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# C IV ABSORPTION IN THE HIGH-REDSHIFT BL LAC OBJECT 0215+015. II. NEW OBSERVATIONS AT 20 km s$^{-1}$ RESOLUTION

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## ABSTRACT

We present high-resolution observations of C IV $\lambda\lambda$1548, 1550 absorption at redshifts $z_a = 1.491$, 1.549, 1.649, and 1.686 in the high-redshift BL Lac object 0215+015. At a resolution of 20 km s$^{-1}$ FWHM, most C IV lines in this object break up into multiple discrete components. Particularly complex profiles are found in the $z_a = 1.549$ and 1.649 systems which are resolved into seven and nine components, spread over 300 and 900 km s$^{-1}$, respectively. By means of a line-profile fitting technique, we have derived accurate estimates of the velocity structure and column densities in the C IV absorbing regions. We find that most components exhibit small velocity dispersions, with Doppler widths $b \leq 18$ km s$^{-1}$; in one case ($z_a = 1.686$) the dispersion is as low as $b \leq 5$ km s$^{-1}$, indicative of cool clouds ($T \leq 1.8 \times 10^4$ K) where C IV is produced primarily by photoionization. The physical parameters of the individual C IV components are broadly in agreement with those typical of clouds in the Galactic halo. We conclude that the $z_a = 1.491$ and 1.686 systems could arise in intervening field galaxies, whereas the complex systems at $z_a = 1.549$ and 1.649 would require the chance superposition of two rich galaxy clusters in line to 0215+015. The implications of this result are examined in detail, and it is concluded that such complex systems may be difficult to interpret as intervening clusters if they are shown by future work to be of common occurrence. We also consider the alternative possibility that the multiple C IV systems are formed in material associated with the BL Lac object, but draw attention to the fact that current models of intrinsic line formation cannot accommodate the high "ejection" velocities implied.

*Subject headings:* BL Lacertae objects — interstellar: matter — line profiles

## I. INTRODUCTION

The origin of the narrow metal-line systems detected in QSO absorption spectra remains uncertain, despite the intense observational efforts devoted to this problem over the past decade (e.g., Weymann, Carswell, and Smith 1981). Yet, the understanding of what might be the distinguishing features between absorption intrinsic to the QSO and that due to intervening material, presumably associated with galaxies in the line of sight, is a prerequisite to making use of absorption line data in the study of the properties and evolution of matter at large redshifts. In recent years the major advances in this field have resulted from statistical studies of large homogeneous samples of QSO spectra at medium and low resolution (e.g., Sargent *et al.* 1980; Young, Sargent, and Boksenberg 1982, hereinafter YSB; Tytler 1982). In YSB it was shown that the clouds giving rise to the C IV $\lambda\lambda$1548.188, 1550.762 systems are uniformly distributed in redshift, as expected for a random distribution of intervening galaxies in a standard Friedmann cosmological model. This same work, however, revealed that QSOs with broad absorption troughs, of which PHL 5200 is the prototype, differ in having an excess of sharp C IV lines near the emission redshift which, from statistical considerations, are likely to arise in material ejected from the QSO with velocities of up to 30,000 km s$^{-1}$.

A complementary approach to these statistical studies is to consider in detail the physical properties of the absorbing systems in cases of particular interest, using spectra obtained at much higher resolution than can be achieved in practice when dealing with large samples of data. We are currently carrying out such a program using the high-resolution facilities available at the Anglo-Australian Telescope (AAT). One of the objects singled out for detailed work is the high-redshift BL Lac object 0215+015, which is currently in a bright phase ($B \sim 14.5$–$16.5$ mag), following its discovery over a decade ago with $B \gtrsim 19.5$ mag (Bolton and Wall 1969). In our first study of 0215+015 (Blades *et al.* 1982, hereinafter Paper I) we reported that this object exhibits a rich absorption spectrum and identified four systems at redshifts $z_a = 1.254$, 1.345, 1.549, and 1.649. From a detailed study of these systems, we showed that the physical properties and chemical composition of the gas at $z_a = 1.345$ resemble very closely those typical of the interstellar medium in the halo of our Galaxy. Thus, this system is most naturally interpreted as arising in an intervening galaxy intersected at a fairly small ($\lesssim 10$ kpc) impact parameter. In contrast with the $z_a = 1.345$ system, the strongest features at $z_a = 1.549$ and 1.649 (apart from Ly$\alpha$) are the C IV doublet lines which exhibit complex profiles, with several components spanning, respectively, $\sim 260$ and $\sim 650$ km s$^{-1}$. On the basis of the complexity of the profiles, it was concluded that these C IV lines are unlikely to represent separate clouds within an individual galaxy, but could be formed either in intervening rich clusters or in ambient material swept up by a wind from the central source, as in the model of Dyson, Falle, and Perry (1980).

Since the data of Paper I were obtained, we have reobserved 0215+015 several times, capitalizing on its continuing high luminosity. Following an outburst in 1981 August, when the object reached $B \approx 14.5$ mag, we extended our spectral coverage to the ultraviolet, using both the AAT ($\lambda = 3870$–$3040$ Å) and *IUE* ($\lambda = 2000$–$3100$ Å); these data are presented in a separate paper (Blades *et al.* 1983, hereinafter Paper III). Another goal of the program was to obtain profiles of the high-redshift C IV systems at the highest resolution achievable with AAT instrumentation ($\sim 20$ km s$^{-1}$) since, even with the high resolution of the data of Paper I ($\sim 50$ km s$^{-1}$), the complex C IV profiles were not fully resolved. In this paper we report the results of these observations and consider their implications for the origin of the C IV gas.

## II. OBSERVATIONS

In Table 1 we give the journal of observations together with other data of relevance to the C IV line profiles. All the observations were carried out at the f/8 Cassegrain focus of the AAT, using the 82 cm camera on the RGO spectrograph with the UCL Image Photon Counting System (IPCS, Boksenberg 1978) as the detector. We used a red-blazed 1200 line mm$^{-1}$ grating in second order to give a dispersion of $\sim 5$ Å mm$^{-1}$ in the wavelength regions of interest. As shown in Table 1, integration times of 3.3 to 5.3 hours were required to achieve signal-to-noise ratios of $\sim 15$ in portions of the BL Lac continuum adjacent to the absorption features of interest. Individual integrations were normally 1000 s; comparison spectra of a Cu-Ar hollow cathode lamp were taken every 2000 s and were later used in the data reduction to calibrate the wavelength scale and to measure the instrumental resolution. The object was regularly beam-switched between two positions on the IPCS photocathode, with equal integration times in each, so as to be able to extract the sky background from the same IPCS channels used for recording the object-plus-sky signal. The flat-fielded, sky-subtracted, spectra were finally smoothed by applying a Gaussian filter of FWHM = 1.5 channels and normalized to the local continuum level.

Portions of the spectra showing the C IV lines of interest are reproduced in Figures 1 and 2. The instrumental resolution appropriate to each profile was deduced from measurement of the FWHM of comparison arc lines extracted, added, and smoothed in the same way as the data. The final resolution was typically 0.27

TABLE 1

JOURNAL OF OBSERVATIONS

| Start Date (UT) | $B$ (mag) | Range (Å) | Integration (s) | Counts per Channel: Object[a] | Sky + Dark | Seeing FWHM (arcsec) | Slit Width (arcsec) | C IV Complex ($z_a$) | Resolution[b] (km s$^{-1}$ FWHM) |
|---|---|---|---|---|---|---|---|---|---|
| 1981 Oct 05.6 | 15.5[c] | 4050–4183 | 12,000 | 140 | 22 | 2–3 | 0.6 | 1.686 | 20.9 |
| | | | | | | | | 1.649 | 19.4 |
| 1981 Oct 29.4 | 16.3[d] | 3852–3985 | 19,000 | 125 | 27 | 1 | 0.6 | 1.549 | 20.1 |
| | | | | | | | | 1.491 | 29–34 |
| 1982 Sep 24.6 | 15.9[c] | 3835–3989 | 16,000 | 150 | 30 | 1 | 0.6 | 1.549 | 22.0 |
| | | | | | | | | 1.491 | 23.3 |

[a] Net counts in continuum.

