XXVth IAP Colloquium (2009 July)

THE CONTINUUM OF QUASARS IN THE LYMAN-ALPHA FOREST

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Abstract. The continuum of quasars in the Lyman-alpha forest is not obvious specially at low spectral resolution and high redshift where there is little unabsorbed continuum remaining. We discuss different methods to derive the continuum of quasar spectra in the Lyman-alpha forest. This is a crucial step toward deriving the mean absorption of the IGM and its evolution with redshift and therefore toward normalization of N-body simulations.

1 Introduction

The main goal in studying the Lyα forest in quasar (QSO) spectra is to determine the underlying matter distribution in the inter-galactic medium (IGM). It is also clear that our physical understanding of the IGM, comes from the detailed comparison of N-body numerical simulations of the growth of structure in the universe with observations of the Lyα absorption (Petitjean 1999; Theuns 2005). One of the key parameters is the total amount of absorption by neutral Hydrogen. In orther to measure this absorption we must first determine the QSO continuum in the Lyα forest.

2 Determination of QSO continuum

In this setion we will apply the different methods of determining the QSO continuum to our QSO sample which is consist of 22 high redshift highly luminous QSOs.

2.1 PL method

One of the methods is to extrapolate in the Lyα forest the Power-Law (PL) continuum calculated over wavelengths redward of the Lyα emission line. In Fig. 1, we show the result of this method applied to 19 QSOs in our sample.

We fitted a function $f_\lambda = A\lambda^{\alpha_\lambda}$, where $\alpha_\lambda = -2 - \alpha_\nu$, to the spectrum longward of Lyα emission. The results for A and α_ν are shown in Table 1. The mean value of the power-law index, α_ν, is -0.60 with a standard deviation of $\sigma = 0.59$. This value is very similar to what was found by Pentericci et al. (2003). They found $\langle\alpha_\nu\rangle = -0.57$, using a sample of 45 high redshift quasars.

2.2 PCS method

In the Principal Component Spectra (PCS) method, the continuum of individual QSOs is predicted using the red side of its spectrum. The first, second and third PCS account for 63.4, 14.5 and 6.2% of the variance respectively, and the first seven PCS take 96.1% of the total variance. The first PCS carries Lyα, Lyβ and high ionization emission line features (O VI, N V, Si IV, C IV) that are sharp and strong. The second PCS has low

