Publications of the Astronomical Society of the Pacific, **112**:586–593, 2000 May

The Lyman Continuum Polarization Rise in the QSO PG 1222+228

Gregory A. Shields
Department of Astronomy, University of Texas, Austin, TX 78712; shields@astro.as.utexas.edu
Received 1999 December 16; accepted 2000 February 4

ABSTRACT. Some QSOs show an abrupt, strong rise in polarization at rest wavelength ∼750 Å. If this arises in the atmosphere of an accretion disk around a supermassive black hole, it may have diagnostic value. In PG 1222+228, the polarization rise occurs at the wavelength of a sharp drop in flux. We examine and reject interpretations of this feature involving a high-velocity outflow. The observations agree with a model involving several intervening Lyman limit systems, two of which happen to coincide with the Lyman continuum polarization rise. After correction for the Lyman limit absorption, the continuum shortward of 912 Å is consistent with a typical power-law slope, $\alpha \approx -1.8$. This violates the apparent pattern for the Lyman limit polarization rises to occur only in "candidate Lyman edge QSOs." The corrected, polarized flux rises strongly at the wavelength of the polarization rise, resembling the case of PG 1630+377. The rise in polarized flux places especially stringent requirements on models.

1. INTRODUCTION

Spectropolarimetric observations with the *Hubble Space Telescope* (*HST*) have revealed an unexpected rise in linear polarization in several QSOs (see review by Koratkar & Blaes 1999). These are radio-quiet "candidate Lyman edge QSOs," in which the continuum flux drops rather rapidly at rest wavelengths $\lambda < 1000$ Å (Antonucci, Kinney, & Ford 1989; Koratkar, Kinney, & Bohlin 1992). Models of accretion disk atmospheres predicted a reduced polarization in the Lyman continuum because of a diminished contribution of electron scattering to the opacity (Laor, Netzer, & Piran 1990). With this motivation, Impey et al. (1995) and Koratkar et al. (1995) used the Faint Object Spectrograph (FOS) on *HST* to obtain ultraviolet spectropolarimetry of several QSOs with redshifts sufficient to bring the Lyman continuum within the observed wavelength band. The surprising result, in several cases, was a rapid *rise* in polarization in the Lyman continuum. From values $\lesssim 1\%$ in the optical and near-ultraviolet, the observed polarization rises around rest wavelength 750 Å to values ∼5% in several objects and to ∼20% in PG 1630+377.

This phenomenon has inspired several attemps at explanation. Blaes & Agol (1996) found that, for effective temperatures $T_{\rm eff} \approx 25{,}000$ K and low effective gravities, a polarization rise of up to ∼5% at about the observed wavelength could occur naturally in QSO disk atmospheres. This results from the interplay of electron scattering, bound-free opacity, and the temperature gradient in the atmosphere. However, Shields, Wobus, & Husfeld (1998, hereafter SWH) showed that the effects of the relativistic transfer function destroy the agreement between this model and observation. Beloborodov & Poutanen (1999) suggested a model involving Compton scattering in a corona or wind, but this model appears to have trouble producing the rapid rise in polarized flux observed in PG 1630+377 (O. Blaes & G. A. Shields 1999, unpublished). Lee & Blandford (1997) discussed the possible role of scattering by resonance lines of heavy elements (see § 5).

SWH showed that if the polarization is assumed to rise sharply at 912 Å in the rest frame of the orbiting gas, then relativistic effects would naturally produce the wavelength dependence of the observed polarization. This may offer a way of measuring the black hole spin, but the physical mechanism for the polarization rise remains unknown.

PG 1222+228 is a $B \approx 15.5$ radio-quiet QSO (Schmidt & Green 1983) whose polarization rise at $\lambda \approx 750$ Å coincides with a sharp drop in flux (Figs. 1 and 2). Impey et al. (1995) noted this and attributed it to a coincidental Lyman limit system (LLS), corresponding to an identified absorption-line system at $z = 1.486$. However, the coincidence of a broad absorption feature with a polarization rise also is observed for broad absorption line (BAL) QSOs. In these objects, outflowing gas at velocities $\sim 10^4$ km s^{-1} produces blueshifted absorption troughs, typically seen in the resonance lines of H I, C IV, N V, O VI, Si IV, and sometimes Mg II (Weymann et al. 1991; Arav, Shlosman, & Weymann 1997). Spectropolarimetric observations (e.g., Ogle 1997; Schmidt & Hines 1999; Ogle et al. 1999) often show a rise in polarization in the troughs, reaching values as high as ∼8%–10% from ∼1% at unabsorbed wavelengths. This is explained in terms of scattering of some of the continuum by an extended region that is not covered by the BAL flow