[b] After smoothing the data with a Gaussian filter of FWHM = 1.5 channels ($\sim 7$ km s$^{-1}$); since the instrumental profile is close to a Gaussian, corresponding values of the instrumental Doppler width $b_{\rm INSTR}$ can be obtained by multiplying the values of FWHM in the table by 0.60.

[c] AAT photoelectric photometry.

[d] RGO photographic photometry.

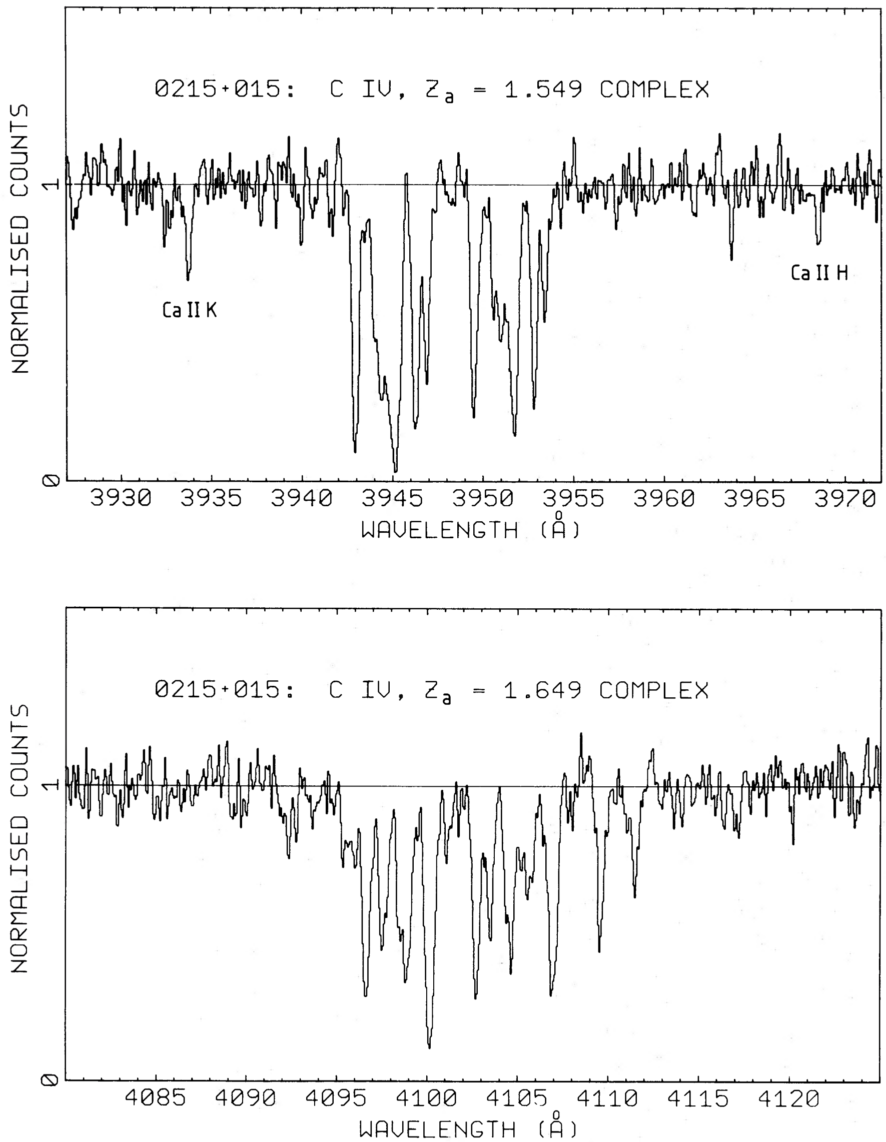


FIG. 1.—Portions of IPCS spectra showing complex absorption profiles of the C IV doublet lines (λλ1548.188, 1550.762 in the rest frame) near redshifts $z_a = 1.549$ (*top*) and $z_a = 1.649$ (*bottom*). The spectra have been normalized by dividing each raw spectrum by a smooth approximation to the continuum level. The instrumental resolution of these line profiles is approximately 20 km s$^{-1}$; other relevant data are given in Table 1. The $z_a = 1.549$ C IV data are from the 1981 Oct 29 spectrum. Also shown in the top figure are the Galactic K and H lines of Ca II λλ3933.663, 3968.468, centered at $v_{LSR} = 0$ km s$^{-1}$ with equivalent widths $W_\lambda(K) = 0.12$ Å and $W_\lambda(H) = 0.060$ Å. The profiles of these lines are well reproduced by a single absorbing cloud with Doppler width $b = 10$ km s$^{-1}$ and column density $N(Ca^+) = 1.3 \times 10^{12}$ cm$^{-2}$.

Å FWHM ( ~ 4 IPCS channels) and is given in the last column of Table 1 for each C IV system in km s$^{-1}$. The 1981 October 29 observation just encompasses the C IV system of $z_a = 1.491$ ($\lambda_{obs} = 3857$, 3863 Å); as the resolution deteriorates quickly near the limits of the spectral range, we have considered only the 1982 September 24 spectrum in obtaining the C IV profiles at $z_a = 1.491$. This latter spectrum was obtained primarily for the purpose of investigating the possibility of time variations in the $z_a = 1.549$ absorption complex, following the discovery of variability in the Fe II λλ2586, 2600 absorption in the $z_a = 1.345$ system (Hunstead *et al.* 1983). These results will be fully discussed in a forthcoming paper. The 1981 and 1982 spectra for the $z_a = 1.549$ C IV system are remarkably similar, but they have not been added here as we wish to consider data of approximately uniform signal-to-noise ratio for all the C IV lines observed.

It is instructive to compare the high-resolution spectra in Figure 1 with the corresponding profiles observed

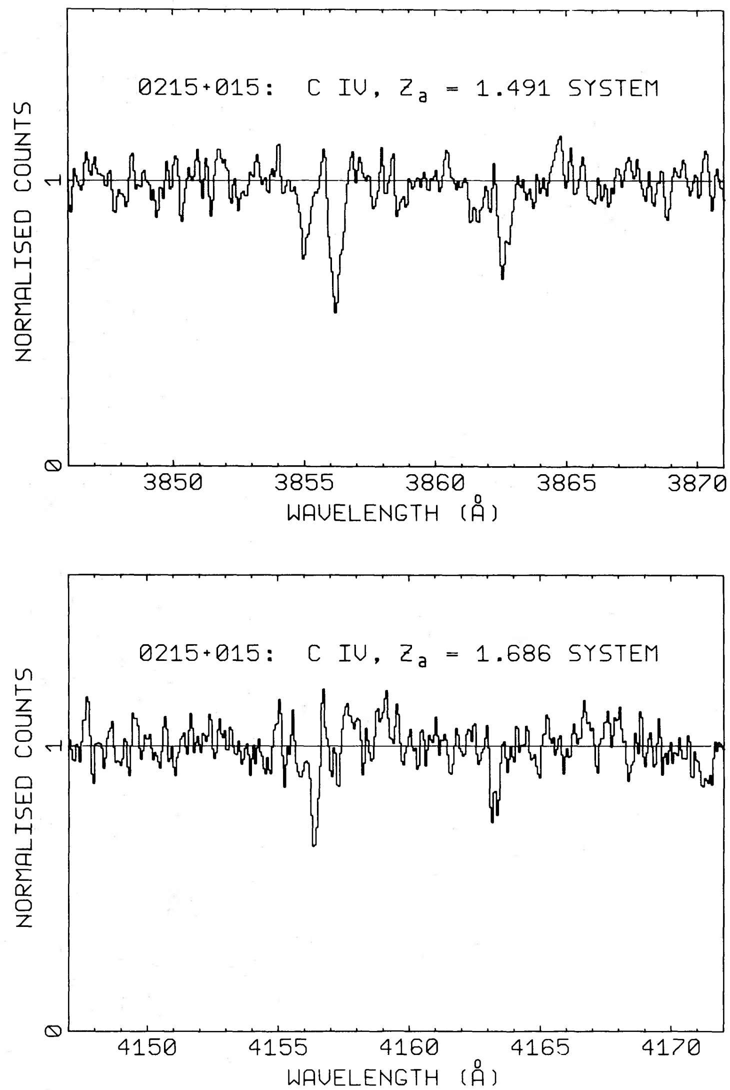


FIG. 2.—As for Fig. 1, showing C IV absorption near $z_a = 1.491$ (*top*) and $z_a = 1.686$ (*bottom*). The former is from the 1982 Sept 24 spectrum.

at medium resolution (FWHM = 1.5 Å, equivalent to ~110 km s$^{-1}$) in Paper I, as shown for the $z_a = 1.549$ C IV in the montage reproduced in Figure 3 here. The smooth appearance of the C IV doublet at 1.5 Å resolution belies a strikingly complex structure, not fully resolved even when recorded with a fivefold improvement in resolving power. Similar considerations apply to the C IV complex near $z_a = 1.649$, which exhibits even higher multiplicity. For comparison, the C IV survey of YSB was based on data at 2.5 Å resolution.

