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Cosmic Rays and Space Weather: Direct and Indirect Relations

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Abstract. There are two kinds of relations between cosmic ray research and space weather effects. Since energetic particles in space and low energy cosmic rays interact with materials of the satellite and airplane systems as well as with the atmosphere, the monitoring of changes of its flux especially during solar flares, space storms and geomagnetic disturbances, is important. The availability of data of ground based neutron monitor measurements provided in real time, especially those with high temporal resolution, is discussed. Cosmic ray particles due to their relatively large gyroradius and mean free path in interplanetary space and due to their high velocity in comparison with velocity of CME propagation, are checked, especially during the past decade, for their relevance in forecasting of geomagnetic disturbances. The change of cosmic ray anisotropy observed on the surface of Earth, due to the change of IMF structures, is seen in many cases few hours before the onset of geomagnetic disturbance. Cosmic ray variability and anisotropy depends on the geometry, speed, direction of propagation and on structures of the IMF inhomogenities and discontinuities propagating in interplanetary space. Onset of high energy particles, if observed with good temporal resolution, is a tool for alert of space storms. There exist network installations, especially those by neutron monitors and by muon directional telescopes, providing cosmic ray anisotropy in real time. Another new experiments are under development. High temporal resolution of the measurements and using several experimental data simultaneously in real time is important for space weather alert signals. An attempt to summarize the status of cosmic ray research relevant for space weather events description and its forecast, is presented.

Introduction

The term Space Weather is defined as "Conditions on the Sun and in the solar wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health." [US National Space Weather Programme, 1995].

Another definition was recently accepted by COST 724 Action in Europe: "Space weather is the physical and phenomenological state of the space environments. Through observation, monitoring, analysis and modelling, the associated discipline aims at: 1) Understanding and predicting the state of the sun, the interplanetary and planetary environments, and the solar and non-solar driven perturbations affecting them, 2) Forecasting and nowcasting the possible impacts on biological and technological systems"[99].

Relations of cosmic ray (CR) study to research of space weather effects were reviewed e.g. in papers or presentations [1, 2, 3] among others. Review of effects of space weather on technological systems can be found e.g. in books [4, 5, 6] and references therein. The development of Sun-Earth relations is reviewed e.g. in paper [107] among others.

The direct relations of CR to space weather research are pertinent to interaction of particles with materials as e.g. those of systems on the satellites, airplanes and on the ground, with the atmosphere and with the biological objects. The indirect relations are relevant to the potential of CR measurements as an additional element in forecasting of geoeffective disturbances and of the space storms. Typical effects to which CR have indirect relations are e.g. geomagnetic disturbances, the storms when Earth encounters disturbance in solar wind and when e.g. ground based technological systems (e.g. pipelines, powerlines) especially at high geomagnetic latitudes are influenced. Some biological effects, if they are caused by changes of geomagnetic field, have also indirect relations to CR.

The satellite failures (memory upsets, dielectric charging, radiation damage of components), the changes in the atmosphere, the influence on communications (SW-fadeout, VHF disturbances, variability of ionisation at different ionospheric layers) as well as navigation errors belong to the direct relations of CR to space weather effects. The same is true for dosimetric changes important for the airplanes, satellites and space missions with the manned crew.

In the following we attempt to present a short survey of selected recent results relevant for the relations between cosmic ray studies and space weather effects.

CR as precursors of geoeffective events

Geomagnetic disturbances

Analysis of CR measurements at neutron monitor (NM) energies showed long time ago the existence of precursors before the arrival of interplanetary shock to the Earth and before the onset of Forbush decrease (FD) [7].

Some types of precursory anisotropies are interpreted as kinetic effects due to interaction of ambient CR with the approaching shock [8]. Due to high CR velocity and its parallel mean free path (λ_{par}), the information about precursory anisotropies related to IMF inhomogenity, is transmitted fast to remote locations: intensity deficit of CR can be observed up to distance $\sim 0.1 \cdot \lambda_{par} \cdot \cos(\Phi)$, where Φ is cone angle of interplanetary magnetic field (IMF) [9].

Mathematical explanation of precursors to FD was proposed in the frame of pitch angle transport near oblique, plane-parallel shock. Assuming different values of power-law index of magnetic turbulence, mean free path and decay length for typical primary energies to which NMs and muon detectors (MD) are sensitive, the loss cone precursors should be observed by NM$\sim$ 4 hr prior to shock arrival, and by MD$\sim$ 15 hr prior to shock arrival [10].

Fluctuations of CR (5 min data) indicated the changes in power spectrum density (PSD, in the time scale region below the diurnal variation) before the onset of geomagnetic storms at a single NM, especially during the solar activity maximum [11, 12]. For lower level of solar activity the asymmetry is less pronounced but it still exists [13].

Changes of NM fluctuation spectrum over long time period are discussed e.g. in paper [19]. Different slopes of PSD and different contribution of the diurnal peak of CR to the muon telescope signal for even and odd solar cycles are reported in paper [109]. The study of the diurnal and semidiurnal peaks of CR variability started long time ago (e.g. in paper [110]). The contribution of the diurnal variation to the CR variability at NM energies is variable (see e.g. [111] and references therein).

