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POLARIZATION NEAR THE LYMAN EDGE IN ACCRETION DISK ATMOSPHERE MODELS OF QUASARS

OMER BLAES AND ERIC AGOL
Department of Physics, University of California at Santa Barbara, Santa Barbara, CA 93106

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ABSTRACT

We calculate self-consistently the structure, spectrum, and polarization of optically thick atmospheres under the conditions expected in quasar accretion disks. We consider a pure-hydrogen composition and neglect the effects of external illumination. We show that, blueward of the Lyman edge, the polarization rises *above* the value expected from an optically thick, pure electron-scattering atmosphere. This arises because of the wavelength dependence of the absorption opacity, combined with the fact that the source function in this region of the spectrum has a steep variation with optical depth. We suggest that this effect may help explain the recent *Hubble Space Telescope* observations of steep rises in polarization blueward of the Lyman edge in several quasars. We predict that the polarization should continue to rise blueward of the wavelength at which the current observations end, that cooler spectra should be more polarized, and that the polarization angle in this region should be parallel to the disk plane.

Subject headings: accretion, accretion disks — galaxies: active — galaxies: nuclei — polarization — radiative transfer

1. INTRODUCTION

The radiation emitted by electron-scattering–dominated accretion disks is expected to be polarized up to ≃12% parallel to the plane of the disk (Chandrasekhar 1960). Much effort has been expended searching for this polarization signature in the optical wavelengths without success (see, e.g., Antonucci 1992), indicating that there is something wrong with the standard geometrically thin disk model. It is possible that the polarization is reduced by an uneven disk surface (Coleman & Shields 1990) or by Faraday rotation by equipartition magnetic fields in the disk photosphere (Agol & Blaes 1996). General relativistic and absorption opacity effects may also decrease the expected degree of polarization below the pure electron-scattering value (Laor, Netzer, & Piran 1990, hereafter LNP).

Recently, *Hubble Space Telescope* spectropolarimetric observations have revealed that, in three radio-quiet quasars, the polarization increases steeply with frequency in the ultraviolet (Impey et al. 1995; Koratkar et al. 1995). In all three objects, the polarization rise begins just blueward of the Lyman edge, strongly suggesting that the rise is associated with the physics of hydrogen. In the context of accretion disk models, these results are particularly disturbing, as the increased absorption opacity blueward of the edge should decrease the importance of electron scattering and reduce the polarization (LNP). What is more, in the case of PG 1630+377, the polarization rises to ≃20%, well *above* the maximum value expected from an optically thick, pure electron-scattering atmosphere and therefore apparently beyond the reach of a standard optically thick accretion disk.

In this Letter, we propose that the resolution of the problem may lie in the treatment of how absorption opacity affects the polarization. In their calculation of the standard disk, LNP simply assumed that absorption opacity reduced the Chandrasekhar polarization by a factor $q = \kappa_{\rm es}/(\kappa_{\rm es} + \kappa_{\rm ab})$, where $\kappa_{\rm es}$ is the Thomson opacity and $\kappa_{\rm ab}$ is the absorption opacity. For a given frequency and radius, this factor was evaluated at the disk photosphere. This approach is technically incorrect and can in fact produce qualitatively wrong answers. The degree of polarization is only proportional to q if $q \ll 1$, i.e., if $\kappa_{\rm es} \ll \kappa_{\rm ab}$, so that the transfer equations can be solved perturbatively (e.g., Gnedin & Silantev 1978; Cheng et al. 1988). Even in this case, the function that q multiplies to yield the degree of polarization is *not* in general the Chandrasekhar polarization, and it can be much larger for steep thermal source functions or even rotated by 90° for flat thermal source functions. In an atmosphere with vertically constant q and with all photon sources at infinite depth (this includes the pure electron-scattering atmosphere in the $q \rightarrow 1$ limit), the polarization in fact *increases* with increasing absorption opacity for q not too small (Loskutov & Sobolev 1979).

In realistic atmospheres, absorption opacity can enhance limb darkening and increase the polarization above the pure-scattering value, provided the source function varies steeply with depth, as shown by Harrington (1969) and Bochkarev, Karitskaya, & Sakhibullin (1985). Unfortunately, these authors never published calculations of the polarization blueward of the Lyman edge. We demonstrate below that, in a complete treatment of the radiative transfer through the atmosphere, absorption opacity can increase the degree of polarization in this region of the spectrum to values substantially larger than the pure electron-scattering case. In § 2, we discuss the assumptions behind our treatment of the accretion disk atmosphere. Then, in § 3, we present our results on the flux and polarization around the Lyman edge. Finally, in § 4 we discuss our conclusions.