## III. ANALYSIS OF C IV ABSORPTION

In order to deduce the physical parameters characterizing the C IV absorptions, we employed a profile fitting method which has already been described in Paper I. Briefly, we assumed that the dispersion of velocities within each component of the multiple profiles is Gaussian, as observed in the local interstellar medium (Hobbs 1969; Blades, Wynne-Jones, and Wayte 1980), with Doppler parameter $b = 2^{1/2}\sigma$, where $\sigma$ is the line-of-sight component of the velocity dispersion. Thus, each component $i$ making up the complex C IV profiles is defined by the dispersion parameter $b_i$, a central relative velocity $v_i$ in the rest frame, and a column density $N_i$ of $C^{3+}$ ions. Theoretical C IV line profiles were then computed for trial sets of values of the parameters $b_i$, $v_i$, and $N_i$, and compared with the observations after convolution with the appropriate instrumental broadening function. Based on this comparison,

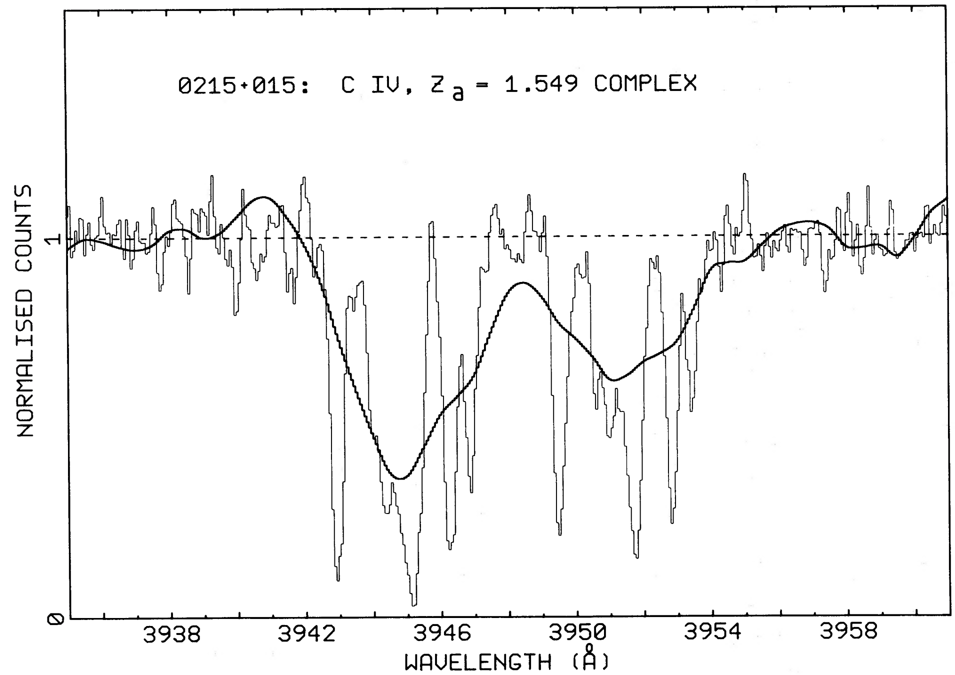


FIG. 3.—Superposition of IPCS profiles of the C IV complex near $z_a = 1.549$ observed at medium (FWHM = 1.5 Å, *thick line*) and high (FWHM = 0.27 Å, *thin line*) resolution. Medium-resolution data are from Paper I.

the parameters of the model fits were subsequently changed in an iterative process, until a satisfactory match between observed and computed profiles was obtained. Obviously, each pair of C IV doublets was fitted together, yielding self-consistent model sets of parameters. Examples of sequential trial fits are illustrated below in the context of the relevant absorption system.

In the fitting procedure, we limited the total number of components contributing to each C IV complex to be the same as the number of absorption features observed to be at least partially resolved. The zero point of the velocity scale was taken to be the central wavelength, in a heliocentric vacuum frame of reference, of the strongest well-resolved component of each C IV system. As in the work of Paper I, we constrained the dispersion parameter $b$ to the largest value compatible with the observed profiles of *both members of each* C IV *doublet*. Formally, the measured equivalent widths of the doublet lines then yield a lower limit to the column density $N(C^{3+})$, in the sense that additional C IV components of small velocity dispersion and substantial optical depth could be masked by the broader absorption features, if the former are fortuitously placed in velocity space relative to the latter (Nachman and Hobbs 1973). The parameters of the model fits to the C IV lines considered in this work are collected in Table 2, together with other relevant data. Figures 4 and 5 illustrate the comparisons between computed and observed profiles for the complex C IV systems near $z_a = 1.549$ and $z_a = 1.649$, respectively. In the top section of each figure we show separately the synthetic profiles of λ1548.188 and λ1550.762, prior to convolution with the instrumental response function, so as to point out clearly the individual components making up the composite profile. The positions of the components are indicated by vertical tick marks, labeled with the letters A to G ($z_a = 1.549$) and A to I ($z_a = 1.649$), followed by the digit 1 or 2, depending on whether the feature indicated is a component of λ1548.188 or λ1550.762, respectively. The lower portion of each figure shows the corresponding overall profile for both doublet lines, convolved with the broadening function and superposed on the observed data points, normalized to adjacent portions of the BL Lac continuum. We now discuss the model fits to the C IV systems individually.

### *a*) $z_a = 1.491$ *Complex*

These C IV lines (see Fig. 2) are well fitted by two components separated by $\sim 90$ km s$^{-1}$, with the parameters given in Table 2. Consideration of the line profiles and of the equivalent widths, which are relatively small and in a useful ratio [$W_\lambda(1548)/W_\lambda(1550) = 1.7$; see Table 2], allows accurate determination of both the column density and the Doppler parameter $b$. The low values deduced for the latter ($b = 10$–$11$ km s$^{-1}$) are directly comparable to $b = 11.8$ km s$^{-1}$, the value ex-