Simple index of *CR daily variability* constructed from three middle latitude NMs with different asymptotic directions (DD) is (i) better correlated with the solar wind velocity *after* that interval (day) than within it; (ii) multiple linear regression of Dst with the "prehistory" of CR variability for 3, 6, 9, 12, 15, 18 hours gives the estimate of linear cross-correlation coefficient ~ 0.46 (based on 183000 hourly data); (iii) $\sim$ 2/3 of cases (83) with sudden Dst depression ($>$ 50nT/h) is accompanied by DD$>$1 while probability of DD$>$1 during geomagnetically quiet times is only 0.07 (based on data from years 1982-2002) [14].

Detailed studies of single events indicated the CR anisotropy onset before the geomagnetic field disturbances. Strong enhancement of CR anisotropy was observed before and during January 1997 CME/magnetic cloud by 7 high latitude stations [15]. Field-aligned anisotropy appeared $\sim$ 9 hours prior to the shock arrival. In advance of strong geomagnetic storms the precursors on neutron monitors [23] and on muon detectors [16] were observed with various lead time up to $\sim$12 hours. Two types of the anisotropy were identifed, namely (i) LC – loss cone, when the detector is magnetically (by asymptotics) connected to CR depleted region downstream of the interplanetary shock; and EV – enhanced variance (not clearly aligned with the ambient magnetic field).

One example of precursory effect in CR is in Fig. 1 [17]. Strong geomagnetic storm accompanied by FD has a clear precursor 10 – 15 hours

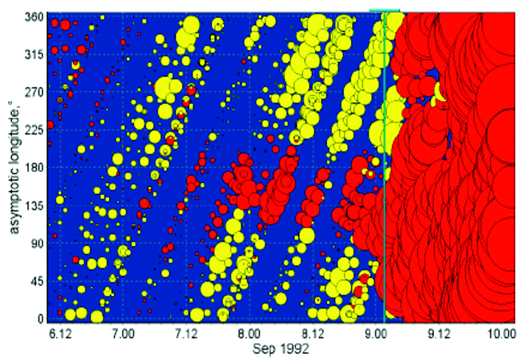


Fig. 1. Pre-increases (yellow) and pre-decreases (red) at various asymptotic longitudes before SSC before and during the geomagnetic storm in September 1992. Radii of circles correspond to the amplitude of CR variation [17].

before the storm onset. Other examples and the discussion on precursors based on CR are e.g. in papers [7, 18, 20, 21, 22].

In some cases also simplified measures of CR anisotropy is found to be changed few hours before the SSC onset. Comparison of middle/low latitude NM with strongly different asymptotic longitudes showed precursors 1-4 hr (change of the ratio of hourly counting rates at Lomnicky Stit and at Haleakala NM) before the decrease of Dst in few cases [24].

There is a large variability of precursory timing from anisotropy onset to the onset of geomagnetic storm. Anisotropy seen in CR during the motion of large scale inhomogenities and related shocks in interplanetary space depend on geometry, velocity and on direction of CME motion, as well as on the magnetic field structure.

There is observed not only variability in timing of precursors before the geomagnetic storms onset based on CR measurements, but also different time shifts between the time when Dst reaches its minimum and the warning based on IMF and solar wind data from ACE location as shown recently for events in cycle 23 [25]. Warning time ranges from 4 up to 30 h.

Geomagnetic storms are caused by the passage of an intense southward directed IMF lasting for sufficiently long intervals of time [26]. From "remote sensing" of interplanetary magnetic structures only by CR it is not easy to identify North-South polarity of the IMF which is important for the geoeffectiveness.

Different parts of energy spectra of CR, at least in some cases, behave differently before the FD. Pre-increase before the FD and particles accelerated at the shock front were indicated by combination of ground based NM and GOES-7 data during October 20, 1989 event [27]:different energy spectra < 1 GeV (shock accelerated, soft) and above (much harder, pre-increase) were oserved.

CR data have different responses to various kinds of interplanetary structures. For example CIR events formed by interaction of slow and fast solar wind streams originated in coronal holes affect the CR density decrease (e.g. [28, 29]). In paper [30]the transient perturbations in heliosphere and in the vicinity of Earth were discussed in connection to space weather perspective. It was found that the precursor to smaller ($< 5\%$) amplitude FD due to weaker interplanetary shock is the enhanced diurnal anisotropy. Larger amplitude ($> 5\%$) FD due to stronger interplanetary shock is related to loss cone type of the precursor.

In paper [31] by using of trajectory tracing in quiet solar wind and in the presence of interplanetary disturbance, the directions of CR arrival to magnetospheric border were obtained and the indications about CR anisotropy was deduced.

Bidirectional streaming of CR within the interplanetary CMEs (ICME) was reported in several papers (e.g. in [32, 33] among others). These signatures are sometimes observed before the onset of geoeffective events.

