Solar Cosmic Rays and Solar-Terrestrial Relations: Observational Evidence and Mechanisms

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Abstract

- **In this brief review we discuss a number of geophysical effects of solar energetic particles (SEPs), or solar cosmic rays (SCR). We concentrate mainly on the observational evidence and proposed mechanisms of some expected effects and/or poor-studied phenomena discovered within 3 last decades, in particular, depletion of the ozone layer; perturbations in the global electric current; variations of the Schumann resonance parameters; effects on the winter storm vorticity; change of the atmospheric transparency; and production of nitrates. Some "archaeological" data on SCR fluxes in the past and upper limit of total energy induced by SEPs are also discussed.**
- **Due attention is paid to the periodicities in the solar particle fluxes. Actually, many solar, heliospheric and terrestrial parameters changing generally in phase with the solar activity are subjected to a temporary depression close to the solar maximum ("Gnevyshev Gap"). Similar gap has been found recently in the yearly numbers of the >10 MeV proton events.**

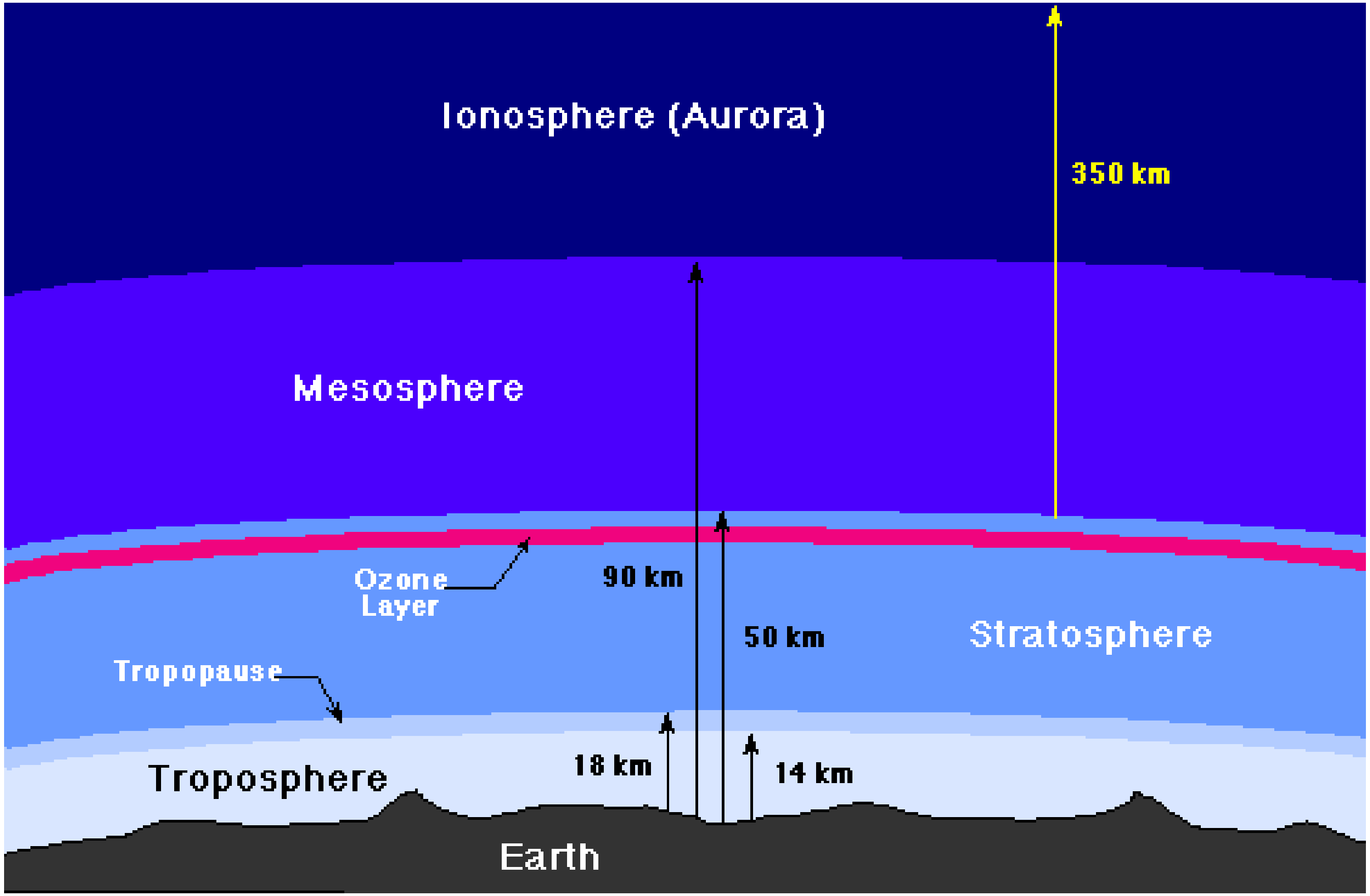
Abstract

- **All above-mentioned findings are evidently of great importance in the studies of general proton emissivity of the Sun and long-term trends in the behaviour of solar magnetic fields. In addition, those data can be very helpful for elaboration the methods for prediction the radiation conditions in space and for estimation of the SEPs contribution into solar effects on the geosphere, their relative role in the formation of terrestrial weather and climate, in the problem of solar-terrestrial relations (STR) in the whole.**

- ***Keywords*: Solar cosmic rays; Ozone layer; Atmospheric transparency and electricity; Nitrate production; Gnevyshev gap**

- ***Reference*: L.I. Miroshnichenko. Solar Cosmic Rays in the System of Solar-Terrestrial Relations. - *J. Atmospheric and Solar-Terrestrial Physics*, 2008, v.70, p.450-466.**