TABLE 2

C IV Absorption Parameters

| Redshift $z_a$ (1) | Component[a] (2) | Model Fit Parameters: $b$ (km s$^{-1}$) (3) | $v$ (km s$^{-1}$) (4) | $N(C^{3+})$ ($10^{13}$ cm$^{-2}$) (5) | Totals: $W_\lambda$ (1548)[b] (Å) (6) | $W_\lambda$ (1550[b]) (Å) (7) | $\Delta v$[c] (km s$^{-1}$) (8) | $N(C^{3+})$ ($10^{13}$ cm$^{-2}$) (9) | $N$(H)[d] ($10^{17}$ cm$^{-2}$) (10) | Averages for Complex[e]: $b$ (km s$^{-1}$) (11) | $v$ (km s$^{-1}$) (12) | $N(C^{3+})$ ($10^{13}$ cm$^{-2}$) (13) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $z_a = 1.686$ System | | | | | | | | | | | | |
| 1.68551 ... | A | 5 | 0 | 1.6 | 0.043 | 0.026: | ... | 1.6 | 1.6 | ... | ... | ... |
| $z_a = 1.649$ Complex | | | | | | | | | | | | |
| 1.64409 ... | A | 25: | −580: | 1.6: | | | | | | | | |
| 1.64694 ... | B | 15 | −257 | 6.8 | | | | | | | | |
| 1.64755 ... | C | 15 | −188.5 | 4.4 | | | | | | | | |
| 1.64810 ... | D | 8 | −126 | 2.5 | | | | | | | | |
| 1.64839 ... | E | 14 | −93 | 4.3 | ← 1.64 → | | 910 (587)[f] | 43.8 (42.2)[f] | 44 (42)[f] | 14±5 (13±3.5)[f] | 115±90 (85±35)[f] | 5±3.5 (5.5±3.5)[f] |
| 1.64921 ... | F | 18 | 0 | 13.2 | | | | | | | | |
| 1.64985 ... | G | 11 | +72 | 1.05 | | | | | | | | |
| 1.65087 ... | H | 13.5 | +188 | 6.2 | | | | | | | | |
| 1.65212 ... | I | 8 | +330 | 3.7 | | | | | | | | |
| $z_a = 1.549$ Complex | | | | | | | | | | | | |
| 1.54752 ... | A | 10 | 0 | 15.5 | | | | | | | | |
| 1.54820 ... | B | 6 | +80 | 4.2 | | | | | | | | |
| 1.54846 ... | C | 10 | +111 | 6.0 | | | | | | | | |
| 1.54871 ... | D | 12: | +140: | 3.0: | 0.890 | 0.685 | 299 | 67.2 | 67 | 10±3 | 50±25 | 9.5±6.5 |
| 1.54896 ... | E | 15 | +170 | 20.0 | | | | | | | | |
| 1.54967 ... | F | 10 | +253 | 13.5 | | | | | | | | |
| 1.55006 ... | G | 9 | +299 | 5.0 | | | | | | | | |
| $z_a = 1.491$ Complex | | | | | | | | | | | | |
| 1.49086 ... | A | 11 | −92 | 1.33 | 0.132 | 0.078 | 92 | 4.63 | 4.6 | 10.5 | 92 | 2.3 |
| 1.49162 ... | B | 10 | 0 | 3.30 | | | | | | | | |

[a] For the $z_a = 1.549$ and $z_a = 1.649$ complexes the letters identifying each component correspond to the labeling in Figs. 4 and 5, respectively.
[b] Equivalent widths in the rest frame.
[c] Total velocity range spanned by the C IV components.
[d] Lower limit to the total column density of gas implied by the C IV absorption. See text for the assumptions involved in the calculation of $N$(H).
[e] The errors quoted are the standard deviations from the mean values.
[f] Bracketed values do not include the contribution from component A.

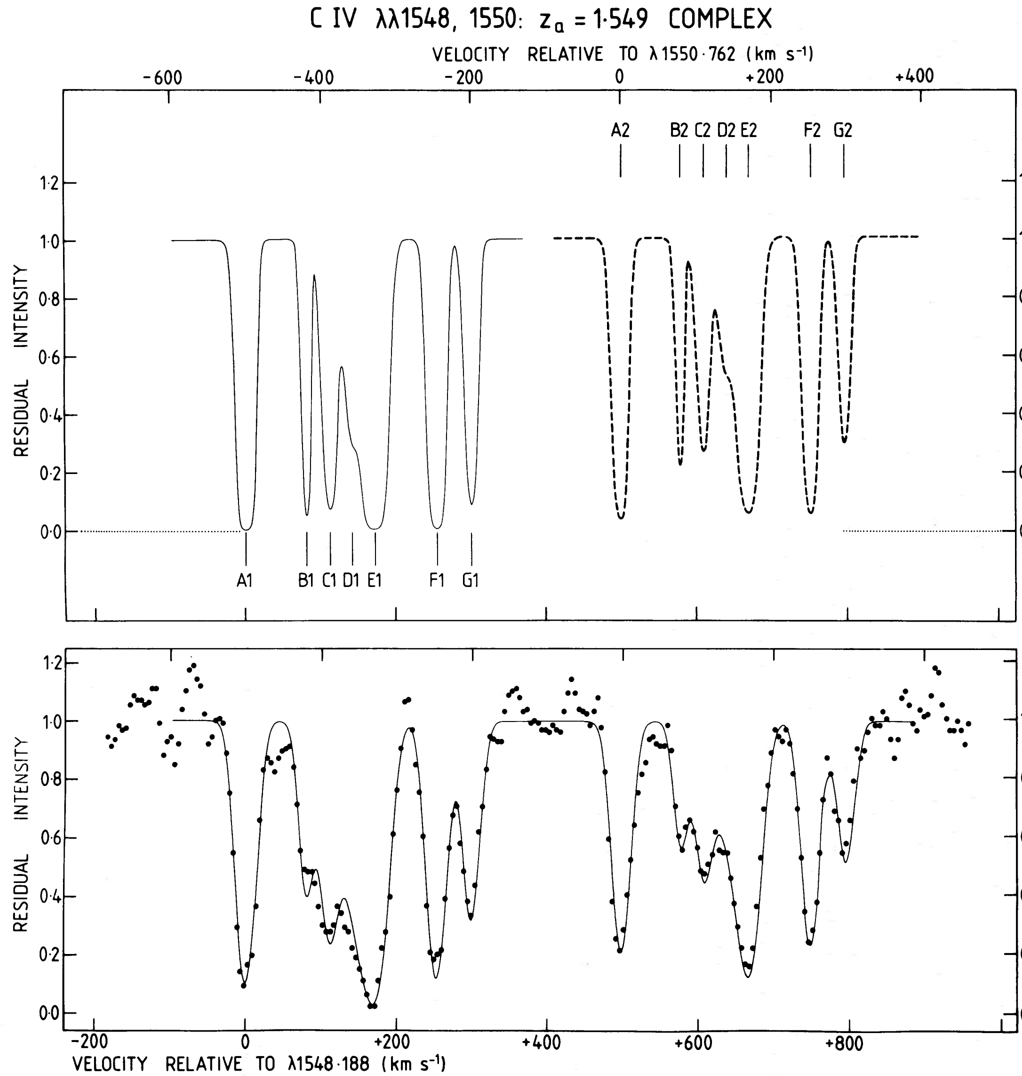


FIG. 4.—Comparison between observed and computed absorption profiles for the C IV doublet lines in the $z_a = 1.549$ complex. *Top*, intrinsic profiles of λ1548.188 (*continuous line*) and λ1550.762 (*broken line*), before convolution with the instrumental broadening function. Positions of the seven individual components making up the multiple profile are indicated by vertical tick marks, labeled A1 to G1 (λ1548.188) and A2 to G2 (λ1550.762). *Bottom*, the overall profile of C IV λλ1548.188, 1550.762, including broadening by the instrumental resolution (*continuous line*), is compared with the observed data points (*dots*) normalized to the local continuum.

pected from thermal broadening alone at $T = 10^5$ K, the temperature at which the fractional abundance of $C^{3+}$ peaks under equilibrium conditions in a collisionally ionized gas ($C^{3+}/C_{TOT} = 0.27$, Shapiro and Moore 1976). This upper limit to the fraction of carbon which could be present as $C^{3+}$, together with the assumption of solar abundance ($C/H = 3.7 \times 10^{-4}$, Snow 1980), leads to the lower limit $N(H) \geq 4.6 \times 10^{17}$ cm$^{-2}$ for the total column density of hydrogen in the $z_a = 1.491$ complex. Values of $N$(H) derived under these assumptions are given in column (10) of Table 2 for each C IV system. Similar lower limits would obtain if the observed C IV is produced primarily by photoionization in cool clouds, rather than by collisional ionization in a hot medium (McKee, Tarter, and Weisheit 1973), as discussed below for the $z_a = 1.686$ system.