Precursory effects in cosmic rays: onset of radiation hazard events

Particles with the energy several tens to hundreds of MeV are most important for the radiation hazard effects during solar radiation storms: for the electronic element failures on satellites, for the communication, for the biological objects especially in space and at high altitudes. The ground based detectors of CR (at energies above the atmospheric threshold and at locations with various geomagnetic cutoff rigidity, if good temporal resolution and network of several stations is in real time operation), can provide useful alerts ranging from several minutes to tens of minutes in advance of the massive arrival of tens to hundreds MeV particles to the vicinity of Earth.

System for short-term radiation hazard forecasting is suggested e.g. by papers [34, 35, 100]. Probability of false alarms, missed alarms and model situation of the work of proposed system for historical events with extremely high fluence of energetic protons is checked. The simultaneous measurements at several NMs providing real time data with 1 minute resolution or better and with high statistics (high mountain, relatively high geomagnetic cutoff rigidity) combined with the reliable measurements of different multiplicities is important for this application.

Monitoring by ground observations

Neutron monitors

High latitude positions of the NMs have two important advantages in comparison with low and medium latitude NMs: (i) narrow interval of asymptotic longitudes near the equatorial plane and (ii) slight or none dependence of geomagnetic disturbances on asymptotics because the changes are mainly below the atmospheric cutoff.

Important information about the anisotropy of CR in interplanetary space provides the chain of high latitude NMs called "Spaceship Earth" which is described in [36]. It is the 11-station network of neutron monitors strategically located to provide precise, real-time, 3-D measurements of the CR angular distribution. It covers near equidistantly in GSE equatorial plane all asymptotic longitudes. More informations and real time data can be found at the site. http://neutronm.bartol.udel.edu/spaceweather/.

Plots in real time with hourly resolution at http://neutronm.bartol.udel.edu/spaceweather/ lossconegraph.htm contain the graphs of CR density (from 1^{st} order anisotropy fit); the averages of CR intensity relative to the density at each NM (different colors mean deficit and increase respectively, radius of circles mean the relative intensity); the deviations from 1^{st} order anisotropy fit at each NM and IMF magnitude, Bz and geomagnetic index Kp.

Spaceship Earth system allowed for the April 15, 2001 event to obtain the detailed time evolution of particle density and anisotropy; the indications about the diffusive transport; the estimate of λ_{par}; to identify the particle injection timing at solar source – results consistent with hypothesis that solar particles were accelerated by CME driven shock [37].

Results of the ground level enhancement real-time alarm system based on 8 high latitude NMs including those at high mountain are presented in [100].Three level alarm system (by number of NMs exceeding threshold value above that of baseline) is suggested. Out of 10 GLEs in 2001-2005 archived data the system produced 9 correct alarms. GLE system gives earlier warning than satellite (SEC/NOAA) alert ranging from 8 to 34 minutes.

Neutron monitor at a single site (at high latitude, with good statistics) allows to obtain real time energy spectrum. It was shown by using the South Pole measurements by combination of NM64 and that lacking the usual lead shielding for January 20, 2005 event [39]. The South Pole NM indicated the temporal evolution of energy spectra in wide energy range by combination with the satellite data which is giving the flux only at lower energies. Fig. 2 (courtesy of J.W. Bieber) is illustrating that.

Observations by more NMs at high latitudes for the same GLE provide the first alert of space storm: for minute 1 of the event (Mc Murdo 11%, Terre Adelie 4%) GLE warning is issued at the end (by 2 stations); For minute 2 (McMurdo 93%, Terre Adelie 73%) alert is issued by 3 stations.

For minute 14 earliest NOAA/SEC proton alert (10 MeV) is issued. (for that time interval the NM increases at Terre Adelie was 1146% and at McMurdo 816%). For each minute from model the pitch angle distribution, the predicted intensity for each grid point is computed and plotted in [39].

More NMs at high latitudes are useful for detailed study of GLE and alerts. From spring 2003 a new neutron monitor in Barentsburg (N 78.06, E 14.22) at Spitsbergen has been installed in operation within the northern polar cap region [40].

In addition to early GLE alerts by ground based NMs the forecasts from satellite data are reported. Recent study [41] demonstrates the important possibility of the short-term forecasting of the appear-

