

*Letter to the Editor***HST observations of the QSO pair Q1026–0045A,B\***Patrick Petitjean<sup>1,2</sup>, Jean Surdej<sup>3,7</sup>, Alain Smette<sup>4</sup>, Peter Shaver<sup>5</sup>, Jan Mücke<sup>6</sup>, and Marc Remy<sup>3</sup><sup>1</sup> Institut d'Astrophysique de Paris – CNRS, 98bis Boulevard Arago, F-75014 Paris, France<sup>2</sup> UA CNRS 173-DAEC, Observatoire de Paris-Meudon, F-92195 Meudon Principal Cedex, France<sup>3</sup> Institut d'Astrophysique, Université de Liège, Avenue de Coïnte 5, B-4000 Liège, Belgium<sup>4</sup> NASA-Goddard Space Flight Center, Code 681, Greenbelt, MD 20771, USA<sup>5</sup> European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748 Garching bei München, Germany<sup>6</sup> Astrophysikalisches Institut Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany<sup>7</sup> Directeur de Recherches du FNRS, Belgium

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**Abstract.** The spatial distribution of the Ly $\alpha$  forest is studied using new HST data for the quasar pair Q 1026–0045 A and B at  $z_{\text{em}} = 1.438$  and 1.520 respectively. The angular separation is 36 arcsec and corresponds to transverse linear separations between lines of sight of  $\sim 300h_{50}^{-1}$  kpc ( $q_o = 0.5$ ) over the redshift range  $0.833 < z < 1.438$ . From the observed numbers of coincident and anti-coincident Ly $\alpha$  absorption lines, we conclude that, at this redshift, the Ly $\alpha$  structures have typical dimensions of  $\sim 500h_{50}^{-1}$  kpc, larger than the mean separation of the two lines of sight. The velocity difference,  $\Delta V$ , between coincident lines is surprisingly small (4 and 8 pairs with  $\Delta V < 50$  and 200 km s $^{-1}$  respectively).

Metal line systems are present at  $z_{\text{abs}} = 1.2651$  and 1.2969 in A,  $z_{\text{abs}} = 0.6320, 0.7090, 1.2651$  and 1.4844 in B. In addition we tentatively identify a weak Mg II system at  $z_{\text{abs}} = 0.11$  in B. It is remarkable that the  $z_{\text{abs}} = 1.2651$  system is common to both lines of sight. The system at  $z_{\text{abs}} = 1.4844$  has strong O VI absorption.

There is a metal-poor associated system at  $z_{\text{abs}} = 1.4420$  along the line of sight to A with complex velocity profile. We detect a strong Ly $\alpha$  absorption along the line of sight to B redshifted by only 300 km s $^{-1}$  relatively to the associated system. It is tempting to interpret this as the presence of a disk of radius larger than  $300h_{50}^{-1}$  kpc surrounding quasar A.

**Key words:** quasars: individual: Q 1026–0045A,B, galaxies: ISM, quasars:absorption lines, galaxies: halo

**1. Introduction**

One way to probe the transverse extension of the gaseous structures giving rise to the Ly $\alpha$  forest seen in the spectrum of quasars

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to observe multiple lines of sight to quasars with small angular separations on the sky and search the spectra for absorptions coincident in redshift.

This technique originated with a suggestion by Oort (1981) to test the possibility that the Ly $\alpha$  forest clouds originate in large pancake structures. The first discoveries of common and associated absorption using pairs of distinct quasars (with separations  $\sim 1$  arcmin) were made by Shaver et al. (1982) and Shaver & Robertson (1983). These already indicated the possible existence of very large absorber sizes (hundreds of kpc), even for the Ly $\alpha$  clouds. At about the same time Sargent et al. (1982) found no detectable tendency for Ly $\alpha$  lines to correlate in QSO pairs separated by a few arcmin. Spectra of pairs of gravitational lens images revealed common absorptions on smaller scales (Weyman & Foltz 1983, Foltz et al. 1984). The idea that Ly $\alpha$  clouds might have large sizes remained controversial until the analysis by Smette et al. (1992), later confirmed by Dinshaw et al. (1994), Bechtold et al. (1994), Crofts et al. (1994), Bechtold & Yee (1994), Smette et al. (1995), D'Odorico et al. (1998).

