POLARIZATION STRUCTURES IN THE THOMSON-SCATTERED EMISSION LINES IN ACTIVE GALACTIC NUCLEI

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ABSTRACT

A line photon incident in an electron-scattering medium is transferred in a diffusive way both in real space and in frequency space, and the mean number of scatterings changes as the wavelength shifts from the line center. This leads to the profile broadening and polarization dependence on the wavelength shift as a function of the Thomson optical depth \( \tau_T \). We find that the polarization of the Thomson-scattered emission lines has a dip around the line center when \( \tau_T \) does not exceed a few. Various structures, such as the polarization flip, are also seen. An application to an ionized halo component surrounding the broad emission line region in active galactic nuclei is considered, and it is found that the polarization structures may still persist. Brief discussions on observational implications are given.

Subject headings: galaxies: active — galaxies: nuclei — polarization — radiative transfer — scattering

1. INTRODUCTION

The astrophysical properties of the electron-scattering atmosphere have been obtained through studies of the polarized radiative transfer by many researchers (Chandrasekhar 1960; Angel 1969; Phillips & Mészáros 1986; etc.). One of the main results from these studies is that the emergent flux is polarized with a high degree of linear polarization up to 11.7\% from a very thick plane-parallel atmosphere in the direction of the plane. A representative application of this study has been found in active galactic nuclei (AGNs), in which the accretion disk presumed to form the central engine with the supermassive black hole has a corona component that may be regarded as a plane-parallel electron-scattering atmosphere (Emmering, Blandford, & Shlosman 1992; Blandford 1990).

Thus far, the study of polarization of the Thomson-scattered radiation has been concentrated on the continuum radiation due to the independence of the Thomson-scattering cross section on the frequency. However, the upper part of the accretion disk is believed to be exposed to the broad emission line region, and therefore the Thomson-reflected component is expected to be present in the broad emission line.

A line photon incident upon an electron-scattering atmosphere will get a wavelength shift due to the thermal motion of a scatterer. Assuming that the atmosphere is governed by a Maxwell-Boltzmann distribution, a typical wavelength shift per scattering is given by the Doppler width. Therefore, the transfer process is approximated by a diffusive one both in real space and in frequency space. It is naturally expected from the random-walk nature of the transfer process that the average scattering number before escape is smaller in the line-center part than in the wing part. It is also well known that the polarization of the scattered flux is sensitively dependent on the scattering number before escape. Therefore, in an electron-scattering atmosphere illuminated by a monochromatic light source, the polarization of the emergent radiation will be dependent on the wavelength shift from the line center and may form a “polarization structure,” which is expected to be characteristic of the Thomson optical depth of the scattering medium. From this consideration, we may expect that the polarized flux will have a different profile from that of the Thomson-scattered flux.

In this Letter, we investigate the polarization of the radiation both reflected by and transmitted through an electron-scattering slab illuminated by a line-emitting source using a Monte Carlo method and discuss possible applications to astrophysical sources, such as AGNs, containing emission-line regions with an electron-scattering atmosphere.

2. POLARIZED RADIATIVE TRANSFER OF THOMSON-SCATTERED LINES

The polarized radiative transfer in an electron-scattering atmosphere can be simply treated by a Monte Carlo method (e.g., Angel 1969). The polarization state associated with an ensemble of photons can be described by a density operator represented by a \( 2 \times 2 \) Hermitian density matrix \( \rho \) (e.g., Lee, Blandford, & Western 1994). A Monte Carlo code can be made by recording the density matrix along with the Doppler shift obtained in each scattering.

In the absence of circular polarization, the density matrix associated with the scattered radiation is related with that of the incident radiation explicitly by

\[
\rho'_{11} = \cos^2 \Delta \phi \rho_{11} - \cos \theta \sin 2 \Delta \phi \rho_{12} + \cos^2 \theta \sin^2 \Delta \phi \rho_{22},
\]

\[
\rho'_{12} = \frac{1}{2} \cos \theta' \sin 2 \Delta \phi \rho_{11} + (\cos \theta \cos \theta' \cos 2 \Delta \phi + \sin \theta \sin \theta' \cos \Delta \phi) \rho_{12} - \cos \theta(\sin \theta \sin \theta') \sin \Delta \phi + \frac{1}{2} \cos \theta \cos \theta' \sin 2 \Delta \phi \rho_{22},
\]

