# OPTICAL CHARACTERISTICS OF THE STRATOSPHERE AFTER THE MT. PINATUBO ERUPTION AS ASSESSED FROM SPECTRAL POLARIZATION LIDAR MEASUREMENTS

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*Some results of experimental investigations using method of spectral polarization laser sensing of the stratospheric aerosol layer (SAL) after the eruption of Mt. Pinatubo volcano are given. Time dependence of the optical depth at 532 nm is analyzed. Scattering ratio profiles, the profiles of aerosol backscattering depolarization ratio as well as the results of lidar observations of the stratosphere at 532 and 1064 nm are presented. Some peculiarities in the formation of microphysical parameters of SAL due to Mt. Pinatubo eruption are discussed.*

Experimental studies of the stratospheric aerosol layer are being carried out at Institute of Physics of Academy of Sciences of Belarus (Minsk, 53.85°N, 27.5°E) with a lidar station[1] ANB–314 since 1985. The lidar station consists of a 500 m diameter receiving telescope and an optical analyzer that splits the scattered radiation collected from the atmosphere into four channels. Optical arrangement of the analyzer provides the possibility of making measurements of polarized and cross–polarized components of scattered radiation at two wavelengths simultaneously. The receiving system is equipped with a mechanical chopper of the near zone to provide linearity of a PMT operation in the photon counting mode (PMT–140 for the visible radiation and the "Kometa" PMT for the IR radiation). A control and data processing block is capable of digitizing the signals with a spatial resolution of 64 m. At present a commercially available ILTI–405B Nd:YAG laser is used in this lidar station as a source of sounding radiation. Sounding of the atmosphere is performed at two wavelengths, 0.532 and 1.064 μm. Processing of lidar returns and scattering ratio, $R(h) = [\beta_a(h) + \beta_m(h)]/\beta_m(h)$, calculations were carried out taking into account the aerosol component of the radiation extinction using the algorithm proposed in Ref. 2. Here $\beta_a(h)$ and $\beta_m(h)$ are the profiles of aerosol and molecular backscatter, respectively. Technique used for determining the profiles of the coefficient of depolarization of radiation scattered by aerosol has been described in Ref. 3.

It is characteristic of the period from mid 80 s till June 1991 that no strong volcanic emissions into the stratosphere occurred. The aerosol overburden of the layer gradually approached the background level. The Mt. Pinatubo volcanic eruption stopped the relaxation process in the stratosphere after the Mt. El–Chichon eruption comparable in its power with Mt. Pinatubo eruption. The integral parameters of backscattering coefficient distribution obtained at the Institute of Physics of Academy of Sciences of Belarus were close to those observed by other authors.[4]

The presence of layers formed by the products of Mt. Pinatubo eruption in the stratosphere was first revealed from the experimental data by early June 1991. Their intensity during this period was insignificant. The layer with R = 1.65 at its maximum at the height of 15.3 km was observed on July 4, 1991, the value $R$ = 1.74 at $h$ = 14.8 km on July, 8 1991, and $R$ = 1.66 at $h$ = 15.3 km on July 9, 1991. The value of the scattering ratio did not exceed 1.37 in the profiles obtained at the end of July and in the beginning of August (the data are presented for the wavelength λ = 0.532 μm). Most obviously consequences of the Mt. Pinatubo eruption impact on SAL were observed since August 9, 1991.

Temporal behavior of the parameter

$$I(h_1, h_2) = \int_{h_1}^{h_2} \beta_a(h')\,\mathrm{d}h' \qquad (1)$$

for $h_1$ = 13 km and $h_2$ = 30 km is shown in Fig. 1 for the period from June 1991 till September 1992. Such a height range was selected because the height of the tropopause over Minsk does not exceed, as a rule, 13 km. It is well seen from these data that optical density of SAL increased, though fluctuating, by almost 70 times during 5 months due to the break through of Mt. Pinatubo eruptive products. Its local decrease was quite distinctly observed in January 1992, what agrees with the experimental data obtained by the scientific–production association "Taifun", Obninsk (private message from Prof. S.S. Khmelevtsov). The value $I(h_1, h_2)$ increased again in February and then gradually decreased with relatively small fluctuations.

