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Differential Evolution of Lyman Alpha Lines

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Abstract. We have analysed a large, homogeneous sample of Lyman alpha lines, observed at intermediate resolution, using the maximum likelihood method. The analysis shows that the evolutionary index γ, is a function of rest equivalent width with stronger lines evolving faster. The mean equivalent width increases with redshift. This behaviour is similar to that exhibited by the heavy element absorption lines in the quasar spectra.

Key words: Galaxies—quasars—absorption lines

1. Introduction

Lyman alpha absorption lines in the spectra of quasars provide a unique source of information about the universe at high redshifts. The clouds producing these lines are very likely intergalactic in nature and a study of the properties of these clouds may also be important for the understanding of galaxy formation.

The evolutionary properties of Lyman alpha lines have been studied by several workers (Sargent *et al.* 1980; Murdoch *et al.* 1986; Lu *et al.* 1991) and it is generally accepted that the population of Lyman alpha lines does show evolution, the number of lines being higher in the past. Atwood *et al.* (1985) found the rate of evolution to depend only marginally on the chosen lower limit to the equivalent width. More recently Giallongo (1991) has shown that the evolution of Lyman alpha lines is differential being progressively slower for stronger lines. This behaviour is opposite to that seen for the heavy element lines of Mg II (Caulet 1989; Petitjean & Bergeron 1990), and also of C IV (Steidel 1990). Giallongo's sample consists of 236 lines from 4 lines of sight, with subsamples consisting of only about 80 lines.

The importance of a large sample size has been emphasized by Liu & Jones (1988) who showed that the small size of the line sample is a major factor in the uncertainty of the evolutionary index γ, which can only be overcome by combining data from several lines of sight. Combining data from different lines of sight observed by different observers suffers from inhomogeneity as different observers use different criteria for deriving line lists. The signal-to-noise ratio (S/N) and the resolution of the different observations also vary. It is therefore highly desirable to use observations made on a large number of quasars by the same observers under similar conditions. Such a large sample of lines is available in the literature. Sargent *et al.* (1988) have listed observations of 52 quasars with resolution of 0.8 Å or 1.5 Å and with a uniform sufficiently high S/N ratio of 20:1. They have used these observations to study the properties of C IV lines. However many of the quasars in their sample have been observed upto sufficiently small wavelengths and cover a large portion of the Lyman alpha forest. There are four additional quasars observed by Steidel (1990) with similar resolution. These can be included in the above sample without degrading it's homogeneity. This sample therefore makes an ideal data set for studying the properties of the Lyman alpha lines. The main drawback that the sample suffers from is that the resolution used by these authors is not very high and line blending could play an important role in determining the properties of this data set. However, analysis of simulated spectra by Parnell & Carswell (1988) has shown that the line blending effects in intermediate resolution spectra do not significantly alter the power law estimates for the redshift dependence of the cloud numbers. A similar conclusion has been reached by Murdoch *et al.* (1986). The intermediate resolution spectra are therefore adequate for studying the line-density evolution (Hunstead 1988).

In this paper we present an analysis of the data of Sargent *et al.* (1988) and Steidel (1990) for studying the evolutionary properties of Ly α clouds, in particular the dependence of these properties on the strength of the lines. In section 2 we describe the data sample and in section 3 we present the results of our analysis.

2. Data sample

The quasars used in this study are listed in Table 1. The minimum wavelength used to determine z_{min} (given in the table for each quasar) is taken to be the larger of the

Table 1. Data sample.

QSO	Resolution Å	Z_{em}	Z_{min}	Z_{max}	Number of lines	Sample
0000 − 263	1.0	4.104	3.303	4.028	121	S1
0014 + 813	1.5	3.377	2.915	3.312	62	S1
0055 + 269	1.1	3.653	3.347	3.584	32	S1
0058 + 019	0.8	1.959	1.789	1.915	18	S1, S2
0114 − 089	1.5	3.199	2.920	3.136	38	S1
0142 − 100	0.8	2.727	2.142	2.671	83	S1, S2
0237 − 233	0.8	2.222	1.752	2.174	47	S1, S2
0424 − 131	0.8	2.166	1.908	2.119	32	S1, S2
0449 − 135	1.5	3.097	2.915	3.036	15	S1
0837 + 109	0.8	3.326	2.990	3.262	66	S1, S2
0848 + 163	0.8	1.925	1.764	1.881	13	S1, S2
0913 + 072	1.5	2.785	2.191	2.729	85	S1
1017 + 280	0.8	1.928	1.632	1.884	15	S1, S2
1159 + 124	0.8	3.502	2.796	3.435	89	S1, S2
1208 + 101	1.1	3.811	3.400	3.740	49	S1
1213 + 093	1.5	2.719	2.516	2.664	12	S1
1247 + 267	0.8	2.039	1.680	1.994	33	S1, S2
1510 + 115	1.5	2.106	1.887	2.060	17	S1
1511 + 091	1.5	2.878	2.455	2.820	55	S1
1548 + 093	1.5	2.749	2.504	2.693	20	S1
1632 + 269	0.8	2.526	1.973	2.473	48	S1, S2
2126 − 158	1.5	3.266	2.922	3.202	30	S1
2000 − 330	1.0	3.777	3.113	3.706	79	S1
2206 − 199	1.5	2.559	1.981	2.506	39	S1