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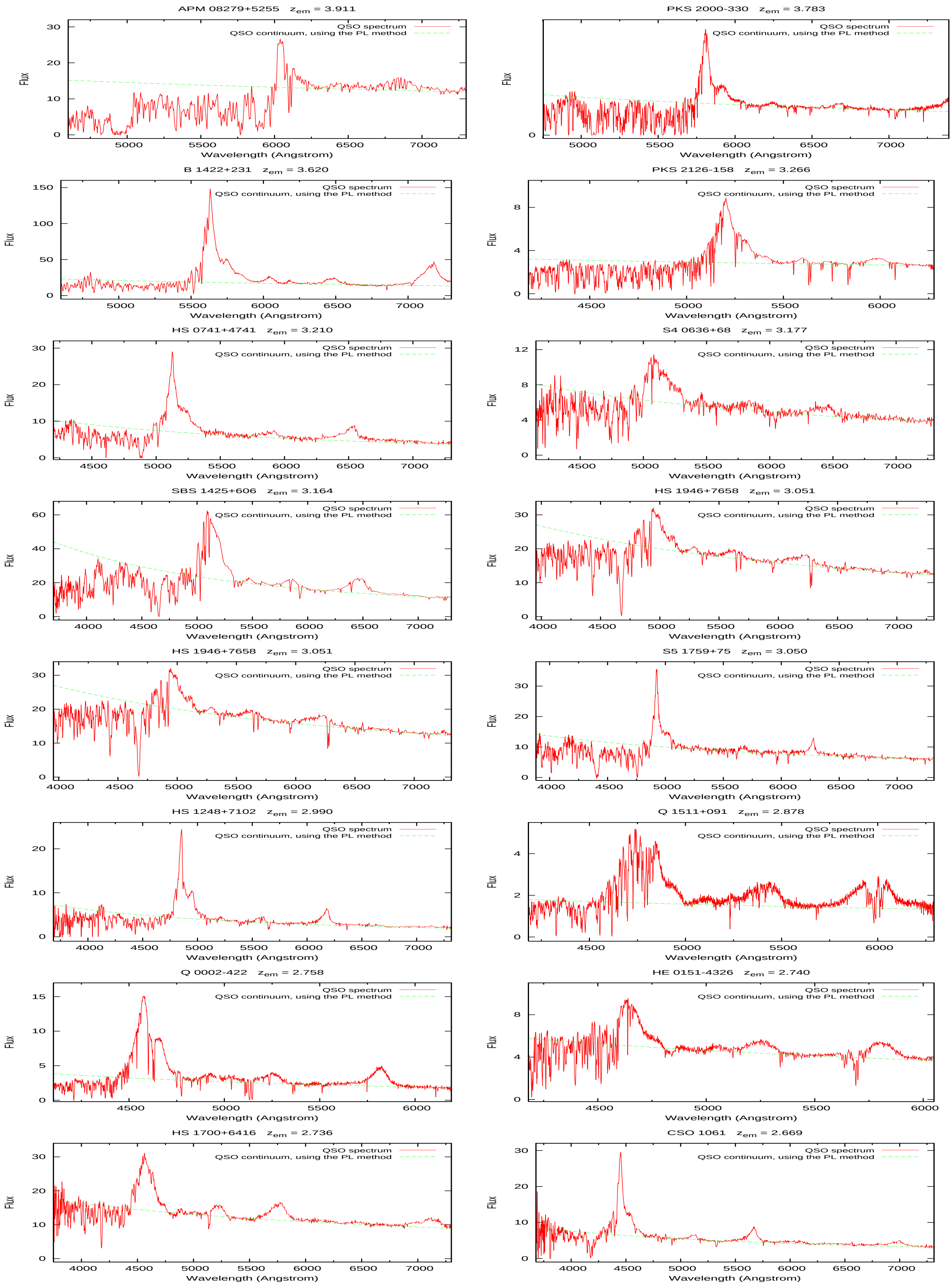

Fig. 1. Power-Law (PL) fitting for 19 QSOs spectra which observed with either EMMI at the ESO-NTT telescope or CARELEC spectrograph at the OHP observatory. We applied a function of $f_\lambda \propto \lambda^{\alpha_\lambda}$, where $\alpha_\lambda = -2 - \alpha_\nu$, to the spectrum longward of Lyα emission.

