Cosmic rays and radioactivity in the near-ground level of the atmosphere

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Abstract. Since 1957 the Lebedev Physical Institute has been performing observations of ionizing radiation in the atmosphere from the ground level up to the height of 30-35 km. The time series of charged particle fluxes in the near-ground levels of the atmosphere at polar latitudes and at mid-latitude obtained in the course of the experiment are presented. The measured fluxes include cosmic ray particles and radioactivity. Over the solid ground radioactivity is observed up to the heights of \( \approx 3 \) km. Over the sea surface radioactivity level is several times less than over the solid ground. It seems that above the ground surface up to \( \approx 1.5 \) km there is a contribution from the cosmic ray air-soil transition effect.

1. Introduction
The long-term observations of charged particle fluxes in the atmosphere conducted by the Lebedev Physical Institute (LPI) of the Russian Academy of Sciences yield the behavior of secondary cosmic rays at different altitudes (residual atmospheric pressure) and latitudes versus time [1]. Galactic cosmic rays (GCRs) impinge upon the Earth’s atmosphere and create the cascades of secondary particles while interacting with the air nuclei. Geomagnetic field and the atmosphere are the energy analyzers of particles: higher energy is required to access the lower latitudes as well as primary particles of higher energy provide the particle fluxes at lower layers of the atmosphere. Time series of charged particle fluxes at altitudes \( H \) above \( \approx 20 \) km (residual atmospheric pressure \( X = 55 \) g/cm\(^2\)) correlate very well with the GCRs arriving at the same latitude (correlation coefficient with the neutron monitor data \( r = 0.98 \)), but this correlation decreases with increase of \( X \). At \( H \) below \( \approx 3 \) km \( r \leq 0.2 \). That means influence of atmospheric factors and natural radioactivity on the ionization in the lower atmosphere. Monte-Carlo simulations of particle fluxes [2, 3] reproduce fairly well the observed values at altitudes between 4 and 22 km, but predict significantly lower fluxes in the near-ground level [4]. It is rather expected since calculations do not take into account a soil radioactivity available in the near-ground air layer. However, the discrepancy is also kept in the data of Antarctic measurements where the radioactivity should be depressed by the ice cover. The aim of this work is to analyze the observational data available and to attempt to separate contributions of secondary cosmic rays and radioactivity. We focus on the atmospheric depth \( X > 700 \) g/cm\(^2\) (\( H < 3 \) km).

2. Observations
A standard particle detector consists of 2 Geiger tubes arranged as a telescope with a 2 g/cm\(^2\) Al filter in between. A radio transmitter returns count rates of an upper omnidirectional counter (hereafter a single counter) and of a telescope while lifting into the atmosphere by the small balloons. A single
counter is sensitive to > 5 MeV protons, > 200 keV electrons, and > 1 MeV muons while for a telescope the energy thresholds are 30 MeV, 5 MeV, and 15.5 MeV, respectively. The detectors are carefully calibrated using several control groups of counters to maintain the homogeneity of the data time series. More than 83,000 of radiosounds were launched at several latitudes since the IGY (1957).

A Geiger tube has an intrinsic background that should be accounted for in the near ground observations where the radiosound count rate is rather low. A self-background was estimated by several approaches including underground experiments. The different estimations range from 4 to 7 pulses per minute. Here we take a self-background value as 6 pulses per min and remove it from a single counter data. It should be emphasized that the data of telescopes are free from the intrinsic background and radioactivity contribution. Radioactivity is low over the oceans and in the Antarctic.

This work employs the data of following observations:

1. several times a week balloon launching at Murmansk (geomagnetic cutoff \( Rc = 0.6 \) GV), Moscow (\( Rc = 2.4 \) GV) during 1957-2011, and Mirny (Antarctica, \( Rc = 0.03 \) GV) during 1963-2011; on-ground pre-flight calibration of detectors at the same sites;

2. (latitude sea survey on the way from Leningrad to the Antarctic with the same devices undertaken in 1987 [5]; more than 300 radiosounds were launched from the ship board;

3. high precision measurements with a balloon-borne instrument B1 consisting of 240 Geiger tubes of the same type (high-latitude Arkhangelsk and mid-latitude Saratov regions) [6].

Figure 1 shows the particle flux time series as observed by a single counter at polar (Murmansk region) and mid-latitude (Moscow region) for the stratosphere and the troposphere altitudes. An 11-year modulation is clearly seen in the stratosphere. An average magnitude of the 11-year cycle in CR was defined as \( \langle A \rangle = 200 (J_{max} - J_{min}) / (J_{max} + J_{min}) \), %, where \( J_{max} \) is averaged CR fluxes in the years 1965, 1977, 1987, 1996, and 2009, while \( J_{min} \) is the averaged CR fluxes in 1958, 1970, 1982, 1990, 2000. At altitude above 25 km \( \langle A \rangle = 44\% \) and \( 29\% \) for \( Rc = 0.6 \) GV and \( Rc = 2.4 \) GV, respectively. An 11-year cycle is not so pronounced at altitudes of 3-4 km, with magnitude about 8% at both latitudes. Figure proves that an 11-year cycle below 3 km is masked by other variations.

Figure 1. Charged particle fluxes in the atmosphere of polar and mid-latitudes. Blue symbols stand for Murmansk (\( Rc = 0.6 \) GV), and red ones, for Moscow (\( Rc = 2.4 \) GV). Left panel: altitudes above 25 km; right panel: altitudes 3-4 km (full symbols) and below 3 km (open symbols).

