavelengths given in the literature (that we were using) were not accurate enough given the quality of the data.

Typical examples are given in Fig. 1. It can be seen that the separation of the two modelled absorption lines, when using published wavelengths, is too large compared to the relative positions of the observed lines. The slight shift is smaller than the pixel size but is coherent over the profile. Note that the wavelength calibration accuracy is of the same order of magnitude than the accuracy of the laboratory measurements. Indeed the C IV wavelengths are $\lambda_1^0 = 1548.204 \pm 0.001$ and $\lambda_2^0 = 1550.781 \pm 0.002$ Å when our accuracy is of the order of 2 mÅ for a mean redshift close to about 2.

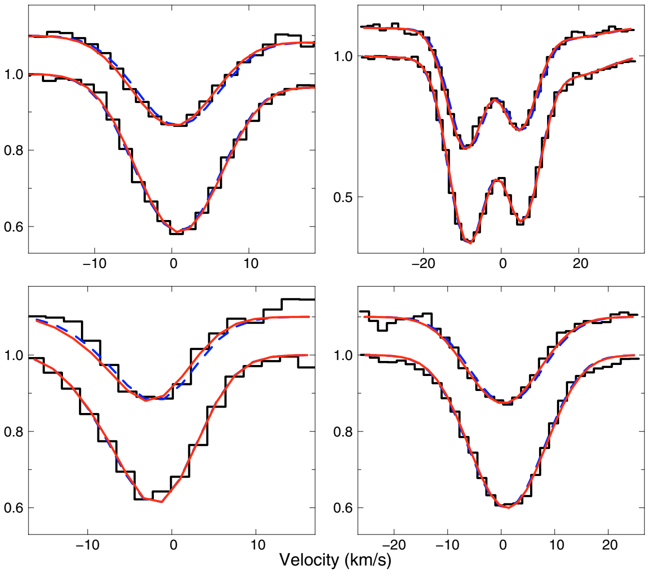

Fig. 1. Four examples of C IV systems in our sample. The dashed lines correspond to fits using the old wavelength ratio. The separation of the two modelled lines (λ1548 is the bottom line and λ1550 the upper line), using published wavelengths, is too large. The solid lines correspond to the best value obtained from the full sample.

3.2. Wavelength ratios

The C IV systems in our sample are found over a large redshift range ($1.3 < z < 3.5$) and therefore are redshifted at very different places in the spectra. It is therefore highly improbable that an observed systematic shift, if any, be due to the wavelength calibration. Although great care was taken in the calibration procedure, this possibility can only be completely dismissed however with an internal calibrator. It happens that the wavelengths of the Si IV doublet are better known than the C IV ones. The two wavelengths are $\lambda_{1,2}^0 = 1393.76018 \pm 4 \times 10^{-5}$ and $1402.77291 \pm 4 \times 10^{-5}$ Å respectively. Therefore, we should not see any significant shift for the Si IV doublet.

We have selected absorption systems with components that are not saturated and that are not blended with other absorptions. We have identified 120 and 34 such, respectively, C IV and Si IV doublets. For each of them we fit the two lines of the doublets with Voigt profiles leaving free the parameter c defined as $\lambda_2/\lambda_1 = (\lambda_2/\lambda_1)^0 \times (1 + c)$. This parameter c measures the deviation of the observed ratio from the published one (marked with the subscript "0"). We vary the parameter c and fit the systems for each value of c. We choose as an estimator of c the value at which χ^2 is at minimum. Errors are derived as usual from the range over which $\chi^2 = \chi^2_{\rm min} \pm 1$. We then compute the mean value of c and reject systems at more than 3σ from the mean. Inspection of the rejected systems show that they are characterized by either a defect in the spectrum or a blend with a line from another system. We end up with 106 C IV and 28 Si IV systems. Results are shown for these systems in Fig. 2 where all measurements of the parameter c are given

