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Long-term cosmic ray experiment in the atmosphere: energetic electron precipitation events during 20-23 solar activity cycles

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Abstract.
More than 400 energetic electron precipitation events (EPEs) were observed in the Earth's Northern polar atmosphere (Murmansk region, 68°57'N, 33°03'E) during a long-term cosmic ray balloon experiment (from 1957 up to now). It is shown that the significant X-ray fluxes, caused by precipitating electrons at the top of the atmosphere, sometimes penetrated down to the atmospheric depth of ~60 *g cm*$^{-2}$ (about 20 *km*). It means that primary energy of precipitating electrons was more than ~ 6 - 10 *MeV*. Here we summarize only the characteristics of the energetic electron precipitation events recorded during solar activity cycles 20 to 23. We discuss results from the analyses of the interplanetary and geomagnetic conditions related to these events in the atmosphere.

1 Introduction

A number of energetic electron precipitation events (EPEs) were observed in the Earth's polar atmosphere (Olenya, Murmansk region, geographical coordinates 68°57' *N*, 33°03' *E*, geomagnetic cutoff rigidity Rc=0.6 *GV* and McIlwain parameter *L*=5.6) during the long-term cosmic ray balloon experiment from 1957 up to now. In these events, which as a rule are associated with geomagnetic storms, significant X-ray fluxes caused by precipitating electrons at the top of the atmosphere sometimes penetrated to the atmospheric depth of ~ 60 *g cm*$^{-2}$ (altitude ~ 20 *km*). In previous papers (Bazilevskaya and Makhmutov, 1999; Makhmutov, et al., 2001) we showed that, first, there is a quasi-11-year cycle in EPE occurrence shifted with respect to solar activity cycle. Our result is in agreement with findings by Gonzales, et al. (1996) on the dual-peak solar cycle distribution of intense geomagnetic storms and low-latitude / geo-effective coronal holes. These coronal holes are the main sources of high speed solar wind streams during the solar cycle descending phases. Second, the yearly rate of EPE occurrence has an ascending trend during the period 1965-1999. There are, at least, two possible reasons concerning this result: (1) an increase of the solar activity level (e.g. Storini, 1995) and, in turn, an increase of the geomagnetic activity during this period (e.g. Vennerstroem, 2000) and/or (2) a long-term global geomagnetic field variation which could led to the 'displacement' of Olenya location in the geomagnetic field close to the auroral oval center. Our calculations of geomagnetic field parameters for Olenya, using the GEO-CGM code (ftp://nssdcftp.gsfc.nasa.gov/models/), for the epochs 1965 and 1995 are not contradicting the last point of view.

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In this paper the electron precipitation event characteristics, evaluated from the balloon experiment during 20-23rd solar activity cycles, are analysed in term of solar cycle variations. The available data on geomagnetic activity (*Dst* and *AE*-indices) and interplanetary medium parameters (*V, B, Bz*) are used in the analyses.

2 Experimental data

2.1 Bremsstrahlung photons absorption spectra in the atmosphere during the electron precipitation events

The balloon measurements were carried out with a standard detector consisting of two Geiger counters and an *Al* filter inserted between the counters (see for details Charakhchyan, 1961; Stozhkov, 1980; Bazilevskaya and Svirzhevskaya, 1998 and references therein). A single counter records the omnidirectional flux of charged particles: electrons with energy E_e>0.2 *MeV*, protons with energy E_p>5 *MeV* and is also sensitive to X-rays (E_{ph}>20 *keV*). In fact, during EPEs omnidirectional counter records the penetrated into the atmosphere bremsstrahlung photons, generated by the precipitating electrons at atmospheric altitudes 70-100 *km*. Some results of the evaluations of the primary energy spectra of precipitating electrons for selected EPEs measurements were presented earlier (Makhmutov, Bazilevskaya et al., 1995). Examples of some recent observations of EPEs in the atmosphere at Olenya on 28 and 29 September, 1999, and 5 May 2000 are shown in Figure 1. The figure displays the bremsstrahlung photons absorption spectra, i.e. the count rates of the omnidirectional counter (ΔN) due to the X - rays, vs. atmospheric depth (X). To evaluate these spectra a pre-EPE quiet time background caused by galactic cosmic rays is eliminated. The enhanced counting rate up to a few thousand per minute at atmospheric depths X below 10 $g\ cm^{-2}$ corresponds to the electron flux at the top of the atmosphere of $J(E_e>300\ keV)$ above $10^4\ cm^{-2}\cdot s^{-1}\cdot sr^{-1}$. For each electron precipitation event we approximated the dependence $\Delta N\ (X)$ as $\Delta N(X)=a\cdot X^m$. So, we determined the power-law index m, coefficient a and maximum atmospheric depth (X_{max}) down to which the X-rays were observed. There is a simple relation: the more the primary energy of precipitating electrons the more the energy of generated secondary photons and, in turn, the largest value of X_{max}. The result of photon absorption spectra parameters estimations

