BELOW THE LYMAN EDGE: ULTRAVIOLET POLARIMETRY OF QUASARS

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ABSTRACT

The Lyman edge at 912 Å is an important diagnostic region for studying quasi-stellar objects (QSOs). In particular, it reveals a great deal about the physical conditions within the atmospheres of accretion disks, a ubiquitous component of QSO theories. A robust prediction of accretion disk models is a significant polarization due to electron scattering just longward (in wavelength) of the Lyman edge, because of the wavelength dependence of the hydrogen absorption opacity. Observations of the Lyman edge regions of QSOs have shown scant evidence for the predicted features; few QSOs show the broad, partial Lyman edges expected to be common according to most theories, and none show the high polarizations expected longward of the Lyman edge. Still, polarization spectra of a small number of QSOs have shown a rising polarization (up to 20%) at wavelengths shortward of the Lyman edge. We have now doubled our sample of intermediate-redshift QSOs observed with the Hubble Space Telescope Faint Object Spectrograph spectropolarimeter to determine the amount of polarization on both sides of the Lyman limit. For this new sample of six objects, polarizations are low and mostly consistent with zero below the Lyman edge. Another important result of the new data is that it strengthens the conclusion that quasars are generally not polarized significantly just longward of the Lyman edge at ~1000 Å. There is no significant statistical wavelength dependence of the polarization longward of the Lyman edge, indicating that simple plane-parallel atmospheres with scattering-dominated opacity are not significant sources of UV flux in quasars.

Subject headings: accretion, accretion disks — polarization — quasars: general — ultraviolet: galaxies

1. INTRODUCTION

One of the fundamental components of most theories of quasi-stellar objects (QSOs) is an accretion disk. As gas is fed into the central regions of the QSO, residual angular momentum causes the gas to settle naturally into a disk. While most theories predict the formation of such a disk, few address the observational consequences of the disk models in detail. These theoretical studies have found that the Lyman edge at 912 Å is a powerful diagnostic feature for the physical characteristics of the disk.

The simplest disk models (quasi-static with viscous dissipation at large optical depth) predict Lyman edges in either emission or absorption, depending on the viewing angle and the physical details of the disk atmosphere. Such Lyman edges would be broadened by rotation of the disk and by general relativistic effects as light passes close to the central black hole. In most QSOs, such edges are not seen, although Koratkar, Kinney, & Bohlin (1992) found a small number of candidate "partial edges" in IUE data.

A second disk signature is the linear polarization, P, of the continuum from the disk. A purely scattering atmosphere will produce high polarization perpendicular to the disk axis. Again, this signature is not seen in any QSOs; in fact, QSOs generally show low optical polarization parallel to the inferred disk axis. Laor, Netzer, & Piran (1990) attempted to show that a disk atmosphere should have significant absorptive opacity and thus can produce dramatically lower optical polarization (albeit still perpendicular to the disk axis and thus inconsistent with the observations). A more robust prediction according to their work, however, is a rise in polarization with decreasing wavelength from the optical into the UV. Just longward of the Lyman edge, P is highest, since it is at these wavelengths that scattering best competes with absorption. Just shortward of the Lyman edge, as the absorption opacity increases, P should drop again. According to Laor et al. (1990), this polarization signature should appear even when no disk signature is seen in total flux.

In our first polarization study of three of the rare objects known from IUE spectra to have partial Lyman edges at the systemic redshifts, we found low polarizations longward of the edges, so we did not confirm the Laor et al. (1990) prediction. Surprisingly, we did find high polarization shortward of the edge in a couple of objects, contrary to the accretion disk predictions of Laor et al. (1990) but qualitatively explicable by effects found in the more detailed calculations of Blaes & Agol (1996); see also Agol & Blaes (1996). The previous studies of intermediate-redshift quasars (Koratkar et al. 1995, hereafter Paper I; Impey et al. 1995) included four objects, one of which shows only a marginal detection of polarization, while the remaining three objects show significant polarization (greater than a few percent) shortward of the Lyman edge. A study of three high-redshift objects observed from the ground failed to...
show any polarization changes at the edge position; most had tight limits on the polarization longward of the edge but noisy data shortward of the Lyman edge (Antonucci et al. 1996). PG 1630 + 377 is the only object yet observed that can be studied in any detail (Paper I). In this object P rises rapidly shortward of the edge, reaching 20% by 1600 Å (650 Å rest wavelength). The Lyα emission line also shows a high (7.3%) polarization at the same position angle. Antonucci et al. (1996) discuss polarization observations and other constraints on disk models in some detail.