minimum observed wavelength at which the line lists are complete and the wavelength of the Lyman β emission line; this is done to avoid the contamination of the sample of Ly α lines by higher order lines in the Lyman series. The maximum redshift for each quasar was taken to be that at which the absorbing material will have a relative velocity of 5000 km s^{-1} with respect to the quasar, so as to avoid the contamination of the line sample by lines produced by material associated with the quasar. The table also lists the number of lines with rest equivalent width larger than 0.1 Å in the redshift range considered for each quasar and the resolution used to study the relevant redshift range. Heavy element lines as well as Ly α lines associated with heavy element systems have not been included in our sample, and the redshift range occupied by these lines is excluded from the total redshift range considered for each quasar if the line could be confused with Ly α line with equivalent width greater than min the W_r^{min} of the sample under consideration. Some of the spectra contain blends of lines with large equivalent widths. We have removed such portions of spectra from our analysis. The remaining lines have rest equivalent width less than 5Å and so the sample is free from damped Lyman alpha lines which could be representatives of a different population of lines possibly produced by the disk material of the intervening galaxies (Wolfe 1988). This sample is referred to as S1. We have, in our analysis, considered subsamples of S1 as will be described in the next section.

3. Analysis and results

We have analysed the sample S1 to study the evolutionary properties as well as the equivalent width distribution of the Ly α lines by using the maximum likelihood method described by Murdoch *et al.* (1986). The number of lines per unit redshift per unit equivalent width interval is given by

$$\frac{\partial^2 N}{\partial z \partial W} = \frac{A}{W^*}(1+z)^{\gamma} e^{(-W/W^*)} \tag{1}$$

Here the evolutionary index γ is assumed to be a constant, independent of the equivalent width, and similarly the mean equivalent width W^* is assumed to be independent of

Table 2. Results of maximum likelihood analysis.

W_r^{min}	S1		S1a		S1b		S2	
Å	n_l	γ	n_l	γ	n_l	γ	n_l	γ
0.1	1098	0.92 ± 0.18	531	1.31 ± 0.44	567	1.14 ± 0.65	444	1.33 ± 0.30
0.2	818	1.55 ± 0.21	359	1.97 ± 0.54	459	1.84 ± 0.72	297	2.16 ± 0.37
0.3	614	1.98 ± 0.25	247	2.08 ± 0.64	367	2.68 ± 0.80	208	2.62 ± 0.44
0.4	448	2.55 ± 0.30	162	3.04 ± 0.81	286	2.42 ± 0.91	138	3.39 ± 0.54
0.5	312	2.85 ± 0.37	107	3.47 ± 1.00	205	2.74 ± 1.07	85	3.83 ± 0.70
0.6	228	2.92 ± 0.43	78	3.70 ± 1.18	150	2.97 ± 1.25	53	4.03 ± 0.90
0.7	170	2.82 ± 0.50	60	2.38 ± 1.35	110	3.64 ± 1.46		
0.8	127	2.67 ± 0.57			81	3.56 ± 1.70		
0.9	94	3.23 ± 0.68			62	3.58 ± 1.95		
1.0	63	3.72 ± 0.86						

the redshift. This assumption is supported by the results of rank correlation test between W and z for a particular sample (Murdoch *et al.* 1986). Any dependence of γ on W can be investigated by using the maximum likelihood method for line samples with different lower limiting rest equivalent widths. If γ indeed varies with W then these samples will result in different values for γ. The results of such an analysis for sample S1 are shown in Table 2. A clear increase in γ with the minimum rest equivalent width, W_r^{min}, is evident. The sample size becomes small for large values of W_r^{min} and the uncertainty in the value of γ becomes large.

