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The spectrum of BAL QSO Q1303+308: intrinsic variability and line-locking stability

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ABSTRACT

A recently taken WHT optical spectrum of the BAL QSO Q1303+308 shows interesting changes in the spectral characteristics of the absorption systems. In particular, the equivalent widths of many of the broad absorption lines have markedly increased with respect to observations taken 15 yr earlier by Foltz et al., with the more blueshifted components showing the greatest increase by a factor of ≈5 in optical depth. Perhaps the most remarkable feature of the data is that, in the rest frame of the quasar, the line-of-sight outflow velocity of the clouds has only increased by $\approx 55\,\mathrm{km\,s^{-1}}$ in a rest-frame time interval of 5–6 yr. Various examples of doublet line locking are still visible in the system, and we present a provisional model analysis of the spectrum showing that theories based on small cloud velocity interactions via line locking can successfully explain the general appearance of the spectrum and its variability. Finally we highlight the need for further ongoing monitoring of this fascinating object.

Key words: line: profiles – quasars: absorption lines – quasars: individual: BAL QSO Q1303+308.

1 INTRODUCTION

Manifestations of the so-called line-locking effect (that is, narrow, blueshifted absorption features of different ion lines separated by line doublet spacings) are seen in the spectra of several broad absorption line quasi-stellar objects (BAL QSO), but the most impressive case of line locking in active galactic nuclei (AGN) is observed in the spectrum of the quasar Q1303+308 (Weymann et al. 1979; Weymann & Foltz 1984; Turnshek et al. 1984; Foltz et al. 1987, hereafter FWMT). In FWMT two spectra of Q1303+308 obtained in 1983 and 1985 were compared. The results from these observations showed interesting ordered structure suggesting that line locking was playing an important role in the velocity system of absorption features seen in this quasar. Further analysis by FWMT showed that the positions of the narrow absorption features in the spectra were practically unchanged during the 2-yr interval, which corresponds to approximately 8.6 months in the rest frame of the quasar. Assuming that the narrow absorption lines are connected with different absorbing clouds, the authors concluded that the acceleration of the clouds is very small – less than $1.7\,\mathrm{km\,s^{-1}}$ per month in the quasar rest frame – and from this they estimated the distance of the cloud from the BAL QSO continuum source to be greater than 3 pc.

In an attempt to place better constraints on the temporal variation of the line-locking phenomena, we obtained a further spectrum of Q1303+308 on the William Herschel Telescope (WHT) on La Palma in 1999 June. This then gives a temporal coverage of roughly 15 yr in the observed frame, or approximately 5 yr in the quasar rest frame. In addition to presenting a comparison of the latest results with the earlier spectrum to investigate the structure and time variability of the spectrum, we also present a preliminary theoretical analysis of the spectrum based on the results of the recent paper by Vilkoviskij et al. (1999, hereafter P1).

The structure of our paper is as follows: The new observations together with an empirical comparison with the earlier published spectra of FWMT are presented in Section 2. In Section 3 we briefly introduce a kinematic model of the spectral structure. Section 4 deals with the spectral variability and physical parameters for the corresponding theoretical models. We finish with some discussion of the results in Section 5.

2 THE OBSERVATIONS

Spectroscopic observations of Q1303+308 were carried out as part of a service programme on the 4.2-m William Herschel Telescope (WHT) on La Palma during the night of 1999 July 8. Three separate integrations of 1800-s duration were made in photometric conditions and subarcsecond seeing, together with observations of a photometric standard, BD +332642. CuAr calibration arcs were taken after each exposure to monitor and