The Earth's Atmosphere



Primary and Secondary Cosmic Rays in the Earth's Atmosphere

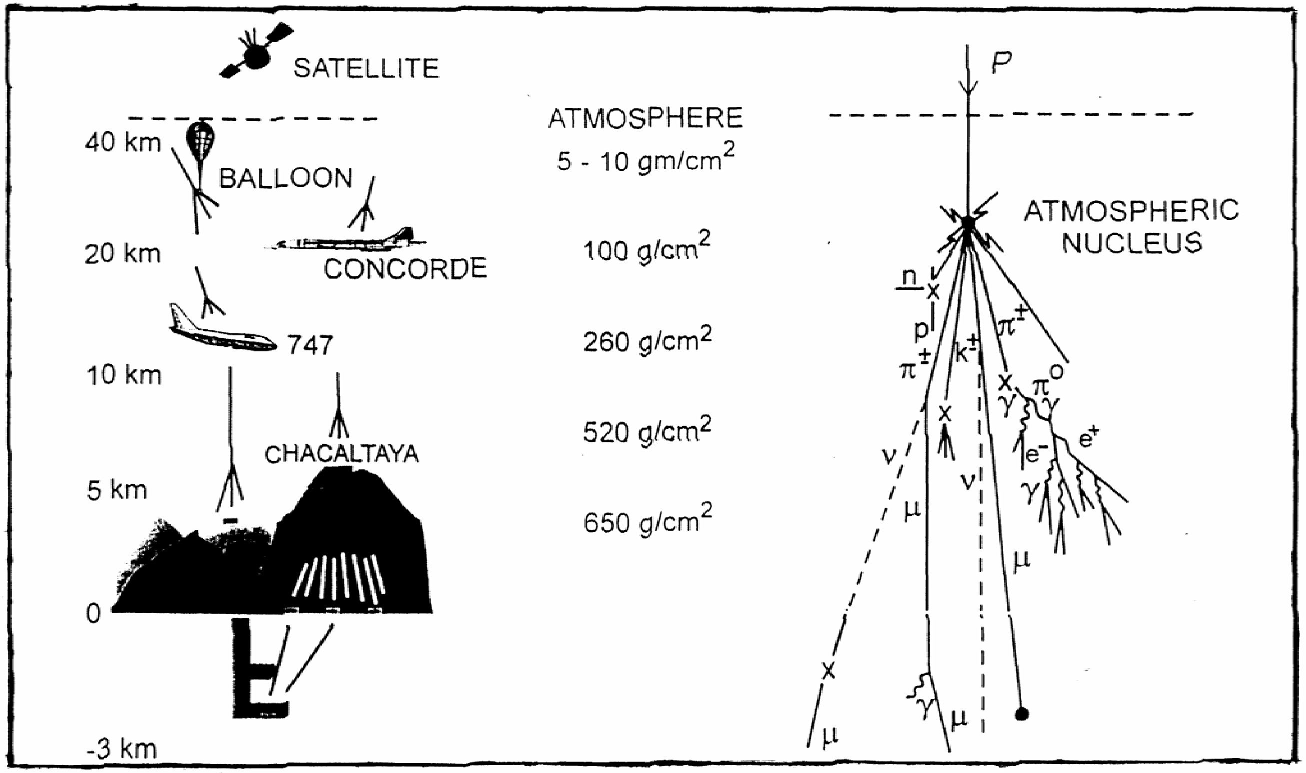
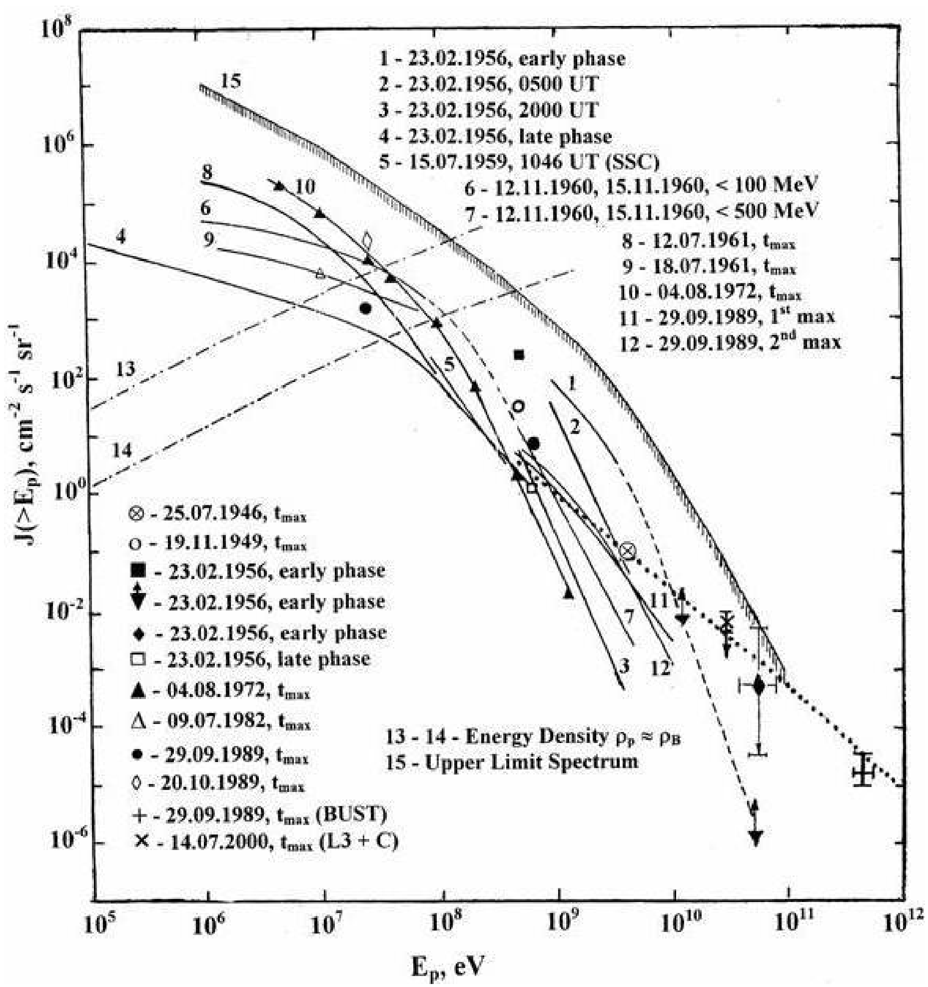


Figure A.1. Primary cosmic rays in space, secondary cosmic radiation cascade in the terrestrial atmosphere, and hard muons at different underground depths (Shea and Smart, 2000).

Integral energy spectra for SCR

Upper Limit Spectrum **for Solar Cosmic Rays (Solar Energetic Particles, SEPs), Miroshnichenko, 1996, 2001, 2003.**
Integral energy spectra for the *largest SPEs* observed near the Earth (1942-2001).
Integral spectrum for galactic cosmic rays (GCR) is also shown (dotted).
A number of geophysical aspects (this presentation).
Astrophysical aspects: upper limit energy for SCR *E ≥ 100 GeV*?



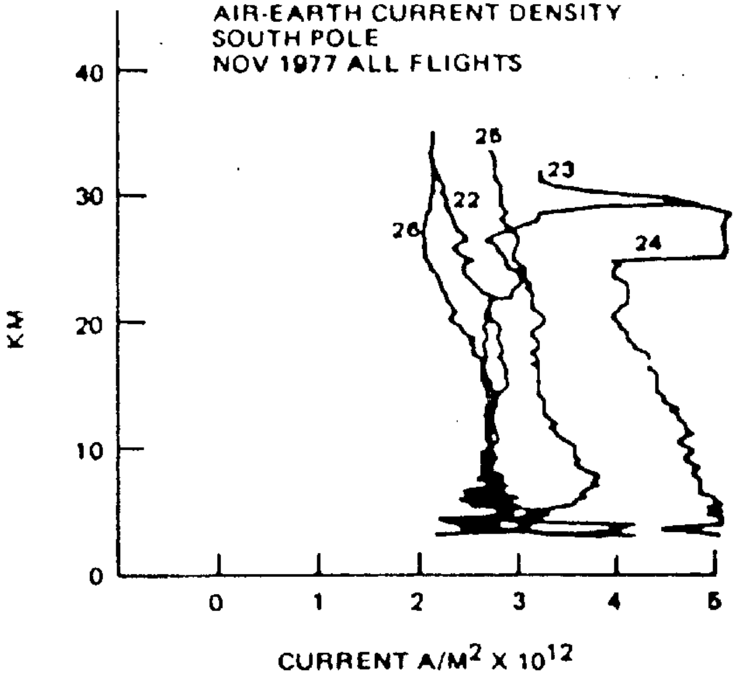
SEPs Effects on the Terrestrial Atmosphere

- **At present, there is serious observational evidence of several expected SEP effects and/or poor-studied solar-atmospheric phenomena. From the point of view of SEPs contribution into solar effects on the geosphere (in particular, on the terrestrial atmosphere), the most important and promising studies seem to be observations and physical, statistical, and modeling investigations that are listed below:**
- **1. Depletion of the ozone layer (*e.g.*, Heath *et al.*, 1977; Zadorozhny *et al.*, 1992; Shumilov *et al.*, 1995; Jackman *et al.*, 1999; Rohen *et al.*, 2006; Fadel *et al.*, 2006; Kirillov *et al.*, 2007) during a number of SEP events, for example, in August 1972, September-October 1989, May 1990, October 2003, December 2006).**
- **2. Perturbations in the global electric current (*e.g.*, Cobb, 1978; Holzworth and Mozer, 1979; Markson and Muir, 1980; Holzworth *et al.*, 1987; Roble, 1985; Kokorowski *et al.*, 2006).**
- **3. Variations of the Schumann resonance parameters (*e.g.*, Schlegel and Füllekrug, 1999).**
- **4. Changes in the atmospheric transparency (*e.g.*, Roldugin and Vashenyuk, 1994; Pudovkin and Babushkina, 1992; Pudovkin *et al.*, 1997).**
- **5. Effects on the winter storm vorticity in the Northern hemisphere (*e.g.*, Veretenenko and Thejll, 2004, 2005).**

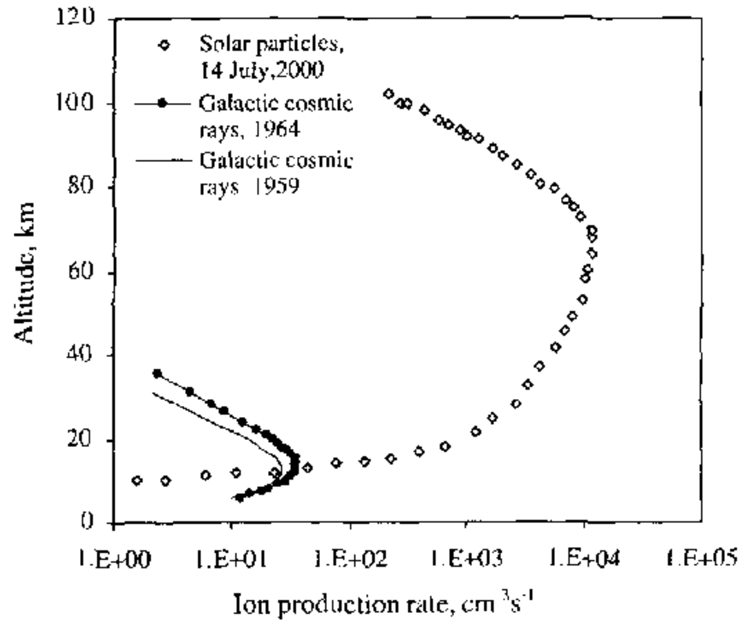
SEPs Effects on the Terrestrial Atmosphere

