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High-energy photons connected to atmospheric precipitations

A. V. Germanenko, Yu. V. Balabin, E. V. Vashenyuk, B. B. Gvozdevsky, and L. I. Schur

Polar Geophysical Institute, KSC RAS, Murmansk, Russia

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Abstract. Increases in intensity of X-radiation in the ground layer of the atmosphere observed during various atmospheric phenomena in two points: Apatity (Kola Peninsula) and Barentsburg (Spitsbergen) have been studied. A clear relationship between the increases and such atmospheric phenomena as rain and snowfall has been found. It is shown that these increases are not connected with any radionuclides. This research suggests that the principal cause of high-energy photons increase during precipitations are bremsstrahlung $X-$rays created by energetic electrons accelerated by electric fields in the clouds. A possible mechanism of generation of $X-$ray photons is discussed.

1 Introduction

The existence of excess radiation associated with thunderstorms is a known fact (Alexeenko et al., 2002; Mendoca et al., 2010; Chilingaryan et al., 2010). It was shown that the main cause of the excess radiation during thunderstorms is the particles accelerated by strong electric fields within thunderclouds (Alexeenko et al., 2002; Mendoca et al., 2010).

Another very interesting phenomenon, related with generation of energetic particles by thunderstorm clouds, are "Terrestrial gamma-flashes" or TGF events (Grefenstette et al., 2009). Short bursts of energetic gamma-ray quanta are observed above thunderstorm clouds during discharges between a cloud and an ionosphere. TGF events are interesting to us in connection with the developed theory of acceleration of charged particles in a discharge (Lehtinen et al., 1997) at the presence of so-called runaway electrons (Gurevich and Milikh, 1992). However, energetic photons studied in the given work do not originate in thunderstorms, but in "quiet" rain clouds.

We organized monitoring of low-energy gamma ($X-$ray) radiations on the ground level and recorded increases, usually associated with precipitations. It should be noted that in the subarctic (Apatity, Murmansk region) and arctic (Barentsburg, Spitsbergen) areas, where the observations were made, thunderstorms are observed extremely seldom. Nevertheless, as the cause of the increases associated with precipitations, we assume the electric field of the clouds (though not as strong as in thunderstorm clouds), which accelerates electrons and creates the bremsstrahlung radiation penetrating to the ground level.

2 Instrumentation

To monitor gamma ($X-$ray)-background at the ground level in Apatity and Barentsburg, we used the scintillation spectrometer based on the NaI(Tl) crystal of 6 cm in diameter and 2 cm thick. The signal after the photomultiplier and the amplifier is continuously recorded in 4 integral channels with a threshold photon energies $> 20, > 60, > 100$ and > 200 KeV. Detection in integral channels allows us continuous estimation of the integral spectrum of high energy photons. Besides it, the spectrometer in Apatity is equipped with the 4096-channel pulse-height analyzer V4K-SATSP-USB, based on the high-speed spectrometric ADC. It allows us to produce accurate measurements of the energy spectrum.

The instrumental complex in Apatity includes also the second NaI(Tl) spectrometer for the check experiments, a detector of charged particles, temperature and pressure sensors, and a precipitation gauge. All these instruments are installed at the loft right under the 1 mm thick iron sheet roof. The NaI(Tl) detector is surrounded along the sides and bottom by lead bricks 50 mm thick to shield them from the surrounding radiation from building walls and the ground.

