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Compton Scattering and the Rises in UV Polarization in Quasars

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Abstract. Optical/UV radiation from accretion disks in quasars is likely to be partly scattered by a hot plasma above the disk. We investigate whether the scattering may produce the steep rises in polarization observed blueward of the Lyman limit in some quasars. We suggest and assess two models. In the first model, primary disk radiation with a Lyman edge in absorption passes through a static ionized "skin" covering the disk, which has a temperature $kT \sim 3$ keV and a Thomson optical depth $\tau_{\rm T} \sim 1$. Scattering in the skin smears out the Lyman edge and produces a steep rise in polarization at $\lambda < 912$ Å. In the second model, the scattering occurs in an optically thin coronal plasma outflowing from the disk with a mildly relativistic velocity. We find that the second model better explains the data. The ability of the models to fit the observed rises in polarization is illustrated with the quasar PG 1630+377.

1. Introduction

Steep rises in polarization blueward of the Lyman limit have been detected in 3 of 10 observed quasars (Impey et al. 1995; Koratkar et al. 1995). Especially challenging is the case of PG 1630+377 where the polarization increases from $\sim 2\%$ at 1000 Å to $\sim 20\%$ at 700 Å. Attempts to explain such a steep rise have not been successful (e.g., Blaes & Agol 1996; see Koratkar & Blaes 1999 for a review). One toy model fitting the data was suggested by Shields, Wobus, & Husfeld (1998). They assume, however, *ad hoc* an arbitrary large jump in polarization at $\lambda = 912$ Å in the disk comoving frame and then fit the observed rise by the relativistically smeared-out jump.

A possible physical mechanism producing the rises in polarization is Compton upscattering of the disk radiation by a hot plasma. Assuming that the disk emits UV radiation with the Lyman edge in absorption, one finds that the upscattering (i) smears out the Lyman edge and (ii) polarizes the radiation. The scattered radiation dominates the spectrum blueward of the edge, and this leads to the rise in polarization at $\lambda < 912$ Å. We investigate here two scenarios:

- **Multiple scattering in a static slab with $\tau_{\rm T} \sim 1$.** The intensity of scattered radiation is limb-brightened in the slab (Sunyaev & Titarchuk

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1985) and the multiply scattered radiation acquires a polarization parallel to the disk normal.

- **Scattering in a mildly relativistic outflow with $\tau_T < 1$.** The disk radiation is limb-brightened in the plasma comoving frame as a result of relativistic aberration (Beloborodov 1998). This effect leads to a parallel polarization, $p \sim 20\%$, of the scattered radiation.

Transfer of polarized radiation in a static corona covering the disk was previously studied in detail (e.g., Haardt & Matt 1993; Poutanen & Svensson 1996; Hsu & Blaes 1998). It has been shown that the corona produces parallel polarization rising toward short wavelengths. Possible relevance to the UV polarization rises in QSOs has been assessed by Hsu & Blaes (1998) who concluded that the predicted rise is not steep enough to explain the data.

Here, we argue that the scattering in a layer at a Compton temperature, $kT_C \sim 3$ keV, would generate a much steeper rise in polarization as compared to a static corona with $kT \sim 100$ keV. The layer may be associated with an ionized "skin" of an accretion disk heated by the corona emission. In §2, we perform calculations of radiative transfer in the skin demonstrating the production of steep rises in polarization. Then, in §3, we investigate the outflow model. Previously, it was suggested as a possible mechanism producing parallel optical polarization (Beloborodov 1998). We now find that the model can reproduce the rises in UV polarization if the disk emission has a Lyman edge in absorption.

2. Comptonization in a Static Slab

Let semi-isotropic radiation propagate into an ionized slab from an underlying disk. With increasing height, the attenuated intensity of unscattered radiation, I_0 (0-th scattering order), gets suppressed at large angles with respect to the normal because photons pass through large optical depths at these angles. It results in a perpendicular polarization in the first scattering order. In the second order, photons come from the slab itself, and their intensity, I_1, is limb-brightened if the slab optical depth, $\tau_T \lesssim 1$. The radiation scattered twice, I_2, then acquires a parallel polarization. The limb-brightening progresses with successive scatterings until the intensity I_N saturates at some I_∞ which is an eigen-function of the transfer problem (Sunyaev & Titarchuk 1985). The resulting parallel polarization progressively increases with scattering orders and then saturates.