As far as we are aware, the only other model to explain the observed polarization rises blueward of the Lyman edge is by Blandford & Lee (1996), who postulate resonance-line scattering in an outflowing wind.

2. THE ATMOSPHERE CALCULATION

We treat the local disk photosphere as an atmosphere with blackbody radiation emerging from below. In the absence of external illumination (i.e., for the standard disk without, e.g., a corona), only two parameters determine the emergent spectrum and polarization from each zone: the local effective

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temperature $T_{\rm eff}$ and the surface gravity g. We assume that g is constant with height in the atmosphere, which is a good approximation provided that the atmosphere scale height is much smaller than the local disk thickness, which we find to be true in our simulations.

We have written a code to calculate fully self-consistent models of non-LTE transfer of polarized radiation through pure-hydrogen atmospheres. The code uses a Feautrier method combined with complete linearization (see, e.g., Mihalas & Mihalas 1984) to calculate all properties of the atmosphere. This includes the frequency, polarization, and angular distributions of the radiation field, as well as the temperature, density, pressure, and level populations, assuming hydrostatic, radiative,[1] and statistical equilibrium. The sources of absorption opacity included are free-free absorption and photoionization from all bound levels of hydrogen. All line opacities are neglected, and the only source of scattering opacity that we consider is Thomson scattering. The polarization dependence of the scattering source function is included. In the absence of any absorption opacity, the code successfully reproduces the polarization results of Chandrasekhar (1960) and Phillips & Mészáros (1986). It also successfully models the temperature distribution in simple pure-hydrogen models of early-type stellar atmospheres (Mihalas 1978). We will discuss details of the calculation in a future publication.

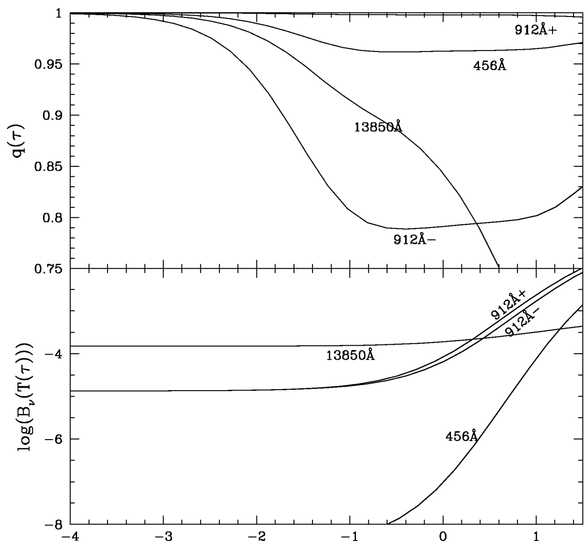

FIG. 1.—Variation of $q = \kappa_{\rm es}/(\kappa_{\rm es} + \kappa_{\rm ab})$ and the thermal source function for various wavelengths for a $T_{\rm eff} = 20{,}000$ K, $g = 130$ cm s^{-2} atmosphere.

3. RESULTS

We have run the code with a range of values of $T_{\rm eff}$ and g appropriate for quasar accretion disk models. Redward of the Lyman edge, the polarization generally rises toward the blue. At the edge, the polarization drops as a result of the increase in absorption opacity and then rises rapidly above the value for pure electron scattering as the bound-free opacity decreases. The polarization peaks at several hundred angstroms and then falls toward the extreme ultraviolet. We find that there is an edge and rise in polarization even if there is none in total flux.

