A Basic Monte Carlo Study of Polarization of Lyα Rayleigh Scattered in the Early Universe

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I. Abstract

In a medium with a high H I column density, far UV photons near Lyα significantly shifted through Doppler effect can be optically thick with respect to Rayleigh scattering. The relevant astrophysical situations include Lyα photons from Lyman Alpha Blobs and broad Lyα emission in active galactic nuclei. Depending on the geometry of the scattering medium these Rayleigh scattered far UV photons near Lyα are expected to be strongly polarized. We investigate polarized radiative transfer of Rayleigh scattered Lyman alpha using a Monte Carlo technique. Adopted scattering geometry includes slabs and cylindrical shells with a range of H I column densities. It is found that a significantly strong linear polarization develops in media with a moderate Rayleigh scattering optical depth. We also find that polarization direction may change as Rayleigh scattering optical depth sharply increases toward Lyα center. In this poster presentation, we discuss basic mechanism of polarization development of Rayleigh scattered Lyα.

II. Introduction

① Rayleigh Scattering

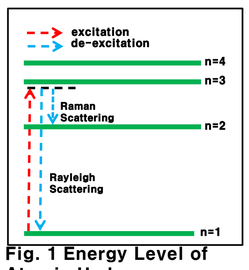


Fig. 1 Energy Level of Atomic Hydrogen

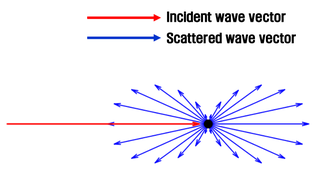
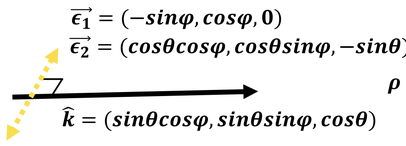


Fig. 2 Phase Function of Rayleigh scattering

- A Far UV photon around Lyman series is incident upon a hydrogen atom in the ground state, which subsequently gets excited.
- 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 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.

② Density Matrix Transition for scattering

$$\vec{\epsilon_1} = (-sin\varphi, cos\varphi, 0)$$
$$\vec{\epsilon_2} = (cos\theta cos\varphi, cos\theta sin\varphi, -sin\theta)$$



$$\hat{k} = (sin\theta cos\varphi, sin\theta sin\varphi, cos\theta)$$

Fig. 3 Wavevector $\hat{k}$ and the polarization basis vectors $\vec{\epsilon_1}$ and $\vec{\epsilon_2}$

$$\rho = \begin{pmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{pmatrix} = \begin{pmatrix} \frac{I+Q}{2} & \frac{U+iV}{2} \\ \frac{U-iV}{2} & \frac{I-Q}{2} \end{pmatrix}$$

Density Matrix Related to Stokes Parameters

The density matrix formalism is adopted to describe the polarized photon in the simulation. The density matrix elements associated with the scattered radiation with the unit wavevector $\hat{k}'$ and polarization vectors $\vec{\epsilon'_1}$ and $\vec{\epsilon'_2}$ are related to those for the incident radiation denoted by $\hat{k}$, $\vec{\epsilon_1}$ and $\vec{\epsilon_2}$.

$$\rho'_{11} = (cos^2\Delta\varphi)\rho_{11} - (cos\theta sin2\Delta\varphi)\rho_{12} + (sin^2\Delta\varphi cos^2\theta)\rho_{22}$$

$$\rho'_{12} = (1/2cos\theta' sin2\Delta\varphi)\rho_{11} + (cos\theta cos\theta' cos2\Delta\varphi + sin\theta sin\theta' cos\Delta\varphi)\rho_{12} - cos\theta(sin\theta sin\theta' sin\Delta\varphi + 1/2cos\theta cos\theta' sin2\Delta\varphi)\rho_{22}$$

$$\rho'_{22} = (cos^2\theta' sin^2\Delta\varphi)\rho_{11} + cos\theta'(2sin\theta sin\theta' sin\Delta\varphi + cos\theta cos\theta' sin2\Delta\varphi)\rho_{12} + (cos\theta cos\theta' cos\Delta\varphi + sin\theta sin\theta')\rho_{22}$$

Density Matrix Formulism for Rayleigh scattering (Ahn and Lee, 2015)

