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THE LYMAN EDGE TEST OF THE QUASAR EMISSION MECHANISM

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ABSTRACT

This is a study of the Lyman edge region in the spectra of 11 high-redshift quasars. We present large-aperture, low-resolution data designed to detect broadened Lyman edge absorption predicted by thermal models of the "big blue bump" continuum component, especially thin accretion disks. We also present high-resolution data on the edge regions and the Lyman α emission lines for nine of the objects.

Three objects have broadened, partial edges near the systemic redshifts, as expected for thermal models. However, in two cases we can identify narrow Lyman lines with the edge absorption, ruling out the disk interpretation. (In the third case there are no high-resolution data available for this test.) Therefore, our data are negative for thermal models, at least for opaque thin accretion disks.

Our spectra show five complete intervening Lyman limit system edges, and they generally appear to be quite broad. The broadening can perhaps be explained by overlapping high-*n* absorption lines if the systems are clustered over a range of a few hundred kilometers per second in velocity.
Subject headings: spectrophotometry — quasars

I. INTRODUCTION

There are at least two reasons to study the Lyman edge region in quasar spectra. The behavior in that region should be a powerful diagnostic of the emission mechanism, and it should reveal the presence of absorbing material such as broad emission line (BEL) clouds in the line of sight.

Regarding the continuum emission, the "big blue bump" component extends from around 1 μm past 1000 Å, and in some cases apparently all the way to the soft X-ray region. Energetically it is very important and possibly dominant. The leading explanation, based on continuum spectral fits, is thermal radiation from a geometrically thin, optically thick accretion disk (Shields 1978; Malkan 1983). However, standard thin disk models predict enormous Lyman absorption edges at the systemic redshift, which are apparently not seen (Kolykhalov and Sunyaev 1984). Lowering the surface gravity weakens the predicted absorption. Sun and Malkan (1987) tried lowering the surface gravity of their models nearly to the limit set by radiation pressure, thereby reducing the edge to 50% or even less (Sun and Malkan 1987, Fig. 3; Sun and Malkan 1988). However, as this limit is approached the disk becomes thick, so the model must be modified in order to produce valid spectral energy distributions. See the discussion of Kolykhalov and Sunyaev (1984) for lower limits to the effective surface gravity of thin disks. In the thin-disk models of Laor and Netzer (1989) the edge behavior is complicated but there is usually a substantial feature of some type. (Laor [1989, private communication] points out the sensitive model dependence of the exact edge behavior.) We are unaware of any thick disk models which incorporate bound-free opacities.

It may be possible to reduce the predicted edges by invoking a more isothermal atmosphere, either by distributed deposition of accretion energy or by X-ray heating from above. The second possibility changes the model rather profoundly, in that the energy no longer derives directly from accretion. Furthermore, such external heating could also drive the edge into emission. In any optically thick thermal model some finite absorption or emission edge must occur, since it is impossible for the source function in the atmosphere to be *exactly* constant. Qualitatively, this applies to thick disks and any other configurations as well. For $\sim$30,000 K gas the opacity changes so enormously at 912 Å that *some* feature should probably be produced. The "Lyman edge test" is therefore a fundamental discriminant between thermal and nonthermal models.

Rotation blurs the edges greatly in titled accretion disk models, so that the observational constraints on edge strength depend on the integrity of the spectral shapes as well as on the signal-to-noise ratio (SNR). Experience with small and large aperture spectra shows that small aperture spectral shapes can be distorted due to refraction, seeing, and (red-sensitive) guiding effects. These effects are very strong in the violet, where $Z \sim 3$ Lyman edges occur. In this paper we derive our overall spectral shapes using 8″–12″ aperture data, and we can detect edges broadened up to $\sim$60,000 km s^{-1}, when intervening Lyman limit absorption systems do not cut the spectrum off too soon.

High-redshift quasars in general do indeed show identifiable "big blue bump" components in their spectral energy distributions, manifest as fairly flat spectral indices shortward of 1 μm in the rest frames (Steidel and Sargent 1987; Neugebauer *et al.* 1987, Fig. 8; Oke and Korycansky 1982). For the objects in our sample, only SS 0014+813 appears to have such data in the literature, and the spectrum does show the flat component (Kuhr *et al.* 1984).

Now what are the prospects for seeing broad emission line clouds in absorption? Good photoionization arguments indicate that the BEL region cloud covering factors are ~10%. If the emitting clouds are much larger than the continuum sources, ~10% of all quasars should have complete Lyman absorption edges. (This assumes that the clouds are transparent longward of 912 Å—otherwise those 10% would simply not be identified as quasars. See § IV*f*.)

Some such candidates have been found, but where follow-up observations have been done the absorbers were found to be extrinsic to the quasars (Baldwin and Smith 1983; Tytler 1982; Bergeron 1986). Therefore, although the large-cloud model is not yet completely ruled out, small cllouds should be considered. It is quite reasonable to invoke a cloud size smaller than the continuum sources. The smooth observed emission-line profiles set a lower limit of $\sim 10^4$ clouds per object (Osterbrock and Matthews 1986). For a BEL region radius of 3 pc for high-luminosity quasars, and a covering factor of 0.1, this means that the cloud sizes must be less that ~0.05 pc. This is less than the upper limits to the continuum source sizes set by variability (~1 pc; see, e.g., the data of Pica and Smith 1983). Actually since the cloud thickness in the radial direction is thought to be only $\sim 10^{-6}$ pc (Kwan and Krolik 1981), the transverse extents may also be very small. They may even be smaller than the region of accretion disks hypothetically radiating the 912 Å continuum (~10 gravitational radii, or $\sim 5 \times 10^{-5}$ pc for a $10^8\ M_\odot$ black hole).

If the cloud sizes are moderately smaller than the continuum sources in size, we expect partial absorption edges, broadened only by the high *n* absorption lines and the internal velocity dispersion. If they are *much* smaller, we expect a ~10% falloff (averaged over all quasars), broadened perhaps as much as the emission lines because many separate clouds would participate.

There is also a possibility that environmental material could produce edges, even broadened edges, at high redshift. We test this idea below.

We designed our observing program to be able to detect and interpret continuum changes at the Lyman edge. Our sample was selected for redshifts of 3 or greater, so that the edge region could be studied from the ground. We excluded all objects with known intervening complete Lyman limit system (LLS) absorption within 150 Å of the systemic edge position. We required high apparent brightness, consistent with getting a variety of radio types. Our maximum magnitude is 17.5 for radio-quiet objects. To get a sufficient number of steep spectrum and flat spectrum radio-loud objects, we had to go down to $V = 18.5$ and $V = 19$, respectively. (Radio spectral indices were taken primarily from Veron-Cetty and Veron 1985.) Radio properties are known to correlate with "associated absorption" clouds which could affect our spectra (Foltz *et al.* 1987). Also, flat spectrum core-dominant radio sources are thought to have their radio jets in the line of sight, while steep spectrum lobe-dominant are thought to lie closer to the sky plane. It is likely that these jets lie parallel to the axes of any accretion disks, so this would give us some control over the accretion disk inclinations.

II. OBSERVATIONS AND REDUCTIONS

Almost all of our results were obtained in a three-night run (1988 February 11/12/13/14) on the KPNO 4 m telescope, using the R-C spectrograph, the "UV fast" camera, and a UV-flooded 800 × 800 TI CCD. Atmospheric conditions were mostly photometric, although scattered cirrus was visible at the ends of nights one and two. On the first night we took low-resolution (~15 Å FWHM) spectra of nine quasars, with total exposure times of ~3000 s per object (Table 1). We used 8″–12″ slit widths so that we could get accurate spectral shapes

TABLE 1

JOURNAL OF OBSERVATIONS

A.

Object	Slit Width	Resolution (FWHM) (Å)	Exposure Time (s)
S5 0014+813......	12″	≈15	5 × 600
0301−005......	8	≈15	3600
0302−003......	8	≈15	3600
S4 0636+680......	8	≈15	2 × 1800
0642+449......	8	≈15	2 × 1500
MC5 0938+119......	8	≈15	2 × 1500
1159+123......	8	≈15	2400
1206+119......	8	≈15	3000
PKS 1402+044......	8	≈15	3600
1442+101......	8	≈15	3000
UT 1607+183......	8	≈15	3000

B.

Object	Slit Width	Resolution (FWHM) (Å)	Exposure Time Lyman Edge (s)	Exposure Time Lyα (s)
S5 0014+813......	1″	≈1.85	2 × 1800	1200
S4 0636+680......	1	≈1.85	2 × 1800	1200
0642+449......	1	≈1.85	2 × 3600	1200
MC5 0938+119......	1	≈1.85	2 × 1800	1200
1159+123......	1	≈1.85	2 × 3600	1200
1206+119......	1	≈1.85	1800 + 1500	1200
PKS 1402+044......	1	≈1.85	3000 + 2400	1200
1442+101......	1	≈1.85	2 × 1800	1200
UT 1607+183......	1	≈1.85	2 × 2400	2100

as required for the detection of highly broadened edges. The second and third nights were spent taking ~1.85 Å resolution data on the edge regions and on the Lyα lines of each quasar, in order to help clarify the phenomena seen at the edges. Here our exposure times were typically 5000 s at the edge positions and 1200 s on the Lyα emission lines. For the high-resolution observations, 1″ slit widths were used, with the slit aligned in the direction of atmospheric dispersion at the midpoint of the exposure. Comparison lamps were observed following each integration. We also obtained large-aperture, low-resolution data for two additional quasars using the same setup as on February 11/12/13/14. One of these additional objects was observed on 1988 February 14/15, and the other on 1988 February 15/16.

The data were flat-fielded, wavelength-calibrated, flux-calibrated, and extinction-corrected using standard IRAF software. The one-dimensional data presented here were created using optimal extraction inside the IRAF APSUM program. For the low-resolution data we also tried straight summation over the 8″–12″ slit widths in order to verify the photometric integrity of the optimal extraction routine. The results were indistinguishable, except for lower noise in the optimally extracted versions.

The high-resolution scans confirmed qualitatively the existence of all of the edges securely detected at low resolution. This was possible because the edges detected turned out to be relatively narrow. Figures 1–10 show the low- and high-resolution scans for each object.

