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MULTI-COLOR PHOTOMETRY OF TWILIGHT SKY BACKGROUND USING RGB ALL-SKY CAMERAS: MICROPHYSICAL INVESTIGATIONS OF AEROSOL IN MIDDLE AND UPPER ATMOSPHERE

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Abstract. We consider the possibilities of three-color (RGB) photometry of twilight background by all-sky cameras for study of microphysical properties of aerosol particles in stratosphere and mesosphere of Earth. Background stratospheric aerosol causes the effect of sky reddening in the dusk area during the light stage of twilight. Measurements conducted during spring and summer of 2016 near Moscow allow finding the size distribution of stratosphere aerosol particles. The same was done for particles of polar mesospheric (or noctilucent) clouds during their display in August 2016 at Lovozero station. The results are in good agreement with the data of direct, lidar and satellite measurements. The method suggested here seems to be simplest and most effective for systematic measurements of aerosol properties in middle and upper atmosphere.

In a present time, a large number of all-sky color cameras is installed in high latitudes for regular aurora monitoring. They operate during the night. However, their work period can be expanded to the twilight, that can be effective for middle and upper atmospheric research. Climate changes observed in mesosphere during recent decades are most sufficient in polar latitudes [*Beig et al.*, 2003]. Negative trend of summer temperature leads to the increase of frequency of appearance of polar mesospheric clouds (or noctilucent clouds, NLC). Anthropogenic sulfur dioxide emission is considered as possible reason of increase of background stratospheric aerosol observed at the altitudes around 20 km even in the case of volcanic-free periods [*Solomon et al.*, 2011].

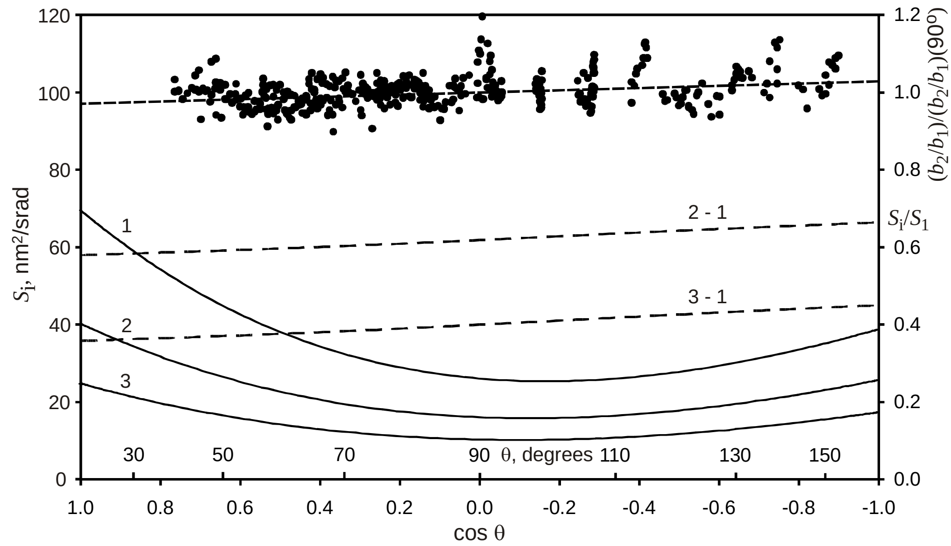

Figure 1. Mie scattering functions S of sphere with radius 60 nm for wavelengths 463 (1), 526 (2), and 590 nm (3), and their ratio. The observational ratio of NLC scattering for bands 1 and 2, b_2/b_1 (single image) is shown in the top, normalized by $b_2/b_1(90°)$ for convenience.

Aerosol particles scatter the solar radiation. This effect is mostly noticeable during the twilight, when lower dense atmospheric layers are immersed in the Earth's shadow. Stratospheric aerosol reveals itself during the light stage of twilight (solar zenith angles 92°-94°), noctilucent clouds are seen during the darker stages (solar zenith angles 96°-98°). Aerosol scattering is seen on the background of single and multiple scattering of solar radiation in the atmosphere. Spectral properties of aerosol component differ from the ones of twilight background. This is related with physical characteristics of scattering on aerosol particles described by Mie theory and also with different conditions of solar illumination (the last is the reason of red color of tropospheric clouds at the sunset). These effects also depend on the sky point and scattering angles. Basing on this effects, aerosol scattering can be separated in studied in all-sky RGB-images.

