The Astrophysical Journal, 397:81–87, 1992 September 20

BROAD ABSORPTION-LINE TIME VARIABILITY IN THE QSO CSO 203

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Received 1991 November 25; accepted 1992 March 23

ABSTRACT

We present spectroscopy of the BALQSO CSO 203 during four epochs over a 17 month time span. These data show three distinct levels in the broad absorption lines (BALs) of Si IV λ1397 and C IV λ1549. We also note possible variations in the N V λ1240 and Al III λ1857 absorption troughs. A broad-band monitoring effort during this period shows that the continuum level remained constant to within 10%. We argue that the triggering mechanism for the absorption-line changes is most likely synchronous with the continuum source photons; however, no correlation with the central source has yet been found. The observed variations are consistent with changes in the ionization level in the broad absorption-line region (BALR). We discuss possible mechanisms for these changes and the implications for the structure of the BALR.

Subject headings: quasars: absorption lines — quasars: individual (CSO 203)

1. INTRODUCTION

It is estimated that about 12% of all QSOs with redshifts larger than 1.5 exhibit broad absorption lines (BALs) (Weymann et al. 1991). These lines indicate that highly ionized gas is flowing away from the central source at speeds from 0 to 0.1*c*. Although this gas is believed to be intrinsic to the environment of the QSO, its location and geometry relative to the continuum source and the broad emission-line region (BELR) is still uncertain. Nor is it certain whether broad absorption-line regions (BALRs) are unique to BALQSOs or whether all QSOs have BALRs and the 12% occurrence rate coincides with the mean fraction of sky covered by the BALR as seen from the central source.

Time variability of BALs has been previously noted in four BALQSOs: Q1303+308 (Foltz et al. 1987), Q1413+117 (Turnshek et al. 1988), Q1246−057 (Smith & Penston 1988), and UM 232 (Barlow, Junkkarinen, & Burbidge 1989, hereafter BJB). There are several mechanisms that could produce the observed variability in the absorption troughs. The data so far do not appear to favor any particular mechanism.

Other AGN absorption-line variability has been reported in three Seyfert galaxies: NGC 4151 (Clavel et al. 1987), NGC 3516 (Voit, Shull, & Begelman 1987), and Markarian 231 (Boroson et al. 1991). In the first two cases the absorption redshifts are within 1000 km s^{-1} of the emission redshifts, while in Mrk 231 the absorption-line outflow velocities range from about 4000 to 8200 km s^{-1} which is more typical of the BALs seen in high-redshift BALQSOs. As Boroson et al. point out, Mrk 231 is probably a heavily obscured low-ionization BALQSO, and the changes observed are likely attributable to a BAL cloud with significant transverse velocity crossing the line of sight to the continuum. This phenomenon may be quite different from the changes for the four BALQSOs and for CSO 203.

Smith & Penston (1988) suggest that continuum fluctuations drive the BAL time variability observed in Q1246−057. Changes in ionizing flux will produce changes in ionization if the BALR is photoionized by the continuum source. Unfortunately, for the 1977–1984 changes in Q1246−057, there was no photometry to correlate with the absorption changes. Normally, variations at a given outflow velocity would be expected in each absorption trough observed. However, the change seen in the Si IV λ1397 BAL and the change seen in C IV λ1549 BAL occurred at two different velocities (Smith & Penston 1988). It is possible that some of the changes at the corresponding outflow velocities were unobservable because the absorption was too weak or too strong to produce large changes in residual intensity. Also, if an ion is near its peak of fractional abundance (see discussion below), it may show little or no change. If continuum fluctuations were responsible for BAL changes, the data could be used to measure the ionization parameter.

In BJB, large changes were found in both the Si IV and C IV absorption in the BALQSO UM 232 (0019+011) across a wide range of velocities in the absorption troughs. These changes were correlated with an increase in brightness, and it was argued that this was an example of a BALR responding to continuum variability. However, recent observations of UM 232 make this simple connection between the UM 232 BAL changes and the continuum variability less certain. One prediction of the photoionization-driven model is that if the continuum level decreases back to the original level, the absorption troughs should change back to their original depths. Photometry shows that UM 232 is again near its prechange brightness, while spectroscopy shows that the absorption troughs have not reverted back to their original depths (Barlow, Junkkarinen, & Burbidge 1992).

In this paper we present data on another BALQSO that shows time variability. CSO 203 (0842+345, $z_e \simeq 2.13$, $V \simeq 17.1$) was recently confirmed as a BALQSO by Thompson, Djorgovski, & Weir (1989). Our spectroscopic data show significant changes in the C IV and Si IV broad absorption lines over the entire velocity range of the troughs. Between 1989

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November and 1991 February three distinct levels have been observed in both these lines, suggesting a progressive process acting within the BALR. These are the first observations of BAL variations over more than two epochs and over a relatively short time scale (2.5 months in the observed frame). Broad-band imaging data over the same time period indicates that the visual continuum level (near the rest wavelengths of 1600–2300 Å) remained approximately constant (within 10%). Although the data do not easily fit the simplest continuum source–driven photoionization model, they do suggest some constraints on possible mechanisms for changes and the implications those mechanisms would have on the nature of the BALR. We present our observations of CSO 203 in § 2, analysis in § 3, discussion in § 4, and a summary of BALQSO variability in § 5.