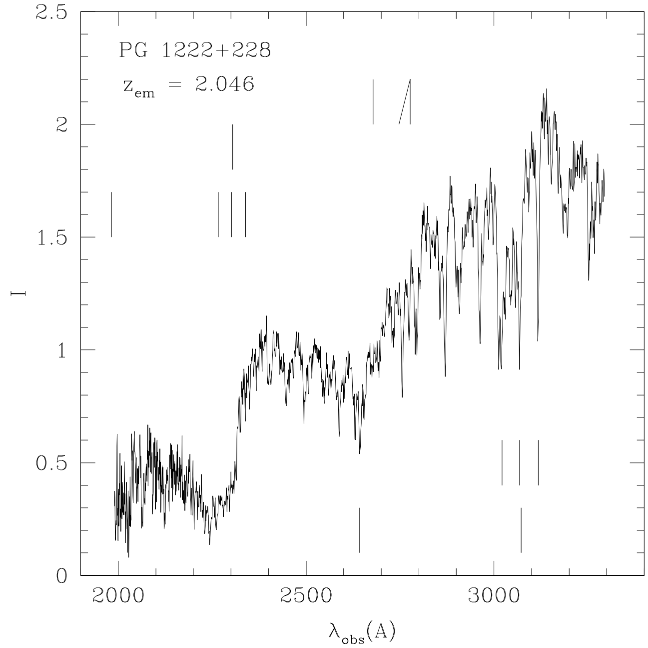

FIG. 1.—Ultraviolet spectrum of PG 1222+228 observed with *HST* by Impey et al. (1995, 1996). Figure gives flux at Earth in units of 10^{-15} ergs s^{-1} cm^{-2} $Å^{-1}$ as a function of observed wavelength. Vertical lines give the positions of the Lyman limit (*above*) and Lyα (*below*) for redshifts $z = 1.174$, 1.486, 1.524, 1.527, 1.565, and 1.938. Also shown is the Lyman limit for the emission-line redshift of 2.046. Data plotted here are from the G190H spectrum for $\lambda < 2224$ Å and G270H for longer wavelengths (see text). Data is binned by 2 pixels. Data courtesy of C. Impey & C. Petri (1999, private communication).

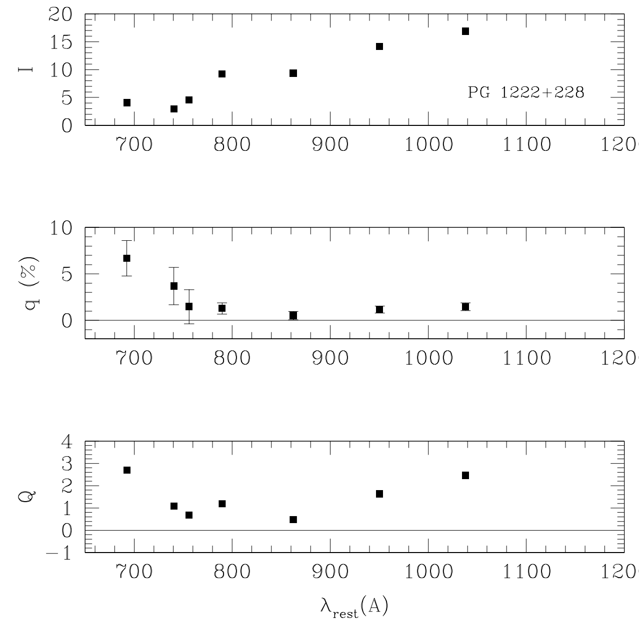

FIG. 2.—Flux and polarization of PG 1222+228 from *HST* observations by Impey et al. (1995, 1996), binned as described in the text. Abscissa is rest wavelength in terms of the emission-line redshift. *I* is the measured flux in units of 10^{-16} ergs s^{-1} cm^{-2} $Å^{-1}$. Rotated Stokes flux *Q*, called Q' in the text, is referred to the mean position angle of 168°. The fractional rotated Stokes parameter, $q = Q/I$, is given as a percentage.

(Hines & Wills 1995; Goodrich & Miller 1995; Cohen et al. 1995). This pattern resembles the polarization rise and flux drop in PG 1222+228.

This paper addresses two questions: (1) Does the polarization rise in PG 1222+228 result from an intrinsic absorber, analagous to the situation in the BAL QSOs? (2) If the drop in flux in PG 1222+228 is an intervening LLS, what are the consequences of correcting the observed, polarized continuum for this absorption?

2. INTRINSIC ABSORPTION IN PG 1222+228?

We first consider the possibility that the flux drop and coincidental polarization rise in PG 1222+228 result from some kind of intrinsic absorption. Two possibilities, considered below, are that it is a BAL outflow or that it is an unusual, intrinsic LLS.

In either case, one issue is the behavior of the polarized flux as a function of wavelength. As discussed above, if the polarization rise results from the selective absorption of the directly viewed continuum but not the scattered continuum, one might expect a smaller drop (but generally not a rise) in the polarized flux, $I_p = pI_\lambda$. In order to examine this, we have rebinned the data of Impey et al. (1995), kindly made available in reduced form by C. Impey & C. Petri (1999, private communication). These data consist of a spectrum with the G190H grating covering 1575–2320 Å at 0.37 Å per pixel and a spectrum with the G270H grating covering the range 2224–3295 Å at 0.52 Å per pixel. The G190H data shortward of 1994 Å have a low signal-to-noise ratio and were not presented by Impey et al. (1995). We used seven wavelength bins: (1) 1994–2224 Å, (2) 2224–2287 Å, (3) 2287–2319 Å, (4) 2319–2492 Å, (5) 2492–2761 Å, (6) 2761–3029 Å, and (7) 3029–3295 Å. Bins 2 and 3 involve an average of the two overlapping spectra, and bin 3 is a narrow bin containing the flux drop at 2300 Å. The resulting values of I_λ, $q \equiv Q/I$, and $u \equiv U/I$ are tabulated in Table 1, along with the polarization, $p = (q^2 + u^2)^{1/2}$, and its position angle, θ. For the polarized flux, we use the rotated Stokes flux Q' and polarization $q' \equiv Q'/I$ (cf. Koratkar et al. 1995), referred to a position angle of 168°. This is based on the mean polarization position angle of the *HST* data, which is in reasonable agreement with optical observations (Stockman et al. 1984; Webb et al. 1993). (The use of q' is appropriate if the position angle of the polarization is constant with wavelength. Table 1 supports this and also shows that the polarization p is reasonably consistent with q'.) These quantities are plotted in Figure 2. The shortest wavelength bin has larger polarized flux than the longer wavelength bins. At face value, this would weigh against an

TABLE 1

CONTINUUM POLARIZATION OF PG 1222+228[a]