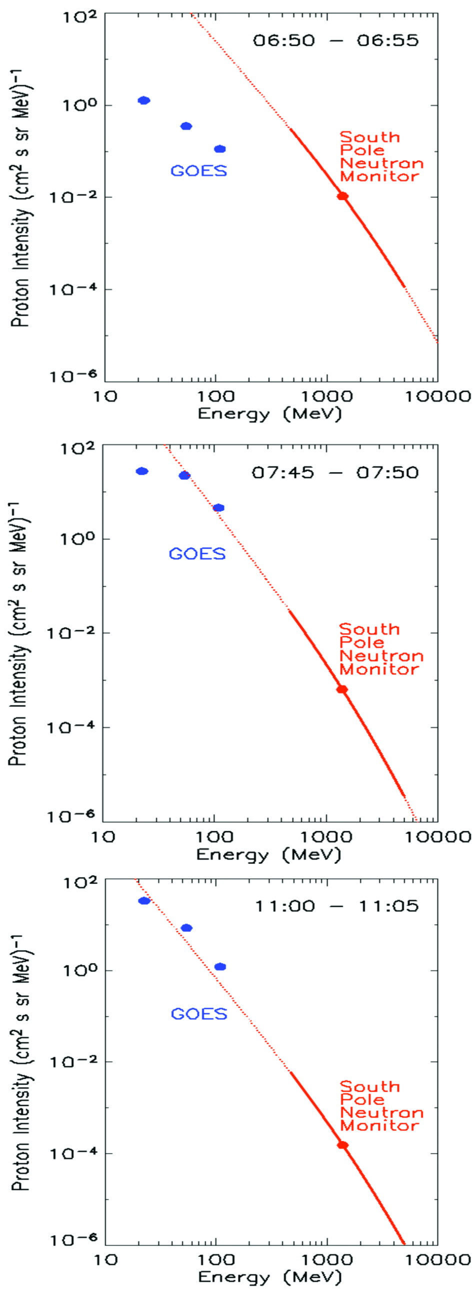


Fig. 2. Evolution of energy spectra of protons obtained by combining the NM at South Pole and GOES energetic particle measurements on January 20, 2005 [39].

ance and intensity of solar ion events by means of relativistic electrons measured on satellites. The onset of 31-50 MeV protons over relativistic electrons is ranging from 10 to >100 min.

Middle latitude neutron monitors have disadvantages (wide interval of asymptotic longitudes, effects of geomagnetic disturbances on acceptance), but they provide useful info about very high energies. Role of NM network for space weather monitoring and forecast is reviewed e.g. in [42]. Combining 15 NM stations with cutoffs from polar to ∼10 GV, real data collection in Athens was organized recently for purposes of prediction of space weather effects [43]. Alerts for SPE and geomagnetic storms are based on algorithms of fast increases in 1 min data and on variability of CR density and anisotropy, respectively. System forecast was succesfully used for GLE and geomagnetic variations in January 2005 [44, 45].

There are several web sites with NM CR data in real time with good time resolution. One of the very informative (including many links to other sources, CR activity index, list of CR storms since 1997, recent GLEs etc) is at IZMIRAN, http://helios.izmiran.rssi.ru/cosray/main.htm. For networking one of important questions is the stability of the detectors checked recently in paper [46].

A Real Time Cosmic Ray Distributed (RECORD) database is using simultaneous data from 6 NM far spaced (in longitude). Using index based on amplitude dynamics of the fluctuation spectrum of CR (similar to [47]), e.g. the alarm of FD in January 2005 was found nearly 1 day before its onset [48].

In addition to use of NM at different sites, there exist installations for space weather monitoring and eventual forecasts at single point.

The combination of high mountain neutron monitors, solar neutron telescope, and muon telescopes at two elevations with high statistical accuracy built in Armenia is in operation for several years [49, 50, 51] with the data available at http://crdlx5.yerphi.am/DVIN/.

For middle latitudes the GLE identification is not always simple due to relatively low flux of high energy protons. Recently the Student statistical criterion was found useful for that [52].

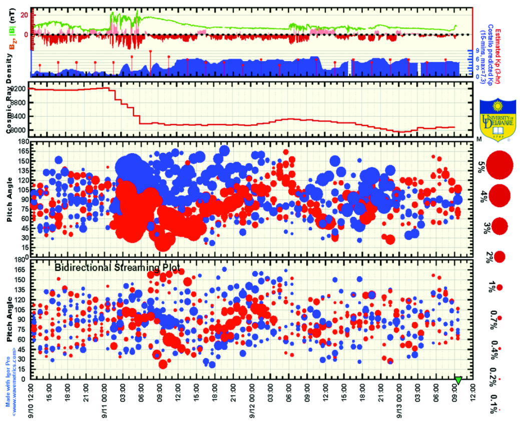


Fig. 3. The anisotropy obtained from Spaceship Earth [38]. Second panel is CR density. Third panel is hourly average of the CR intensity at each station relative to CR density. Fourth panel is residual deviation after subtracting the fitted 1^{st}order anisotropy. Red and blue circles mean deficit and excess of intensity, respectively. A bidirectional CR streaming is indicating that the Earth was within a large ICMEs (in the lowest panel red at $\sim 90^{\circ}$ pitch angle, blue at the edges for residual deviation nearly parallel to **B** – solid line below). Although a loss cone precursor was not observed (low PA are not covered well), the bidirectional streaming is apparent from ∼1800 on Sept 11 to ∼0300 on Sept 12 [38].

