Polarization of Rayleigh Scattered Lyα in Active Galactic Nuclei

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I. Abstract

Active Galactic Nuclei (AGNs) are characterized by a non-thermal continuum and many prominent emission lines. AGNs are usually classified by Type 1 and Type 2, where Type 1 AGNs exhibit both broad and narrow emission lines. In contrast Type 2 AGNs show only narrow emission lines. AGN unification model assert that all ANGs have both broad and narrow line regions with an optically thick molecular torus outside the broad line region hiding it from view of low latitude observers. Assuming the presence of high column neutral hydrogen in the molecular torus region, we propose that far UV radiation around Lyα will be significantly polarized through Rayleigh scattering. Adopting a Monte Carlo technique we compute fluxes and degrees of linear polarization Rayleigh scattered Lyα in a slab region and a torus region. Due to the enormous range of scattering optical thickness dependent on the wavelength we obtain a number of interesting cases where polarization flip occurs as the wavelength varies from the line center to the far wing regions. We conclude that Rayleigh scattering may induce uniquely polarized Lyα distinguishable from other emission lines, which will shed much light on the unification models of AGNs.

II. Introduction

① Active Galactic Nuclei

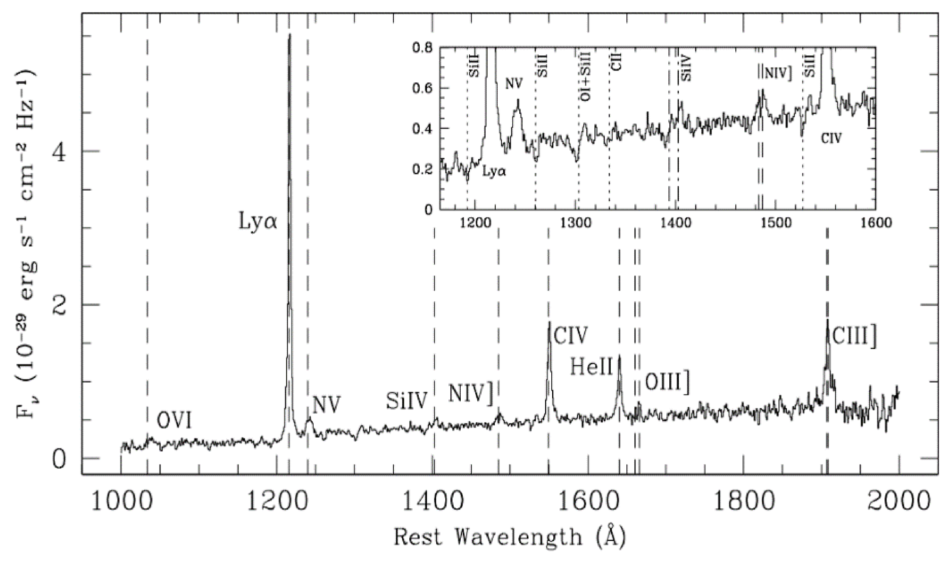

Fig. 1 UV Spectrum of Type 2 AGNs by Hainline et al. 2011

1. AGNs are characterized by a non-thermal and featureless continuum with prominent broad and narrow emission lines that cover wide range of ionization and excitation.
2. Type 1 AGNs have broad permitted lines and semi-forbidden lines with a width of 5,000km/s. They also exhibit forbidden lines that are narrow with a width ~500km/s.
3. Type 2 AGNs show only narrow emission lines.
4. The hardness of X-ray spectra of Type 2 AGNs is larger than Type 1 AGNs.