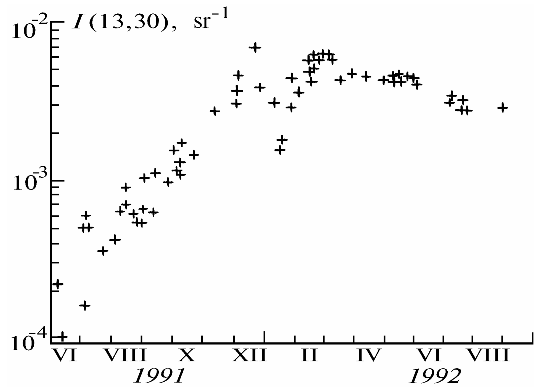


*FIG. 1. Temporal behavior of the parameter* $I(13, 30)$.

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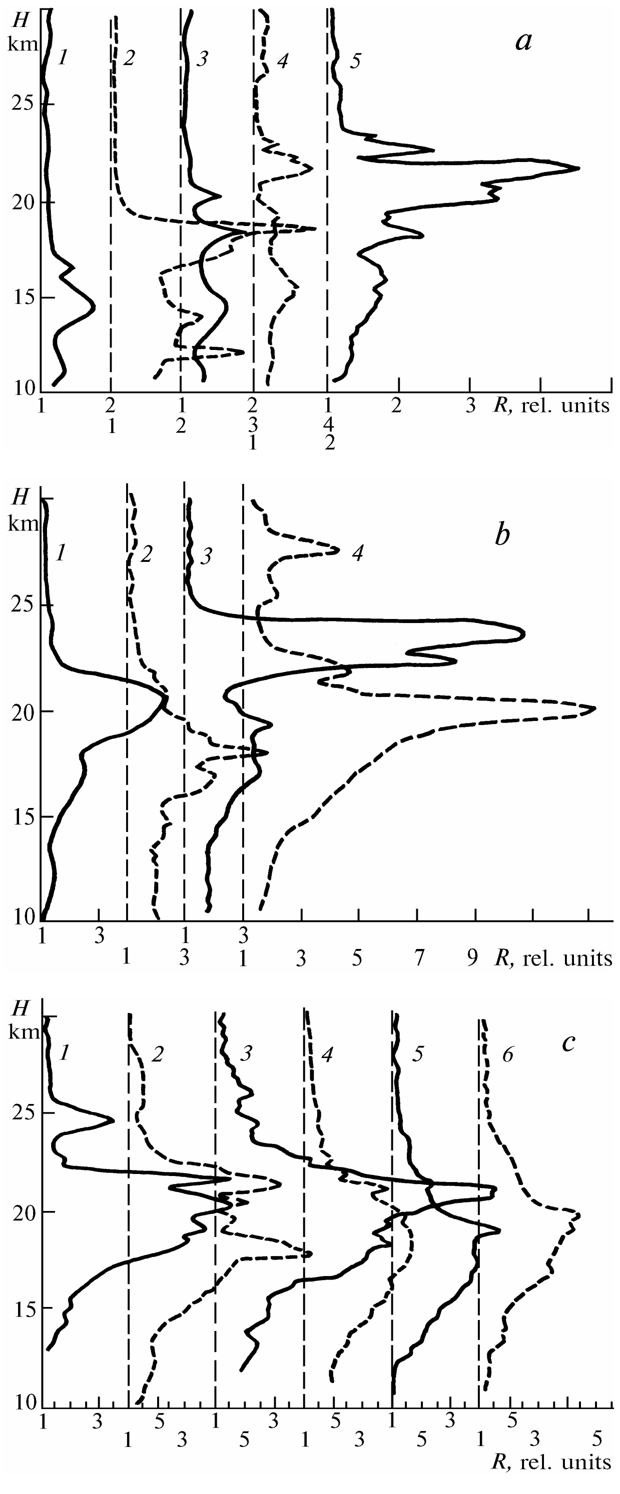


*FIG. 2. Scattering ratio profiles R(h) at the wavelength* λ = 532 nm *(a) 1) July 8, 1991, 2) August 14, 1991, 3) September 12, 1991, 4) September 26, 1991, 5) October 11, 1991. (b) 1) November 14, 1991, 2) December 6, 1991, 3) December 8, 1991, 4) December 25, 1991. (c) 1) January 31, 1991, 2) February 8, 1992, 3) March 2, 1992, 4) June 6, 1992, 5) July 10, 1992, 6) August 30, 1992.*