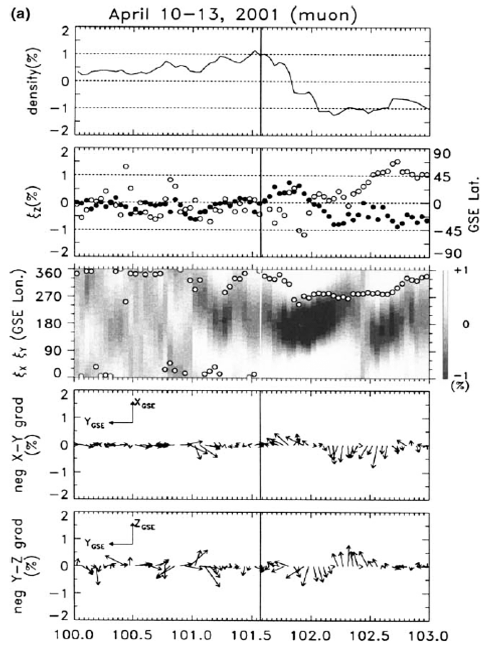


Fig. 4. Potential possibilities of muon detector network providing alert well before the geomagnetic disturbance with SSC onset on April 11, 2001 [53]. The anisotropy enhancement is seen half a day before SSC (third panel). Density gradients deduced from anisotropy show CR depleted region in CME approaching and passing the Earth.

Combined monitoring system by ground based measurements at different CR energies

Paper [38] describes the real-time system to monitor CR for space weather forecasting, combined of NMs and muon detectors. Event in september 2005 is illustrating the possibilities of the system in Fig. 3.

It was shown that multidirectional muon telescopes at high energies of primary CR provide indication about the anisotropy change well before the geomagnetic storm onset. Around CR depleted region a ($\mathbf{B} \times \mathrm{grad}\, n$) drift flow driven by a density (n) gradient $\perp$ to $\mathbf{B}$ (IMF) may appear sometimes before shock passage.

Geometry of CME on October 29, 2003 was deduced from the muon anisotropy in paper [54]. Network of muon telescope detectors covering by asymptotics many directions in interplanetary space is important for detailed anisotropy study at high CR energies. The site http://neutronm.bartol.udel.edu/spaceweather/ presents, similarly to NM plots, also the real-time plots of muon network loss cone, bidirectional streaming and CR flow direction in GSE system. At present the muon real-time data are based on observations from multi-directional muon detectors in 3 locations: Nagoya (Japan), São Martinho (Brazil), and Hobart (Australia). From March 22, 2006 muon hodoscope began operating at the University of Kuwait and is now contributing real time data to that site.

The first european muon device of similar type situated in Germany [55] is in testing operation and will cover other asymptotic directions. The new installations of muon detectors in other places are important for detailed study of the CR anisotropy at high energy.

CR and energetic particle effects on materials

Satellite anomalies and radiation effects

There are many effects of energetic particles and cosmic rays on technological systems, especially on satellites and airplanes. Among satellite anomalies the effects of plasma induced charging (external and internal), sputtering effects, surface erosion due to the oxidation, phantom commands, induced mode switching, loss of attitude control/orientation, loss of signal phase and amplitude lock, solar cell degradation and common electronic malfunctions are listed recently e.g. in paper [56].

A complete review on particle interaction and displacement damage in silicon devices operated in radiation environment including (not only) the effects in space can be found in paper [101].

The satellite anomalies were studied recently for example in paper [57]. The authors found clear difference between satellite anomaly probability and various physical characteristics of interplanetary space, geomagnetic field and energetic particles of different energy and type. The table in the study [57] indicates the differences especially for quiet and dangerous days in the values of proton flux and in its daily maximum for >10 MeV. The same is valid for the high energy electron fluence.

Relations between the occurrence of high and low-orbit satellite anomalies and the solar, interplanetary and geomagnetic activity as well as energetic particle fluxes is statistically studied on large data set ($\sim$ 5700 satellite anomalies) in papers [58, 59, 60].

The satellite anomalies vs CR activity indices were also studied in recent years. Earlier, various indices of CR activity (empirical) were introduced (e.g. [61, 62, 63] among others). For several NMs the variability index is routinely produced. For example the CR index of Moscow neutron monitor station is available in real time at http://helios.izmiran.troitsk.ru/cosray/indices.htm. Fig. 6 shows the relation between CR variability/anisotropy to the probability of the satellite anomalies.

There are much more works done on satellite anomalies which are not included in the reference list. One of reviews of radiation field including galactic and solar cosmic rays beyond the low Earth orbit can be found e.g. in [66] and more complete review of radiation hazard in space e.g. in [102]. The predictions of radiation situation near Mars are described in [103]. One of the summaries of geophysical aspects of solar energetic particles is presented in paper [104]. Models of solar energetic particle fluxes are recently discussed e.g. in the study [105]

For the construction of models and predictions of the satellite and space probe anomalies, the monitoring of energetic particle flux, its variability as well as the energy spectra and angular distri-