Recently, Dinshaw et al. (1995) derived a radius of  $330h_{50}^{-1}$  kpc at  $z \sim 0.7$  for spherical clouds from observation of Q0107–0232 and Q0107–0235 separated by 86 arcsec. Larger separations have been investigated by Crofts & Fang (1997) and Williger et al. (1997). Both studies conclude that the clouds should be correlated on scales larger than 500 kpc.

Here we present observations of Q1026–005 A ( $m_r = 18.4$ ,  $z_{\text{em}} = 1.438$ ) and B ( $m_r = 18.5$ ,  $z_{\text{em}} = 1.520$ ), two distinct quasars separated on the sky by 36 arcsec or  $300 h_{50}^{-1}$  kpc ( $q_o = 0.5$ ) at  $z \sim 1$ .

**2. Observations**

The observations were carried out on the Hubble Space Telescope using the Faint Object Spectrograph with the G270H grating over the wavelength range 2250–3250 Å, for a resolution of 1.92 Å FWHM. A total of 5300 s integration time was accumulated on both quasars. The data were calibrated using the

standard pipeline reduction techniques. The zero point of the wavelength scale was determined requiring that Galactic interstellar absorptions occur at rest. Most of the lines are weak or blended except Mg II  $\lambda$ 2803; the error on the wavelength determination should be smaller than 0.3 Å however. The spectra are shown in Fig. 1, the line-lists are given in Table 1. The position of absorption features are determined by gaussian fits. Lower limits on equivalent widths of Ly $\alpha$  lines are at the  $3\sigma$  level. The mean signal to noise ratio is 15 varying from 10 in the very blue to 20 on top of the Ly $\alpha$  emission lines.

### 3. Results

#### 3.1. The metal line systems

Metal line systems are present at  $z_{\text{abs}} = 1.2651$  and 1.2969 in A,  $z_{\text{abs}} = 0.11, 0.6320, 0.7090, 1.2651$  and 1.4844 in B.

In A, the system at  $z_{\text{abs}} = 1.2651$  is detected by strong H I  $\lambda$ 1025,1215 absorptions and has a Si IV  $\lambda$ 1393,1402 doublet associated. There are strong H I  $\lambda$ 1025,1215 absorptions at the same redshift along the line of sight to B. The fact that the positions of the H I absorptions in A and B are nearly identical ( $\lambda$ 2753.67 and  $\lambda$ 2753.74 Å for Ly $\alpha$  respectively) argues for the two absorptions being produced by the same object. If true the transverse dimension is larger than the  $310 h_{50}^{-1}$  kpc separation between the two lines of sight. The system at  $z_{\text{abs}} = 1.2969$  has strong H I ( $w_r(\text{Ly}\alpha) = 2.9$  Å), C II, C III, O I, N III, Si II, Si III, Si IV absorptions.

In B, both  $z_{\text{abs}} = 0.6320$  and 0.7090 systems have strong Si II  $\lambda$ 1526, Fe II  $\lambda$ 1608, Al II  $\lambda$ 1670 and C IV  $\lambda$ 1550 absorptions. As said before the  $z_{\text{abs}} = 1.2651$  system is common to A and B. The presence of metals is revealed only by a  $\lambda$ 3155.87 feature that we identify as Si IV  $\lambda$ 1393. The associated Si IV  $\lambda$ 1402 line is not detected but could be lost in the noise. The strong system at  $z_{\text{abs}} = 1.4842$  shows N III, C III, Si III and possibly O VI associated absorptions. O VI absorption seems to be detected in most of the low and intermediate redshift systems (Bergeron et al. 1994, Vogel & Reimers 1995, Burles & Tytler 1996) and has been observed in a few high redshift Lyman limit systems (Kirkman & Tytler 1997). Although the velocity difference with the quasar is larger than  $4000 \text{ km s}^{-1}$ , there is a possibility that the system is associated with the quasar. In addition we tentatively identify a weak ( $w_r \sim 0.3$  Å) Mg II system at  $z_{\text{abs}} = 0.11$  in B. Mg II  $\lambda$ 2803 is possibly blended with C IV  $\lambda$ 1548 of a possible weak C IV system at  $z_{\text{abs}} = 1.0106$ .