To focus on composition of charged particle fluxes at altitudes below ~3 km we averaged the data at Murmansk, Moscow, and Mirny for the whole period of observations (> 50 years). Between \( X = 700 \) and 900 g/cm\(^2\) (down to \( H = 1-3 \) km) the results of observations at different sites coincide with the sea survey data. The latter were averaged at all latitudes since latitudinal effect at heights below 3 km is within observational uncertainty. At lower altitudes the fluxes increase toward the earth surface which is due to the local radioactivity contribution which is especially clear at observations with high statistics (Arkhangelsk and Saratov). A telescope is not sensitive to radioactivity. The results at all sites of observations but in the sea expedition are in agreement with each other and with the data of the pre-flight calibration. This can be used for reconstruction of omnidirectional fluxes of secondary CRs. A ratio of the fluxes as measured by a single counter and a telescope \( R \) depends on the particle energy spectrum and their angular distribution. Deep in the atmosphere the cascades of secondary CRs are just absorbed and the energy spectrum is equilibrium [7]. According to [5] the angular distribution of charged particles in the atmosphere below ~400 g/cm\(^2\).
does not change. Actually, both statements are not strictly correct since $R$ slightly decreases with altitude at $X = 550-750$ g/cm$^2$ and can be fitted as $R = 1.27E-3X + 4.77$. It is reasonable to expect that this dependence would not change if there is no contribution from radioactivity. Then we can use this dependence to find single counter records due to secondary CRs (i.e. omnidirectional fluxes of secondary CRs) using the telescope observational data.

The data of pre-flight detector calibration were used to estimate local radioactivity. Interpolation to the ground level yields $R = 3.46 \pm 0.06$. Multiplication of the telescope data by this value and subtraction from the counter data gives radioactivity. Figure 2 presents temporal variations of the local radioactivity which strongly depends on the site of observation being the highest at Moscow region. The annual variation is connected to the seasonal snow cover, which prevents the radon exhalation. At Murmansk region, the sudden increase of annual waves occurred in 2001 when a radio receiver was transferred to a new location, 60 km southward. A certain effect of the Chernobyl disaster can be seen at Murmansk and Moscow in 1986, but there is no effect from the Fukushima reactor accident in 2011. In Antarctica, radioactivity is very low as was expected. Assuming the isotropic angular distribution of natural radioactivity the mean values of particle fluxes are estimated as $\sim 0.029$ cm$^{-2}$s$^{-1}$, $\sim 0.019$ cm$^{-2}$s$^{-1}$, and $\sim 0.0013$ cm$^{-2}$s$^{-1}$ for Moscow, Murmansk, and Mirny respectively.

![Figure 2](image-url) Figure 2. The count rates of a single counter due to local radioactivity at Moscow (red), Murmansk (blue) and Mirny, Antarctica (green). Occasional negative values at Antarctica result from uncertainties of observation and analysis.

3. Composition of ionizing radiation in the near-ground atmosphere

Figure 3 demonstrates the omnidirectional charged particle fluxes in the near-ground atmosphere. The results of observations in the atmosphere at Murmansk, Moscow and Mirny are supplemented by the observations on the ground level. The blue curve presents omnidirectional particle flux reconstructed from the averaged telescope data. We believe that this curve gives the real secondary CR fluxes. It is consistent with fluxes taken from single counters down to $X \sim 800$ g/cm$^2$ (height 2 km). Below a contribution to single counters from radioactivity is seen, especially in the results of high-precision measurements at Arkhangelsk and Saratov. The results of GEANT4 calculations are shown by the solid black [2] and grey [3] curves. Both curves are lower than the CR curve at $X > 850$ g/cm$^2$. The results of the sea survey are lower than CRs (blue curve) and more or less consistent with the expected from the GEANT4 simulations.

A possible explanation may be connected to the CR albedo from the ground due to transition effect at the air-ground boundary. The values of critical energy are 88 MeV for air, 79 MeV for water, and $\sim 40$ MeV for soil. Therefore, there is virtually no transition effect between the air and water leading to agreement of the sea survey results with calculations. These results are also free from radioactivity.
The transition effect exists at the air-ground boundary and contributes to the CR (blue) curve. It corresponds to a difference between CR curve and GEANT4 results.

![Graph showing atmospheric depth vs. flux](image1)

**Figure 3.** Omnidirectional particle fluxes vs. residual atmospheric depth. Blue curve is reconstructed from the telescopes flux, black and grey curves are GEANT4 results [2, 3].

![Graph showing composition of particle fluxes](image2)

**Figure 4.** Composition of particle fluxes in the near-ground level: secondary CRs (blue, left scale); right scale: albedo (brown), radioactivity (symbols as in figure 3).

### 4. Conclusion
Analysis of the results of more than 50 year observations of charged particles in the atmosphere supplemented by the results of the pre-flight calibration argues that the charged particle fluxes in the near-ground level consist of secondary cosmic rays, local radioactivity, and albedo particles due to transition effect at the air-soil boundary. The albedo is absent over the sea surface because of close values of critical energy in air and water. The particle composition is shown in figure 4. Cosmic ray fluxes are steadily decreasing downward and make ~0.03 cm$^{-2}$s$^{-1}$ at a sea level. Radioactivity contribution is noticeable below ~3 km. It strongly depends on location and is rather variable. Radioactivity is very low if any near the sea surface and at Mirny (Antarctica). Albedo flux is not more than ~10% of the CR flux at the air-soil boundary and absent at the air-water boundary. Further clarification will be directed to more accurate estimate of the value of intrinsic counter background.

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