\[
\rho'_{22} = \cos^2 \theta' \sin^2 \Delta \phi \rho_{11} + \cos \theta'(2 \sin \theta \sin \theta' \sin \Delta \phi + \cos \theta \cos \theta' \sin 2 \Delta \phi) \rho_{12} + (\cos \theta \cos \theta' \cos \Delta \phi + \sin \theta \sin \theta')^2 \rho_{22},
\]

where the incident radiation is characterized by the wavevector \( \mathbf{k}_i = (\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta) \) and the outgoing wavevector \( \mathbf{k}' \) is correspondingly given with angles \( \theta' \) and \( \phi' \) with \( \Delta \phi = \phi' - \phi \). The circular polarization is represented by the imaginary part of the off-diagonal element, which is zero in a plane-parallel system and is shown to be decoupled from the
In Figure 1, we plot the profile obtained for investigated An and An other matrix elements. The angular distribution of the radiation field is described by the trace part, from which the scattered wavevector is naturally chosen in the Monte Carlo code.

3. RESULT

3.1. Profile Formation and Polarization of the Transmitted Component

The radiative transfer in an electron-scattering atmosphere as a diffusive process is studied by Weymann (1970). He considered a plane-parallel atmosphere with Thomson optical depth \( \tau_t \) that embeds a monochromatic source in the midplane and computed the line profile of the emergent flux by adopting the Eddington approximation. According to his result, the mean intensity \( I \) satisfies the diffusion equation given by

\[
\frac{\partial^2 I}{\partial \tau^2} + \frac{3}{8} \frac{\partial^2 I}{\partial \lambda^2} = -3\delta(x), \tag{2}
\]

where the wavelength shift \( x \equiv (\lambda - \lambda_0)/\Delta\lambda_0 \). Here, \( \Delta\lambda_0 = \lambda_0 \nu_0/c \) is the Doppler width and \( \lambda_0 \) is the wavelength of the monochromatic source.

With the two-stream–type boundary conditions, Weymann (1970) proposed an approximate solution given by

\[
J(x, \tau) = \sum_{n=1}^{\infty} A_n \cos \left[ a_n (\tau - \tau_n/2) \right] \exp \left[ -2\sqrt{6} a_n |x|/3 \right], \tag{3}
\]

where \( a_n \) is determined from the relation

\[
(a_n, \tau_n) \tan (a_n \tau_n/2) = \sqrt{3} \tau_n \tag{4}
\]

and \( A_n \) is obtained from

\[
A_n = 4\sqrt{6} \tau_n^{-1} (a_n \tau_n/2) \left[ (a_n \tau_n)^2 + a_n \tau_n \sin (a_n \tau_n) \right]^{-1}. \tag{5}
\]

In Figure 1, we plot the profile obtained for \( \tau_t = 8 \) investigated by Weymann (1970) (solid line), and we show the corresponding Monte Carlo results (dotted line). Here, the radiation source is isotropic and located in the midplane. The agreement between these two results is good within 1 \( \sigma \), except near the center. The thermal broadening of the profile depends sensitively on the Thomson optical depth \( \tau_t \). The scattering number contributing to a given wavelength shift is plotted by the dashed line in the lower panel, and it generally increases monotonically from the line center to the wings. In Figure 2, we show the profile and the polarization of the reflected and the transmitted radiation transferred through an electron-scattering slab illuminated by an anisotropic monochromatic source outside the slab, viewed at \( \mu = 0.5 \). The horizontal axis represents the wavelength shift in units of the Doppler width \( \lambda_0 \nu_0/c \) associated with the electronic thermal motion. Here, the scattering medium is assumed to be governed by a Maxwell-Boltzmann distribution with temperature \( T \), and \( \lambda_0 \) is the wavelength of the monochromatic incident radiation. The Thomson-scattering optical depth \( \tau_T \) of the slab is assumed to take values of 0.5, 3, and 5. We first discuss the transmitted radiation.