Grating	λ_{min}	λ_{max}	I	q (%)	u (%)	p (%)	θ	q'
G190H......	1994	2224	4.04 ± 0.04	5.8 ± 1.8	−3.4 ± 2.6	6.4 ± 2.0	165 ± 16	6.7 ± 1.9
Both	2224	2287	2.94 ± 0.04	2.4 ± 2.0	−3.8 ± 2.1	4.0 ± 2.0	151 ± 26	3.7 ± 2.0
Both	2287	2319	4.59 ± 0.05	0.2 ± 1.8	−3.4 ± 1.9	2.9 ± 1.9	136 ± 31	1.5 ± 1.8
G270H......	2319	2492	9.27 ± 0.04	1.0 ± 0.6	−1.0 ± 0.6	1.2 ± 0.6	157 ± 26	1.3 ± 0.6
G270H......	2492	2761	9.33 ± 0.02	0.5 ± 0.4	−0.0 ± 0.4	0.3 ± 0.4	179 ± 48	0.5 ± 0.4
G270H......	2761	3029	14.14 ± 0.03	0.9 ± 0.4	−0.8 ± 0.4	1.2 ± 0.4	159 ± 17	1.2 ± 0.4
G270H......	3029	3295	16.85 ± 0.04	1.7 ± 0.4	0.2 ± 0.4	1.6 ± 0.4	4 ± 14	1.5 ± 0.4

[a] Data of Impey et al. (1995, 1996) rebinned with respect to the apparent LLS at 2300 Å. Wavelength limits (observed) are given in Å. Stokes parameters are given as I, the measured flux (units of 10^{-16} ergs cm^{-2} s^{-1} Å^{-1}), $q \equiv Q/I$, and $u \equiv U/I$. The quantity q' is Q/I rotated to position angle 168°. Quoted uncertainties are 1 σ, derived from uncertainties in individual pixel measurements. Polarization p is corrected for bias (Wardle & Kronberg 1974, eq. [A3]).

intrinsic absorber model for PG 1222+228, but it involves a single wavelength bin with substantial error bars. Therefore, we consider other aspects of the two outflow models.

2.1. BAL Absorption

The rest wavelength of the onset of the absorption feature in PG 1222+228 is ∼750 Å. Some BAL QSOs show absorption by Ne VIII λ775 (e.g., Arav et al. 1999; Telfer et al. 1998). This might be a candidate for the feature in question, inasmuch as BALs often set in at a wavelength somewhat blueshifted from the emission-line redshift. However, Ne VIII normally is accompanied by absorption in O VI λ1035, N V λ1240, and C IV λ1550. There is no indication of broad C IV or Mg II absorption in the spectrum of PG 1222+228 (Sargent, Steidel, & Boksenberg 1988; Steidel & Sargent 1992). The *HST* spectrum shows a shallow trough at 3000–3070 Å that could be a weak O VI feature, but this may simply be a cluster of lines, including several strong Lyα lines indentified by Impey et al. (1996). Photoionization models by Hamann (1997) indicate a range of ionization parameters for which the fractional abundance of Ne^{+7} exceeds that of O^{+5}. However, given the normal ratio of oxygen to neon abundances, the O VI feature would likely be strong in a situation giving strong Ne VIII.

The flux drop at 750 Å does not recover, with decreasing wavelength, in a way suggestive of a BAL (Fig. 1). The spectrum has not fully recovered by rest wavelength 650 Å, corresponding to an an outflow velocity of more than 40,000 km s^{-1} if attributed to Ne VIII. Some moderately narrow "mini-BAL" features have been observed at such high velocities (Hamann et al. 1997), but true BAL troughs rarely reach such velocities. The same can be said in connection with the possibility that the λ750 feature corresponds to a blend of features including N III, N IV, O IV, S VI, and Ne VIII seen in BAL QSO spectra at this wavelength (e.g., Arav et al. 1999). Moreover, given the range of ionization stages contributing to this blend, C IV and Si IV absorption would likely accompany it.

Recent work has shown that BAL QSOs systematically have weak soft X-ray emission. BAL QSOs have optical to X-ray slopes $\alpha_{ox} \lesssim -2.0$, whereas non-BAL QSOs tend to have α_{ox} in the range −1.3 to −1.8 (Brandt, Laor, & Wills 2000). Here α_{ox} is defined by $F_x/F_o = (\nu_x/\nu_o)^{\alpha_{ox}}$, where F_x and F_o are the flux densities (F_ν) at 2 keV and 3000 Å, respectively. *ROSAT* pointing observations give a flux of 6×10^{-14} ergs s^{-1} cm^{-2} for PG 1222+228 at a significance level of 3.3σ (R. F. Mushotzky 1999, private communication). If we assume a "normal" power-law slope of $\alpha = -1.6$ over the 0.2–2 keV *ROSAT* band (Brandt et al. 2000), we find $F_x = 1.5 \times 10^{-31}$ ergs s^{-1} cm^{-2} Hz^{-1} at 2 keV rest energy. Optical spectrophotometry (Wampler & Ponz 1985; Bechtold et al. 1984) implies $F_o \approx 1.1 \times 10^{-26}$ ergs s^{-1} cm^{-2} Hz^{-1} at rest wavelength 3000 Å. (These are observed fluxes at the wavelength corresponding to the indicated rest wavelength.) From this, we find $\alpha_{ox} = -1.8$ for PG 1222+228. This result is uncertain because of the marginal X-ray detection and the possibility of variability, but at face value it is more consistent with a non-BAL than a BAL QSO. (Wilkes et al. [1994] quote an uncertain value $\alpha_{ox} \approx -1.8$ from *Einstein* data.)

We conclude that the flux drop at 750 Å in PG 1222+228 is unlikely to be a BAL feature.