- **6. Production of nitrates (*e.g*., Crutzen *et al*., 1975; Randall *et al*., 2005; Dreschhoff and Zeller, 1990; Dreschhoff *et al.*, 1997; Dreschhoff and Zeller, 1998).**
- **7. Upper limit of total energy induced by SEPs estimated by direct satellite data and indirect data of nitrate abundance in the polar ice (*e.g*., Gladysheva *et al.*, 1995).**
- **9. Periodicities and "Gnevyshev gap" (GG) effects in the solar particle fluxes (*e.g*., Storini *et al*., 2003; Miroshnichenko, 2001; Bazilevskaya *et al*. 2006).**
- **10. "Archaeological" SCR fluxes in the past (*e.g*., Dreschhoff and Laird, 2006).**
- **The most characteristic results, the most important references and figures to characterize the effects under consideration are given below. Besides, we mention briefly a number of interesting physical mechanisms proposed recently in this field. It should be also noted a permanently growing interest to the role of GCR and SCR in solar-atmospheric phenomena and Space Weather formation (*e.g*., Gurevich *et al*., 1999, 2002; Svenmark, 2000; Stozhkov, 2003; Dorman, 2004; Beer, 2004; Perov, 2005).**

Проводимость атмосферы и профили ионизации от СКЛ и ГКЛ

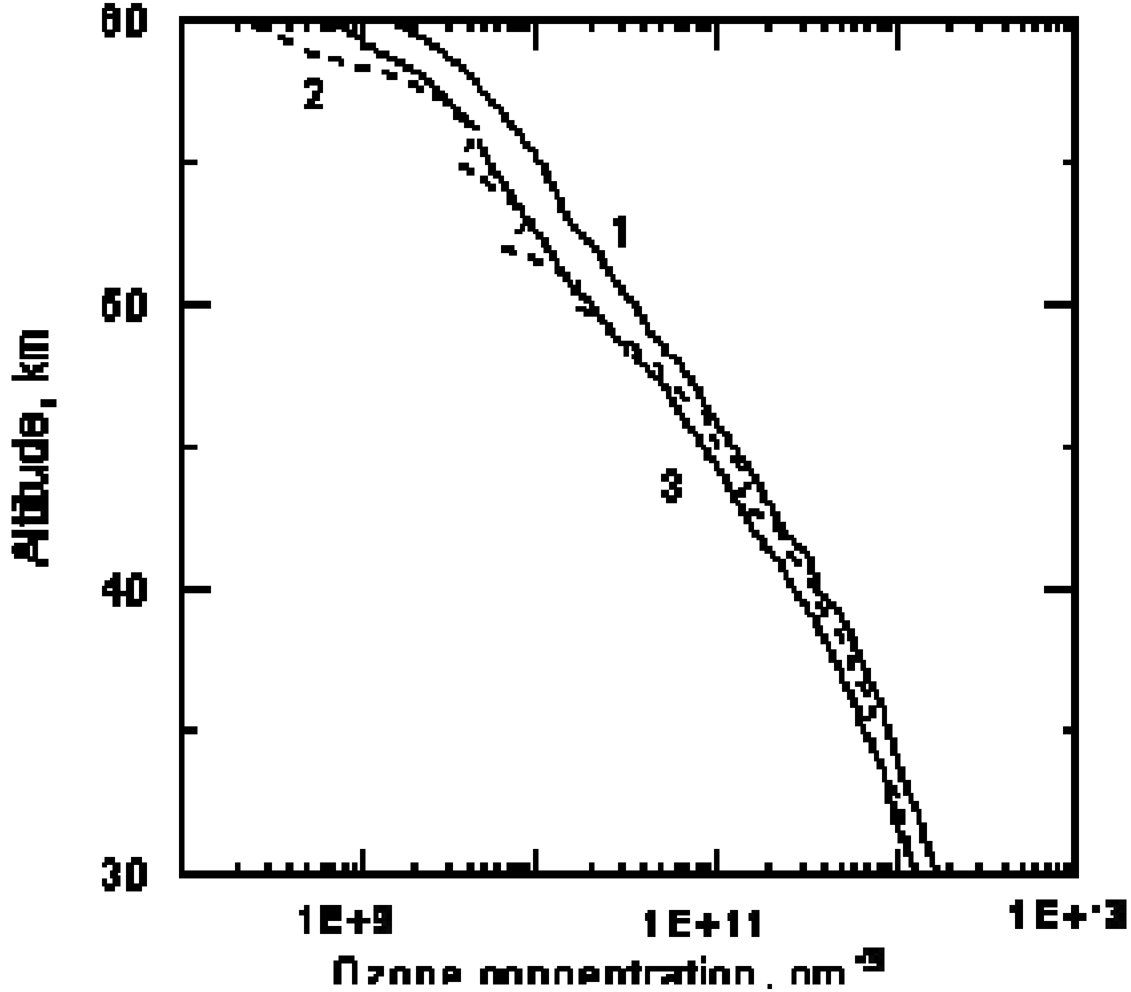


Слева: **Плотность тока «воздух Земля» над Южным полюсом по измерениям в стратосфере во время GLE 22 ноября 1977 г. (Cobb, 1978).**



Справа: **Скорость образования ионов в полярной атмосфере во время GLE 14 июля 2000 г.** за счет СКЛ **(Quack et al., 2001),** в сравнении с ионизацией от ГКЛ **в минимуме (1964 г.) и максимуме (1959 г.) солнечной активности (Neher, 1971). Compiled by Bazilevskaya, 2005.**

Figure 1. **Profiles of O3 concentrations measured on *POAM-III* satellite in October 2003: *1* – 22:00 UT of 27 October (before SEP event); *2* – 22:00 UT of 28 October (11 hours after SEP event onset); *3* – 22:00 UT of 30 October (after SEP events of 28 and 29 October) (see for details: http://www.cpi.com/products/poam/download.html).**



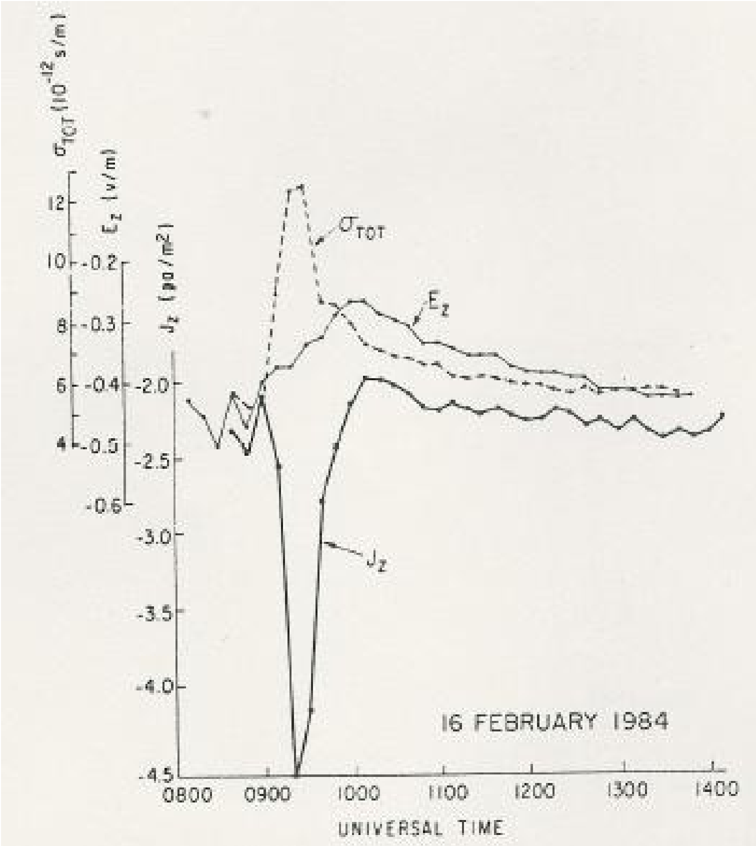


Figure 2. **Total conductivity (*σ -total*), vertical electric field (*E-Z*) and vertical current density (*J-Z*) during the solar proton event of 16 February 1984**

(Holzworth *et al*., 1987).