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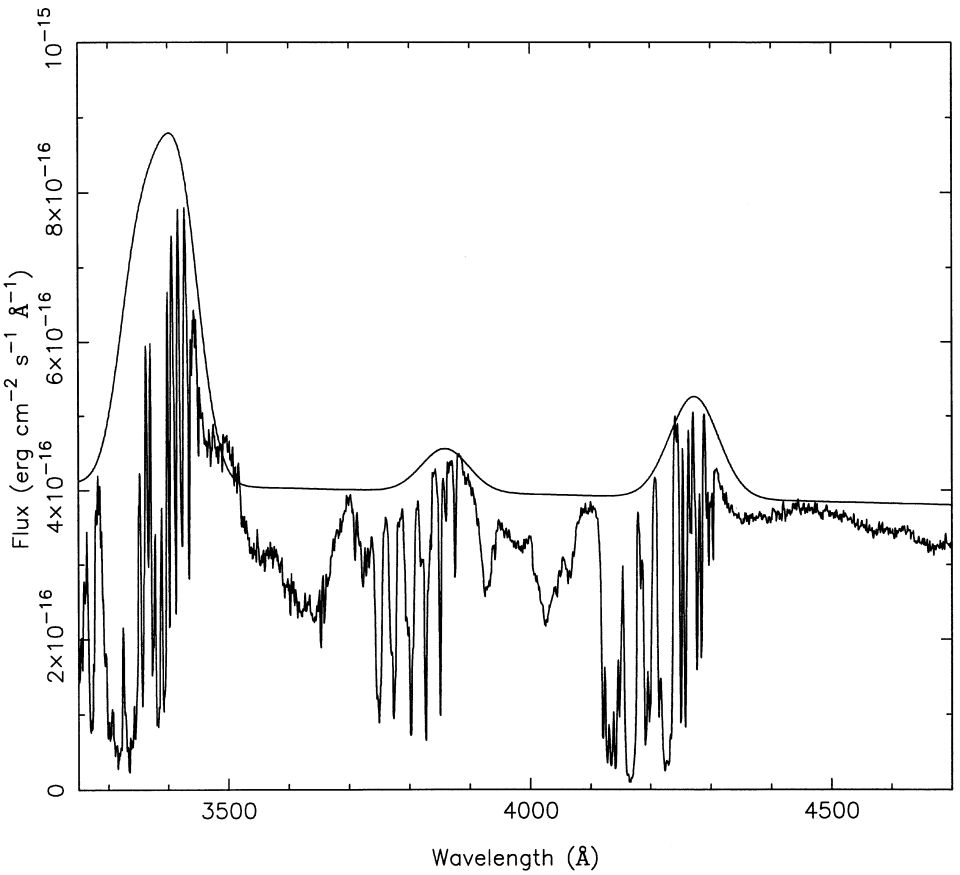

Figure 1. The WHT spectrum of BAL QSO Q1303 + 308 with an idealized absorption-line-free model overplotted.

remove any spectrograph flexure. All observations were taken on the blue arm of the ISIS double-beam spectrograph, using a thinned EEV 4k × 2k charge-coupled device (CCD) as detector and the R600B grating. At a central wavelength of 3900 Å, this corresponds to a sampling of 0.436 Å pixel^{-1} and gives an effective resolution of ≈0.9 Å, or 25 km s^{-1} in the rest frame of the quasar.

The spectra were reduced in the standard manner using the IRAF package. Bias correction, trimming and two-dimensional flat-fielding based on tungsten lamp exposures were first performed. Target spectra, arcs and standard were extracted and the quasar spectra were then wavelength-calibrated and fluxed using the appropriate arcs. Residual variations in the wavelength calibration due to flexure and errors in the wavelength solution are at the level of one-fifth of a pixel, or 0.1 Å. Finally the three individual spectra were combined and trimmed to the range 3250–4700 Å, the unvignetted part of the spectrograph for this setup, to produce the spectrum shown in Fig. 1.

In order to compare the new spectrum with the earlier work, the main absorption components in BAL QSO Q1303+308, annotated using the same convention as FWMT, are shown in Fig. 2 in regions centred on the N V, Si IV and C IV systems. Three additional prominent systems, denoted X, Y and Z, are labelled as well as the six components (A–F) listed by FWMT. Estimates of the central wavelengths and redshifts, equivalent widths (EWs) and a comparison with the earlier data are given in Table 1. For the narrow lines the centring error is around 0.1 Å. Coupled to the residual systematic errors in the wavelength calibration, this corresponds to a redshift error of ±0.0001. For the broad lines the error in the computed wavelength depends strongly on the asymmetry/complexity of the system, but can be several times larger. In a similar way, the errors in the EW for the strong lines are well defined at the level of ±0.05 Å; however, for the broad lines and blended components the errors can be much larger and indeed difficult to estimate.