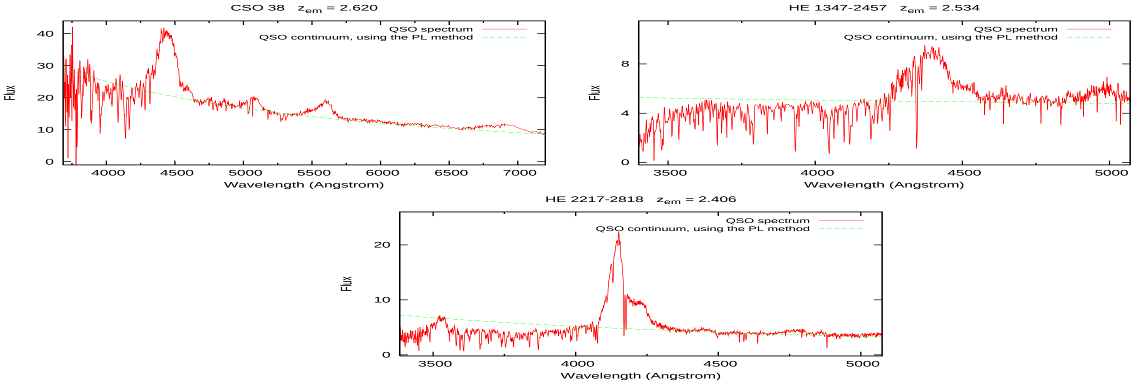

Figure 1: Continued

Table 1. Power-Law parameters

Name	z_{em}	A	α_ν
APM 08279+5255	3.911	1.50935e+03	-1.45574
PKS 2000-330	3.783	7.39332e+04	-0.78169
B 1422+231	3.620	2.02762e+11	0.66013
PKS 2126-158	3.266	2.35525e+02	-1.48501
HS 0741+4741	3.210	5.05487e+07	-0.15307
S4 0636+68	3.177	5.64659e+05	-0.66045
SBS 1425+606	3.164	1.14368e+09	0.07775
HS 1946+7658	3.051	1.23170e+06	-0.70512
S5 1759+75	3.050	1.60915e+06	-0.59173
HS 1248+7102	2.990	5.66922e+07	-0.06733
Q1511-091	2.878	9.14438e+02	-1.25283
CSO 1107	2.830	4.90872e+05	-0.57063
Q0002-422	2.758	2.02927e+07	-0.13941
HE 0151-4326	2.740	1.55700e+05	-0.77611
HS 1700+6416	2.736	7.96108e+03	-1.24191
CSO 1061	2.669	1.89574e+06	-0.50183
CSO 38	2.620	8.88044e+07	-0.18198
HE 1347-2457	2.534	2.74693e+02	-1.52395
HE 2217-2818	2.406	6.73808e+07	-0.02501
Mean	3.021	1.07471e+10	-0.59873

ionization emission line features (Fe II, Fe III, Si II, C II) that are broad but not sharp. We used the projection matrix, the two sets of the first ten components, and their weights of the spectra in the training set of Suzuki et al. (2005). The first and second set of components are respectively generated by using both the blue- and red-side and only the red side wavelengths of the spectra in the training set.

We made a code which works well to reproduce the results of Suzuki et al.. To find the smooth continua in our QSO sample, we masked all the absorption lines which were in the red side of the spectra. We divided each spectrum in bins of length 0.5 Å in the rest-frame. The flux were normalized by taking the average of 21 pixels around 1280 Å where no emission line is seen. We then applied our code to all of the QSOs in our sample which recovered the rest-wavelength range between 1020, the Lyβ+O IV emission-line belend, and 1600Å, the C IV emission line. The results of this method for the 12 QSOs are shown in Fig. 2.

As shown in Figure 2, this method, which is totally automatic, works well to generate the weak emission lines in the Lyα forest. The shape of predicted continua seems relatively good. However, there is some bad fitting around the strong emission lines and for some spectra.