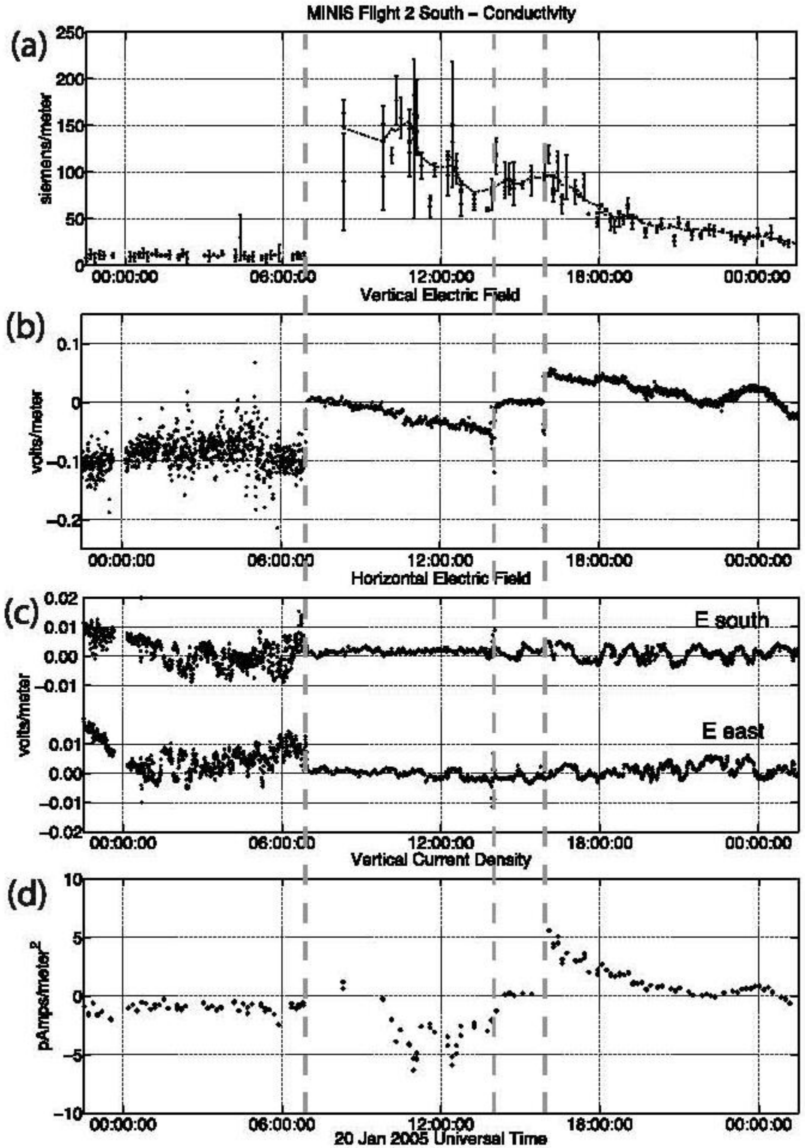


Figure 3. **Fluctuations of electric field parameters in the stratosphere during the large solar proton event of 20 January 2005**

(Kokorowski *et a*l., 2006).

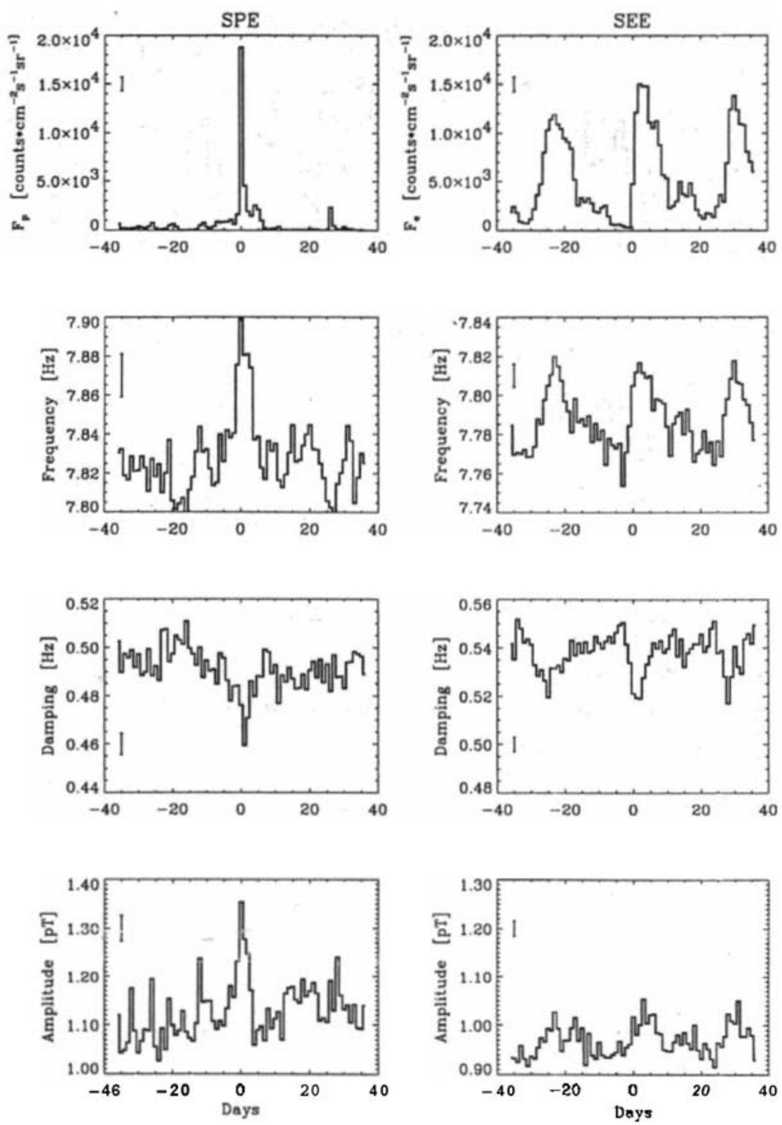


Figure 4. **Variations of the parameters of Schumann resonance: proton flux (first row); SR frequency (second row); SR damping (third row); SR amplitude (fourth row) for two strong SPEs in October 1989 and March 1991. Plotted are daily means of the four quantities (Schlegel and Füllekrug, 1999).**