The main differences in the spectrum are that the 1999 data show stronger and generally more complex absorption; and the A–F absorption components are blueshifted by 0–1 Å with respect to the earlier 1983 + 1985 data. In particular, features A and B are now blended and form complex absorption troughs of at least three components, making direct detailed comparison with the earlier results difficult. However, if we take the deepest narrow absorption feature in the Si IV$_{1393}$ trough labelled A + B to be the same component A as seen before, the observed wavelength is now 1349.2 Å, 0.65 Å blueward of the previous measurement. Likewise, taking the average of the shifts of the doublet lines, components C, D and F appear to be blueshifted by 0.61, 0.71 and 1.05 Å respectively. As noted before by FWMT, two of these strong Si IV doublets, C and F, are separated by the doublet spacing and appear to be still line locked with doublet D. It is again difficult to say much about component E since there are possibly three components in this trough, although the main one, listed in Table 1, appears essentially at the same position given in the earlier study.

All of the EWs have increased dramatically, with the more blueshifted components showing the greatest increase by a factor of ≈5 in total amount of absorption. Perhaps the most remarkable feature of the data is that, in the rest frame of the

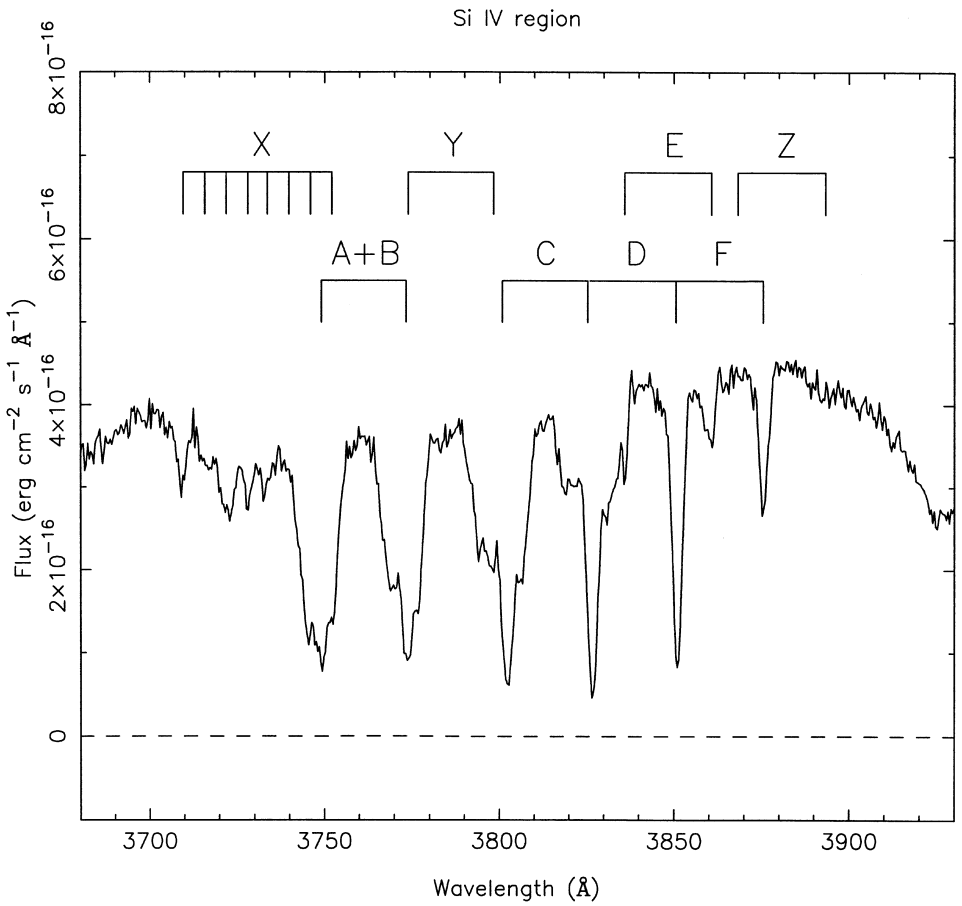

Figure 2. The region of the spectrum presented in Fig. 1 containing the Si IV absorption features. This should be compared directly with fig. 3 of FWMT to see the evolution in the spectral signature of the various absorption systems. In particular, note how the growth of systems X and Y has changed the overall appearance, and that system D is still line locked with systems C and F.

quasar, the line-of-sight outflow velocity of the clouds has only increased by $\approx$55 km s^{-1} in a rest frame time interval of 5–6 yr.

