ISSN 1068-3356, Bulletin of the Lebedev Physics Institute, 2016, Vol. 43, No. 2, pp. 80–86. © Allerton Press, Inc., 2016.
Original Russian Text © R.A. Antonov, D.V. Chernov, Yu.I. Stozhkov, 2016, published in Kratkie Soobshcheniya po Fizike, 2016, Vol. 43, No. 2, pp. 48–58.

Study of the Energy Spectrum and Mass Composition of Primary Cosmic Rays in the Energy Range of 10^{18}–10^{20} eV using a Balloon Setup in Antarctica (SPHERE-Antarctica Project)

R. A. Antonov[a], **D. V. Chernov**[a], and **Yu. I. Stozhkov**[b]

[a] *Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, 119991 Russia*
[b] *Lebedev Physical Institute, Russian Academy of Sciences,*
Leninskii pr. 53, Moscow, 119991 Russia; e-mail: stozkov@fian.fiandns.mipt.ru

Received November 25, 2014

Abstract—An Antarctic balloon experiment for measuring the energy spectrum and elemental composition of cosmic rays in the ultrahigh-energy range (10^{18}–10^{20}) eV is proposed. Scientific equipment will measure fluorescence caused by an extensive air shower formed in the atmosphere by an ultrahigh energy particle and Cherenkov light of this shower reflected from a snow surface. It is assumed that the balloon will fly in the circumpolar orbit in Antarctica at a height of ∼25 km for (2–3) winter (in the Southern Hemisphere) months. For this time, ∼3000 events caused by particles with energies above 10^{18} eV and (200–300) events caused by particles with energies above 10^{19} eV will be detected.

DOI: 10.3103/S106833561602007X

Keywords: cosmic rays, fluorescent and Cherenkov light, energy spectra, balloon.

Currently, several large ground-based experimental setups operate in the energy range of primary cosmic rays (PCR) 1–100 EeV, which record extensive air showers (EASs) [1–5]. However, the results of their measurements are not in good agreement due to principal disadvantages of the technique used in these experiments.

In the energy range of 10^{18}–10^{20} eV, the EAS development maximum is near sea level; therefore, it is difficult to study its development using ground-based setups. The geometry of the proposed balloon experiment makes it possible to study EAS characteristics in this extreme energy range with much better accuracy.

The best method for studying the energy spectrum in this energy range is the calorimetric method for measuring the total flux of EAS Cherenkov light, proposed by A. E. Chudakov [6]. Currently, this method is not used in any experimental setup in this energy range.

The second, also proposed by A. E. Chudakov, quasicalorimetric method for recording EAS fluorescent light [7] also cannot be adequately used in existing setups.

In this paper, we propose a new version of a balloon setup of small size and weight, which can be at a height of ∼25 km over the Antarctica surface covered with ice and snow during polar night for one-three months and record both EAS fluorescent light and the total flux of EAS Cherenkov light reflected from the snow surface.

Recently, long-term (to 46 days) flights with scientific equipment were performed over Antarctica during the Antarctic summer period. During the Antarctic winter (from May to September), a large ice belt covered with snow is formed around Antarctica so that the mainland shoreline shape becomes close to circular. It should promote the formation of more stable circular circumpolar air flows. This can make it possible to perform even longer flights.

The search for the most appropriate flight trajectories will be performed at the first preparatory stage of the experiment.

The proposed method makes it possible to obtain information on the shower development in the atmosphere, to determine the depth of the EAS development maximum and the zenith tilt angle of the

EAS axis. These data make it possible to analyze the mass composition and energy spectrum of primary cosmic rays (PCRs).

1. Project objective. The SPHERE-Antarctica project objective is the study of the PCR energy spectrum and elemental composition in the energy range of 10^{18}–10^{20} eV. This energy range is of particular interest from the viewpoint of the study of particle acceleration mechanisms in sources in both our Galaxy and outside it. The energy spectrum shape irregularities and mass composition measurements can yield information on the role of the extragalactic component of PCRs and answer the question whether the Greisen–Zatsepin–Kuzmin effect takes place.

A main advantage of the SPHERE-Antarctica project is simultaneous recording of EAS fluorescent light and the total flux of EAS Cherenkov light. This increases the methodical accuracy of energy and particle type measurements and makes it possible to sufficiently accurate determine the arrival direction of the PCR particle. The high angular resolution of the ultrahigh-energy particle arrival in the SPHERE-Antarctica project allows detection of individual PCR sources in the energy region over 10^{19} eV.

