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Transmission characteristics of linearly polarized light in altostratus help explain "UV-sky-pol" paradox

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The perception of skylight polarization in the ultraviolet (UV) by some species is surprising, because the degree of polarization (DoP) of light from the clear sky is considerably lower in the UV than in the visible spectral range. This is the so-called "ultraviolet paradox of the perception of skylight polarization (UV-sky-pol paradox)". To explain the "UV-sky-pol" paradox, we analyzed the polarization retention characteristics of parallel polarized light transmits in altostratus at multiple wavelengths. According to the polarization sensitive bands of flies, honeybee, scarab beetles and spider, the study wavelength was set at 350 nm, and the wavelength of control group was set at 400, 450, 500, 550 and 600 nm, respectively. Then, we used the polarized light Monte Carlo method to simulate the forward transmission of 100000 parallel polarization photons in altostratus. Calculation results show that the polarization retention characteristics are excellent at the 350 nm wavelength. Finally, we analyzed the transmission characteristics of parallel polarized light passes through a droplet at 0°–15° forward scattering angle. The analysis results show that there have been significant polarization retention channels in the UV band around 350 nm. This study can help to elucidate the "UV-sky-pol" paradox.

Keywords: polarization, atmospheric scattering, altostratus, UV-sky-pol paradox.

1. Introduction

In many species, the linear polarization of downwelling light is detected by upward pointing ommatidia in the so-called dorsal rim area of the compound eye [1,2]. The spectral type of the dorsal rim area receptors is UV in flies [3], honeybees [4], desert ants [5], locust [6], certain scarab beetles [7], spiders [8] and so on. It is surprising that so many species use the UV component of the polarized skylight, because the DoP of light from the clear sky is lower in the UV than in the visible spectral range. Why have these species chosen the UV spectral of the polarized skylight? Researchers have conducted studies in terms of environmental optics. Barta and Horváth [9] proved by model calculation that DoP of skylight originating from the cloudy region is highest in the

UV when the air layer between a cloud and a ground-based observer is partly sunlit at higher solar elevations. WANG *et al*. [10] confirmed Barta and Horváth's calculation results by an experiment. Wang used a sky-polarimetric approach and built a polarized skylight sensor that modelled the processing of polarization signals by insect photoreceptors in the UV, visible and near infrared spectral ranges. They showed that light from the cloudy sky had maximal DoP in the UV, and under both clear and cloudy skies the angle of polarization of skylight could be measured and detected with a higher accuracy in the UV than in the visible spectral range. ZHAO *et al*. [11] studied the polarization patterns of skylight under different sky conditions by polarized imaging measurements, in which the aerosol optical thickness and clouds were taken into account. The results showed that both the aerosol and cloud disturbed the polarization patterns of the skylight, but the patterns of angle of polarization showed great robustness.

The above-mentioned studies reflect that certain species detect the polarization of downwelling light in the UV spectrum which is related with the cloud environment. In this work, we analyzed the polarization transmission characteristics of parallel polarized light at multiple wavelengths in altostratus. It may help to elucidate the "UV-sky-pol" paradox.

2. Background

2.1. Environmental setting

Altostratus is a middle altitude cloud which is characterized by a generally uniform gray to bluish-green sheet or layer. It is lighter in color than nimbostratus and darker than high cirrostratus. As showed in Fig. 1, altostratus was set as the collection of droplets, and the complex situation of mixing water clouds and ice clouds were not considered in this work. Altostratus was constructed as a lognormal distribution function, which could reflect the effective diameter of altostratus droplets [12]. It was set as lognormal distribution with a standard deviation of 0.1. And the mean diameter was

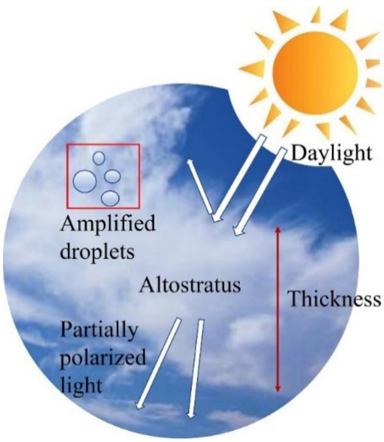

Fig. 1. Schematic diagram of sunlight propagation in altostratus.