III. RESULTS

In order to interpret the edges, it is necessary to have a good estimate of the systemic redshift. We measured the redshift of the Lyα emission lines on our high-resolution profiles, where the bias due to the Lyα forest can be largely avoided. These redshifts were assumed to be the systemic values. They are on average ~500 km s^{-1} blueward of the peaks on the low-resolution spectra, because of the effects of resolving the forest absorption. (Gaskell [1982] and Wilkes [1988] have concluded that Lyα [and C IV] may have a blueshift of a few hundred to a thousand km s^{-1} relative to the systemic velocity, whereas such an effect is not seen in Junkkarinen's [1988] C IV study. This level of uncertainty does not affect our discussion.)

We describe the individual spectra below. They have very low noise levels, but the Lyα forest provides a strong effective noise source below the observed Lyα emission position. The behavior at the edge positions is varied and sometimes puzzling. Table 2 summarizes the properties of the detected absorption edges.

We also include in Table 2 our Lyα equivalent width measurements. In making these measurements our continuum points on the blue sides of the lines were set in the middle of the Lyα forest absorption, i.e., we treated the forest as noise and did not use the upper envelope to estimate the true continuum. This compensates for forest absorption of the blue halves of the emission lines. Sargent *et al.* (1988) followed the opposite procedure, and so derived systematically lower equivalent widths for the objects in common. Our method must be used when the true quasar properties are required, such as for study of the Baldwin effect for Lyα.

1. *S4 0014+813* (*Fig. 1a–1c*)—This turned out to be a very instructive case. The spectrum shows a remarkable absorption edge near the systemic position. It has the properties expected for an accretion disk atmospheric edge: it is both spectrally resolved and partial. As for all of our edges, the Lyα forest makes the velocity range measurement somewhat subjective. We estimate that this edge starts somewhere between ~ −3900 km s^{-1} and systemic, and that it continues until ~ +11,600 km s^{-1}. (Our wavelength ranges refer to the appearance of the plots and do not exclude the possibility that the broadening is simply the result of high-*n* absorption lines or other effects.)

The high redshift of much of the edge relative to systemic is striking and seems inconsistent with absorption by cosmologically distributed intervening matter along the line of sight. The broadening seems to disfavor that hypothesis as well (but see below, and also § IV). A natural explanation for the positive velocity would be a gravitational redshift of thermal accretion disk radiation. Disk models show that the gravitational redshift must compete with the blueshift of the edge due to the Doppler effect together with Doppler favoritism for the approaching side (Sun and Malkan 1988). The gravitational redshift only wins for nearly face-on disks, but it happens that S4 0014+813 is likely to be face on because it is a flat spectrum radio source. The Galactic foreground reddening is substantial [$E(B-V) \sim 0.18$ (Burstein and Heiles 1982)], but reddening is too gradual to affect the edge much.

The low-resolution spectrum of this quasar shows another

TABLE 2

LYMAN EDGE PROPERTIES OF HIGH-REDSHIFT QUASARS

Object	$\lambda_{Ly\alpha}$[a] (Å)	Adopted z	LLS[b] $v < 10{,}000$	λ Range $v < 10{,}000$ (Å)	LLS[b] $v > 10{,}000$	λ Range $v > 10{,}000$ (Å)	EW$_{Ly\alpha}$[c] (Å)
S5 0014+813......	5330	3.384	45%	3950–4170	100%	3455–3510	56.4
0301−005......	[d]	3.119	...	...	100%	3585–3670	173.1
0302−003......	[d]	3.275	33%	3835–4055	...	...	219.7
S4 0636+680......	5076	3.175	>30%	3580–4080	100%	3580–3610	72.2
0642+449......	5351	3.402	85%	3935–4000	100%	~3790	154.9
MC5 0938+119......	5094	3.190	...	...	55%	3625–?	226.7
1159+123......	5470	3.500	50%	4145–4200	100%	3373–3472	250.1
1206+119......	4994	3.108	100%	3715–3850	...	...	142.6
PKS 1402+044......	5110	3.203	100%	3730–3755	...	...	255.3
1442+101......	5530	3.549	...	...	...	...	79.1
UT 1607+183......	5005	3.117	...	...	100%	3390–3500	65.3

[a] Wavelengths determined from high-resolution Lyα.

[b] Percentage drop in the continuum of the Lyman limit system (LLS) centered at velocities of <10,000 km s^{-1} and >10,000 km s^{-1} from the quasar rest position of 912 Å, respectively.

[c] Rest equivalent widths in Å.

[d] See text, §§ III, 10 and 11.

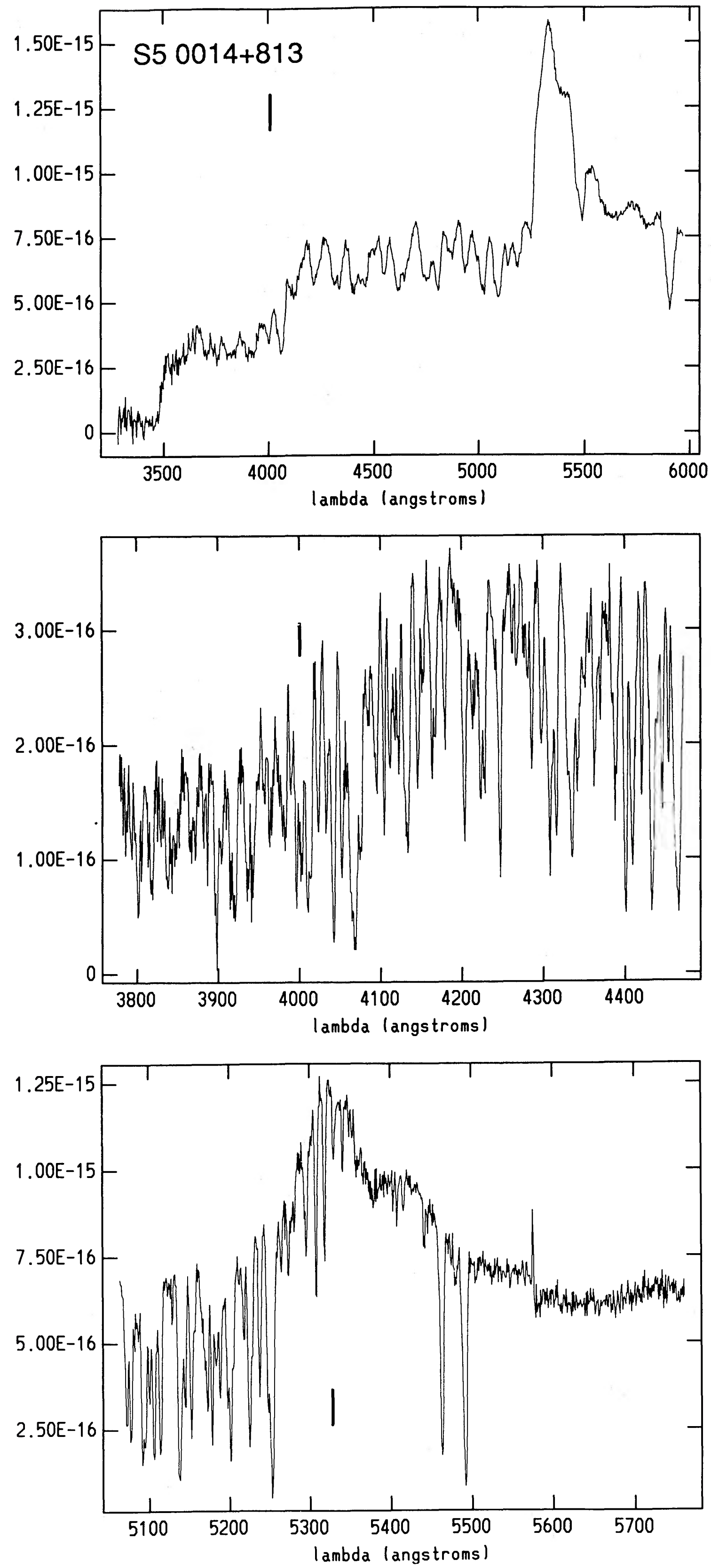

FIG. 1.—(*a*) Large aperture, low resolution spectrum of S5 0014+813. The systemic edge position for the adopted redshift is marked. (*b*) Small aperture, high-resolution spectrum of the systemic Lyman edge region, with the systemic edge position indicated. The small-aperture fluxes are often much lower than the large aperture values due to light losses on the slit jaws. (*c*) Small aperture, high-resolution spectrum of the Lyα region, with the adopted Lyα peak marked.