Based on the small number of QSOs observed in the UV in polarization at the time of Paper I, we could say little about whether high polarization shortward of the Lyman edge is common. Hence, we have significantly expanded the UV polarization database by observing six bright, z > 1 QSOs both below and above the Lyman edge. In this paper we discuss these new spectropolarimetric ultraviolet observations from the Hubble Space Telescope Faint Object Spectrograph (HST/FOS). A difference with respect to our previous study, however, is that only two of the new objects were suspected to have partial edges in total flux at the systemic redshift. The rest were simply selected because they show significant flux at short wavelengths.

2. OBSERVATIONS

In their IUE archival search, Koratkar et al. (1992) identified six QSOs with partial Lyman edges consistent with edges from simple, thin accretion disks. The possible observational detection of accretion disk edges in these low-redshift quasars indicates that we are more likely to see the accretion disk and thus detect the polarization changes, as predicted by theory. Also, since these objects are low-redshift active galactic nuclei (AGNs), we expect the UV continuum shortward of Lyα to be less affected by intervening absorption (the Lyα forest). Three objects of the IUE sample (PKS 0405 - 123, PG 1338 + 416, and PG 1630 + 377) have already been discussed in Paper I. Our present sample includes two more objects (PG 0117 + 213 and PG 0743 - 673) from the IUE sample (see §3 for the new evaluation of these targets as possible partial Lyman edge candidates). The post-COSTAR FOS polarimetry capability does not extend to λ < 1600 Å, hence the sixth object (PG 1538 + 447 at z = 0.770) in the IUE list was not observed.

The four other QSOs in the present sample are objects with significant flux at the Lyman edge and shortward of the Lyman edge, extending to rest wavelengths ≤ 800 Å. In PG 1630 + 377 the rise in P occurs at rest wavelengths of 770 Å and below. The shortest wavelength that could be observed for the present sample was defined by either (1) the shortest wavelength at which the FOS polarimeter could work, which was 1600 Å, or (2) the existence in most objects of a sharp Lyman edge due to foreground gas at a lower redshift than the QSO. This latter constraint is often a significant one. The present sample consists of six radio-quiet QSOs, which are given in Table 1.

We observed the six objects, in cycles 5 and 6, with the HST/FOS spectropolarimeter to determine the amount of polarization on both sides of the Lyman limit at 912 Å. The targets were acquired in the 4'3 aperture using the binary acquisition procedure of the FOS. All observations were obtained using the FOS blue detector and the 1'0 aperture. Details of the observations are given in Table 1. Except for PG 0117 + 213, all observations were obtained at eight wave plate positions using the “B” wave plate, which is optimized for UV observations. PG 0117 + 213 was observed at four wave plate positions, since these observations were conducted before the change in the FOS spectropolarimetric observing strategy recommended by the FOS team. Because of the fewer wave plate positions, the PG 0117 + 213 data cannot be corrected as accurately for the FOS instrumental polarization (see details below).

The polarimetry calibrations are described in Allen & Smith (1992). The data were recalibrated using Allen’s calibration program, POLAR, because the current STSDAS pipeline calibration of polarization data is inadequate for post-COSTAR data. The basic calibration procedure is described in the HST Data Handbook (1998). The various calibration steps are (1) correction for dead diodes, (2) conversion to count rates, (3) subtraction of the background, (4) flat-field correction, (5) computation of the wavelength solution, (6) conversion to absolute flux, (7) correction for the wavelength-dependent FOS instrumental polarization, and (8) calculation of the Stokes parameters. In the postcalibration data reduction, the data were binned in various ways, depending on the signal-to-noise ratio (S/N) of the different data sets.