2. OBSERVATIONS

Spectral data of CSO 203 were taken with the Lick Observatory 3 m Shane Telescope in 1989 November, 1990 November, 1991 February, and 1991 April. For convenience, we shall refer in this paper to these four dates as epochs 1, 2, 3, and 4, respectively. The exact days of the Lick spectroscopic observations are given in Table 2. During each run, low-resolution (∼12 Å) and higher resolution (∼3 Å) spectra were obtained using the CCD-UV/Schmidt spectrograph. Additional data were obtained at the Palomar Observatory Hale 5 m telescope in 1991 February using the double spectrograph.

Low-resolution spectra are shown in Figure 1 from 1991 February (epoch 3). The system response function versus wavelength was set using spectrophotometric standards and wide-slit observations. The absolute scale was fixed at 5500 Å, using $m_\lambda = -2.5 \log f_\nu - 48.64$ and broad-band V imaging data ($V \simeq m_{5500}$). The following emission lines are indicated: Lyβ λ1025, O VI λ1035, Lyα λ1215, N V λ1240, Si IV λ1397, O IV] λ1402, C IV λ1549, C III] λ1909, and Mg II λ2799. We have found several narrow metal line absorption systems, most of which are probably due to intervening absorbers unrelated to the BALs. The strongest lines of these systems are indicated by lowercase letters; each system is assigned one letter. The measured redshifts are 0.720, 1.162, 1.474, 1.574, 1.685, and 1.797 corresponding to a, b, c, d, e, and f, respectively. Systems a and b were identified from the Mg II doublet splitting, and c, d, e, and f from the C IV doublet splitting. All but system b were identified using the higher resolution spectra.

The BALs for O VI, N V, Si IV, and C IV are evident blueward of their respective emission lines. The BAL for Lyα appears to be very weak and partly overlaps the blue edge of the N V trough. The predicted position of the Al III λ1857 BAL is also indicated in Figure 1. Unfortunately, the Fe II λ2600 line of the intervening system b falls at the same position. We have marked the position of the slightly stronger Fe II λ2382 line of system b (at 5250 Å). Due to the combination of Fe II λ2600 and the depression in the apparent continuum at 5600 Å caused by surrounding weak broad emission, it is difficult to say how much (if any) of the Al III BAL is visible in 1991 February. However, the absorption feature appears to be stronger in a spectrum of CSO 203 taken in 1988 by Thompson et al. (1989), indicating that the Al III BAL has weakened in the more recent epochs.

A program to monitor the continuum brightness of BALQSOs has been conducted with smaller telescopes by taking direct images through broad-band filters. Stars near the QSO are used for comparison to provide accurate measures of differential broad-band magnitudes between the various epochs. Broad-band data for CSO 203 were obtained between 1989 December and 1991 April using the Lick 1 m Nickel telescope and the KPNO No. 1 36 inch (0.9 m) telescope. The results (shown in Table 1) are given as differential magnitudes in V and r relative to 1991 April 17, which (with photometric conditions) yielded magnitudes of $V = 17.17 \pm 0.03$ and

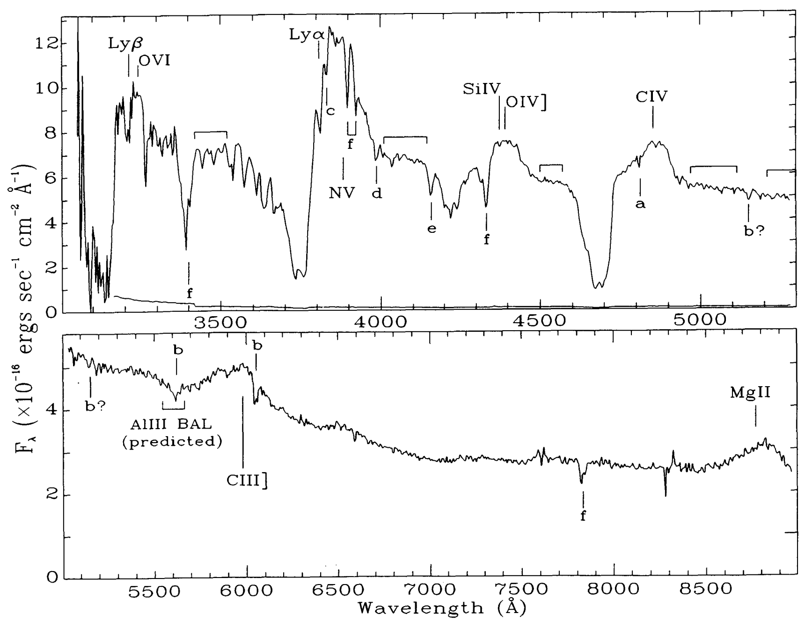

FIG. 1.—Low-resolution spectra of the BALQSO CSO 203. The top spectrum was taken at Lick in 1991 February and April with 12 Å resolution and the bottom segment at Palomar with the red side of the double spectrograph with 18 Å resolution. The most prominent emission lines are marked. The lowercase letters indicate features due to several narrow-line absorption systems. The error for the blue segment is shown at the bottom of the top plot. Adopted continuum regions are indicated by brackets above the blue segment.