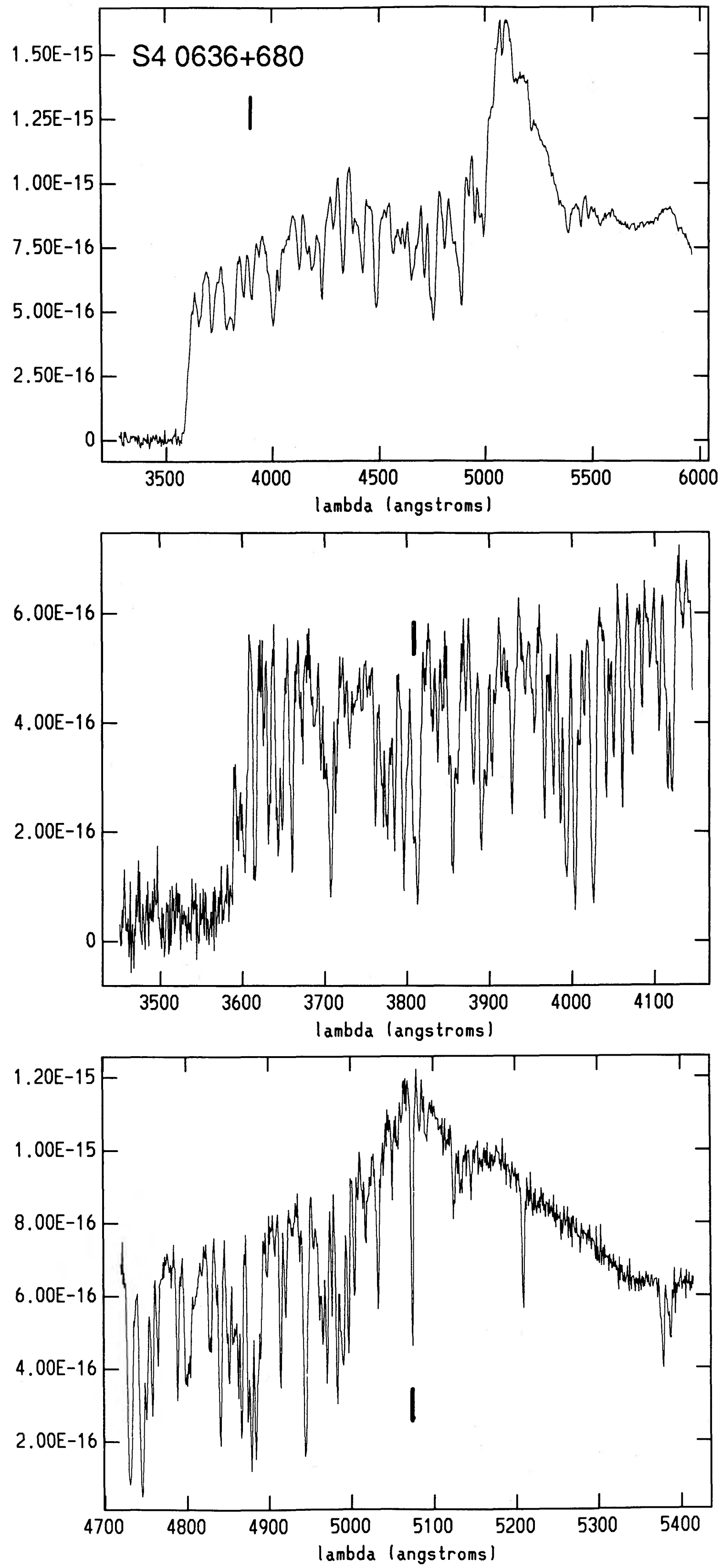

FIG. 2.—(*a*–*c*) Same as Fig. 1, but for S4 0636+680

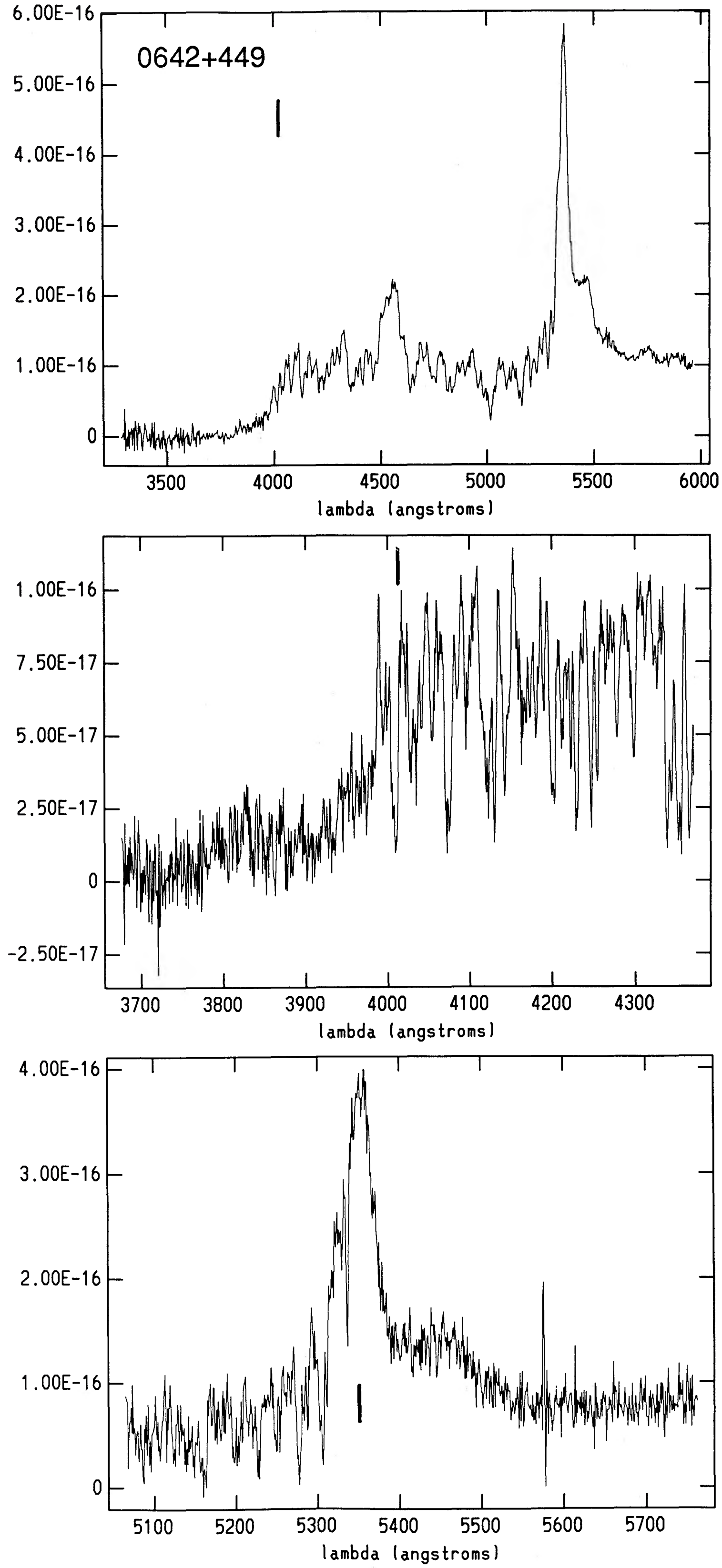

FIG. 3.—(*a–c*) Same as Fig. 1, but for 0642+449

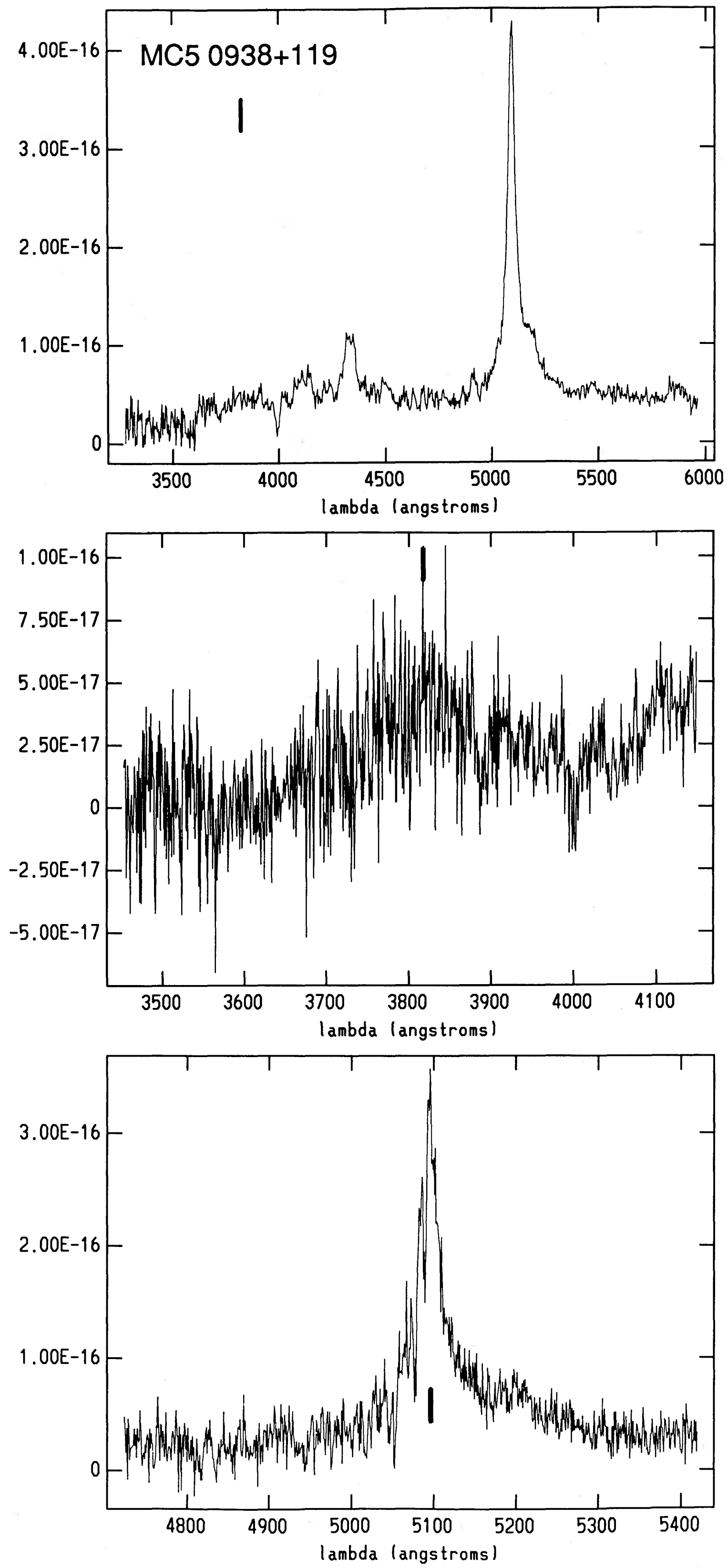

FIG. 4.—(*a–c*) Same as Fig. 1, but for MC5 0938 + 119

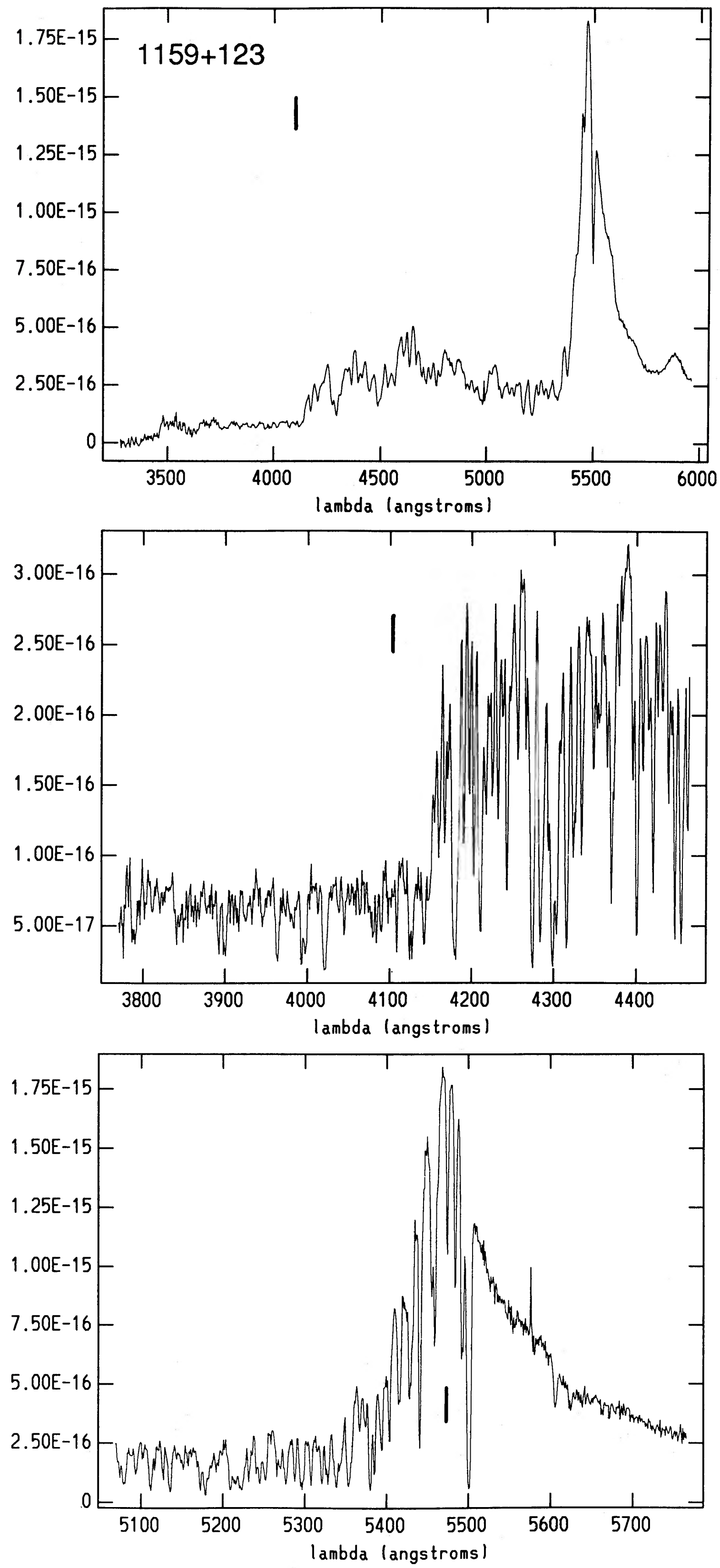

