

## Long-term cosmic ray observations in the atmosphere

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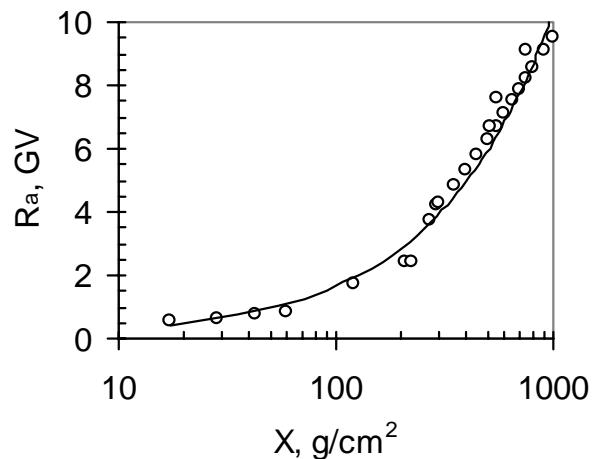
**Abstract.** We present experimental data on cosmic ray fluxes in the atmosphere from the ground level up to 30–35 km obtained at the several latitudes for the period from 1957 till now. The geomagnetic and atmospheric rigidity cutoffs are used to study the modulation processes of cosmic rays in a wide range of rigidities. The empirical relation between cosmic ray flux measured in the atmosphere and on the ground level and interplanetary magnetic field strength was established and it was found that in the heliosphere from 1937 till present time the magnetic flux from the Sun did not increase.

### 1 Introduction

The regular cosmic ray measurements in the atmosphere are made from the middle of 1957 till now. The standard radiosondes are used in this experiment (see for detail Charakhchyan et al., 1976; Bazilevskaya et al., 1991). Now we have homogeneous data sets on cosmic ray fluxes from the ground level up to 30–35 km obtained at the several latitudes with different geomagnetic cutoff rigidities  $R_c$ , namely: at the northern and southern (Antarctic) polar latitudes,  $R_c = 0.6$  and  $0.03$  GV correspondingly, and at the northern middle latitude,  $R_c = 2.4$  GV.

We have also used the atmosphere as a natural absorber of cosmic rays: at the definite atmospheric depth  $X$ ,  $\text{g/cm}^2$ , only cosmic ray particles with the rigidity  $R$  (or energy  $E$ ) more than  $R_a$  contribute to count rate of our detectors (Geiger counters) where  $R_a$  is the atmospheric rigidity cutoff. The values of  $R_a(X)$  shown in Fig. 1 were defined from the latitude and stationary measurements of cosmic

ray fluxes (Stozhkov et al., 2001). Thus, using the different atmospheric depths we can study the cosmic ray modulation effects in the rigidity range  $R > 0.5$  GV up to  $R > 10$  GV.



**Fig. 1.** The value of atmospheric rigidity cutoff vs. atmospheric depth  $X$ . The points were obtained from the latitude cosmic ray measurements and solid curve is the approximation  $R_a = 0.043X^{0.8}$  where  $R$  is in GV and  $X$  is in  $\text{g/cm}^2$ .

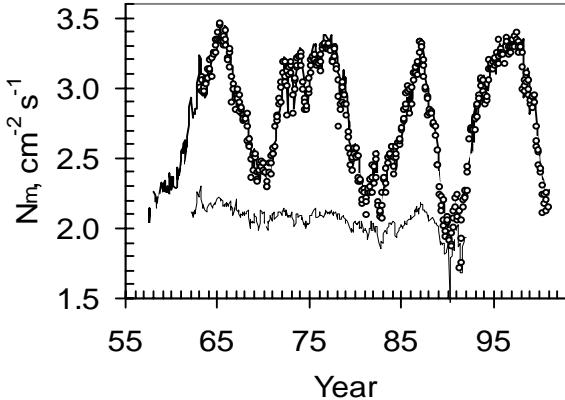
### 2 Experimental data

In Fig. 2 and 3 the time dependences of cosmic ray fluxes measured in the atmosphere at Pforzheim maximum ( $N_m$ ) at  $X = (25–50)$   $\text{g/cm}^2$  and at  $X = (500–600)$   $\text{g/cm}^2$  are presented.