The technique and measurement area sizes even for such modern ground-based experimental setups as the Auger, TA, and Yakutsk appear insufficiently efficient for these purposes. The projected JEM-EUSO orbital setup, although features a large effective measurement area, has some disadvantages. A comparison of the proposed setup with the above-listed setups is given in Section 4.

2. Equipment. A flat lens with spherical aberration correction $\sim$0.5 m in diameter and $\sim$0.2 m^2 in area focuses EAS light to a photodetector $\sim$30–50 cm in diameter. As a detector, it is planned to use $\sim$1000 planar semiconductor diodes with quantum efficiency $\eta_{\max} = 0.4$ at the maximum. The average effective quantum efficiency for a wavelength range of 300–600 nm is $\eta = 0.27$. The total viewing angle of the entire setup is $\sim$1 sr. The total viewing angle of one pixel is $Q = 10^{-3}$ sr.

Each detector pixel sees an EAS track area of length $L \sim 1$ km which corresponds to the detection time $t \approx 3$ μs.

The setup dimensions are $\sim 0.5\times0.5\times0.5$ m^3. The approximate setup weight is 20–50 kg.

3. Recording of EAS fluorescent and Cherenkov light. Starry sky background. The average number of photoelectrons from starry sky photons for the time $t = 3 \cdot 10^{-6}$ s will be

$$n_s = I_s \cdot S \cdot Q \cdot t \cdot \eta \cdot C_t,$$

where $I_s \approx 10^{12}$ photon·m^{-2}·sr^{-1}·s^{-1} [8–10], $C_t \approx 0.7$ is the total light reflectance from the snow surface, protective glass surface, and lens surface,

$$n_s = 10^{12} \cdot 0.2 \cdot 10^{-3} \cdot 3 \cdot 10^{-6} \cdot 0.26 \cdot 0.7 \approx 1.1 \cdot 10^2.$$

Then the number of photoelectrons n_b corresponding to the root-mean-square fluctuations of the starry sky background in one pixel is

$$n_b = (110)^{0.5} \approx 10.5 \,\text{photoelectrons}.$$

Fluorescent light recording. The desired signal n_{fl} of EAS fluorescent light 3.0 μs in duration in one of 784 detection channels for an EAS with an energy of 10^{20} eV is given by

$$n_{\text{fl}} = N_{\max} \cdot 5 \cdot L \cdot S \cdot (4\pi H^2)^{-1} \cdot \eta \cdot C_L,$$

where $N_{\max} = E/(1.3 \cdot 10^9 \text{ eV}) \approx 8 \cdot 10^{10}$ is the number of particles at the EAS maximum, 5 is the number of fluorescent light photons per 1 m of particle trajectory, $L \approx 10^3$ m is the particle trajectory length seen by one pixel, $S \approx 0.2$ m^2 is the lens area, $H \approx 25$ km is the setup height, $\eta = 0.27$ is the detector quantum efficiency, $C_L \approx 0.8$ is the reflectance from the protective glass and lens surfaces. Then

$$n_{\text{fl}} = 8 \cdot 10^{10} \cdot 5 \cdot 10^3 \cdot 0.2 \cdot (4\pi)^{-1} \cdot (25 \cdot 10^3)^{-2} \cdot 0.27 \cdot 0.8 \approx 2.2 \cdot 10^3 \,\text{photoelectrons}.$$

The signal-to-background ratio for EAS fluorescent light measurements is $(n_{\text{fl}}/n_b) = 2.2 \cdot 10^3/10.5 = 2.1 \cdot 10^2$ for EAS with an energy of 10^{20} eV and $(n_{\text{fl}}/n_b) = 2.1$ for EAS with an energy of 10^{18} eV.

The threshold energy of EAS fluorescent light detection is $\sim 2 \cdot 10^{18}$ eV.

Each pixel sees a part of a fluorescent track 1 km long; however, pulse temporal structure measurements will make it possible to obtain additional information for the fluorescent track for showers with energies above the threshold.