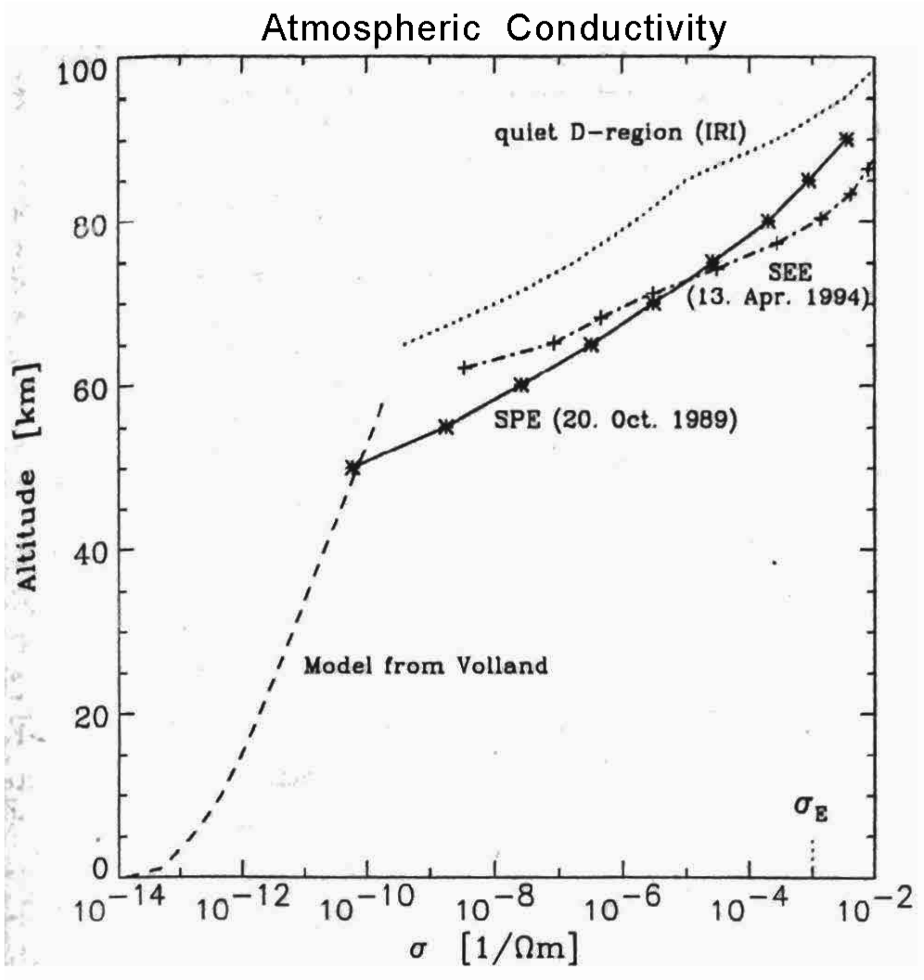


***Figure 5*. Conductivity profiles in the Earth-ionosphere cavity for different conditions (Schlegel and Füllekrug, 1999): Comparison of the effects of strong SPE (October 1989) and SEE (April 1994) events with a model by Volland (1984) and quiet D-region (IRI).**

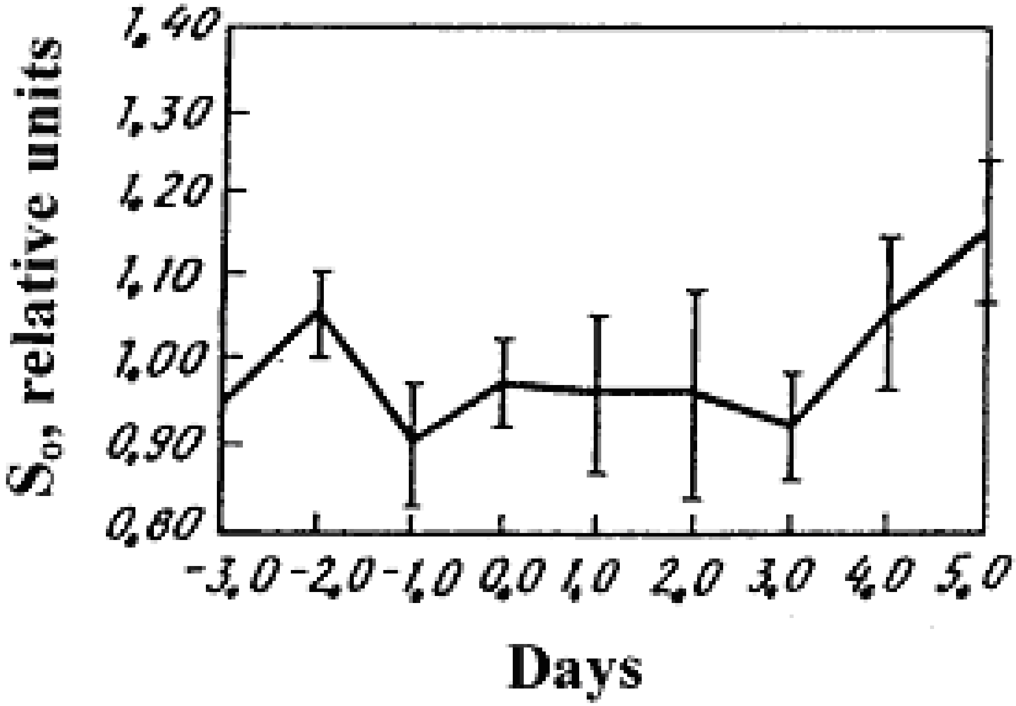


***Figure 6*. Variations of the solar insolation *S*0 observed at the Earth's surface in the course of solar proton events in 1980-1984 (Pudovkin *et al*., 1997).**

A point *t* = 0 corresponds to the day of event onset; short vertical lines show the mean square deviations of the measured *S*0 values.

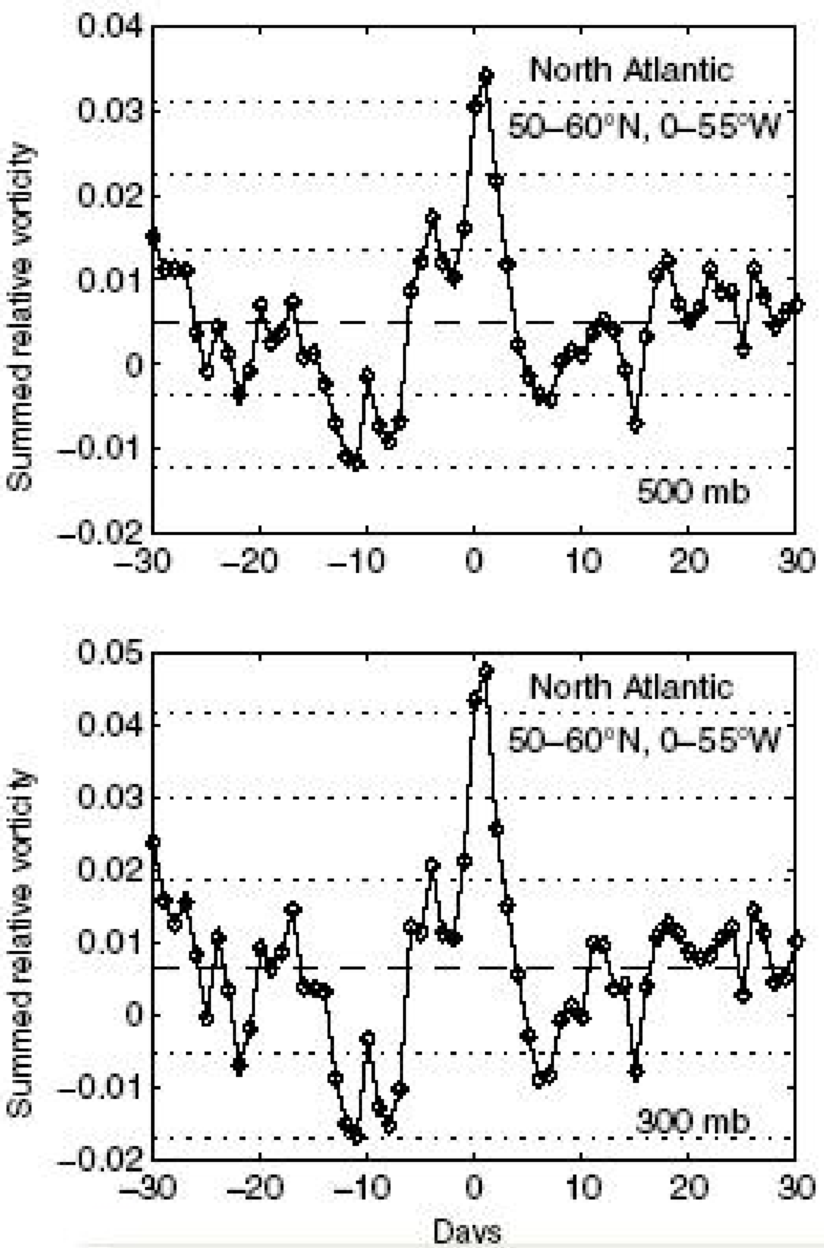


***Figure 7*. Mean changes of the relative vorticity sums (in s-1) in different region of the North Atlantic (Veretenenko and Thejll, 2005). Number of solar proton events *N* = 48 (1980-1996), cold period (October – March). Day 0 corresponds to the day of the event onset.**