### b) $z_a = 1.549$ Complex

As shown in Figure 4, seven components are required to fit the C IV lines in this system. The seven components span ~ 300 km s$^{-1}$, so that blending between λ1548.188 and λ1550.762 features (separated by 499 km s$^{-1}$) is not a problem. A minimum of four components (B to E) is necessary to reproduce the absorption

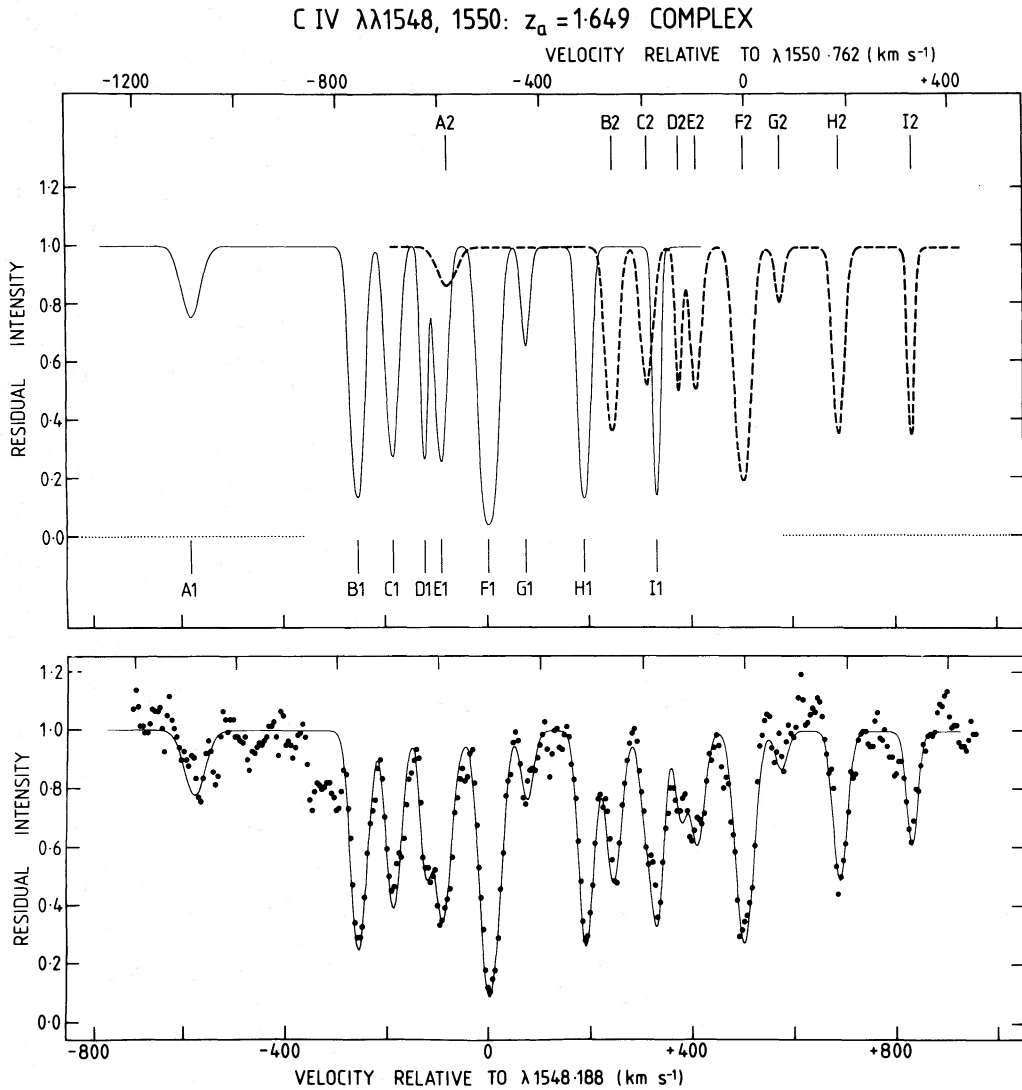


FIG. 5.—Comparison between observed and computed absorption profiles for the C IV doublet lines in the $z_a = 1.649$ complex. The symbols and lettering have the same meaning as in Fig. 4.

profile between $v \approx +50$ and $v \approx +200$ km s$^{-1}$; the reality of component D is supported by the observed asymmetries of the blue wings of the corresponding features in both λ1548 and λ1550. However, since component D is not resolved, the corresponding parameters are of necessity less certain than is generally the case; at still higher resolution this whole group (B to E) may well break up into more than four components. Note that all the components in this complex are extremely narrow, with $b$ values (see Table 2) comparable to that of the instrumental function ($b = 12.1$ km s$^{-1}$). Nevertheless, the relative strengths of doublet members are useful indicators of both $b$ and $N(C^{3+})$ since the individual lines are not heavily saturated. We illustrate this in Figure 6, with an example of the sensitivity of the fit to variations in $b$ and hence $N(C^{3+})$ for component F. The λ1548 absorption line (F1, *top row* of Fig. 6) is saturated and allows a wide range of solutions. However, only $b$ values between 9 and 11 km s$^{-1}$ are consistent with the profile of the weaker λ1550 line (F2, *bottom row* of Fig. 6), indicating that the column density probably lies in the range $1.8 \times 10^{14}$ cm$^{-2} \geq N(C^{3+}) \geq 1.2 \times 10^{14}$ cm$^{-2}$. Conservatively, we can state that the column densities given in Table 2 for components of the $z_a = 1.549$ complex are unlikely to be in error by more than a factor 2 on the basis of extensive trial fits with extreme values of the model parameters. It is instructive to note that the total column density we now measure, $N(C^{3+})_{TOT} = 6.72 \times 10^{14}$ cm$^{-2}$, is only ~ 70% greater than the value deduced in Paper I from spectral data at ~ 50 km s$^{-1}$ resolution, although in the earlier profiles we only resolved three components.

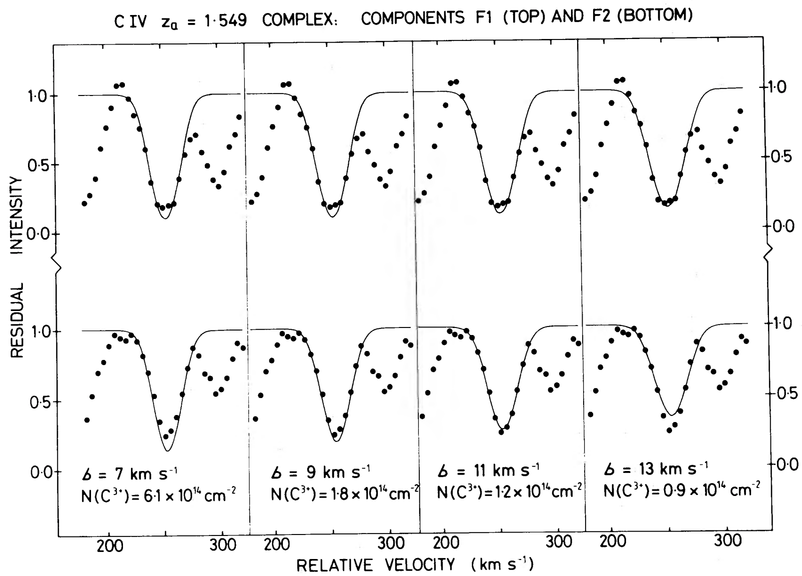


FIG. 6.—Examples of sequential attempts at fitting the profiles of component F in the λ1548 (*top*) and λ1550 (*bottom*) lines of the $z_a = 1.549$ complex, showing the sensitivity of the fitting procedure to the model parameters. *Dots*, observed data points, corresponding to sections of the line profiles enlarged from Fig. 4; the continuous lines show theoretical profiles computed with different values of the velocity dispersion parameter $b$, as indicated. The measured equivalent widths of the λ1548 and λ1550 lines fix the column density of $C^{3+}$ ions to the values given at the bottom. The high resolution and signal-to-noise ratio of the data allow an accurate determination of both $b$ and $N(C^{3+})$.