② AGN Unification Model

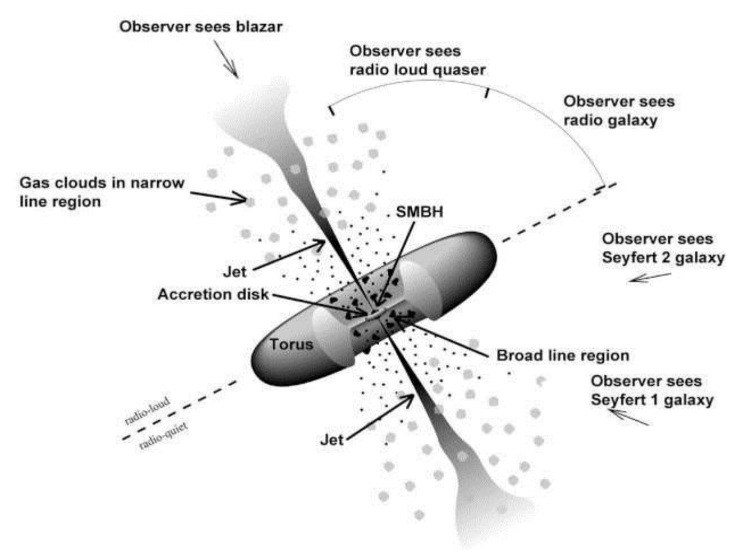

Fig. 2 Unification Model

Components	Effect in Spectrum
Super Massive Black Hole	*→ Non-thermal continuum*
Broad Line Region (BLR)	*→ Broad emission line, width of ~5,000km/s*
Narrow Line Region (NLR)	*→ Narrow emission line, width of ~500km/s*
Optically Thick Molecular Torus	*→ Obscuring BLR, Rayleigh scattering of Lyα*