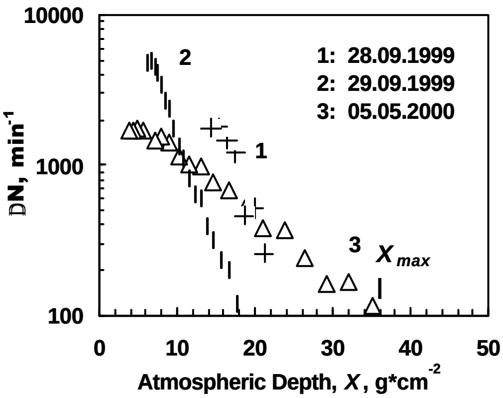

Fig.1. The bremsstrahlung photon absorption spectra: counting rate of the omnidirectional counter vs. atmospheric depth during the electron precipitation events on 28 Sep (08:14 - 08:32 UT), 29 Sep (08:19 - 09:10 UT) 1999, and 5 May (08:32 - 09:29 UT) 2000 as observed at Olenya (68°57' *N*, 33°03' *E*). The pre-EPE quiet time background counting rate is eliminated.

(i.e. the parameters X_{max}, and absolute values of m-indices, $|m\text{-}ind|$), for the EPEs observed during 1965-2000 is shown in Fig. 2. We choose this time interval because of availability both of interplanetary and geomagnetic data for the main part of EPEs. We note some features of the data presented: **(1)** a very wide distributions of X_{max} (10-60 $g\ cm^{-2}$) and $|m\text{-}ind|$ - values during the descending phases and years close to the minimum of solar activity cycles 20 to 22. It means that primary energy of incident electrons varied from a few tens *keV* up to (or more) ~ 6 - 10 *MeV* during these precipitation events at L=5.6; we suggest these events were mainly originated from geomagnetic disturbances caused by interaction of the high speed solar wind streams from solar coronal holes and Earth's magnetosphere; **(2)** an extended distribution of X_{max} is a peculiarity of the solar cycle 20 in comparison with that in cycle 21 and 22. This fact is in accordance with the distributions of geomagnetic storms with Dst <-50 nT in solar cycle 20 and 21 (Gonzales, et al., 1996).

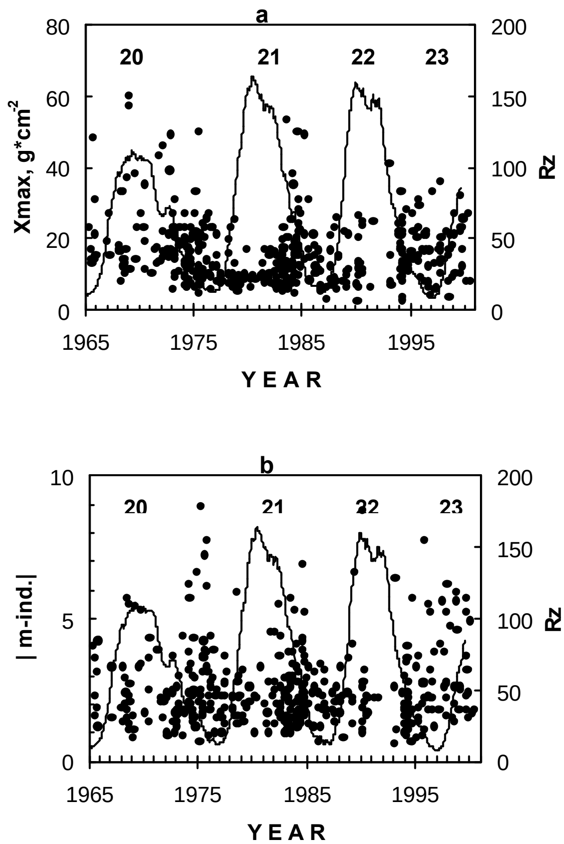

Fig.2 Yearly sunspot number (Rz, solid line, both panels), X_{max} (panel **a**) and absolute values of m-indices (panel **b**), characterizing EPEs observed in the atmosphere during the solar cycles 20-23rd.