The introduction of the COSTAR mirrors introduced two ∼ 7" reflections in front of the FOS polarizer. These reflections therefore convert some of the linear polarization into circular polarization, requiring a correction to the linear polarization data. The residual wavelength-dependent instrumental polarization is ≤ 0.2% in observations of unpolarized standard stars after this correction is performed. Figure 1 shows the COSTAR-induced polarization in the unpolarized standard star BD + 28°4211. The

| Object          | z      | Rest Wavelength Range Observed (Å) | Grating Used | Exposure Time (s) |
|-----------------|--------|-----------------------------------|--------------|-------------------|
| PG 0117 + 213...| 1.493  | 623 - 930                         | G190H        | 10500             |
| PG 0743 - 673...| 1.512  | 892 - 1321                        | G270H        | 3100              |
|                 |        | 627 - 923                         | G190H        | 8693              |
|                 |        | 885 - 1311                        | G270H        | 4420              |
| PG 1247 + 267...| 2.038  | 763 - 1084                        | G270H        | 3640              |
| PG 1522 + 101...| 1.321  | 679 - 999                         | G190H        | 6630              |
|                 |        | 958 - 1419                        | G270H        | 1200              |
| PG 1718 + 481...| 1.084  | 755 - 1113                        | G190H        | 4600              |
|                 |        | 1067 - 1580                       | G270H        | 1640              |
| UM 18           | 1.899  | 543 - 800                         | G190H        | 10950             |
|                 |        | 767 - 1136                        | G270H        | 3640              |
discontinuity seen in $U$ around 2700 Å is due to the break between the G190H and G270H gratings. A note on how polarizations are calculated and manipulated should be made here. Since $P = (Q^2 + U^2)^{1/2}$ is a positive-definite quantity, it is often replaced by a "debiased" quantity, involving not only $Q$ and $U$ but also their uncertainties. As Miller, Robinson, & Goodrich (1988) show, however, the error distribution of the debiasing method normally used in optical polarimetry has a rather unsatisfactory form. Simmons & Stewart (1985) discuss various debiasing schemes. Throughout this paper we choose to quote the standard, biased polarization, $P = (Q^2 + U^2)^{1/2}$. This has the advantage of making the original Stokes parameters more readily accessible to the reader. We stress that all calculations, such as correction for instrumental polarizations or averaging over wavelength bins, are done on $Q$ and $U$, which are essentially unbiased.

The binned $Q$, $U$, $P$, and $h$ are given in Table 2, and Figures 3–8 show the Stokes parameters $Q/I$ (%) and $U/I$ (%) and the total flux for each object. In §3 we have calculated the 95% confidence level upper limits on polarization, using the confidence intervals derived by Simmons & Stewart (1985).

3. RESULTS
The new objects generally have low polarization. A brief description of each one follows.

3.1. PG 0117 + 213
This object was fitted by a massive, thin accretion disk by Laor (1990). It was selected in this sample because of the partial systemic edge seen with IUE. Our FOS observations show that the Lyman edge region in this object is highly affected by intervening material at $z \sim 1.36$ (noted by...
Koratkar et al. (1992), which has associated Lyx and Lyβ absorption lines (see Fig. 3).

Longward of the Lyman edge there are hints of polarization. Since the position angle is approximately constant with wavelength, one could combine all the bins longward of the Lyman edge and get polarization $P = 0.8\% \pm 0.5\%$ at $\theta = 116^\circ \pm 9^\circ$, but the uncertainty here includes a large (0.4%) contribution from uncertainties in the post-COSTAR polarization correction, given that it was taken in POLSCAN = 4 mode rather than POLSCAN = 8.

No polarization is detected shortward of the Lyman edge. The upper limits of the UV linear polarization (95% confidence level, as derived by Simmons & Stewart 1985) shortward and longward of the Lyman limit are $P = 1.4\%$ and $1.6\%$, respectively (see Table 3).