FIG. 5.—(*a–c*) Same as Fig. 1, but for 1159 + 123

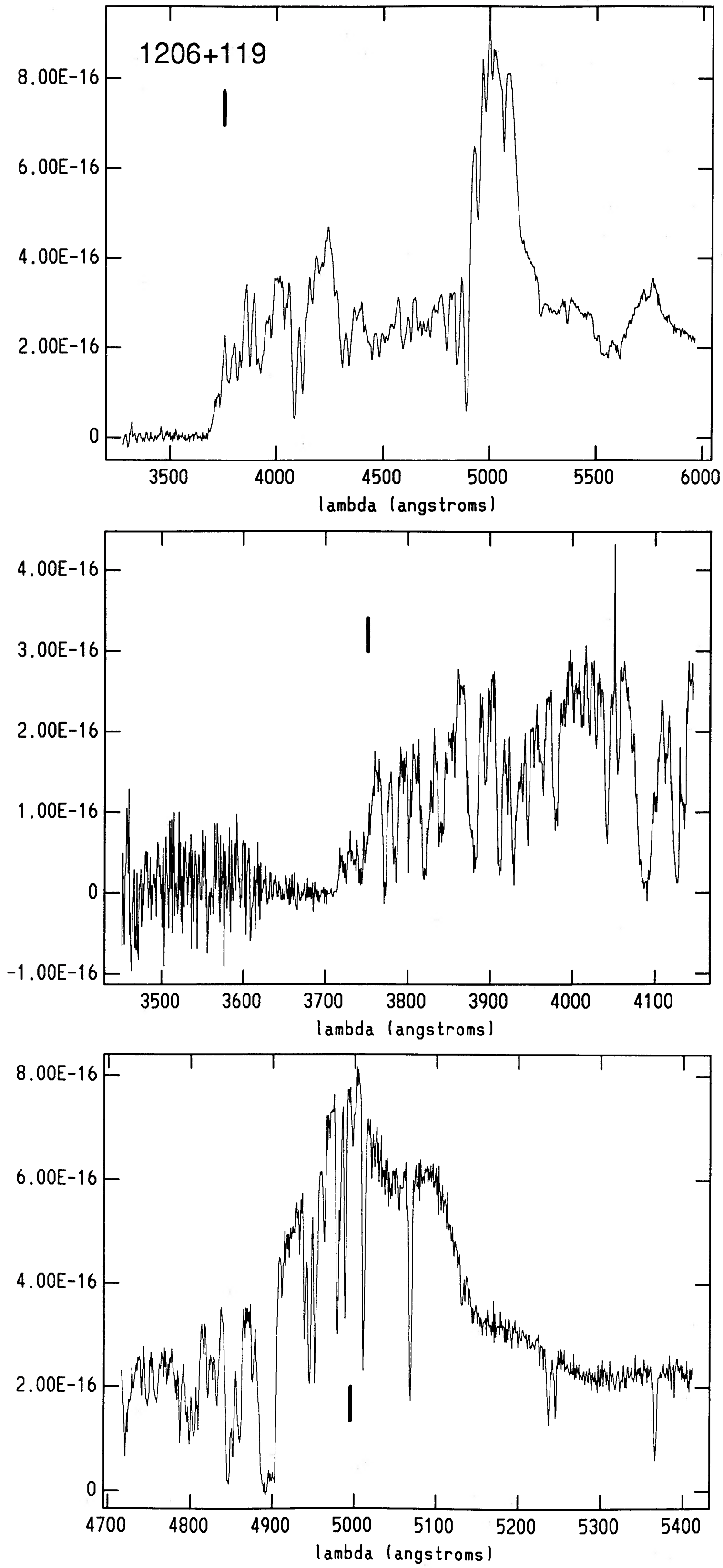

FIG. 6.—(a–c) Same as Fig. 1, but for 1206+119

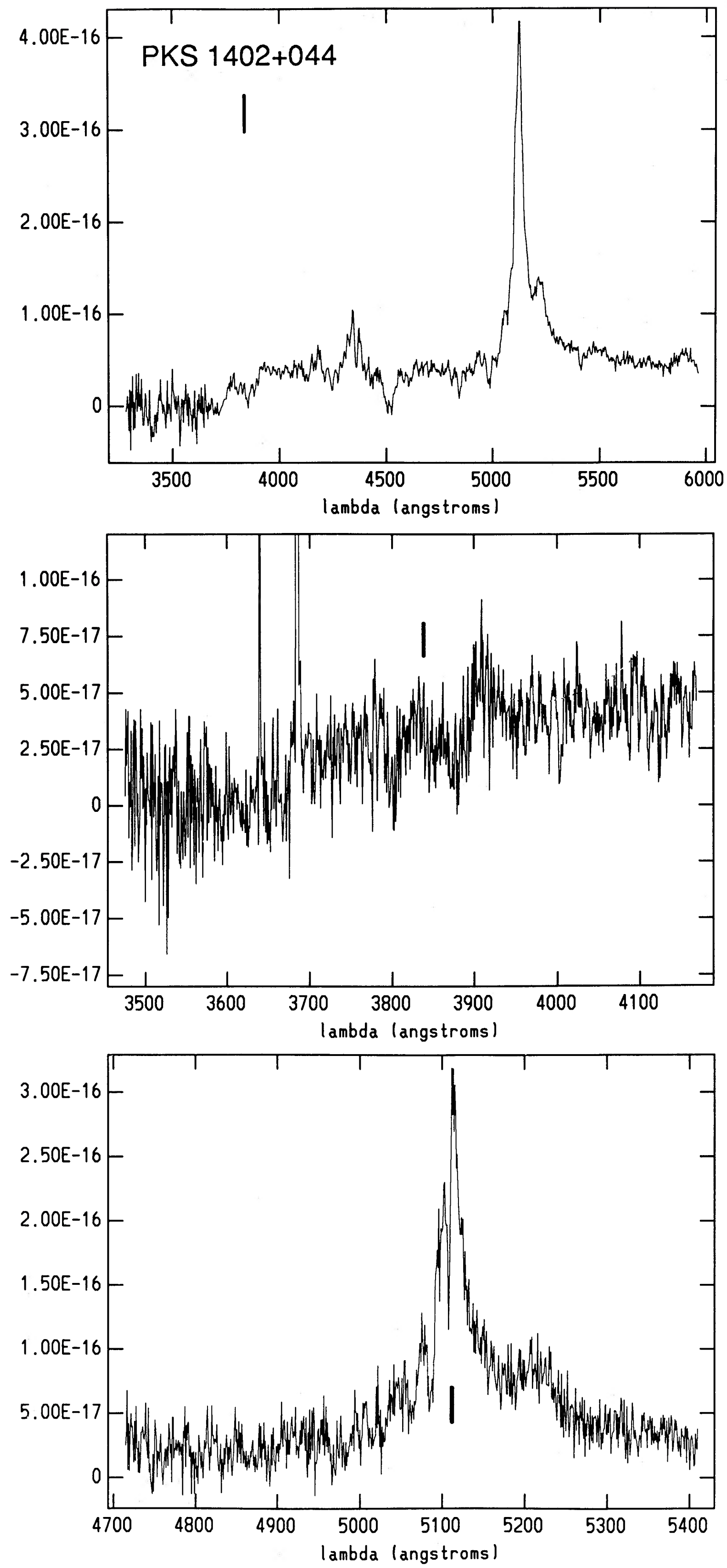

FIG. 7.—(*a–c*) Same as Fig. 1, but for PKS 1402+044. We could not remove the cosmic ray hits near 3700 Å on Fig. 7*b*.