#### 3.2. The associated system in A and the proximity effect

There is a strong associated system detected in A by its H I Ly $\alpha$  and Ly $\beta$  absorptions. Two components are seen at  $z_{\text{abs}} = 1.4401$  and 1.4420 with  $w_r(\text{Ly}\alpha) = 0.58$  and 0.40 Å respectively. The two components are *redshifted* relative to the QSO by 260 and 490  $\text{km s}^{-1}$ . Since the true redshift of the quasar is poorly known, these values are very uncertain. We do not detect any metal lines in the system. The O VI lines have  $w_r < 0.20$  Å; the C IV lines are redshifted outside the wavelength range of the data. Interestingly enough, there is a H I absorption system

**Table 1.** Line list

Q1026-0045A				Q1026-0045B				(a)	
$\lambda_{\text{obs}}$ (Å)	$w_{\text{obs}}$ (Å)	Ident.	$z$	$\lambda_{\text{obs}}$ (Å)	$w_{\text{obs}}$ (Å)	Ident.	$z$		
1	2233.76	1.53	Ly $\gamma$	1.2968	1	2229.2	0.6	SiII1304	0.7090
2	2244.20	1.10	CII1977	1.2970					
3	2259.87	0.51	Ly $\alpha$	0.8589			<0.45		u/u/u
4	2273.23	0.55	NIII1989	1.2967					
		<0.60			2	2274.68	0.67	SiIV1393	0.6320
					3	2281.17	2.19	CII1334	0.7093
					4	2288.50	0.9	Ly $\alpha$	0.8825
		<0.65						SiIV1402	0.6320
								Ly $\beta$	1.4843
5	2319.2	0.35	Ly $\delta$	1.4419	5	2312.30	0.49		
6	2323.54	1.28	Ly $\beta$	1.2653	6	2323.65	0.73	Ly $\beta$	1.2654
		<0.40			7	2330.03	1.22	Ly $\alpha$	0.9166
								Ly $\epsilon$ 1.4846	
7	2338.16	1.32	Ly $\beta$	1.2802	8	2337.93	0.50	Ly $\alpha$	0.9231
					9	2344.34	0.50	FeII2344	0.0000
8	2355.48	1.95	Ly $\beta$	1.2964	10	2359.85	0.96	Ly $\delta$	1.4847
9	2368.92	1.28	Ly $\alpha$	0.9486	11	2368.97	1.19	Ly $\alpha$	0.9486
10	2375.03	2.08	Ly $\gamma$	1.4405	12	2376.05	1.51	Ly $\gamma$	1.4438
			Ly $\gamma$	1.4419				FeII2344	0.0000
			Ly $\alpha$	0.9536				Ly $\alpha$	0.9545
11	2380.26	0.77	CII1036	1.2968					u/u/u
12	2382.97	0.90	FeII2382	0.0000	13	2382.25	1.52	FeII2382	0.0000
								SiIV1393	0.7092
13	2392.90	1.13	Ly $\alpha$	0.9683			<0.38		u/A/u
					14	2397.06	0.56	SiIV1402	0.7088
					15	2415.90	1.00	Ly $\gamma$	1.4841
		<0.45			16	2419.8	0.32	Ly $\alpha$	0.9904
		<0.45			17	2424.53	0.42	Ly $\alpha$	0.9943
					18	2427.30	0.65	CII1977	1.4844
					19	2444.15	0.85	Ly $\alpha$	1.0105
14	2450.0	0.75	Ly $\alpha$	1.0153			<0.28		u/A/u
15	2454.0	0.34	Ly $\alpha$	1.0186	20	2454.32	0.63	Ly $\alpha$	1.0189
16	2458.47	0.61	Ly $\alpha$	1.0223	21	2458.65	0.30	NIII1989	1.4840
17	2474.3	0.25	Ly $\alpha$	1.0353	22	2475.8	0.35	Ly $\alpha$	1.0365
					23	2491.71	0.83	SiII1526	0.6321