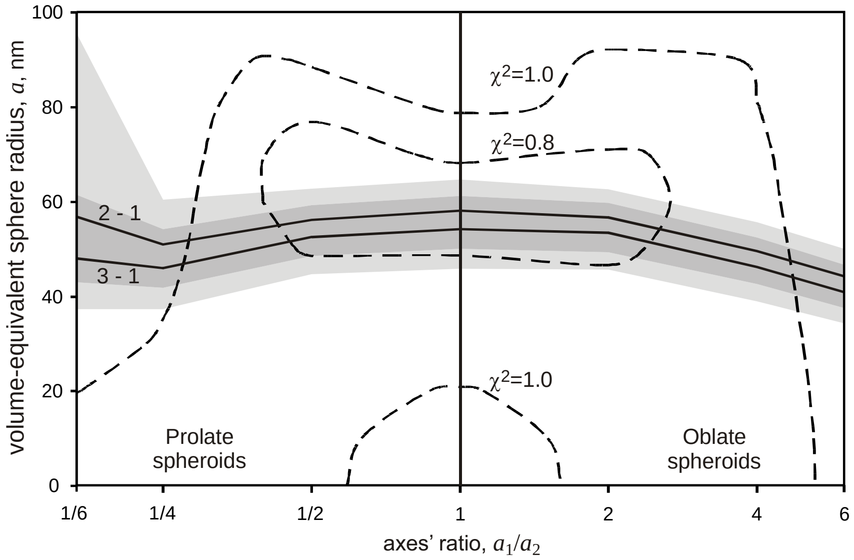

Figure 2. Possible values of volume-equivalent radius and axes' ratio of ice spheres and spheroids basing on polarization (dashed lines) and color analysis (comparison of NLC in wavelengths 2-1 and 3-1, see Fig. 1).

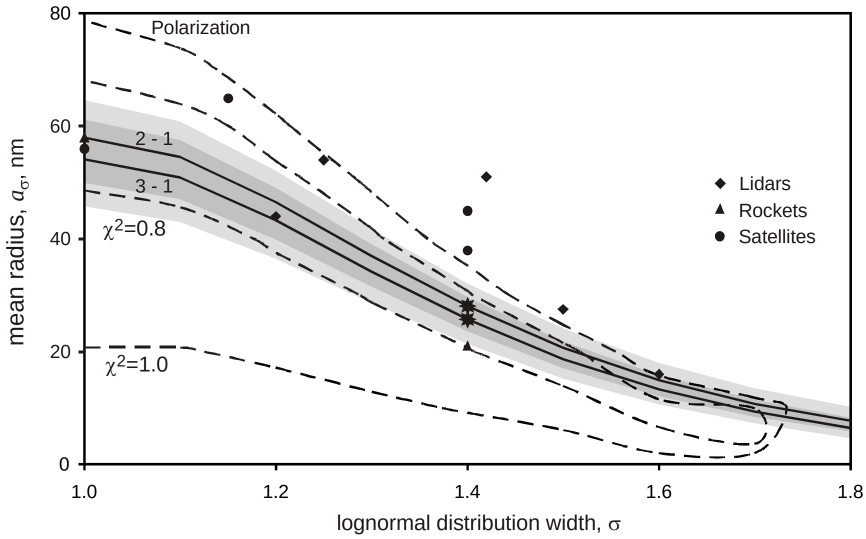

Figure 3. Possible parameters of lognormal size distribution of spherical particles of NLC. The results of this work are shown by bold lines and error areas (the same wavelengths 1, 2 and 3 as in Figs. 1-2). Dashed lines correspond to polarization analysis.

Noctilucent clouds are formed of water ice at the temperatures below 150 K in upper mesosphere (80-90 km). The condensation nuclei are hydrate ions [*Witt*, 1969] or fragments of meteor particles moderated in the same atmospheric layer [*Hunten et al.*, 1980]. NLC particles consist of tiny ice particles with scattering properties close to Rayleigh law ($\sim\lambda^{-4}$), that explains their color. However, the color ratio of scattering coefficients slightly depend on scattering angle θ. As we can see in Fig. 1, this dependence is close to linear by cos θ. To fix this effect, NLC must be observed in the most part of the sky, including the dusk-opposite part. These bright clouds were observed at August, 12, 2016, by all-sky RGB-camera in Lovozero station (68.0°N, 35.1°E). We should note that it happened less than one day after Perseid meteor shower maximum. Increased level of dust in mesosphere in the same season was fixed earlier by polarization measurements [*Ugolnikov and Maslov*, 2013, 2014].

