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The high-redshift deuterium abundance: the $z=3.086$ absorption complex towards Q 0420 − 388

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ABSTRACT

The redshift $z_{\rm abs}=3.08$ absorption complex towards the $z_{\rm em}=3.12$ quasar 0420 − 388 has high H I column density components with heavy element abundances ~1/10 solar. A low-redshift component of the complex has H I column density $\sim 10^{18}$ cm^{-2}, and some of the higher order Lyman lines are clean enough to permit a measurement of the deuterium column density for this component. However, while the putative deuterium column density is fairly well-determined, the H I column density is very uncertain so, if the deuterium identification is correct, the D/H ratio for this component could have any value $>2\times10^{-5}$. The D I/O I ratio is much better constrained, and has a value ~2. If the O I/H I ratio is constant throughout the complex, then D/H $\sim 2\times10^{-4}$.

Key words: galaxies: abundances – quasars: absorption lines – quasars: individual: 0420 − 388.

1 INTRODUCTION

The possibility of measuring the D/H ratio in high-redshift absorption systems in quasar spectra was first noted by Adams (1976), and subsequently explored by Webb et al. (1991) and Khersonsky, Briggs & Turnshek (1995). The first observational results from studies of the redshift $z=3.32$ Lyα absorption system in the spectrum of the $z=3.42$ quasar 0014 + 813 (Songaila et al. 1994; Carswell et al. 1994) have led to suggestions that the primordial D/H ratio may be as high as $\sim 2.5\times10^{-4}$, if a feature in the wing of a strong Lyα line is indeed due to deuterium and is not confusing velocity structure. Since the chances of such confusion are high (perhaps 10 per cent), and a ratio as large as this has profound consequences for our understanding of light-element synthesis (e.g. Steigman 1994), it is important to check this finding for similar high-redshift absorption systems. Unfortunately, these are rare. Indeed, the 0014 + 813 system is unique among those known in that it has a combination of low heavy-element abundances (Chaffee et al. 1985, 1986) and H I column density and Doppler parameter in a range where the detection of deuterium Lyα is possible. Confirmation (or otherwise) that the high D/H ratio inferred for 0014 + 813 reflects the true primordial deuterium abundance is important, but further work is hampered by the lack of known low heavy-element abundance systems in which to measure it.

An alternative way of testing the result is to measure the D/H ratio in systems which have some heavy-element enrichment, and estimate the primordial value by extrapolating the D/H ratio versus metallicity to zero metallicity. This clearly requires that more systems should be measured, and that the degree of heavy-element enrichment should be determined. Also, since heavy-element systems tend to show considerable velocity structure, the analysis may be complex and the results uncertain. However, a measurement in any system which has lower than solar heavy-element abundances would be useful to see if the suggested primordial value is at all reasonable. Here we report on an attempt to do this for the $z = 3.085$ system towards the $z = 3.12$ quasar Q 0420 − 388.

2 OBSERVATIONS

Spectra of Q 0420 − 388 were obtained using the CTIO 4-m and AAT échelle spectrographs. Details of the observations are given in Table 1. The observing set-up and data reduction procedures for the CTIO observations were similar to those described by Williger et al. (1994), and for the AAT observations similar to those described by Carswell et al. (1991). The spectra were extracted using a variant of the optimal scheme described by Marsh (1989), and the estimated errors in the flux in each spectral element retained as an aid in the later analysis. Voigt profiles, convolved with the instrument profile, were fitted to the spectral features using the same techniques as Rauch et al. (1992).

3 ANALYSIS OF ABSORPTION LINES

Multicomponent Voigt-profile fits to the features in the $z = 3.086$ complex were performed simultaneously to the first 10 lines in the Lyman series for H I and D I, O I 948, 950, 988 (triplet), 1039 and 1302, Si II 1020, 1190, 1193, 1260 and 1304, C II 1036 and 1334, and Fe II 1063, 1125 and 1144. The parameters for all these lines were taken from Morton (1991), with the exception of Si II 1304, where a revised value for the oscillator strength from Tripp, Lu & Savage (in preparation) was used. The redshifts for all ions in any velocity component were constrained to have the same value, and the Doppler parameters ($b = \sqrt{2}\sigma$) were constrained by assuming a gas temperature of 10^4 K. Any excess Doppler width above the value corresponding to this temperature was assumed to arise from turbulence, which was taken to be the same for each ion in the component. The total Doppler parameter for any ion is $b_{\rm total} = \sqrt{b^2_{\rm thermal} + b^2_{\rm turbulence}}$.

Table 1. Details of the observations of Q 0420 − 388.

Telescope	Date	Observations Exposure (hrs)	Wavelength range (A)	Resolution km s^{-1}	Comments
AAT	1990.01.31	2.0	3740 - 4450	9.5	Incomplete coverage
AAT	1991.2.8 - 15	8.8	3740 - 4450	9.5	Incomplete coverage
AAT	1991.10.11 - 13	9.3	4150 - 5160	8	Incomplete coverage
CTIO 4m	1992.10.21	4.0	3600 - 6025	13	Noisy below 4500A

Table 2. Fitted parameters for the $z = 3.086$ complex.

n	Ion	z	±	b	±	log$N$	±	Blended with
1	HI	3.09561	0.00010	25	10	12.87	0.16	Lyα
2	HI	3.09406	0.00007	41	8	13.36	0.09	Lyα
3	HI	3.09237	0.00004	14	5	13.07	0.12	Lyα
4	HI	3.08937	0.00010	26	3	16.69	0.22	Lyα
5	HI	3.08830	-	14	-	16.92	> 2	
6	CII	3.08830	-	7	-	15.02	0.22	
7	OI	3.08830	-	7	-	15.15	0.11	
8	SiII	3.08830	0.00002	7	1	14.04	0.14	
9	FeII	3.08830	-	6	-	13.64	0.14	
10	HI	3.08815	-	14	-	19.29	0.98	
11	CII	3.08815	-	6	-	15.23	0.68	
12	OI	3.08815	-	5	-	14.72	0.26	
13	SiII	3.08815	0.00003	5	1	14.02	0.30	
14	FeII	3.08815	-	5	-	13.43	0.23	
15	HI	3.08812	-	44	-	17.99	0.44	
16	CII	3.08812	-	43	-	13.53	0.24	
17	SiII	3.08812	0.00008	43	9	12.89	0.10	
18	FeII	3.08812	-	42	-	13.16	0.55	
19	HI	3.08646	-	23	-	17.27	0.43	
20	CII	3.08646	-	20	-	14.38	0.06	
21	OI	3.08646	-	19	-	13.99	0.13	
22	SiII	3.08646	0.00002	19	2	13.56	0.06	
23	HI	3.08595	-	21	-	18.60	0.57	
24	DI	3.08595	-	19	-	14.57	0.32	
25	CII	3.08595	-	17	-	13.34	1.63	
26	OI	3.08595	-	17	-	14.35	0.22	
27	SiII	3.08595	0.00007	17	6	12.80	0.96	
28	HI	3.08576	-	23	-	17.85	0.30	
29	DI	3.08576	-	21	-	14.26	0.52	
30	CII	3.08576	-	19	-	14.25	0.20	
31	OI	3.08576	-	19	-	13.86	0.61	
32	SiII	3.08576	0.00007	19	3	13.46	0.20	
33	FeII	3.08576	-	19	-	12.54	1.49	
34	HI	3.08370	0.00002	9	2	14.25	0.14	Lyα
35	HI	3.08361	0.00035	138	38	14.07	0.21	Lyα
36	HI	3.08082	0.00003	27	5	14.40	0.19	Lyα
37	HI	3.07979	0.00058	80	41	13.57	0.29	Lyα