③ Rayleigh Scattering

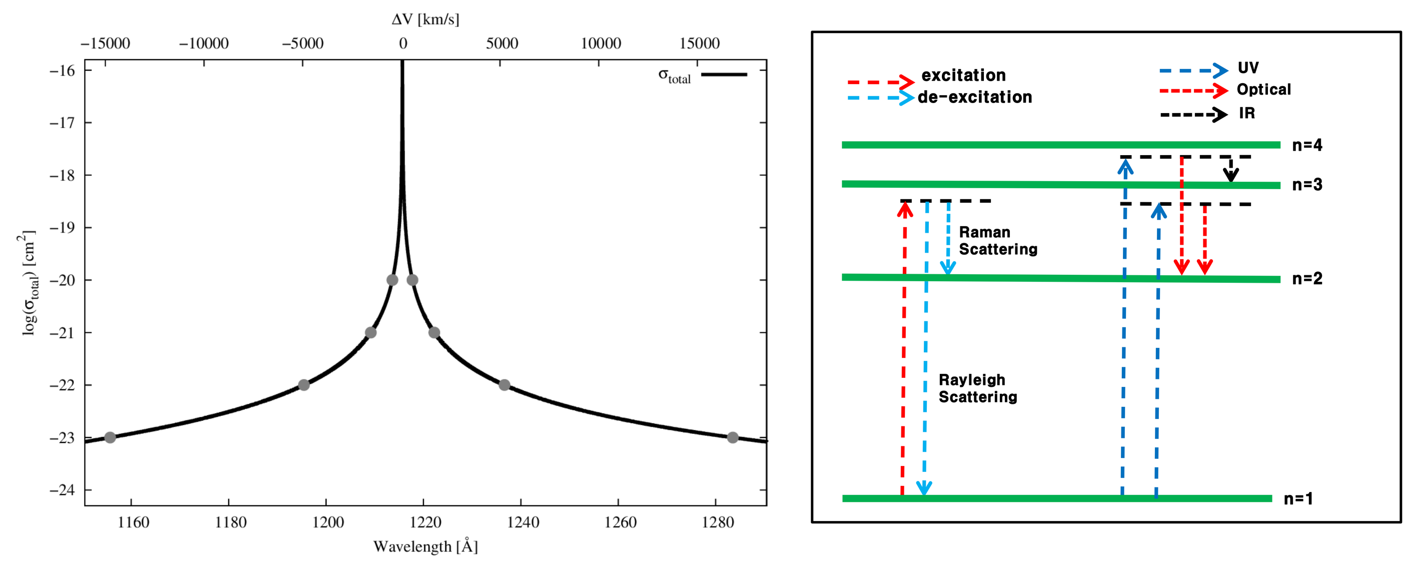

Fig. 3 Cross Section and Hydrogen Atomic Level

- Far UV photons around Lyman series excite hydrogen atoms in the ground state.
- The excited hydrogen atom may de-excite into an excited state resulting in reemission of a lower energy photon, which is called ***Raman Scattering.*** If the de-excitation is made into the ground state, then result is an elastic scattering, which is also called ***Rayleigh scattering.***
- Lyα can be dominantly Rayleigh scattered by atomic hydrogen and also optically thick. Therefore, Lyα may show distinguished polarization compared with other hydrogen and metal lines.

III. Scattering Geometry

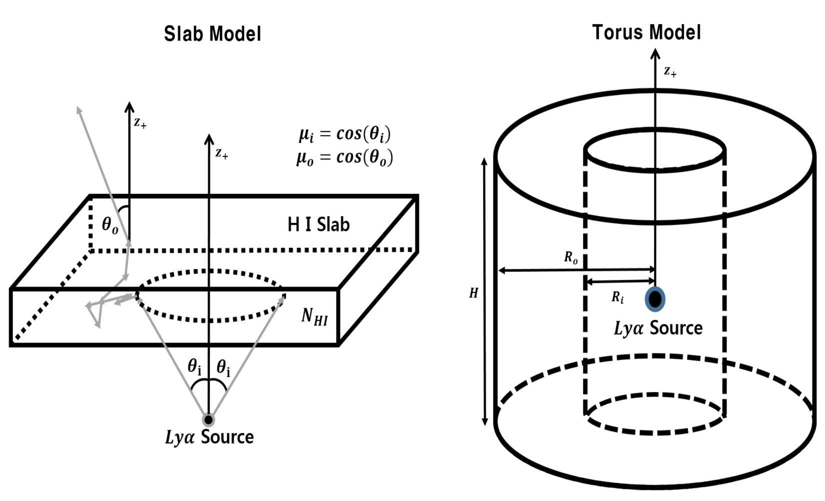

Fig. 4 Slab and Torus Model

- We consider two models, slab geometry for fundamental study and torus geometries for the AGN unification scheme.
- We assume a flat input between 1216Å-70Å and 1216Å+70Å, and collect emergent photons according to ejected direction μ_o.
- The slab geometry has a finite thickness and infinite lateral extension. We consider H I column densities $N_{HI} = 10^{20-23}$ and fix incidence angle μ_i.
- Torus geometry is investigated with a finite cylindrical shell characterized by height H and outer and inner radii R_o and R_i.
- In the torus model, we assume an isotropic source and set $R_o = 2R_i, A = {}^{H}/_{R_i}$ and $N_{HI} = n_{HI}(R_o - R_i)$.