TABLE 1

MAGNITUDES RELATIVE TO 1991 APRIL 17

UT	V	r	$(V-r)$
1989 Dec 27[a]	−0.062	−0.084[b]	+0.022
1990 Feb 25	−0.065	−0.034	−0.031
1990 Feb 28	...	−0.020	...
1990 Mar 20[a]	−0.110[c]	−0.088[b]	−0.022
1990 Nov 20	...	−0.059	...
1990 Nov 25	−0.052	−0.038	−0.014
1991 Feb 6	−0.015	−0.007	−0.008
1991 Feb 10	−0.028	−0.004	−0.024
1991 Apr 23	+0.019	+0.032	−0.013

[a] KPNO No. 1 36 inch (0.9 m) telescope.
[b] $r1$ filter.
[c] Mould system V filter.

$r = 17.19 \pm 0.03$. The 1 σ formal error in the differential magnitudes is 0.01. The Lick observations used a special night sky–blocking red filter "Rs" with a bandpass of 6100–7450 Å (measured at 50% of peak transmission). The "$r1$" filter used at KPNO (bandpass 6100–7230 Å) is similar to Gunn r but may be too different from "Rs" to be certain of changes less than 0.1 mag. The V data were taken with our own V filter (5000–5900 Å), except for 1990 March where the "Mould system" V was used (5050–5900 Å). Although there may be a trend in the data indicating that CSO 203 was becoming slightly fainter, the level of change (~0.05 mag) is small.

To accurately compare the absorption troughs among epochs, a continuum has been fitted using the spectral regions indicated in Figure 1. Lyα forest lines contaminate the regions blueward of the Lyα emission line and all the regions are contaminated to varying degrees by weak blended emission lines. Since a single power law or polynomial does not produce an adequate fit, we have used piecewise linear fits between adjacent continuum segments. Although this certainly does not represent the true continuum (and neglects the blue wings of the BELs), it provides a consistent means of comparing continuum divided data between the epochs.

The higher resolution spectra do not provide enough wavelength range even for these piecewise linear continuum fits, so continua were fitted to the low-resolution data from each epoch. The higher resolution spectra were then corrected to match the shape of the low-resolution spectra. This was done by rebinning both, dividing the lower by the higher resolution spectrum, fitting a first- or second-order polynomial, and multiplying this fit by the higher resolution data. The piecewise continuum fit could then be applied directly to the higher resolution spectrum. The data were corrected to vacuum, heliocentric wavelengths, and continuum divided to produce normalized intensity spectra. Figure 2 compares the Si IV and C IV BALs in epochs 1 and 2, which show changes over 383 days. The brackets indicate outflow velocities between 8000 and 14,500 km s^{-1} for C IV and Si IV relative to an emission redshift of $z_e = 2.133$ derived from the peak of the C III] emission line. Figure 3 compares epochs 2 and 3 which show smaller changes over 77 days, and Figure 4 compares epochs 3 and 4 which show no significant changes over a 73 day period. Figure 5 compares the N V and Lyα BALs during epochs 2 and 3. The predicted extent of the strongest part of the BALs (outflow velocities between 8000 and 14,500 km s^{-1}) and the predicted positions of the emission lines are indicated. The original dispersion of the spectra shown in Figures 2–5 was 1 Å pixel^{-1} with a FWHM resolution of 3 Å. The data have been rebinned to 2 Å per pixel to reduce the noise. The dotted line at the bottom of each graph is the 1 σ error (per 2 Å bin) of the difference between the spectra.

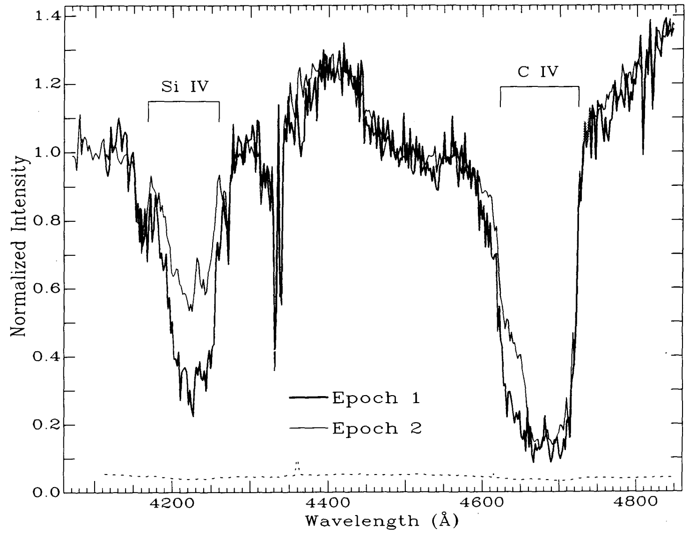

FIG. 2.—Continuum-divided spectra of CSO 203 comparing the Si IV and C IV broad absorption lines from epochs 1 and 2. These spectra were taken with the Shane 3 m telescope using the same spectrograph, grating and detector with a resolution of about 3 Å. The dotted line at the bottom of the plot represents the formal 1 σ error in the difference between the spectra shown. The brackets indicate outflow velocities between 8000 and 14,500 km s^{-1}.