n	Ion	z	±	b	±	log$N$	±	Blended with
38	HI	3.07766	0.00006	24	8	13.15	0.11	Lyα
39	HI	3.01252	0.00010	20	3	17.43	0.23	SiII 1193
40	HI	3.01162	0.00059	41	29	14.11	0.52	SiII 1193
41	HI	3.00263	0.00003	2	13	13.13	> 2	SiII 1190
42	HI	3.00131	0.00005	61	6	14.04	0.04	SiII 1190
43	HI	2.99995	0.00004	11	5	12.92	0.14	SiII 1190
44	HI	2.85010	0.00011	9	13	12.83	0.65	FeII 1144
45	HI	2.84954	0.00003	16	11	15.01	1.38	FeII 1144
46	HI	2.84898	0.00015	17	8	13.32	0.38	FeII 1144
47	HI	2.78403	0.00004	27	4	14.00	0.07	FeII 1125
48	HI	2.78339	0.00004	15	4	13.50	0.13	FeII 1125
49	HI	2.78224	0.00003	47	4	14.24	0.05	FeII 1125
50	HI	2.57641	0.00003	23	3	13.38	0.05	FeII 1063
51	HI	2.49323	0.00002	4	4	12.46	0.13	OI 1039
52	HI	2.48474	0.00003	22	5	13.86	0.07	CII 1036
53	HI	2.48399	0.00004	23	4	13.96	0.08	CII 1036
54	HI	2.44583	0.00056	68	41	13.62	0.20	Lyβ
55	HI	2.44538	0.00005	17	5	13.65	0.16	Lyβ
56	HI	2.43241	0.00008	5	8	12.42	0.61	SiII 1020
57	HI	2.43033	0.00003	22	4	13.10	0.07	SiII 1020
58	HI	2.32504	0.00013	67	33	13.72	0.12	OI 988
59	HI	2.32397	0.00005	23	7	13.53	0.17	OI 988
60	HI	2.32322	0.00014	36	31	13.33	0.28	OI 988
61	HI	2.32262	0.00003	14	4	13.33	0.16	OI 988
62	HI	2.32209	0.00011	23	23	12.95	0.33	OI 988
63	HI	2.26731	0.00031	76	42	13.73	0.23	Lyγ
64	HI	2.19759	0.00028	44	43	12.96	0.34	OI 950
65	HI	2.19749	0.00003	3	7	12.64	0.29	OI 950
66	HI	2.19565	0.00083	79	35	14.76	0.64	Lyδ
67	HI	2.19105	0.00006	9	9	12.76	0.33	Lyδ
68	HI	2.19046	0.00006	8	8	13.37	0.52	Lyδ
69	HI	2.19032	0.00031	19	18	13.03	0.88	OI 948
70	HI	2.18987	0.00008	15	13	13.09	0.57	OI 948
71	HI	2.18950	0.00021	26	47	13.08	0.93	OI 948
72	HI	2.18876	0.00011	17	26	12.92	1.20	OI 948
73	HI	2.18833	0.00125	59	171	13.24	1.28	OI 948
74	HI	2.11601	0.00460	112	594	14.32	2.83	Lyζ
75	HI	2.10566	0.00163	41	51	15.03	3.09	Lyη
76	HI	2.08948	0.00561	19	51	14.81	> 2	Lyι

Note: For the components of the $z = 3.086$ complex, the redshift and Doppler-parameter errors are shown against Si II. Other ions were constrained to have the same redshift, and the Doppler parameters linked by assuming a temperature of 10^4 K and the same turbulent width.