set as 7.5 and 10 μm, respectively [13, 14]. In additionaccording to the polarization sensitive bands of flies, honeybee, scarab beetles, spiders and so on [15], the study wavelength was set at 350 nm, and the wavelength of control groups was 400, 450, 500, 550, and 600 nm, respectively. The cloud thickness was set from 50 to 900 m with a spacing of 50 meters.

2.2. Retention rate of polarization state: RoPS

To describe the change in the polarization state of forward-scattered light, we defined a new parameter: RoPS (retention rate of polarization state) [16],

$$\mathrm{RoPS} = \frac{\pm P_{\eta\text{-forward}}}{P_{0\text{-forward}}} \tag{1}$$

where, $P_{0\text{-forward}}$ is the total intensity of the forward transmitted light, and $P_{\eta\text{-forward}}$ is the intensity of the η type polarized light. The η type polarized light has the same state of polarization as the initial light. And ± represents the type of η type polarized light, which has a classification form similar to that of the Stokes parameters.

RoPS is Stokes–Mueller matrix transformation form, but it avoids the effect introduced by calculation of orthogonal component intensity difference. When evaluating the polarization state characteristic of light waves during forward transmission, RoPS has higher calculation accuracy than Stokes parameters.

2.3. Polarization-tracking Monte Carlo

We used a polarization-tracking Monte Carlo program to study parallel polarization for the forward transmission [17]. One million parallel polarization photons were launched into a slab represented by one particular particle distribution for each environment. Photons propagated in a given distance and then the aggregated polarization was calculated from the photons that arrived in a given area. After a scattering event, the photon direction was changed, and a new meridian plane was found. The resulting scattered polarization state changed on the new meridian plane and the new parallel electric field components. This process continued until the photon was scattered in or out the front or back face of the medium. Furthermore, the time of scattering was assumed to be ≤ 15 by considering the actual detector threshold. It is a maximum threshold for the maximum number of scatterings before a photon is killed in the model. The setting is a random setting and can be revised according to the detector threshold. Photons that exit the front face of the slab were considered as the transmitted photons. This process continued for all the photonslaunched. Then, the result was calculated by the formula (1).

3. Results

Figure 2 shows transmission results for altostratus clouds of 7.5 and 10 μm mean diameter droplets at optimized wavelengths in the thickness from 50 to 900 m. Figure 2(a)

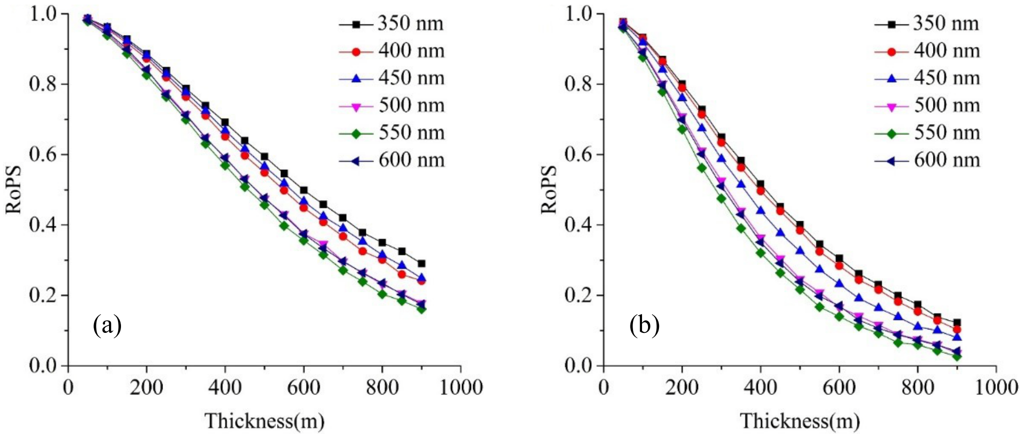

Fig. 2. Simulation results of parallel polarized light transmited in altostratus. (a) 7.5 μm diameter, (b) 10 μm diameter.