③ Imaging Polarimetry

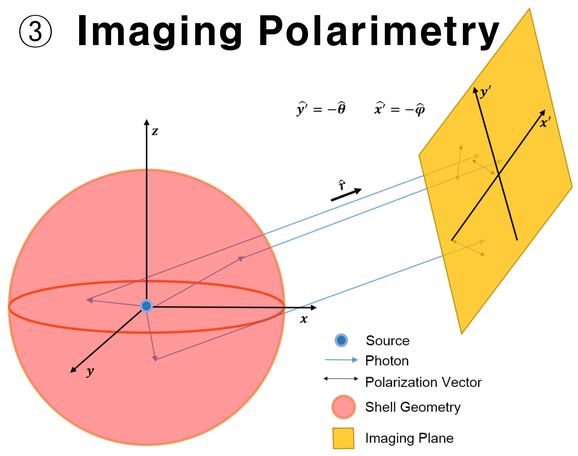


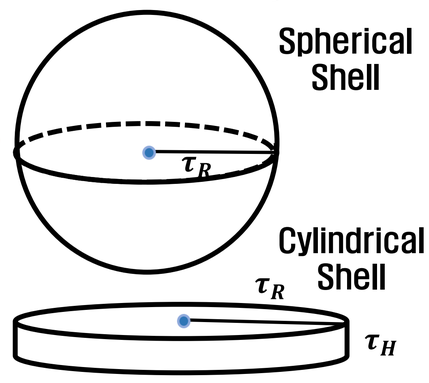
Fig. 4 How to collect scattered photons

In this simulation, We collect photons Rayleigh scattered by atomic hydrogen. For imaging by escaped angle θ_o, we define new coordinate x' and y'. When photons escape from scattering region, last scattering position is projected to x', y' plane.

$$x' = -\hat{\varphi} \cdot \vec{r}, \qquad y' = -\hat{\theta} \cdot \vec{r}$$

$\vec{r}$: **Position Vector at last scattering point**

④ Geometry



$$\tau_R/\tau_H = 10$$

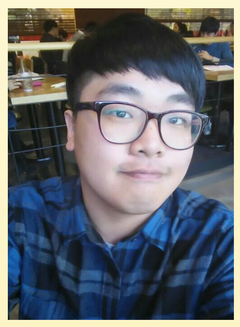
Fig. 5 Two Geometry of Scattering Region

We consider two symmetric geometries. The spherical shell shows symmetry to any direction. Also the cylindrical shell is symmetric to z-axis. We used three optical depth $\tau_R = 1, 10$ and 100.

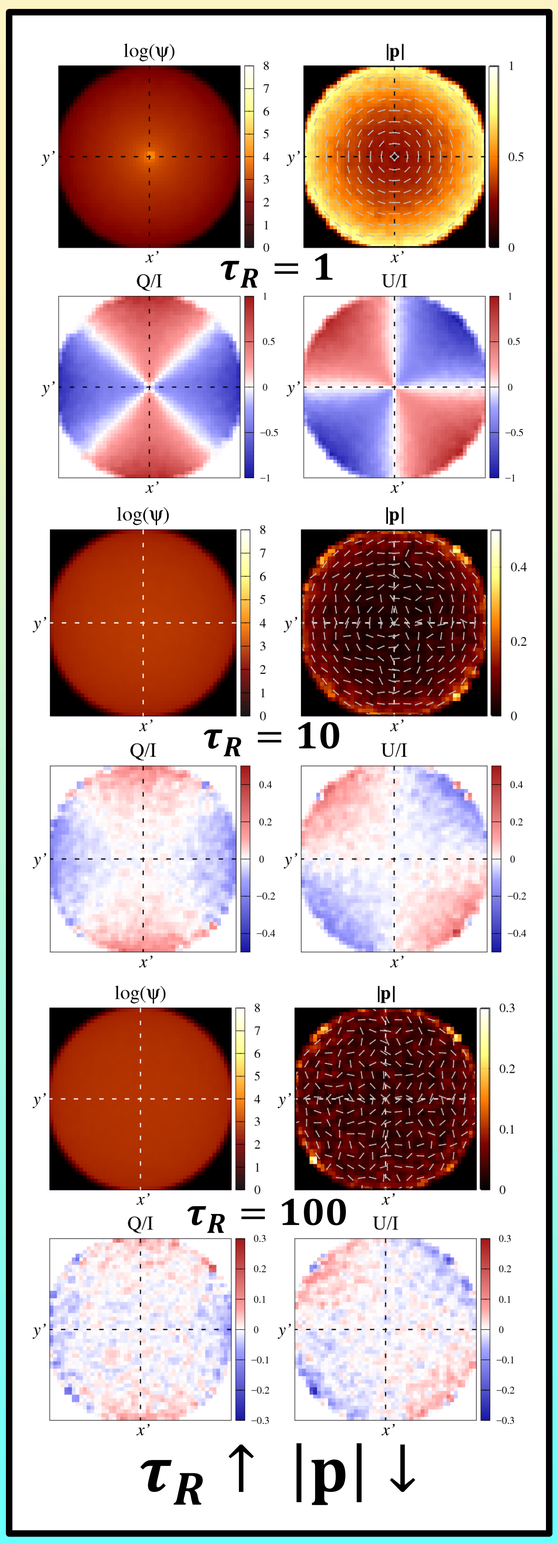
Summary and Discussion

1. **In the spherical shell cases, Ly alpha is polarized with the direction tangentially oriented to form concentric ring-like structures, where the degree of polarization peaks where the optical depth is near unity.**
2. **In the cylindrical shell cases with $\tau_R = 1$, the overall result is similar to those of the spherical shell cases except that the degree of polarization is sensitively dependent on the observer's line of sight.**
3. **One particularly interesting behavior is obtained in the case of highly flattened cylindrical shells $\tau_R = 10$ and 100, where polarization may develop in the direction perpendicular to concentric ring tangents.**