Correspondence to: A. V. Germanenko
(germanenko@pgia.ru)

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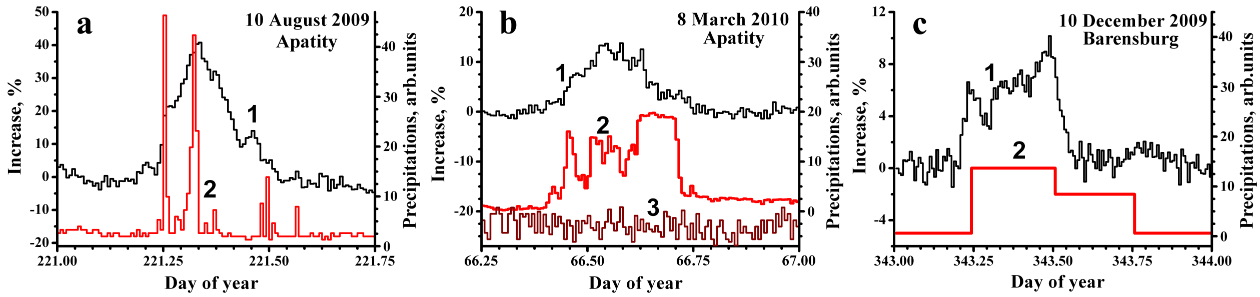

Fig. 1. Typical events of $X-$ray increases (black lines, 1) related to precipitations (red lines, 2). **(a)** rainfall event of 10.08.2009 in Apatity; **(b)** snowfall event of 8.03.2010 in Apatity, 3 is the Geiger telescope channel; **(c)** snowfall event of 10.12.2009 in Barentsburg, Spitsbergen.

The precipitation gauge allows us to evaluate the intensity of precipitation in the form of rain and snow. The principle of its operation includes the measuring of intensity of the scattered back on particles of precipitation radiation from the infrared source. The instrument is not calibrated and thus allows identifying only the presence of precipitations and qualitative estimation of their intensity. Therefore, the intensity of precipitations in the paper is given in arbitrary units.

The detector of charged particles was installed in Apatity in 2010. The instrument consists of eight upper and eight lower rows of Geiger counter tubes (1.9 cm diameter and a 9.8 cm length) separated by aluminum absorber with a thickness of 7 mm. The effective area of these rows is 160 cm^2. Three data channels are recorded: total count rates of the 1) upper and 2) lower counter rows and 3) total count rate in coincidence between the upper and lower layer (number of particles which cross simultaneously upper and lower counters and aluminum absorber between them). The upper and lower counter layers are sensitive to electrons > 0.2 MeV, protons > 5 MeV and gamma rays with energy > 20 KeV (with a detection efficiency of less than 1%). The coincidence signal detects mainly electrons with energies > 5 MeV, protons > 30 MeV and muons with energies > 20 MeV. Secondary muons are the main contribution to the third-channel record, while the first and second channels detect mainly the electronphoton component of secondary cosmic rays.

The instrumental complex in Apatity includes also two neutron monitors: one of the standard type: 18 NM-64, and a lead-free section consisting of 4 neutron-sensitive counter tubes.

In Barentsburg the NaI(Tl) detector is installed indoors next to the neutron monitor. The detector is placed inside the cylindrical steel "cup" with a wall thickness of 8 mm, which allows registration of arriving $X-$rays from the top hemisphere only.

In Apatity and Barentsburg the $X-$ray registering instruments have been connected to the data collection systems of neutron monitors at these stations. The data of spectrometers are continuously registered together with the data of neutron monitors with a periodicity of 1 time per minute.

3 Observations

Continuous monitoring using gamma spectrometers in Apatity and Barentsburg was started in the summer-autumn period of 2009. During the observations, we detected sporadic increases in the intensity of $X-$ray radiation. It was also noted that the increase events were almost always accompanied by intense precipitations, with dense and low altitude ($200-600$ m) cloudiness, so called "nimbostratus clouds", data on http://rp5.ru/1122/ru.

Figure 1 shows typical profiles of the count rate increase in the $X-$ray channel > 20 keV and precipitations for the Apatity and Barentsburg stations. A good correlation between the strengthening of rain and increases of the $X-$ray intensity in Apatity is seen in Fig. 1**(a)**. Similarly, a good correlation is observed between the $X-$ray increase and snowfall in Apatity, Fig. 1**(b)**. Curve 3 is the data of Geiger telescope channel which doesn't show any increase. It can specify lack of charged particles in the event, connected to precipitations.