In Figure 1, we show the variation of $q(\tau)$ and the source function with optical depth for various wavelengths for a $T_{\rm eff} = 20{,}000$ K, $g = 130$ cm s^{-2} atmosphere, neglecting non-LTE effects. At short wavelengths, the source function varies steeply with optical depth because, in the Wien region, the Planck function depends sensitively on the temperature. In this atmosphere, the maximum polarization is achieved at 456 Å when the source function is very steep at $\tau = 1$ *and* the absorption opacity is not too strong relative to the electron-scattering opacity ($q \simeq 1$). The physics here is in qualitative agreement with the results of Bochkarev et al. (1985). The large gradient in source function causes stronger limb darkening, so for small μ, relatively more photons are seen due to scattering than due to emission, causing an increase in polarization. In addition, if q is too small at $\tau = 1$ (as at 912 Å−, i.e., at a wavelength just short of the Lyman edge), then overall more photons emerge from the atmosphere without scattering, decreasing the polarization and in fact the limb darkening. If the source function at $\tau = 1$ is very flat (as at 13850 Å), then limb darkening is weak and the scattered photons will mostly come from the side rather than below. This causes the polarization plane to be vertical, i.e., causes p to become negative, for $\mu \gtrsim 0.3$ at this wavelength.

In Figure 2, we show the dependence of polarization on $T_{\rm eff}$ for $\mu = 0.548$. The values of g have been chosen so that the atmosphere is nearly at the Eddington limit (including absorption opacity) in each case. The polarization for a pure electron-scattering disk at the same viewing angle would be $\simeq$2%. We easily obtain values larger than this blueward of the Lyman edge. In fact, in the lowest temperature atmosphere, such large values are even obtained redward of the edge because of the longer wavelength Wien turnover in the Planck function. Note that all the polarizations approach the pure electron-scattering value at zero wavelength because, in this limit, the absorption opacity vanishes and the thermal source function is

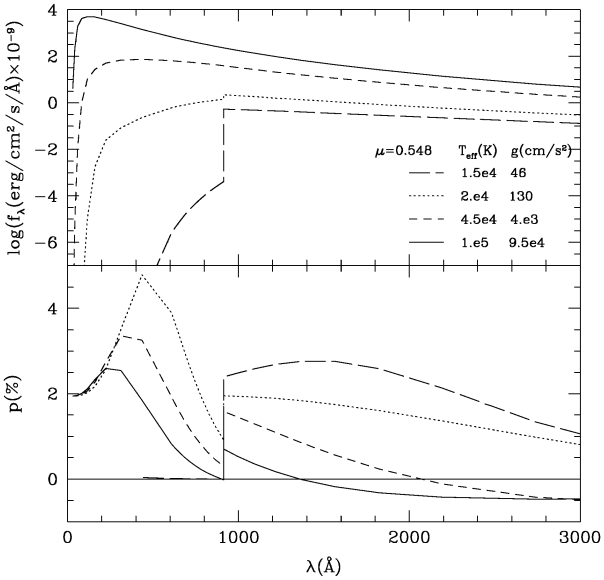

FIG. 2.—Total flux and polarization of the emerging radiation field as a function of wavelength for different effective temperatures and surface gravities, at $\mu = \cos i = 0.548$, where i is the inclination angle of the line of sight to the observer with respect to the normal of the plane of the atmosphere.

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[1] In principle, substantial viscous dissipation might occur right near the disk photosphere, so that radiative equilibrium will not be valid. However, given that we have no basic understanding of dissipation in disks, we neglect this possibility here.

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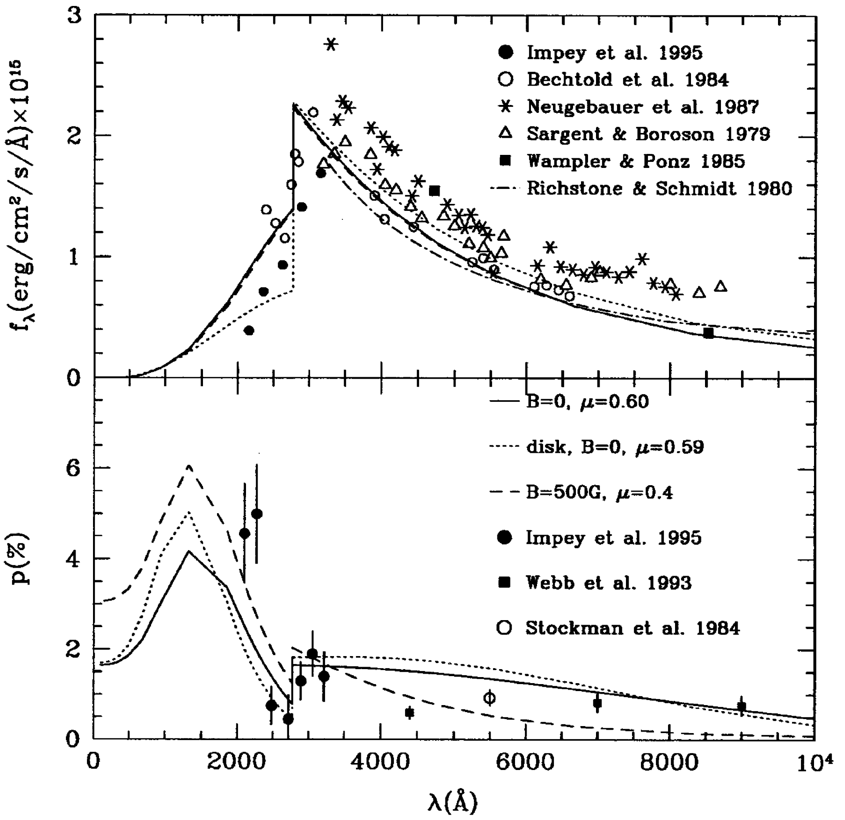