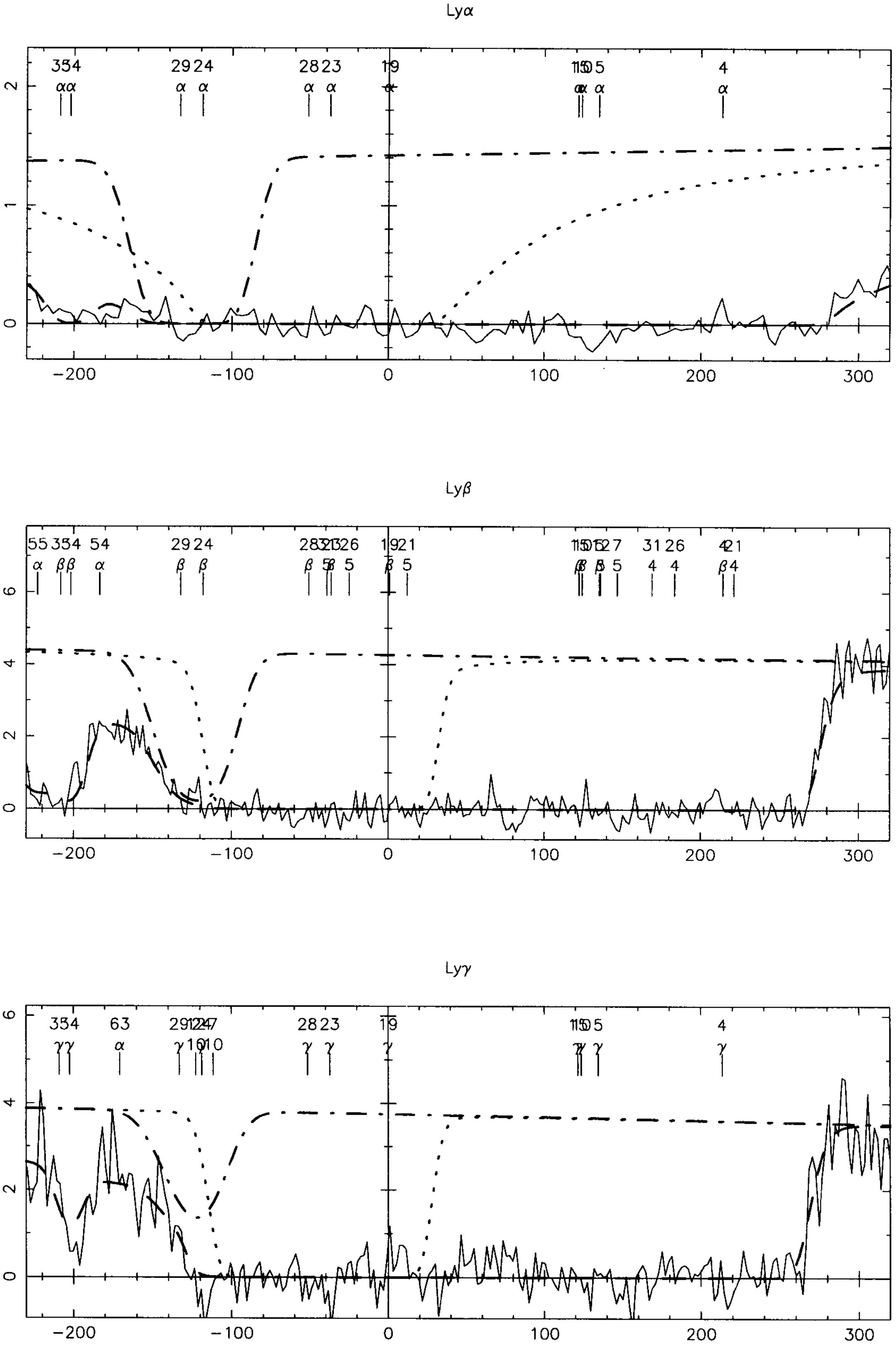

Figure 1. The data (solid line) and fitted line profiles (dash) for all features, on a velocity scale relative to $z = 3.08646$. The upper numbers above each tick mark correspond to the system numbers given in Table 2, with a different system number for each ion at a given redshift, where the lower symbols identify different lines from the ions involved. So, for example, in the Lyα panel, the Dα and Lyα at $z = 3.08595$ are numbered 24 and 23 respectively, and at $z = 3.08576$ the corresponding numbers are 29 and 28. The caption over each panel refers to the ion and line at $z = 3.08646$ (which is not necessarily detectable) used to define zero velocity. For the Lyman series, the two D I components (dash–dot) and the corresponding H I (dot) are also shown.