3 THEORETICAL MODEL OF THE SPECTRAL STRUCTURE

If we suppose (cf. FWMT) that the deep narrow absorption lines are linked to separate large clouds, it is difficult to explain the observed line-locking effect. This effect could appear if the scattering of the radiation in the 'locked' resonance lines is the main physical reason for the acceleration of the clouds. However, the optical depths, τ, of the clouds in the 'locked' Si IV doublet are large enough such that estimates of the acceleration from equation (1) in FWMT have to be diminished by $\exp(-\tau)$, and then represent less than 1 per cent of the total acceleration by 'unlocked' lines, implying that locking due to this doublet seems doubtful. On the other hand, supposing that the observed acceleration results from drag force by hot gas, one cannot expect any line locking.

In our opinion, the narrow absorption lines in the QSO spectrum can be explained not with absorption by individual clouds having different velocities and corresponding optical depths, but with a velocity structure of a system of small clouds having a similar distribution of masses. This view is supported by the dynamical model calculated in the framework of the so-called 'interaction subsystems theory' (P1). In P1 it was shown that the structure of spectra similar to Q1303+308 appears naturally in the dynamical model simulation because of the 'ladder' structure of the velocity distribution of small clouds. This structure has been explained using the so-called 'self-line-locking' effect, which can appear in the two-phase medium as a result of the non-linear interaction of the drag force and the radiation pressure force (see P1 for more details), where the positions of the constant-velocity 'plateaux' are influenced by ordinary line-locking effects.

In the present paper we consider a kinematic model, based on the physical ideas of this dynamical model. In the Sobolev approximation for the continuum gas flow, the absorption depth τ_j for the jth line in the moving gas is

$$\tau_j = (e^2/m_e c)\lambda_j f_j n_{ij} V_T/(\mathrm{d}V/\mathrm{d}r), \quad (1)$$

where e and m_e are the electron charge and mass, c the velocity of light, λ_j the line wavelength, f_j the oscillator strength, n_{ij} the specific density of the ith ions which emit the jth line, V_T the turbulent velocity, and $\mathrm{d}V/\mathrm{d}r$ the gradient of the matter flow velocity.

For the matter flow consisting of cloudlets, equation (1) is transformed to

$$\tau_j = (e^2/m_e c)\lambda_j f_j S_{cl} N_{ij} n_{cl} V_T/(\mathrm{d}V_{cl}/\mathrm{d}r), \quad (2)$$

where S_{cl} is the cross-section of a cloud, N_{ij} are the column densities in a cloudlet of the ith ions multiplied by the level populations for the jth transitions, n_{cl} is the cloudlet volume

Table 1. The main absorption systems along the line of sight to BAL QSO Q1303+308.

System epoch	Redshift	λ_{obs}(Å) 1999 Si IV	EW_{obs}(Å)	Redshift	λ_{obs}(Å) 1983+1985 Si IV	EW_{obs}(Å)	Comments
A	1.6895	3748.5:	7.41	1.6905	3749.85	1.20	A + B now blended together,
		3773.0:	7.00		3774.06	0.97	including components
B	1.6903			1.6928	3753.12	0.44	of X and Y
					3777.42	0.45	
C	1.7280	3802.33	4.05 (8.59)	1.7286	3802.95	1.70	Wavelength and EW are main component but at least three
		3826.79	3.76 (7.05)		3827.39	2.03	other blended cpts including system Y
D	1.7451	3826.79	3.76	1.7461	3827.39	2.03	D is line locked with
		3850.93	2.68		3851.79	1.62	C and F
E	1.7522	3835.84	0.30	1.7522	3835.95	0.30	Wavelength and EW are
		3860.73	0.18: (0.60)		3860.65	0.22	main cpts; maybe two others
F	1.7627	3850.93	2.68	1.7636	3851.79	1.62	
		3875.52	1.22		3876.77	0.61	
X-I	1.6616						Blend of four cpts seen best
X-II	1.6660						in C IV but visible in Si IV
X-III	1.6704						II seems to be line locked with
X-IV	1.6748						I and II, and III with II and IV
Y	1.7077	3773.9:					Visible as complex blend in
		3798.3:					C IV – mixed with C cpt in Si IV
Z	1.7754						Not visible in Si IV but clear in C IV and N V

Notes:
1. Systems X, Y and Z are visible in 1983+1985 data but overall troughs are now much deeper.
2. Other possible line-locking examples at red edge of N V where E is locked to D and F (also noted by Foltz et al. 1987).
3. Additional components further to the blue are two obvious broad complex absorption troughs at redshifts 1.5337: and 1.6015:, visible in both Si IV and C IV.
4. Where given, the ( ) in EW columns are total for the blend.
5. There is evidence for other weak doublets in the spectrum and those listed in the table are only the more obvious systems.

density, V_T is the cloudlet turbulent velocity, and $V_{cl}(r)$ is the velocity of a cloudlet at distance r.