18	2497.51	1.29	Ly $\alpha$	1.0544	24	2497.24	0.49	Ly $\alpha$	1.0542
19	2503.30	1.30	Ly $\beta$	1.4405					C/A/A
20	2504.66	1.20	Ly $\beta$	1.4419	25	2506.65	0.59	Ly $\beta$	1.4438
					26	2521.88	0.26	Ly $\alpha$	1.0744
		<0.38			27	2526.44	1.52	Ly $\alpha$	1.0782
								CIV1548	0.6321
								CIV1550	0.6321
					28	2531.03	0.46	Ly $\beta$	1.4844
					29	2548.25	1.22	Ly $\beta$	1.4844
					30	2563.70	0.84	OVI1031	1.4844
21	2568.5	0.38	Ly $\alpha$	1.1128			<0.28		u/u/u
22	2575.22	1.70	Ly $\alpha$	1.1183	31	2575.37	0.82	Ly $\alpha$	1.1184
					32	2577.5	0.59	OVI1037	1.4841
23	2586.35	0.50	FeII2586	0.0000	33	2587.9	0.42	FeII2586	0.0000
24	2600.58	1.40	FeII2600	0.0000	34	2601.2	1.23	FeII2600	0.0000
					35	2608.74	0.79	SiII1526	0.7087
					36	2625.28	0.51	FeII1608	0.6322
					37	2645.44	0.83	CIV1548	0.7087
					38	2650.08	0.67	CIV1550	0.7089
					39	2669.58	0.42	Ly $\alpha$	1.1959
		<0.35			40	2726.96	0.90	AlII1670	0.6321
25	2733.15	1.06	SiII1190	1.2968					
			SiII1206	1.2650					
26	2736.63	0.52	Ly $\alpha$	1.2511			<0.25		A/u/u
27	2740.75	0.87	SiII1193	1.2968					
		<0.32			41	2745.29	0.75	Ly $\alpha$	1.2582
					42	2748.47	0.63	FeII1608	0.7088
28	2753.67	2.42	Ly $\alpha$	1.2651	43	2753.74	1.50	Ly $\alpha$	1.2651
29	2772.06	3.10	SiII1206	1.2976					
			Ly $\alpha$	1.2802					
30	2792.35	6.62	Ly $\alpha$	1.2969					A/A/A
31	2796.05	2.20	MgII2796	0.0000			<0.36		M $_a$
32	2803.60	1.17	MgII2803	0.0000	44	2796.90	1.95	MgII2796	0.0000
33	2807.94	0.44	Ly $\alpha$	1.3097	45	2803.54	0.98	MgII2803	0.0000
34	2820.08	0.73	Ly $\alpha$	1.3197			<0.36		u/u/u
35	2849.12	0.80	Ly $\alpha$	1.3436	46	2819.87	0.74	Ly $\alpha$	1.3195
							<0.24		C/C/u
					47	2854.78	1.10	AlII1670	0.7086
36	2895.00	1.85	SiII1260	1.2969					A/A/A
37	2961.76	0.28	Ly $\alpha$	1.4363					
38	2966.45	0.97	Ly $\alpha$	1.4401					
39	2968.69	1.42	Ly $\alpha$	1.4420	48	2971.09	1.30	Ly $\alpha$	1.4439
40	2991.08	0.30	OII302	1.2970					
41	2995.36	0.66	SiII1304	1.2964					
					49	2997.47	0.66	SiII1206	1.4844
					50	3008.06	0.40	Ly $\alpha$	1.4743
								AlII1854	0.6219
								Ly $\alpha$	1.4842
								AlII1862	0.6252
42	3065.05	0.86	CII1334	1.2967	51	3020.05	1.75	Ly $\alpha$	1.4842
					52	3027.51	0.53	AlII1862	0.6252
					53	3104.81	0.36	MgII2796	0.1103
					54	3113.13	0.30	MgII2803	0.1104
								CIV1548?	0.1016
								CIV1550?	0.1016
43	3156.92	0.32	SiIV1393	1.2650	55	3118.00	0.20	SiIV1393?	1.2643
					56	3155.87	0.57	SiIV1393?	1.2643
44	3177.14	0.24	SiIV1402	1.2649	57	3168.43	0.44	AlII1854?	0.7083
45	3201.42	0.62	SiIV1393	1.2970					
46	3222.51	0.54	SiIV1402	1.2972					