In a hot slab, the scattering is accompanied by a photon blueshift. After N scatterings, a photon of initial energy ε acquires an energy of $\sim (1+4kT/m_ec^2)^N\varepsilon$. One thus expects a strong impact of the slab on both the disk spectrum and polarization. If the original UV spectrum has a Lyman edge in absorption then the edge energy, $\varepsilon_L = 13.6$ eV, delineates two regions in the emerging spectrum. At $\varepsilon > \varepsilon_L$, the scattered radiation dominates the observed flux, and the further away from the edge, the higher are the scattering orders contributing to the spectrum. The radiation is therefore parallelly polarized at $\varepsilon \gg \varepsilon_L$. By contrast, at $\varepsilon < \varepsilon_L$, all scattering orders contribute to the spectrum, which leads to a small net polarization.

A slab with temperature, $kT \sim 100$ keV, produces a gradual growth in parallel polarization toward high energies, so that p reaches $\sim 10 - 15\%$ at

$\varepsilon \gtrsim 1$ keV (Hsu & Blaes 1998). The polarization maximum is blueshifted far away from the edge because the gain in energy per scattering is large, $\Delta\varepsilon/\varepsilon \sim 4(kT/m_e c^2) \sim 4/5$. The high T is thus the reason for the slow growth of p with respect to wavelength. If the Comptonization occurred in a slab of a relatively low temperature, then a large number of scatterings would be accompanied by a modest blueshift, and $p(\lambda)$ at $\lambda < 912$ Å would be much steeper. With this motivation, we consider a transition layer between the UV disk and the corona as a possible location of the Comptonization.

If the hot corona is patchy then the bulk of UV radiation comes directly from the disk without being scattered in the corona. At the same time, the whole UV disk may be covered by an ionized "skin" Compton heated by the coronal emission to an equilibrium temperature, $kT_{\rm C}$, of a few keV. We model the skin as a slab of optical depth, $\tau_{\rm T} \sim 1$, and temperature, $kT \sim 1-10$ keV. Below the slab, we assume a blackbody source with temperature, $kT_{\rm bb} = 3$ eV. The Lyman edge in the source spectrum is modelled as a sharp jump down to zero intensity at 912 Å. In the calculations of radiative transfer in the slab, we use the iterative scattering method (Poutanen & Svensson 1996). The calculations are similar to those performed previously, except that, keeping in mind the transition layer, we study a range of low temperatures.

The results for $\tau_{\rm T} = 1$ and $kT = 1, 3$, and 10 keV are presented in Figure 1a for a disk inclination $\cos\theta = 0.23$. The polarization is close to its maximum at this inclination. With increasing $\tau_{\rm T}$, p first decreases, then changes its sign, and in the limit $\tau_{\rm T} \gg 1$ one arrives at the standard Chandrasekhar-Sobolev perpendicular polarization. An increase in T leads to a larger energy gain per scattering that makes the rise in polarization less steep. On the other hand, a decrease in T and/or $\tau_{\rm T}$ leads to a reduction of the flux blueward of the Lyman edge. This is a general tendency of the Comptonization model: dramatic rises in polarization imply modest fluxes blueward of the edge. A compromise is achieved in the case of $\tau_{\rm T} \sim 1$ and $kT \sim 3$ keV. In this case, the predicted behavior of the flux and polarization resembles the data on PG 1630+377 (see Fig. 1a). The edge is smeared-out at large inclinations while it is strongly pronounced at modest inclinations. Additional smearing-out may be present due to relativistic effects near a Kerr black hole.

A robust feature of the model is that p changes sign across the edge, and the small polarization redward of the edge is perpendicular to the disk normal (see also Haardt & Matt 1993). By contrast, the data favor the same position angle blueward and redward of the edge (Koratkar et al. 1995). The constancy of the position angle is better seen in PG 1222+228 (Impey et al. 1995). Besides, optical polarization measured in many objects tends to be parallel to the disk normal (e.g., Antonucci 1992). The predicted perpendicular redward polarization thus appears to contradict the data.