3.2. 0743–673

This object was also selected for an apparent partial systemic Lyman edge in the IUE total-flux spectrum. However, our FOS data show no Lyman edge. Koratkar et al. (1992) had noted that this object was a “weak” candidate for a discontinuity at the Lyman edge due to an accretion disk, because they could not evaluate the significance of the Lyman edge discontinuity in the low S/N IUE data.

| Object | $\lambda$ (Å) | $Q$ (%) | $U$ (%) | $P$ (%) | $\theta$ |
|--------|----------------|---------|---------|---------|---------|
| PG 0117 + 213 | $2007 \pm 137$ | $0.1 \pm 1.8$ | $-0.1 \pm 1.8$ | $0.1 \pm 1.8$ | ... |
| | $2194 \pm 50$ | $0.2 \pm 0.8$ | $-0.3 \pm 0.8$ | $0.4 \pm 0.9$ | ... |
| | $2400 \pm 93$ | $-0.3 \pm 0.7$ | $0.1 \pm 0.7$ | $0.3 \pm 0.8$ | ... |
| | $2568 \pm 75$ | $-1.2 \pm 0.6$ | $-0.3 \pm 0.6$ | $1.2 \pm 0.7$ | $96^\circ \pm 14^\circ$ |
| | $2755 \pm 112$ | $-0.2 \pm 0.5$ | $-0.9 \pm 0.5$ | $0.9 \pm 0.6$ | ... |
| | $3035 \pm 168$ | $-0.6 \pm 0.4$ | $-0.6 \pm 0.4$ | $0.8 \pm 0.6$ | $113^\circ \pm 14^\circ$ |
| | $3248 \pm 449$ | $-0.2 \pm 1.1$ | $-2.4 \pm 1.1$ | $2.4 \pm 1.2$ | $133^\circ \pm 13^\circ$ |
| PG 0743–673 | $1727 \pm 157$ | $-1.8 \pm 2.5$ | $-0.6 \pm 2.5$ | $1.8 \pm 2.5$ | ... |
| | $2072 \pm 188$ | $-1.6 \pm 0.9$ | $0.5 \pm 0.9$ | $1.7 \pm 0.9$ | $82^\circ \pm 15^\circ$ |
| | $2417 \pm 94$ | $-0.1 \pm 0.8$ | $-0.2 \pm 0.8$ | $0.2 \pm 0.8$ | ... |
| | $2587 \pm 75$ | $-0.6 \pm 0.8$ | $-0.1 \pm 0.8$ | $0.6 \pm 0.8$ | ... |
| | $2744 \pm 83$ | $0.4 \pm 0.8$ | $-0.8 \pm 0.8$ | $0.9 \pm 0.8$ | ... |
| | $3059 \pm 234$ | $0.2 \pm 0.4$ | $-0.5 \pm 0.4$ | $0.5 \pm 0.4$ | ... |
| PG 1247 + 267 | $2363 \pm 143$ | $-0.7 \pm 0.6$ | $-1.4 \pm 0.6$ | $1.6 \pm 0.6$ | $121^\circ \pm 11^\circ$ |
| | $2620 \pm 114$ | $0.4 \pm 0.6$ | $-0.2 \pm 0.6$ | $0.4 \pm 0.6$ | ... |
| | $2924 \pm 114$ | $0.3 \pm 0.5$ | $-0.3 \pm 0.5$ | $0.5 \pm 0.5$ | ... |