Noticeable variations of the parameters $I(h_1, h_2)$, the number of observed layers, their location, intensity, the values of the scattering ratio at maximum were observed from July till October, 1991. For example, this is seen from Fig. 2*a* where some profiles of the scattering ratio are given. Each curve in Fig. 2 is characterized by its own $X$–axis scale. Based on the dependences $R(h)$ one could judge that the eruptive products in SAL over mid–latitudes during this period were mainly concentrated at the heights $h \geq 15$–25 km and their mixing was insignificant. The formation of a stable SAL occurred by November, 1991. Some maxima continued to appear against this background during this period (see Fig. 2*b*). Very often several maxima were observed on this background level. The maximum value of the scattering ratio was observed at the Minsk lidar station on December 25, 1991. The value $R(h)$ was 13.2 at the height of 19.8 km.

Some typical height dependencies $R(h)$ for the period of 1992 are given in Fig. 2*c*. It is seen that the absence of significant local maxima in the scattering ratio profiles is characteristic of the period from June to August.

The method of recording the profiles of $Q_a(h)$ of the degree of depolarization of the radiation scattered by aerosol in the backward direction proved to be a convenient tool of controlling the aerosol phase state. The algorithm for calculating $Q_a(h)$ and the experimental technique are described in Ref. 3. Their specific feature is that one make an additional calibration measurement in which the sounding radiation has linear polarization in the plane oriented at the angle of 45° relative to the optical axes of the analyzer of the receiving system. In this case both channels (recording cross polarized components of scattered radiation) are equally acceptable for recording each component. The profiles of the number of photons recorded coincide accurate to a constant factor determined by the amplification coefficients of each channel. The differences are caused only by noise. So, in addition to the increase of accuracy of data processing (there is no need for *a priori* value of $Q_a(h)$ at a reference point), the additional calibration measurement makes it possible to control over the level of errors in counting photons in both channels along all the sounding path.

The common feature of the data obtained at the lidar station of the Institute of Physics of Academy of Sciences of Belarus is the following. The parameter $Q_a(h)$ in SAL formed by the eruptive products has, as a rule, lower values than in neighbour layers (see Fig. 3*a*, the profile $R(h)$ is presented here also). The value $Q_a(h)$ itself is also small enough. In our opinion, this is indicative of that the particles in SAL are mainly spherical (liquid droplets).

Measurement data on vertical profiles of $Q_a(h)$ agree with the data from Ref. 5 where very low depolarization of radiation scattered by the main stratospheric aerosol layer formed due to the Mt. Pinatubo eruption was noted. According to measurement data of 1991–1992, the profiles $Q_a(h)$ had, as a rule, the shape and numerical values similar to those in Fig. 3*a*. However, sometimes we observed the $Q_a(h)$ profiles as shown in Fig. 3*b*. In this case $Q_a(h)$ values are, on the whole higher, and their increase is observed at altitudes out of the layer formed by the Mt. Pinatubo eruptive products. Possibly, such tendencies are caused by freezing of particles at low temperatures in the stratosphere.