### *c*) $z_a = 1.649$ *Complex*

From Figure 5 it can be seen that nine components, ranging from $v = -580$ to $+330$ km s$^{-1}$, are indicated by this extremely complex C IV profile. The wide velocity span of the absorption leads to some overlap between λ1548 and λ1550 lines; at this high resolution, however, the relevant features can be deblended without difficulty. The feature labeled A1 is only marginally stronger than the noise, but its reality is supported by the failure of D1 and E1 to reproduce the red wing of the observed profile without component A2 (see Fig. 5). Nevertheless, the parameters quoted for component A are considered uncertain. Conversely, the unlabeled feature immediately to the blue of B1 ($\lambda^{\rm helio}_{\rm VAC} = 4097.03$ Å), although of comparable strength to A1, is not matched by a corresponding λ1550 component; its identification as C IV λ1548 is therefore rejected. Apart from these uncertainties, the parameters of the remaining components are well determined. In general, the components of the $z_a = 1.649$ complex tend to be broader and less saturated than those near $z_a = 1.549$, and have $b$ values often greater than that of the instrumental response ($b = 11.7$ km s$^{-1}$), as can be seen from inspection of Table 2. Consequently, we estimate that the values of $N(C^{3+})$ given in Table 2 are unlikely to be in error by more than 50%, this being a conservative upper limit. In the example given in Figure 7, the profile of component H1 by itself constrains $b$ to the range 13–15 km s$^{-1}$, corresponding to a well-determined column density $N(C^{3+}) = (6.0 \pm 0.5) \times 10^{13}$ cm$^{-2}$. Consideration of the profile of component H2 (not shown in Fig. 7) favors $b = 13.5$ km s$^{-1}$ and $N(C^{3+}) = 6.2 \times 10^{13}$ cm$^{-2}$. Apart from component A, which may well be multiple, we suspect that we have now fully resolved most of the components of this C IV complex. This is suggested by the symmetry of the individual line profiles, the satisfactory model fits, and the fact that the mean separation between adjacent components ($\Delta v$ in Table 2) is several times the resolution of the data (Bahcall 1975), whether component A is included in the average or not. Overall, there is good agreement with the earlier analysis of this complex in Paper I, and although the $b$ values of most components were clearly overestimated in fitting profiles observed with the coarser resolution, the total column density we now derive, $N(C^{3+}) = 4.38 \times 10^{14}$ cm$^{-2}$ is only 30% greater than the earlier estimate.

### *d*) $z_a = 1.686$ *System*

This is a newly discovered system identified by a broad Lyα line at $\lambda = 3266.13$ Å and a weak C IV doublet (shown in Fig. 2) which corresponds to a feature in the blue wing of Lyα (Paper III). The C IV lines are very narrow; the best fit to both lines is obtained with $b = 3$ km s$^{-1}$ and $N(C^{3+}) = 2.8 \times 10^{13}$ cm$^{-2}$. However, since λ1550 appears to be affected by noise, we prefer the more conservative upper limit $b \leq 5$ km s$^{-1}$, corresponding to $N(C^{3+}) \geq 1.6 \times 10^{13}$ cm$^{-2}$, derived from consideration of the profile of λ1548 alone. This is a remarkably low velocity dispersion, implying an upper

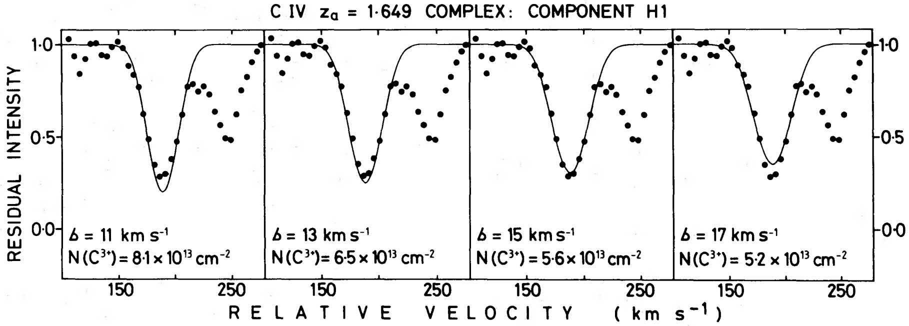


FIG. 7.—Sequential attempts at fitting the profile of component H in the λ1548 line of the $z_a = 1.649$ complex, showing the sensitive dependence of the fit on the value of the velocity dispersion parameter $b$. This constrains the column density $N(C^{3+})$ to a narrow range of values. The symbols have the same meaning as in Fig. 6.

limit to the temperature of the gas $T_U = 1.8 \times 10^4$ K, on the assumption that the broadening of the lines is due to thermal motions alone ($kT_U = \frac{1}{2}mb^2$). This result strongly suggests that the C IV at $z_a = 1.686$ is produced by photoionization in cool clouds. Calculations of steady-state ionization balance (Shapiro and Moore 1976) show that essentially no C IV is produced by collisional ionization at the above temperature ($C^{3+}/C_{TOT} \ll 0.001$). It is worth noting that the above value of $T_U$ is close to $T_U = 1.7 \times 10^4$ K deduced for a weak member of the Lyα forest in PHL 957, also from consideration of the line width (Chaffee *et al.* 1983). As these authors point out, such a low kinetic temperature requires efficient cooling, implying that the Lyα cloud in question either is of a high density or consists of processed rather than primordial material. The discovery of weak and narrow C IV lines associated with the $z_a = 1.686$ Lyα line in 0215+015 tentatively supports the latter conclusion. However, it is not clear at present what proportion of the "Lyα only" systems would show corresponding weak metal lines when observed at sufficiently high resolution and signal-to-noise ratio.

## IV. DISCUSSION

In this section we consider the alternative possibilities that the observed C IV absorption lines are formed in intervening galaxies in the line of sight to 0215+015, at the distances implied by their redshifts, or in material in the immediate environment of the BL Lac object. Two points are noteworthy in the context of this discussion:

i) From the work of Paper I, we note that in the redshift interval $\Delta z \approx 0.7$ we have detected three C IV systems which would qualify for inclusion in the YSB sample ($z_a = 1.254$, 1.549, 1.649). The implied line density per unit redshift, $n = 4.3$, is greater than, but not inconsistent with, the mean value, $n = 1.49 \pm 0.29$, appropriate to the 33 QSOs forming the YSB sample. In particular, one member of this sample has $n = 4.2$, and two others have $n = 3.5$. Considering that our attention was drawn to 0215+015 because of its very rich absorption spectrum, it is not surprising to find that the density of strong C IV systems is near the upper end of the range appropriate to the unbiased YSB sample.

ii) As argued in Paper III, the redshift of 0215+015 is likely to be $z \sim 1.7$, on the basis of the highest absorption redshift detected ($z_a = 1.719$) and the number of single Lyα lines present. A useful lower limit to the redshift is obtained by assuming that the velocity of the $z_a = 1.719$ system relative to the BL Lac nucleus is at most $-4000$ km s$^{-1}$, the highest "infall" velocity detected in surveys of systems with $z_a > z_{em}$ (Weymann *et al.* 1979; Sargent, Young, and Boksenberg 1982). The lower limit $z_{0215+015} > 1.683$ then implies "ejection" velocities $v_e > -280$, $+3800$, $+15{,}520$, and $+22{,}220$ km s$^{-1}$ for the $z_a = 1.686$, 1.649, 1.549, and 1.491 systems, respectively. These lower limits are compatible with the range of ejection velocities appropriate to the narrow absorption lines crowding near the emission redshift in QSOs with broad absorption troughs (YSB).

From the above two points we conclude that the *distribution of redshifts* in 0215+015 is consistent with either the intervening or the intrinsic interpretation.

### *a*) *Intervening Galactic Halos*

C IV gas is an important and pervasive constituent of the interstellar medium in galactic halos, as indicated by the large body of relevant *IUE* data now available (see York 1982 and references therein). In Paper I, we showed that the physical properties of the gas at $z_a = 1.345$ in 0215+015, including C IV, are very similar to those typical of the Milky Way halo in the direction of the Large Magellanic Cloud. More recently, Pettini and West (1982) have published the results of a large-scale survey of C IV absorption in the inner regions of the Galactic halo. This study has revealed that within ~ 3 kpc of the disk, $N(C^{3+})$ is typically in the range $1.5 \times 10^{13}$ to $3 \times 10^{14}$ cm$^{-2}$. At the spectral resolution of *IUE* (~ 25 km s$^{-1}$), which is comparable with that of the present data, C IV lines formed within this distance are normally single, with velocity dispersion parameters $b \lesssim 20$ km s$^{-1}$. Thus, the column densities and velocity widths of the *individual* C IV components in the high-redshift systems listed in Table 2 are clearly in good agreement with the values appropriate to C IV lines formed over pathlengths of a few kpc through galactic halos similar to that of our Galaxy, as viewed from the Sun. The low values of $b$ deduced for some of the components, indicative of gas temperatures below $T \sim 10^5$ K, are not incompatible with a halo origin, and indeed photoionization by the integrated QSO radiation field has been proposed as a major mechanism for the production of high ionization species in the Galactic halo (York 1982; Fitzpatrick and Savage 1983; Hartquist, Pettini, and Tallant 1983). Furthermore, studies of the distribution of gas away from the Galactic plane (Pettini and West 1982; Pettini *et al.* 1982; York *et al.* 1982; de Boer and Savage 1982) suggest that the shape of the halo is likely to be highly oblate, with the C IV gas extending at most to a few kpc from the plane, but probably covering a wide area of the disk. On the basis of this evidence, we expect that a typical line of sight through galactic halos similar to that of the Milky Way will produce C IV absorption lines consisting of two or more components with parameters comparable to those of Table 2, given that in general a line of sight through a galaxy will sample longer path lengths than those studied with *IUE* from the Sun's location (see also Fig. 5 of Weisheit and Collins 1976). This conclusion is supported by our results for 0215+015: of all the C IV systems which we have detected with spectral resolutions of 20 km s$^{-1}$ (this paper) and 50 km s$^{-1}$ (Paper I), at $z_a = 1.254$, 1.345, 1.491, 1.549, 1.649, and 1.686, only the last one, which is also the weakest, does not exhibit multiple structure.