Mean values of X_{max} and m-indices for each solar cycle are given in Table 1.

2.2 Interplanetary medium data

We used OMNI hourly interplanetary plasma data: average field magnitude (B), magnetic field component in GSM coordinate system (Bz) and solar wind velocity (V). These data, as well as geomagnetic indices, were obtained via INTERNET from http://nssdc.gsfc.nasa.gov/omniweb/ow.html site. For each EPE we determined hourly values of *B*, *Bz* and *V*, corresponding to the time of the EPE observation in the atmosphere. First, we tried to estimate correlations between *B, Bz, V* and parameters X_{max} and *m-ind*.. No simple correlations were found between interplanetary plasma data and characteristics of the observed EPEs. Second, we calculate the mean values of the selected interplanetary parameters and geomagnetic indices related to the observed EPEs, as well as the mean characteristics of these EPEs for each of the solar cycles 20-23, which are presented in Table 1. As a preliminary result we can stress out there is no significant difference in terms of these parameters between solar cycles under consideration. Figure 3 shows the distributions of the interplanetary parameters for the total period 1965-2000. It is seen that the electron precipitation in the atmosphere were observed, mainly

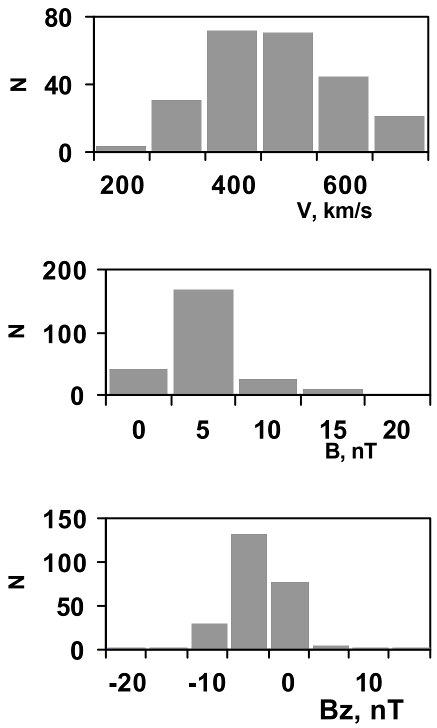

Fig. 3 Distributions of average solar wind velocity (*V*) , interplanetary magnetic field magnitude (*B*) and magnetic field component (*Bz*) during the EPEs observed in the atmosphere for the period 1965-2000.

when solar wind speed *V* was in the range 400-600 *km/s*, average magnetic field *B*=5-10 *nT* and GSM component *Bz*= -10–5 *nT*. Also, there are a number of events observed during the very disturbed periods, characterized by *V* ~ 800 *km/s*, *B* ~ 20 *nT*, *Bz* ~ 15 *nT* (sometimes *Bz* < -20 *nT*). It is important in the future to separate these disturbances, as well as the EPEs, by their solar/interplanetary origin, i.e. coronal hole, coronal mass ejection, interplanetary shock waves related to intense solar flares, etc.; i.e. to make a study similar to one performed for cosmic ray events by Iucci et al. (1988).

2.3 Geomagnetic indices

To characterize the geomagnetic conditions we used the available hourly planetary geomagnetic equatorial *Dst*-indices for the period 1965-2000, and auroral electrojet *AE*-index during 1965-1987. The mean values of these parameters for each solar cycle (**SC** 20 – **SC** 21/23) are listed in Table 1. No meaningful difference in the mean values of all parameters during the 4 solar cycles is found. The summary distributions of *Dst* and *AE* indices are shown in Figure 4. No a simple correlation between the two sets of parameters, geomagnetic and characteristics of the precipitation events, were found. Nevertheless, it should be pointed out that EPEs with X_{max}=10-30 $g\ cm^{-2}$ were observed during small, moderate and intense geomagnetic storms (*Dst* =0 – (-200) *nT*). Only during moderate and small storms (*Dst* > -50 *nT*, *AE* < 100 *nT*) bremsstrahlung photons