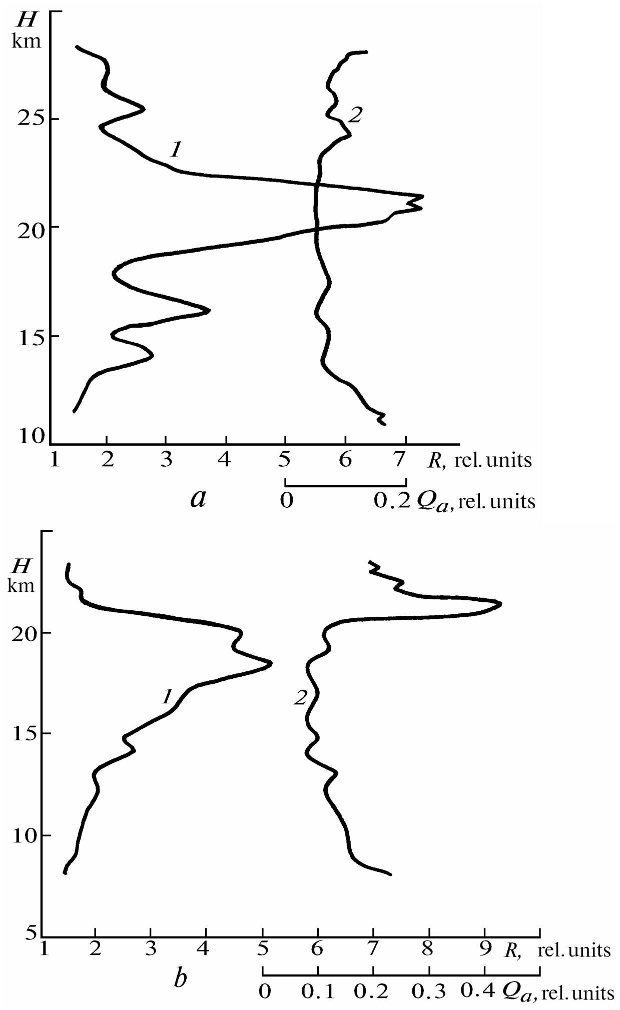


*FIG. 3. Profiles of the scattering ratio $R(h)$ (1) and the depolarization coefficient $Q_a(h)$ (2). (a) February 19, 1992 and (b) December 7, 1991.*

The variations of the spectral dependencies of optical parameters of the disperse medium allow one to judge the variability of their microphysical parameters. For this purpose we analyze in this paper differences in the scattering ratio profiles measured at two wavelengths, $\lambda = 532$ and $\lambda = 1064$ nm.

Laser sounding at the wavelength $\lambda = 1064$ nm is convenient because the same laser serves as a source of light at both wavelengths. However, in spite of relatively higher power of radiation, measurements in the photon counting regime in the IR range come across a number of technical difficulties (modern photoelectron multipliers have low quantum efficiency in this spectral range). Therefore, in order to provide more or less reliable recording of lidar returns at $\lambda = 1064$ nm one should specially select a PMT with a sufficiently high quantum yield of the photocathode, to cool the cathode for suppressing thermal component of the dark current, to optimize the parameters of the PMT's voltage divider, and finally to increase the measurement time, by accumulating photocounts from about 50000 laser shots. These operations make it possible to carry out laser sounding of stratospheric aerosol layer in the photon counting regime at $\lambda = 1064$ nm. At the same time it was quite difficult to find a reference point for measurement at $\lambda = 1064$ nm. As a rule, it occurred during the period of measurements that the aerosol concentration was essential in the region of tropopause and noticeably varied, while the signal recorded from heights greater than 25 km was essentially noisy. In this connection, in our opinion, the analysis is more objective of not the profiles $R(H, \lambda = 1064)$ or of the ratio $\beta_a(h, \lambda_1)/\beta_a(h, \lambda_2)$ but the height variability of the parameter

$$\alpha(h) = \frac{\beta_a(h, \lambda_1)\, b_a(h', \lambda_2)}{b_a(h, \lambda_2)\, b_a(h', \lambda_1)} . \tag{2}$$

As the numerical simulation and the experience of real data processing show, the values of the parameter $\alpha(h)$ quite weakly depend on the *a priori* choice of the value of scattering ratio at a reference point, and, in addition, the profile of $\alpha(h)$ makes it possible to judge the spatial variations of the aerosol microstructure.

Vertical profiles $\alpha(h)$ obtained from data of lidar sensing of the stratosphere during the post Mt. Pinatubo eruption period can be divided into two groups of profiles having distinctly specific shapes. One of them is characteristic of the period from November 1991 till January 1992 (see Fig. 4 *a*, the profile of the scattering ratio at $\lambda = 532$ nm is also shown here). Such an altitude behavior of $\alpha(h)$ shows that there occurred an increase of the average particle size in the height range from 10 to 12 km. Then the particle size keeps constant within SAL and decreases above it. Of course, these conclusions are valid only for particles optically active in the wavelength range 532–1064 nm.

The second kind of profiles $\alpha(h)$ is characteristic of the period starting from February 1992 (see Fig. 4 *b*). Such altitude dependences of the parameter $\alpha(h)$ can be explained by a decrease in the average size of scatterers with increasing height.