While the characteristics of the C IV systems at $z_a = 1.491$ and $z_a = 1.686$, as summarized in Table 2, can be understood in terms of single intervening galaxies, the multiple structure and wide velocity range of the complex C IV lines near $z_a = 1.549$ and $z_a = 1.649$ require, in the context of the intervening hypothesis, the presence of rich clusters of galaxies in line to 0215+015. Intervening clusters have been invoked in at least two other cases as the most plausible interpretation of highly complex C IV systems analogous to those considered here. At 40 km s$^{-1}$ resolution the C IV at $z_a = 1.79$ in the QSO B2 1225+317 ($z_{\rm em} \approx 2.2$) exhibits five components spanning $\sim 400$ km s$^{-1}$ (Pettini *et al.* 1983); an origin in material intrinsic to the QSO would in this case imply exceedingly high ejection velocities ($v_e \approx 41{,}000$ km s$^{-1}$). The $z_a = 1.97$ complex in Q0119−046 ($z_{\rm em} = 1.937$) spans 1090 km s$^{-1}$, showing at least four components at 50 km s$^{-1}$ resolution (Sargent, Young, and Boksenberg 1982); the line profiles indicate that several more components may in fact contribute to the absorption lines. The implied "infall" velocities relative to the QSO are in the range 2780 km s$^{-1}$ $\leq v \leq$ 3870 km s$^{-1}$. It is difficult to understand these negative velocities in terms of ejected material, unless the emission lines are significantly blueshifted relative to the underlying structure, as recently suggested by Gaskell (1982, 1983); consequently Sargent, Young, and Boksenberg favored a collapsing rich cluster of galaxies, of which the QSO is a member, as the most likely site for the complex C IV absorption. Returning to the $z_a = 1.549$ and 1.649 complexes in 0215+015, we note further that the velocity spread of the components ($\Delta v \approx 300$ km s$^{-1}$ and 900 km s$^{-1}$, respectively) is somewhat smaller than expected from consideration of the velocity dispersions of rich clusters of galaxies ($\sigma_v = 600$–1500 km s$^{-1}$, Bahcall 1981). We feel, however, that this is not a serious difficulty, in view of the large scatter in the measured values of $\sigma_v$ and the fact that, in the context of the intervening cluster explanation, the C IV systems would be due to only three or four galaxies and are therefore unlikely to sample the full velocity dispersion of the cluster.

We have attempted to determine the likelihood of this interpretation using as a test case the Coma Cluster, for which both the luminosity function and the projected density of galaxies as a function of distance from the cluster center have been measured (Godwin 1976; Abell 1977). In the calculation, we have followed Sargent *et al.* (1979) in assuming that galactic dimensions scale with luminosity according to the relation (Holmberg 1976):

$$R/R_\star = (L/L_\star)^{5/12}, \qquad (1)$$

where $R_\star$ is the radius of a galaxy of fiducial luminosity $L_\star$, corresponding (Schechter 1976) to:

$$M^\star_{B(0)} = -19.1 + 5 \log h_{100}, \qquad (2)$$

where $h_{100} = H_0/100$. Assuming that $R_\star = 44 h_{100}^{-1}$ kpc, derived from the observed density of QSO C IV systems at $\langle z \rangle = 1.71$ (YSB), is applicable to galaxies of luminosity $L_\star$ in the Coma Cluster, we have calculated, as a function of distance from the cluster center, the corresponding average number of galactic halos overlapping in projection. Since only galaxies brighter than $V_{25} = 17.5$ were included in the measurements by Godwin (1976) of galaxy number density versus distance from the cluster core, we have repeated the above calculation twice, using the luminosity function to estimate correction factors appropriate to limiting magnitudes $V_{25} = 18.5$ and $V_{25} = 19.5$, assuming no mass segregation. For $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$, these limiting magnitudes correspond respectively to absolute magnitudes $M_v = -16.9$ (comparable to the SMC), $-15.9$, and $-14.9$ (comparable to the dwarf irregular galaxy IC 1613 in the Local Group).

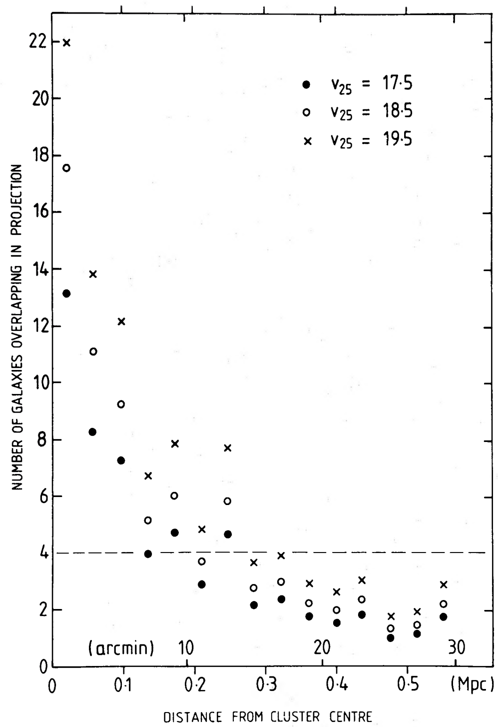


FIG. 8.—The estimated number of galactic halos which would overlap in projection in a cluster as rich as Coma is plotted as a function of radial distance from the cluster center, assuming $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$. See text for other assumptions entering the calculation. The different symbols correspond to different limiting magnitudes in the counts of galaxy density, according to the key in the top right-hand corner ($V_{25}$ is the galaxy $V$ magnitude measured within the 25 mag arcsec$^{-2}$ isophote). Depending on the limiting magnitude, impact parameters of 0.22–0.35 Mpc would be expected to intersect four galaxy halos on average (*broken horizontal line*), as required to account for the level of multiplicity of the complex C IV systems.

From inspection of Figure 8, and assuming two C IV components per galaxy, as argued earlier, it appears that we can account for the observed multiplicity of the $z_a = 1.549$ and $z_a = 1.649$ C IV complexes (seven and nine components, respectively) with a line of sight intersecting a cluster as rich as Coma within ~ 0.22 Mpc of the cluster center for $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$. Clearly, the impact parameter required depends on the limiting magnitude of the galaxy counts: if the extension of our calculation to $V_{25} = 19.5$ is valid, a line of sight passing within ~ 0.35 Mpc of the cluster center can still account for the complexity of the high-redshift C IV absorption.

A possible objection to this line of reasoning is that the Coma Cluster, used here as a convenient example, is known to exhibit a large fraction of H I–deficient spirals (Sullivan and Johnson 1978; Bothun, Schommer, and Sullivan 1982*b*; Chincarini, Giovanelli, and Haynes 1983). However, the question of whether clusters in general tend to contain gas-deficient spirals is not yet clear, owing primarily to difficulties in measuring galaxy gas deficiencies reliably (see Giovanelli, Haynes, and Chincarini 1982; Bothun, Schommer, and Sullivan 1982*b*). Theoretically, current ideas on cluster development (Sarazin 1979) suggest that processes leading to gas stripping in cluster spirals may be most efficient in a relatively late and short-lived stage in the cluster evolution. This is to some degree borne out by the existence of X-ray coronae (Bechtold *et al.* 1983) and H I–rich galaxies (Bothun, Schommer, and Sullivan 1982*a*) in clusters with morphologies suggestive of dynamically unrelaxed, young structures. Thus, it is reasonable to assume that at epoch $z = 1.6$ most clusters would not yet be virialized and that member galaxies would retain substantial fractions of their interstellar media.

