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THE PUZZLE OF THE LYMAN CONTINUUM POLARIZATION OF QSOS

Gregory A. Shields,[1] Eric Agol,[2] and Omer Blaes[3]

RESUMEN

Mediante espectropolarimetría reciente de cuasares se ha encontrado un sorprendente incremento en la polarización del contínuo de Lyman en varios objetos. Discutimos algunos intentos recientes para explicar este hecho, que incluyen el papel de la absorción de Lyman en PG 1222+228. Presentamos nuevos resultados teóricos que involucran dispersión por electrones en una corona caliente o en un viento por encima de un disco de acreción, y la polarización que resulta del efecto relativista de la radiación que regresa. Potencialemente estos mecanismos pueden alcanzar niveles de polarización observables en longitudes de onda cortas, pero ninguno logra explicar cuantitativamente los incrementos en la polarización del contínuo de Lyman. Se requiere urgentemente mayor capacidad para llevar a cabo espectropolarimetría en el ultravioleta desde satélites para esclarecer este fenómeno.

ABSTRACT

Recent spectropolarimetry of QSOs has revealed a surprising rise in polarization in the Lyman continuum of several objects. We discuss several recent attempts to interpret this feature, including the role of Lyman limit absorption in PG 1222+228. We present new theoretical results involving electron scattering in a hot corona or wind above an accretion disk, and polarization resulting from the relativistic returning radiation. These mechanisms can lead to potentially observable polarization at short wavelengths, but neither has quantitative success in fitting the observed Lyman continuum polarization rises. A renewed capability for ultraviolet spectropolarimetry from space is urgently needed to provide further clues to the nature of this phenomenon.

Key Words: **ACCRETION, ACCRETION DISKS — BLACK HOLE PHYSICS — GALAXIES:ACTIVE — POLARIZATION — QUASARS:GENERAL**

1. INTRODUCTION

Accretion onto black holes is widely believed to power active galactic nuclei (AGN). The accretion flow likely takes the form of an orbiting disk, which gives efficient energy production and defines a natural axis for jets and double radio sources. Specific observational confirmation of the presence of disks in AGN has, however, been elusive.

Disks in AGN are defined by the black hole's mass, M, its dimensionless angular momentum, a_*, and the accretion rate, $\dot{M}$. For much of the relevant range of parameters, the disk should be geometrically thin and optically thick. In this case, the disk may emit much of its power as thermal emission in the optical and ultraviolet. Observations of QSOs indeed show a strong, broad continuum component, called the "Big Blue Bump", that is suggestive of disk emission (e.g., Shields 1978; Malkan 1983). Much effort has gone into observations at infrared to X–ray wavelengths, polarization studies, and related theory, in an attempt to confirm that this emission does indeed come from a thermally emitting disk (see review by Koratkar & Blaes 1999). The case today remains inconclusive.

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[1] Department of Astronomy, University of Texas at Austin.
[2] Department of Astronomy, Johns Hopkins University.
[3] Department of Physics, University of California, Santa Barbara.

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One reason for the difficulty of proving the presence of disks in AGN is the high orbital velocity of the material in the emitting zone. This tends to mask spectral features of a disk that might have diagnostic value. The bulk of the thermal continuum should come from dimensionless radii $r_* \equiv R/R_g \approx 10$, where $R_g = GM/c^2$ is the gravitational radius. The corresponding orbital velocity is $\sim 0.3c$. Detection of highly broadened Fe Kα emission has been cited as an argument for a relativistic disk (Tanaka et al. 1995), but spectral features in the optical and ultraviolet have not been identified. One potential feature is the Lyman edge of hydrogen, at rest wavelength 912 Å. Depending on the parameters, this feature may be in emission or absorption or absent. It seems likely to be present in some fashion at least in some objects, albeit highly broadened by Doppler broadening and relativistic effects (cf. Koratkar & Blaes 1999). In fact, only a small fraction of QSOs, the so-called "Lyman edge candidate QSOs", show indications of a broadened Lyman edge in absorption (e.g., Antonucci, Kinney & Ford 1989; Koratkar, Kinney & Bohlin 1992).