2.2. An Instrinsic Lyman Limit System?

Impey et al. (1995) suggested that the flux drop at 750 Å was an intervening LLS. We show below that Lyman limit absorption does indeed give a good fit to the spectrum. This fit, however, leaves open the question of the location of the absorbing gas. Because of the coincidence with the polarization rise, we consider here the possibility that the feature is an *intrinsic* LLS, associated with a high-velocity outflow from the QSO. Impey et al. (1996) identify Lyα absorption lines at $z = 1.4857$, 1.5238, 1.5272, and 1.5650 that might be associated with the $\lambda 750$ feature, if it is taken to be an LLS. A redshift of 1.486 corresponds to an outflow velocity $\sim 60{,}000$ km s^{-1}. As noted above, this is not unprecedented for a QSO outflow producing absorption lines. However, the lines associated with the redshift systems in question in PG 1222+228 are narrow, and narrow lines with relative velocities greater than 5000 km s^{-1} usually are assumed to be intervening. For a Lyman edge optical depth of unity, the measured equivalent widths of the Lyα lines are consistent with a Doppler parameter $b \lesssim 30$ km s^{-1} (see below), normal for an intervening LLS. In contrast, the mini-BALs observed at such high velocities have widths of order 1000 km s^{-1} (Hamann et al. 1997). Could the feature in PG 1222+228 nevertheless be caused by ejected material with a high outflow velocity and a small velocity dispersion?

We are not aware of any other case in which a high-velocity LLS with narrow lines has been shown to be intrinsic. However, the existence of many intrinsic, narrow, high-velocity absorption systems in QSOs has been proposed by Richards et al. (1999). These authors compare the incidence of absorption-line systems, per unit relative outflow velocity, for highly luminous QSOs with that for less luminous ones. In the velocity range 5000–75,000 km s^{-1}, they find that absorption systems have a substantially larger frequency in luminous systems. Since intervening systems should have no dependence on QSO luminosity (assuming that discovery systematics are accounted for), Richards et al. conclude that at least the excess number of systems in the high-luminosity QSOs are intrinsic.

A peculiar absorption-line ratio in the $z = 1.94$ system in PG 1222+228 has been noted by Ganguly et al. (1998). These authors present high-resolution spectra that show two narrow components, separated by ~ 17 km s^{-1}, with very different strengths of the Al II and Al III absorption lines. Photoionization models indicate that the component with strong aluminum lines must have an anomalously high abundance of aluminum. This is reminiscent of claims of unusual abundances in BAL QSOs, including an excess of aluminum (e.g., Turnshek et al. 1996; Junkkarinen et al. 1997; Shields 1997). The reality of these abundance anomalies is in doubt, because of the effects of partial covering of the continuum source (Arav 1997). However, the basic observation of anomalously strong Al lines may be a possible parallel between PG 1222+228 and the BAL QSOs, where outflowing gas is clearly present. If this is a hint that the narrow, $z = 1.94$ system may be intrinsic, perhaps it adds plausibility to the idea that the $z = 1.486$ system (or its neighbors) may also be intrinsic.

What might be the geometry of an intrinsic LLS in PG 1222+228? In order to explain the polarization rise, the absorber would have to intercept the line of sight to the continuum source but not the scattering source. The latter is often attributed to a wind driven off the inner edge of a "dust torus" (Krolik & Begelman 1986). The location of this may be related to the dust sublimation radius, $\sim 0.2 L_{46}^{1/2}$ pc, where L_{46} is the bolometric luminosity of the central source in units 10^{46} ergs s^{-1} (Laor & Draine 1993). The absorbing material, at a velocity of $\sim 0.2c$, would be at a smaller radius in order not to cover the scattering source. Its high velocity suggests an origin at a small radius where the escape velocity is of order the observed outflow velocity. The escape velocity from a central mass of M is $0.2c$ at a radius $10^{15.6} M_9$ cm, where $M_9 \equiv M/10^9\ M_{\odot}$. Let us assume the absorbing material is at a radius of $\lesssim 10^{18}$ cm, large enough to obscure the ultraviolet-emitting part of an accretion disk but not the scattering source. At the observed speed, the crossing time would be a few years or less. Thus, the material should change radius substantially in the 7 years between the Sargent et al. (1988) and the Impey et al. (1996) observations, and one might expect some change of velocity. These authors, however, quote velocities for the $z = 1.486$ and 1.524 systems that agree to within $\Delta z \approx 0.001$. This corresponds to a change in outflow velocity of less than ~ 100 km s^{-1}. Such precise stability seems difficult to achieve. (Note, however, the stability of narrow features within the BAL profiles of some QSOs; cf. Weymann 1997.) A further problem involves the narrowness of the absorption lines. The radius of the ultraviolet-emitting part of the disk would be at least ~ 10 gravitational radii, or about $10^{15.1} M_9$ cm. If the absorber is at a radius $\lesssim 10^{18}$ cm, then the line of sight through the absorber to different parts of the continuum source would likely give noticeably different projected flow velocities. The observed line widths (see below) are $\lesssim 30$ km s^{-1}, less than one-thousandth of the outflow velocity.

These difficulties with the intrinsic absorber model for PG 1222+228 encourage us to examine the straightforward idea of an intervening LLS.

3. INTERVENING ABSORPTION

Impey et al. (1995, 1996) attributed the flux drop at observed wavelength 2300 Å to an LLS associated with the $z = 1.4857$ absorption line system. They identify absorption lines of H I, C III, N I, N II, Si II, and Si III. They also identify systems at $z = 1.5238$, 1.5272, and 1.5650, which have multiple Lyman lines and, for $z = 1.5238$, C III. Sargent, Steidel, & Boksenberg (1988) measure C IV $\lambda\lambda 1548$, 1551 in the $z = 1.486$ and 1.524 systems with equivalent widths ~ 0.7 Å. However, Steidel & Sargent (1992) give a spectrum showing no detectable Mg II absorption.