It is characteristic of the whole period of observations of SAL formed due to Mt. Pinatubo eruption that practically all profiles $R(h)$ have several local maxima. It is worth noting here that lidar data have been acquired with the height resolution of 128 m and the number of photocounts recorded in each time gate well exceed the level of statistical spread. Besides, the construction of ANB–314 lidar station has a peculiarity that even if no polarization measurements are done, lidar returns at $\lambda = 532$ nm are recorded in two channels simultaneously. The difference between the two channels is that only 10% of received radiation is directed into one of them. It is natural, therefore, that minima and maxima in the profiles of scattering ratio $R(h)$ reconstructed based on data from both channels coincide. It is also understandable that the noise level in the low intensity channel is higher. Since each channel is an independent optoelectronic system such a coincidence of $R(h)$ shapes is indicative of a true altitude structure of SAL. Note also that time required for acquiring a single profile was about 50 minutes while the whole cycle of measurements, including polarization and calibration measurements, took several hours. However, no significant variations in the successively measured profiles occurred, what was indicative of a presence of large–scale inhomogeneities in SAL structure. It is characteristic that different layers of SAL differ from each other mostly by the number density of particles, the microstructure of the ensembles of scatterers being more stable with height, as is seen from Figs. 3 and 4.

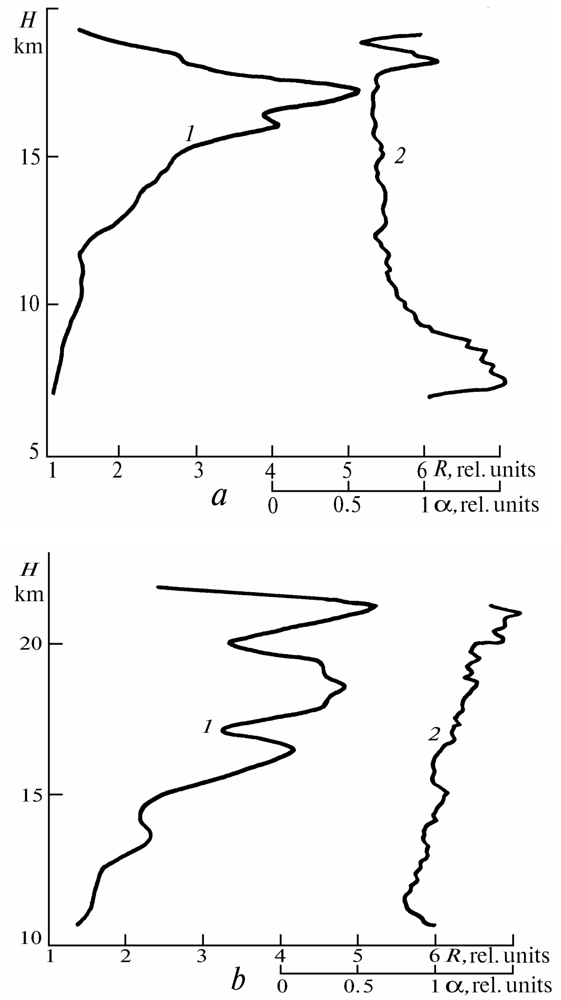


*FIG. 4. Profiles of the scattering ratio $R_a(h)$ (1) and the parameter $\alpha(h)$ (2). (a) January 13, 1992 and (b) May 2, 1992.*

## CONCLUSION

Volcanic eruption of Mt. Pinatubo resulted in a 70 times increase of the optical depth $\tau$ of stratospheric aerosol layer at the latitude of 53.85°N. A gradual increase of the optical depth has been observed since mid summer 1991 till December 1991. In January 1992 a local minimum of $\tau$ took place. Beginning from February 1992 the optical depth of the stratospheric aerosol layer started to decrease with relatively low fluctuations.

A stationary stratospheric aerosol layer formed during the post Mt. Pinatubo eruption period was observed at altitudes from the tropopause to 25 km. It is characteristic of this layer that it had a multilayer (stratified) structure caused by variations of the aerosol concentration at relatively stable, with height, microstructure of aerosol particles ensemble.

Measurement data on the aerosol scattering depolarization factor $Q_a(h)$ showed that the stratospheric aerosol layer of the Mt. Pinatubo eruptive products was formed of spherical liquid droplets. Sometimes layers with enhanced content of nonspherical particles were recorded of heights out of the main maximum of the layer. Data of double frequency laser sounding of the stratospheric layer show that mean size of particles, optically active in the wavelength range from 532 to 1064 nm kept almost constant till January 1992 and started to decrease with increasing height since February 1992.

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