FIG. 3.—Total flux and polarization vs. observed wavelength (z = 2.047) of PG 1222+228. Solid curves show the best least-squares fit to the UV polarization data (the seven shortest wavelength points) for a $T_{\rm eff}$ = 20,000 K, g = 130 cm s^{-2} atmosphere model, yielding μ = 0.59 with χ^2 = 15. Also shown are curves for the multitemperature disk model described in § 3, with best-fit μ = 0.60 and χ^2 = 18. Finally, a case illustrating the effects of Faraday rotation in a single-temperature atmosphere model is shown, with μ = 0.4, B = 500 G, $T_{\rm eff}$ = 20,000 K, and g = 130 cm s^{-2}, yielding χ^2 = 23. The theoretical fluxes shown in the upper half of the figure were scaled by an arbitrary constant for each model to roughly agree with the (nonsimultaneous) flux data.

irrelevant. At very long wavelengths for this inclination angle, p is negative, which has the potential of explaining the fact that the optical polarization is aligned with the radio axes in Seyfert 1 galaxies. This will depend however on the radial temperature gradient in the disk, and we will explore this in future work.

Figure 3 presents the results of a single-temperature LTE atmosphere fitted to the ultraviolet polarization data of PG 1222+228 (Impey et al. 1995). We did not fit the flux, which is scaled by an arbitrary constant to compare to the observations. The steepest rise in polarization blueward of the Lyman edge occurs for $T_{\rm eff} \simeq$ 20,000 K, so we used this model atmosphere to make a best fit to the UV polarimetric data from Impey et al. (1995), minimizing χ^2 by varying μ. The model provides a qualitative fit to both the observed spectrum and the polarization, particularly given that we did not attempt to fit the spectral energy distribution of total flux. This suggests to us that this physics may indeed be responsible for the observations. However, there are clearly quantitative differences between the fit and the data. Blueward of the edge, the two shortest wavelength polarization data points are both above the fit while the next two points are below, indicating that our model does not produce as fast a rise as observed.

We have also calculated disk spectra by summing LTE atmospheres over radius with g and $T_{\rm eff}$ calculated from a standard (Novikov & Thorne 1973) accretion disk model, with the corrections of Page & Thorne (1974), Eardley & Lightman (1975), and Riffert & Herold (1995). We increased g by 20% to take into account the effects of increased opacity due to bound-free absorption on the vertical structure of the disk. We took the emitting area of each annulus to be given by the Euclidean expression and neglected the relativistic transfer function on the spectrum and polarization, i.e., Doppler shifts, aberration, gravitational redshift, and relativistic rotation of the plane of polarization. We note, however, that LNP have shown that these effects can depolarize the spectrum at short wavelengths. The disk model parameters were taken from Webb et al. (1993): $M = 5.3 \times 10^9\ M_\odot$, $L = 0.092 L_{\rm Edd}$, α = 0.1, and a = 0. The disk extends from the inner edge, with $T_{\rm eff}$ = 24,000 K and g = 300 cm s^{-2}, to $r = 50 r_g$, where $T_{\rm eff}$ = 11,000 K and g = 14 cm s^{-2}. The best fit to the polarization is shown in Figure 3. The polarization does not fit as well as for the 20,000 K atmosphere because the maximum temperature in this disk is slightly higher (maximum T = 25,500 K at $r = 9.5 r_g$). The jump in flux across the Lyman edge is much stronger for the disk we calculated than for the 20,000 K atmosphere because of the contribution of lower temperature regions, which are less ionized, making a stronger edge. This is a well-known problem in accretion disk models of quasars.