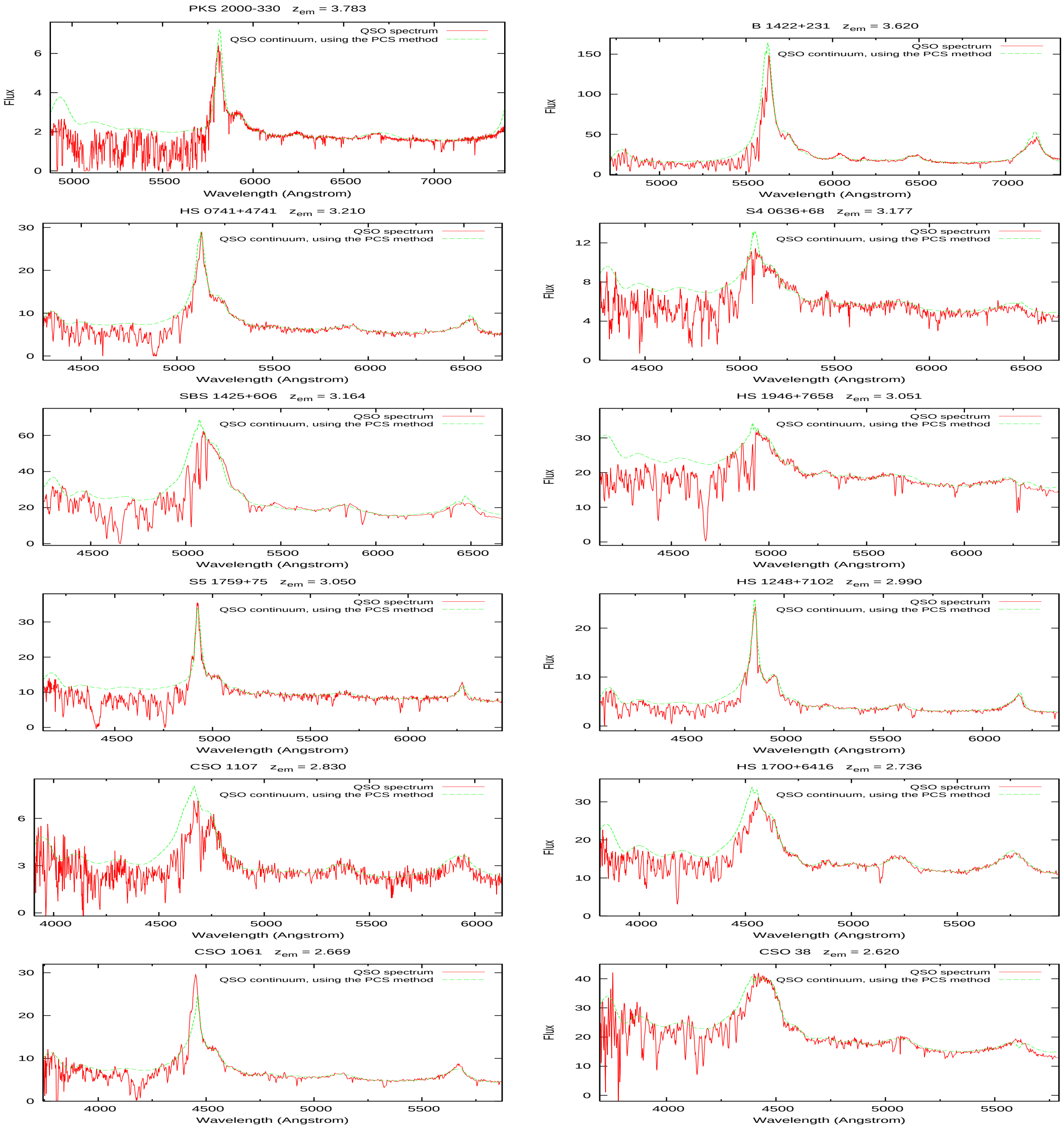

Fig. 2. Predicting continuum using the Principal Component Spectra (PCS) method for 12 QSOs.

2.3 IE method

In the Iterative Estimating (IE) method, the continuum is produced by minimising the sum of a regularisation term and a χ^2 term, which is computed from the difference between the quasar spectrum and the continuum estimated during the previous iteration (Aracil et al. 2004). In Fig. 3, the final results of applying this method for 19 QSOs are shown. Two continua are plotted. Continuum1 and continuum2 are respectively the lowest and highest continuum obtained after changing the parameters.

This is another automatic method for which, to estimate the continuum in the Lyα forest, it is not necessary to have a large wavelength range of data in the red side of the Lyα emission (e.g. see QSO continuum of Q 1511+091 or Q 0002-422 in the Fig 3), whereas, it is necessary in the two previous methods. This is an important advantage of this method. At high redshift, this method underestimates the absorption in the Lyα forest. The reason is that it assumes, by construction, that most of the points outside strong absorption features are representative of the intrinsic QSO continuum. This is a crude assumption because (i) blending is strong for $z > 3$ and (ii) low resolution convolves the spectrum on scales larger than the width of a typical absorption feature.