| | $3170 \pm 132$ | $-1.1 \pm 0.5$ | $-0.4 \pm 0.6$ | $1.2 \pm 0.5$ | $100^\circ \pm 14^\circ$ |
| PG 1522 + 101 | $1658 \pm 82$ | $3.8 \pm 1.9$ | $-2.8 \pm 1.9$ | $4.7 \pm 1.9$ | $162^\circ \pm 11^\circ$ |
| | $1828 \pm 87$ | $0.6 \pm 1.1$ | $-0.1 \pm 1.1$ | $0.6 \pm 1.1$ | ... |
| | $2005 \pm 87$ | $-0.1 \pm 0.8$ | $-0.6 \pm 0.8$ | $0.6 \pm 0.8$ | ... |
| | $2233 \pm 85$ | $-0.4 \pm 0.5$ | $-1.0 \pm 0.5$ | $1.1 \pm 0.5$ | $123^\circ \pm 12^\circ$ |
| | $2272 \pm 48$ | $-0.3 \pm 1.4$ | $0.1 \pm 1.4$ | $0.3 \pm 1.4$ | ... |
| | $2408 \pm 87$ | $-0.5 \pm 0.8$ | $1.0 \pm 0.8$ | $1.2 \pm 0.8$ | ... |
| | $2582 \pm 87$ | $-0.2 \pm 0.8$ | $0.9 \pm 0.8$ | $0.9 \pm 0.8$ | ... |
| | $2666 \pm 197$ | $-0.2 \pm 0.5$ | $-0.3 \pm 0.5$ | $0.3 \pm 0.5$ | ... |
| | $3179 \pm 115$ | $-2.0 \pm 0.9$ | $0.1 \pm 0.9$ | $2.0 \pm 0.9$ | $89^\circ \pm 12^\circ$ |
| PG 1718 + 481 | $1726 \pm 150$ | $-0.2 \pm 0.7$ | $0.3 \pm 0.7$ | $0.3 \pm 0.7$ | ... |
| | $2006 \pm 78$ | $0.2 \pm 0.5$ | $-0.6 \pm 0.5$ | $0.6 \pm 0.5$ | ... |
| | $2162 \pm 78$ | $0.3 \pm 0.4$ | $0.8 \pm 0.4$ | $0.8 \pm 0.4$ | $34^\circ \pm 13^\circ$ |
| | $2280 \pm 40$ | $0.9 \pm 0.5$ | $0.3 \pm 0.5$ | $0.9 \pm 0.5$ | ... |
| | $2284 \pm 60$ | $1.9 \pm 0.7$ | $-0.5 \pm 0.7$ | $2.0 \pm 0.7$ | $172^\circ \pm 10^\circ$ |
| | $2542 \pm 198$ | $0.2 \pm 0.3$ | $0.3 \pm 0.3$ | $0.4 \pm 0.3$ | ... |
| | $2918 \pm 177$ | $0.5 \pm 0.3$ | $0.3 \pm 0.4$ | $0.5 \pm 0.3$ | ... |
| | $3194 \pm 99$ | $0.1 \pm 0.6$ | $0.5 \pm 0.6$ | $0.5 \pm 0.6$ | ... |
| UM 18 | $1858 \pm 157$ | $-0.9 \pm 2.0$ | $-1.2 \pm 2.0$ | $1.5 \pm 2.0$ | ... |
| | $2167 \pm 152$ | $0.4 \pm 0.8$ | $-0.8 \pm 0.8$ | $0.9 \pm 0.8$ | ... |
| | $2416 \pm 193$ | $1.5 \pm 0.8$ | $-0.6 \pm 0.8$ | $1.6 \pm 0.8$ | $169^\circ \pm 14^\circ$ |
| | $2790 \pm 109$ | $0.2 \pm 0.8$ | $0.2 \pm 0.8$ | $0.3 \pm 0.8$ | ... |
| | $3008 \pm 109$ | $-0.2 \pm 0.8$ | $0.5 \pm 0.8$ | $0.5 \pm 0.8$ | ... |
| | $3205 \pm 88$ | $0.0 \pm 1.0$ | $-1.3 \pm 1.0$ | $1.3 \pm 1.0$ | ... |