Nitrates

SOLAR PROTONS PROVIDE THE ENERGY TO DRIVE AN ENDOTHERMIC REACTION

$$NO + O_3 \rightarrow NO_2 + O_2$$

$$NO_2 + O \rightarrow NO + O_2$$

$$\text{Net: } O_3 + O \rightarrow O_2 + O_2$$

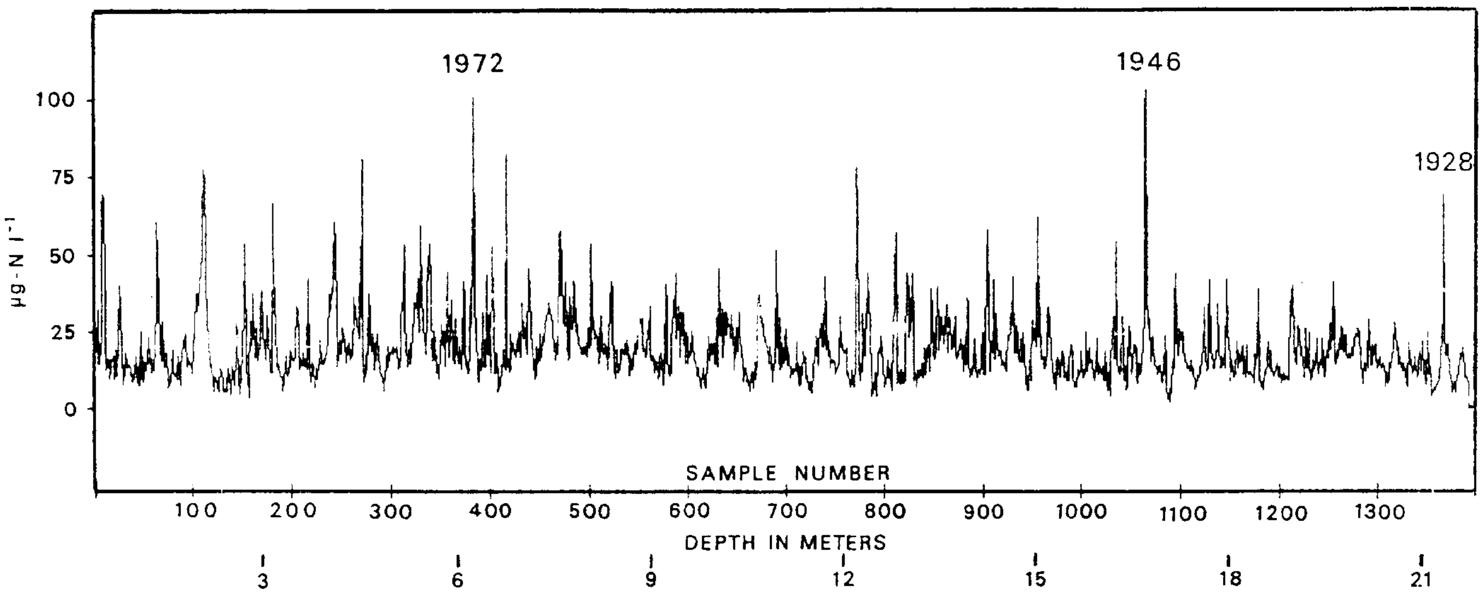
"odd nitrogen" (complex of nitrate radicals designated by the symbol NO_y)
Nitrate deposition in polar ice are markers of the HNO_3 precipitation.

Contemporary state-of-the-art measurements of the denitrification of the polar atmosphere find significant nitric acid trihydrate particles (called NAT rocks) in the polar stratospheric clouds.

Some of the HNO_3 is transported to the troposphere, where it is precipitated downward to the surface.

Paper 725, Kepko et al.

***Figure 8*. Nitrate concentration profile from the Windless Bight core on the Ross Ice Shelf (Antarctic) by the data of Kansas University, USA (Dreschhoff and Zeller, 1990). The *x*-axis is proportional to true depth below the surface; the *y*-axis represents nitrate concentration in *mg* per unit of the entire length of the core. At least three major flares occurred in 1928, 1946, and 1972 are visible in the records as large concentration peaks.**



Nitrates and distribution of SEP events

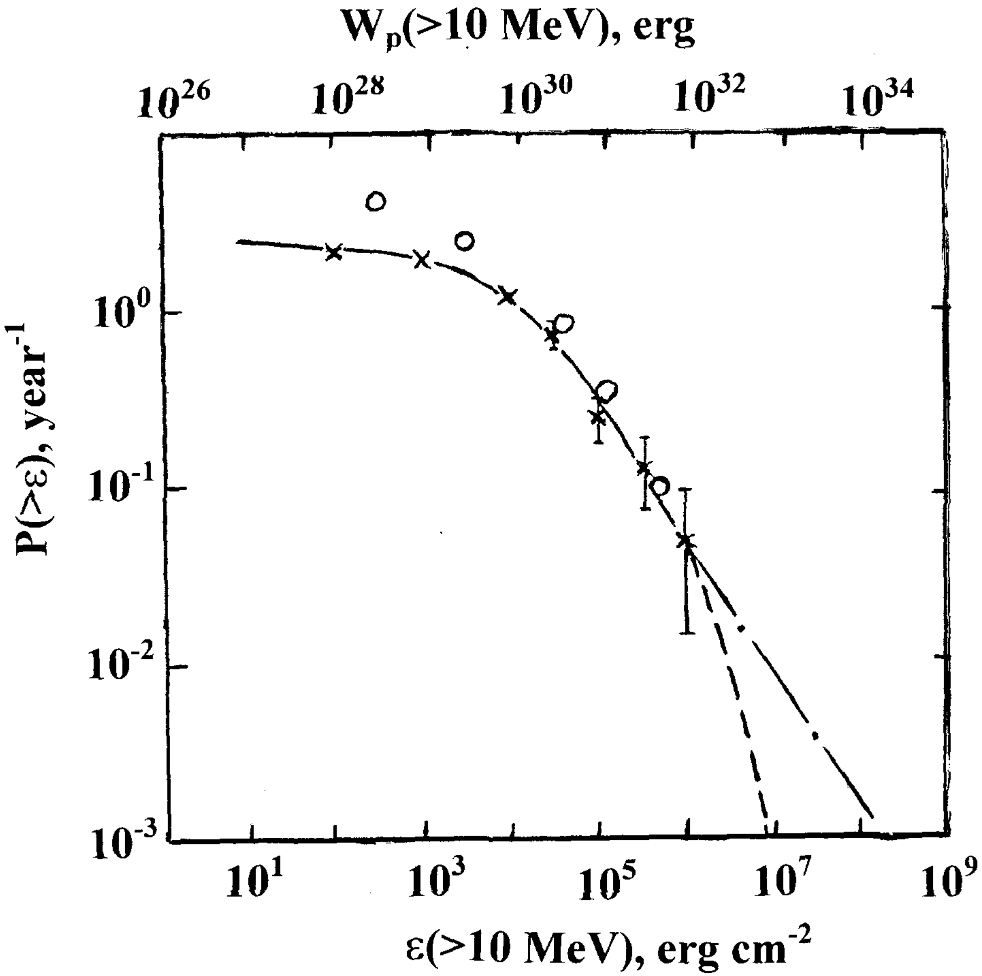


***Figure 9*. Integral distribution of SEP events in the solar cycles 19-21 as a function of the >10 MeV proton energy fluence ε. Circles (dotted-dashed line) – occurrence rate of SEP events by direct satellite data; Crosses (dashed line) – 3-month averages of the occurrence rate by nitrate data (Gladysheva *et al.*, 1995).**

The dashed line only (crosses) could be in agreement with available data on the nitrate content in the polar ices.