Simple estimates suggested that the 2300 Å flux drop might be too gradual to be attributed to the converging Lyman lines of the $z = 1.486$ system. Therefore, we computed a model spectrum involving an assumed power-law continuum and absorption by the hydrogen lines and bound-free continuum. The column density of H I was parameterized by the Lyman edge optical depth, τ_H, and the lines were assumed to have a Gaussian profile with a Doppler parameter set to a typical value $b = 30$ km s^{-1}. (A larger line width would give an excessive equivalent width for Lyα for the required τ_H. The observed decrement of the Lyman line equivalent widths actually suggests a narrower core line width, with some of the Lyα equivalent width being attributable to a broader component of modest column density. These details do not affect our conclusions.) Inclusion of 50 Lyman lines proved more than adequate to trace the convergence to the continuum optical depth. The model spectrum was convolved with a single-component Gaussian instrumental line profile following the discussion of Impey et al. (1996), using an FWHM of 2.9 Å for G190H and 4.2 Å for G270H. If only the $z = 1.486$ system contributes to the LLS, then the Lyman line convergence is too close to the Lyman limit (912 Å) to fit the observed feature. However, allocation of some H I column density to both the $z = 1.486$ and 1.524 systems gave a good fit. Two additional LLSs appear to be associated with the $z = 1.938$ and 1.174 systems. Figure 3 shows the resulting model spectrum, along with the observed flux, binned in intervals of $\sim$7.3 Å. The model has $\tau_H = (1.0, 0.5, 0.8, 0.6)$ for $z = (1.174, 1.486, 1.524, 1.938)$, respectively. (The value of τ_H for $z = 1.174$ is uncertain because of the poorly determined amount of scattered light below 2000 Å.) The three distinguishable LLSs show good agreement with the expected ν^{-3} behavior of the Lyman continuum optical depth above threshold, for an intrinsic continuum slope in the range $\alpha \approx -1.5$ to -2.0. This is consistent with the slope -1.8 found by Zheng et al. (1997) for their composite QSO spectrum in the wavlength range 600–1050 Å. A value $\alpha = -1.8$ is assumed in the fit shown in Figure 3. The gradual descent of the observed flux toward the Lyman limit for the $z = 1.938$ system is a puzzle, but it may involve the effects of unrelated absorption lines. An understanding of this is important, as it would play a role in the classification of PG 1222+228 as a candidate Lyman edge QSO. Observations at higher spectral resolution would help to clarify the situation.

Sargent, Steidel, & Boksenberg (1989) discuss the statistics of LLSs in QSOs. For the redshift range in question, they give a mean incidence of LLSs of $N(z) \approx 1.5$ per unit redshift. Their data show many QSOs with multiple LLSs, although the number of LLSs in PG 1222+228 may be somewhat higher than typical. However, the efforts to measure Lyman continuum polarization in QSOs to some extent targeted the candidate Lyman edge QSOs, and objects with LLSs of moderate optical depth may have an enhanced probability to be included.

We conclude that an intrinsic power-law continuum, together with cosmologically intervening Lyman limit absorption, provides a straightforward explanation of the ultraviolet spectrum of PG 1222+228.

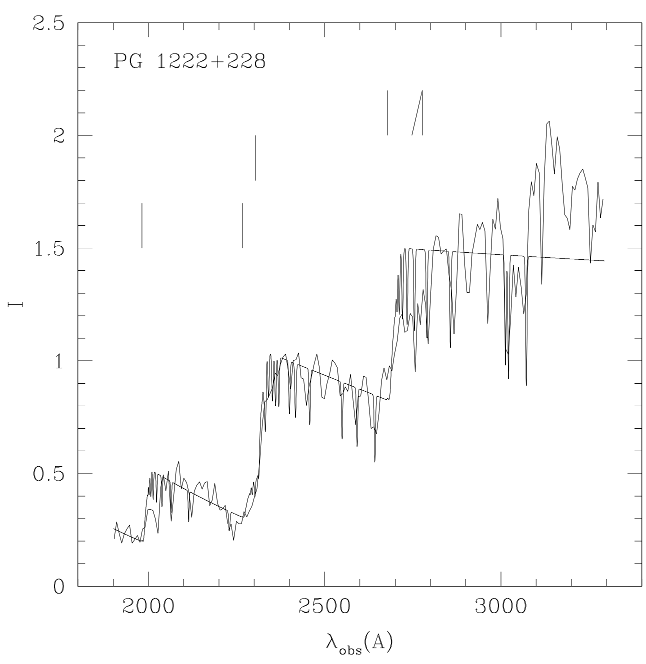

FIG. 3.—Observed flux of PG 1222+228 compared with the model involving power-law continuum and absorption by H I Lyman lines and continuum at four redshifts as described in the text. Observations have been binned into intervals of approximately 7.3 Å for clarity. Axes are the same as in Fig. 1.

4. THE INTRINSIC POLARIZED CONTINUUM

The various LLSs in PG 1222+228 substantially attenuate the observed continuum. What is the behavior of the *polarized flux* when corrected for the absorption? In view of the uncertainties in the measured polarization, a sufficient procedure is to estimate the polarized flux by multiplying the measured polarization in the chosen wavelength bins by the assumed intrinsic continuum flux. For this, we use the same wavelength bins described earlier and the $I_\nu^{PL} \propto \nu^{-1.8}$ power-law continuum used in our fit. The resulting rotated Stokes flux, $Q'_* = q' \times I_\lambda^{PL}$, is shown in Figure 4. We see that the Stokes flux now rises strongly with decreasing wavelength in the region of the polarization rise. This resembles the result found for PG 1630+377 by Koratkar et al. (1995). A rising polarized flux is an important constraint on models for the origin of the polarization rise.