Rearranging equation (2) and integrating over dV_{cl} we see that the radial dependence $r(V_{cl})$ is given by

$$r(V_{cl}) = (m_e c/e^2)\int_0^{V_{cl}} \tau_j(V'_{cl})/(\lambda_j f_j S_{cl} N_{ij} n_{cl} V_T)\, dV'_{cl}, \quad (3)$$

where $\tau_j(V'_{cl})$ can be obtained from the observed spectrum (see below),

$$\lambda_j = \lambda_{jD}(V'_{cl}) = \lambda_j\sqrt{(1 - V'/c)/(1 + V'/c)}$$

is the Doppler-shifted wavelength with the velocity V'_{cl} relative to the initial position at $V'_{cl} = 0$; the values of S_{cl}, N_{ij}, n_{cl} and $V_T(r)$ are unknown functions of velocity and radius [$f(r)$] in the general case.

The calculation of $\tau_j(V_{cl})$ is possible if we define the unabsorbed continuum spectrum of the radiation flux density, $F_c(\lambda)$, which requires estimating several free parameters – the level of the continuum, its slope, and the widths and amplitudes of the emission lines. After choosing some $F_c(\lambda)$, we can then define the absorption depths at every λ and at every velocity value $V_{cl}(\lambda)$ using the known relativistic relation

$$V_{cl} = c[1 - (\lambda_{jD}/\lambda_j)^2]/[1 + (\lambda_{jD}/\lambda_j)^2]$$

and the standard definition of optical depth,

$$\tau_j(V_{cl}) = -\ln[F_{obs}(\lambda)/F_c(\lambda)], \quad (4)$$

where $F_{obs}(\lambda)$ is the observed radiation flux density.

4 SPECTRAL VARIABILITY AND VALUES OF PHYSICAL PARAMETERS

Though some variabilities in BAL QSO spectra have been noted before (Barlow, Junkarinen & Burbidge 1989; Hamann, Barlow & Junkarinen 1997; Michaltsianos et al. 1997), the dramatic change of depth of the absorption lines in Q1303+308 makes this object even more unique. In the framework of the individual cloud hypothesis, there is no a priori justification to increase the amount of matter in the clouds; hence the growth in the absorption has to be explained by an increase in absorption cross-section, particularly in the high-velocity clouds X, Y and Z.

In the small-cloudlets model there are several possibilities for variable absorption. To start with, consider the variations of the mass flow of the cloudlets. If we take into account, as in P1, that the source of the small clouds is the result of gradual fragmentation of more massive clouds, the explanation for the rapid variability is quite natural. Let us suppose that the mass flow of the cloudlets is proportional (to the first approximation) to the luminosity of the central object. Then, if the central luminosity rises quickly, the front of the enhanced photon outflow will run through the large-size cloud flow to the observer, and the front of the increasing mass flow of the cloudlets will follow the photon front. As a result, the observer will see an increase in luminosity and variations in the Doppler-shifted velocity of the clouds, and an increase in absorption, though possibly with some time lag.