The hot, low density gases in the atmosphere of an AGN disk should be highly ionized. Electron scattering should then give significant plane polarization. A drop in polarization in the Lyman continuum was predicted by Laor, Netzer & Piran (1990) because of the increased absorption opacity from photoionization of hydrogen. With this motivation, spectropolarimetry was obtained with the *Faint Object Spectrograph* on the *Hubble Space Telescope* (*HST*) for a number of QSOs (Impey et al. 1995; Koratkar et al. 1995). For several candidate Lyman edge QSOs, a surprising rise in polarization was found. From values of only $\sim 1\%$, the polarization rises rather steeply around rest wavelength ~ 750 Å, reaching $\sim 5\%$ in PG 1222+228 and $\sim 20\%$ in PG 1630+377. Weaker polarization rises at a similar wavelength were found in several other QSOs. Until recently, these polarization rises appeared to be associated only with candidate Lyman edge QSOs (Koratkar et al. 1998).

Lyman continuum polarization rises in QSOs have generated considerable theoretical interest. An interesting stellar atmosphere effect was proposed by Blaes & Agol (1996), in which the combined effects of electron scattering and photoionization opacity give a polarization rise somewhat to the short wavelength side of the Lyman edge. This occurs for just the range of disk effective temperatures, T_{eff} , that should give a Lyman edge in absorption in the total flux. This process did not give polarizations as high as 20%, however. Moreover, Shields, Wobus & Husfeld (1998, SWH) found that relativistic effects caused an additional blueshift of the polarization rise, relative to the wavelength in the rest frame of the orbiting gas. The observed polarization rise then would occur at a wavelength too short to fit the observations. SWH noted that if the polarization rises abruptly at the Lyman edge in the rest frame of the gas, relativistic effects give a good fit to the observed wavelength dependence of the polarization rise in PG 1630+377. The fit provides a possible measure of the black hole spin. However, no physical reason for the postulated polarization rise is known. Recently, Beloborodov & Poutanen (1999, BP) have offered an explanation for the polarization rises in terms of electron scattering in a corona or wind above the disk. In a different approach, Lee & Blandford (1997) discussed scattering by resonance lines of heavy elements as a possible cause of the Lyman continuum polarization rises. However, they did not give a quantitative model of the observed polarization rises.

We report here theoretical investigations of several aspects of Lyman continuum polarization rises in QSOs. In §2, we summarize recent results on PG 1222+228, concerning the apparent coincidence of its polarization rise with an intervening Lyman limit system (LLS). In §3, we present new results for electron scattering winds and coronae. In §4, we discuss the relevance of relativistic returning radiation to the Lyman continuum polarization rises. Our conclusions are summarized in §5.

2. THE STRANGE CASE OF PG 1222+228

PG 1222+228 is a radio quiet QSO of apparent magnitude $B \approx 15.5$ (Schmidt & Green 1983). Impey et al. (1995) observed a polarization rise at $\lambda \approx 750$ Å that coincides with a sharp drop in flux (Figure 1). They suggested that this was a coincidental LLS, corresponding to an observed narrow absorption line system at $z = 1.486$. Shields (2000) considered the possibility that the agreement in wavelength between the polarization rise and the absorption feature was not a coincidence. Broad absorption line (BAL) QSOs often show a rise in polarization in the BAL troughs (Schmidt & Hines 1999; Ogle et al. 1999; and references therein), reaching values as high as ~ 8 to 10 percent from ~ 1 outside the troughs. This is explained by a geometry in which the polarized flux results from a scattering source (perhaps an electron scattering wind) that is larger than the continuum source. The outflowing gas producing the absorption troughs blocks the line of sight to the continuum source but not the scattering source. In the troughs, one sees mainly the less luminous, but highly