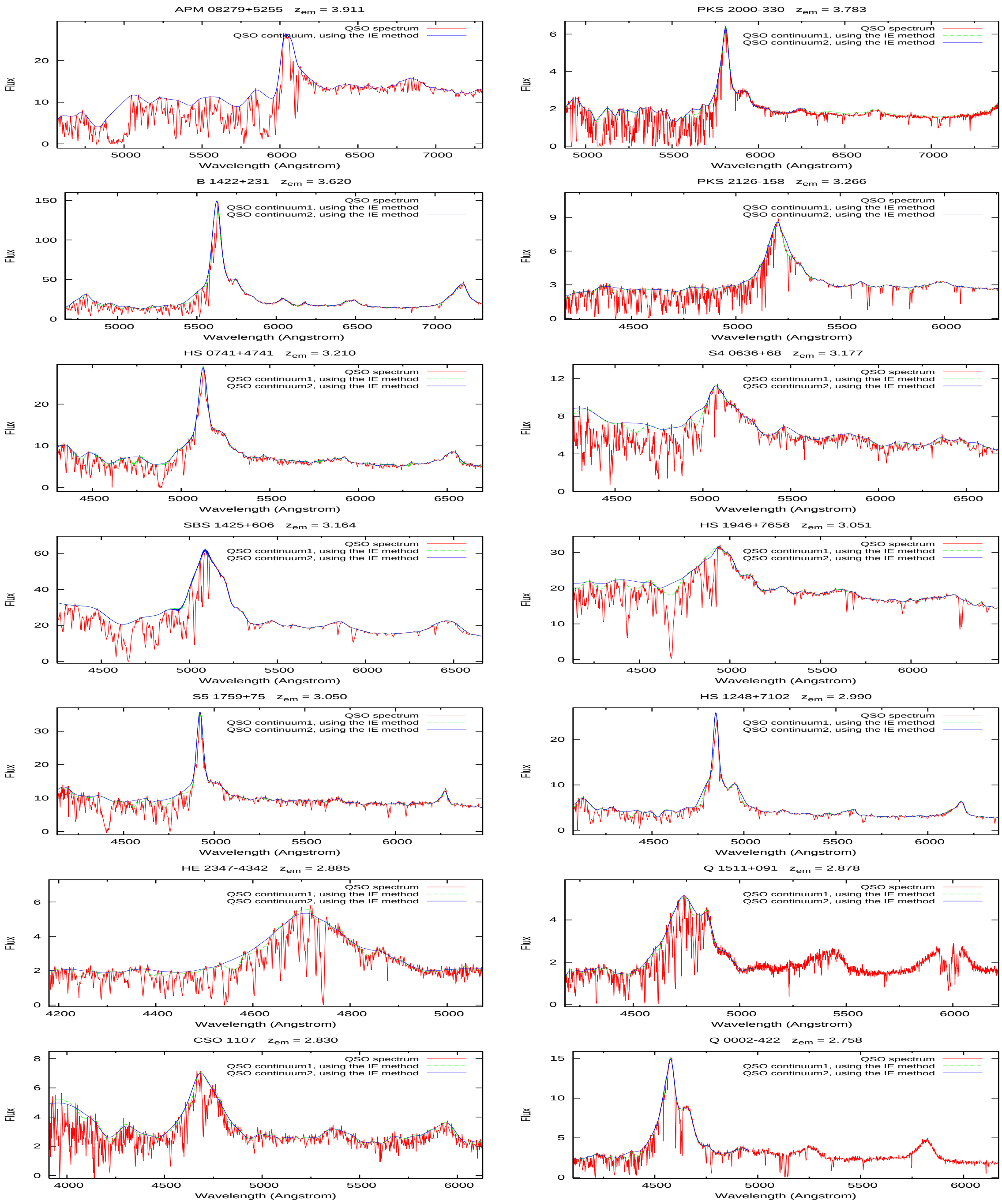

Fig. 3. Two estimated QSO continua (solid and dashed curves), using the Iterative Estimating (IE) method, for 19 QSOs.