SWH showed that the wavelength dependence of the flux and polarization in PG 1222+228 and PG 1630+377 could be fit with an ad hoc model involving an accretion disk. The disk radiates as a blackbody, but the brightness temperature is depressed below the effective temperature for wavelengths below the Lyman limit, simulating a Lyman edge in the disk atmosphere. The polarization is assumed to rise abruptly at 912 Å by an arbitrary amount. Relativistic

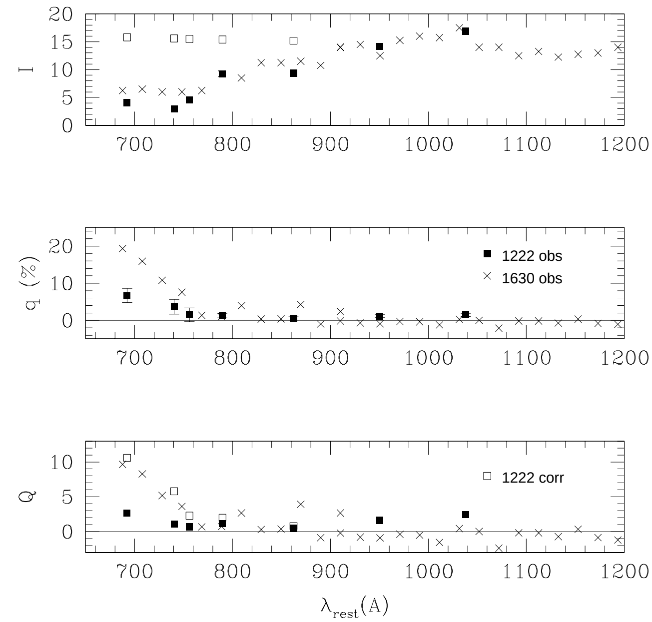

FIG. 4.—Flux and rotated Stokes flux of PG 1222+228 before (*filled squares*) and after (*open squares*) correction for absorption by Lyman limit systems as described in the text. Also shown (*crosses*) are observations of PG 1630+377 by Koratkar et al. (1995). For PG 1630+377, the Stokes flux has been rotated to the mean position angle of 127°, following Koratkar et al. The plotted values of I and Q have been scaled to correspond to the peak values in PG 1222+228 in order to emphasize the wavelength dependences. The corrected, polarized flux of PG 1222+228 (Q'_* in the text) rises strongly below 750 Å, resembling the case of PG 1630+377. Axes are the same as in Fig. 2.

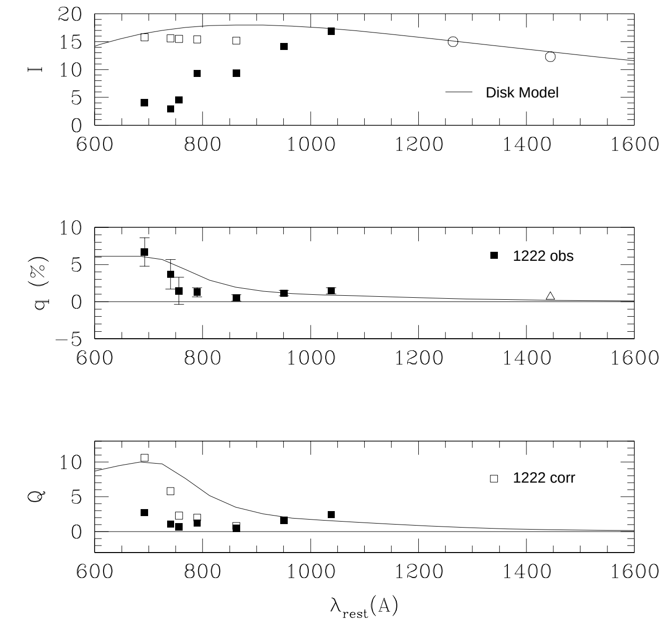

FIG. 5.—Accretion disk model compared with observations of PG 1222+228 (see text). Observations are from Impey et al. (1995; *squares*), Bechtold et al. (1984; *open circles*), and Webb et al. (1993; *open triangle*). Model disk with $a_* = 0.5$, $M_9 = 8.8$, and $\dot{M}_0 = 86$ is viewed at angle $\mu_{\rm obs} = 0.25$. Axes are the same as in Fig. 2.

effects give a blueshifted, but still fairly abrupt polarization rise in the observed spectrum. The models are characterized by a_*, the dimensionless angular momentum of the hole; the black hole mass; the accretion rate, $\dot{M}_0 \equiv \dot{M}/(1\ M_\odot\ {\rm yr}^{-1})$; and the viewing angle, $\mu_{\rm obs} = \cos\theta_{\rm obs}$. SWH found that $a_* = 0.5$ gave approximately the observed wavelength for the polarization rise, for a relatively edge-on viewing angle. Their fits to both objects had a fairly low value of $T_{\rm max}$, the maximum disk effective temperature, as required by the dropping flux in the Lyman continuum region. The correction for LLS absorption in PG 1222+228 hardens the far-ultraviolet spectrum, and a higher value of $T_{\rm max}$ is required to fit the energy distribution. Figure 5 shows the continuum flux and polarization for a model with $a_* = 0.5$, $M_9 = 8.8$, and $\dot{M}_0 = 86$. (We have assumed $H_0 = 70$ km s^{-1} Mpc^{-1}and $q_0 = 0.5$.) The model agrees reasonably well with the corrected flux in the Lyman continuum and with the longer wavelength measurements. Although the corrected flux was assumed to be a power law, a disk continuum would also likely fit the observed flux, given some freedom to adjust the LLS optical depths. This model has a step-function rise in polarization from negligle polarization at wavelengths longward of 912 Å to an ad hoc value of 2.1 times the Chandrasekhar (1960) value for a pure scattering atmosphere. The model predicts an observed polarization and polarized flux that rise at a wavelength substantially blueshifted from 912 Å, but the rise is more gradual than observed. This underscores the need for improved polarization measurements of this object. If the relativistic transfer function gives too gradual a polarization rise, even for an instantaneous polarization rise in the rest frame of the orbiting gas, then accretion disk models for the polarization rise will face a serious problem.