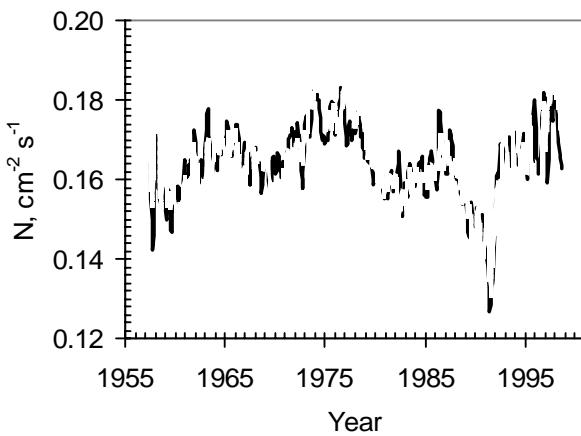
The cosmic ray flux peaks observed in 1962–63 (Fig. 2) and in 1958–59 (Fig. 3) were due to nuclear bomb explosions. From the data given in Fig. 3 one can conclude that in the troposphere cosmic ray fluxes were higher in the

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positive phases of 22-year solar magnetic cycles (1971–79 and 1991–99) than in the negative ones (1959–69 and 1981–89) that is 22-year wave is observed. In contrary, our data in the stratosphere (Fig. 2) and neutron monitor data show the increased (or equal) cosmic ray fluxes in the negative phases.

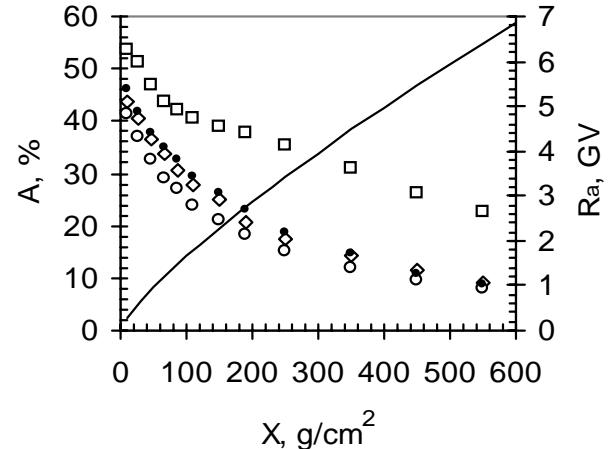


**Fig. 2.** The time dependence of monthly averaged cosmic ray fluxes recorded in the atmosphere at Pforzheim maximum at the north polar latitude with  $R_c = 0.6$  GV (upper curve, thin line), at the south polar latitude with  $R_c = 0.03$  GV (open points), at the north middle latitudes with  $R_c = 2.4$  and  $6.7$  GV (middle and bottom curves accordingly).



**Fig. 3.** The time dependence of 3 monthly smoothed cosmic ray fluxes recorded in the atmosphere at  $X=500$ – $600$  g/cm $^2$  at the north polar latitude with  $R_c = 0.6$  GV (light curve) and at the north middle latitude with  $R_c = 2.4$  GV (solid curve). At  $X=500$  g/cm $^2$  the atmospheric rigidity cutoff equals  $R_a = 6.2$  GV.

In Fig. 4 the changes of cosmic ray fluxes,  $A = [N_{65}(X) - N_i(X)]/N_{65}(X)$ , in the solar activity maxima relative to 1965 are depicted versus  $X$ . The value of  $A$  decreases with the growth of  $X$  and at the ground level  $A \approx 5\%$ .



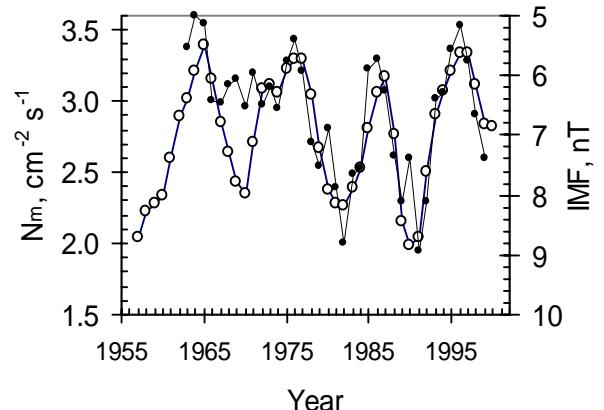
**Fig. 4.** The changes of cosmic ray fluxes  $A$  in the solar activity maxima relative to 1965:  $\diamond$  – (7–9).59;  $\circ$  – (7–9).70;  $\bullet$  – (10–12).82;  $\square$  – (6–8).91. The value of  $R_a$  is shown by solid curve.