Cherenkov light recording. The signal of the Cherenkov light reflected from snow for EAS with an energy of 10^{20} eV is

$$n_{\mathrm{ch}} = (2.5 \cdot 10^7 \cdot E \cdot S \cdot \eta \cdot C)/[2\pi \cdot (2.5 \cdot 10^4)^2],$$

where $C \approx 0.7$ is the total reflectance from the snow surface, protective glass surface, and lens surface; E is given in TeV. Then we obtain

$$n_{\mathrm{ch}} = (2.5 \cdot 10^7 \cdot 10^8 \cdot 0.2 \cdot 0.27 \cdot 0.7)/[2\pi \cdot (2.5 \cdot 10^4)^2] \approx 2.4 \cdot 10^4 \text{ photoelectrons.}$$

Due to the fact that reflection from snow is diffusive according to the Lambert law to EAS axis tilt angles of $\sim 80°$, the signal-to-background ratio for recording EAS Cherenkov light is $(n_{\mathrm{ch}}/n_b) = 2.4 \cdot 10^4/10.5 \approx 2.3 \cdot 10^3$ for EAS with an energy of 10^{20} eV and $(n_{\mathrm{ch}}/n_b) \approx 23$ for EAS with an energy of 10^{18} eV.

At a viewing angle of ~ 1 sr and a device flight time of 90 days of polar night at a height of 25 km, $\sim 10^5$ EASs with energies above 10^{18} eV and several hundreds of events with energies above 10^{19} eV can be detected.

The threshold energy of recording EAS Cherenkov light is $2 \cdot 10^{17}$ eV. Cherenkov light reflected from snow twice passes through the atmospheric boundary layer before it will be recorded by the setup. This causes additional light scattering whose consideration causes a certain increase in the threshold energy of Cherenkov light recording by the setup.

4. Comparison with other experiments. When comparing the SPHERE-Antarctica project with other experiments, it should be taken into account that the possible number of detected events, presented in Section 3, can be obtained with a single setup during one long-term (two-three months) flight over Antarctica. This is caused by unique wind conditions in Antarctica in the winter period, i.e., the circumpolar circular motion of air in the central Antarctica region and the practical absence of wind in the circumpolar region.

Table 1 compares the main parameters of the SPHERE-Antarctica, Auger [1, 2], TA [3, 4], and Yakutsk [5] setups. First of all, a comparison should be performed with the Auger setup operated as long as 9 years, whose effective area is significantly larger than the areas of all other setups.

In the Auger and TA experiments, the main method for determining the primary cosmic particle energy and PCR mass composition is recording the shape of the EAS cascade curve development in the atmosphere using four (in the case of the Auger) or three (for the TA) detectors of EAS fluorescent light. In this case, scattered Cherenkov light and light absorption in the dense atmospheric boundary layer between the detector and shower, reaching several tens of kilometers, have an appreciable effect. The area used for this purpose is only 2% of the area on which EAS charged particle detectors are arranged. For the Auger setup, these areas are 60 and 3000 km^2 for the energy region above $3 \cdot 10^{18}$ eV and 120 and 3000 km^2 in the energy region above 10^{19} eV, respectively. The corresponding energy dependences of the total exposure are given in [1].

Difficulties in the use of ground-based detectors of Cherenkov light for determining the PCR energy and mass composition in the Auger and TA setups are illustrated by the fact that the PCR mass composition in the energy region above (10^{18}–10^{19}) eV appears significantly different. According to the results of the TA setup, the cosmic ray composition is purely proton, whereas, according to the Auger setup data, it consists of heavy nuclei.

The events for which charged particle detectors can be used, as noted in [3], cannot be individually analyzed for the purpose of the somewhat accurate determination of the EAS axis position and incidence angle. According to the incidence angle, showers are classified into two groups: from 0° to 60° and from 60° to 90°. A bank of simulated EASs is constructed, whose data are compared with the set of detected EASs. Based on the comparison, experimental points are plotted.

Taking into account the width of the spatial distribution of EAS particles near sea level, the distances between detectors (1.5 km), and the fact that the number of particles and their spatial distribution depend strongly on the nucleus type and the EAS development model, the systematic error of points in the particle energy spectrum can be significant.