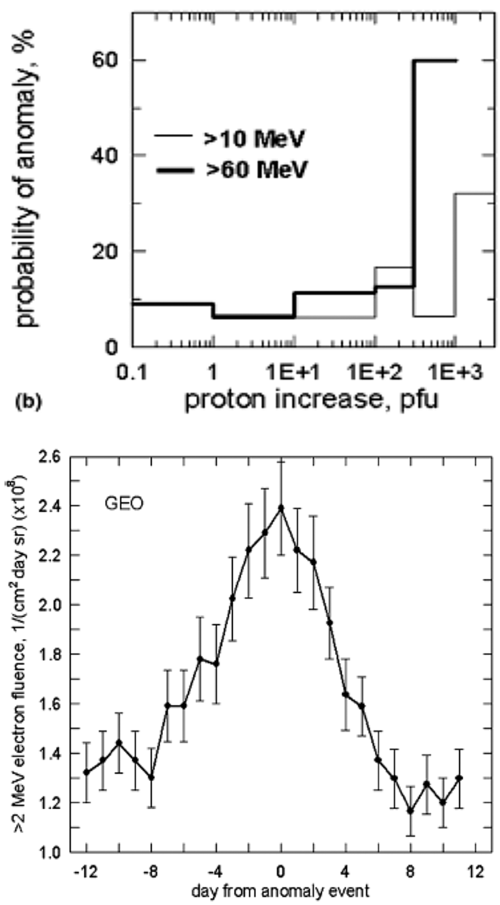
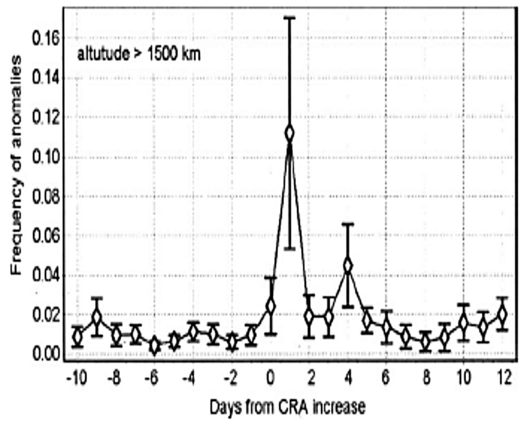


Fig. 5. Upper panel: the anomaly probability increases (especially for high altitude, high inclination orbits) with energetic proton fluence. Lower panel: the importance of relativistic electron fluxes for the anomalies at geostationary orbits and at low-altitude (<1500 km) high inclination (>55°) orbits was indicated (from papers [58, 59, 60]).



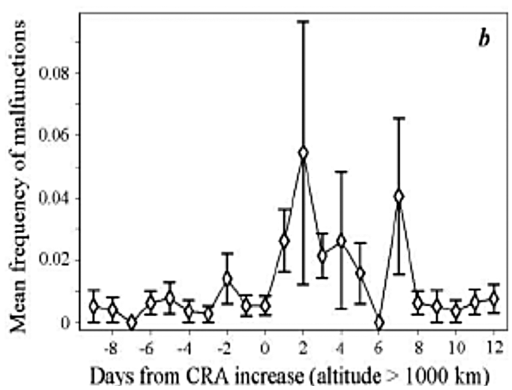


Fig. 6. Upper panel: the authors of [64]found clear relationship of high altitude satellite anomalies and the increase of CR anisotropy index. Lower panel: even a CR variability index constructed from a single high mountain middle latitude station with high statistical acurracy (Alma-Ata) has the relation to the frequency of the satellite anomalies [65].

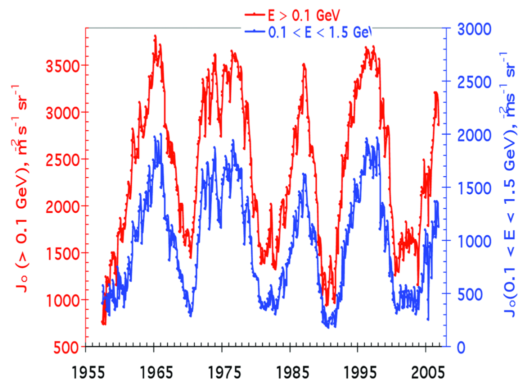


Fig. 7. Monthly means of galactic cosmic ray fluxes (E > 0.1 GeV, red) and (0.1 < E < 1.5 GeV, blue) falling on the top of the atmosphere. Homogeneous longest sets of data have been obtained from measurements of charged particles in the stratosphere from July 1957 till December 2006. About 80 thousands of radio sounds launchings were performed during this period [67]. Yearly means can be found in [68].

bution is important to be provided systematically along with utilizing data from earlier experiments.

CR and atmosphere

The role of cosmic rays in atmospheric processes is very important and it is in the centre of interest for example due to the study of causes of global changes and of the electricity effects in the atmosphere. Here we mention only few selected points.

For these type of studies (i) the reliable long time series of cosmic ray measurements not only by NMs and MDs (ground), but also at high altitudes; and (ii) codes of computations of ionisation and dose, are needed.

Recently some of the atmospheric effects by CR are briefly reviewed in [69]. Consistency of different models used for ionisation computation by CR was found and the electron production rate caused by galactic CR was estimated at higher altitudes.

One physical model to calculate the cosmic ray induced ionisation in the atmosphere can be found in paper [70].

High energy CR accelerated at Sun/in interplanetary space strongly affect the ionisation, especially at high latitudes. For the event January 20, 2005 the dose in the south was significantly increased due to the strong anisotropy of proton flux (Fig. 9).

CR and solar energetic particles affect the chemistry at upper/middle atmosphere (e.g. [73, 74]). Recently the authors of [75] found two weak and short (<12 h) ozone depletions at outer boundary of polar cap in connection with January 2005 GLE. For mesospheric ozone decrease a N-S asymmetry was found (decrease weaker in southern regions).