As we see in upper panel of Fig. 1, color ratio of NLC light scattering actually turns red from dusk area to the opposite sky part. This effect is also influenced by the conditions of solar illumination, absorption by stratospheric ozone in Chappuis bands. Procedure of separation of twilight background and analysis of NLC light scattering is described in details in [*Ugolnikov et al.*, 2017]. Results are shown in Figs. 2 and 3. Analysis of monodisperse models of spherical and non-spherical particles is performed in Fig. 2 in comparison with polarization analysis [*Ugolnikov et al.*, 2016ab]. Good agreement is clearly seen, effective size of monodisperse ice particle in NLC is close to 60 nm.

Possible parameters of lognormal size distribution of NLC spherical particles are shown in diagram in Fig. 3 in comparison with polarization measurements [*Ugolnikov et al.*, 2016ab] and recent lidar, rocketborne and satellite data (see references in [*Ugolnikov et al.*, 2017]). Agreement is seen again; if we assume that particles have a lognormal size distribution with width σ=1.4 [*Von Savigny and Burrows*, 2007], than mean particle radius will be close to a half of monodisperse value, being equal to 30 nm (asterisks in Fig. 3).

Stratospheric aerosol layer [*Junge et al.*, 1961] appears at the altitudes about 20 km and consists of sulfur acid droplets [*Rosen*, 1971]. The number and size of particles sufficiently increase after volcanic eruptions, when large amount of sulfur dioxide is emitted to the stratosphere. However, aerosol is also found in the stratosphere during volcanically-quiet period. Stratospheric aerosol particles are larger than the ones on NLC, they have weaker wavelength dependence of scattering. This leads to red excess of light scattered by these particles on the background of Rayleigh and multiple scattering. Effect gets stronger in dusk area, since aerosol particles scatter most part of radiation in a forward direction.

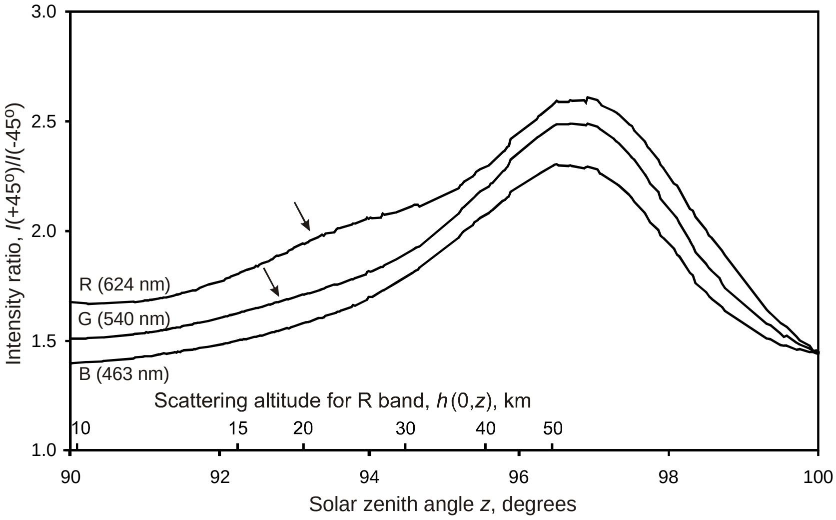

Figure 4. Twilight sky brightness ratio in symmetric points of solar vertical (evening twilight of March, 27, 2016). Arrows show the effect of aerosol scattering in stratosphere.