More specifically, as can be seen from equation (2), τ_j depends

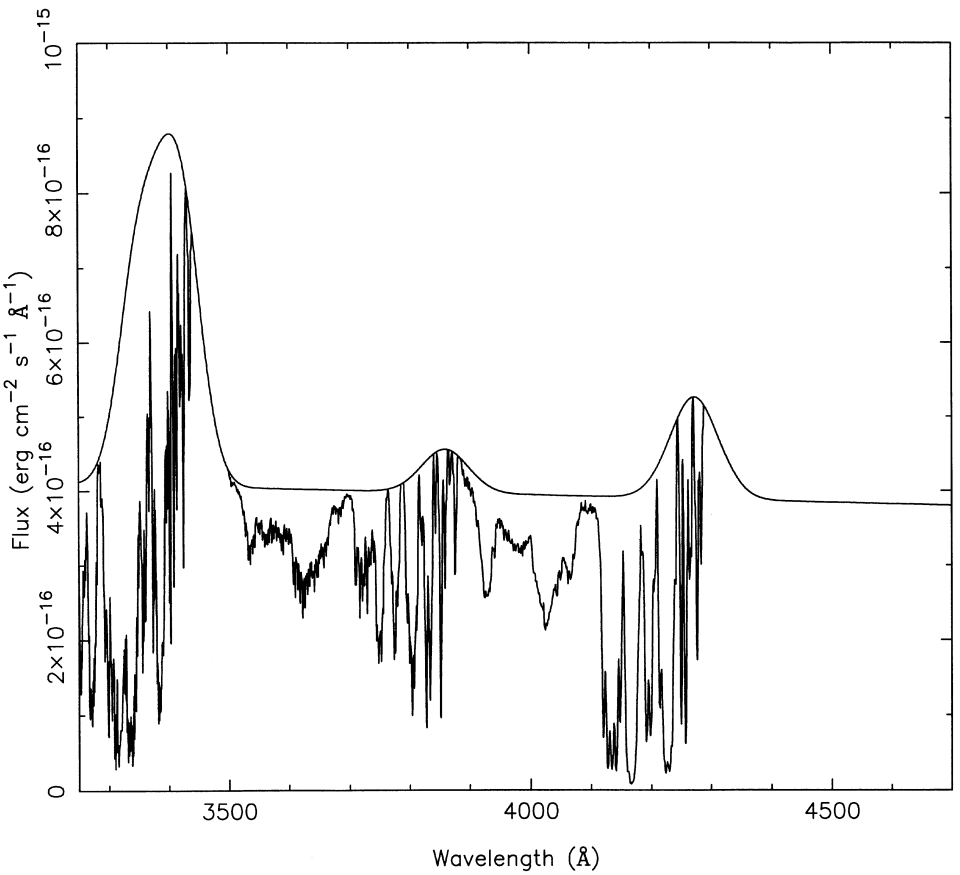

Figure 3. The best-fitting theoretical model spectrum of BAL QSO Q1303+308 with an idealized absorption-line-free model overplotted. Compare this spectrum with the WHT data shown in Fig. 1.

on the product $S_{\rm cl}N_{ij}n_{\rm cl}V_{\rm T}/({\rm d}V_{\rm cl}/{\rm d}r)$, so every factor of the product can influence the variability. As $V_{\rm T}/({\rm d}V_{\rm cl}/{\rm d}r)$ defines the structure of the spectrum, and has been almost invariable during the last 14–16 yr, we must consider the product $S_{\rm cl}N_{ij}n_{\rm cl}$. This value depends on the mass and volume density of the clouds, so variations can be explained with the cloudlet flow variations, discussed above. The only independent variables remain n_i, the ith ion densities. Of course, these n_i values depend on the ionizing radiation flow $F(\nu)$ and its spectral distribution. Both correlations and anticorrelations with $F(\nu)$ are possible, depending on the position of the n_i before or after the maximum of the $n_i(F(\nu))$ function.

Clearly, to delineate which of these types of variation are playing a role in Q1303+308 requires repeated long-term monitoring of both spectral and luminosity variations of the quasar on something like a yearly basis. However, with the data to hand we can outline a plausible theoretical interpretation and build on this with future work.

As the structure of the observed spectrum is evidently similar, at least in the blueshifted regions of both C IV and Si IV ion lines, we can investigate the hypothesis of the pure kinematic explanation for the spectral structure.

First, we derive the cloudlet velocity field from the behaviour of the absorption due to one line of the C IV ion, in the 3840–4400 Å region. In practice we have to derive $\tau_j(V_{\rm cl})$ for a C IV line from the observed spectrum, which is the result of the overlapped absorption by both lines of the doublet at most wavelengths, making the procedure more complicated. We proceed by deriving $\tau_j(V_{\rm cl})$ for the strong component of the doublet and then introduce the correction for the influence of the second weaker component using a simple iterative procedure.

Secondly, we take the obtained velocity field for calculations of the absorption in the Doppler-shifted lines of the other ions (Si IV doublet, N V doublet and Lyα of the H I ions) by using ${\rm d}V_{\rm cl}/{\rm d}r$ to compute $\tau_j[\lambda_{j{\rm D}}(V_{\rm cl})]$ for all jth lines, including the C IV lines, from equation (2). The result of the calculations with the best-fitting free parameters (see below) are presented in Fig. 3. Comparing Figs 3 and 1, one can see that the calculated spectrum is similar to the observed one, suggesting that, at least to first order, this prescription for modelling the observed spectrum is a valid one. The parameters obtained for the best fit are listed below:

(i) The adopted continuum parameters are $f_{\rm c} = 4.1 \times 10^{-16}$ at $\lambda = 3225$ Å, with a linear slope of -1.7×10^{-20} Å^{-1}.