It was shown that even solar energetic particle events with relatively low fluxes strongly affect the mesospheric chemistry at elevated latitudes

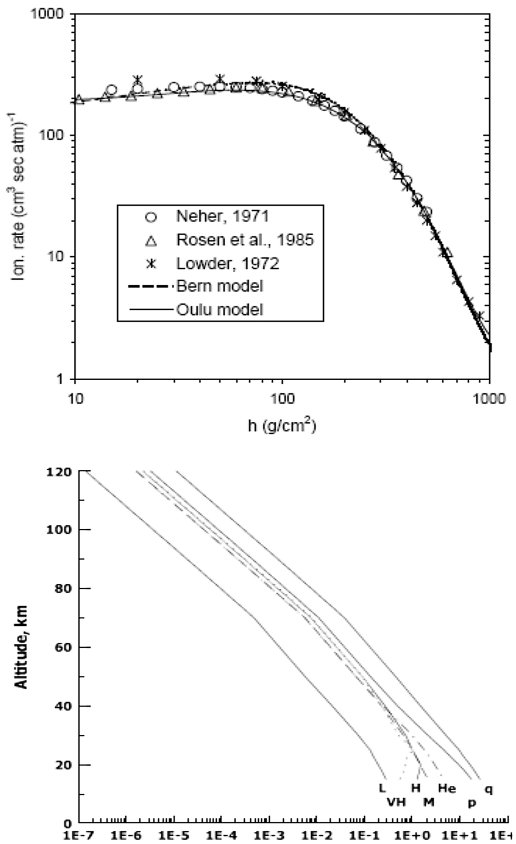


Fig. 8. Measured and calculated ion production rate for solar maximum. Lower panel: Electron production rate (cm^{-3}.s^{-1}) by GCR in solar minimum [69].

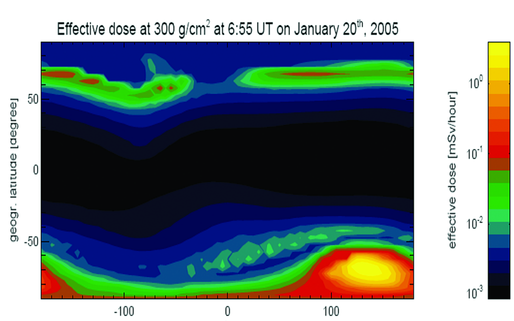


Fig. 9. Results of the computations of the dose done by using the code PLANETOCOSMICS http://cosray.unibe.ch/∼laurent/planetocosmics/ (group of University of Bern, Switzerland) for January 20, 2005 event [71, 72].

and their impact is different in the day and night hemispheres. When different solar energetic particle (SEP) events have comparable maximum flux, the most relevant SEP feature is its fluence. SEPs with low content of high energy particles result in a smalller perturbation of the lower atmospheric layers. The seasonal conditions are important for SEP influence in the atmosphere.

In paper [76] there were summarized the effects of strong geomagnetic storms and FD on ozone in northern higher middle latitudes, and complete them for storms not accompanied by strong FD. FDs seem to play a very important role in the effects of geomagnetic storms on total ozone. Although majority of strong FD appear during geomagnetic disturbances, there are rarely also other types of events [77] which can be used for discrimination between FD and geomagnetic activity effects separately, however the statistics is not sufficient yet for such type of study.

While GLE increase ionisation and dose in the atmosphere, strong FD indicate clear depression of the dose measured on airplanes [78, 79].

Lantos (in paper [106]) reviewed doses on airplanes during FDs in 1981-2003 and using NMs he proposed a simplified method to estimate dose variations from galactic cosmic ray variations during Forbush decreases. Recently, there were reported some empirically found relations of CR to atmospheric processes. We mention only few of those results.

Paper [80] indicates that long-term increase of pressure in North Atlantic (1874-1995) coincided with secular rise of solar/geomagnetic activity accompanied by galactic CR decrease. Authors stress the possible links between long-term variations in cyclonic activity at extratropical latitudes of North Atlantic and solar activity/galactic CR variations on time scales $\sim$10 – $\sim$100 yr. The effect of intensification of the cyclone regeneration in North Atlantic by solar proton events is reported in [81].

In papers [82, 83] there were analyzed empirically the relations between hurricane occurrence and the behavior of CR, geomagnetic and solar activity indices in days before and after events. The authors report specific profile of CR and indices before the events, which may be assumed as one eventual type for the alerts.