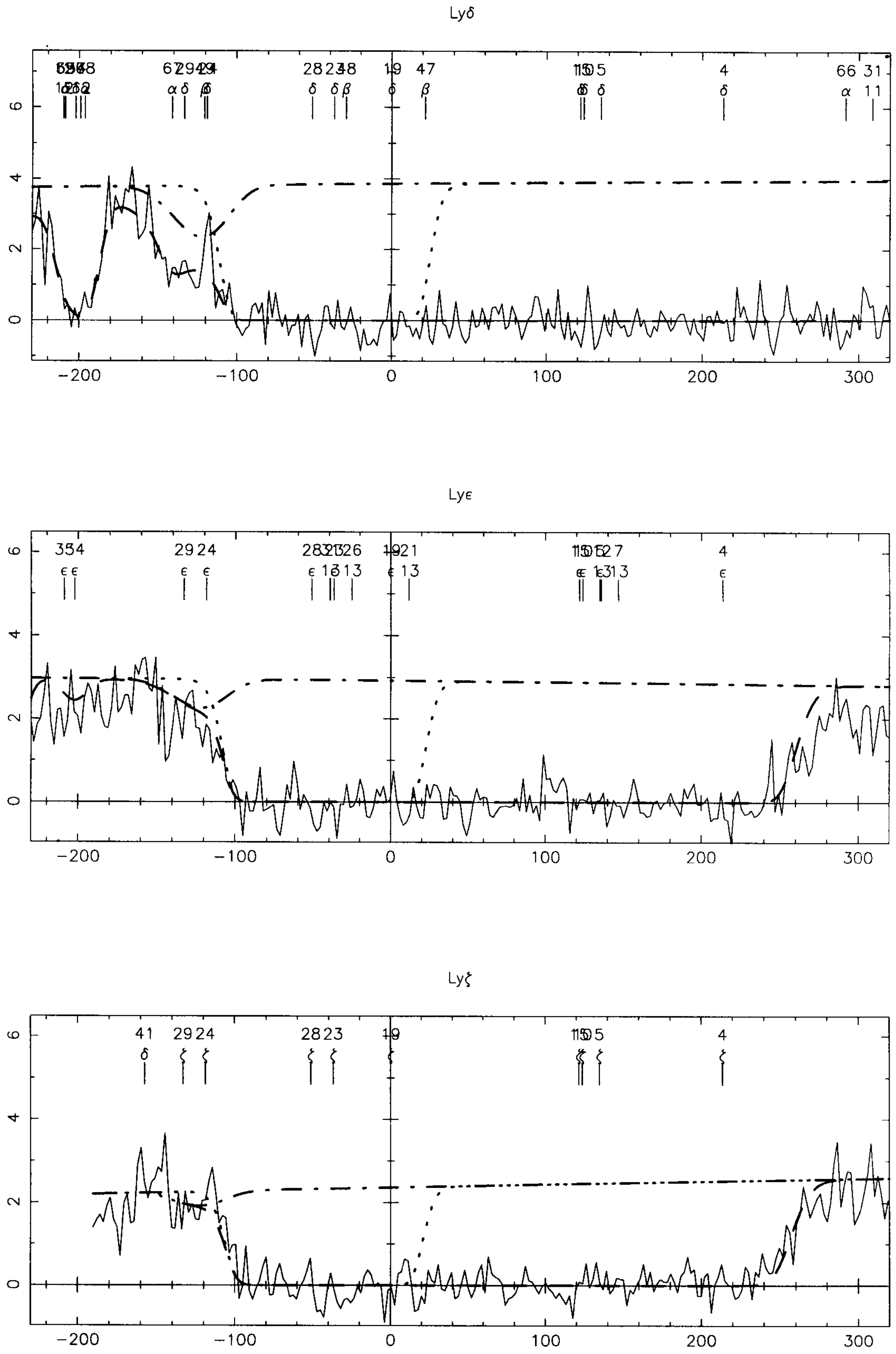

Figure 1 – *continued*

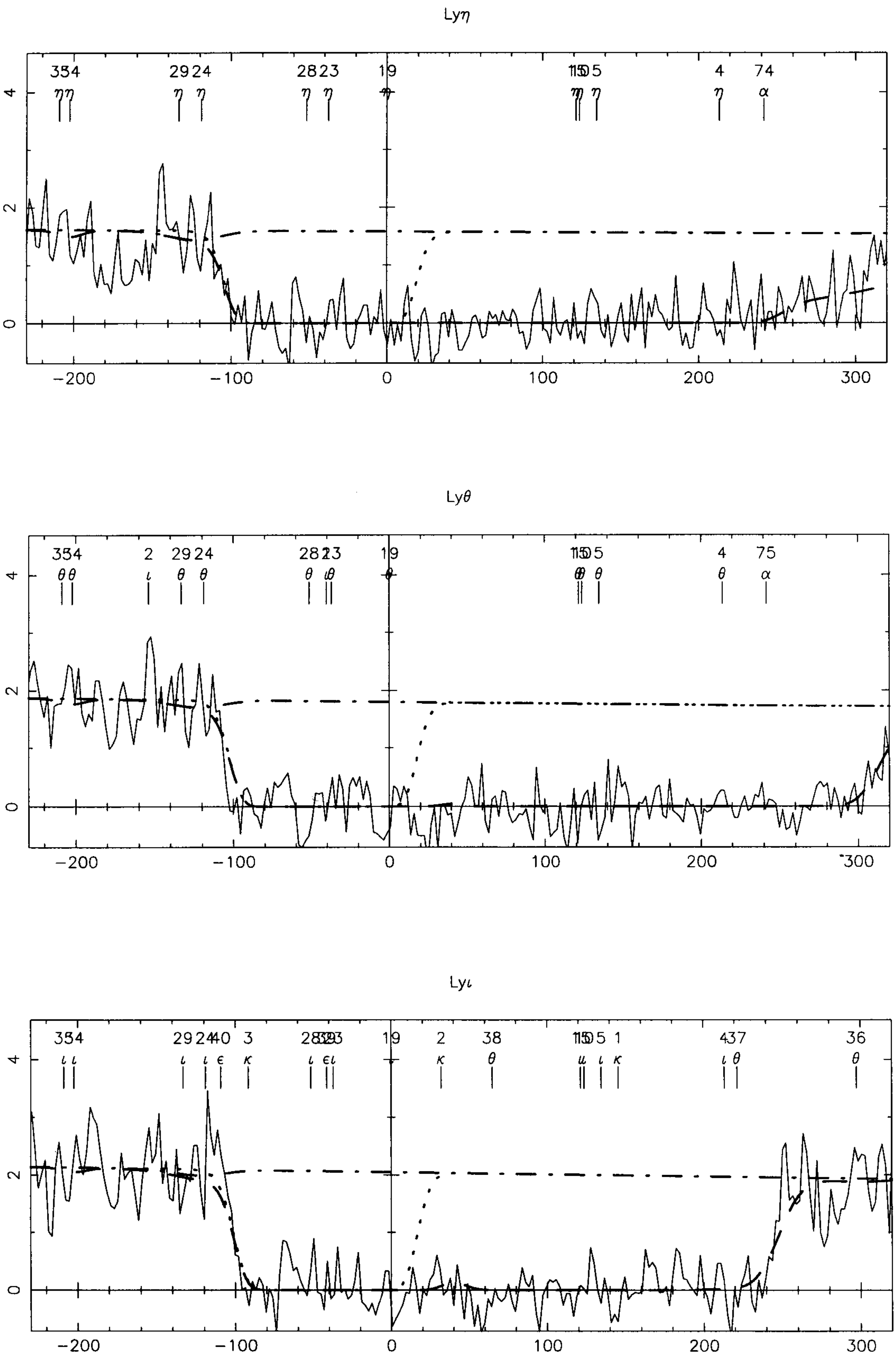

Figure 1 – *continued*

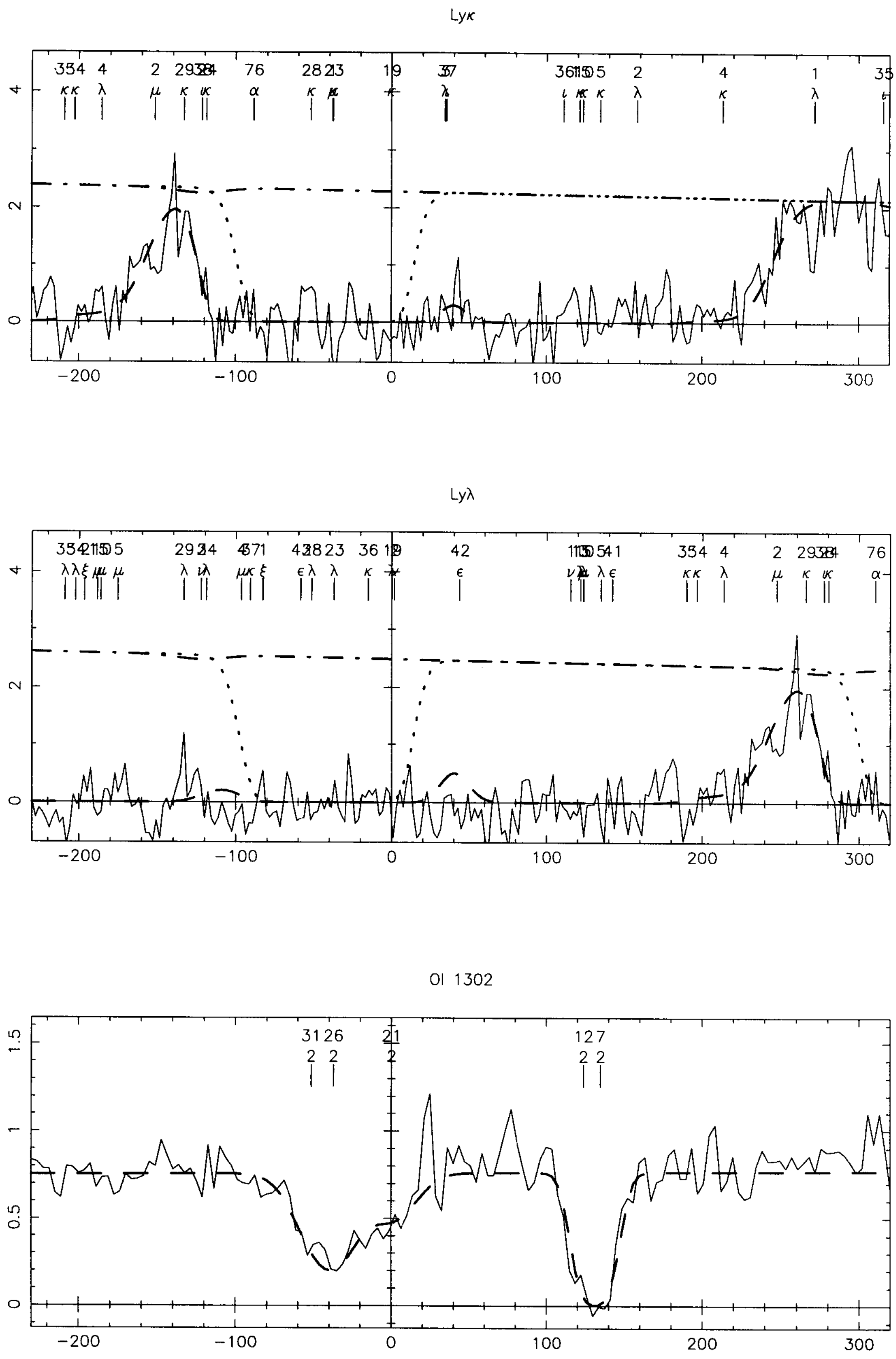

Figure 1 – *continued*

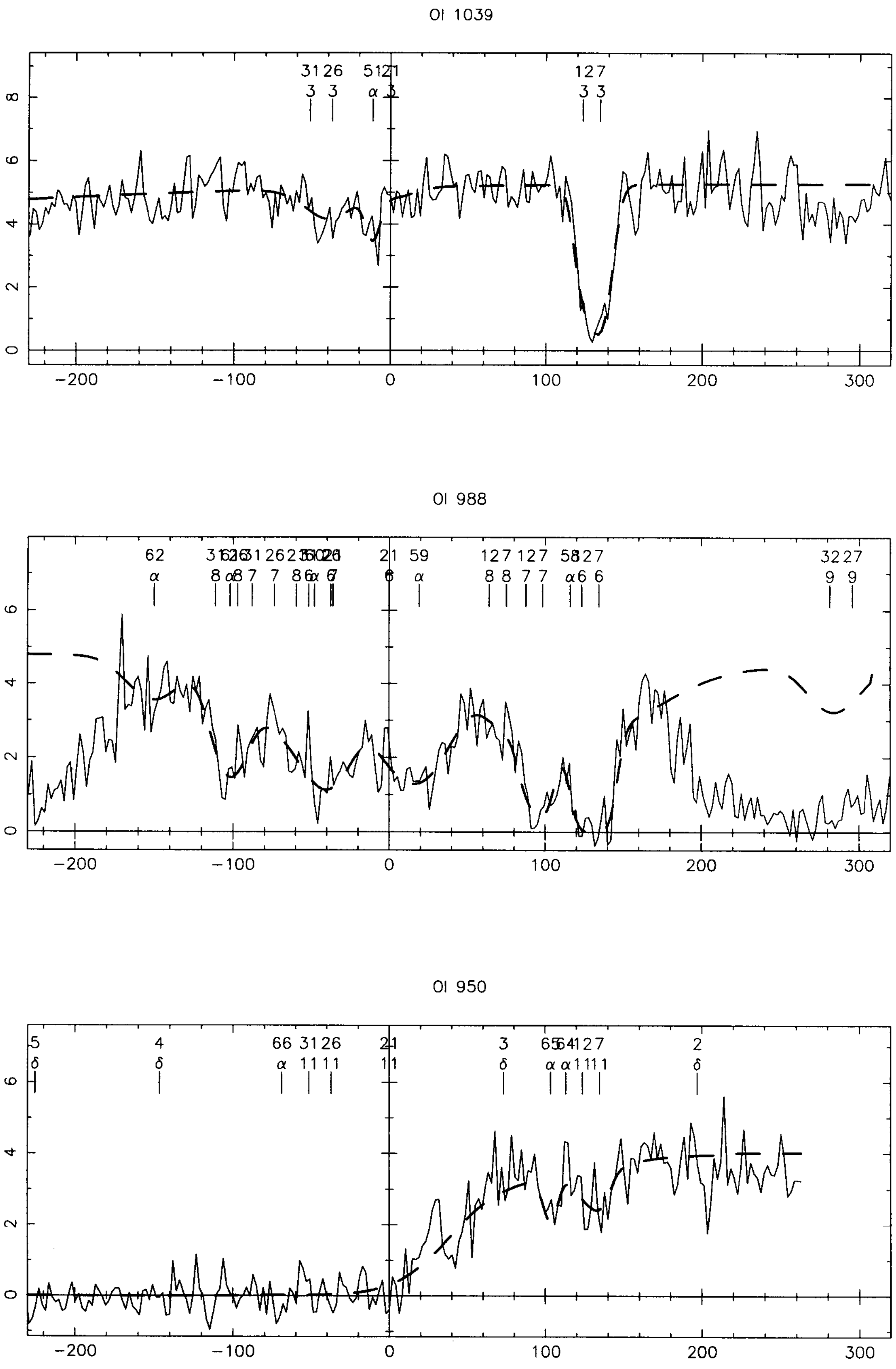

Figure 1 – *continued*

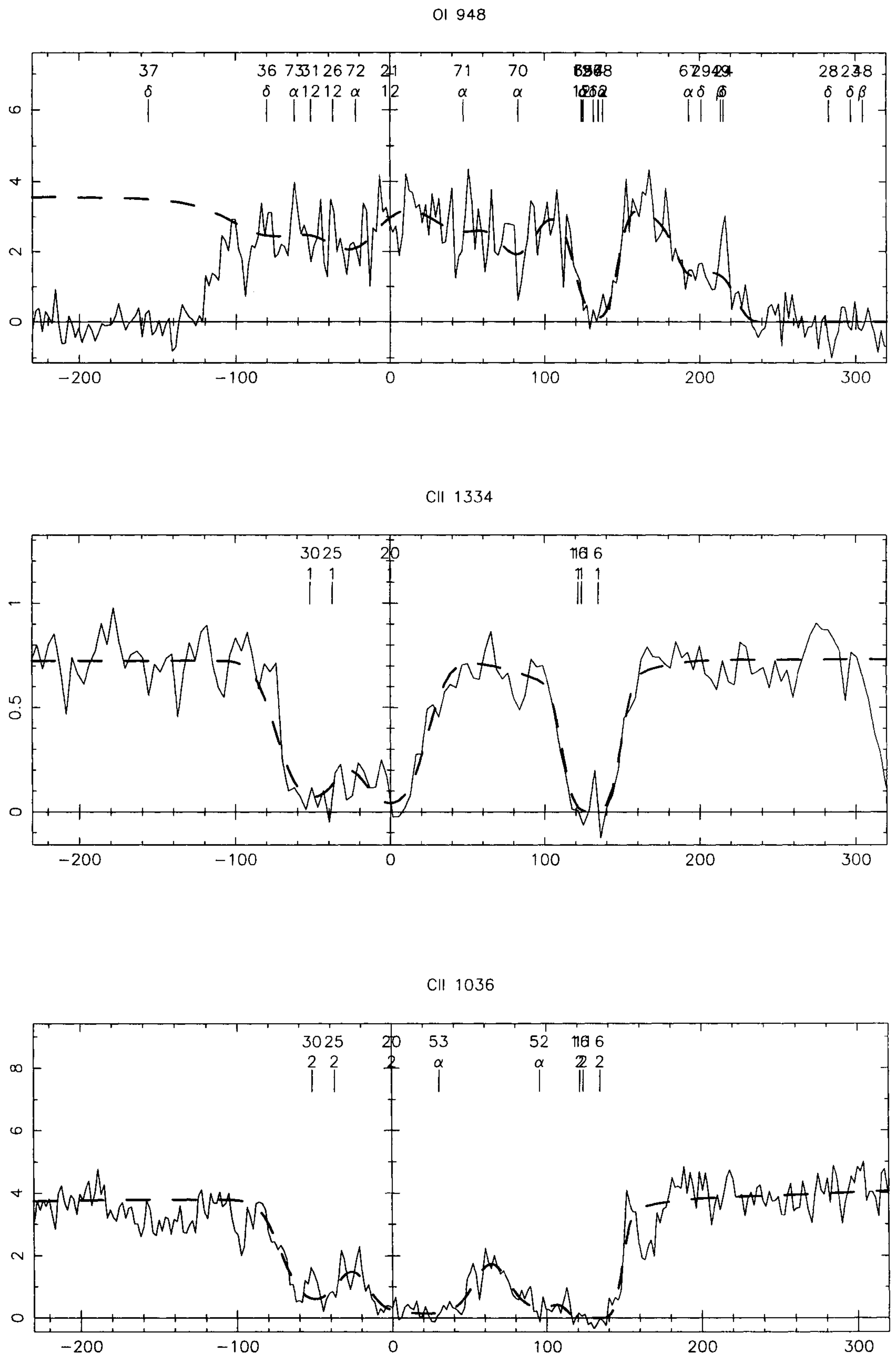

Figure 1 – *continued*

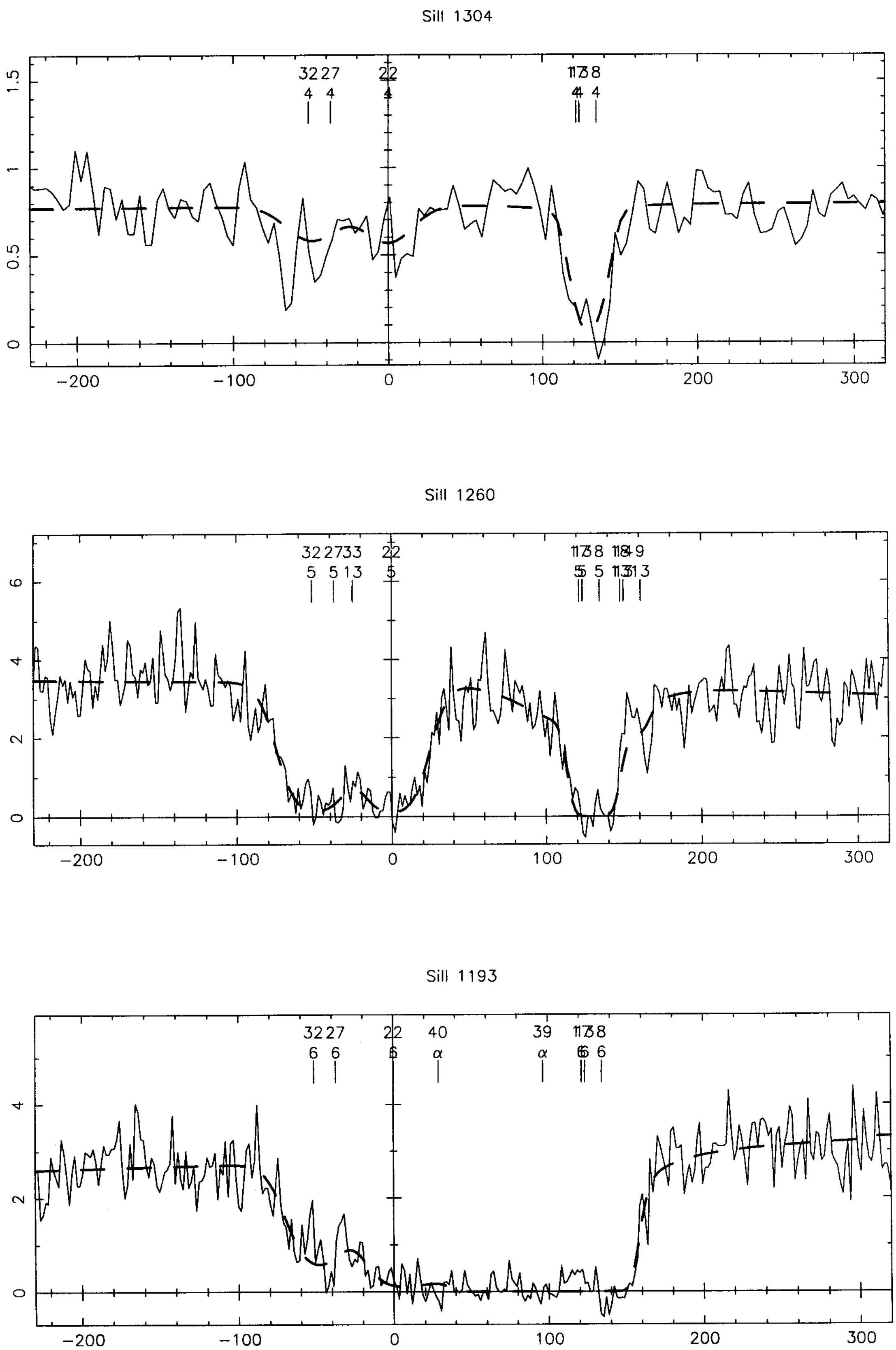

Figure 1 – *continued*

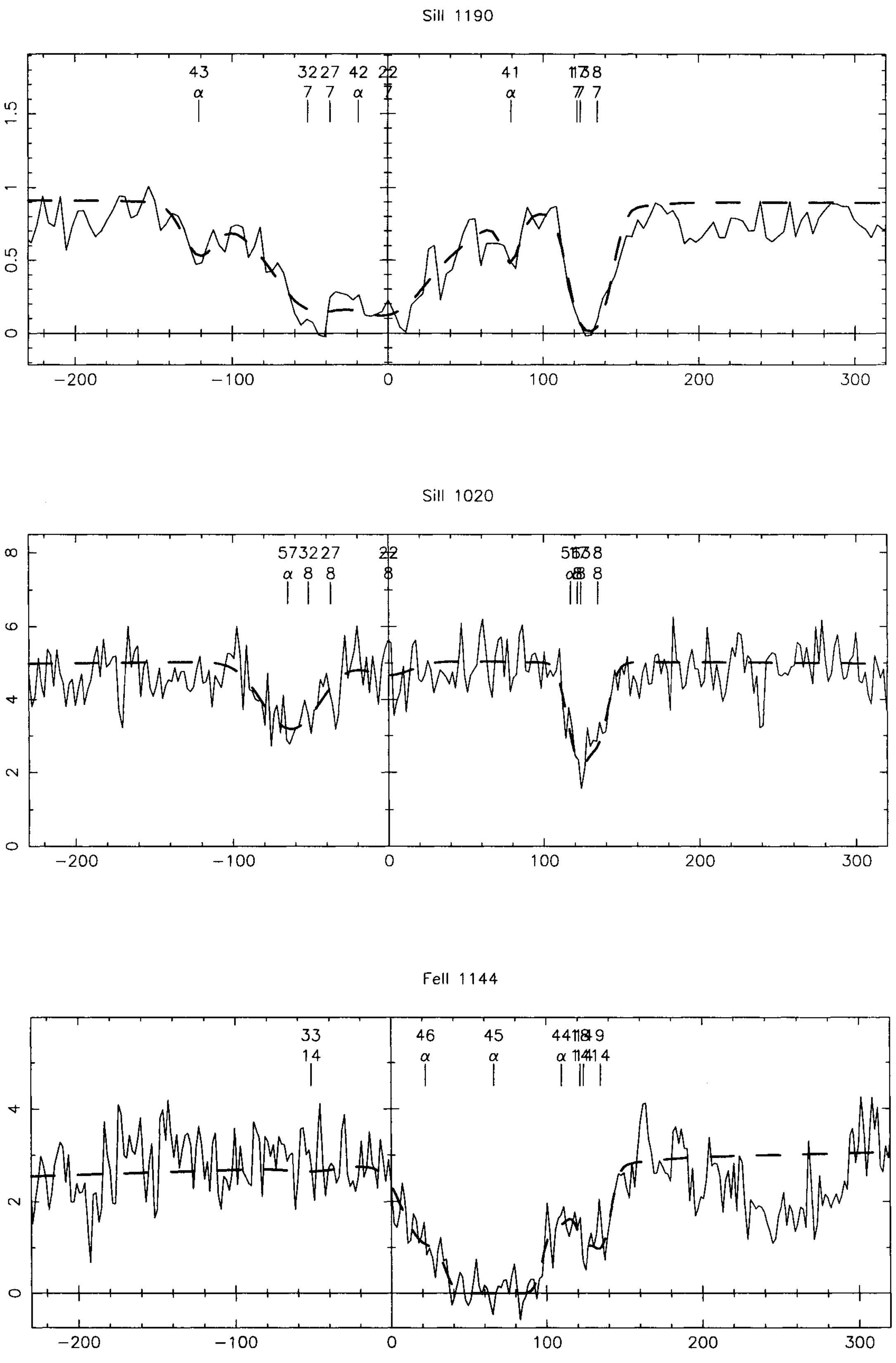

Figure 1 – *continued*

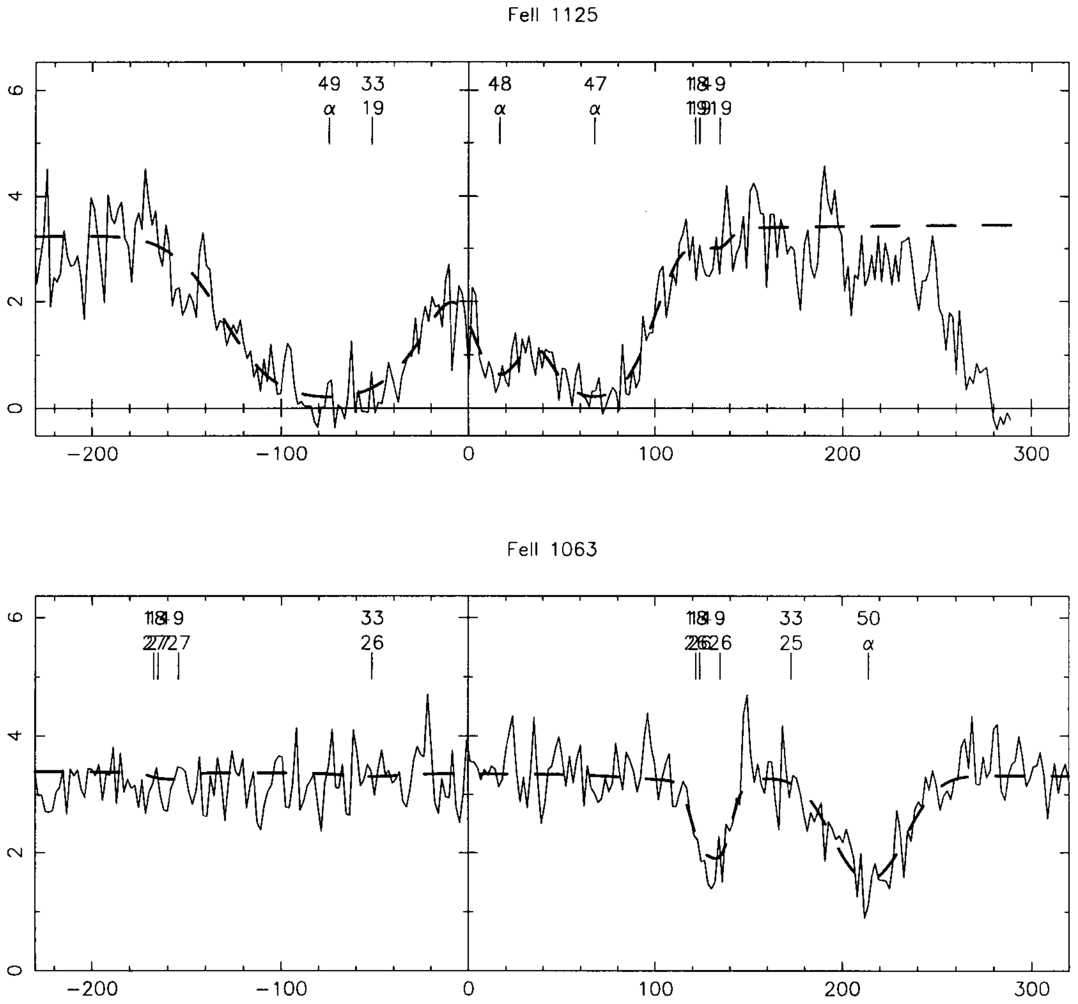

Figure 1 – *continued*

If the column densities are unconstrained, then the final results for the individual components for H I are very uncertain. Table 2 and Fig. 1 show the results of the profile-fitting procedure