The trend of increasing γ with increasing W_r^{min} indicates that γ is higher for lines with higher equivalent width, the stronger lines evolving faster. Such an apparent rise in the evolutionary index with W_r^{min} is predicted by Liu & Jones (1988) as a result of finite resolution and the crowding of lines. If the observed effect is indeed due to the crowding of lines, the effect should be higher for the sample of high redshift lines compared to the sample of low redshift lines, as the number of lines per unit redshift interval increases with redshift. In order to check this we divided the sample S1 into two subsamples. Subsample S1a containing lines with $Z \leqslant 2.9$ and the subsample S1b containing lines with $Z > 2.9$. The dividing redshift, (i.e. $z = 2.9$) was chosen so as to have roughly an equal number of lines in both subsamples. The results of the maximum likelihood analysis for the two subsamples are given in Table 2. The rate of increase of γ with W_r^{min} is somewhat higher for S1a compared to that for S1b. As the quasars in sample S1 are observed at two different resolutions it is possible that the effective resolution of the two subsamples are different. This can happen if the quasars in either of the subsamples were observed preferentially at one value of resolution. In order to check this we have plotted in Fig. 1 the redshift

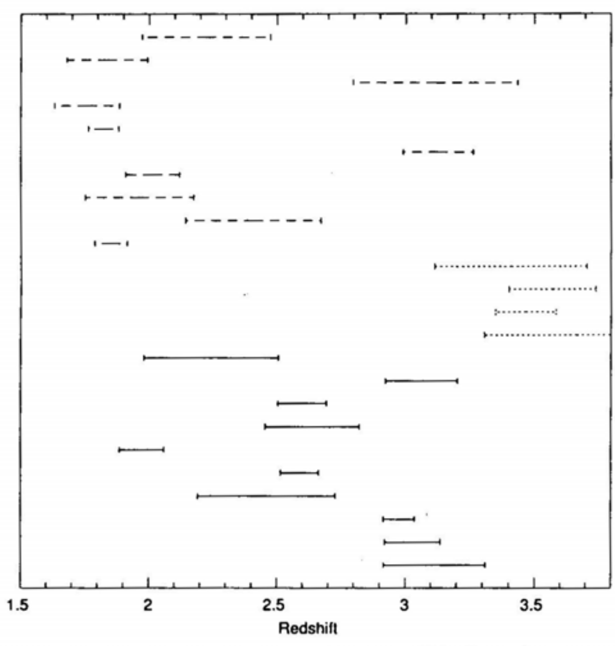

Figure 1. Redshift path for quasars in sample S1. The solid, dotted and dashed lines indicate resolution of 1.5, 1.0 and 0.8 Å respectively.

path observed for different quasars, indicating the resolution used for each observation. A larger fraction of quasars in the subsample S1a appear to have been observed at higher resolution compared to the quasars in the subsample S1b. The total redshift path is 1.937, 0.0 and 2.577 for S1a and 1.014, 1.893 and 0.807 for S1b, observed with resolutions of 1.5, 1.0 and 0.8 Å respectively. However this should enhance the effect mentioned above i.e. the trend of increase in γ with $W_r^{\min}$ should be even higher in the sample S1b compared to that in Sla. As no such difference is evident and as the trend of increasing γ with $W_r^{\min}$ persists to sufficiently high values of $W_r^{\min}$, the trend possibly reflects a real increase in γ with W.

Our sample still suffers from one drawback and that is the difference in the resolution used for observing different quasars. To remove this inhomogeneity we have constructed a sample S2 of the quasars in S1 which have been observed at the resolution of 0.8 Å. The results of the maximum likelihood analysis for this sample is also included in Table 2. The sample size for S2 is small and we have not subdivided it further. The increase in γ is evident atleast upto $W_r^{\min}$= 0.4 and possibly upto 0.6 Å

From all the above discussion we conclude that the increase of γ with increasing W is probably real and not an artifact of crowding of the lines or the small size of the sample. Such an increase in γ with equivalent width will also be reflected in the increase of W^* with redshift. In order to confirm this, we have performed the maximum likelihood analysis for redshift limited subsamples of S1. The results of the analysis are given in Table 3 where we have also included the mean observed equivalent width for each redshift bin. Both the mean equivalent width W^* as well as the mean observed equivalent width increase with redshift.

In the above analysis we have taken the maximum redshift for each quasar to be that giving a relative velocity of the absorbing material of 5000 km s^{-1} with respect to the quasar. If the proximity effect is indeed present, we should take the maximum redshift to be that corresponding to a distance of 8 Mpc from the quasar (Lu *et al.* 1991). We have repeated our analysis for this case and find that there is no appreciable difference between values of γ found for this case and the values presented in Table 2. The conclusions presented above therefore remain unchanged.

Faster rate of evolution of Lyman alpha lines with higher equivalent width is similar to that observed for heavy element lines in the quasar spectra. Our results are however completely opposite to those of Giallongo (1991) whose sample though small is observed at higher resolution. However it seems highly unlikely that the difference in trend in the variation of γ found for the two samples can be caused by the difference in resolution used for observing the two samples, in view of the results of Parnell & Carsewell (1988). Analysis of a larger, homogeneous sample at high resolution may help to resolve this controversy.

Table 3. Variation of mean equivalent width with redshift.

Redshift interval	n_l	W^* (Å)	w_{mean}
1.6 – 2.5	376	0.262 ± 0.013	0.362
2.5 – 3.2	372	0.310 ± 0.016	0.410
3.2 – 4.1	350	0.434 ± 0.023	0.534

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