(a) Coincidences are marked by a "C", anti-coincidences by a "A" and ambiguous cases by a "u" for  $w_r > 0.2, 0.3$  and  $0.6$  Å.

\* A colon means uncertain value or identification

at  $z_{\text{abs}} = 1.4439$  along the line of sight to Q 1026–0045B. The velocity difference between this system and the  $z_{\text{abs}} = 1.4420$  in A is about  $230 \text{ km s}^{-1}$  only.

It is unlikely that the  $z_{\text{abs}} \sim z_{\text{em}}$  system is intrinsically associated with the central AGN. Such systems usually have high metal content and are expected to exhibit strong O VI and N V absorptions (Petitjean et al. 1994, Hamann 1997), absent from the spectra of Q1026–0045 A & B. The three absorptions are thus part of an object or group of objects which transversal dimension exceeds the  $300h_{50}^{-1} \text{ kpc}$  separation between the two lines of sight.

The absence of metals in the system associated with A, over the observed wavelength range, suggests an intergalactic origin. The higher velocity of the gas along the line of sight to B argues against the simple picture in which the gas would be collapsing toward A. In that case, we would expect the gas along the line of sight to B to have a projected velocity smaller than the velocity of the gas just in front of A. A model where the gas would be part of a rotating disk can be accommodated if the component at  $z = 1.4420$  is at the same redshift as the quasar. In this case however one could wonder why the gas is metal deficient.

The relative equivalent widths of the hydrogen lines in the Lyman series of the system at  $z_{\text{abs}} = 1.4842$  toward B are indicative of H I column densities in excess of  $10^{16} \text{ cm}^{-2}$ . The presence of strong metal lines suggests that the gas is associated with the halo of a galaxy. Very deep imaging in this field to search for any enhanced density of objects would help to understand the nature of these intriguing systems.

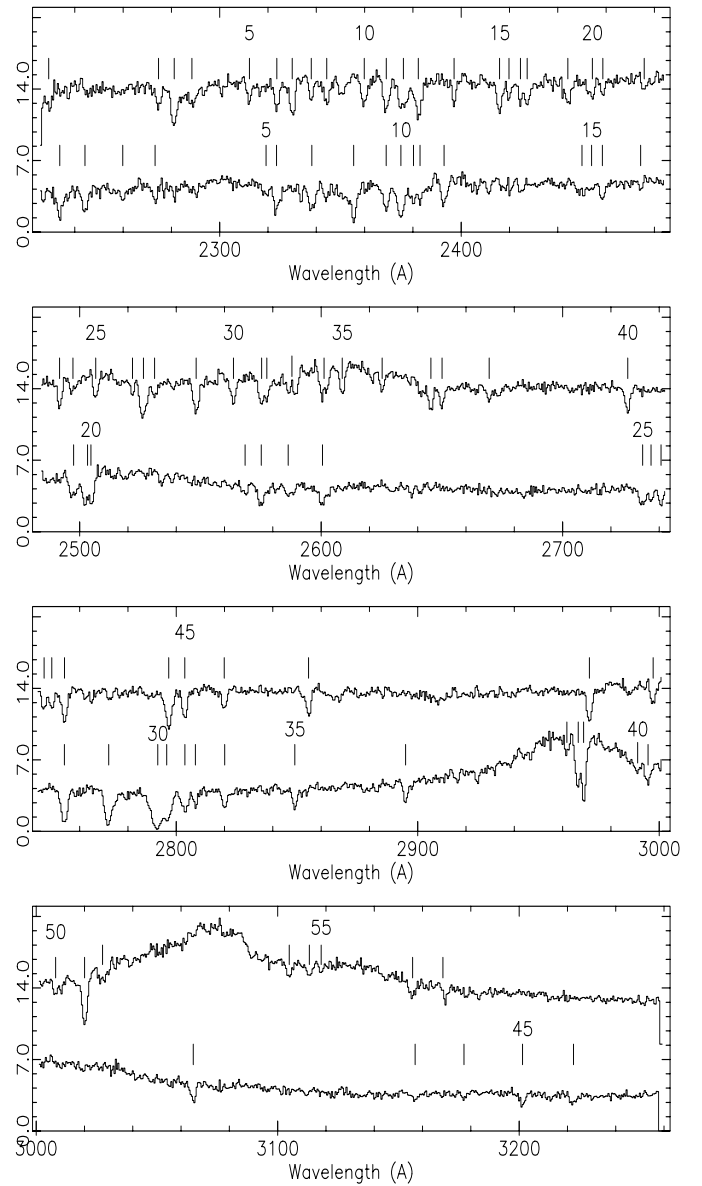
There are only two systems in both lines of sight from  $z = 1.3436$  to  $1.520$ , the associated system in A (and its counterpart in B) and the metal system at  $z = 1.4842$  in B. The number of lines with  $w_r > 0.24 \text{ \AA}$  expected in this redshift range is  $7 \pm 2$  (Bahcall et al. 1996). It is probable that we see the effect of the enhanced photo-ionizing field due to the proximity of the quasars.