Because of the random-walk nature of the Thomson-scattering process, the average number of scattering increases as the wavelength shift increases toward the wing regime. When \( \tau_t \leq 1 \), near the line center, the emergent photons are scattered mostly only once. This implies that these singly scattered photons are mainly contributed from those incident nearly normally. The photons propagating in the grazing direction (with small \( \mu_1 = k \cdot \hat{z} \)) tend to be scattered more than once due to

Fig. 1.—Profiles of the emergent radiation from an electron-scattering plane-parallel atmosphere embedding a monochromatic source at the midplane. The Thomson optical depth is \( \tau_t = 8 \). Top: The solid line represents the result which Weymann obtained using a diffusion approximation, and the dotted line shows the Monte Carlo result. The horizontal axis represents the wavelength shift in units of the Doppler width \( \Delta\lambda_0 = \lambda_0 \nu_0/c \). Bottom: The dashed line represents the mean scattering number before escape, which increases as the wavelength shift increases.

Fig. 2.—Reflected (left) and transmitted (right) radiation in an electron-scattering plane-parallel atmosphere with Thomson optical depth \( \tau_T \) that is illuminated from a pointlike monochromatic source outside the atmosphere. The line of sight \( k \) is chosen such that \( \mu = k \cdot \hat{z} = \pm 0.5 \), where the normal direction to the plane is \( \hat{z} \), the positive \( \mu \) corresponds to the transmitted component, and the negative \( \mu \) corresponds to the reflected one. The polarization direction is denoted by the sign of the degree of polarization, where a positive degree of polarization implies polarization in the direction perpendicular to the plane and a negative in the parallel direction, respectively. As \( \tau_t \) exceeds \( \sim 5 \), the transmitted component is polarized in the parallel direction and approaches the result that Chandrasekhar obtained.
the large Thomson optical depth $\tau_t/\mu_e$ in this direction. However, with small $\tau_t$ there is nonnegligible contribution from photons with grazing directions.

The resultant polarization is determined from the competition of the parallel polarization from photons with initially nearly normal incidence and the perpendicular polarization from grazingly incident photons. Thus, when $\tau_t \lesssim 1$, a weak perpendicular polarization is obtained near the center, and as $\tau_t$ increases the polarization flips to the parallel direction, which is shown in the case $\tau_t = 3$.

On the other hand, the multiply scattered photons are mostly those with grazing incidence. These photons mainly contribute to the wing part. Since the scattering optical depth is small, the scattering plane must coincide approximately with the slab plane in a thin atmosphere. The polarization develops in the direction perpendicular to the scattering plane, and therefore the emergent photons are polarized in the direction perpendicular to the slab plane when the Thomson depth is small.

When $\tau_t \gtrsim 5$, the dependence of the polarization on the wavelength shift decreases and the overall polarization tends to lie in the direction parallel to the slab plane. Therefore, the degree of polarization shows a maximum at the line center, as is shown in Figure 2. The overall parallel polarization is obtained because the contribution of the singly scattered flux decreases and the increased mean scattering number before escape leads to an anisotropic radiation field dominantly in the slab plane direction throughout the wavelength shifts of the emergent radiation. According to the Monte Carlo result for a continuum source obtained by Angel (1969), when $\tau_t \sim 6$, the polarization reaches the limit of the semi-infinite slab that Chandrasekhar (1960) investigated (see also Lee & Ahn 1998).

3.2. Polarization of the Reflected Component

We next discuss the properties of the reflected component. First, all of the reflected components are polarized in the perpendicular direction with respect to the slab plane for all of the scattering optical depths. Here, one of the most important points to note is that the linear degree of polarization shows a local minimum at the line center. The contribution from the singly scattered photons also plays an important role in determining the polarization behavior of the reflected component around the line center. In the line center, the mean scattering number is also smaller than in the wing part. Because the light source is assumed to be isotropic, the singly scattered photons that constitute the line-center part are contributed almost equally from all of the initial directions. Therefore, the integrated polarization becomes small.

On the other hand, in the wing part, the mean scattering number increases due to diffusion. The main contribution to the reflected component is provided by the multiply scattered photons near the bottom of the slab. Therefore, the scattering planes just before reflection are mostly coincident with the slab plane, and hence the reflected radiation becomes strongly polarized in the direction perpendicular to the slab plane. As $\tau_t$ increases, the contribution from singly scattered photons decreases and the polarization dip in the center part becomes negligible.