Broad absorption-line equivalent widths were measured from all the data taken at higher resolution and are shown in Table 2 with their 1 σ errors. These errors were derived from photon counting statistics and include both the random errors of the pixels within the absorption line and the random error of the low-resolution piecewise continuum fit and high-resolution continuum match. The systematic error in our choice of continuum is not included. Neglecting any systematic error in the data reduction and calibration of each individual epoch, these errors yield a measure of the "repeatability" of our measure-

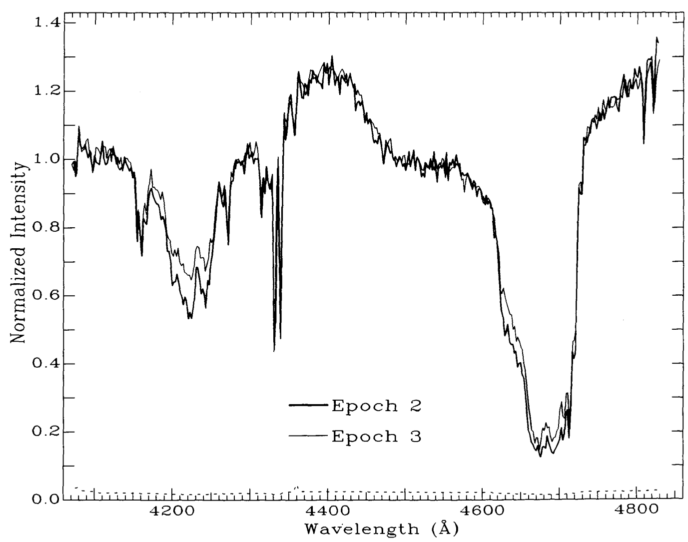

FIG. 3.—Continuum-divided spectra of CSO 203 comparing the Si IV and C IV BALs from epochs 2 and 3.

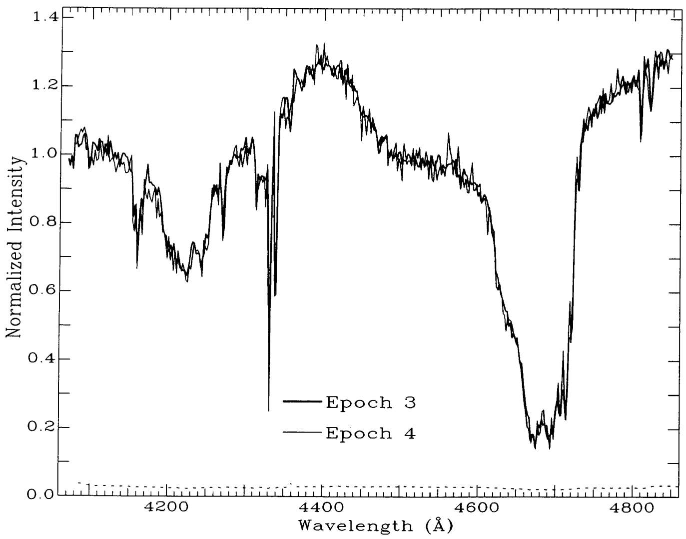

FIG. 4.—Continuum-divided spectra of CSO 203 comparing the Si IV and C IV BALs from epochs 3 and 4.

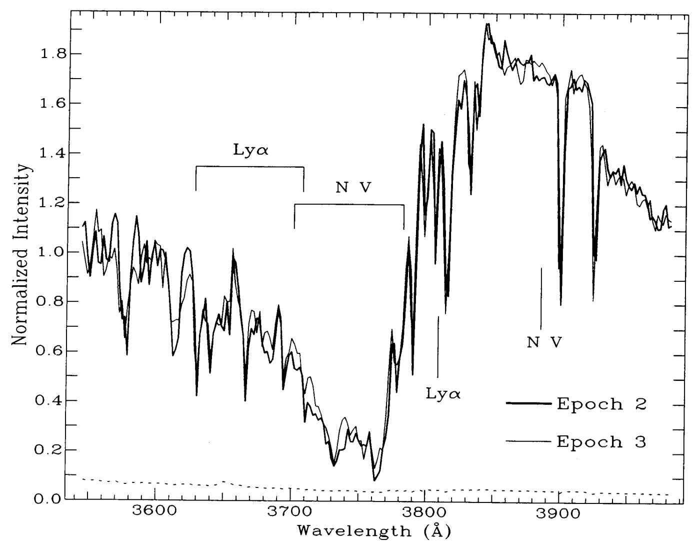

FIG. 5.—Continuum-divided spectra of CSO 203 comparing the Lyα and N V BALs from epochs 2 and 3.

ments and thus the significance of changes in the BALs. They are not intended to represent the full error in the "true" value of the equivalent widths. The wavelength range used for each measurement corresponds to outflow velocities between 8000 and 14,500 km s^{-1}. The changes in the Si IV and C IV lines during the first three epochs are evident, as are the apparent lack of significant changes between epochs 3 and 4. Columns (3) and (4) in Table 2 gives the number of days from the previous epoch in both the observed and QSO reference frames. Between the epochs 2 and 3 our data show no significant change within the predicted region of the Lyα BAL, although there may have been a slight decrease in equivalent width for the N V trough (see also Fig. 5). Measurements of the emission-line equivalent widths showed no significant time variability.