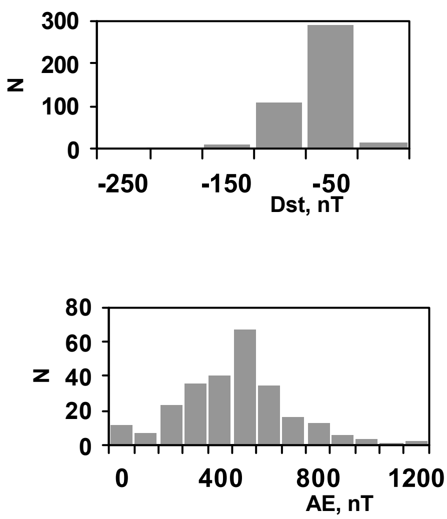

Fig. 4 Distributions of equatorial ring current index (*Dst*) for 1965-2000 period and auroral electrojet index (*AE*) for 1965-1987 period.

penetrate down to atmospheric depth *X*=40-60 $g\ cm^{-2}$. Such photons could be generated by precipitating electrons with energy more than ~ 6 - 10 *MeV*. During these events the hard photons absorption spectra (<*m*> ~ -2) were recorded in the atmosphere.

3 Conclusions

The results of the analyses here reported could be expressed as follows: **(1)** there is a very wide distribution of EPEs parameters (X_{max} =10-60 $g\ cm^{-2}$ and |*m-ind*|=1.5–8) during the descending phases and years close to the minimum of solar activity cycles 20-22;

(2) there is no a simple correlation between the sets of the considered parameters: interplanetary/geomagnetic and characteristics of the electron precipitation events observed in the atmosphere; **(3)** the EPEs with X_{max} =10-30 $g\ cm^{-2}$ were observed during small, moderate and intense geomagnetic storms (*Dst* = 0 – (-200) *nT*); **(4)** only during moderate and small storms (*Dst* > -50 *nT*, *AE* < 100 *nT*) bremsstrahlung photons penetrated down to atmospheric depth X=40-60 $g\ cm^{-2}$. Such photons could be generated by precipitating electrons with energy more than ~ 6 - 10 *MeV*. During these events the hard photons absorption spectra (<*m*> ~ -2) were recorded in the atmosphere;

Table 1. Mean values (**Mean**) and standard deviations (**STD**) of interplanetary medium parameters, geomagnetic indices and characteristics of EPEs observed in the atmosphere for each of the solar cycles 20-23 (N: number of selected events).

Solar Cycle	Parameter	Mean	STD
SC 20	*B, nT*	6.6	2.2
	Bz, nT	-1.6	3.1
N=89	*V, km/s*	559	124
	Dst, nT	-33	21
	AE, nT	510	201
	Xmax, g cm^{-2}	18.4	10.2
	m-ind.	-2.6	1.5
SC 21	*B, nT*	8.9	3.5
	Bz, nT	-1.5	4.8
N=68	*V, km/s*	508	97
	Dst, nT	-44	29
	AE, nT	518	222
	Xmax, g cm^{-2}	14.1	8.2
	m-ind.	-2.4	1.1
SC 22	*B, nT*	6.6	2.6
	Bz, nT	-1.2	2.4
N=47	*V, km/s*	564	130
	Dst, nT	-46	26
	Xmax, g cm^{-2}	15.4	7.8
	m-ind.	-2.4	1.6
SC 23	*B, nT*	8.6	4.1
(incl. 2000)	*Bz, nT*	-1.6	5.2
N=36	*V, km/s*	472	84
	Dst, nT	-39	24
	Xmax, g cm^{-2}	17.4	8.0
	m-ind.	-3.6	2.2

(5) the electron precipitation events in the atmosphere were mainly observed when interplanetary plasma varied in the ranges: solar wind speed *V*=400-600 *km/s*, magnetic field average *B*=5 -10 *nT* and GSM component *Bz*=(-10)–5 *nT*. Also, there are a number events observed during the very disturbed period, characterized by V ~ 800 km/s and B ~ 20*nT*, Bz ~ 15 *nT* (sometimes *Bz* < -20 *nT*). Usually such interplanetary disturbances and associated largest geomagnetic storms are produced by coronal mass ejections from the sun (Gosling et al., 1991; Landi et al., 1998).

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