The effectiveness of the Geiger counter for charged particles is close to 100%, and for gamma rays it is of the order of 1%. Thus, the channel of coincidences registers from 100% effectiveness charged particles and is completely unreceptive to gamma radiation.

Figure 1**(c)** shows the typical profiles of > 20 keV $X-$ray increase and the precipitations (snowfall) for the station Barentsburg. Unfortunately, the precipitation data were available to us only from local weather stations averaged over 3 h [http://meteocenter.net/20107_fact.htm], but still the link between the $X-$ray increase and a period of snowfall is seen.

There were 99 $X-$ray increase events observed from June 2009 to April 2010. The intensity increased from 5 to 45% of the background and duration of an increase varied from one hour to two days. 97% of these events were accompanied by precipitations of varying duration and intensity. The amplitude of increases differs for different seasons. In winter the amplitude of increases was on the average less and there was not fixed any increase greater than 25%.

In addition, the connection of the type of precipitation with the increase amplitude was noted. Fine, dry snow with the wind (blizzard) or permanent drizzling rain was rarely accompanied by an increase. Most of the increase events were accompanied by heavy rains or snowfall with no strong wind.

During 2010 in Apatity, only 3 thunderstorms in the summer season were observed. Increases of photons in these thunderstorms were small, $< 5-10\%$, which is quite low for the summer season. The low bound of cumulus clouds in these thunderstorms exceeded 1000 m (http://rp5.ru/1122/ru), that we consider a reason why $X-$ray increases were so small.

4 Check experiments

For clearing up the nature of increases observed on detectors NaI(Tl), it was required to carry out a series of additional checking experiments.

4.1 Estimation of an upper limit of $X-$rays energy

We carried out measuring with the second identical NaI(Tl) spectrometer in Apatity covered totally from different directions with lead bricks by width of 5 cm. It did not register any effect during the increases on the main spectrometer. Thus, the maximum energy of the photons causing increases during precipitations does not exceed unities of MeV. Otherwise, we would have observed any increase on the detector covered by lead.

4.2 Lack of radon contamination

There is a radioactivity in the atmosphere which is formed by decay products of radon and other natural and anthropogenic radionuclides. We needed to be convinced that increases on gamma-ray spectrometers are not linked to washout with precipitation of any radioactivity from the atmosphere. It is known, for example, that rain scavenges radon progenies efficiently and they also emit gamma radiation in the energy range of hundreds keV. A source of radon in the atmosphere is the earth's crust. In the winter season, this radon source in Apatity and Barentsburg does not operate. The upper layer of ground is frozen and the width of the layer of snow covering ground exceeds 1 m. Nevertheless, increases of $X-$rays during precipitation in the winter season are observed with the same effectiveness as in the summer (Fig. 1**(b)** and **(c)**).

4.3 Lack of radioactive contamination in the rain-water

For checking the connection of effect described here with a radioactivity of atmospheric precipitations, we have used the data of the regional laboratory of radiochemical control. This laboratory carries out regular measurements of all radionuclides, both natural, and an anthropogenic origin for the last few years. Weekly samples of precipitations (all amount of precipitation, collected for a week) are analyzed. We compared the weekly records of radioactivity in precipitations in Apatity with increases on our gamma-spectrometer. There is no regular connection of occasional radioactivity enhancements with increase events detected by our gamma-spectrometer and which we attributed to the $X-$ray bremsstrahlung events.

In several cases of considerable $X-$ray increases, the samples of precipitations in the form of rain and snow have been collected and analyzed with radiochemical methods.

Here we consider results of the test of the collected rainwater in the event on 10 October 2010, when an increase of about 25% was observed.

The gamma-spectrometric analysis of 2 l collected rain water has shown the usual presence of the natural and induced radio nuclides. Namely: the trace amount is registered of natural radionuclides of series ^{232}Th and ^{238}U, daughter products of their decay (^{226}Ra, ^{212,214}Pb, ^{212,214}Bi, etc.), ^{40}K, ^{7}Be and anthropogenic radionuclide ^{137}Cs. By "trace" we mean that it is much less than normalized value for potable water. And it is quite unlikely that it could cause the $X-$ray increases registered.