3. ANALYSIS

Assuming that scattered light and emission from the BAL gas are negligible, the BAL contains no unresolved narrow lines, and the BAL gas completely covers the continuum source in each outflow velocity segment, we can estimate the optical depth (τ) from the residual intensity (I_r) by $\tau = -\ln [I_r(\lambda)]$. Figure 6 shows the optical depth of the Si IV BAL in epoch 3 and fractional decreases in τ for the Si IV BALs plotted as a function of outflow velocity. The contributions of the weaker red components of the Si IV and C IV doublets have been removed from the BAL troughs. This method of subtraction is described in Junkkarinen, Burbidge, & Smith (1983).

If our measure of optical depth is accurate, then τ as a function of velocity is directly proportional to the column density of the associated ion as a function of velocity. Further, if the absorption at each velocity is produced by a homogeneous volume of gas moving at that velocity, then the column density of an ion is directly proportional to the fractional abundance of the ion in that volume of gas. In this case, the measured fractional change in τ is an estimate of the fractional abundance for each ion. These changes in fractional abundance can be compared to those expected from curves of fractional abundance versus ionization parameter as produced by photoionization models.

As seen in the second graph of Figure 6, the change across the Si IV trough is relatively flat in comparison to the change observed in UM 232 (see Fig. 4 of BJB). In the UM 232 data the Si IV showed a significant trend of decreasing fractional change with velocity. In the CSO 203 data, a similar (although much weaker) trend appears across the deepest part of the trough between 9500 and 12,000 km s^{-1}.

There may be several types of systematic errors affecting the values in Figure 6. We discuss three of the most significant ones here.

1. If our continuum estimate is incorrect, there will be a systematic error in our estimate of optical depth. Specifically, let I_e be the difference (in normalized intensity) between the true continuum and our adopted continuum, then $\tau = -\ln [I_r/(1 + I_e)]$. If the continuum we used were lower than

TABLE 2

BROAD ABSORPTION-LINE EQUIVALENT WIDTHS

Epoch (1)	UT (2)	Earth Δ Days (3)	QSO[a] Δ Days (4)	Lyα (5)	N V (6)	Si IV (7)	C IV (8)
1........	1989 Nov 5, 6	...	...	...	...	45.9 ± 0.7	80.1 ± 0.5
2........	1990 Nov 24	383	122	27.0 ± 0.6	56.1 ± 0.4	26.6 ± 0.4	71.5 ± 0.2
3........	1991 Feb 8, 9	77	25	24.7 ± 0.6	52.1 ± 0.4	20.4 ± 0.3	65.9 ± 0.2
4........	1991 Apr 22, 23	73	23	...	...	22.2 ± 0.5	64.8 ± 0.4

[a] Δt(Earth frame) = $(1 + z_e) \times \Delta t$(QSO frame).

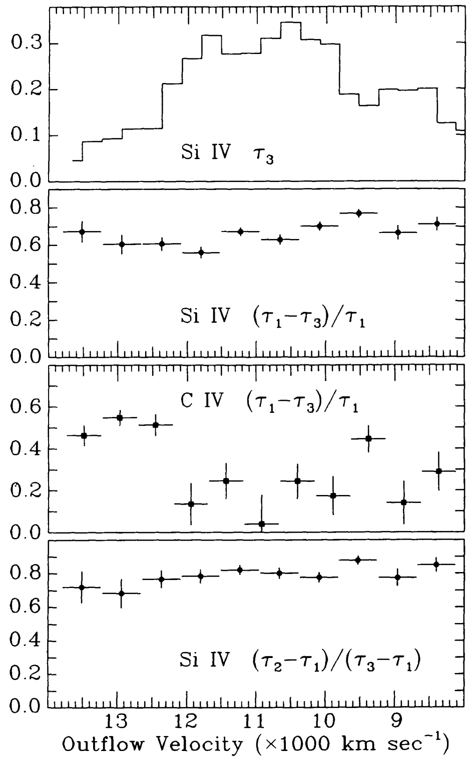

FIG. 6.—The top graph shows the optical depth, $\tau = -\ln[I_r(\lambda)]$, in the Si IV BAL at epoch 3 with the red component of the Si IV doublet subtracted. The second and third graphs show the fractional decrease in optical depth between epochs 1 and 3 for Si IV and C IV. The bottom plot shows the change in optical depth in epoch 2 relative to epochs 1 and 3. The top plot was rebinned to 4 Å per bin, while the other three have been rebinned to 8 Å per bin.

the true continuum ($I_e > 0$), then the values of τ presented in Figure 6 would be too small and the fractional decrease values would be too large (especially at small optical depths). The opposite would be true if our continuum were too high.