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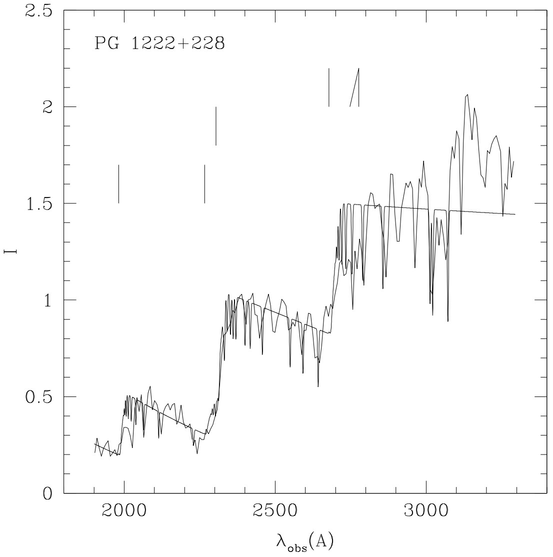

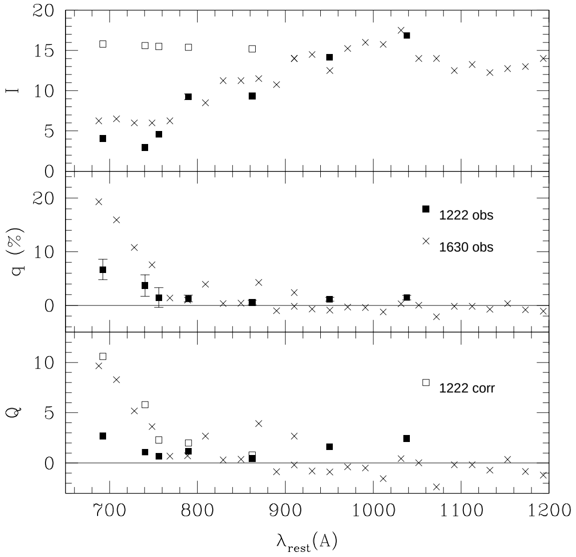

Fig. 1. *HST* spectrum of PG 1222+228 (Impey et al. 1995) fit with a model involving several Lyman limit systems. See text and Shields (2000) for details. Reproduced from Shields (2000). Copyright 2000, Astronomical Society of the Pacific; reproduced with permission.

Fig. 2. Polarized flux of PG 1222 corrected for Lyman limit absorption. Note rise in polarized flux in the Lyman continuum, resembling the case of PG 1630+377 (Koratkar et al. 1995). Adapted from Shields (2000). Copyright 2000, Astronomical Society of the Pacific; reproduced with permission. See Shields (2000) for references to observations.

polarized scattering source. Could a similar geometry explain the polarization rise in PG 1222+228?

The flux drop in PG 1222+228 is close to the wavelength of Ne VIII $\lambda775$, observed in some BAL QSOs (e.g., Arav et al. 1999). However, the feature in PG 1222+228 does not recover with decreasing wavelength within a normal velocity range. Expected BALs such as C IV and N V are not present, and the soft X–ray emission of PG 1222+228 is stronger than is typical for BAL QSOs (Shields 2000). Alternatively, Shields (2000) considered the possibility of an intrinsic, high velocity LLS. Such a feature would be unprecedented. However, Richards et al. (1999) argue that a large fraction of the narrow, high velocity absorption line systems in luminous QSOs, usually assumed to be intervening, are in fact intrinsic. In order to obscure the continuum source but not the scattering source, the outflowing gas would be quite close to the central source. In this case, the lack of measurable change in velocities in the associated narrow lines, over a period of seven years, argues against this picture.

Reverting to the intervening LLS interpretation, Shields (2000) showed that a good fit to the flux drop in PG 1222+228 was given by LLS associated with observed absorption line systems at z= 1.486 and 1.524 (see Figure 1). The fit is supported by the recovery of the continuum below the edge in a manner consistent with the ν^{-3} dependence of the optical depth and a typical intrinsic power-law continuum $L_\nu \sim \nu^{-1.8}$. Two additional LLS occur at $z = 1.174$ and 1.938. The quality of the fit and the straightforward nature of this explanation support the conclusion that the Lyman continuum polarization rise in this QSO is a coincidental feature that happens to agree in wavelength with the LLS at $z = 1.486$, 1.524.