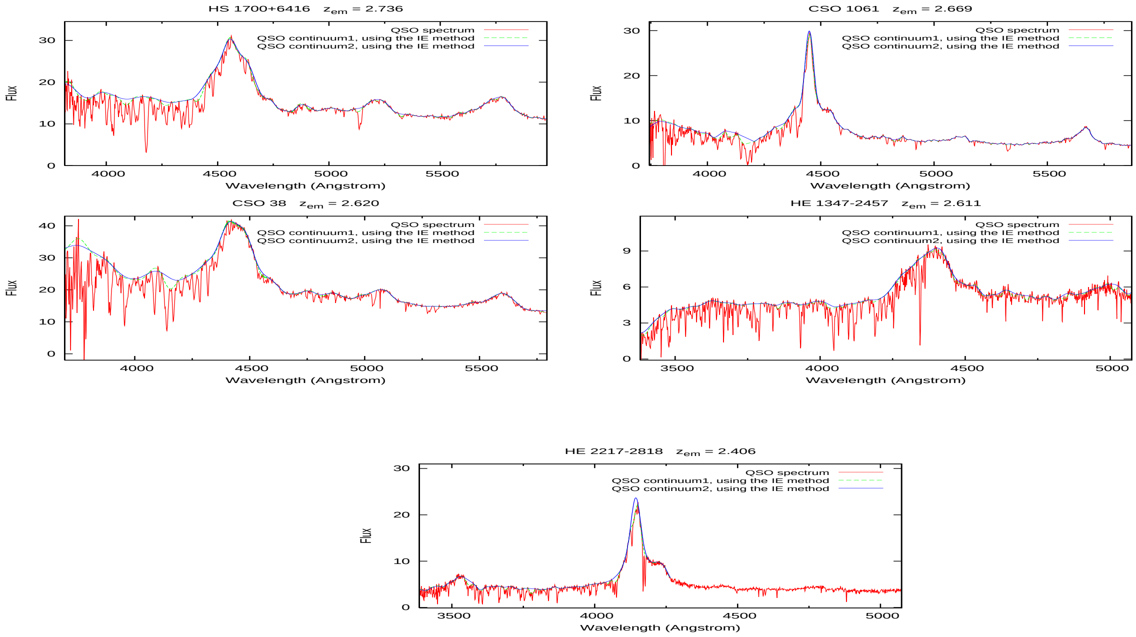

Figure 3: Continued

2.4 SL method

The Smooth Local (SL) method fits the continuum of a spectrum to regions of the Lyα forest deemed 'free of absorption lines' *as judged by eye*. This is done by attempting to identify unabsorbed regions within the forest and to connect them by smoothing splines. In Fig. 4, the result of this method are represented for 20 QSOs.

As seen in the Figure 4, we chose a smooth fitting using unabsorbed regions. As for the IE method, one of the advantages of this method is that to estimate the continuum in the Lyα forest, it is not necessary to have a large wavelength range of data in the red side of Lyα emission (e.g. see QSO continuum of HE 2217-2818 in the Fig 4). The observer is able to chose the points used in the spline interpolation. This makes the method dependent on subjective decision. This proves however not to be that a problem (see results).

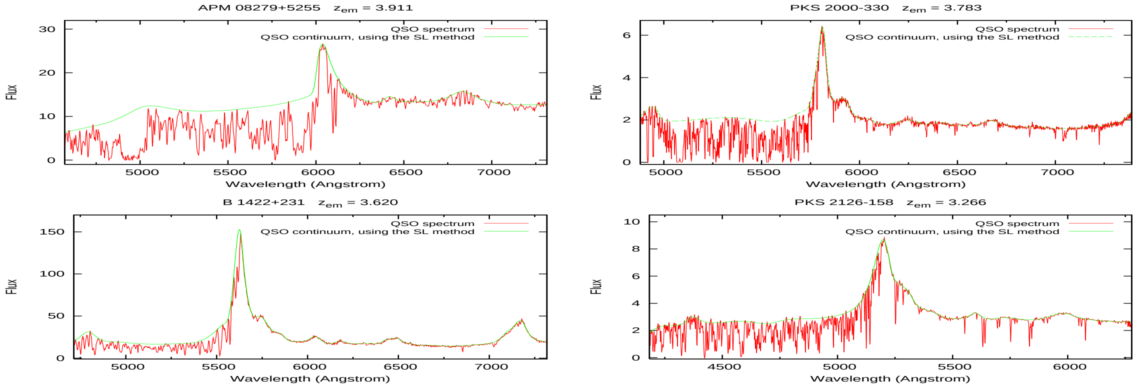

Fig. 4. The results of the Smooth Local (SL) continuum fitting for 20 QSOs.

