南極点における宇宙論観測へのライダー観測の応用

髙倉　理 [1], Jessica Avva Zebrowski[2], Anna Coerver[3], William Holzapfel[3], Jasper R. Lewis[4]

[1] 京都大学理学研究科物理学第二教室（〒606-8502 京都府京都市左京区北白川追分町）

[2]Kavli Institute for Cosmological Physics（Chicago, IL 60637, USA）

[3]Univ. of California, Berkeley, Department of physics（Berkeley, CA 94720, USA）

[4]NASA's Goddard Space Flight Center（Greenbelt, MD 20771, USA）

Application of lidar data in cosmological observations at the South Pole

Satoru TAKAKURA[1], Jessica AVVA ZEBROWSKI[2], Anna COERVER[3],
William HOLZAPFEL[3], and Jasper R. LEWIS[4]

[1]*Department of physics, Faculty of Science, Kyoto Univ., Kyoto, Kyoto 606-8502*

[2] *Kavli Institute for Cosmological Physics, Chicago, IL 60637, USA*

[3] *Department of physics, University of California, Berkeley, CA 94720, USA*

[4] *NASA's Goddard Space Flight Center, Greenbelt, MD 20771, USA*

Abstract: The South Pole is one of the best sites for ground-based telescopes observing cosmological signals at millimeter waves. The South Pole Telescope (SPT) observes the cosmic microwave background (CMB) to probe linear-polarization signals generated in the early universe. The extremely cold and dry atmosphere helps to minimize the low-frequency noise due to emission from inhomogeneous water vapor. However, ice crystals in the tropospheric ice clouds can be another noise source. Non-spherical ice crystals tend to align horizontally and produce horizontally polarized radiations. In this study, we use lidar data taken by Micro Pulse Lidar (MPL) at the Atmospheric Research Observatory (ARO), where 1.2 km away from SPT. We compare the appearance of excess noise in SPT and the existence of clouds in MPL data and find a qualitative agreement. Further comparison will improve the understanding of cloud properties.

Key Words: Micro Pulse Lidar, Cloud, Cosmological observations, Cosmic Microwave Background, Polarization

1. Introduction

Cosmic microwave background (CMB) is one of the most powerful tools for modern observational cosmology. CMB is a relic radiation from the beginning of the Universe. It is almost isotropic but has very small anisotropies. Precise measurements of the anisotropies by many experiments including COBE, WMAP, and Planck satellites, have revealed that the evolution of the Universe is well described by the so-called ΛCDM model.

Recently, many ground-based CMB experiments are trying to detect the primordial B-mode polarization, which is parity-odd pattern of linear polarization anisotropies at degree scales. It is expected to be the evidence of the cosmic inflation, an exponential expansion at the beginning of the Universe. The sensitivity of the instruments is getting improved by increasing the number of detectors. However, the expected signal is so small that it has not been detected yet.

One of challenges for ground-based CMB experiments is the atmosphere. The atmosphere is turbulent and fluctuates following Kolmogorov power-law spectrum. Emission from inhomogeneous water vapor is one of the dominant noise sources of the intensity (unpolarized) signal at degree scales. This unpolarized noise, however, can be removed from polarization signals by gain calibration of detectors or by polarization modulation technique.

The main noise source in polarization measurements is found to be the tropospheric ice clouds. Ice crystals in the clouds scatter thermal radiation from the ground and produce polarization signals. The POLARBEAR experiment at the Atacama Desert in Chile observed the coincidence between the existences of polarized noise bursts and clouds[1)]. For precise estimation of the impact of clouds on CMB measurements, however, more detailed studies are required in both millimeter wave measurements and cloud measurements.

In this work, we study the polarization signal from clouds at the South Pole using data from the SPT-3G receiver installed in the South Pole Telescope (SPT). SPT-3G has multichroic polarization detectors sensitive at 90, 150, and 220 GHz bands, which enables us to measure the spectral index (or color ratio) of the cloud signal. In addition, we use Micro Pulse Lidar (MPL) data at the South Pole to evaluate atmospheric conditions.

2. Scattering of millimeter waves by ice crystals

At the frequency bands, 90, 150, and 220 GHz, used in CMB experiments, the wavelength is a few millimeters. On the other hand, the size of cloud particles is about 10 μm to 100 μm, which is smaller than the wavelength. Thus, the scattering is described by the Rayleigh approximation. It predicts that the cross section is proportional to $a^6 \nu^4$ for scattering and $a^3 \nu^2$ for absorption, where a is the particle radius, ν is the frequency of the light, and the model of complex refractive index of ice[3] is used. As shown in Fig. 1, the scattering becomes dominant at higher frequencies with larger particles. On the other hand, the emission contributes at lower frequencies with smaller particles. The balance of the two can change within the range of the typical size of ice crystals. The effect will appear as the change of the effective spectral index between 4 (for scattering) and 2 (for emission).

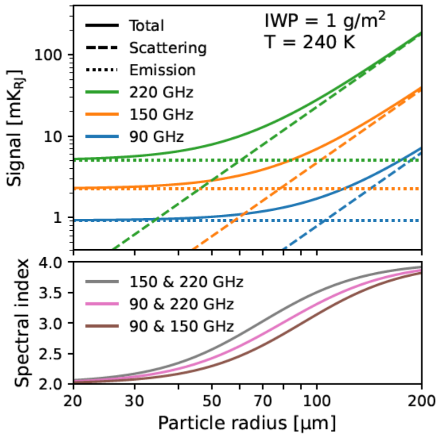

Figure 1. Dependence of the cloud signal on the particle size of ice crystals. (Top) Contributions of emission and scattering at each frequency band. (Bottom) Effective spectral index.