This result implies that the observed, polarized flux should be corrected for the intervening absorption. Figure 2 shows the corrected Stokes flux, Q'_λ, rotated to the mean position angle of 168 degrees. (Q' has the advantage of avoiding the positive bias of the polarization in data with low signal–to–noise, as discussed by Koratkar et al. 1995.) This quantity rises strongly with decreasing wavelength in the region of the polarization rise. This behavior resembles the case of PG 1630+377, and it poses especially severe demands on theoretical models. The harder ultraviolet flux after correction for absorption requires a higher effective temperature for

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the accretion disk atmosphere. Shields (2000) found a reasonable fit for $a_* = 0.5, M_9 = 8.8$, and $\dot{M}_0 = 86$. These parameters give a luminosity $L = 0.36 L_{Edd}$, barely compatible with a geometrically thin disk.

A consequence of this analysis is that PG 1222+228 may not be a true Lyman edge quasar. All known polarization rise QSOs have heretofore been associated with candidate Lyman edge QSOs (Koratkar et al. 1998). Correspondingly, the presence of a Lyman edge in absorption in the disk continuum has been a feature of several proposed models for the Lyman continuum polarization rises. The existence of a polarization rise QSO without a Lyman edge in the total flux would be a challenge for such models.

3. WINDS AND CORONAE

BP have investigated an explanation for the Lyman continuum polarization rises that involves a hot corona or wind overlying the accretion disk. Coronae above AGN disks have been considered before in various contexts, although the heating mechanism is uncertain (e.g., Haardt & Maraschi 1991). In the case of a static corona, BP assume a plane parallel geometry with an underlying photosphere that emits a black body continuum at $kT = 3$ eV and a sharp Lyman edge in absorption. For a Thomson optical depth $\tau_{\rm T} = 1$, a substantial number of photons undergo more than one scattering before escaping from the top of the corona. The polarization of a scattered photon depends on its direction going into the last scattering. For photons scattered twice or more, the source of the photons for the last scattering is the corona itself. Therefore, the source is effectively limb brightened. This results in a substantial degree of polarization, parallel to the disk axis (positive in our convention). For frequencies below the Lyman edge, the flux is dominated by the primary emission together with singly scattered photons, and the polarization is essentially the perpendicular (negative) polarization of an electron scattering atmosphere (Chandrasekhar 1960). Just above the Lyman edge, the scattered flux is dominated by singly scattered photons. At frequencies substantially above the Lyman limit, however, most of the observed flux consists of multiply scattered photons, and this leads to an increasing, parallel polarization. This model naturally gives an increase in polarization in the Lyman continuum, rising toward shorter wavelengths.

The observed flux drop and polarization rise become more gradual as the coronal temperature increases (BP's Figure 1). Indeed, Hsu & Blaes (1998) calculated the polarization in a similar geometry with $kT \sim 100$ keV, and found a gradual increase in polarization to values $\sim 10 - 15\%$ at photon energies above 1 keV. BP find a polarization rise to nearly 20% at 600 Å, resembling the observed polarization rise in PG 1630+377.

We have made independent calculations of the polarization in the BP model, using a code based on the iterative scattering method of Poutanen & Svensson (1996). Our results confirm the behavior of the flux and polarization found by BP for their assumed parameters. However, a plot of the polarized flux is revealing (Figure 3). Following Koratkar et al. (1995), we give the observed, polarized flux in terms of the rotated Stokes flux, Q'. The observed polarized flux is essentially zero redward of the Lyman limit, and rises steeply at about 750 Å. The model's polarized flux shows a more gradual rise. Redward of the Lyman limit, the model polarization is perpendicular to the disk axis, as noted by BP. Just below the Lyman edge, it crosses into positive (parallel) values, and rises rather gradually before actually dropping at wavelengths below ~750 Å. This is rather different from the observed behavior. Conceivably, some additional polarization process, such as scattering by material at larger radius, just offsets the negative polarization at longer wavelengths. In Figure 3, we also show the resulting polarization if a wavelength independent polarization of 2.5% is added to the model, resulting in zero polarization at longer wavelengths. The polarized flux is computed from the resulting polarization and the total flux. The polarized flux rise is still too gradual and fails to reach the observed values at the shortest wavelengths.