Note.—Values of $\theta$ with formal uncertainties larger than 15$^\circ$ indicate less than 2 $\sigma$ detections of the polarization and hence are omitted from the last column. The value of polarization $P = (Q^2 + U^2)^{1/2}$ in this table. All values in the table have been rounded off to the first decimal. The polarization uncertainty for PG 0117 + 213 includes a large (0.4%) contribution from uncertainties in the post-COSTAR polarization correction, given that it was taken in POLSCAN = 4 mode rather than POLSCAN = 8.
FIG. 3.—FOS spectropolarimetry of PG 0117+213. The normalized Stokes parameters $Q/I$ and $U/I$ are shown in the top two panels, binned on either side of the Lyman edge, represented by the right-angled line. The bottom panel shows the total flux, $F_\lambda$, binned by 4 pixels = 1 diode. The value of $F_\lambda$ is given in units of $10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$.

No polarization is detected either shortward or longward of the Lyman edge (see Fig. 4). The upper limits of the UV linear polarization are $P = 7.5\%$ and $0.9\%$, shortward and longward of the Lyman limit, respectively (see Table 3).

3.3. PG 1247+267

Hints of polarization both shortward and longward of the edge position are seen. Since the position angles for all the bins are close, one could combine them to produce $Q = -0.4\% \pm 0.3\%$ and $U = -0.5\% \pm 0.3\%$ (see Fig. 5). This object is near the North Galactic Pole, where little interstellar polarization is expected. PG 1247+267 shows optical polarization of $0.41\% \pm 0.18\%$ at $\theta = 97^\circ \pm 12^\circ$ (Berriman et al. 1990), consistent with the HST/FOS UV data ($P = 0.6\% \pm 0.3\%$ at $\theta = 118^\circ \pm 12^\circ$; the upper limit on polarization is 1.1\%; see Table 3).

3.4. PG 1522+101

In this object, at longer wavelengths there is a marginal detection in $Q$ at the very edge of the G270H grating at 3180 Å (see Fig. 6 and Table 2). The UV polarization in the wavelength range longward of the Lyman edge is $P = 0.6\% \pm 0.3\%$ at $\theta = 76^\circ \pm 15^\circ$. If real, it is probably not from dust in the Galaxy at this sky position and this far into the UV. The optical polarization from Berriman et al. (1990) is $0.30\% \pm 0.15\%$ at $\theta = 97^\circ \pm 14^\circ$, which is consistent with the HST/FOS data.

At the shortest wavelength bin (rest wavelength of ~714 Å), there may be a marginal detection of polarization. If real, this would be at the wavelengths where we would have expected to see a rise in polarization, similar to that seen in Paper I. Since the detection of polarization is in a single wavelength bin and it has low significance, the data are also consistent with no detection of polarization shortward of the Lyman edge.

Once again, the upper limits of the UV linear polarization, shortward and longward of the Lyman limit, are $P = 3.3\%$ and $1.4\%$, respectively (see Table 3).

3.5. PG 1718+481

All data are consistent with zero polarization (see Fig. 7), while the optical polarization from Berriman et al. (1990) is

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**TABLE 3**

Upper limits on the UV polarization

| OBJECT                              | Shortward | Longward |
|-------------------------------------|-----------|----------|
| PG 0117+213...                     | 1.4       | 1.6      |
| PG 0743–673...                     | 7.5       | 0.9      |
| PG 1247+267...                     | 1.1       | 1.1      |
| PG 1522+101...                     | 3.3       | 1.4      |
| PG 1718+481...                     | 1.0       | 0.9      |
| UM 18...                            | 2.8       | 0.6      |

**Note.**—These upper limits of the UV linear polarization are 95% confidence levels as derived by Simmons & Stewart (1985).
0.40% ± 0.08% at $\theta = 76^\circ \pm 6^\circ$. The upper limits of the UV linear polarization, shortward and longward of the Lyman limit, are $P = 1.0\%$ and $0.9\%$, respectively (see Table 3).

### 3.6. UM 18 = 0002 + 051

All data are consistent with zero polarization (see Fig. 8). The UV linear polarization upper limits, shortward and longward of the Lyman limit, are $P = 2.8\%$ and $0.6\%$, respectively (see Table 3).

### 4. DISCUSSION AND CONCLUSIONS

Of the six QSOs identified by Koratkar et al. (1992) as candidate targets that have partial Lyman edges consistent with edges from simple, thin accretion disks, we now have spectropolarimetric observations for five QSOs. We showed in § 3.2 that one of these candidates, PG 0743 + 673, no longer qualifies as a partial Lyman edge object.

There are only 13 high- and intermediate-redshift QSOs that have spectropolarimetry observations shortward of the Lyman edge region. These objects come from this paper, Paper I, Impey et al. (1995), and Antonucci et al. (1996). At this point any detailed statistical tests of polarization distributions are certainly not warranted, given the inhomogeneous selection criteria and data quality and the highly model-dependent predictions. Yet, Lyman edge spectropolarimetry results can be summarized as follows:

1. Of the 13 objects, only three objects (PG 1630 + 377, PG 1338 + 416, and PG 1222 + 228; Paper I; Impey et al. 1995) show significant polarization at wavelengths shorter than 912 Å (Lyman edge). To these three objects we can add one more marginal detection (PKS 0405 − 123; Paper I). All 13 objects in the sample show a polarization signature that is inconsistent with any simple accretion disk model. Furthermore, approximately 30% of the sample show a rise in polarization shortward of the Lyman edge. This observed rise in polarization is qualitatively consistent with the disk models of Blaes & Agol (1996). A number of different interpretations of the UV signature have been given by Lee & Blandford (1997), Shields, Wobus, & Husfeld (1998), and by us in Paper I. We urge the interested reader to consult those papers for more details.