IV. Slab Model

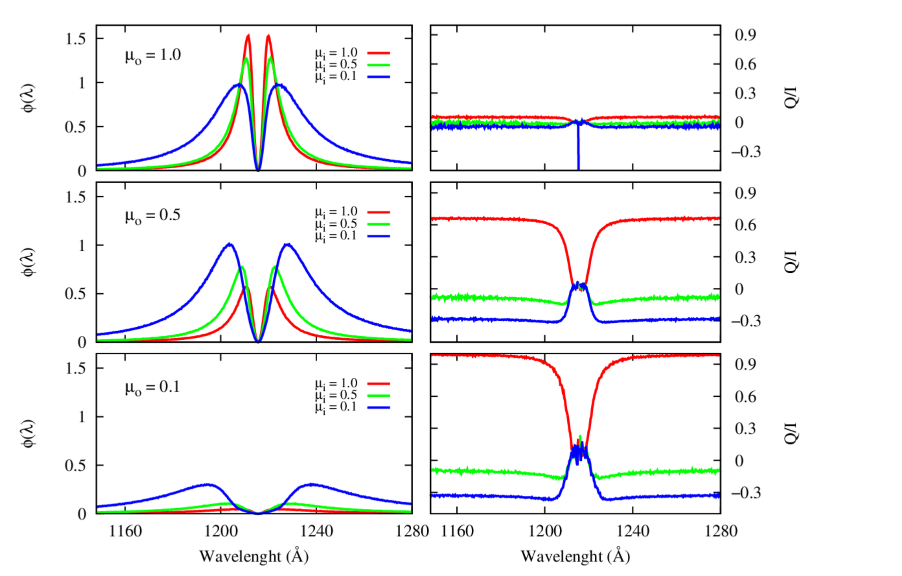

Fig. 5 Transmitted Flux and Polarization

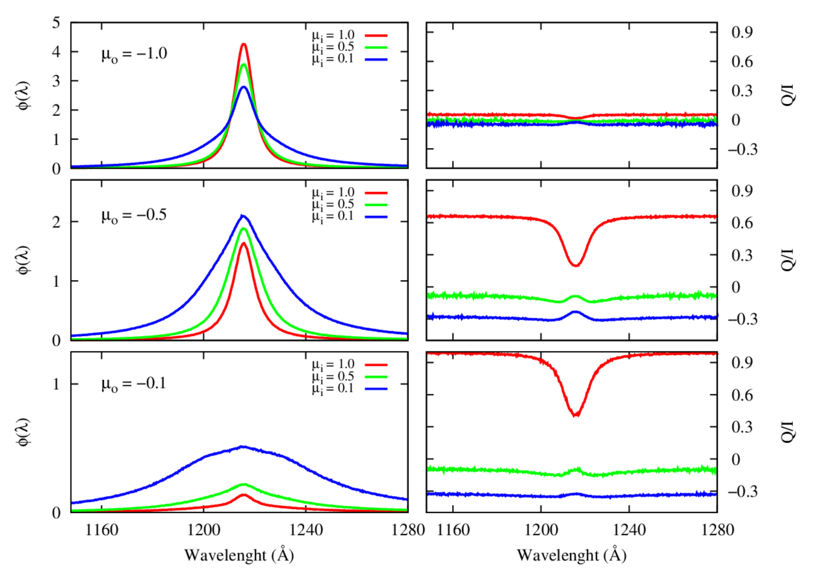

Fig. 6 Reflected Flux and Polarization

- We collect Rayleigh scattered photons and compute the flux and degree of polarization by slab. Fig. 5 shows transmitted spectra and degree of polarization according to emergent direction $\mu_o = (0.9-1.0), (0.4-0.5), (0.0-0.1)$, and the Fig. 6 shows the same data for Rayleigh reflected radiation.
- In the wing parts where the Rayleigh scattering optical depth is low, the slab geometry exhibits symmetry between transmitted and reflected radiation.
- Transmitted radiation shows a central dip that is very weakly polarized. Reflected radiation exhibits central minimum in the degree of polarization that results from multiple scattering effects. However, in the reflected radiation, the single scattered and therefore highly polarized component persists in the line center region.