BP reject the static corona model on the basis of the change in sign of polarization around the Lyman limit, which is not observed. They also note that in this model, a strong Lyman edge in absorption would be seen for relatively face on viewing angles, and such edges are rarely if ever in observed in QSOs. Our results for the polarized flux further strengthen the case against a static corona as a cause of the Lyman continuum polarization rise in PG 1630+377 and similar objects.

BP find more promise in a model involving a corona with a mildly relativistic outflow velocity. Beloborodov (1998) showed that, for an outflow velocity $\beta \equiv v/c = 0.45$ (as might occur for an $e^{\pm}$ plasma accelerated by the radiation pressure of the disk emission), the scattered radiation can be strongly polarized parallel to the disk axis. This results from the fact that the disk emission is effectively limb brightened by

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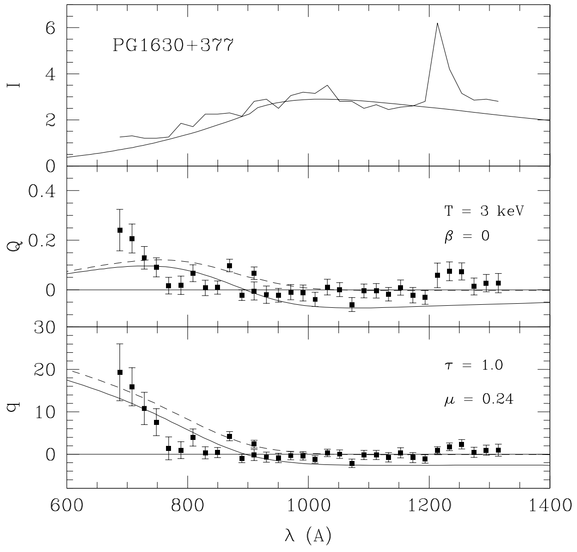

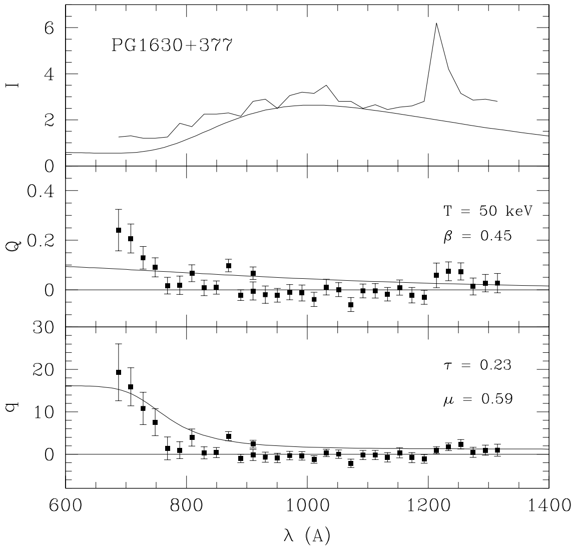

Fig. 3. Polarization versus wavelength in static corona overlying accretion disk. Solid line shows model results; dashed curve shows model results plus an added wavelength independent polarization of 2.5%. See text for details. Observations from Koratkar et al. (1995).

Fig. 4. Polarization versus wavelength in electron scattering wind overlying accretion disk. See text for details.

relativistic aberration in the rest frame of the scattering material. BP performed single–scattering, frequency dependent calculations with allowance for a high wind temperature and resulting shift of the frequencies of scattered photons. For the primary disk continuum, BP assumed a toy continuum that simulates a Lyman edge in absorption smeared out by relativistic effects near the black hole. For a wind optical depth of $\tau_{\rm T}$ = 0.23 and kT = 50 to 100 keV, the polarization rises in a way resembling that observed in PG 1630+377. The polarization rise largely results from the dropping flux below the Lyman edge, whereas the polarized flux, resulting from the hot, moving corona, does not show the Lyman edge.