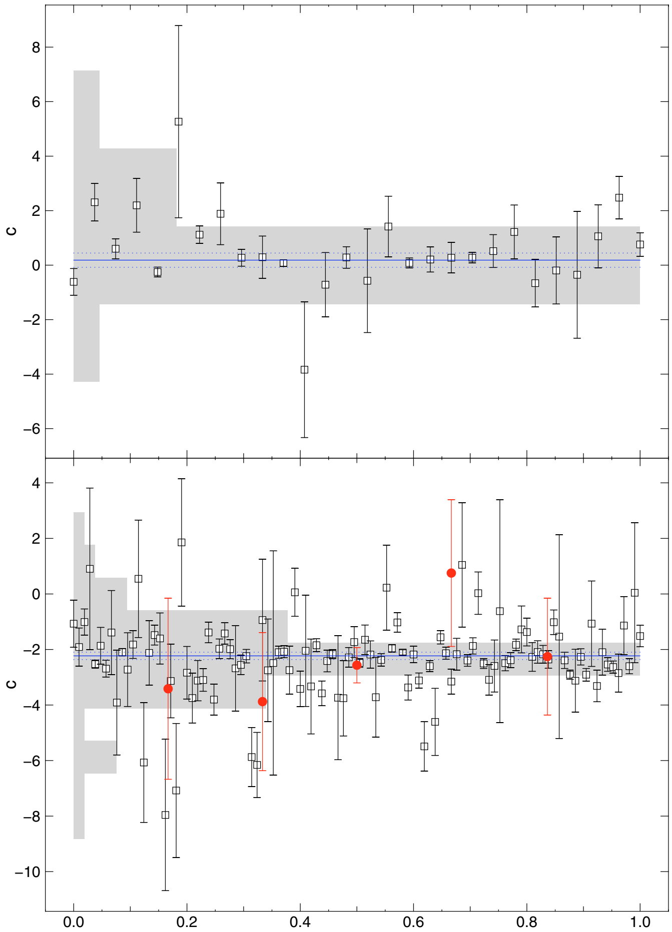

Fig. 2. The fitted parameter c defined as $\lambda_2/\lambda_1 = (\lambda_2/\lambda_1)_0 \times (1 + c)$, where the "0" subscript indicates published values, is plotted versus an arbitrary ranking scale for the 106 C IV (lower panel) and 28 Si IV (upper panel) doublets. Systems are ordered by increasing redshift. The histograms show the distribution of c values. The weighted means of c are $(-2.23 \pm 0.04) \times 10^{-6}$ and $(0.18 \pm 0.09) \times 10^{-6}$ for, respectively, C IV and Si IV. The means and 3σ limits are indicated by solid and dashed lines respectively. Five additional measurements using the publicly available Keck spectrum of APM 08279+5255 are overplotted as filled circles and are consistent with the UVES measurements.

for Si IV (upper panel) and C IV (lower panel) versus an arbitrary ranking scale. Systems are ordered by increasing redshift however. One sigma errors are shown for each of the systems. The weighted means of the ratios are $(-2.23 \pm 0.04) \times 10^{-6}$ and $(0.18 \pm 0.09) \times 10^{-6}$ for, respectively, C IV and Si IV.

The scatter in the measurements is larger than what is expected from most of individual errors. This is probably because effects like continuum fitting and blending are not accurately taken into account when estimating individual errors. We therefore estimate the non weighted means and obtain: $(-2.27 \pm 0.13) \times 10^{-6}$ and $(0.60 \pm 0.31) \times 10^{-6}$ for, respectively, C IV and Si IV. Our result is not changed. Note that the measurement on Si IV is less accurate because there are nearly 4 times less Si IV systems as compared to C IV systems. It is apparent that although the measured value for the Si IV doublet is compatible with zero within errors, the one for the C IV doublet is not.

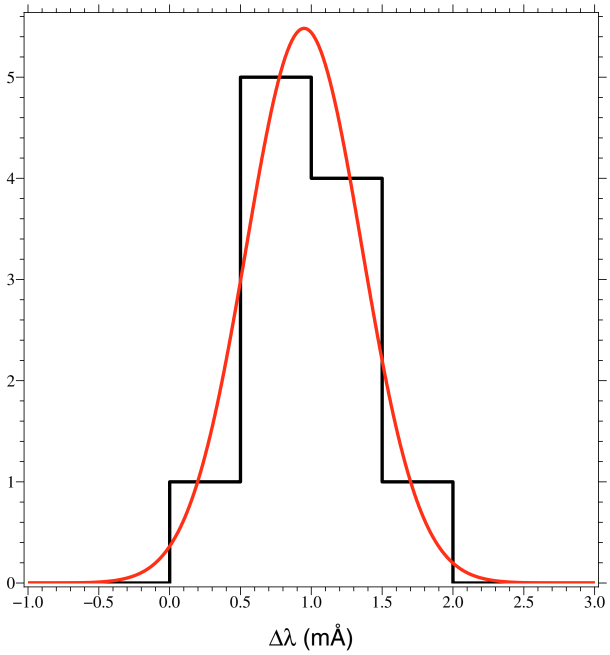

Fig. 3. Histogram of the wavelength shift to be applied to the published wavelength of C IVλ1548. We find $\Delta\lambda$ = 0.90 mÅ and σ = 0.6 mÅ.