3.3. Application to an Ionized Galactic Halo

Loeb (1998) proposed to measure the virial temperature of galactic halos using the scattered flux of quasar emission lines. With this in mind and for a simple application, we consider a hemispherical halo with the Thomson optical depth $\tau_t = 0.1$ with an emission-line source located at the center. It is assumed that the emission source is anisotropic and illuminates the halo uniformly in the range $\mu = \cos \theta \geq 0.6$, where $\theta$ is the polar angle. The observer’s line of sight is assumed to have the polar angle $\theta_i = \cos^{-1} 0.5$, so that the direct flux from the emission source does not reach the observer. Here, the incident line profile is chosen to be triangular, superposed with a flat continuum. The half-width of the triangular profile at the bottom is set to be 1 Doppler width $\Delta \lambda_\nu$. This choice is rather arbitrary; nevertheless, considering the complex profiles and widths that typical quasar emission lines exhibit, our choice can be regarded as a tolerable approximation. The line strength is normalized so that the equivalent width $EW$ is equal to $10 \Delta \lambda_\nu$. Figure 3 shows the result, where the linear degree of polarization is shown by the solid line with 1 $\sigma$ error bars, the scattered flux is shown by the solid line, and the polarized flux is shown with the dotted line. Two local maxima in the polarization are obtained in the wing parts, and accordingly the polarized flux possesses larger width than the scattered flux does. The locations of the polarization maxima are nearly equal to the Doppler width, and therefore they can be a good measure for the electron temperature. The slight difference of the widths shown in the scattered flux and the polarized flux may not be useful to put observational constraints on the physical properties of the Thomson-scattering medium. However, the dependence of polarization on the wavelength in the Thomson-scattered emission lines is quite notable and can provide complementary information in addition to that possibly obtainable from the scattered flux profile.

4. OBSERVATIONAL IMPLICATIONS: AGN SPECTROPOlarimetry

Spectropolarimetry has been successfully used toward a unified picture of AGNs, according to which narrow-line AGNs such as Seyfert 2 galaxies and narrow-line radio galaxies are expected to exhibit the broad emission lines in the polarized flux spectra (Antonucci & Miller 1985; Ogle et al. 1997). The ionized component located at high latitude that is responsible for the polarized broad emission lines is also proposed to give
rise to absorption/reflection features, both in X-ray ranges (Krolik & Kriss 1995).

The scattering geometry considered in Figure 3 may be also applicable to Seyfert 2 galaxies. However, the typical widths of the broad lines of order 10,000 km s\(^{-1}\) require very hot scattering gas of \(T \sim 10^7 \text{ K}\) for a possible polarization structure considered in this work. The strong, narrow emission lines provide a polarization-diluting component, which dominates the center part of the broad-line features. Especially in the case of hydrogen Balmer lines, atomic effects may also leave a similar polarization dip in the center part (Lee & Yun 1998).

Another application of the Thomson-scattering process is found in the upper part of the accretion disk of AGNs. Little or negligible polarization is obtained from a large number of polarimetric observations of AGNs, which is inconsistent with the expectation that the emergent radiation from a thick electron-scattering plane-parallel atmosphere can be highly polarized up to 11.7%. There have been various suggestions including the ideas of corrugated disk geometry, magnetic field effects, and atomic absorptions (e.g., Laor, Netzer, & Piran 1990; Koratkar et al. 1998; Agol & Blaes 1996). Negligible polarization is also obtained when the atmosphere has a small Thomson optical depth, \(\tau_T \leq 3\) (e.g., Chen, Halpern, & Titarchuk 1997).

It remains an interesting possibility that the upper part of the disk is illuminated by the broad emission line sources, and therefore the broad lines may include the Thomson-reflected component from the disk. The polarization in general will be sensitively dependent on the relative location of the emission region with respect to the accretion disk. The origin of the broad emission line region is still controversial, ranging from models invoking a large number of clumpy clouds confined magnetically or thermally to an accretion disk wind model (Murray & Chiang 1995). The existence and nature of the outflowing wind around an accretion disk also constitute main questions of the unified view of broad absorption line quasars, and the polarization of the broad lines reflects the importance of resonant scattering and electron scattering (e.g., Lee & Blandford 1997). Several polarimetric observations reveal some hints of polarized broad emission lines (e.g., Goodrich & Miller 1995; Cohen et al. 1995).

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