A more serious difficulty with ascribing the complex C IV systems to intervening rich clusters is posed by the fact that clusters as rich as Coma (richness class 3, Mottmann and Abell 1977) are quite rare (Abell 1958; Dressler 1980) and that the probability of intersecting the central regions of two clusters of this kind is very small at the present epoch. While several cases of overlapping clusters are known (Richter and Huchtmeier 1982; Lucey 1983 and references therein), the clusters involved are only moderately rich, with densities of galaxies which are apparently insufficient to account for the extreme multiplicity of the C IV systems near $z_a = 1.549$ and 1.649. For example, from the galaxy counts in the Hydra I cluster ( = Abell 1060) by Smyth (1980), which include all galaxies with $V_{25} \leq 17$, corresponding to $M_v = -15.7$ if $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$ (Richter, Materne, and Huchtmeier 1982), we estimate that a line of sight through the center of the cluster would on average intersect only two galactic halos. Clearly, then, the two outstanding questions are: (i) How common are highly complex absorption systems of the type found in 0215+015? (ii) What is the low-luminosity limit of relation (1) above, as far as C IV–producing halos are concerned? If dwarf galaxies with $M_v \geq -15$ possess extensive, metal-rich, gaseous halos, we would expect, on the basis of known cluster luminosity functions, considerably higher probabilities of intersecting several C IV regions than predicted above. If this is indeed the case, medium richness clusters, or the outer regions of rich clusters, would be sufficient to produce the observed C IV component multiplicities, thus greatly enhancing the probability of intersecting such concentrations of galaxies in a random line of sight. Available 21 cm data show that low-luminosity, late-type galaxies both in the field (Huchtmeier and Richter 1982) and in clusters (Bothun, Schommer, and Sullivan 1982*a*), do indeed exhibit extended H I distributions, often to several Holmberg radii. However, we are still ignorant with regard to both the metal content of these extended gaseous envelopes and the limit in luminosity and Hubble type of the parent galaxies.

Finally we recall that direct evidence for high-redshift absorption arising in cosmologically intervening material has recently been provided by observations of close QSO pairs (Shaver, Boksenberg, and Robertson 1982; Shaver and Robertson 1983; Robertson and Shaver 1983, private communication). Three examples are now known where absorption in the higher-redshift member of a pair occurs at a redshift close to the emission redshift of the other member. In each case the projected separations and the velocity differences are consistent with the absorption occurring in an intervening galaxy in a moderately rich cluster of which the lower-redshift QSO is also a member. Alternatively, the absorption could arise in a very extended ($d \sim 0.5$–$1 h_{100}^{-1}$ Mpc) gaseous halo associated with the lower-redshift QSO. However, in the case of Q0307−195AB (Shaver and Robertson 1983), an *additional* absorption system, well removed from the emission redshifts of the pair, is common to both QSOs (the velocity difference of the absorption seen in the two spectra is $\Delta v \approx 300$ km s$^{-1}$). The most natural interpretation is that this absorption system is due to two foreground galaxies belonging to the same cluster.

### *b*) *Intrinsic Origin*

As mentioned earlier, QSOs with very broad absorption lines have been found to show an excess of sharp C IV lines near the emission redshift (YSB), with velocities relative to the QSO within the range covered by the broad absorption troughs ($v \lesssim 0.1c$). As the latter are most naturally interpreted as material outflowing from the central source (Drew and Giddings 1982), an intrinsic origin appears likely for the narrower features too. At intermediate resolution ($\sim 2$ Å) these typically show widths of a few hundred km s$^{-1}$, although at present relevant data are available for only few objects (Boksenberg *et al.* 1978; Clowes *et al.* 1979; YSB). Thus, it is possible that the unusually wide C IV lines at $z_a = 1.549$ and $z_a = 1.649$ in 0215+015 are due not to the chance superpositions of several galaxies in line of sight, but to a mechanism which produces intrinsically complex absorption features in material associated with the BL Lac object. Clearly, this question is best addressed by comparing the data considered here with similar resolution profiles of the C IV lines in trough QSOs. We are currently carrying out such a study using AAT spectra of the trough QSO 1309−056 at 40 km s$^{-1}$ resolution. A preliminary analysis of the absorption systems occurring close to the emission lines in this object has revealed a higher degree of multiplicity than is the case in 0215+015, with the C IV lines breaking up into more than 12 components spanning more than 1300 km s$^{-1}$. These extremely complex systems mostly exhibit a high degree of ionization, with strong N V $\lambda\lambda$1238.808, 1242.796, as found in general for systems with $z_a \approx z_{\rm em}$ (Weymann *et al.* 1979), but contrary to the situation common for systems with $z_{\rm em} - z_a > 0.1c$ and for the Galactic halo (York 1982). However, less complex and less highly ionized systems, more closely resembling the $z_a = 1.549$ and $z_a = 1.649$ complexes in 0215+015, also appear to be present. Clearly, a great deal of work is still required, particularly on QSOs with broad absorption troughs, before the sharp lines seen in the latter can be related to other classes of QSO absorption lines.

In Paper I we pointed out that the properties of the complex C IV systems in 0215+015, particularly $z_a = 1.649$, are in broad agreement with the predictions of the ejection model of Dyson, Falle, and Perry (1980). This work considers the formation of a thin, cool shell of gas behind the shock front produced by a hypersonic QSO wind acting on the ambient material. The authors propose the swept-up shell as a possible site of some QSO absorption systems. In a later paper (Falle, Perry, and Dyson 1981) it is shown that the thin shell can be accelerated by radiative driving; radiatively driven instabilities within the shell could then lead to fragmentation into narrow components of width $\sim 20$ km s$^{-1}$. This is also a typical width for C IV clouds in the Galactic halo; therefore, in principle, the two cases are hard to distinguish, at least on kinematical grounds. However, a major problem is that only relatively low velocities are attainable with this model, which is limited to the case of the flow remaining optically thin in the continuum. Falle, Perry, and Dyson estimate that under the most favorable conditions, which include a central source with a flat spectrum (spectral index $\alpha = 0.5$, where $f_\nu \propto \nu^{-\alpha}$), a maximum velocity of $\sim 3000$ km s$^{-1}$ can be achieved. Clearly then, the model cannot account for the high velocities implied by the $z_a = 1.549$ and $z_a = 1.649$ systems ($v_e > 15{,}520$ and 3800 km s$^{-1}$) relative to 0215+015, which is a steep-spectrum source ($\alpha = 1.8$; Paper I). While the basic ideas of the model may still be valid, the analysis developed in Falle, Perry, and Dyson (1981) is not directly applicable here.

## V. CONCLUSIONS AND FUTURE WORK

We have shown that highly complex C IV systems as observed in 0215+015 could be formed by intervening rich clusters of galaxies, provided that (*a*) systems of such complexity are not common and (*b*) at early epochs cluster galaxies of low luminosity possess metal-rich halos with properties broadly consistent with those of the halo of our Galaxy. Clearly it is important to test both these points. The statistics of the multiplicity of C IV systems in QSOs can be investigated with present means, although such a program will require a generous allocation of observing time on a large telescope. On the other hand, the question of the extent and metallicity of gaseous halos of dwarf galaxies, both in the field and in clusters, can only be properly addressed with Space Telescope observations, although preliminary ground-based work utilizing the Ca II lines would be valuable. We have also emphasized the importance of studying in detail the characteristics of narrow absorption systems in QSOs showing evidence of mass outflow, so as to establish whether or not these systems can be distinguished physically from other classes of QSO absorption lines, and whether they are peculiar to QSOs with broad absorption troughs. If the high-redshift systems in 0215+015 were intrinsic to the BL Lac object, their apparent similarity to C IV clouds in galactic halos would seriously limit the usefulness of QSO absorption lines as probes of the early universe.

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