### 3 Cosmic rays and interplanetary magnetic field

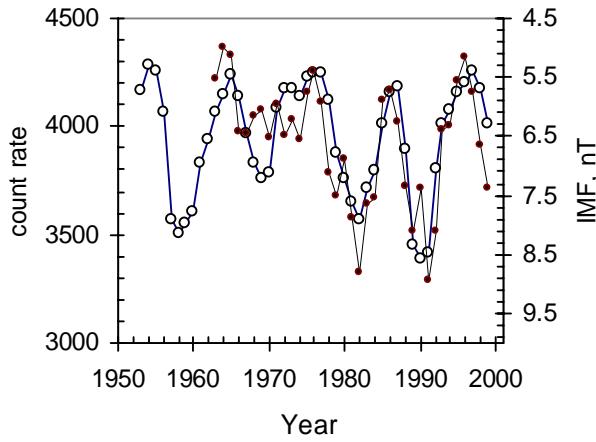
The moving interplanetary magnetic field irregularities ( $\delta B$ ) are responsible for the main part of cosmic ray modulation. The  $\delta B$  values have larger amplitudes when averaged IMF is stronger (Burlaga and Ness, 1998). So, one can expect that the relationship exists between cosmic ray fluxes and the mean IMF (Belov et al., 1999; Cane et al., 1999; Stozhkov et al., 2001).

In Figs. 5 – 7 the yearly averages of cosmic ray fluxes observed in the atmosphere, at Climax neutron monitor and muon fluxes on the ground together with IMF strength are shown.

The correlation coefficients  $r$  of cosmic ray flux (CR) and IMF for the period of 1972–99 are maximal when the time shift between CR and IMF is  $T = 0$ :  $r = -0.87 \pm 0.05$  and  $r = -0.85 \pm 0.06$  for stratospheric and neutron monitor data.



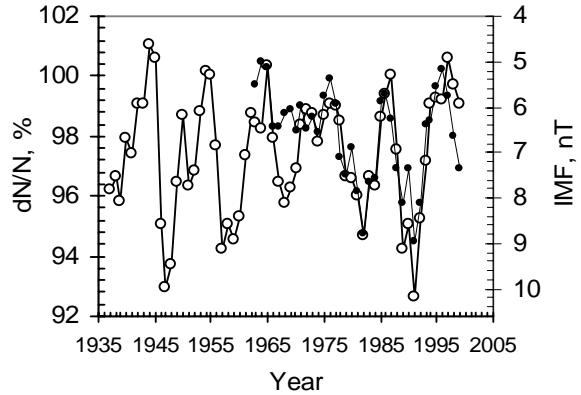
**Fig. 5.** Cosmic ray flux in the polar atmosphere at Pforzheim maximum,  $N_m$  ( $R_a = 0.7$  GV; open points) and IMF strength (dark points) vs. time.



**Fig. 6.** Count rate of Climax neutron monitor ( $R_c = 3$  GV; open points) and IMF strength (dark points) vs. time. The data on IMF presented in Figs. 5 – 8 were taken from Internet ([http://nssdc.gsfc.nasa.gov/omni\\_web/](http://nssdc.gsfc.nasa.gov/omni_web/)).

The muon data set was constructed from the ionization chamber data (IC) (Charakhchyan and Stozhkov, 1981; Krymsky et al., 1995; Ahluwalia, 2000) and from our calibration telescope data (CT). The IC data were normalized to CT data according to the expression:  $(IC)_{norm} = 2.6 \times (IC) - 160$  where (IC) is the ionization chamber count rate relative to 1987. In Fig. 7 the data covering the period from 1937 till now are shown together with IMF. For the period of 1972–99 the correlation coefficient between CR and IMF is maximal at  $T=0$  and equals  $r(\text{CR}, \text{IMF}) = -0.86 \pm 0.05$ .