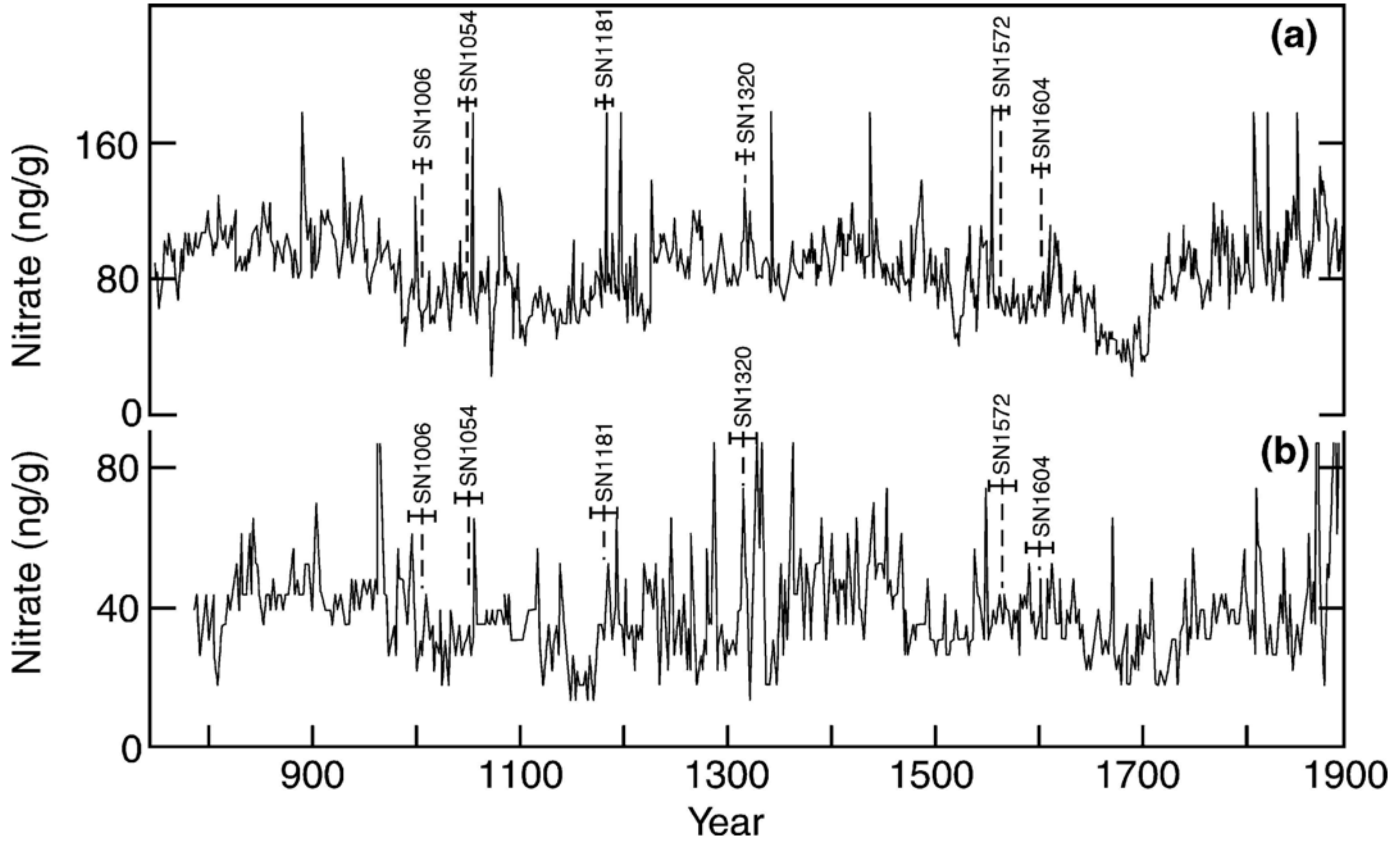


Figure 10. **Nitrate concentration in the South Pole core representing ~1200 years (*a*), and the time equivalent upper part of the Vostok core (*b*). Historical SNe are indicated for the respective nitrate anomalies. Minimum errors (~10 years for South Pole record; ~30 years for Vostok record) are indicated by error bars (Dreschhoff and Laird, 2006).**

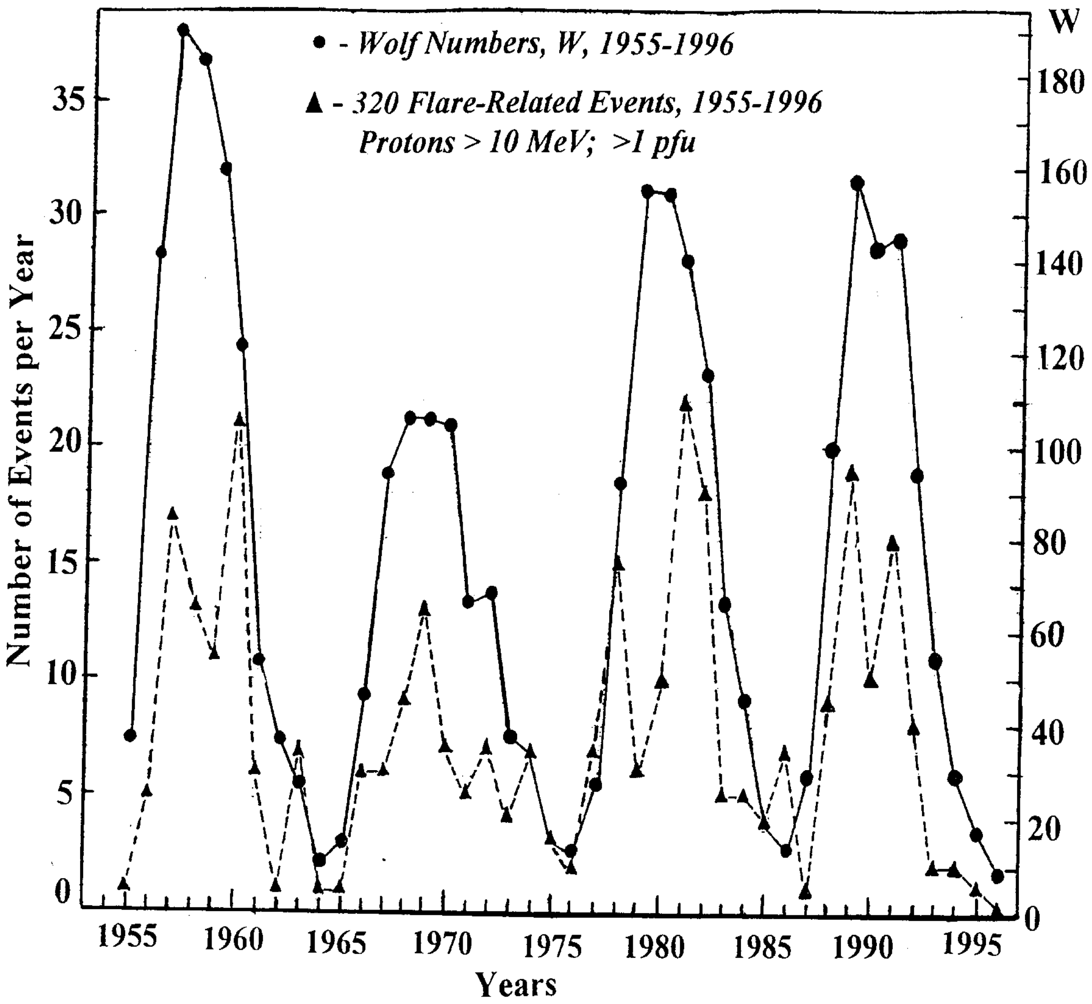
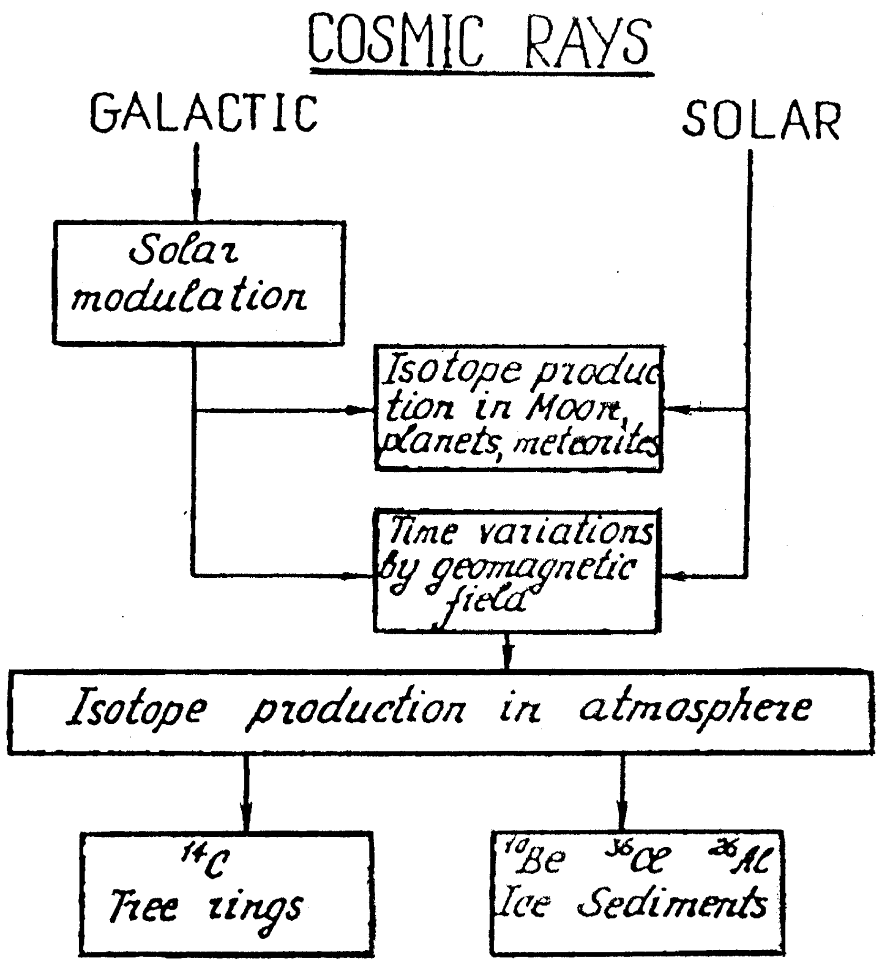