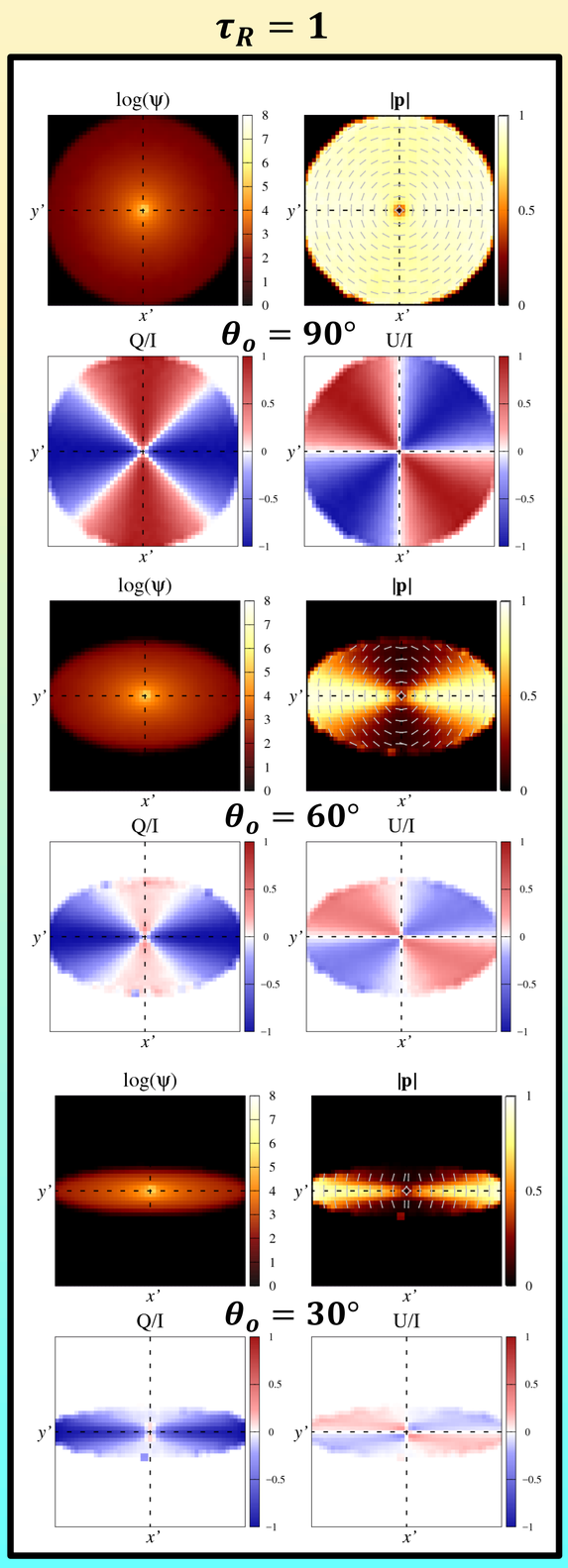
Hello, I'm Seok-Jun. Thank you for your interest. Any comments are welcome and will be appreciated. I can be reached at csj607@gmail.com