The detected total specific alpha-activity, 0.0002 Bk/l, is more than 2 orders of magnitude lower than the normalized value for potable water (0.2 Bk/l). The total specific beta-activity is of an order of magnitude lower than the normalized value for potable water (1 Bk/l).

4.4 Lack of charged component

The scintillation detector NaI(Tl) of a gamma-spectrometer is sensitive both to the electromagnetic component of radiation and to the charged one. Clarifying the relative contribution of the charged component of radiation to the increases detected by a spectrometer is possible with the help of a charged particle detector based on Geiger counters. It is known that effectiveness of these counters with regard to the charged component of radiation is two orders of magnitude higher than to gamma-ray quanta. Connection of two layers of counters on coincidence, as described in Sect. 2, ensures detecting the charged component of radiation only. In Fig. 1**(b)** an example is shown of joint registration by these two detectors during an increase event on 8 March 2010. There are no charged components (electrons and muons) in the radiation causing the increase on the NaI(Tl) detector.

5 Discussion

As it was shown above, the increases in the count rate of the gamma-ray spectrometers during precipitations are not related with radioactivity of the atmosphere, including radon. They also are not caused by charged particles. Increases should be caused by photons whose upper energy limit is less than 1 MeV. The probable source of these particles is the $X-$ray bremsstrahlung produced by electrons accelerated in a rain (snowfall) cloud. Near the Earth's surface the

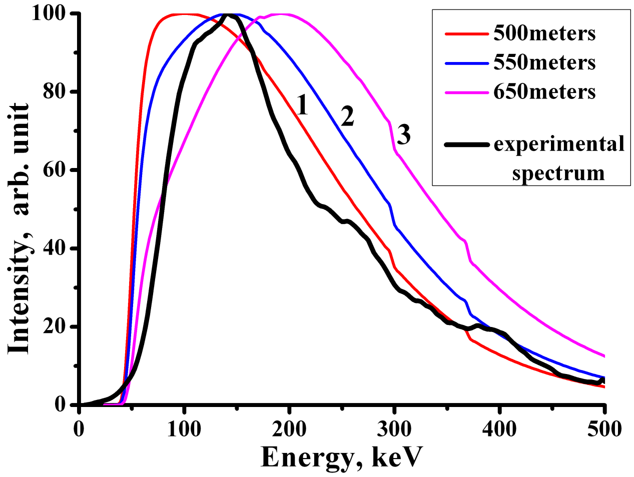

Fig. 2. Comparison of model spectra (color curves) with the experimental one (black line).

electric field in quiet weather is about 100 V/m. Inside the rain clouds the electric field strength is much higher and may reach kilovolts per meter and even tens of kV/m (Rust and Trapp, 2002). This is enough to accelerate electrons up to the energies sufficient to produce $X-$ray radiation, which can reach terrestrial surface and cause appreciable increases in the count rate of the gamma - detectors.

The intensity of the photons is determined by the generation of energetic electrons and positrons in the form of bremsstrahlung and the alternative process of absorption in the air. When passing through the matter, the electron loses energy due to ionization and radiation losses. In our low-energy energy domain ($E_e < 1\,\mathrm{MeV}$) a decisive contribution to the energy losses gives the ionization process. Radiation losses become significant at much higher energies (Lazutin, 1986).

6 Spectra of increases and interpretation of experimental data

At the instrumental complex in Apatity we also obtained energy spectra of photons during increases with the help of the 4096-channel pulse-height analyzer. The calibration of the spectrometer was carried out with the help of radioactive gamma-sources ^{241}Am (lines of 26 and 60 KeV) and ^{137}Cs (662 KeV). The spectrum of photons causing an increase was obtained by a subtraction from the measured spectrum during the increase of a spectrum of a quiet background before the increase. In Fig. 2 by a thick line is shown one of the experimental spectra obtained in the event on 8 March 2010 (Fig. 1**(b)**). The spectrum has a gradual form. There are not narrow peaks characters for lines of radionuclides.