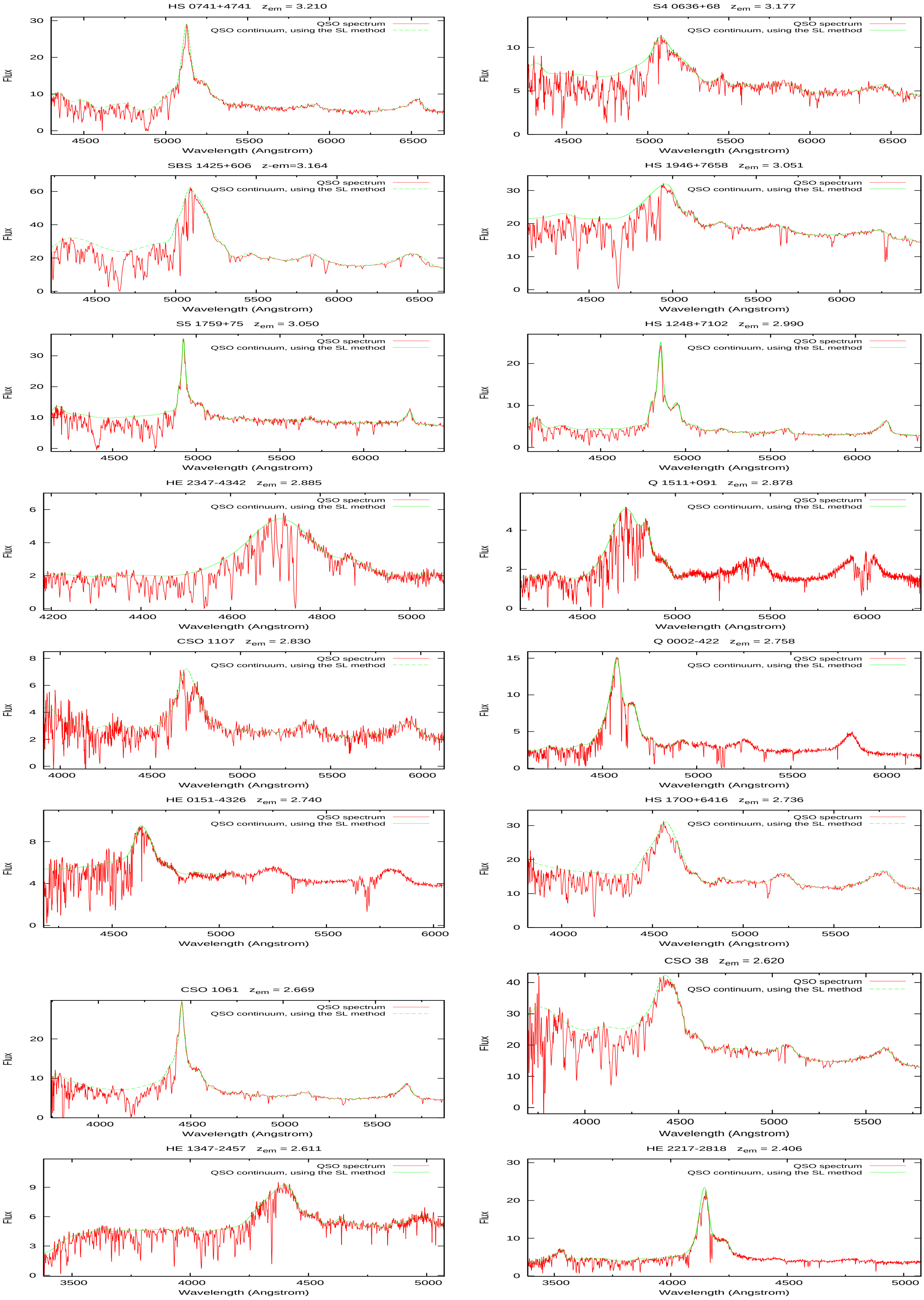

Figure 4: Continued

3 Results

The aim of our work was to compare the different methods of determining the QSO continuum. It is clear that having a high S/N ratio in the QSO spectra plays an important role in determining a good continuum. For that and at high spectral resolution, e.g. with UVES and HIRES, it needs a large exposure time with a large telescope. To reduce the integration time needed to obtain a good S/N ratio, it would be better to work at lower spectral resolution. As we show in Aghaee et al. 2008, measured DA values is relatively the same in both high and intermediate spectral resolution spectra, if we use the SL method. But the SL method is not an automatic method and depends on subjective decision. This problem can be overcome to a first approximation, if we make a *correction* according to the result of DA measured in Aghaee et al. 2008.

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