The adopted model parameters give a bolometric luminosity $L/L_{\rm E} = 0.36$, where $L_{\rm E}$ is the Eddington limit. Such a high value of $L/L_{\rm E}$ is barely consistent with a geometrically thin disk. A larger value of a_* would allow a larger mass for the required $T_{\rm max}$, but then the polarization rise would occur at a wavelength shorter than observed (cf. SWH). Evidently, an accretion disk fit to the corrected continuum of PG 1222+228, in the manner of SWH, pushes the disk parameters to the limits. Conceivably, the thickening of the disk corresponding to the large value of $L/L_{\rm E}$ may be related to the origin of the polarization rise.

5. DISCUSSION

The Lyman continuum polarization rises are among the more puzzling recent observational discoveries concerning QSOs. The wavelength dependence, rising rather abruptly at nearly the same rest wavelength in the several known cases, suggests a connection with the bound levels of atoms. The proximity of the feature to 912 Å further suggests an association with the Lyman edge of hydrogen. The ad hoc model of SWH supports an association with the Lyman edge and raises the possiblity of confirming the presence of a relativistic disk and constraining its parameters. However, attempts to fit the feature with a physical model have encountered difficulties. This is an important problem for QSO theory.

Are the reported polarization rises real? The coincidence of the polarization rise in PG 1222+228 with a sharp drop in flux might raise the question of background problems with the FOS spectropolarimeter. Impey et al. (1995) argue that the polarization is unlikely to be less than 2.7% around 2000 Å under any reasonable assumption for the FOS background. However, the degree of polarization in the far-ultraviolet is uncertain by at least a factor of 2 because of systematic errors involving background and scattered light in the FOS. The observed polarization rises in several QSOs occur at different observed wavelengths but similar rest wavelengths. We are not aware of any polarization rises of this nature in FOS spectropolarimetry of BL Lac objects or stars. There is an urgent need for a renewed capability for ultraviolet spectropolarimetry from space to confirm and extend the measurements.

Lyman continuum polarization rises have heretofore been associated with the candidate Lyman edge QSOs (see discussion by Koratkar et al. 1998). Our results suggest that PG 1222+228 may not be a true member of this class. Measurements of the Lyman continuum polarization in additional QSOs are needed to clarify the frequency of occurence of the phenomenon and to look for correlations with features in the continuum flux, in the line intensities and polarization, and other properties. Observations to shorter rest wavelengths are needed to determine whether the polarization falls or continues to rise. Measurements of the time dependence of the polarization rises would be most interesting. The emitting radius of an accretion disk would be light-weeks.

Lee & Blandford (1995) considered a model for the far-ultraviolet polarization rise of QSOs that did not involve the Lyman edge. Noting that a number of resonance lines of heavy elements fall in the rest wavelength range where the polarization rises, they suggested that resonance scattering of the QSO continuum might produce the observed polarization. Such a model could produce a rising polarized flux, since the polarization could be essentially zero at wavelengths without scattering contributions. As noted above, the polarization rise in PG 1222+228 may be too steep for models involving an accretion disk. In this case, alternative models such as resonance scattering may hold promise. We note that the polarized flux spectrum of PG 1630+377 (Koratkar et al. 1995) shows a strong rise at the wavelength of the N V emission line.

The claim by Richards et al. (1999) that luminous QSOs have many intrinsic, narrow, high-velocity C IV absorption systems has important implications. This would complicate the use of such systems to probe the evolution of galaxies and the intergalactic medium. The mechanism for producing the absorbing clouds would add another challenge to the subject of outflows from QSOs. Surveys of QSOs at different luminosities, to a uniform standard of signal-to-noise ratio, would allow confirmation of the claimed higher incidence of absorption in more luminous QSOs. Tests of the intrinsic nature of narrow absorptions have been summarized by Barlow, Hamann, & Sargent (1997). These include time variability of the depth and profile of the lines and evidence for saturated but nonblack line profiles. Detection of changes in the velocities of the lines would be most revealing. Chemical abundances may be an indicator, given evidence for high abundances in the broad absorption- and emission-line regions of QSOs (e.g., Hamann & Ferland 1993). If C IV systems in high- and low-luminosity QSOs have similar, mostly subsolar abundances, this might argue for their intervening nature.

The author is grateful to C. Impey and C. Petri for providing advice and the reduced *HST* observations and to C. Sneden for the use of a computer subroutine. The work has benefitted from discussions and communications with R. Antonucci, O. Blaes, R. Blandford, R. Ganguly, M. Malkan, R. Mushotzky, G. Richards, R. Weymann, and B. Wills. This material is based in part upon work supported by the Space Telescope Science Institute under grant GO-07359.02. This work was carried out in part at the Institute for Theoretical Physics, University of California, Santa Barbara, supported by NSF grant PH 94-07194.