Table 1. Comparison of main parameters of the SPHERE-Antarctica, Auger [1, 2], TA [3, 4], and Yakutsk [5] setups

Setup	SPHERE-Antarctica	Auger	ARRAY (TA) Telescope	Yakutsk
Operating time		9 years	4 years	40 years
Measurement area, km^2	1000	3000 for D_p, 60 for D_{fl}	700	10
Number of detectors D_p		1600	507	58
Number of detectors D_{fl}		4 at the periphery	3 at the periphery	no
Number of detectors D_{ch}		no	no	58
Positioning discreteness of D_p and D_{ch}		1.5 km	1.2 km	0.5 km
EAS Cherenkov light threshold	$E_{\text{ch}} \sim 2 \cdot 10^{17}$ eV	$E_{\text{ch}} \sim 3 \cdot 10^{18}$ eV		
EAS fluorescent light threshold	$E_{\text{fl}} \sim 2 \cdot 10^{18}$ eV	$E_{\text{fl}} \sim 5 \cdot 10^{17}$ eV		
Number of events with $E > 3 \cdot 10^{18}$ eV	~3000 for 1 year (2–3 months of flight)	~82300 for D_p, 1470 for D_{fl} (2%) for 9 years		
Number of the events with $E > 10^{19}$ eV	200–300 for 1 year	~8000 for D_p, ~145 for D_{fl} for 9 years		

D_p are ground-based charged particle detectors, D_{ch} are ground-based detectors of EAS Cherenkov light, D_{fl} are ground-based detectors of EAS fluorescent light; the setup operating time in the main mode is given.

When using fluorescence detectors, without which the analysis of the mass composition would be simply impossible, the detail of the analysis of the PCR energy spectrum shape and nuclear composition is limited by the effective measurement area smallness (~60 km^2).

For a two-three-month flight of the SPHERE-Antarctica setup, a two times larger number of events with energies above $3 \cdot 10^{18}$ eV can be detected, than by the Auger setup for 9 years of its operation. The estimate of ~3000 events per year was obtained under the assumption that the total spectrum has the form $N(> E) \sim E^{-2}$ in the energy region $> 10^{18}$ eV. Let us estimate the number of events which will be recorded by the SPHERE-Antarctica setup. We proceed from the fact that ~150 events with energies $\geq 10^{19}$ eV were recorded in the Auger experiment for 9 years. Taking into account the difference in areas, ~1000 and ~120 km^2, for the SPHERE-Antarctica and Auger, respectively, and the difference in measurement times over the year, ~20% and 13% [1], we obtain ~220 events per year.

At the Yakutsk setup, the EAS energy is determined by the shower Cherenkov light flux at a fixed distance from the shower axis (200–300 m). Taking into account the long distance between Cherenkov light detectors (~0.5 km), the error in the determination of the EAS zenith tilt angle, and the dependence of the calculated value on the EAS development model, the energy determination accuracy cannot be high. In [5], it is indicated that the spectral data obtained at the Yakutsk setup were renormalized to the Auger and TA data, and it is planned to upgrade the setup to improve the EAS energy determination accuracy. The area of this setup will be hundred times smaller than the SPHERE-Antarctica setup area.

Currently, the shapes of the energy spectrum measured in the Auger, TA, and Yakutsk experiments in the energy range of $(10^{18}–10^{19})$ eV are in poor agreement with each other. The data on mass composition are also contradictory.

The technique for measuring the PCR energy spectrum and mass composition in the energy range of $(10^{18}–10^{20})$ eV by recording the EAS cascade curve shape with simultaneous energy measurements using the calorimetric method by the total flux of EAS Cherenkov light, which is planned to be used in the SPHERE-Antarctica experiment, seems to be most adequate. The total Cherenkov light flux very weakly depends on the primary nucleus type. The determination accuracy of the EAS zenith arrival angle in the SPHERE-Antarctica experiment will be improved by recording not only the amplitude, but also the temporal structure of pulses and time intervals between pulses of EAS Cherenkov and fluorescent light.

The HiRes setup consisted of two ground-based optical detectors, spaced from each other by a distance of $\sim$12 km, and did not incorporate ground-based EAS charged particle detectors. Both optical detectors independently recorded EAS fluorescent light, some events were recorded simultaneously by both detectors. By the results of processing of such events, an EAS spectrum to energies of $\sim 6 \cdot 10^{17}$ eV was constructed. By results of processing of all events detected by at least one of detectors, the spectrum to energies of $\sim 3 \cdot 10^{19}$ eV was constructed. The determination accuracy of the depth of the EAS maximum in the atmosphere was $\sim$50 g$\cdot$cm^{-2} [13].