3. Scattering in a Coronal Outflow

A corona above an accretion disk need not be static and formation of mildly relativistic outflows is very likely. Moreover, there are indications from X-ray observations for bulk motion in coronas of black hole sources (Beloborodov 1999a; Zdziarski, Lubiński, & Smith 1999). Here, we consider a toy model in which the

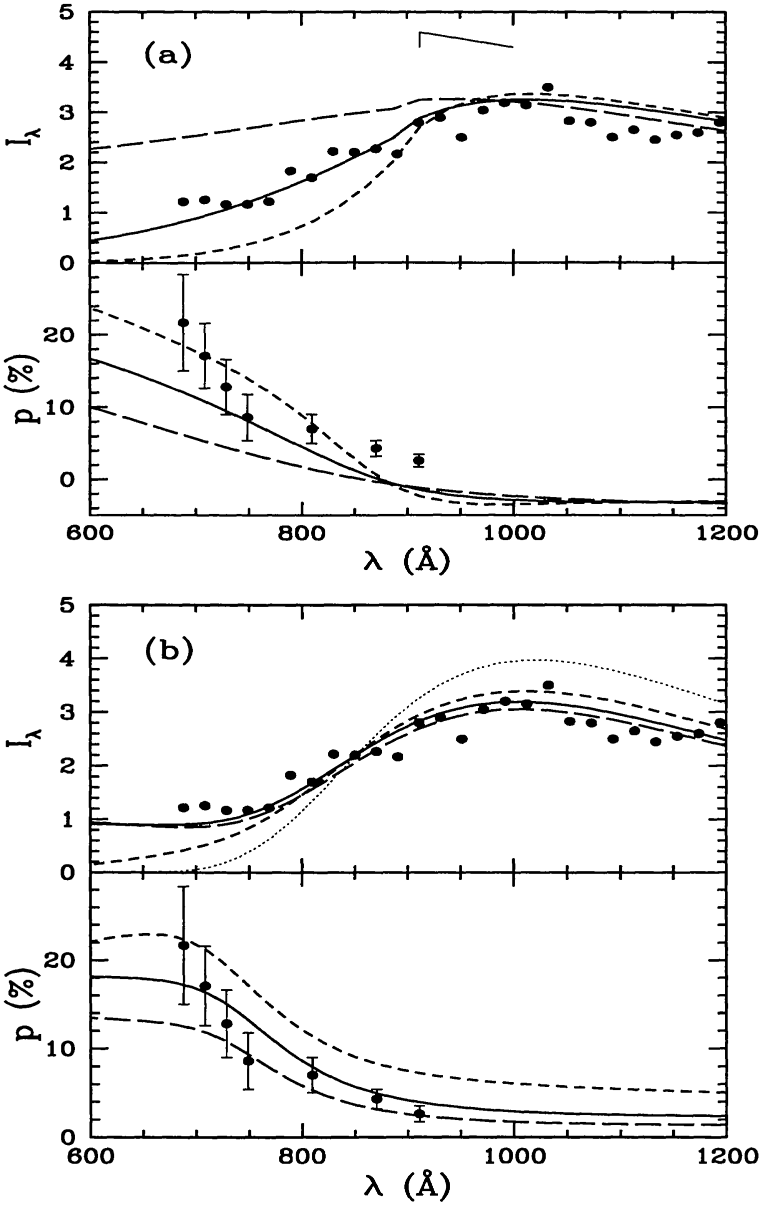

Figure 1. (a) The spectrum, I_λ (in arbitrary units), and polarization, p, from a disk covered by an ionized "skin" of optical depth, $\tau_{\rm T} = 1$, as viewed at inclination $\theta = 77^{\rm o}$. The sign of p is chosen so that $p > 0$ corresponds to the case where the electric vector is parallel to the disk normal. The dashed, solid, and long-dashed curves correspond to skin temperatures kT =1, 3, and 10 keV, respectively. Below the skin, we assume unpolarized blackbody emission of temperature 3 eV with a sharp Lyman edge in absorption. (b) The outflow model with $\beta = \beta_* = 0.45$ and column density, $N_c = 0.23\sigma_{\rm T}^{-1}$, as viewed at inclination $\theta = 60^{\rm o}$. The assumed original disk emission is shown by the dotted curve. Dashed, solid, and long-dashed curves correspond to outflow temperatures kT =3, 50, and 100 keV, respectively. The polarimetric data for PG 1630+377 show the detections above the 2.5σ level.

outflow is replaced by a slab of outflowing plasma with a column density, N_c. The underlying UV disk is assumed to emit isotropically. A typical velocity of the outflow is then $\beta \sim \beta_* = (4-\sqrt{7})/3 \approx 0.45$. Here, β_* corresponds to equilibrium with the disk radiation field (i.e., the bulk acceleration by the radiative pressure is balanced by the Compton drag at $\beta = \beta_*$). The equilibrium must be established if the outflow is composed of $e^{\pm}$ pairs (e.g., Beloborodov 1999b).