REFERENCES

Antonucci, R. R. J., Kinney, A. L., & Ford, H. C. 1989, ApJ, 342, 64
Arav, N. 1997, in ASP Conf. Ser. 128, Mass Ejection from AGN, ed. N. Arav, I. Shlosman, & R. J. Weymann (San Francisco: ASP), 208
Arav, N., Korista, K. T., de Kool, M., Junkkarinen, V. T., & Begelman, M. 1999, ApJ, 516, 27
Arav, N., Shlosman, I., & Weymann, R. J., eds. 1997, ASP Conf. Ser. 128, Mass Ejection from AGN, ed. N. Arav, I. Shlosman, & R. J. Weymann (San Francisco: ASP)
Barlow, T. A., Hamann, F., & Sargent, W. L. W. 1997, in ASP Conf. Ser. 128, Mass Ejection from AGN, ed. N. Arav, I. Shlosman, & R. J. Weymann (San Francisco: ASP), 13

Bechtold, J., et al. 1984, ApJ, 281, 76
Beloborodov, A. M., & Poutanen, J. 1999, ApJ, 517, L77
Blaes, O., & Agol, E. 1996, ApJ, 469, L41
Brandt, W. N., Laor, A., & Wills, B. J. 2000, ApJ, 528, 637
Chandrasekhar, S. 1960, Radiative Transfer (New York: Dover)
Cohen, M. L., Ogle, P. M., Tran, H. D., Vermuellen, R. C., Miller, J. S., Goodrich, R. W., & Martel, A. R. 1995, ApJ, 448, L77
Ganguly, R., Churchill, C. W., & Charlton, J. C. 1998, ApJ, 498, L103
Goodrich, R. R., & Miller, J. S. 1995, ApJ, 448, L73
Hamann, F. 1997, ApJS, 109, 279
Hamann, F., Barlow, T., Cohen, R. D., Junkkarinen, V., & Burbidge, E. M. 1997, in ASP Conf. Ser. 128, Mass Ejection from AGN, ed. N. Arav, I. Shlosman, & R. J. Weymann (San Francisco: ASP), 19
Hamann, F., & Ferland, G. 1993, ApJ, 418, 11
Hines, D. C., & Wills, B. J. 1995, ApJ, 448, L69
Impey, C., Malkan, M., Webb, W., & Petry, C. 1995, ApJ, 440, 80
Impey, C., Petry, C., Malkan, M., & Webb, W. 1996, ApJ, 463, 473
Junkkarinen, V., Beaver, E. A., Burbidge, E. M., Cohen, R. D., Hamann, F., & Lyons, R. W. 1997, in ASP Conf. Ser. 128, Mass Ejection from AGN, ed. N. Arav, I. Shlosman, & R. J. Weymann (San Francisco: ASP), 19
Koratkar, A., Antonucci, R., Goodrich, R. W., Bushouse, H., & Kinney, A. 1995, ApJ, 450, 501
Koratkar, A., Antonucci, R., Goodrich, R., & Storrs, A. 1998, ApJ, 503, 599
Koratkar, A., & Blaes, O. 1999, PASP, 111, 1
Koratkar, A., Kinney, A. L., & Bohlin, R. C. 1992, ApJ, 400, 435
Krolik, J. H., & Begelman, M. C. 1986, ApJ, 308, L55
Laor, A., & Draine, B. T. 1993, ApJ, 402, 441
Laor, A., Netzer, H., & Piran, T. 1990, MNRAS, 242, 560
Lee, H.-W., & Blandford, R. D. 1997, MNRAS, 288, 19
Ogle, P. 1997, in ASP Conf. Ser. 128, Mass Ejection from AGN, ed. N. Arav, I. Shlosman, & R. J. Weymann (San Francisco: ASP), 78
Ogle, D. C., Cohen, M. H., Miller, J. S., Tran, H. D., Goodrich, R. W., & Martel, A. R. 1999, ApJS, 125, 1
Richards, G. T., York, D. G., Yanny, B., Kollgaard, R. I., Laurent-Muehleisen, S. A., & Vanden Berk, D. E. 1999, ApJ, 513, 576
Sargent, W. L. W., Steidel, C. C., & Boksenberg, A. 1988, ApJS, 68, 539
———. 1989, ApJS, 69, 703
Schmidt, G. D., & Hines, D. C. 1999, ApJ, 512, 125
Schmidt, M., & Green, R. F. 1983, ApJ, 269, 352
Shields, G. A. 1997, in ASP Conf. Ser. 128, Mass Ejection from AGN, ed. N. Arav, I. Shlosman, & R. J. Weymann (San Francisco: ASP), 214
Shields, G. A., Wobus, L., & Husfeld, D. 1998, ApJ, 496, 743 (SWH)
Steidel, C. C., & Sargent, W. L. W. 1992, ApJS, 80, 1
Stockman, H. S., Moore, R. L., & Angel, J. R. P. 1984, ApJ, 279, 485
Telfer, R. C., Kriss, G. A., Zheng, W., Davidsen, A. F., & Green, R. 1998, ApJ, 509, 132
Turnshek, D. A., Kopko, M., Jr., Monier, E., Noll, D., Espey, B. R., & Weymann, R. J. 1996, ApJ, 463, 110
Wampler, E. J., & Ponz, D. 1985, ApJ, 298, 448
Wardle, J. F. C., & Kronberg, P. P. 1974, ApJ, 194, 249
Webb, W., Malkan, M., Schmidt, G., & Impey, C. 1993, ApJ, 419, 494
Weymann, R. J. 1997, in ASP Conf. Ser. 128, Mass Ejection from AGN, ed. N. Arav, I. Shlosman, & R. J. Weymann (San Francisco: ASP), 3
Weymann, R. J., Morris, S. L., Foltz, C. B., & Hewett, P. C. 1991, ApJ, 373, 23
Wilkes, B. J., Tananbaum, H., Worrall, D. M., Avni, Y., Oey, M. S., & Flanagan, J. 1994, ApJS, 92, 53
Zheng, W., Kriss, G., Telfer, R. C., Grimes, J. P., Davidsen, & A. F. 1997, ApJ, 475, 469