As a final check, we have used the only Keck data publicly available, a very good spectrum of APM 08279+5255 (Ellison et al. 1999; Petitjean et al. 2000), to perform the same analysis on the 5 C IV systems suitable for this. The measurements are overplotted in Fig. 2 and are compatible with our findings.

4. Wavelengths

We can try and derive the absolute value of the C IV wavelengths by fitting together the C IV and Si IV doublets, using Si IV as an anchor. This can be done only on a few systems as both doublets should meet the previous selection criteria. Only 11 systems are available for this overall fit for which we fix the Si IV wavelengths. We vary the two C IV wavelengths maintaining their ratio at the value derived in the previous section. The histogram of the shifts $\Delta\lambda$ to be applied to λ_1^0 is given in Fig. 3. We find that the best values for the two wavelengths are $\lambda_{1,2}$ = 1548.2049 and 1550.7785 ± 0.0012 Å. Due to lack of statistics, the accuracy is not better than in the laboratory. Wavelengths are consistent within errors with Griesmann & Kling measurements.

This procedure could be questionned as it is known that C IV profiles can be slightly more extended than Si IV ones. We have checked that our selection criteria avoid this potential problem by comparing the C IV and Si IV Doppler parameters derived for the components used in the fits (see Fig. 4). Indeed, we note, as expected if the Si IV and the C IV profiles are consistent, that most of the points lie between the curves ($b_{\rm CIV} = b_{\rm SiIV}$) expected for turbulent broadening and ($b_{\rm CIV} = \sqrt{m_{\rm SiIV}/m_{\rm CIV}}\, b_{\rm SiIV}$) expected for thermal broadening. This supports the idea that the two doublets can be fitted together consistently and used for this measurement.

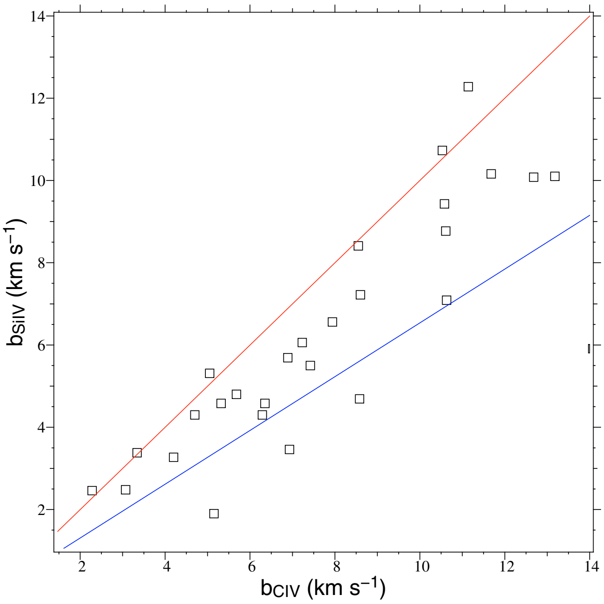

Fig. 4. The Doppler parameter of C IV components is shown versus the Doppler parameter of Si IV corresponding components as measured in the fits of the 11 C IV–Si IV systems. Most of the points lie between the curves ($b_{CIV} = b_{SiIV}$) expected for turbulent broadening and ($b_{CIV} = \sqrt{m_{SiIV}/m_{CIV}} b_{SiIV}$) expected for thermal broadening.

5. Conclusion

We have used high quality and high spectral resolution data of high redshift quasars gathered during the ESO large programme "Cosmic evolution of the intergalactic medium" to constrain the wavelengths of the C IV doublet. We have fitted 106 C IV and 28 Si IV doublets. The latters are well fitted using the published wavelengths. This is not the case of the formers for which published wavelengths are not consistent with astrophysical data. The weighted mean of the derived ratio λ_2/λ_1 for Si IV is consistent with the wavelengths published in the literature. On the contrary, the ratio has to be corrected adding a correction factor c defined as $\lambda_2/\lambda_1 = (\lambda_2/\lambda_1)^0 \times (1+c)$ of $c = (-2.23 \pm 0.13) \times 10^{-6}$ for C IV. Note that the precision here is not high enough to discuss any variation of α. For this, a highly focussed procedure has to be implemented. Additional C IV measurements using the publicly available Keck spectrum of APM 08279+5255 are consistent with the UVES measurements. Our best estimates of the wavelengths are $\lambda_{1,2}$ = 1548.2049 and 1550.7785 ± 0.0012 with their ratio better defined as $\lambda_2/\lambda_1 = 1.00166228 \pm 0.13 \times 10^{-6}$.

This testifies the quality of the wavelength calibration of the data obtained with UVES. This is of great importance for future studies based on the unique data set gathered during the ESO large programme "Cosmic evolution of the intergalactic medium".

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