(ii) The amplitudes with respect to the continuum level of the four broad emission lines corresponding to C IV, Si IV, N V and Lyα are 0.22, 0.10, 0.54 and 0.76 respectively; all were taken to have the same velocity dispersion of 4.1×10^8 cm s^{-1}.

(iii) The relative amounts of every ion are the product of the element n abundance $\alpha(n)$ and the relative ion amount $n(i)$. We use the standard cosmic abundances of elements $a(n)_{\rm st}$, so our free parameters $n(i)$ are determined under the precision of the relations $a(n)_{\rm real}/a(n)_{\rm st}$. Here all the $n(i)$ but one, $n(2) = n({\rm Si\,IV})$, are supposed to be independent of velocity, while $n({\rm Si\,IV})$ is multiplied by the function $q(V)$ to model correctly the spectrum in the high-velocity region of this ion, shown in Fig. 4. The adopted $n(i)$ are 0.14, 0.33, 0.40 and 8.0×10^{-6}.

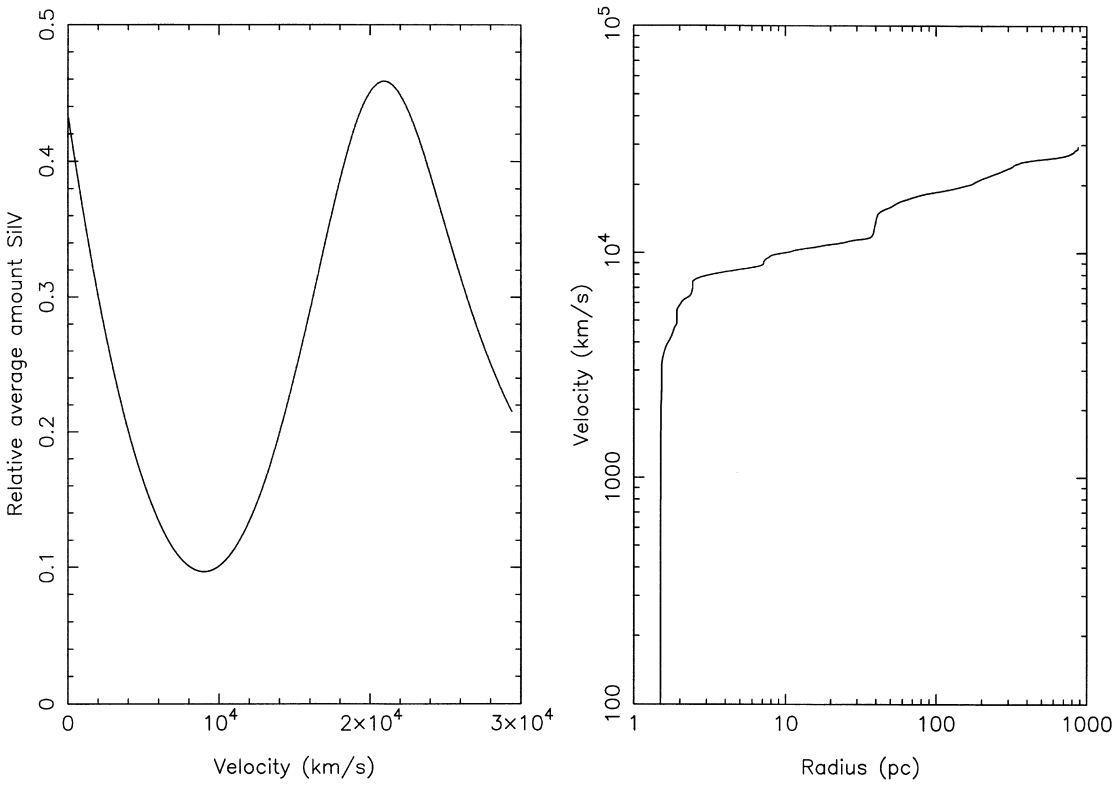

Figure 4. The average relative abundance of the Si IV ion as a function of velocity (left panel), and the velocity variation versus distance for the cold clouds (right panel).