2. There are a total of five objects (PG 0117 + 213 from the present sample; PG1630 + 377, PG 1338 + 416, and PKS 0405 − 123; Paper I; 0014 + 813: Antonucci et al. 1996) that show candidate partial Lyman absorption edges due to accretion disks at the systemic redshift in total flux. Of these five objects, two (PG 1630 + 377 and PG 1338 + 416) have sufficient S/N at rest wavelengths of ≤750 Å and show significant polarization shortward of the Lyman edge (at least a few percent, detected at 4 $\sigma$ or greater significance). If the rise in UV polarization seen in PG 1630 + 377 is characteristic of objects with partial Lyman edges, we need to observe rest wavelengths as short as ~700 Å. The effective shortest rest wavelength observed in PG 0117 + 213 and PKS 0405 − 123 is ~800 Å. Thus, in these objects, we could have missed the rise in polarization, although we do have a marginal detection for PKS 0405 − 123. The object 0014 + 813 does not have sufficient S/N shortward of the...
Lyman edge. To summarize, of the objects that show candidate partial Lyman absorption edges in total flux, approximately 40% show polarization shortward of the Lyman edge.

3. We have eight objects in the sample of 13 that do not show a partial Lyman edge feature in total flux. Only one object out of these, PG 1222+228 (Impey et al. 1995), shows significant polarization shortward of the Lyman edge ($P = 4.6\% \pm 0.9\%$). The rest show no detection of polarization in the 912 Å spectral region. The linear polarization upper limits shortward of the Lyman edge in the remaining objects is $\leq 4\%$.

4. PG 1630+377 is the best studied object (see Paper I) and shows UV polarization reaching 20% at 650 Å rest wavelength. Such a high degree of polarization is rare in (nonblazar) QSOs.

Perhaps the simplest result of the current data is that it strengthens the conclusion that quasars are generally not polarized significantly just longward of the Lyman edge at $\sim 1000$ Å. This paper, Paper I, Impey et al. (1995), and Antonucci et al. (1996) together present good observations of about 20 objects in the region just longward of the Lyman edge, all with low-UV polarization ($\leq 1.5\%$). Further, there is no significant statistical wavelength dependence to the polarization, as predicted by the models of Laor et al. (1990). From these observations we conclude that simple plane-parallel atmospheres with a scattering-dominated opacity are not significant sources of UV flux in quasars.

Briefly recapitulating the previous discussions here, we note that models from the 1980s generally assumed that AGN accretion disks are powered by viscous dissipation below the atmospheres and that the atmospheric opacities are dominated by electron-scattering opacity in the annuli that produce the rest optical and UV. This results in 0%–11.7% polarization (Chandrasekhar 1960), depending on inclination, in a direction perpendicular to the symmetry axis of the disks. Pioneering optical polarimetry observations showed much smaller polarizations, which are parallel to the axes when the latter could be inferred from a radio jet position angle (Stockman, Angel, & Miley 1979; Antonucci 1988). To explain the low observed polarization, subsequent models by Laor et al. (1990) suggested that electron scattering was only important in the $\sim 1000$–2000 Å range, with the Lyman continuum and free-free absorption opacity dominating shortward and longward of that interval, respectively. Other, more detailed calculations revealed that a lower fraction of absorption opacity was required to reduce the predicted polarization than was assumed by Laor et al. (1990); they also revealed that under rather special circumstances a large polarization parallel to the disk axis could be produced shortward of the Lyman edge (Blaes & Agol 1996, and references therein). The observed rise in UV polarization shortward of the Lyman edge has been interpreted in the context of both accretion disk models and nondisk related models. Here we do not further discuss the polarization and depolarization mechanisms discussed in detail in Paper I. An additional key com-
Application in the accretion disk models is that AGN variability data require that the disk atmosphere is actually illuminated from above, (e.g., Antonucci 1988; Sincell & Krolik 1997), perhaps producing a strong polarization that cannot be calculated rigorously without specification of the illumination geometry.

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