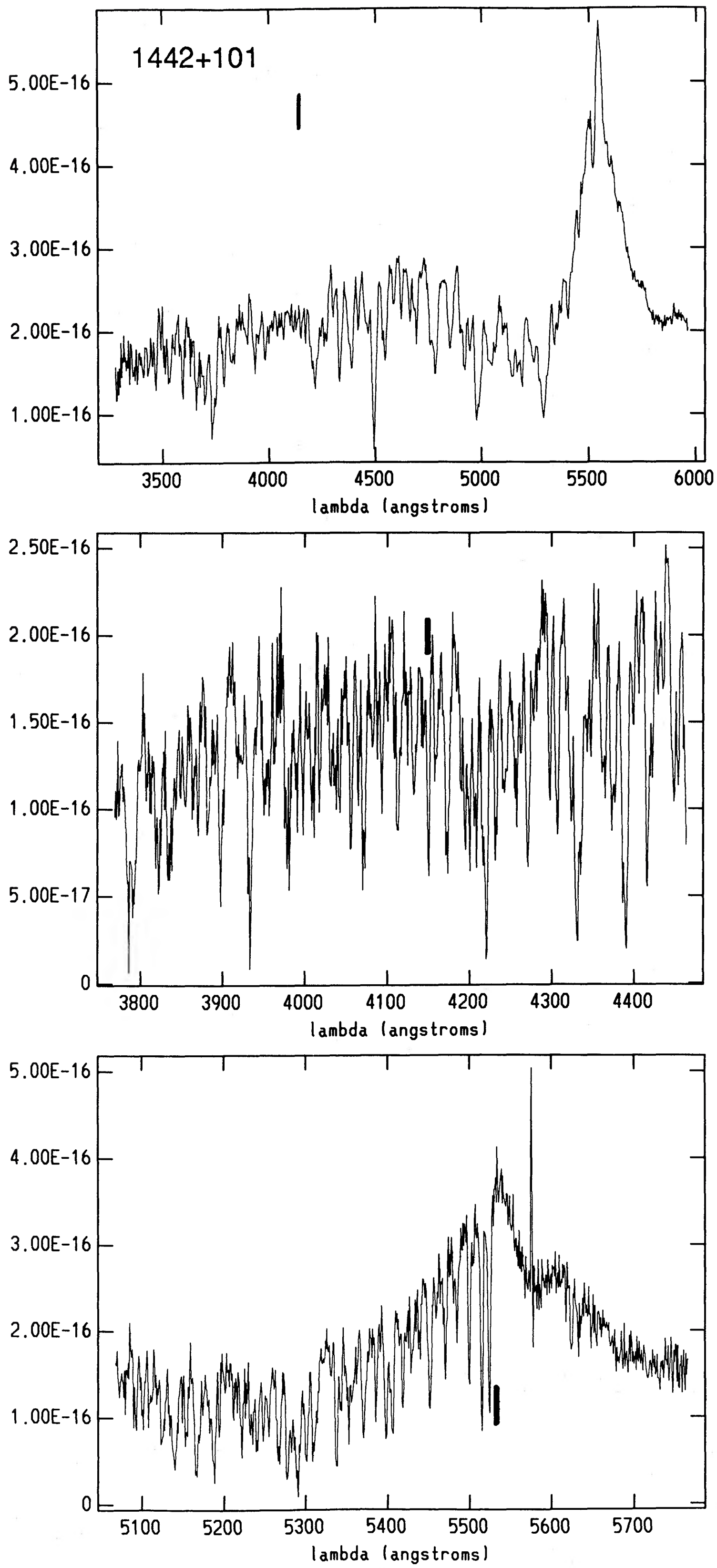

FIG. 8.—(*a–c*) Same as Fig. 1, but for 1442+101

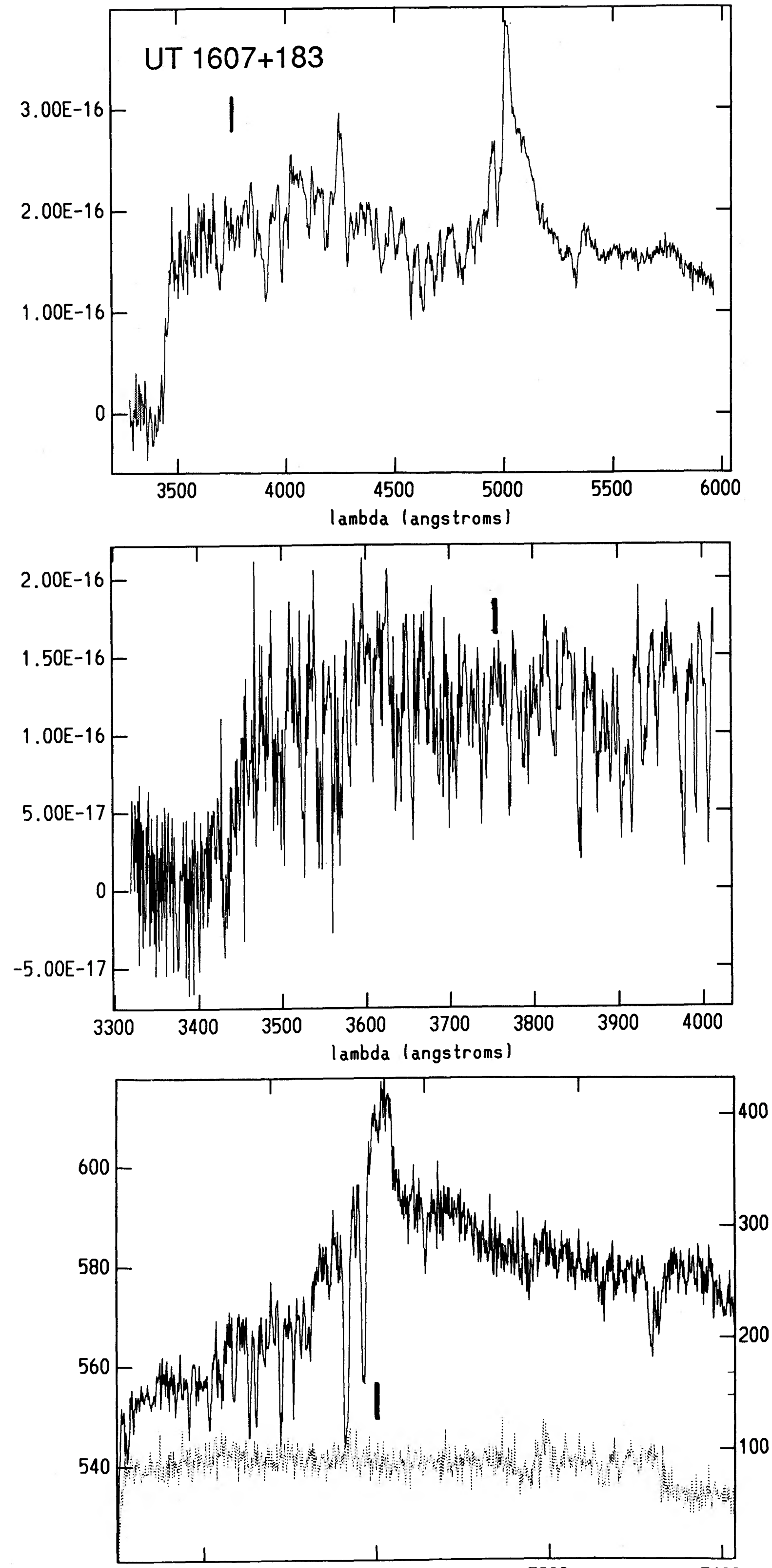

FIG. 9.—(*a–c*) Same as Fig. 1, but for 1607+183. The flux and wavelength calibration scans for Fig. 10*c* were lost in a file transfer from the telescope computer, so the wavelength scale is approximate (±10 Å), and no flux calibration was possible. We show the total count spectrum including the background, and also the background spectrum properly scaled.

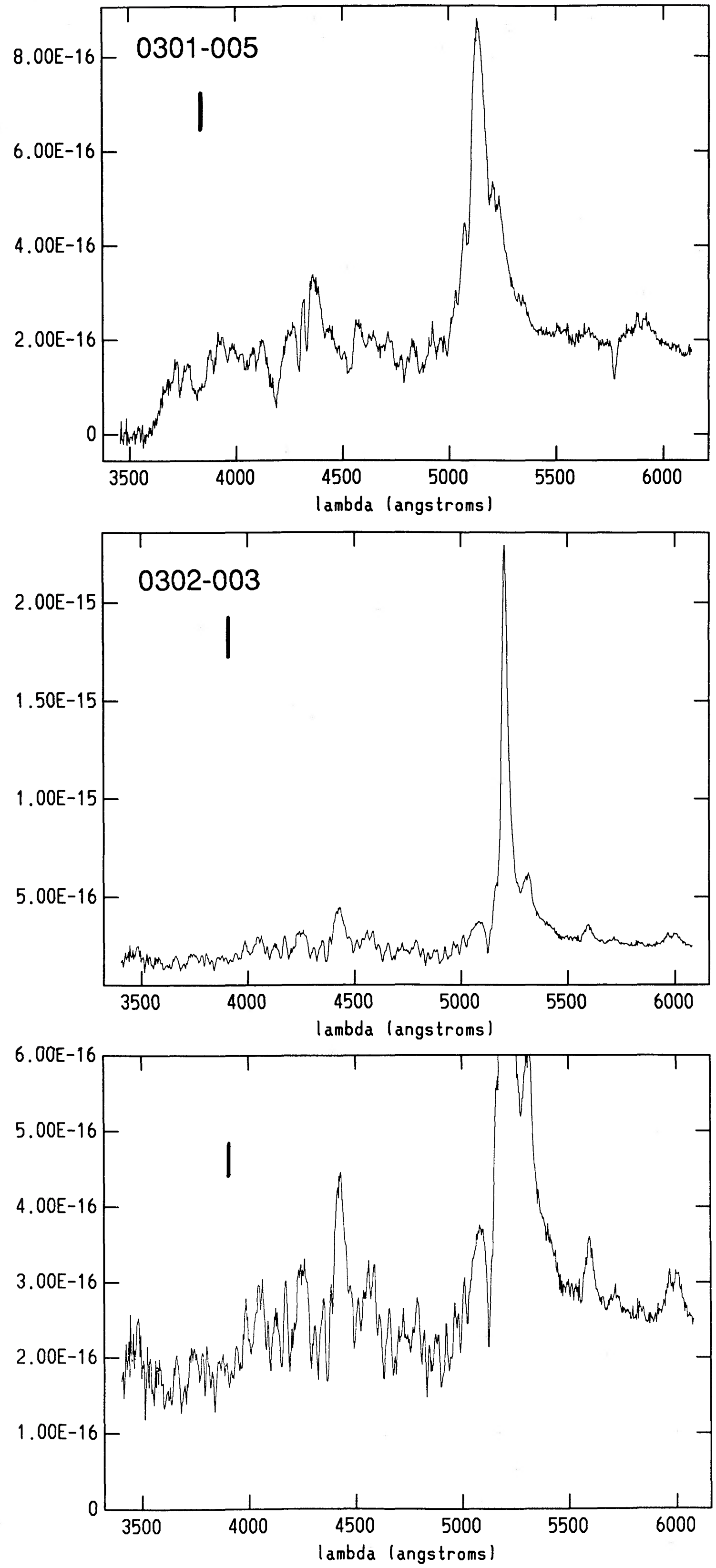

FIG. 10.—(*a*) Large-aperture, low-resolution spectrum of 0301−005; (*b*) large-aperture, low-resolution spectrum of 0302−003; (*c*) Same as (*b*), but with expanded vertical scale.

interesting feature. There is a complete LLS at ~ 3490 Å. The spectrum indicates that the edge could be ~ 55 Å wide, although high-resolution data on this part of the spectrum would be necessary in order to be sure that the spectral broadening is real.