shows RoPS for altostratus clouds of 7.5 μm mean diameter droplets. Compared with the RoPS value of control groups, RoPS values peak at the 350 nm wavelength. Figure 2(b) shows RoPS for altostratus clouds of 10μm mean diameter droplets. Similar to Fig. 2(a), RoPS values also peak at the 350 nm wavelength. In short, for altostratus clouds of 7.5 or 10 μm mean diameter droplets, parallel polarization displays superior persistence at the UV wavelength of 350 nm.

4. Discussion

1-RoPS is used to characterize the polarization properties. The smaller the 1-RoPS reflects, the better the polarization state retention characteristics. When light is scattered in the altostratus clouds, the intensity of scattered light is mostly stronger in small

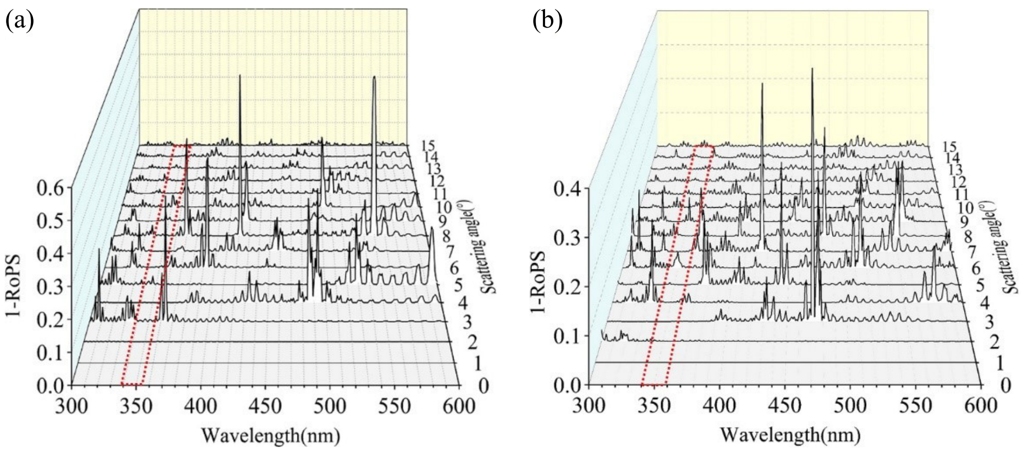

Fig. 3. 1-RoPS *vs.* wavelengths at the scattering angle of 0°–15°. (a) 7.5 μm diameter, (b) 10 μm diameter.

incident light angle. Species observe that this part of the light may be more favorable. As showed in Fig. 3, we chose 0°–15° forward scattering angles for discussion. Figure 3(a) shows 1-RoPS values for altostratus clouds of 7.5 μm mean diameter droplets.1-RoPS values approach to zero in the bands of 338–355 nm. Figure 3(b) shows 1-RoPS values for altostratus clouds of 10 μm mean diameter droplets. Close to the result of Fig. 3(a), 1-RoPS values approach to zero in the bands of 340–359 nm. The analysis results show that there have been significant polarization retention channels in the UV band around 350 nm.

5. Conclusions

To help explain why it is advantageous for some species to detect celestial polarization in the UV, we simulated polarization persistence characteristics of parallel polarized light in altostratus at wavelengths of UV to visible spectral range. Through polarization -tracking Monte Carlo simulation, we showed that the polarization retention characteristics of parallel polarized light was excellent at the 350 nm wavelength. The analysis results show that there have been significant polarization retention channels in the UV band around 350 nm.

This work proves by calculation that the polarization retention characteristics of skylight originating from altostratus is highest in the UV. It can help to elucidate the "UV-sky-pol" paradox.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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