under these circumstances. The Lyβ, γ, δ and ε profiles in the $z=3.086$ complex suggest the presence of components which include D I at the same redshifts as the $z=3.08595$ and $z=3.08576$ components seen in the other lines. However, the weakness of the higher order D I features in the higher order Lyman lines implies significant blending of lower redshift Lyα lines with Dγ and Dδ (see Fig. 1). All the Lyα lines needed to obtain good fits to all the Lyman lines and heavy-element lines which fall in the Lyα forest are listed in Table 2, and shown in the fitted profiles in Fig. 1. A number of these supplementary Lyα lines are not very well-constrained, and no attempt was made to constrain their parameters further by, for example, including higher order lines for them. They should be treated as the minimum additional lines required to fit the line profiles for the $z=3.086$ lines of interest, and do not form a well-determined Lyα forest sample. Note that not all heavy-element ions are required in all components. Those where the column density is so low as to not affect the overall fit are omitted from the table.

For the two velocity components in which the D I lines have been identified ($z=2.08595$ and 3.08576), we may estimate the heavy element abundance by using the O I/H I ratio, since O I is well constrained and the ionization potentials of O I and H I are very similar. For $z=3.08595$, we find $\log(\mathrm{D/H})=-4.0$ and $\log(\mathrm{O/H})=-4.2$, so the heavy elements are about 1/10 solar. For $z=3.085756$, $\log(\mathrm{D/H})=-3.6$ and $\log(\mathrm{O/H})=-4.0$. However, it is clear from Table 2 that the component-by-component column densities for most ions are highly uncertain. The main cause of the uncertainty in each component is the presence of a neighbour in the blend. Reducing the column density in a component of interest may be compensated by increasing the column density in neighbouring components to yield very similar line profiles. For both redshift components the 1σ error estimates in both $\log(\mathrm{D/H})$ and $\log(\mathrm{O/H})$ are about 0.6–0.7. These are so large as to make the numbers almost meaningless.