Faraday rotation by a photospheric magnetic field could in principle steepen the rise in polarization, because longer wavelengths will be more depolarized (see Agol & Blaes 1996). We therefore calculated models including a vertical magnetic field by using a new treatment that incorporates the effects of Faraday rotation directly in the full radiative transfer equation (Agol, Blaes, & Ionescu-Zanetti 1996). Figure 3 shows a case with a 500 G magnetic field in the $T_{\rm eff}$ = 20,000 K,

$g = 130$ cm s^{-2} atmosphere. This model actually yields a poorer fit to the UV polarization data, but it illustrates how photospheric magnetic fields may affect the models. We have also calculated some models with the $n = 1$ and 2 levels of hydrogen in non-LTE. In principle, this could change the polarization because the gradient of the thermal source function is no longer that of the Planck function. However, we have found that the polarization rise is similar, although the Lyman edge can be in emission in total flux. This agrees with the results of Störzer, Hauschildt, & Allard (1994), who found that non-LTE effects tend to reduce the absorption edge or even drive it into emission.

Finally, we have tried fitting the data of PG 1338+416 and PG 1630+377 (Koratkar et al. 1995), but the results are much less satisfactory since we cannot reproduce the quick rise in polarization with wavelength and the data have no drop in polarization right at the Lyman edge as does our model. If we put an arbitrarily steep source function in the atmosphere, then we can reproduce the steep rise. In future work, we will see whether we can find the physical reason such a steep source function might occur.

4. CONCLUSIONS

If the rise in polarization blueward of the Lyman edge in PG 1222+228 arises from an optically thick atmosphere with hydrogen bound-free opacity, as suggested by the fit from our spectrum, then we predict that the polarization will continue to rise toward the ultraviolet. It will then start to drop at several hundred angstroms in the quasar rest frame, although this might be affected by additional sources of opacity from elements heavier than hydrogen. This can currently be tested by further observations with the *Hubble Space Telescope*, using the G130H grating. However, the spectrum is severely absorbed at shorter wavelengths, which will make these observations difficult. More generally, we expect that higher temperature atmospheres will not show such steep rises in polarization in this wavelength region because the steepness of the source function relies on the sensitive temperature dependence of the Wien limit of the Planck function. We therefore predict that quasars with continuum spectra that indicate low-temperature atmospheres are the best ones to look at for steep rises in polarization. For the same reason, we do not expect dramatic rises in polarization to be associated with longer wavelength atomic edges unless the atmosphere is much cooler. Note that both these predictions depend on the actual vertical temperature gradient not being very steep itself at unit optical depth. If for some reason it is, then high polarization could again be produced. Last, we predict that the polarization blueward of the Lyman edge is perpendicular to the symmetry axis in these objects. We would encourage radio observations to look for extended emission to test this prediction.

The results presented here are just preliminary steps toward calculating self-consistent accretion disk models, and we have not yet achieved a good quantitative fit to the flux and polarization data. It is clear that if stellar atmosphere physics is responsible for the observed rises in polarization, then this problem is intimately related to the Lyman edge problem in quasars (Antonucci, Kinney, & Ford 1989; Koratkar, Kinney, & Bohlin 1992). In future work, we will attempt to tackle both the polarization and Lyman edge problems by examining more sophisticated models, including the height dependence of g, relativistic effects, and further sources of opacity. We will also look at possibilities other than simple thin disks, such as disks that are not completely optically thick and disks with illumination from a corona or other external source. In an optically thin disk, the fact that the rise starts somewhat blueward of the Lyman edge might be caused by the isotropic emission of Lyman continuum photons that are produced immediately blueward of the edge from recombinations in a cool atmosphere. Shorter wavelengths suffer true absorption with little reemission and can therefore be more anisotropic and polarized. On the other hand, reducing the optical depth of a disk will make it hotter at a fixed effective temperature. Two-phase models (see, e.g., Svensson & Zdziarski 1994) might produce steep rises in polarization by ensuring a relatively cool inner disk. High levels of polarization might also be produced from coronal UV emission that is scattered off the cold disk (cf. Matt, Fabian, & Ross 1993, who calculated this effect in X-rays).

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