We have modified our iterative scattering code to reproduce the wind model of BP. Consider a plane parallel, vertical wind with constant Lorentz factor $\gamma = (1-\beta^2)^{-1/2}$. The radiation field is time independent in the lab frame, but spatial gradients in this frame will mean that it will not be time independent in the comoving frame. Using standard Lorentz invariants (e.g. Mihalas & Mihalas 1984) we may write the lab frame radiative transfer equation in terms of comoving frame quantities, viz.

$$\mu \frac{\partial \mathbf{I}_\nu}{\partial \tau_{\rm T}} = (1-\beta\mu)\left[\frac{\sigma_{\rm CS}(\nu_{\rm c})}{\sigma_{\rm T}}\mathbf{I}_\nu - \frac{1}{\gamma^3(1-\beta\mu)^3}\mathbf{S}_{\rm c}\right]. \tag{1}$$

Here $\mathbf{I}_\nu$ is the lab frame specific intensity Stokes vector; $\sigma_{\rm CS}(\nu_{\rm c})$ is the thermal Compton scattering cross section, evaluated at the comoving frame frequency $\nu_{\rm c} = \gamma(1-\beta\mu)\nu$; and $\mathbf{S}_{\rm c}$ is the comoving frame polarized source function, evaluated from the comoving frame intensity at the comoving frame frequency and direction cosine $\mu_{\rm c} = (\mu-\beta)/(1-\beta\mu)$. Expressions for $\sigma_{\rm CS}$ and $\mathbf{S}_{\rm c}$ may be found in Poutanen & Svensson (1996).

We iteratively solved the lab frame transfer equation in the same way as in the static corona model. For $\beta = 0.45, kT = 50$ keV, and $\tau_{\rm T} = 0.23$, we obtained good agreement with BP's predicted flux and polarization as a function of wavelength (Figure 4). (BP used a single scattering approximation, which is a good approximation at these wavelengths and low optical depths. We follow BP in using a plane parallel wind truncated at some optical depth, $\tau_{\rm T}$, as a crude approximation to a wind that presumably diverges at some height comparable with the radius, above which there is little further optical depth.) Once again, however, the polarized flux seems to provide a more vivid test of agreement with observation. Figure 4 shows that the polarized flux rises much more gradually, with decreasing wavelength, than is observed. The model thus appears to have difficulty

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giving a quantitative fit to the data for PG 1630+377. In retrospect, this conclusion may seem unsurprising. The polarized flux is a direct measure of the scattered radiation, and since the electron scattering cross section does not change across the Lyman edge, neither should the polarized flux change.

Both the static corona and wind models rely on the presence of a deep Lyman edge in absorption to give a rise in polarization in the Lyman continuum. The results described above for PG 1222+228 suggest that this object may not be a Lyman edge quasar, once correction is made for the intervening LLS absorption. In this case, coronal scattering models may face a further difficulty.

4. RETURNING RADIATION

Radiation leaving the surface of a disk near a black hole will suffer various relativistic effects as it propagates away from the point of emission. These include the relativistic Doppler effect, the gravitational redshift, the relativistic aberration, and general relativistic bending of the light path. The bending causes some light, mainly from the innermost parts of the disk, to return to the equatorial plane and strike the disk, often at a larger radius. This "returning radiation" is minor for disks around nonrotating black holes but can be substantial for rapidly rotating holes (Cunningham 1976). This is true because a larger black hole angular momentum gives a smaller value of the radius r_{ms} of the innermost stable circular orbit, usually taken to be the inner edge of the disk. For prograde disks around rapidly rotating black holes with $a_* = 0.9978$, the returning radiation flux can amount to some 20% of the locally generated flux at larger radii (Cunningham 1976). Because polarization of light emitted from a scattering atmosphere depends strongly on the directionality of the radiation going into the last scattering, the returning radiation might have a substantial effect on the polarization of the total radiation from the disk.

This process has been considered recently by Agol & Krolik (2000) in the context of the inner boundary conditions for disks around black holes. Krolik (1999) and Gammie (1999) have discussed the possibility that plunging material inside r_{ms} exerts a magnetic torque on the material just outside r_{ms}, causing an increase in the angular momentum flow outwards through the disk and the associated local dissipation of energy. Agol & Krolik discuss several implications of this process, including the equilibrium black hole spin, the disk energy distribution, and polarization. They parametrize the effect of the inner torque in terms of $\Delta\epsilon$, the increase in efficiency of energy production per unit mass accreted, where $\epsilon \equiv L/\dot{M}c^2$, compared with zero inner torque. They trace the trajectory of the emitted photons using a numerical method described by Agol (1997). The effect of a strong inner torque is to increase dramatically the flux emitted by the innermost radii in the disk, just outside r_{ms}. This radiation is strongly affected by gravitational bending; and it can increase greatly the amount of returning flux striking the disk at larger radii. For a_* near unity, a large fraction (up to 58%) of the extra flux resulting from the inner torque returns to the disk. Agol & Krolik (2000) raised the possibility that the polarization resulting from returning radiation might be relevant to the Lyman continuum polarization rises.