In the energy region above 10^{19} eV, the data of all four setups (Auger, TA, Yakutsk, and HiRes) are in poor agreement.

The advantages of the SPHERE-Antarctica setup over the HiRes setup are as follows.

(i) The thinner atmospheric layer from the EAS trajectory to the detector.

(ii) Purer air from the EAS trajectory to the detector.

(iii) Simultaneous recording of EAS fluorescence and total Cherenkov light flux, which improves the determination accuracy of the shower energy and records the intersection point of the fluorescent trajectory and the Earth's surface, which improves the determination accuracy of the depth of the EAS maximum.

In 2016–2017, it is planned to launch the JEM-EUSO orbital station intended for measuring the PCR energy spectrum and mass composition in the energy range of $(10^{18}–10^{20})$ eV. The orbit altitude is 350–400 km, the optical system diameter is 2.1 m, the viewing angle is $\pm 30°$, the number of pixels on the focal surface is $3.2 \cdot 10^5$, the length of the EAS fluorescent light region seen by one pixel near sea level is $\sim$550 m. The angular resolution of each pixel is 0.07°.

The calculations and the results of measurements of the Tatiana satellite [11] showed that the time fraction efficient for measurements, determined by alternation of day and night, moonlight, and clouds, is 0.12 of day. In this regard, it was believed that the presence of clouds in the layer below 3 km will not affect the possibility of measuring the depth of the EAS development maximum. It was believed that the depth of the maximum is above 3 km in the entire energy range. According to the calculations [11], the determination accuracy of the EAS energy is 30%, and the measurement accuracy of the depth of the EAS development maximum is 120 g/cm^2. The light detector sensitivity range is (330–400) nm. It was accepted that measurements can be performed if the moonlight brightness does not exceed 500 photon$\cdot$m$^{-2}\cdot$ns^{-1}.

Let us compare characteristics of the SPHERE-Antarctica and JEM-EUSO setups. The energy threshold range for measuring EAS fluorescent light for the JEM-EUSO is $(1-3) \cdot 10^{19}$ eV which is several times higher than the threshold of the SPHERE-Antarctica setup for measuring EAS fluorescent light and several tens of times higher than the threshold of the SPHERE-Antarctica setup for measuring EAS Cherenkov light. The JEM-EUSO setup cannot record Cherenkov light somewhat accurately.

The possibility of studying the mass PCR composition using the JEM-EUSO setup is questionable in connection with the low determination accuracy of the depth of the EAS maximum ($\sim$120 g/cm^2).

The SPHERE-Antarctica setup will determine the depth of the maximum with much better accuracy due to Cherenkov light recording simultaneously with fluorescent light in each shower. Simultaneous recording of the EAS fluorescent track and Cherenkov light reflected from the surface makes it possible to study the PCR flux anisotropy in the energy range of $(10^{18}-10^{20})$ eV.

An advantage of the JEM-EUSO setup is that the effective EAS measurement area is hundred times higher, than that of the SPHERE-Antarctica setup. In the case of launching two-three setups per year, this difference can be decreased to one and a half orders of magnitude. It is not improbable that it will become possible to obtain data in the energy range of $(10^{18}-10^{21})$ eV as well.

In any case, the SPHERE-Antarctica project implementation will become a good connecting link between the Auger, TA, Yakutsk, and JEM-EUSO setups.

5. Light absorption in the atmosphere. The fraction of light reaching the Earth's surface after vertical passing through the entire atmospheric layer is e^{-K}, where K is the extinction coefficient including light absorption and scattering. The quantity K depends on the light wavelength λ (see Table 2 [14]).

The fluorescent light spectrum consists of several lines in the range from 300 to 450 μm. The average fluorescent light absorption and scattering loss in the atmosphere is $\sim$0.3.

Table 2. Dependence of light absorption parameters on the wavelength [14]

λ, nm	K	e^{-K}	$1-e^{-K}$
300	0.058	0.05	0.95
360	0.57	0.57	0.43
400	0.36	0.70	0.30
500	0.15	0.86	0.14
550	0.098	0.91	0.09

The Cherenkov light spectrum extends to the deep infrared as $\sim E^{-3}$. The average effective loss for Cherenkov light reflection from the snow surface is $\sim$0.14. Taking into account that Cherenkov light passes through the atmosphere, the loss will be also $\sim$0.30. As a result, the correction to the calculated thresholds for both Cherenkov and fluorescent light is $\sim$30%. This correction is insignificant, since the main objective of the experiment is the study of the PCR energy spectrum and mass composition in the energy region $\geq 10^{18}$ eV.