Next we study our high-resolution data to help determine the nature of the partial, systemic edge. In Figure 1*c* we show a high-resolution spectrum of the Lyα region, with our adopted line peak marked. The absorption line at 5252 Å could be Lyα from a cloud producing the edge. If so, its narrow profile would rule out an accretion disk origin for the absorption, because there is no rotational broadening. (Even a disk viewed precisely face-on would have some broadening due to the range of gravitational redshifts of the contributing disk annuli.) Chaffee *et al.* (1985) studied the curve of growth of the high-*n* lines associated with the 5252 Å Lyα line and concluded that *it does have sufficient column density to produce the partial edge.* Therefore the absorbing cloud probably produces the edge, with the apparent broadening due to the combined effects of the high-*n* lines and other absorbers.

2. *S4 0636+680* (*Fig. 2a–2c*)—This flat-spectrum radio quasar shows an intervening edge (a normal LLS) near ~ 3590 Å. The high-resolution data suggest that it might be spectrally resolved or double. They also show a flat-decrement Lyman line series at $Z = 2.903$, which may arise in the same cloud.

Longward of the LLS wavelength, there is a continuum falloff which *could* be interpreted as a $\sim 30{,}000$ km s^{-1} broad absorption edge at the systemic redshift. The breadth of this possible edge, and the LLS at ~ 3590 Å, mean that the velocity is too poorly determined to make a search for associated narrow lines. Galactic foreground reddening contributes to the continuum falloff [$E(B-V) \sim 0.09$ according to the Burstein and Heiles 1982 maps].

3. *0642+449 = OH 471* (*Fig. 3a–3c*)—This is a steep-spectrum radio quasar showing complete absorption by a wavelength of 3800 Å. No atmospheric edge can be complete, especially in a disk with a range of temperatures, so an absorber external to the continuum source is definitely involved. The spectra show a strong Lyman series through Lyγ at $Z = 3.113$. (Shortward of Lyγ the SNR becomes low.) This cloud is probably contributing significantly to the edge.

Looking at the low- and high-resolution spectra together, this object seems to have a separate partial edge extending from 3935 Å to 4000 Å (-6000 km s^{-1} to -1100 km s^{-1}). (See also the spectrum of Wolfe *et al.* 1986.) Such a blueshift is possible for an accretion disk which is close to edge-on. The width of the partial edge, only 0.01*c*, if the rather small for this interpretation, however.

The significant velocity dispersion could alternatively mean that BEL clouds are producing the edge. The BEL clouds probably have very little internal velocity dispersion, a circumstance which minimizes their effectiveness as Lyα absorbers. However, the clouds which dominate the production of emission lines are thought to have column densities greater than $\sim 10^{22}$, so they would produce damped Lyα. Even a single canonical BEL cloud would produce a conspicuous damped Lyα absorption line. We see no strong Lyman line series corresponding to our edge at 3935 Å to 4000 Å. Many absorbing clouds of low velocity dispersion and low individual column densities could explain the data.

Galactic reddening affects the overall continuum shape of this object [$E(B-V) \sim 0.16$; Burstein and Heiles 1982].

4. *MC5 0938+119* (*Fig. 4a–4c*)—There is no obvious edge at the systemic redshift in this flat-spectrum radio quasar. The fact that the edges are not universal suggests that they are not a fundamental byproduct of the emission mechanism, but are due to an absorption process of some other kind. There is, however, some type of structure in the spectrum. There may be a partial edge at ~ 3600 Å. This is supported by the appearance of the spectrum of Beaver *et al.* (1976).

5. *1159+123* (*Fig. 5a–5c*)—An interesting absorption edge is observed near the systemic position in this radio-quiet object. (See also the spectrum of Hazard *et al.* 1986.) The edge starts at $\sim +3100$ km s^{-1} (~ 4145 Å) and appears to extend to $+6900$ km s^{-1}, but it could possibly be intrinsically sharp and just broadened by forest lines. It is partial ($\sim 70\%$), apparently due to partial covering rather that limited optical depth because there is no rapid recovery shortward of the edge. However, the partial-covering argument is not conclusive because of the limited wavelength coverage and the unknown underlying continuum shape. (Accretion disk edges would probably show rapid recoveries. They would also generally be broader than this observed edge.)

Between 3365 Å and 3466 Å the spectrum of 1159+123 is extinguished, presumably by normal LLS clouds. (No corresponding Lyman lines would fall on our high-resolution scans.) As in some other cases, it is interesting to note that this intervening edge does not appear to be simple and sharp at this resolution.

There is a strong Lyα absorption line at ~ 5501 Å, corresponding to a velocity fairly close to the blue limit of the near-systemic edge (Fig. 5*c*). The Lyα absorption cloud does have a substantial column density, because we see corresponding Ly lines at least up to Lyη. The N V doublet is present, and C III at 977 Å may be as well. The 5501 Å absorption line absorbs the emission line as well as the continuum, so that it arises in front of the BEL region. If it is really associated with the edge, then the partial nature of the edge must therefore derive from limited optical depth rather than partial covering. The fact that the flux does not recover below the edge would then imply a somewhat fine-tuned downturn in the intrinsic spectrum.

The Lyα scan shows that the absorption lines extend to substantial positive velocities—here up to $\sim +2000$ km s^{-1} for the 5501 Å Lyα line. This could mean either that the forest clouds (and the metal system corresponding to Lyα at 5501 Å) have substantial peculiar velocities, or else that the systemic redshift is substantially higher than indicated by the high-resolution Lyα profile. (Neither of these interesting possibilities much affects the discussion in this paper.)

6. *1206+119* (*Fig. 6a–6c*)—Our spectra (and the data of Hazard *et al.* 1986) show a complete absorption edge near the systemic position in the spectrum of his radio-quiet quasar. Again the complete absorption requires an extrinsic rather than an atmospheric edge. The edge starts at ~ -2600 km s^{-1}. It extends to at least $+1000$ km s^{-1}, and possibly to $+7000$ km s^{-1}.

The absorption line at 4890 Å–4900 Å is very strong. The trough is not uniformly black because it is a blend: identification of the short wavelength, black side as (damped) Lyα leads to the discovery of corresponding Ly series lines up to Lyη, as well as C II λ1334, Si II λ1304, O I λ1302, Si II λ1260, and probably C III λ977.

Although ~ 3400 km s^{-1} blueshifted relative to the starting edge position, the absorption lines are probably associated with it. This means that the continuum is effectively extinguished at a rest wavelength of 922 Å. Note that the edge absorber cannot be a BEL cloud because the corresponding narrow lines absorb Lyα emission photons as well as continuum photons. The spectrum also shows absorption in the 5525 Å–5615 Å region, which could possibly be a Si IV broad absorption line, although there is no corresponding feature for N V. A check of the two-dimensional spectrum shows no obvious problems such as cosmic-ray hits at that wavelength.

7. *PKS 1402+044* (*Fig. 7a–7c*)—The optical spectrum of this steep-radio-spectrum quasar is rather confusing. There is complete absorption starting at 3728 Å. The spectra are too noisy to show many associated Lyman lines, but a possible Lyα can be seen.

The edge may be sharp, or it may continue to 3755 Å or even $\sim$3900 Å (see Fig. 7*a* and *b*, and also the data of Wolfe *et al.* 1986). The velocities are -8300 km s^{-1} at 3728 Å, -6200 km s^{-1} at 3755 Å, and $+5200$ km s^{-1} at 3900 Å. Since the absorption is complete, it is not indicative of a disk atmosphere.

8. *OQ172 = 1442+101* (*Fig. 8a–8c*)—This well-known steep-spectrum radio quasar was first repoted by Wampler *et al.* (1973), and additional spectroscopy can be found in Baldwin *et al.* (1973). It shows no obvious feature at the systemic edge position, although a 10%–20% broadened edge cannot be ruled out.

9. *UT 1607183* (*Fig. 9a–9c*)—We thank B. Wills for telling us about this steep-spectrum radio emitter. There is no edge detectable at the systemic position. However, there is a complete absorption edge with a substantial relative blueshift. It happens to fall within our high-resolution wavelength range, and appears spectrally resolved, extending from $\sim$3390 Å to $\sim$3500 Å.

There is a strong absorption line visible in the low-resolution spectrum; it must be Lyα, because corresponding high-*n* lines are seen at high resolution, at least up to Lyε. This system has a redshift of 2.758, and it may produce the absorption edge. This suggests that intervening material can simulate a resolved edge even in our high-resolution data, and so it must be considered even for resolved edges near the systemic redshifts.

10. *0301−005*—For this object and the next one, we have only low-resolution large-aperture data. Neither one is a known radio emitter. For 0301−005 we measure a wavelength of 5016 Å for the Lyα emission line peak in the low-resolution spectrum (Fig. 10*a*). Applying a 500 km s^{-1} blueshift for the effects of the forest (see above), we adopt a redshift of 3.119. There is no obvious edge near the systemic redshift, but there is a complete and very broad LLS extending from $\sim$3585 Å to $\sim$3670 Å. The broadening could be attributed to multiple components covering a huge velocity range, or to high-*n* lines from a few clouds of high column density over a moderate velocity range.

11. *0302−003*—This optically selected quasar happens to be projected only $\sim$23′ or $\sim$6.5 Mpc from the previous one (for $H_0 = 75$, $q_0 = \frac{1}{2}$). The 0302−003 spectrum shows a partial edge at $\sim$3585 to 3670 Å (Fig. 10*b*, *c*). We adopt a systemic redshift of 3.275 using same method as for 0301−005. Then the partial edge has a relative velocity of $-10{,}700$ km s^{-1} to -7000 km s^{-1}. It is a candidate accretion disk edge, but we cannot make a sensitive check for associated narrow absorption lines because we have no high-resolution data.