We consider here this possibility in the context of the toy model described by SWH. In their model, a given point on the disk emits a black body continuum at the local effective temperature for $\nu < \nu_H$; for higher frequencies, it emits as a black body at $T = 0.8409T_{eff}$. This crudely simulates a Lyman edge in an LTE atmosphere with a large Lyman continuum opacity. However, whereas SWH postulated a sharp increase in polarization at the Lyman edge, we assume here that the emitted radiation has the polarization of an electron scattering atmosphere at all frequencies. Our purpose is to explore whether relativistic returning radiation can give a polarization rise at the Lyman edge in the radiation observed from the disk as a whole. This might occur because the drop in brightness temperature in the Lyman continuum will cause the Lyman continuum to be emitted from smaller radii in the disk than the radiation just redward of the Lyman limit. The radiation observed will have a larger contribution of scattered, returning radiation in the Lyman continuum than at longer wavelengths. The scattered returning radiation, becoming more important just at the Lyman limit, could give an abrupt rise in polarization.

SWH gave a model for PG 1630+377 with $a_* = 0.5$, $M_9 \equiv M/10^9\ M_\odot = 5$, and $\dot{M}_0 \equiv \dot{M}/1\ \mathrm{M}_\odot\ \mathrm{yr}^{-1} = 27$, giving a maximum disk effective temperature of $38,000$ K. Using the numerical method of Agol (1997), we computed the polarization, including scattering of the returning radiation according to the diffuse reflection law of Chandrasekhar (1960). Figure 5 shows that the polarization of the observed radiation is affected insignificantly by the returning radiation, except at very high frequencies that carry little flux. The weak effect

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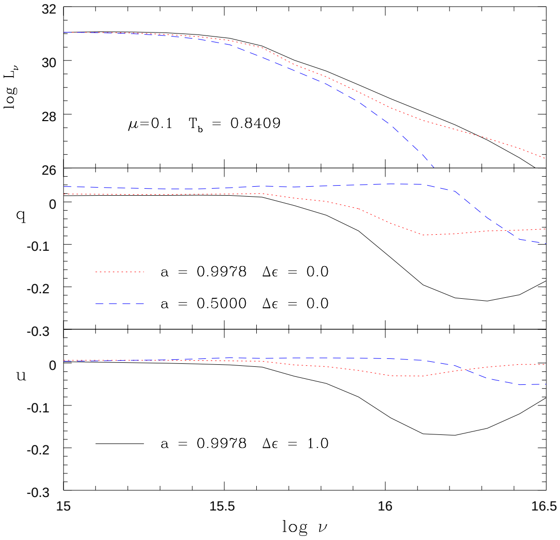

Fig. 5. Polarization of thermal emission from accretion disk including returning radiation. See text for details.