Conclusions. The proposed miniature balloon setup will make it possible to obtain more accurate data on the energy spectrum in the energy range of $(10^{18}-10^{20})$ eV and mass composition of PCR in this energy range. A similar experiment with much bulky and heavy equipment was planned previously [12], but was not implemented because of objective factors. In the case of sufficient financing, two or three units of the SPHERE-Antarctica setup can be launched.

REFERENCES

1. M. Unger and E. J. Ahn, "Inferences about the Mass Composition of Cosmic Rays from Data on the Depth of Maximum at the Auger Observatory," in *Proceedings of the 33rd International Cosmic Ray Conference, Rio de Janeiro, 2013*; http://www.cbpf.br/ icrc2013/papers/icrc2013-0690.pdf.
2. A. Schulz, "The measurement of the Energy Spectrum of Cosmic Rays above $3 \cdot 10^{17}$ eV with the Pierre Auger Observatory," in *Proceedings of the 33rd International Cosmic Ray Conference, Rio de Janeiro, 2013*; http://www.cbpf.br/ icrc2013/papers/icrc2013-0769.pdf.
3. Y. Tsunesada, "Collaboration for The Telescope Array. Telescope Array Composition Measurements," in *Proceedings of the 33rd International Cosmic Ray Conference, Rio de Janeiro, 2013*; http://www.cbpf.br/ icrc2013/papers/icrc2013-0132.pdf.
4. D. Bergman, "Collaboration for The TA/TALE. Telescope Array Measurements of the UHECR Energy Spectrum," in *Proceedings of the 33rd International Cosmic Ray Conference, Rio de Janeiro, 2013*; http://www.cbpf.br/ icrc2013/papers/icrc2013-0221.pdf.

5. A. Ivanov, "The Yakutsk Array Experiment: Main Results and Future Directions," EPJ Web of Conferences **53**, 04003 (2013); URL: http://dx.doi.org/10.1051/epjconf/20135304003.
6. A. E. Chudakov, in *Proceedings of the 5th Interamerican Symposium on Cosmic Rays, Vol. 2* (Laboratorio de Fizica Cosmica de la Univ. Mayor de San Andres, La Paz, Bolivia, 1962), p. 44.
7. A. E. Chudakov, "Possible Method for Recording EASs by Cherenkov Radiation Reflected from the Snowed Earth's surface," *Experimental Methods for Studying Ultrahigh-Energy Cosmic Rays. Proceedings of the All-Union Symposium, Yakutsk, 1972* (Yakutsk Branch, Siberian Branch of the Academy of Sciences of the USSR, 1974), pp. 69–74.
8. K. K. Chuvaev, Dokl. Akad. Nauk SSSR **87**, 551 (1952).
9. F. E. Roach and J. L. Gordon, *The Light of the Night Sky* (Reidel, Dordrecht 1973; Mir, Moscow, 1977).
10. M. Bott-Bodenhausen, I. Holl, A. Kabelchaht, et al., Nuclear Instrum. Methods Phys. Res. A **315**, 247 (1992).
11. "The JEM-EUSO Mission: Status and Prospects," in *Proceedings of the 32nd International Cosmic Ray Conference, Beijing, 2011* (IHEP Chinese Acad. Sci., Beijing, 2011); URL: http://arxiv.org/abs/1204.5065.
12. R. A. Antonov, D. V. Chernov, L. A. Kuzmichev, et al., "Antarctic Balloon-Borne Measurements of the CR Spectrum above eV (project)," in *Proceedings of the 27th International Cosmic Ray Conference, Hamburg, Germany, 2001* (Copernicus Gesellschaft, Katlenburg-Lindau, 2001), Vol. 2, pp. 828–831.
13. R. U. Abbasi, T. Abu-Zayyad, G. Archbold, et al., Astrophys. J. **622**, 910 (2005).
14. Yu. M. Timofeev and A. V. Vasil'ev, *Fundamentals of Theoretical Atmospheric Optics* (Physical Faculty, St.Petersburg State University, 2007) [in Russian].