From the data presented in Figs. 5 – 7 in the frame of the convection–diffusion model (Parker, 1963) we found the relationship between CR and IMF in 1972–99 and then calculated the values of IMF for the years of 1937–71 from the expression  $N = N_0 \times \exp(-\alpha B)$  where  $N$  is cosmic ray flux,  $N_0$  and  $\alpha$  are constants (see Table). In the Table the

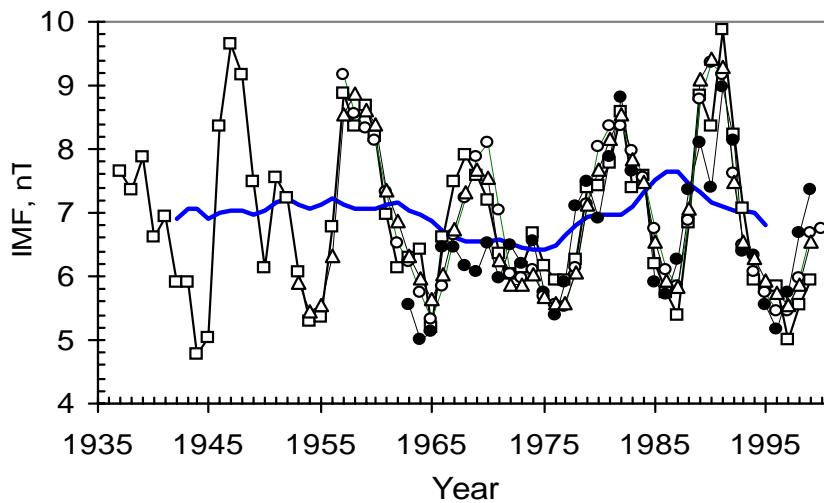


**Fig. 7.** Yearly averages of muon flux (open points) and IMF (black points) vs. time.

**Table.** The  $N_0$  and  $\alpha$  values in the expression  $N = N_0 \times \exp(-\alpha B)$ .

Experiment	Rigidity cutoff, GV	$N_0$	$\alpha, \text{nT}^{-1}$	Period
Stratosphere	$R_a = 0.7$	$6.85 \text{ cm}^{-2} \text{ s}^{-1}$	0.13	1957–2000
NM Climax	$R_c = 3.0$	5885	0.058	1953–1999
Muon data	$R_a = 9.0$	109.6, %	0.017	1937–2000

values of  $N_0$  are in the units given in Figs. 5 – 7. In Fig. 8 the calculated and experimental data on IMF are presented. There is a good coincidence between all sets of calculated IMF values. It is seen that the IMF smoothed with the  $T = 11$  years does not increase from 1935 till present and this result is in the contradiction with the conclusion of Lockwood et al. (1999).



**Fig. 8.** The experimental (●) and calculated values of IMF. The calculations were made from the stratospheric data  $N_m$  (○); neutron monitor Climax (Δ); muon data (□). Thick line is the average value of IMF smoothed with the period  $T = 11$  years.

#### 4 Conclusion

Cosmic ray measurements in the atmosphere allow us to study modulation effects in a wide energy range using the atmosphere as a natural absorber of particles. The atmospheric rigidity cutoff  $R_a$  is expressed through the atmospheric pressure  $X$  as  $R_a = 0.043X^{0.8}$  where  $R$  is in GV and  $X$  is in g/cm<sup>2</sup>.

The amplitude of 11-year CR variations decreases with the growth of  $X$ : for polar regions at  $X=10$  g/cm<sup>2</sup> it equals about  $A \approx 50\%$  and near the ground  $A \approx 5\%$ .

The long-term data set on the ground muon flux was constructed from the ionization chamber data and counter telescope data. This data set covers the period from 1937 till present time.

The tight relationship between CR and IMF strength is observed. It allows finding IMF strength before the era of its direct measurements in the interplanetary space. The results obtained show that from 1935 till present any significant increase of the mean IMF is not observed. For the period of 1980–present time the direct measurements of photospheric magnetic flux of the Sun do not show any increase of this value except 11-year changes (De Toma et al., 2001).

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