of returning radiation is not surprising, since for a moderate value of a_* and no inner torque, there is little returning radiation. We have calculated a model of the same nature, still with $\Delta\epsilon = 0$, but with $a_* = 0.9978$. This model also has $\dot{M}_0 = 27$, but it has $M_9 = 60$, so as to give again a maximum effective temperature of 38,000 K. (This is a simple device to preserve a substantial Lyman edge in the local emission and a rough fit to the observed energy distribution.) Figure 5 shows that there is now a significant degree of polarization in the Lyman continuum region, reaching about 6% at observed frequency of log $\nu = 16.1$. However, this falls well short of the observed 20% polarization of PG 1630+377; and the polarization rise is too gradual to explain the observed rises in PG 1630+377 or PG 1222+228. (In order to show a wider range of frequencies, we use a log ν scale in Figure 5. However, inspection of Figures 3 and 4 suffices to show that the observed polarization rise is much more abrupt than predicted by this model.) As noted by SWH, for a rapidly rotating black hole and the required disk effective temperature, the Lyman continuum is emitted at small radii. This emission suffers strong relativistic effects that give a gradual rise in the observed polarization, reaching a maximum at wavelengths much to the blue of the Lyman limit. As a further example, we considered the case $a_* = 0.9978$ and $\Delta\epsilon = 1$, so that most of the disk's luminosity results from the inner torque and comes from small radii. This should give the maximum effect of returning radiation. In order to preserve $T_{max} = 38,000$ K, this model had $M_9 = 60$ and $\dot{M}_0 = 1.6$. Figure 5 shows that the model has strong polarization at high frequencies, reaching roughly 25% at a frequency of log $\nu = 16.3$. Again, the polarization rise is much too gradual to the fit the observations. There is a large rotation of the position angle of the polarization resulting from general relativistic effects (see also Figure 11 of Agol & Krolik 2000).

As noted by SWH, a moderate black hole spin is required to avoid excessive blueshifting and smearing of the polarization rise. However, returning radiation then is insufficient to give polarization rises of the observed magnitude. This dilemma seems likely to doom any attempt to use relativistic returning radiation to explain the presently known instances of a Lyman continuum polarization rise. The strong polarization resulting from returning radiation might nevertheless be observable in some QSOs. In general, it will occur for disks around rapidly rotating black holes, generally at high frequencies where the flux is rapidly dropping. Only at frequencies above the black body peak for the hottest radii in the disk will the emission be dominated by the innermost radii that give strong returning radiation.

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5. CONCLUSIONS

We have explored several models to explain the Lyman continuum polarization in QSOs. Neither Compton scattering nor returning radiation appear to be capable of explaining the strong, rapid rise in polarized flux observed for PG 1630+377. The same seems likely to be true for PG 1222+228, especially after correction for the LLS absorption.

Quite apart from the issues discussed above, there is the observed polarization of the Lyα line in PG 1630+277. It is polarized in a similar positional angle to the 800 Å continuum polarization, to a degree of about 3% (Koratkar et al. 1995). The wavelength of the feature in polarized flux actually is on the red wing of the emission line in total flux, roughly at the expected wavelength of the N V λ1240 resonance line (cf. Shields 2000). Certainly, the emission line in the polarized flux does not share the large blueshift of the polarization rise in the continuum, if it is indeed associated with the Lyman edge of hydrogen. Discussions of the Lyman continuum polarization rise have tended to ignore the "Lyα" feature, although Koratkar et al. (1995) did suggest scattering of optically thin hydrogen emission followed by passage through an absorbing layer of modest optical depth at the Lyman limit. From another point of view, however, there are only two natural position angles in the context of a disk geometry (parallel and perpendicular to the disk axis). The polarized Lyman continuum and Lyα could come from two different sources, which might coincidentally have the same position angle. The polarized Lyα feature has a normal broad emission-line width, and presumably comes from material at a radius $\sim 10^4 R_g$. The polarized Lyman continuum may come from a smaller radius, as in the models of SWH and Blaes and Agol (1996). Here, for a thermal intrinsic line width, thermalization may suppress the Lyα emission, suggested by simple estimates based on the black body limit.

From a broader perspective, most proposals for the Lyman continuum polarization rise seem contrived to explain this particular observation, rather than following naturally from a more comprehensive theory of AGN. Thus, they do not address the issue of the statistical incidence of the polarization rise phenomenon. Unfortunately, there is currently no observational capability to confirm and extend the measurements of Lyman continuum polarization in QSOs. The Lyα forest is an increasing problem at higher redshifts, and there is an urgent need for a renewed capability to do ultraviolet spectropolarimetry from space.

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Eric Agol: Dept. of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218 (agol@pha.jhu.edu).
Omer Blaes: Dept. of Physics, University of California, Santa Barbara, CA 93106 (blaes@physics.ucsb.edu).
Gregory A. Shields: Dept. of Astronomy, Univ. of Texas, Austin TX 78712 (shields@astro.as.utexas.edu).