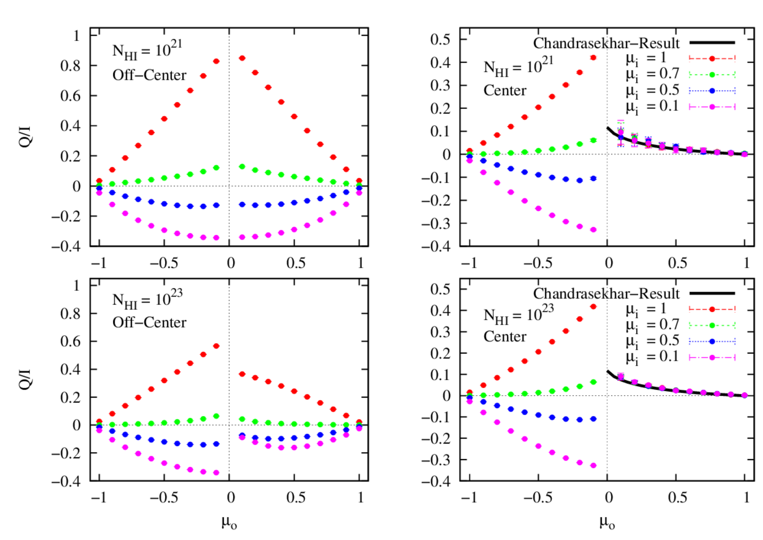

Fig. 7 Total Degree of Polarization in Slab Geometry

- Fig. 7 shows the angular dependence of polarization. Also we divide the input radiation into two parts depending on the optical depth. In Fig. 7, left panels show the 'off-center' wavelength part with $\tau_s < 10$ and right panels are for the 'center' part for $\tau_s > 10$.
- The left panels are for the two column densities, $N_{HI} = 10^{21,23}$. For $N_{HI} = 10^{21}$, symmetric behavior of polarization between reflected and transmitted part is apparent.
- The polarization of optically thick transmitted components shows the limiting behavior obtained by Chandrasekhar for very high Thomson thick slab.