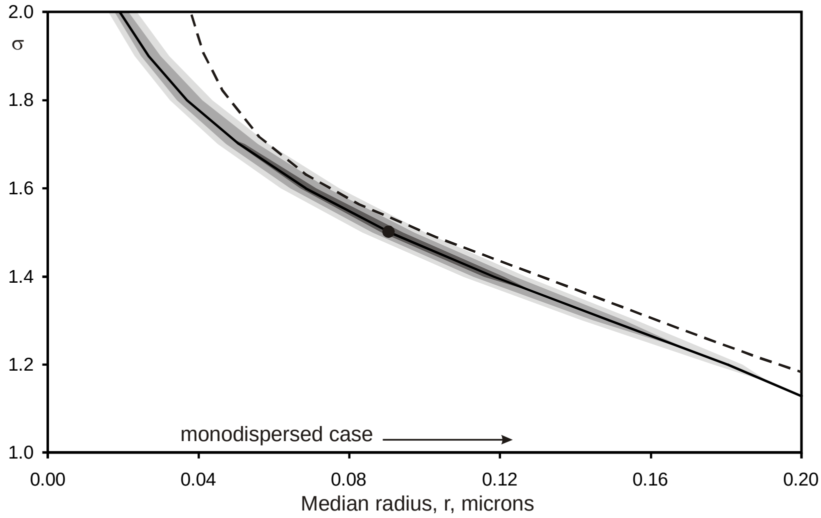

Figure 5. Retrieved characteristics of particle log-normal size distribution: solid line and gray areas (single, double and triple error) - twilight analysis (the same date as in Fig. 4), 21.4 km, dashed line - [*Bourassa et al*., 2008].

During spring and summer 2016, all-sky RGB-photometry was conducted near Moscow (55.2°N, 37.5°E). Fig. 4 shows the behavior of brightness ratio in symmetrical solar vertical points (zenith angle 45°) during the evening twilight of March, 27, 2016. This value was described in [*Ugolnikov*, 1999]. It increases from the sunset to the deep stage of twilight (solar zenith angle 97°) due to increasing difference of effective single scattering altitudes in these solar vertical points. During the even darker stage brightness asymmetry disappears, as the single scattering fades on the background of multiple scattering.

Effects noted above are observed for all spectral bands. However, additional dusk excess of brightness is seen for R channel at solar zenith angle about 93° (arrow in Fig. 4), it corresponds to effective scattering in the Junge layer. Analysis of sky color behavior in a solar vertical during the twilight performed in [*Ugolnikov and Maslov*, 2017] allowed studying the size distribution of sulfur acid droplets. The diagram analogous to NLC in Fig. 3 is shown in Fig. 5 in comparison with space limb measurements [*Bourassa et al.*, 2008]. The range of possible parameters is a thin line, that is typical for such particles. Fig. 6 shows the vertical profile of mean radius with assumed size distribution width. The results of RGB-photometry are close to the satellite values again, however, twilight profile is smoothed due to the thickness of effective scattering layer during the twilight.

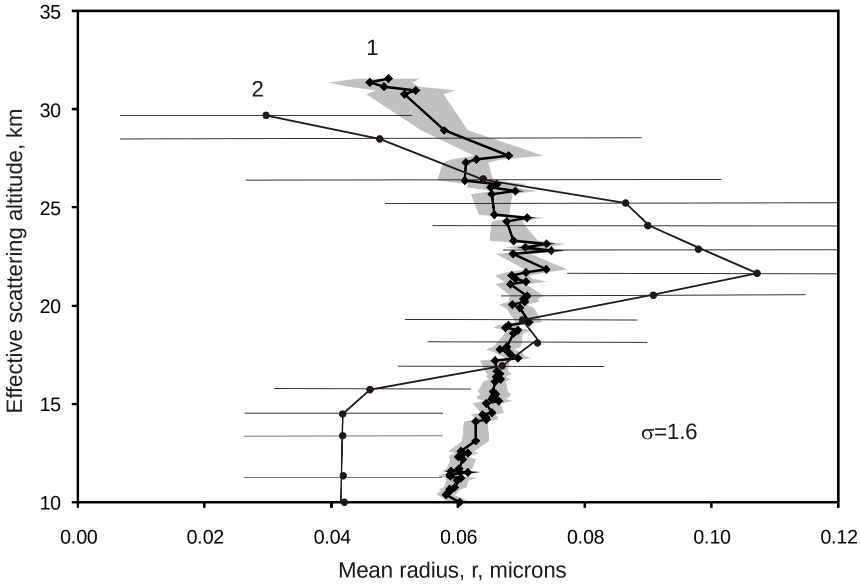

Figure 6. Vertical profiles of mean particle radius, 1 - this work, the same twilight as in Figs. 4-5, 2 - [*Bourassa et al*., 2008].

Methods of aerosol microphysical study described here are planned to be used during continuous all-sky survey by color cameras in different locations.

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