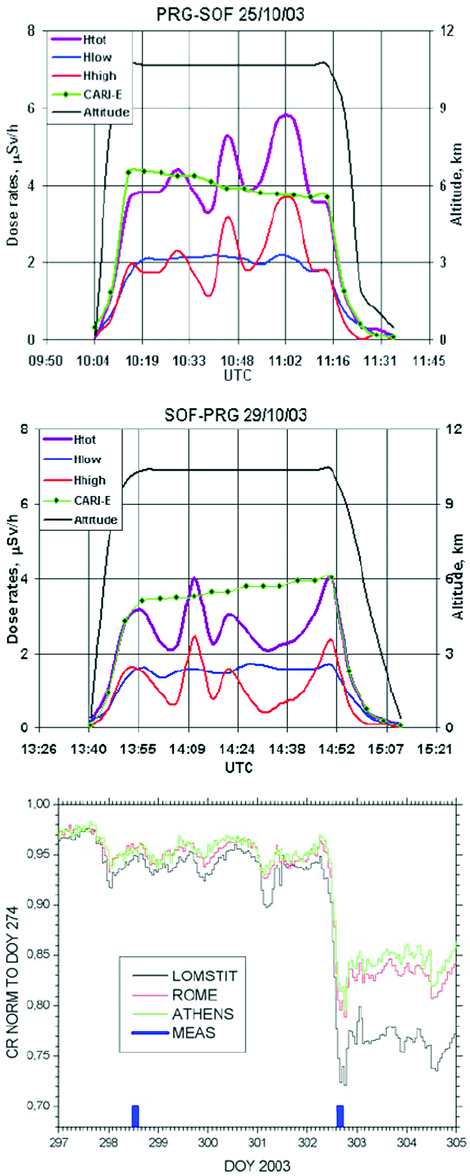


Fig. 10. The doses measured on the same route at airplanes between Prague and Sofia are clearly different during the FD on day 302 (middle panel), in comparison with day 298 (upperpanel). The blue intervals in the bottom panel correspond to the time of the dose measurements. The existing models using galactic CR flux only are not well describing the situation during the decreases of CR [78].

The periodicities in minimum temperature in northern Mexico for 1929-1974 have been found similar to those which can be related either to CR fluxes, occurrence of SSC, geomagnetic activity, solar magnetic flux emergence (among them that at $\sim$1.7 yr) [84].

Role of CR (among other factors) in GEC – the global electric circuit linking the electric field and the current flow in lower atmosphere, ionosphere and magnetosphere forming a large spherical condenser, which is charged by thunderstorms to several hundred kV, is discussed recently with the extensive list of references in [85].

CR in relation to health and to chronobiology ?

In CR time series there are many quasi-periodicities with their variable contribution to the signal over long time interval of CR observations. Quasi-periodicities $T > 27$ days up to $\sim$115 days in CR are described e.g. in papers [86, 87]. Long-term evolution of low frequency in CR is described e.g. in paper [108]. Occcurrence in mid-term periodicities in solar wind, geomagnetic activity and CR was studied e.g. in paper [88]. Different periodicities in the range 4 - 47 months in several solar indices and CR were reported in [89].

Fluctuations of solar magnetic flux at $\sim$1.3 year and $\sim$1.7 year with the alternating importance during even and odd solar cycles were found in study [90]. The periodicity $\sim$1.7 year was first reported in CR time series in the paper [91]. Such quasiperiodicity is also the dominant fluctuation in the solar magnetic flux [92]. Similar quasi-periodicity is recently reported also in the solar motion due to the inner planets [96].

It is of some interest to check the similarities in quasiperiodicities of CR time series with those reported in chronobiology. The progress in chronobiology reviewed in [93] mentions some relations to the studies of periodicities in CR. According to ([94], personnal communication) only at one frequency there is congruence of studied variables in a healthy man over 4 decades with solar, geomagnetic and CR frequency and it is the period of $\sim$1.7 year.

Alignment of various data on health (epidemiological, physiological etc) with the variations of

CR, geomagnetic activity and atmospheric pressure suggests the possibility of links among these environmental variations and health risks, such as myocardial infarctions and ischemic strokes, among others [95].

In the study of relations between car accident events and CR, solar and geomagnetic activities the indications on such relation to outer conditions, especially around the epoch of solar minimum was reported [97]. In paper [98] there were found significant differences in some parameters of mental performance and health of aviation personnel during the solar minimum and solar maximum epochs.

Most of these type of studies are empirical (statistical). The processes involved depend on many parameters, and both the clear causality as well as the mechanisms behind are not completely and satisfactorily clarified yet.

Concluding remarks

Real-time ground level event alert system based on NMs is an important new tool for early warning of radiation storms. A combination with the high energy electron alerts on satellites/space probes may be of interest.

Combination of high latitude neutron monitor and muon directional measurements provides continuous real-time monitoring of the variation of CR density and anisotropy in the interplanetary space which is important for eventual alerts of geomagnetic disturbances.

Real time global networking using existing systems and adding more available measurements (middle/low latitudes, satellite observations with the large geometrical factor) are needed for possible, “remote sensing” of the redistribution of large scale interplanetary magnetic field and plasma structures.

Using old data sets and its detailed analysis is important to check the various alert systems with using cosmic ray signatures in the connection with space weather events. The same is required for the quiet time periods.

Empirically found relations of cosmic ray variability to atmospheric processes and especially to health characteristics require more interdisciplinary studies.

This paper is based on collection of only limited number of papers relevant to the title. The author apologizes for not including other papers, e.g. those on solar flare and/or interplanetary space accelerated particles; on magnetospheric transmissivity of energetic particles; on space climatology and galactic cosmic ray variability, in particular.

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