(iv) The maximal and minimal values, $V_{\max}$ and $V_{\min}$, of the cloudlet velocities, defined relative to $V = 0$, which is taken to be equal to the line positions at redshift $z = 1.759$, derived by Turnshek et al. (1984) from the C III] emission line are used. Accepted best-fitting parameters are $V_{\max} = 2.3 \times 10^9\,\mathrm{cm\,s^{-1}}$ and $V_{\min} = -6.4 \times 10^8\,\mathrm{cm\,s^{-1}}$, the full velocity range being $2.94 \times 10^9\,\mathrm{cm\,s^{-1}}$, if $V_{\min}$ is the zero-point. This means that z(abs) of the zero-velocity absorption line is more than $z = 1.759$ adopted for the emission lines. Moreover, one can see from comparison of Figs 1 and 3 that the most redshifted details in the C IV and N V ion spectra have even higher z(abs)! This can be explained by absorption by some 'infalling' clouds, or by noting that systematic offsets between different ionization states in quasar spectra are not uncommon (e.g. McIntosh et al. 1999).

The distance of the flow can be estimated from equation (3). As was mentioned in Section 3, the equation contains some unknown function of radius, though certain limits can be estimated from the observations. By using the various theoretical considerations and constraints following from our previous dynamical model calculations of P1, we obtain the solution $r(V_{\mathrm{cl}})$, and, accordingly, $V_{\mathrm{cl}}(r)$, which is shown in Fig. 4. One can see that the behaviour of $V_{\mathrm{cl}}(r)$ derived here for quasar Q1303+308 is qualitatively similar to that obtained in our previous dynamical model simulation (see fig. 3 of P1).

5 DISCUSSION AND CONCLUSION

Though there are different approaches to the theory of BAL QSOs (Arav & Begelman 1994; Murray & Chang 1997), the only one explicitly containing the line-locking effect model is P1, so we concentrate on the compatibility of this analysis of the observed spectra with the results of P1.

Let us discuss first of all the main sources of possible errors in our model calculations.

(i) The effects of atmospheric extinction have been ignored both in deriving the model spectrum and in the theoretical analysis. However, since the model solutions and parameters are completely determined by the relative values of observed flux to continuum flux, the effect of differential atmospheric extinction is minimal. At this stage reliable absolute luminosity information is not available.

(ii) We also neglect the possible influence of lines of other ions (such as Fe II, III and Al II, III), which in principle at least could cause some confusion, but in practice is unlikely.

(iii) We assume that the amounts of the ions, $n(i)$, excluding Si IV, are independent of the velocity (and the distances) of the clouds, though some dependence is possible. In fact, some common dependence of $n(i)$ on r is included in the previously mentioned radial function $f(r)$, but real differences in the $n(i)$ would lead to the deviation of the calculated spectrum from the real one.

Taking into account all these uncertainties, as well as the natural photon noise in the observed spectrum, one can say that some differences between the observed and calculated spectra are quite expected, and the close similarity of the calculated and observed spectra supports the proposed physical model.

The main conclusion is that the theory developed in P1 is compatible with the analysis of the spectrum of the BAL QSO Q1303+308. This means that the absorption profiles are determined by the velocity structure of the small-cloud flow, which are

generated due to disruption of the large clouds. The last ones are usually invisible in absorption as a result of their larger distances in velocity space. In the 'universal unification scheme', which was suggested in P1, the large clouds are cut from the internal surface of the obscuring tori, so BAL QSO are the objects intermediate between QSO1 and QSO2. As regards the 'separate large clouds' model, it cannot be definitively rejected, but severe question marks remain.

The next conclusion is that the rise of the depths of the absorption features in this quasar during the last 14 yr shows the increasing amounts of absorbing matter and/or absorbing ions along the line of sight. These were probably generated by some physical 'signal' (possibly spectral luminosity variation of the central object), within a time-scale at least as short as 5 yr in the rest frame. Such variations are common in QSOs, but directed observations to monitor the overall luminosity of Q1303+308 are needed to address this issue directly.

It is clear that Q1303+308 is a unique natural laboratory for the precise investigation of many important physical parameters of BAL QSOs. Optical spectral monitoring as well as observations in other bands – in particular, in the far-ultraviolet with the *Hubble Space Telescope* – are highly desirable if we want to refine our ideas of the physics of the inner regions of these AGN.

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