When viewed from the outflow comoving frame, the disk radiation is limb-brightened. This effect has a maximum at $\beta = \beta_*$ and leads to a parallel polarization, $p \sim 20\%$, of the scattered radiation (Beloborodov 1998). The observed weak polarization redward of the Lyman edge, $p \lesssim 2\%$, indicates that only a modest fraction of the disk radiation is scattered in the outflow. In a slab geometry, it implies that the outflow column density, $N_c < \sigma_{\rm T}^{-1}$. However, blueward of the edge, where the original disk emission crucially decreases, the scattered radiation can dominate the observed flux. This occurs due to Doppler blueshift of scattered photons. In addition to the Doppler effect due to bulk motion, there may be Doppler shifts due to thermal motions in the outflow. We therefore consider outflows with a range of temperatures, $kT \sim 1 - 10^2$ keV.

To calculate the spectrum and polarization of the scattered radiation, we first transform the disk radiation into the outflow comoving frame (see Beloborodov & Poutanen 1999). In the comoving frame, we use the scattering matrix for a hot static plasma (Nagirner & Poutanen 1993; see also Poutanen & Svensson 1996). Then, we transform the scattered radiation back to the lab frame. Due to a modest optical depth, the single scattering approximation is reasonable.

The results depend on the primary polarization and spectrum of the disk. We assume: (i) Zero original polarization. This is likely to be the case due to depolarization in the disk by Faraday rotation (e.g., Agol & Blaes 1996). (ii) In order to emulate the observed spectrum of PG 1630+377, we use a toy primary intensity in the form, $I_\varepsilon \propto \varepsilon^2 \exp[-(\varepsilon/\varepsilon_0)^6]$, and choose $\varepsilon_0 = 13$ eV. This spectrum emulates a smeared-out Lyman edge. The original smearing-out may be, e.g., the result of relativistic effects near the black hole.

The emerging radiation is shown in Figure 1b for $N_c = 0.23\sigma_{\rm T}^{-1}$ and inclination $\theta = 60^\circ$. The polarization has a wide maximum at $\cos\theta \sim \beta$ (cf. Beloborodov 1998). One can observe how a high temperature increases the flux at $\lambda < 800$ Å. On the other hand, a high T reduces the polarization of the up-scattered radiation (Poutanen & Vilhu 1993; Nagirner & Poutanen 1994). This effect is due to mildly relativistic thermal motions that cause random aberration of light in the electron rest frame. The random character of the "thermal aberration" leads to a reduction of any systematic polarization. A reasonably good fit to the PG 1630+377 data is obtained for $kT \approx 50 - 100$ keV.

4. Conclusions

Contrary to our initial pessimistic expectations at this workshop, we have found that Comptonization of UV radiation with a Lyman edge in absorption can produce very steep rises in polarization blueward of the edge. Redwards, the predicted polarization is low and weakly dependent on wavelength.

We model the Comptonizing plasma as a hot slab with three parameters: (i) optical depth $\tau_{\rm T}$, (ii) temperature T, and (iii) bulk velocity, β. Our first (static) model emulates an ionized skin of an accretion disk. It has $\tau_{\rm T} \sim 1$, $kT \sim 3$ keV, and $\beta = 0$. The skin produces a steep rise in parallel polarization blueward of the Lyman edge. The predicted polarization, however, changes its sign across the edge, which is not favored by the observations. Another potential difficulty is the strong Lyman edge predicted at modest inclinations.

In our second (outflow) model, the plasma velocity, $\beta \sim 0.5$, is in equilibrium with the disk radiation field (Beloborodov 1998) and its optical depth, $\tau_{\rm T} < 1$. A steep rise in polarization is then generated for a wide range of parameters. The predicted polarization is parallel to the disk normal at all wavelengths.

Both models predict rises in polarization in those objects where there is a Lyman edge or a dramatic spectral break in the original disk spectrum. The maximum $p \sim 20\%$ is then achieved at favorable inclinations. The skin model has the maximum at $\cos\theta \sim 0.25$, and the outflow model – at $\cos\theta \sim 0.5$.

The outflow model appears to be more promising. Note that a slab geometry is a rough approximation for an outflow. A real outflow is at least 2D (axisymmetric) or it consists of localized ejecta from the disk (Beloborodov 1999a). A full 2D model should include self-consistently the effects of relativistic disk rotation and gravitational redshift, which are important near a Kerr black hole.

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