V. Torus Model

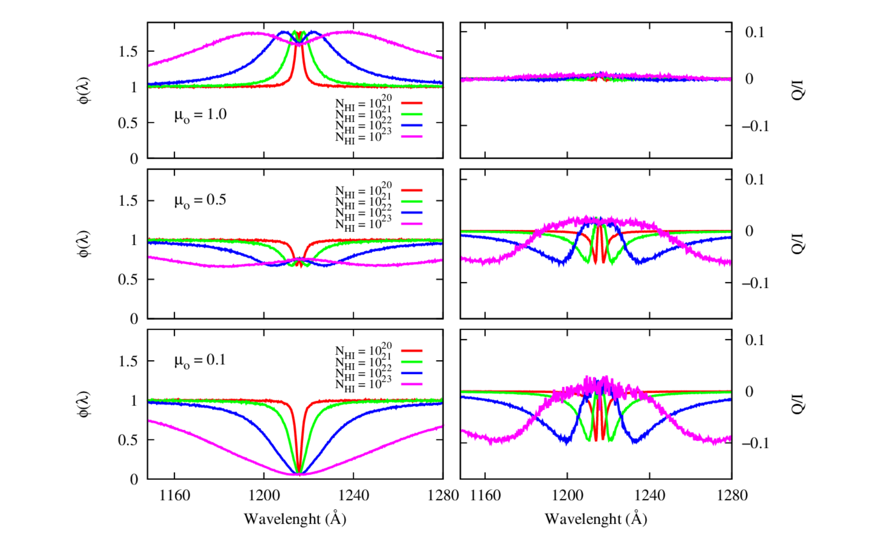

Fig. 8 Flux and Polarization in a Tall Torus, A = 2

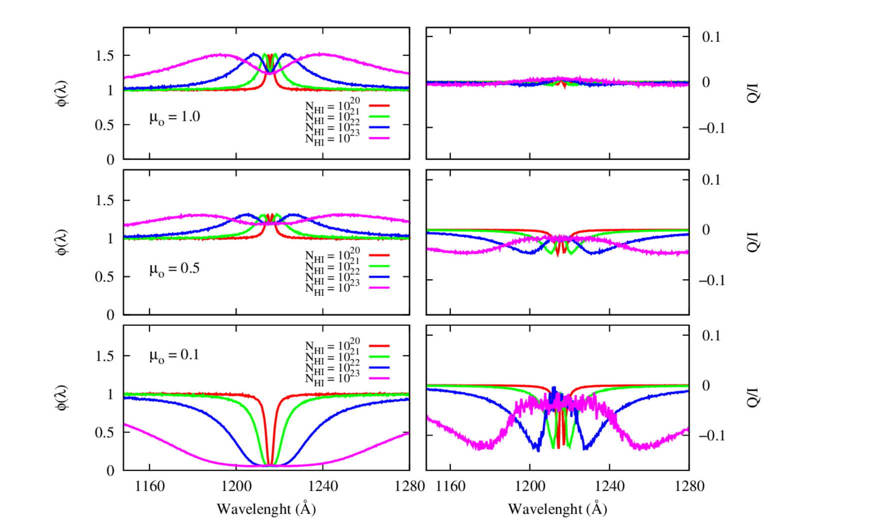

Fig. 9 Flux and Polarization in a Short Torus, A = 1

- We consider two torus models with differing $A = {}^{H}/_{R_i}$ and overplot flux and degree of polarization for various values of N_{HI}.
- An interesting feature is positively pol arized (polarized along the equatorial plane) central part in the case of the tall torus ($A = 2$). They escape the tall torus through repeated scattering on the inner wall resulting in electric field relaxed in the direction perpendicular to the z-axis.

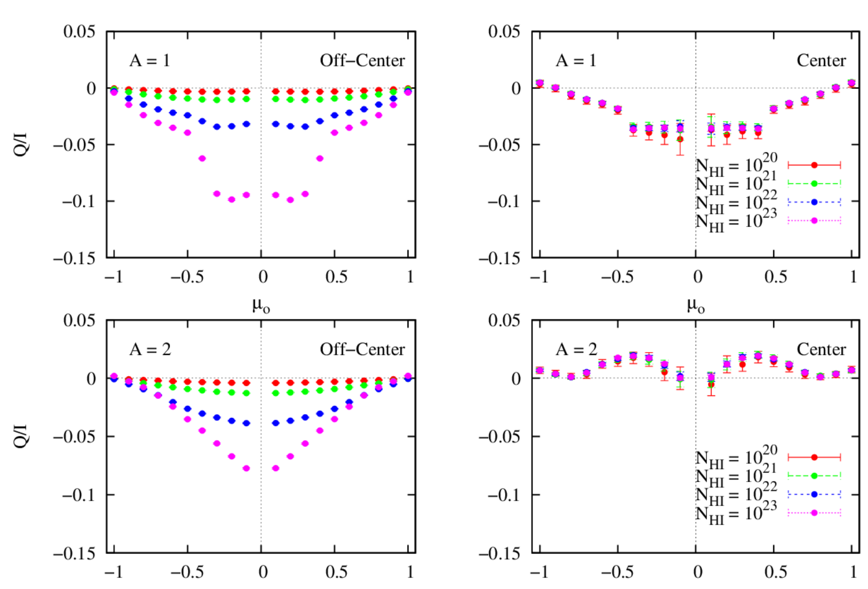

Fig. 10 Total Degree of Polarization in Torus Geometry

- Fig. 10 shows the angular distribution of polarization. Top panels are for a short torus ($A = 1$) and bottom panels are for a tall torus ($A = 2$)
- The left panels show polarization of photons with low Rayleigh scattering optical depths. They are mainly polarized in the direction parallel to the symmetry axis due to a small number of scatterings occurring in the equatorial plane.
- For optically thick photons to escape the tall torus, they need to climb up along the inner wall through many scatterings leading to eventual relaxation of the electric field parallel to the equatorial plane.

VI. Summary and Discussion

- Using a Monte Carlo technique we investigated the polarized transfer of Lyα Rayleigh scattered in AGN.
- Slab and torus geometries were adopted to study the fundamental properties of polarization arising from Rayleigh scattering.
- Central dip with low polarization characterizes the Rayleigh transmitted Lyα in a slab geometry, whereas persistent polarization is observed in the Rayleigh reflected radiation.
- In a torus geometry with the shape parameter A exceeding unity, polarization near the line center develops in the direction perpendicular to the symmetry axis whereas the wing parts are polarized in the parallel direction.
- We predict that Type 2 AGNs may exhibit more strong polarization around Lyα.

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