2. Light scattered by and emitted by the BAL gas may tend to "fill in" the bottom of a BAL trough, making our values of τ too small.

3. The BALR may not completely cover the continuum source and the optical depth calculated would be too small for the part of the line of sight covered by the clouds.

For systematic errors (2) and (3) above, let I_s be the contribution to I_r from scattered/emitted light or continuum light which is not covered by the BALR. The equation for τ becomes $\tau = -\ln[(I_r - I_s)/(1 - I_s)]$. For a given I_r, it can be shown that larger values of I_s would increase τ and would also increase the fractional change, $(\tau_i - \tau_f)/\tau_i$, for $\tau_i > \tau_f$. Therefore, systematic errors caused by conditions (2) and (3) will make our estimates of τ and the fractional decrease too small (especially at large optical depths).

Considering conditions (1), (2), and (3), we have $\tau = -\ln[(I_r - I_s)/(1 + I_e - I_s)]$. The random error in our continuum fit around the Si IV and C IV BALs derived from photon-counting statistics is less than 1%. The systematic error is certainly larger than this but probably less than 10% ($|I_e| < 0.1$). This is based on visual inspection of Figures 2, 3, and 4. If I_s remains constant between 1 and 3, then I_s must be less than I_r in epoch 1. This allows us to determine an upper limit for the "true" value of τ for epoch 3. For the blue side of the C IV trough (at 4640 Å observed wavelength or ~13,400 km s^{-1} outflow velocity), $\tau_3 \lesssim 1.2$, and for the middle of the Si IV trough (4220 Å or 10,900 km s^{-1}), $\tau_3 \lesssim 0.8$.

While Si IV in the second graph of Figure 6 shows similar levels of change at all velocities, the C IV values show a break around 12,000 km s^{-1} with the fractional decrease being significantly smaller in the deepest region of the BAL (10,000–12,000 km s^{-1}). This apparent break could be caused by systematic errors (2) and/or (3) mentioned above. A value for $I_s \sim 0.10$ (with $I_e \sim 0$) would make the values for the fractional decrease for C IV near the middle of the BAL about the same as the values on the blue side of the trough (see the third graph of Fig. 6). This would eliminate the break and make the second and third graphs of Figure 6 look qualitatively similar.

An additional systematic error would occur if the BALR coverage of the continuum source varied as a function of outflow velocity. As discussed by Kwan (1990) as a possible contributor to the apparent weakness of Lyα BALs relative to the strength of the BALs formed by doublet transitions, this condition may cause the absorption for a doublet transition to appear stronger than a singlet transition with a larger opacity. Within the wavelength range of a doublet BAL, light of a particular wavelength coming from a portion of the source not covered by the clouds at one velocity could be absorbed by clouds at a different velocity provided the difference in velocity is equal to the doublet separation. A trough may appear as much as twice as deep in the case where all the clouds at any given velocity covered a portion of the continuum source not covered by clouds whose velocity differed by the doublet separation, than in the case where the portion of continuum source covered did not vary with velocity. This maximum factor of 2 increase in absorption depth also requires that the gas with each velocity segment be optically thick so that both components of the doublet absorb essentially the same amount of incident radiation (see Kwan 1990).

The fourth graph in Figure 6 shows the relative change in epoch 2. If we assume that the BAL is undergoing a continuous process, this represents how far the trough has "progressed" in the intermediate state in epoch 2 from the original state in epoch 1 toward the final state in epochs 3 and 4. Most notable is that the entire trough has "progressed" about the same amount (~80%) toward the final state.

4. DISCUSSION

One possibility for the observed changes in the BAL troughs of CSO 203 is an increase in the ionization parameter U (as defined in BJB). The fact that the variations appear to occur approximately simultaneously across the trough is what one would expect from a variation in the ionizing flux and the relative variations among the ions are at least consistent with this. The absence of any observed change in the flux is of course in contradiction to this mechanism. We will first explore possible models which retain changes in the ionization parameter as the basic mechanism driving the variability without being in conflict with the lack of observed flux changes.

In the following analysis, we will assume that the BAL gas can be treated as optically thin to continuum radiation at all wavelengths. In general, the fractional abundance of an ion will reach a peak at some value of the ionization parameter, U_p, and this value will be larger for ions with higher ionization potentials (see BJB and references therein). Since, in CSO 203, both the Si^{+3} and C^{+3} ion column densities have decreased and the N^{+4} ions may have shown a sight decrease, the ionization parameter must be larger than $U_p(C^{+3})$ and may be close to $U_p(N^{+4})$. Furthermore, for a given $\Delta U/U$, the fractional decrease in fractional abundance for an ion species increases the further U is from the peak of that ion species. If $\Delta U/U$ is the same at all velocities (as would be the case if the change were due to a change in the ionizing flux), then the two graphs in Figure 6 of $\Delta\tau/\tau$ give a relative measure of U across the troughs. Also, since the abundance of a lower ionization species peaks at lower values of U, the fractional changes should be greater for the lower ionization species, i.e., $\Delta N/N(Si^{+3}) > \Delta N/N(C^{+3}) > \Delta N/N(N^{+4})$. This is consistent with our results.