IV. DISCUSSION

Our conclusions will ultimately derive from the fact that few if any quasar spectra show accretion disk edges or BEL cloud edges. Therefore the conservative approach is to give possible cases of such edges the benefit of every doubt.

a) Are Any of the Edges Intrinsic to the Quasars?

This paper is about quasars and not cosmologically distributed absorbing clouds, so we must consider which of our edges might be intrinsic and which extrinsic to the objects under study. Unfortunately this is not just a matter of whether or not the edges appear broad. Clustered intervening clouds with low-velocity dispersion (tens of km per second) but high column density ($> \sim 10^{18}$?) can show broadened edges in low-resolution data due to overlapping high-*n* absorption lines. One piece of evidence that this happens in nature is that Tytler (1982) finds that the half-power points in observed LLSs occur at rest wavelengths of 918 Å on average, by comparison with the associated Mg II absorption. In order for the unsaturated high-*n* lines to have sufficient equivalent width to depress the continuum, they need to be broadened or clustered over several hundred km per second. Clustering is more likely, since studies of absorption line ratios indicate much smaller values of the Doppler *b*-parameter. The intensively studied $Z = 3.5519$ metal-containing absorption system in PKS 2200−330 is fairly narrow, with an actual clustering velocity range of $\sim$900 km s^{-1} (Hunstead *et al.* 1986). The individual components have *b*-values much smaller than this. However, in the 10 Å resolution discovery spectrum by Peterson *et al.* (1982) the edge looks $\sim$30,000 km s^{-1} wide! In the case of PKS 2200−330 the Lyα rest equivalent width is 3.43 Å, a line strength which we could easily detect. Although our large-aperture spectra are comparable in resolution to that of Peterson *et al.* (1982), our small aperture data are nearly as high in resolution as the data of Hunstead *et al.* (1986). If all objects behave as PKS 2200 − 330, our high-resolution data would not be misleading regarding the true velocity range of the edge. However, each case is considered individually in § III.

Tytler (1982) and Lanzetta (1988) have concluded that the LLS statistics are consistent with *all* $\tau > 1$ edges in quasar spectra being intervening. Could that be true of all of the edges in this paper? Lanzetta's best-fit evolution formula is $N(Z) = 0.55(1 + Z)^{0.48}$. As we can see from Figure 11, this predicts the incidence of complete or nearly complete systems in our data fairly well. (Our histogram has not been corrected for the inability to detect systems at redshifts below other systems in the same object.) Our plot also shows that we detect several weaker edges. They are all near the systemic redshifts. This provides a bit of evidence that the weak edges are actually intrinsic. There is no published estimate of the incidence of weak systems due to cosmologically distributed clouds.

There are several other minor arguments for attributing the weak edges to intrinsic processes. All three good cases seem to have significant redshifts of their midpoints relative to systemic. None of these edges recovers strongly at wavelengths below the edge, suggesting partial covering rather than small optical depths (but see the discussion in § III). Finally, since weak edges require low column densities, the edge broadening cannot be attributed to high-*n* lines from a single system unless the *b*-value are greater than $\sim$100 km s^{-1}. (Clustered systems are possible.)

We will tentatively assume that the weak edges near systemic redshift (those in S5 0014+813, 0302−003, and 1159+123) are intrinsic, and that the other edges are intervening. As noted, our approach is to give the thin accretion

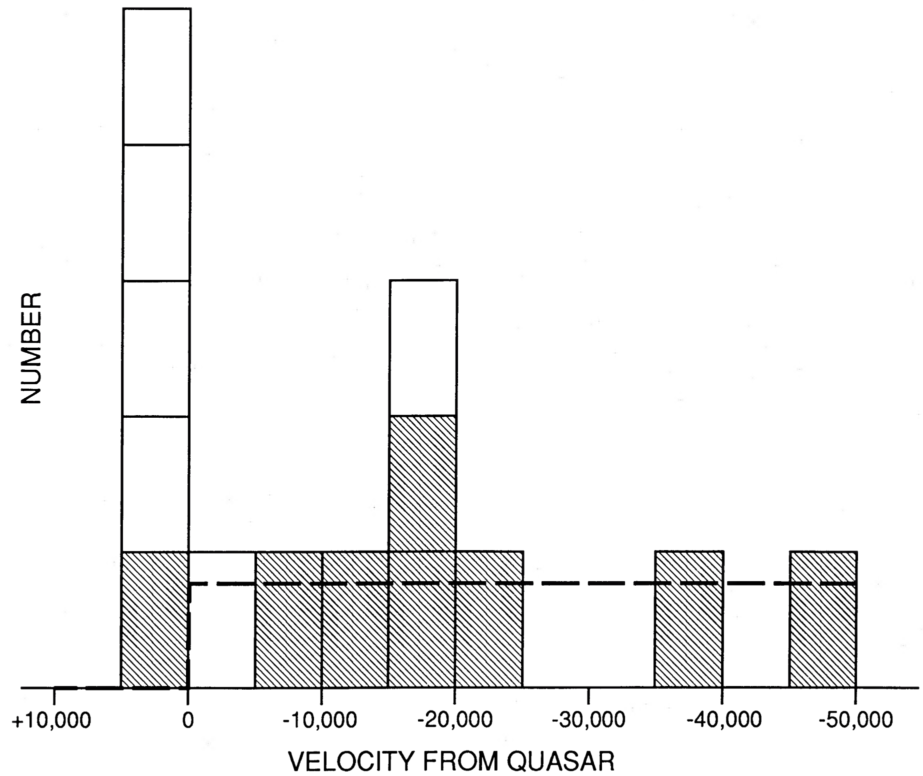

FIG. 11.—Histogram of the number of edges detected as a function of velocity relative to that of the quasar. Filled rectangles indicate complete edges, and empty rectangles indicate partial edges. The expected number of intervening edges with $\tau > 1$ is taken from Lanzetta (1988).

disk model the benefit of every doubt, and see whether it must still be rejected.

b) If Some of Our Edges Are Intrinsic to the Quasars, Can They Be Attributed to Accretion Disk Atmospheres?

S4 0014+813 has an edge apparently indicative of thermal disk emission (it is broadened, partial, and perhaps even gravitationally redshifted), but we cannot favor this interpretation. Chaffee *et al.* (1985) have concluded that a narrow absorption line system has sufficient column density to produce the edge. There is also a strong absorption line system associated with the partial edge in 1159+123. If these identifications are correct, the edges cannot be due to disks, because the lines are very narrow. Recall that for the third object, 0302−003, no high-resolution data were available for making this test.

A second reason why the disk interpretation is doubtful is that an explanation which is fundamental to the emission mechanism implies that the edges should be fairly universal, especially because our data can show even highly broadened edges. We have some objects with no edges near the systemic positions. Furthermore, *Kinney et al.* (1985, and in preparation) *find no partial systemic edges in the spectra of 22* $Z < 0.8$ *quasars* with reasonably good *IUE* data. (The *IUE* data are noisy but they do not suffer from the effects of the Lyα forest, and for these 22 objects they could show edges like those which we report here.)

A third concern relates to the redshifts of the edges relative to the systemic position. The influence of disk inclination on the edge positions gives some flexibility in fitting the spectra. Specifically, occcasional redward deviations from systemic can be attributed to gravitational redshifts in face-on models, while blueward deviations can be attributed to Doppler shifts in more edge-on disks. However, it may be illegitimate to invoke *any* orientation effects in accretion disks. The reason is that the models predict substantial polarization perpendicular to the disk (radio jet?) axes, whereas we actually observe small polarization parallel to the jet axes (see Antonucci 1987). An optically thick disk corona or wind could depolarize the disk radiation, *but it would also isotropize it.* (See Antonucci 1987 for a listing of other disk problems.)

Coleman and Shields (1988) have proposed roughing up the disk surface in order to get rid of the predicted polarization. The requirements for fitting the observations are quite specific. The substantial polarization perpendicular to the disk axes must essentially always be converted to a small polarization parallel to the disk axes. Furthermore in these models the scattering photosphere must follow the surface roughness closely. This requirement may conflict with the nearly-Eddington accretion rates derived from spectral fits, and the low surface gravities required to get sufficient electron scattering to produce weak Lyman edges.

Let us pursue the idea that the low incidence of partial edges means that most disks are surrounded by hot opaque coronae or winds. This could result in most edges being broadened beyond recognition, and it would also destroy the polarization signature. It would exacerbate the problem with the time scale and nature of variability (see Antonucci 1987). It would also imply that the objects with observable edges should show the strong disk polarization.

c) If the Edges are Intrinsic to the Quasars, Can They Be Attributed to Absorption By Broad Emission Line Clouds?

Another possible explanation for the systemic edges is absorption by BEL (or related) clouds. We know that the BEL clouds are there, and that they have a nonnegligible covering factor. (Oke and Korycansky 1982 find that $\sim 8\%$ is expected for similar objects, based on their spectral slopes and Lyα emission equivalent widths. Energetic arguments lead to very high covering factors; Netzer 1985.) This can account for the fact that some objects show edges and some do not, assuming only that the clouds are not both small and distributed in a spherically symmetric manner about each quasar. In fact, since our edge incidence and optical depths are both significant, the absorbers must reprocess substantial Lyman continuum emission. However, *clouds of the high column densities normally invoked to explain certain emission line ratios would produce damped Lyman lines, which would be seen in some cases and are not.*

Of course, the lack of strong Lyα absorption could be taken as evidence for low column densities and low b-values in the Lyα-emitting clouds. Still, if the *partial* absorption is in fact due to BEL clouds, we can conclude that the individual clouds are probably smaller than the continuum sources. If the continuum source sizes are ~ 10 gravitational radii for 10^8 solar mass black holes, the clouds would need to have transverse sizes of less than $\sim 10^{13}$ cm. In this scenario the clouds would cross the continuum sources on time scales of days. Rapid variability of the edges would be possible. Such variability is not apparent in a comparison of our data to published data for several objects.