We tried to simulate the observed $X-$ray spectra in the frames of our above suggestion about the bremsstrahlung origin.

The energy spectrum of electrons in the energy range ($E < 1\,\mathrm{MeV}$) can be approximated by an exponential law (Lazutin, 1986).

$$\frac{dN(E)}{dE} = N_0 \cdot e^{-E/E_0}, \qquad (1)$$

where E_0 is characteristic energy, which varies in the range from tens to hundreds keV.

At simulation we use expressions for conversion of an electron flux in a $X-$ray bremsstrahlung in view of simultaneous losses on ionization in air.

$$\frac{dN(h\nu)}{d(h\nu)} = \alpha^{\log_2 \frac{E_0}{5}} \cdot \rho \cdot \left(\frac{h\nu}{E_0}\right)^{-\frac{3}{2}} \cdot \frac{dN_e}{dE} \qquad (2)$$

where $\frac{dN(h\nu)}{d(h\nu)}$ is spectrum of photons for a given electron spectrum with an exponent E_0, $\alpha = 1.63$, $\rho = 3.48 \cdot 10^{-4}$.

It should be noted that the one must account for effects of absorption in the air of both electrons and produced by them $X-$ray photons. Due to the strong absorption of electrons with energies of tens or hundreds KeV in the air, it is expected that only particles produced no higher than $300-600$ m can reach the ground level. This is also confirmed by the fact that almost all registered increases we observed in the overcast with the lower edge of the clouds from $200-600$ m. We obtain the expression that describes the spectrum of $X-$ray radiation at the Earth's surface after accounting for losses due to absorption of both electrons and gamma rays:

$$N(h\nu) = \int_0^l \Bigg[\exp(\mu(h\nu)\cdot(l-x)) \cdot \int_{h\nu}^{\infty} Q(E,h\nu)\cdot \exp\left(-\frac{E}{E_0} + (k\cdot x)\right) dE \Bigg] dx, \qquad (3)$$

where:
l is height of generation of accelerated electrons.
μ is linear attenuation coefficient of gamma - radiation.
$Q(E,h\nu)$ is differential cross section of bremsstrahlung.
k is specific losses of electrons in the air (220 keV/m).

Calculations are made in the energy range of $X-$ray $h\nu$ from 0 to 1000 keV (step 4 keV) and for the heights of the generation of electrons from 100 to 1000 m (step 50 m). For the altitude of generation we accept the altitude of the lower edge of the clouds.

Figure 2 shows the results of model calculations according to formula (3) of the spectra of bremsstrahlung photons at the Earth's surface, produced by accelerated electrons in the atmosphere at height l for different values of this parameter from 500 to 650 m, which is suppose the lover edge of clouds.

A thick curve shows the spectrum of photons measured in the event of 8 March 2010 (Fig. 1**(b)**). It is evident that the measured spectrum agrees well with the model obtained for the generation altitude band of $500-550$ m with an integral exponential spectrum with $E_0 = 100$ keV.

It is necessary to note, that this value E_0 appeared to be optimal. At greater E_0 the spectrum is enriched with high energies and differs more from the observed one.

7 Conclusions

Continuous measuring (monitoring) by $X-$ray spectrometer in the atmospheric surface layer of the arctic (Spitsbergen archipelago) and subarctic (Apatity) regions discovered systematic relationships between increases in the low-energy gamma ($X-$ray) background and precipitation as rains and snowfalls at a low and dense cloudiness.

As the reason of $X-$ray increases the bremsstrahlung, $X-$ray radiation produced by electrons, accelerated in electric fields inside rain clouds, is suggested. The calculated $X-$ray spectrum obtained in the model assumptions, are in satisfactory agreement with the measurements.

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