Nevertheless, the total column density for each ion is well constrained in most cases, since to a first approximation, removing material from one component is balanced by having to add it elsewhere for a best fit. Because of this effect, we seek the D/H ratio and heavy-element abundances for the sum of the two components showing deuterium. The totals

Table 3. Ion column densities in the $z=3.087$ complex.

Ion	log$N$	±
Sum z = 3.085756 and z = 3.085951 systems:		
HI	18.66	0.37
DI	14.75	0.12
CII	14.30	0.03
OI	14.47	0.07
SiII	13.55	0.05
Sum all components:		
HI	19.39	0.06
DI	>14.75	
CII	15.50	0.36
OI	15.37	0.04
SiII	14.47	0.09
FeII	13.95	0.10
Sum all components, H/D/O tied:		
HI	19.37	0.02
DI	15.67	0.12
CII	15.51	0.37
OI	15.37	0.03
SiII	14.47	0.10
FeII	13.96	0.10

for the two systems from which deuterium may be seen are shown in Table 3. We now find, for the summed column densities from the $z=3.085953$ and $z=3.085756$ systems, $\log(\mathrm{D/H})=-3.9\pm0.4$ and $\log(\mathrm{O/H})=-4.2\pm0.4$. Thus the D/H ratio, while it is better constrained, still has a large possible range dominated by the uncertainties in the H I column density. Indeed, it is possible to provide a satisfactory fit to the complex with $\log(\mathrm{D/H})=-4.7$ for the two lowest redshift components, i.e. roughly the value in the Galactic interstellar medium.

To remove some uncertainty caused by the complex velocity structure (at the cost of a further assumption) we could constrain the D I/H I/O I ratios to be the same for all velocity components. This is effectively demanding that the D/H ratio should be the same for all components, and, if the O I/H I ratio is similar to the O/H ratio, that the heavy-element enrichment (at least for oxygen) should also be the same for all components. Under these circumstances (see Table 3), $\log(\mathrm{D/H})=-3.7\pm0.1$ and $\log(\mathrm{O/H})=-4.0\pm0.1$, so at this level of precision, the oxygen abundance is about 1/10 solar.

Since the ionization potentials for H I and O I are almost coincident, there is reason to expect that under many circumstances, O I/H I ~ O/H, as was assumed above. However, this is not true under all circumstances – see Péquignot (1990). The Péquignot models are for higher densities than apply here, so we have run CLOUDY photoionization models (Ferland 1992) to check the assumption. There are several approaches to this, but we have run models simply with an estimate of the background flux at $z=3.086$ ($f=1$ in Table 4) or 15 times that value, and assumed that the cloud is a slab illuminated from two sides ('background' in Table 4) or from one side only ('quasar'). For example, a 'quasar' ionizing model, and a cloud density of 0.1 hydrogen atoms cm^{-3} (so the ionization parameter $\log U=-1.75$), $\log(\mathrm{O/H})=\log(\mathrm{O\,I/H\,I})+0.1$ from Table 4. If the density is 10^{-2} cm^{-3}, then the neutral fraction is lower, and $\log(\mathrm{O/H})=\log(\mathrm{O\,I/H\,I})+0.2$, so the metallicity estimate will be lower by that amount. The picture which emerges is that O I/H I usually provides a good indication of the heavy-element abundances, but it may underestimate those abundances. Applying the approximate ionization corrections from Table 4 to the other ions listed in Table 3 yields total abundances, for all, of about 1/10 solar, within the errors, so for the complex as a whole, there is no evidence for dust depletion of the refractory elements or of any differential enrichment of the gaseous medium.

Table 4. Ionization corrections $\log(X/H)=\log(\mathrm{ion/H\,I})-\Delta$.

log$U$	log$n_{\rm H}$	CII	OI	SiII	FeII	
$f=15$		$\Delta=$				
-0.75	-2.0	0.4	-0.2	0.8	0.3	quasar
-1.75	-1.0	0.4	-0.1	0.7	0.3	quasar
-2.75	0.0	0.4	0.0	0.6	0.3	quasar
-2.75	0.0	0.5	0.0	0.7	0.4	background
$f=1$						
-3.93	0.0	0.2	0.0	0.3	0.2	background
-1.93	-2.0	0.6	-0.2	0.9	0.4	background
0.07	-4.0	0.6	-0.2	1.0	0.4	background

One parameter we have fixed almost arbitrarily, the temperature within each component, deserves comment. In practice, the column densities are not very sensitive to the temperature for values below about 30 000 K, since turbulence dominates all but H I and D I under these circumstances. The H I column densities are high, so the Doppler parameter makes little difference to their values, and the D I is measurable only in two components for which the turbulent velocity is high, so the estimate of the D I column density is little affected by assuming a temperature of 10 000 K.

While the presence of deuterium does help improve the fit to the data, it is not required. The feature could arise from a confusing system showing H I lines offset by about −80 km s^{-1}, or, since the putative detection is dominated by the feature in Lyβ, a confusing Lyα at redshift $z=2.446\,50$. Indeed, it is possible to model the complex without any such additional components. Under these circumstances, the H I column density at $z=3.08595$ increases by a factor of about 1.6 to yield broader Lyβ and Lyγ in order to compensate for the absence of deuterium, leaving only Lyϵ as a significantly poorer fit. An additional Lyα at $z\sim2.150\,94$ blended in with that feature is all that is needed to restore a good overall fit. Column densities for other components, and other species, are little affected.

4 CONCLUSIONS

Deuterium lines may have been detected in the $z=3.086$ complex towards 0420−388, but a single confusing Lyα system either within the complex or blended with Lyβ would explain the absorption line profiles as well. If the deuterium identification is correct, then the D/H ratio is $\log(\mathrm{D/H})=-3.9\pm0.4$ in the components where it is seen. The large error arises because of difficulties in determining the H I column density for the relevant components in the blend. Since for heavy-element systems complex velocity structure is the norm, it may be that, apart from in a few lucky cases, attempts to determine the D/H ratio will be frustrated by determinations of the H I column density being confusion-limited.

The O I column density is well-constrained by the 1302 line and several lines of differing oscillator strength in the

Lyα forest. The overall O I/H I ratio is well-determined and provides a good estimate of the heavy-element abundance. Thus for cases where the D/H ratio can be measured with adequate precision and the Lyα forest line density is not too high, it should generally be possible to determine the heavy-element abundances as well. Consequently, measuring D/H as a function of O/H should be possible.

For the system studied here, estimates of the O, C, Si and Fe abundances relative to H, after an approximate ionization correction, all give results $\sim 1/10$ solar. This indicates that there is little dust depletion overall. It also reveals a significant degree of nuclear processing, and suggests that either the deuterium production or destruction is not the same in this system as in the Galaxy, or that the deuterium identification is spurious.

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