If BEL clouds cause the edges we can get some information about the cloud velocity fields. In the three good cases (S5 0014+813, 0302−003, and 1159+123), the clouds would seem to be infalling. In the canonical clouds of enormous column density, the high n-lines would be damped, and could extinguish the continuum longward of 912 Å. However, we can rule that out because there is no damped Lyα and Lyβ. Perhaps the edges could be broadened and shifted by high n-lines from a multitude of low column density, low velocity dispersion BEL clouds.

The BEL cloud hypothesis for the Lyman edge absorbers cannot explain the difference between the incidence of the weak edges at high and low redshift. (Recall that no such edges are seen in the *IUE* data of Kinney *et al.* [1985, and in preparation].) Can this hypothesis at least accommodate that fact, without leading to contradictions? The Lyα emission-line equivalent widths of high-redshift quasars are not generally higher than for low-redshift objects. In fact (perhaps owing to their luminosities), their emission-line equivalent widths are actually lower in general (Baldwin *et al.* 1977; Kinney *et al.* 1985). According to Figure 2 of Kinney *et al.* (1985), objects in the luminosity range of those in this paper typically have several times lower Lyα equivalent widths than those in the luminosity range of the Kinney *et al.* (1985) *IUE* objects. Our Lyα emission-line equivalent widths are not as low as those of most quasars in their luminosity range, however.

We can think of two reasons why the equivalent widths might be low in high-redshift objects, despite the apparently higher covering factors. First, the ratio of the number of ionizing continuum photons to 1216 Å continuum flux may be lower. Our photometrically valid large aperture data show spectral slopes of ~ -1 to -2 in the Lyman edge-Lyα wavelength interval, steeper on average than the slopes Kinney *et al.* (1985) measured for their objects. The Lyα forest adds noise to the measurements, which are shaky anyway because of the small wavelength interval used. The forest can only make the observed continuum bluer in the Lyβ–Lyα range, but below Lyβ the high n-lines from many redshift systems can cause a reddening. Bechtold *et al.* (1984) and Steidel and Sargent (1987) have argued that the apparent redness of the UV continua of high-redshift quasars is in fact the result of absorption by intervening material. The other reason that the equivalent widths may be lower in the high-redshift quasars is that their emission lines could lie on top of Lyα absorption from clouds producing the edges. In general this effect would be second-order in the covering factor, and the spectra show no evidence for it. In conclusion we cannot argue that the partial, systemic edges are the result of absorption by BEL clouds.

d) Can the Edges Be Attributed to Absorption By Environmental Material?

We have considered the possibility that the edges are produced by environmental material at distances of 10–100 kpc from the quasars. Different environments could explain the lack of similar edges in the *IUE* data on lower redshift objects. Furthermore, Barthel and Miley (1988) have invoked clouds of high covering factor and high column density around high-redshift quasars in order to explain the bending of radio jets. Such material would produce absorption edges near the systemic redshifts. It would also produce copious Lyα emission on scales of order 10″ around the quasars. Our standard reductions of the data as presented here were done with optimal extraction techniques, which are insensitive to extended emission, so we reexamined our two-dimensional images and reextracted the large-aperture (8″–12″ × 2′) spectra in various ways. We did not detect any extended Lyα emission. This (and the published Lyα imaging surveys) strongly disfavor the hypothesis of large covering factors of high column density cool material surrounding high-redshift quasars.

e) Some Related Ideas in the Literature

The case of 3C 273 is interesting and partially analogous to our objects. Reichert *et al.* (1988) discovered that the continuum of this object is depressed below the Lyman edge, using some noisy but statistically significant data from the *Voyager* spacecraft. Because of the noise level and the limited spectral coverage they could not be sure that the depression was an edge rather than simply due to spectral curvature; because of problems with subtraction of geocoronal Lyβ, they could not tell whether or not the apparent edge was spectrally resolved. Nevertheless the 3C 273 continuum seems to behave like those of some of our objects, and much of the thoughtful discussion in Reichert *et al.* (1988) is relevant here. They emphasize the strong constraints obtainable from the absence of any corresponding Lyα absorption in 3C 273. Specifically, for extrinsic absorption it is necessary to invoke a cloud with very low velocity dispersion, and with a column density just below that required for damping the Lyα absorption line. For that reason they favored the accretion disk interpretation. Considering our data and those on 3C 273 as a group, plausible corresponding narrow lines are often seen, so that we cannot favor the general applicability of the accretion disk model.

Reichert *et al.* (1988) rejected absorption by the BEL clouds for 3C 273 because that object shows no strong X-ray absorption, but the X-rays may be beamed from the jet in that particular case, so they may not follow the same path as the UV light of the "big blue bump". For the BEL cloud idea, that leaves the problem of the lack of Lyα absorption which in the case of 3C 273 could conceivably be hiding under the Lyα emission line if the absorption were very broad. Reichert *et al.* (1988) mentioned the interesting idea that the absorption could be due to thermal material entrained in the jet, which is thought to lie near the line of sight in 3C 273. Our edges occur in steep-spectrum and radio-quiet quasars as well, which is not expected in this hypothesis.

Reichert *et al.* (1988) point out that the edge detections and limits result in very low limits to any reddening of the quasar continua, because any dust along the line of sight to the quasars would probably be accompanied by some neutral gas. For a Galactic dust-to-gas ratio, the limits on $A(V)$ are only 10^{-4}! As Reichert *et al.* (1988) also point out, this is not encouraging for attempts to solve the emission-line "energy budget" problem with reddening (e.g., Netzer 1985). Perhaps the quasar continuum could keep the gas very highly ionized without destroying the dust (Laor 1989, private communication).

Because our objects were selected for high redshift and high apparent brightness, they have a good chance of being amplified by gravitational lensing, according to Surdej *et al.* (1988). Where possible, we have examined our spatial profiles for evidence of widths greater than the point spread functions as determined from nearby field stars, and there is no obvious broadening. The possibility that our quasars are boosted somewhat in flux by gravitational lensing is interesting, but it does not affect our discussion in any obvious way. It may have helped our signal-to-noise ratios.

f) Why Are No BEL Clouds Ever Seen in Absorption?

Substantial covering factors are expected for the BEL clouds based on photon-counting and energetic arguments, as noted above. A canonical BEL cloud seen in absorption would produce damped Lyman absorption lines. The lines should absorb continuum but not emission line flux. Let us consider the fact that no such thing has ever been demonstrated in a quasar spectrum.[1] This seems to rule out emitting clouds larger than the continuum source size. In fact even small clouds would sometimes produce partial but damped Lyman lines unless the covering factors are always very small. Even if we abandon the high column density idea, it is surprising that no good cases of BEL cloud Lyman edges are known. (For this we would at least require edges whose corresponding Lyα absorption removes only continuum photons.)

We should consider seriously the possibility that quasars with BEL clouds along the line of sight are classified as something else, either *IRAS* galaxies or radio galaxies. This does not mean equating these different classes completely, but merely that some objects could have a classification which depends on viewing aspect. Regarding the radio quasars, Barthel (1989) shows that some perceived problems with the beaming model could be resolved if the nuclei have opaque tori perpendicular to the radio jet axes as inferred from spectropolarimetry (Antonucci 1984, 1987; Antonucci and Miller 1985). This would mean that nearly edge-on radio quasars and broad line radio galaxies are classified as distant narrow-line radio galaxies. (Spectropolarimetry arguments support this strongly in the case of 3C 234; Antonucci 1984.) Antonucci (1989) discusses the generalization of this idea, including tests with radio depolarization mapping.) E. S. Phinney (1988, private communication) has commented that all of the sight lines through BEL clouds might possibly pass through the opaque tori as well, in which case no object classified as a quasar would show BEL cloud absorption. Wills and Browne (1986) have presented strong evidence that the BEL region in radio quasars must be in a flattened configuration, perpendicular to the radio axes. That is just what is required for the idea to work.

V. CONCLUSIONS

One of our main conclusions is that it would be extremely sloppy and naive to assume that partial edges near the systemic redshifts are necessarily due to accretion disk atmospheres, since we can often and possibly always find associated narrow absorption lines. Observing objects with slightly lower redshifts will not change this because the incidence of LLS absorption is virtually independent of redshift (see § IV*a*) as presumably is any BEL absorption. Any candidate accretion disk edges must be carefully searched at high resolution for metal lines and also Lyman series lines.

We are not able to attribute the partial systemic edges reported here to accretion disk edges, BEL clouds, or environmental material in a convincing manner. They may be due to intervening material, despite the weak arguments to the contrary, but their significance and origin are still open questions.

Few if any quasars show Lyman edges from accretion disk atmospheres. In order to interpret the partial systemic edges as atmospheric, we need to explain why they are not more universal, why the "big blue bump" does not show the expected high polarization perpendicular to the radio axes, and why the variability is so rapid, with amplitude and phase independent of wavelength. (See Antonucci 1987.) In at least two cases out of three, associated narrow absorption lines seem to rule it out entirely, and we are making some new observations to study this further. The first two objections could be overcome by supposing that hot opaque coronae or winds surround most disks. Those showing the partial edges would be those with directly visible disks. Although this would exacerbate the variability problem, it is sufficiently interesting that we are measuring the polarization of known objects with partial edges, in the hope that they indicate unreprocessed accretion disk radiation.

In general thick disks should produce smaller edges than thin disks due to the lower effective surface gravity. Within the context of the present data alone, this is a possible explanation of the spectra. Some have in fact argued that the very luminous quasars, such as the subjects of this paper, are supercritical accretors, while the nearby lower luminosity objects are subcritical (e.g., Padovani 1988). However, it is important to recall that the relatively low luminosity objects studied with *IUE* also lack Lyman absorption edges (Kinney *et al.* 1985, and in preparation).

The disk model has enough problems that other ideas for the production of the "big blue bump" should be considered. Free-free emission from a hot gas with a range of temperatures and a high ionization parameter is attractive in many ways—in particular it does not produce edges or unseen polarization signatures.—The attractive idea is discussed in some detail by Antonucci and Barvainis (1988). Variability time scale is a problem only if we require a one-zone model to explain both the big blue bump and the 2 cm radio emission. Small opaque thermally emitting blobs expected by Ferland and Rees (1988) would avoid the polarization problem, and for extremely high densities, the Lyman edge problem as well. Of course nonthermal models such as that of O'Dell *et al.* (1987) do not predict any absorption edges.

[1] See Baldwin and Smith (1983). Also note that the possible BEL cloud edge found by Kinney *et al.* (1985) was shown by Bergeron (1986) to be due to a foreground galaxy.

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