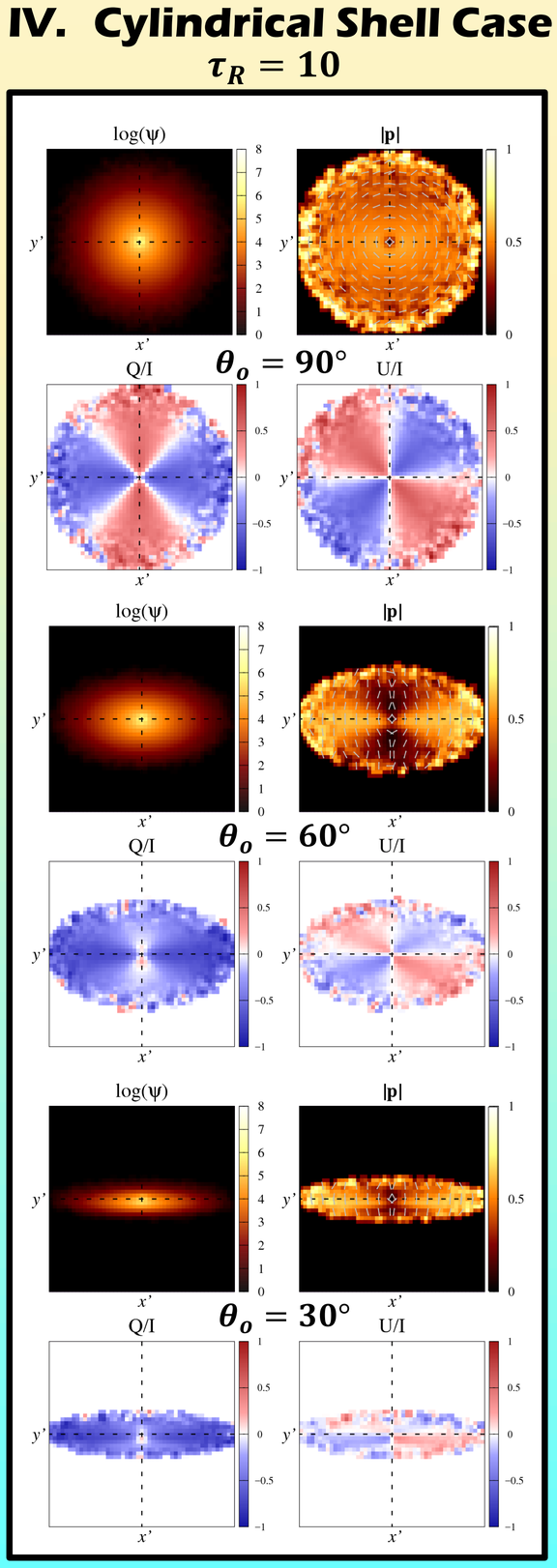


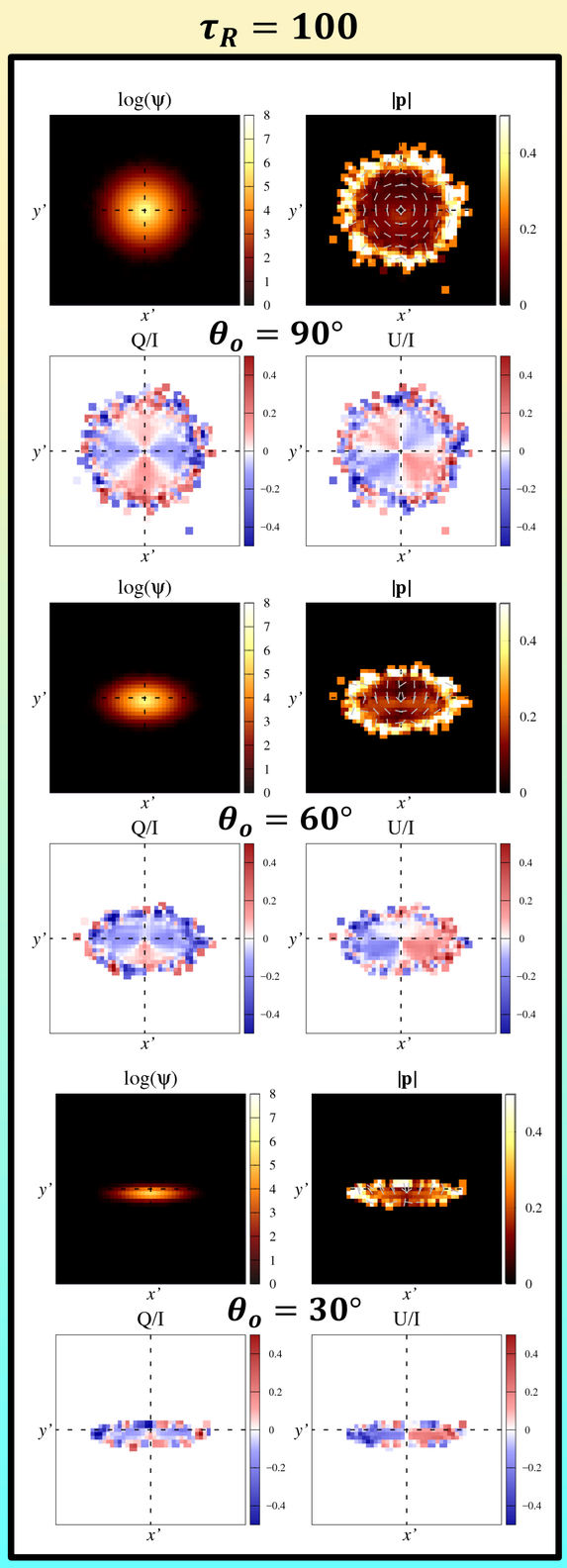
III. Spherical Shell Case



IV. Cylindrical Shell Case







2017 The Snowbird Cosmic Lyman-Alpha Workshop in Utah