Photoionization by the observed continuum source would provide a synchronizing mechanism because the ionizing photons are in step with the photons that produce the observed spectrum. Changes in the absorption troughs produced by a mechanism that does not propagate through the BALR at very nearly the speed of light would cause an observable delay in the changes as a function of outflow velocity. (This assumes that velocity is a monotonic function of the distance from the continuum source.) Such a delay would not have been detected by us only if the difference in crossing time between the photons from the continuum source and the disturbance causing the changes was much shorter than the shortest time scale for observed BAL trough changes which is 25 days (between epochs 2 and 3) in the QSO rest frame. Let β be the speed of the disturbance divided by the speed of light and T be the lifetime of the BALR in years in the QSO frame. If we assume that a minimal size along our line of sight of the BALR is given by the observed 6000 km s^{-1} velocity difference across the absorption trough multiplied by T (neglecting acceleration and assuming the BALR starts from a compact region), then the maximum delay time of 25 days yields $\beta \gtrsim 1/(1 + 3.42/T)$. Since the basic structure of most BALs in QSOs observed over the last decade have remained relatively stable, T is probably much larger than a few years. As an example, if the troughs maintained their basic properties for 30 yr, then $\beta \gtrsim 0.90$. The short time scale changes in CSO 203 across all outflow velocities therefore strongly suggests a mechanism which involves photons or a hydrodynamic or hydromagnetic phenomenon which is relativistic.

The current data do not particularly favor any single mechanism for the BAL changes. We present here four possibilities along with the problems and the constraints imposed by each.

1. It is possible that the clouds in the BALR are photoionized by the observed continuum source and that the time scale for changes as given by the photoionization/recombination relaxation time is long. Our imaging data show no changes between the rest wavelengths of 1100 and 2200 Å larger than 10%. Even allowing that the change in flux at the ionizing potential of C^{+3} (~200 Å) may be a factor of 2 larger, these changes are probably too small to trigger the large changes seen in C IV and Si IV BALs which suggest a change in ionizing flux of at least 30%.

Since U is probably between $U_p(C^{+3})$ and $U_p(C^{+4})$, we consider the time-dependent photoionization/recombination equation neglecting all ionization states except C^{+3} and C^{+4} so that $N(C) = N(C^{+3}) + N(C^{+4})$. We further assume equilibrium at $t = 0$ and that n_e and the recombination coefficient, $\alpha_R(C^{+3}, T_e)$, remain constant. Therefore,

$$\frac{dN(C^{+3})}{dt} = n_e N(C^{+4})\alpha_R - \Gamma(t)N(C^{+3}) ,$$

where

$$\Gamma(t) \equiv \int_{\nu_0(C^{+3})}^{\infty} \frac{4\pi J_\nu(t)}{h\nu} a_\nu(C^{+3})d\nu ,$$

where $J_\nu(t)$ is the incident flux at time t, and a_ν is the photoionization cross section. Let $x(t) = N(C^{+3})/N(C)$, $\tau = tn_e\alpha_R$, and

$$\omega(\tau) = \int_0^\tau \left\{1 + \frac{\Gamma(t)}{\Gamma(0)}\left[\frac{1 - x(0)}{x(0)}\right]\right\}dt ,$$

then

$$x(\tau) = \left[x(0) + \int_0^\tau e^{\omega(\tau')}d\tau'\right]e^{-\omega(\tau)} .$$

The simplest assumption is to postulate a large change in brightness just prior to 1989 December. The analytical solution shows that our data are inconsistent with a single large change in brightness before epoch 1 because the change seen between epochs 2 and 3 is too large relative to the upper limits on changes between epochs 3 and 4. However, the data are consistent if we allow two additional large flux changes (>30%)—a decrease and an increase separated by at least a few months during the gap in our imaging data between 1990 March and November. Although we cannot rule out such possibilities, we consider such a frequency of large flux changes unlikely given the usual rarity of such changes in optically selected QSOs.

In any case, the relaxation time scale would be on the order of 50–100 days in the QSO rest frame. Given a recombination coefficient for C^{+3} of 8.5×10^{-12} cm^3 s^{-1} ($T_e = 10{,}000$ K), this would imply electron densities on the order of 2–4 × 10^4 cm^{-3}. A radial distance can be derived using the definition of U given in BJB (with $\alpha = -1.5$). A value of the ionization parameter of $U \sim 0.04$ (as suggested by the line ratios), would place the BALR on the order of $1 \times (50/H_0)$ kpc from the photoionizing source—much farther than the typical estimate of ~1 pc of the BELR. The bottom graph of Figure 6 shows that for CSO 203, the fractional change at the intermediate epoch was almost independent of velocity. This implies that n_e would be approximately independent of outflow velocity. Also, these low densities are inconsistent with the presence of metastable Fe II broad absorption lines in the QSO 0059−2735 (Hazard et al. 1987) which require densities significantly larger than 10^4.