In addition, ice crystals have non-spherical shapes, and tend to be horizontally aligned facing their broad side down. The horizontally aligned particles produces horizontal polarization in both scattering and emission. Fig. 2 shows the polarization fraction depending on the shape and the observation angle. For particles with typical aspect ratio of 0.5 or 4, the polarization fraction becomes about 10% at the elevation of 50°.

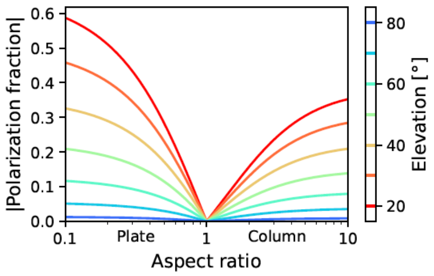

Figure 2. Polarization fraction of the signal from ice crystals with different shapes at different observing angle.

Since the distribution of clouds are not uniform, this polarized signal from clouds becomes a noise source for polarization measurements at the large-angular scales. To distinguish the actual B-mode polarization signal from other spurious noises, it is necessary to know properties of all noise sources and to estimate their impacts. The properties of noise from clouds should be highly dependent on the properties of cloud particles. Thus, the comparison with cloud properties measured by other atmospheric observations is interesting to validate the model.

3. South Pole Telescope

SPT is a 10 m-aperture telescope at the South Pole observing CMB anisotropies at millimeter waves. The SPT-3G, the third-generation receiver on SPT, was deployed in 2017. SPT-3G consists of 16,260 polarization-sensitive transition-edge-sensor (TES) bolometer detectors observing at 90, 150, and 220 GHz bands in the atmospheric window. During an observation, the telescope scans right and left in azimuth over 100° at the speed of 1°/s stepping the elevation. See Sobrin et al. (2022)[2] for more details about the instrument and observation.

We calculate common-mode Stokes Q and U polarization signals by averaging detector timestreams for each band for each of ten wafers. Here, vertical and horizontal polarization correspond to positive and negative Stokes Q, respectively, and diagonal polarizations corresponds to Stokes *U*. The first order polynomial filter is applied for each right-going or left-going scan. Then, we take average of the covariance among those averaged signals from ten wafers, which gives us the variance of the sky signal free from the bias due to the detector noise.

In some observations, we find that the variance in *Q* polarization becomes significantly larger than that of *U* polarization especially at 220 GHz. It agrees with the signal of horizontal polarization from clouds with high spectral index due to Rayleigh scattering. We check the atmospheric condition during these observations using the MPL measurements.

4. Micro Pulse Lidar

In the South Pole, a MPL is operated at the Atmospheric Research Observatory since 1999 to present as one of stations of MPLNET. The distance between the SPT and MPL is about 1.2 km, which is close enough for qualitative comparison of atmospheric conditions. The MPL is a Mie-scattering lidar using a pulse laser with a wavelength of 532 nm. It measures the profile of backscattering signal along the zenith in the range from 0.25 km to 30 km (above ground level, AGL) with altitude resolution of 30 m and temporal resolution of one minute. The MPL is polarization sensitive and thus can distinguish ice clouds and liquid water clouds.

The recent data of MPLNET are processed with the version 3 processing system[4]. The details of the version 3 cloud detection are explained in Lewis et al. (2016)[5]. However, the calibrations of the South Pole MPL data are still preliminary, and thus the products are not validated yet. Even so, the data are useful for qualitative investigation of the atmospheric condition.

5. Comparison

Fig. 3 shows the comparison of the normalized relative backscatter (NRB) of MPL and the *Q* polarization noise in SPT for each scan from one example observation. There is a significant burst in *Q* noise especially at 220 GHz. At the same time, clouds with high NRB appears around AGL of 2 km. The volume depolarization ratio is about 30% indicating that most of clouds consist of ice crystals. Although there is a difference in line of sights, this coincidence strongly suggests that the cause of the *Q* noise is the clouds.

In the latter half of the observation, however, the *Q* noise becomes quiet though some clouds are still seen in MPL. This could be due to variations of cloud properties, especially in particle size. SPT can see signals mainly from large particles, whereas MPL can detect small particles as well as large particles.

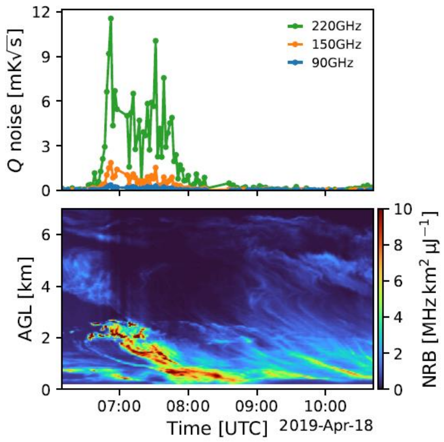

Figure 3. Comparison of the Stokes Q polarization noise and the MPL measurements.

Acknowledgements

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