***Figure 11*. Yearly numbers of the >10 MeV proton events at intensity threshold > 1 pfu in comparison with the level of solar activity measured in Wolf numbers, *W*, for the period of 1955-1996 (Miroshnichenko, 2001).**

Cosmogenic Isotope Production in the Earth's Atmosphere

Радиоуглерод C-14 в земной атмосфере и биосфере.
Отложения других космогенных изотопов (Be-10, Cl-36, Al-26) в полярных льдах, на дне озер и т.п.



Summary-I

- **Solar cosmic rays may be considered only as one of a series of channels of solar activity impact on the terrestrial environment, *i.e*., as a part of the problem "Sun-Earth" (or Space Weather). In this general context, it is important to estimate a real contribution of SCR terrestrial effects into STR.**
- **Of course, the energy introduced by the fast solar particles into the Earth's atmosphere is evidently not enough for a direct impact on stratospheric and tropospheric processes (*e.g*., Vitinsky *et al*., 1976). Nevertheless, from the data considered above, one can see that SCR are capable of making a certain contribution to geophysical perturbations. This means that if the correlation between the SEP events and meteorological phenomena reflects real relations, the mechanisms of such relations probably must be very subtle (e.g., trigger one). In turn, such a correlation may be very important for theoretical models of proposed trigger mechanisms, for accurate simulations of solar-atmospheric effects.**
- **All this, in our view, gives grounds to scrutinize the properties of SCR within the framework of general problem of the dynamics and rhythmic of helio-geophysical processes and estimate quantitatively a relative contribution of accelerated solar particles into the mechanism(s) of solar-terrestrial relationships in the whole. It may be noted, at least, two promising possibilities.**
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Summary-II

- **At the modern level of understanding of the STR problem, it may be done, first of all, by taking into account a real (non-uniformly power-law) form of observed SCR spectrum (*e.g.*, Quack *et al.*, 2001). In their analysis of the mesospheric and stratospheric effects of three large SEP events (GLEs occurred in October 1989, July 2000, and April 2001), these authors have divided the proton spectrum in up to three separate power-laws. Note that the spectrum extended to about 800 MeV while in previous studies the energy range normally was limited to up to 300-400 MeV.**
- **The second promising way is to use time-dependent models for the production and loss of minor components of the middle atmosphere (*e.g.*, Fadel *et al.*, 2006; Kirillov *et al.*, 2007). Of course, in every SEP event under consideration, some fine tuning in both parts of the calculation model, the calculation of ionization profiles as well as the subsequent chemical model, is required.**

Summary-III

In conclusion it should be noted that investigations are carried out very intensively in this important and promising field, and we tried only to focus attention of the researchers on some new results, aspects and links of the effects under consideration. It is necessary to fulfill a number of model studies, taking into account available qualitative (theoretical) and quantitative (observational) premises of SCR influence on the geosphere, to estimate their relative role in the formation of terrestrial weather and climate. Evidently, the STR problem is multi-level in nature and requires to unite the efforts of many groups of solar and geo-physicists.

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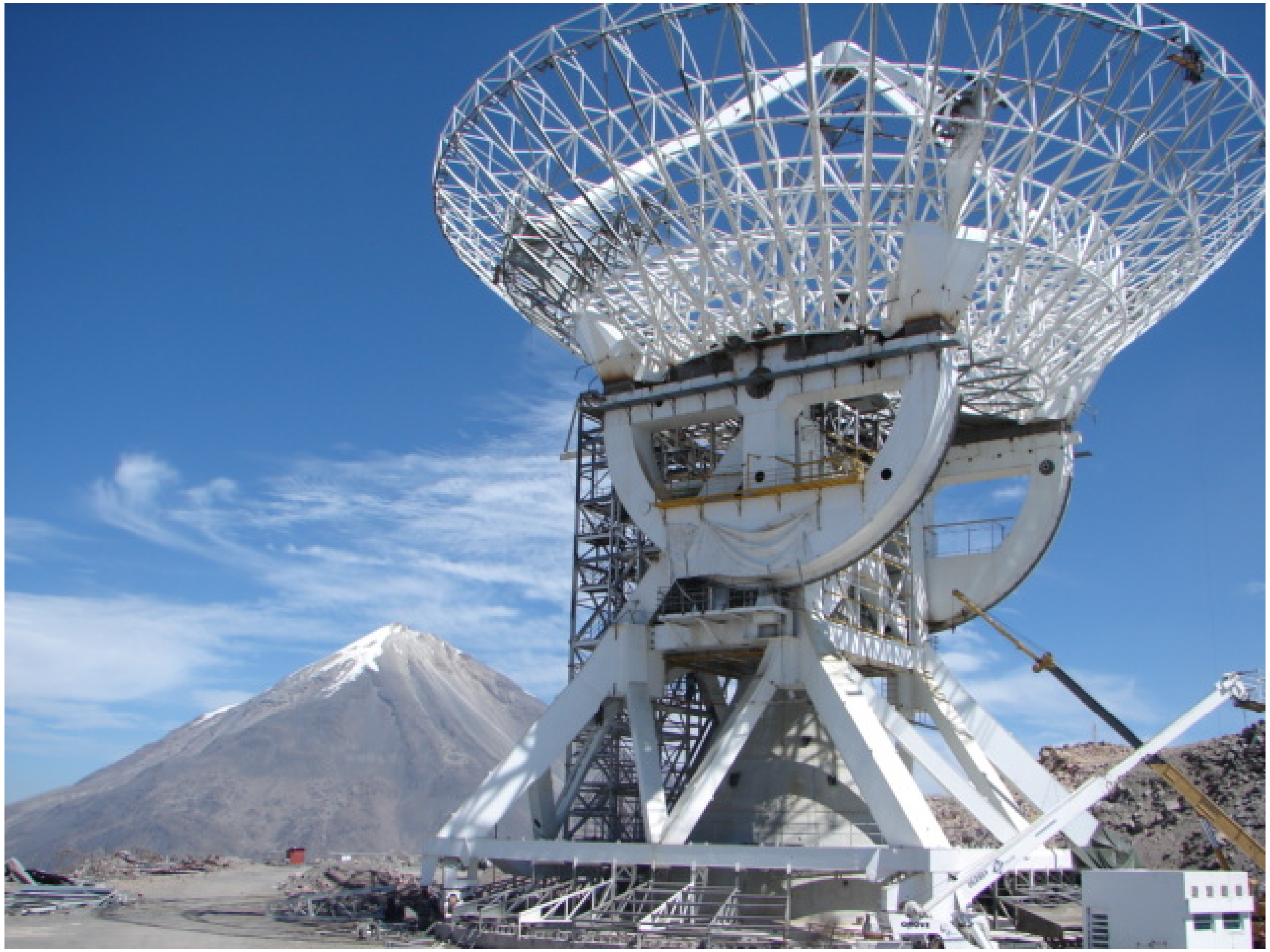
Pico de Orizaba y Radio Telescopio a Sierra Negra



Solar Neutron Telescope Laboratory (Abajo): Piensa en Grande…

Leonty, Xavier, Octavio y Miguel
(Sierra Negra, 29 de Marzo, 2006)

Alejandro, Leonty, Xavier y Octavio (Sierra Negra, 29 de Marzo, 2006)

¡Saludos de Sierra Negra!

¡MUCHAS GRACIAS!