Although the recombination times for Si^{+3} and C^{+3} are nearly the same, the times for N^{+4} and Al^{+2} are on the order of a factor of 2 shorter and longer, respectively. Unfortunately, the Al III BAL is too weak and the data inadequate to tell what these changes were like. The possible change in the N V BAL between epochs 2 and 3 can be made consistent with the appropriate sequence of flux changes. Future observations of BAL changes which include more frequent broad-band monitoring and data on BALs with various recombination times will help substantiate or rule out this low-density scenario.

2. It is possible that the BAL clouds are not seeing the same continuum we observe. There could be a nearly collimated ionizing source which is directed at the BALR and is not parallel with our line of sight to the observed continuum source. Large changes in the ionizing source could be producing the BAL changes.

The main problem with this is that the geometry would have to be rather unique. The BALR would have to be situated at the intersection of the ionizing beam and our line of sight to the observed continuum source. This is apparently inconsistent with the idea that the 12% incidence of BALs in QSOs coincides with the mean fraction of sky covered by the BALR as seen from the central source.

3. Since we can only observe down to rest wavelengths of 1000 Å, it is possible that the far-UV continuum is varying independently of the observed continuum. One difficulty with this is that the observed BELs did not vary and they should show some response (possibly delayed) to these far-UV continuum variations. It might be possible that the ionizing source comes from an X-ray or gamma-ray source which affects the BALR differently than the BELR. Another possibility is that an optically thick narrow-line absorption cloud with a strong helium edge lies between the continuum source and the BALR. Transverse motion of this cloud to our line of sight could change the continuum flux near the ionization potentials of C^{+3} and Si^{+3} without a corresponding change of flux at the observed wavelengths.

4. Dynamic changes such as expansion, contraction, or transverse motions of the clouds are not ruled out by our observations. In Boroson et al. (1991), the appearance of a new absorption system in Mrk 231 is explained as the transverse motion of a cloud across the line of sight. This could explain the changes in CSO 203 if all the sections of the BALR had similar transverse motions and similar gradients of column density in the transverse direction. However, the structure and motions of the BALR would have to be somewhat unique to produce changes in the level of absorption bracketed by periods of no variations. Also, the motions would be required to conspire in such a way as to maintain the appearance of a mechanism propagating along our line of sight at near relativistic speeds. If the column density in all sections of the BALR along our line of sight changed in the same manner at the same time, we would have expected to see an observable delay in the changes as a function of velocity due to a light-crossing time of the continuum photons which is probably larger than the minimum time scale of changes (see above).

A decrease in n_e due to an expansion of the clouds is another possibility. If the BALR is filled with very small cloudlets whose internal sound-crossing time is very small, they would respond nearly instantaneously to changes in the pressure of the confining medium. However, as noted earlier, the observations appear to require that the disturbance causing such pressure changes propagate at near-relativistic speeds.

5. SUMMARY

We conclude by summarizing some tentative results about BALQSO absorption trough time variability. These results are based on changes observed in five QSOs with limited spectral sampling, and very limited photometry on two QSOs. Further observations and a better understanding of QSO BAL variability will show if the following points are significant or incidental or simply misleading due to small number statistics.

1. Large changes in the BAL troughs are not exceedingly rare. Detections have been made in the cases of UM 232 and CSO 203. We estimate that the total number of BALQSOs with multiepoch observations is probably in the range 25–50 with various number of spectra per object but only a few with more than two or three spectra separated in time by more than a month.

2. The time scale for large BAL changes from beginning to end is in the range 1 week to 6 months in the QSO rest frame. This is based on the CSO 203 observations presented here. The other observations of changes in BALs are consistent with this time scale.

3. If UM 232 and CSO 203 are typical, then the character of the change is a transformation from a beginning state to a new and different end state. The spectra appear to be "stuck," at least for a period of time, in both the beginning and end states. The changes seem to be in response to some sudden change in their environment, rather than being related to a steady evolution of the BALR.

The large BAL changes seen so far have both shown decreases in absorption, which is probably a selection effect of the sample, since those BALQSOs which are monitored for changes tend to be those which already have strong troughs. Both increases and decreases in absorption must occur in order to maintain the mean number of BALQSOs. We expect that there may be some QSOs which start with no absorption or very weak absorption and which later show stronger absorption.

4. For both UM 232 and CSO 203, the BAL changes observed occur at all velocities in the BALR. This is consistent with a model in which an "ionization front" propagates out from the central source in step with the photons that produce the observed spectrum.

5. Photometric observations of the continuum brightness of the BALQSOs during the time the spectra are varying do not support the simplest high-density photoionization models for the time variability. The BALR could have low densities and long response times to changes in ionizing flux. However, the expected response of the BALs as a function of time does not fit the data without postulating a rather contrived sequence of unobserved continuum changes. The present data do not clearly favor any one of the many possibilities for the mechanism causing the BAL changes.

Thanks are due to the staffs of Lick Observatory and KPNO for their help and support in obtaining these data. We also thank Ross Cohen for useful discussions and for helping us obtain our fourth epoch spectral data. This research has been supported by NASA contract NAS 5-29293 and NAG 5-1630. Research on QSOs at the Observatories of the Carnegie Institution of Washington is supported in part by NSF grant 9005117 which is gratefully acknowledged.

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