### 3.3. The Ly $\alpha$ forest

#### 3.3.1. The line-lists

Table 1 lists all the absorption features detected at the  $3\sigma$  level in the spectra. Identification of Ly $\alpha$  lines is sometimes uncertain due to blending with lines from the numerous metal line systems. We discuss here individual lines.

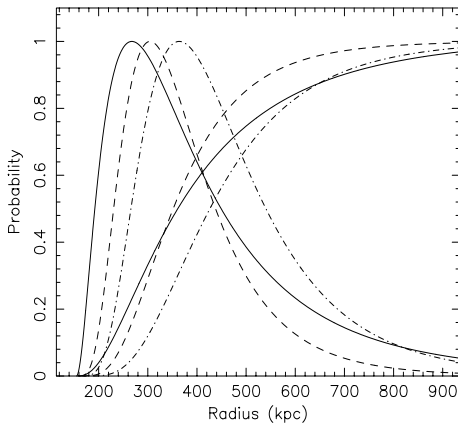
In Q 1026–0045A, the  $\lambda 2259$  feature could be partly Ly $\epsilon$  from the  $z_{\text{abs}} = 1.4420$  system but given the strength of the other lines in the series, the contribution is most certainly negligible. There is a broad feature centered at  $2452 \text{ \AA}$  that we decompose into two components at  $2450$  and  $2454 \text{ \AA}$ . This feature is uncertain however. Galactic Fe II  $\lambda 2374$  absorption should not contribute too much to the  $\lambda 2375$  feature that is mostly Ly $\gamma$  at  $z_{\text{abs}} = 1.4405$  and  $1.4420$ . The line is quite strong however and could be partly produced by a Ly $\alpha$  absorption at  $z_{\text{abs}} = 0.9536$ . The two lines at  $\lambda 2458$  and  $\lambda 2474$  could correspond to a Si IV  $\lambda 1393, 1402$  doublet at  $z_{\text{abs}} = 0.7639$ . The corresponding C II  $\lambda 1334$  line would be blended with Ly $\beta$  at  $z_{\text{abs}} = 1.2964$  but the



**Fig. 1.** Spectra of Q1026–0045 A (bottom) and B (top). Flux is given in units of  $10^{-16} \text{ erg/s/cm}^2/\text{\AA}$ . The spectrum of B has been shifted by 8.5 in the same units. Line identification can be found in Table 1.

feature at  $\lambda 2736$  could be C IV  $\lambda 1550$  at the same redshift with no C IV  $\lambda 1548$  detected. The line however is displaced by more than  $1 \text{ \AA}$  from the expected position which is not acceptable. We thus consider the Si IV identification as doubtful.

