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A light-scattering study of the scattering matrix elements of Arizona Road Dust

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ABSTRACT

We report measurements of the light scattering matrix elements of Arizona Road Dust, which has irregular shapes. Our experimental apparatus used photodiode arrays to detect scattered light simultaneously at many angles including small angles that are necessary for accurate characterization of large particles. The setup was calibrated with single slit diffraction and water droplet scattering. Guinier analysis yielded the dust particle size. Q-space analysis of the dust scattering yielded a comprehensive description of scattering in terms of power laws with quantifiable exponents.

1. Introduction

Scattered light from spherical particles has been studied for more than 100 years and is well understood [1,2]. However, light scattering from irregularly shaped particles remains a puzzle. Not only does scattering from irregularly shaped particles hold inherent intellectual interest, such scattering plays an important role in affecting the global radiation budget. In this paper we describe light scattering experiments conducted on Arizona Road Dust (AZRD), which is a canonical example of irregularly shaped particles similar to many other dusts that can be found in the atmosphere. Curtis et al. have studied AZRD and the scattering angles were 17–172° [3]. The Amsterdam group has studied a number of aerosol particles with an apparatus that allowed for measurements from 3° to 177° [4,5]. Our apparatus has some advantages over other similar instruments such that it detects light at many angles simultaneously. Our apparatus was built to detect from a small angle of 0.32° to 157°. This factor of 10 decrease in the smallest forward angle is very important for detecting the beginning of scattering angle functionality in the small angle limit, especially for large particles, and to determine particle sizes. In this paper, we present our apparatus, which can detect scattered light at many angles simultaneously, the calibration methods for the whole system, and the results from three different sizes of AZRD. Our work also differs from previous work in that Q-space analysis [6–8] is applied to our experimental results. Instead of plotting scattered intensity vs. the scattering angle θ on a linear scale, Q-space analysis graphs scattered intensity vs. the magnitude of the scattering wave vector q on a log–log scale. The scattering wave vector q has a magnitude of $2k\,\sin(\theta/2)$, where $k=2\pi/\lambda$. We find that Q-space analysis reveals power law functionalities with quantifiable exponents. Moreover, Q-space analysis with Guinier analysis (discussed in Section 5) indicates particle sizes. The importance of our work is the validation of our novel experimental apparatus, demonstration of the utility of the Q-space analysis, and describing light scattering from aerosols of irregularly shaped particles.

2. The scattering matrix

The optical scattering information about a given particle is completely described by the 4 by 4 scattering matrix.

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When the particles are randomly oriented and have a plane of symmetry, the scattering matrix has eight non-zero elements:

$$\begin{pmatrix} S_{11} & S_{12} & 0 & 0 \\ S_{21} & S_{22} & 0 & 0 \\ 0 & 0 & S_{33} & S_{34} \\ 0 & 0 & S_{43} & S_{44} \end{pmatrix},$$

where $S_{21}=S_{12}$ and $S_{43}=-S_{34}$ [9,10]. Thus, six of the matrix elements are independent. This matrix applies to an ensemble of randomly oriented AZRD particles [11].

The intensity and polarization of a beam of light can be specified by a Stokes vector:

$$\begin{pmatrix} I & Q & U & V \end{pmatrix}^T,$$

where T is the transpose operator. I represents the total intensity, Q represents the difference between the horizontally and vertically polarized intensities, U represents the difference between the $+45^\circ$ and -45° polarized intensities, and V represents the difference between the right-handed and left-handed polarized intensities [9,10].

The Stokes vector of the scattered light is obtained by multiplying the incident light Stokes vector by the 4 by 4 scattering matrix:

$$\begin{pmatrix} S_{11} & S_{12} & 0 & 0 \\ S_{12} & S_{22} & 0 & 0 \\ 0 & 0 & S_{33} & S_{34} \\ 0 & 0 & -S_{34} & S_{44} \end{pmatrix} \cdot \begin{pmatrix} I_{inc} \\ Q_{inc} \\ U_{inc} \\ V_{inc} \end{pmatrix} = \begin{pmatrix} I_{sca} \\ Q_{sca} \\ U_{sca} \\ V_{sca} \end{pmatrix} \quad (1)$$

By sending certain polarized light incident upon the particulate system and then detecting the difference between certain polarized scattered intensities, one can measure all six matrix elements [9,10].

3. Experiment

3.1. Experimental apparatus

Fig. 1 is a schematic diagram of the experimental apparatus. The laser beam with $\lambda=532$ nm passed through a linear polarizer or a wave plate on its way toward the aerosol from which it scattered. A linear polarizer or a wave plate was placed between the aerosol particles and the detector for both forward and side scattering. The forward scattering detection followed a design by Ferri [12] with a beam stop placed at the focal point of a Fourier lens to block the light directly from the laser. The scattered light was collected by a lens that imaged the Fourier plane onto the detector. For the side scattering, a custom elliptical mirror (Optiforms) collected a wide range of angles. The intersection of the incident light and the aerosol was at one focal point of the elliptical mirror, and an iris was placed at the other focal point. This scattered light was then collimated by a lens. Two 16 channel photodiode arrays (Hamamatsu S8558) were used as detectors at a total of 31 angles. One channel of the side detector was sacrificed as a monitor. The two detectors were connected to a data acquisition box connected to a computer. The use of photodiode arrays to detect light at many angles simultaneously allows for quick and efficient procurement of data, eliminates problems regarding aerosol stability, and makes detection at small angles easier.

Based on the information of the scattered light Stokes vector and the scattering matrix described in Section 2, one can measure all six matrix elements by manipulating the polarizers and wave plates. To measure S11, we send circularly polarized light (produced by a $\lambda/4$ wave plate after the vertically polarized laser with fast axis 45° from vertical) and measure the intensity of the scattered light. To measure –S12, send circularly polarized light and measure the difference between the vertically and hor-

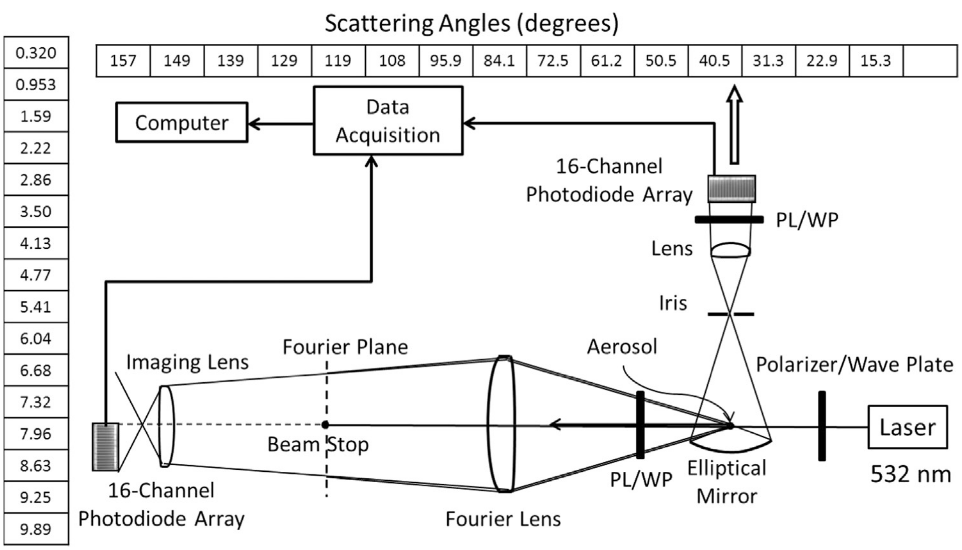

Fig. 1. A schematic diagram of the experimental apparatus.