In Q 1026–0045B, there is a broad feature at  $\lambda 2288.5$  that cannot be accounted for by Si IV  $\lambda 1402$  at  $z = 0.6320$  only. The feature at  $\lambda 2376$  may have a double structure. Ly $\gamma$  at  $1.4438$  and Fe II  $\lambda 2374$  definitively contribute to this feature which is strong enough however to be partly produced by Ly $\alpha$  absorption at  $z_{\text{abs}} = 0.9545$ . Since C IV  $\lambda 1550$  at  $z_{\text{abs}} = 0.6321$  has  $w_{\text{obs}} = 0.46 \text{ \AA}$ , C IV  $\lambda 1548$  at the same redshift should have  $w_{\text{obs}} < 0.92 \text{ \AA}$ . Consequently there is a Ly $\alpha$  line at  $z_{\text{abs}} = 1.0782$  with  $w_{\text{obs}} > 0.6 \text{ \AA}$ .



**Fig. 2.** Probability distribution  $P(R)$ , normalized to one at its peak, and cumulative distribution versus cloud radius from the number of coincidences and anticoincidences of  $\text{Ly}\alpha$  lines with  $w_r > 0.2$  (dashed-dotted lines), 0.3 (dashed lines) and 0.6 Å (solid lines). The peak of the probability is at  $R = 267, 305$  and  $364h_{50}^{-1}$  kpc for  $w_r > 0.6, 0.3$  and  $0.2$  Å respectively.

We detect 11 and 12  $\text{Ly}\alpha$  lines with  $w_r > 0.2$  Å over the redshift range 0.8335–1.3436 along the lines of sight to A and B respectively. The density of lines with  $w_r > 0.24$  Å detected by the HST in the same redshift range is  $\sim 17 \pm 3$  (Jannuzi et al. 1998). The number of lines we detect is thus small. This might be a consequence of blending effects. Two lines observed along A and B are said coincident when their redshifts are within  $200 \text{ km s}^{-1}$ . The Lyman $\alpha$  forest is sparse at low redshift which implies that the probability for random coincidence is negligible (only 0.05 for  $w_r > 0.2$  Å). Last column of Table 1 indicates for each  $\text{Ly}\alpha$  line with  $w_r > 0.2, 0.3, 0.6$  Å whether there is coincidence (C) or anti-coincidence (A). A letter (u) marks lines that are out of the sample or uncertain cases because of blending effects.

### 3.3.2. Correlations

The numbers of coincidences and anticoincidences for  $w_r > 0.2, 0.3$  and  $0.6$  Å are 4, 3, 1 and 7, 8, 3 respectively. Assuming that the  $\text{Ly}\alpha$  clouds are spheres of radius  $R$ , we calculate the probability density for  $R$  (see Fig. 2) following Fang et al. (1996). The peak of the probability is at  $R = 267, 305$  and  $364h_{50}^{-1}$  kpc for  $w_r > 0.6, 0.3$  and  $0.2$  Å. There is a hint for the dimensions of the structures to be larger for smaller equivalent widths. This property is expected in simulations (Charlton et al. 1997). However as shown by Fang et al. (1996) and Crofts & Fang (1997), the radius determined by this method increases with the separation of the lines of sight indicating that the assumption of a single structure size is invalid. This has been recognized to be

a characteristic of the spatial distribution of the  $\text{Ly}\alpha$  gas in the simulations (Charlton et al. 1997). It is clear that better statistics in the data are needed to have a better understanding of the structures especially to discuss the difference between real size of the clouds and correlation length (Cen & Simcoe 1997).

It is intriguing to note that the velocity difference  $\Delta V$  between lines coincident in redshift along the two lines of sight is small. Considering all the pairs, we find 4 and 8 pairs with  $\Delta V < 50$  and  $200 \text{ km s}^{-1}$  respectively. There is no pair, even along one single line of sight with  $200 < \Delta V < 400 \text{ km s}^{-1}$ . This has been shown to favor disk-like structures (Charlton et al. 1995) but should be studied in more detail.

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