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On low energy cosmic rays and energetic particles near Earth

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Abstract. This paper is an update of the review paper (Kudela, 2009) including selected results and activities over the past 7 years related to ground based measurements of Cosmic Rays (CR), modulation of CR by the heliosphere, solar CR, transitional CR variations, geomagnetic filtering, energetic/suprathermal particles in the Earth's surrounding, and relations of CR to space weather effects and atmospheric processes.
Key words: cosmic rays

1. Introduction

In 2012 a century since the discovery of cosmic rays (CR) by Victor F. Hess (1912) was celebrated. Several reviews on CR and on history of its research were published around that anniversary (e.g. Walter and Wolfendale, 2012; Müller, 2012; Grupen 2013; de Angelis 2014; Bazilevskaya 2014; Muraki 2011; Logachev *et al.* 2013 among others). History of CR research is described in several books and papers. One of the recent extensive and detailed reviews is in the book (Dorman and Dorman, 2014).

This paper is an attempt to update the papers (Kudela, 2009; 2012) and to include some specific parts not covered earlier. It is not an exhaustive/complete review on energetic particles in space. In the subsequent sections some of new papers published after 2009 are mentioned. Very high energy CR results are not included, and only the direct CR measurements are inserted with references. Since the main point here is CR and energetic particles in the surrounding of the Earth, there are not mentioned results from several important missions to planets and e.g. the STEREO mission.

Variations on long term scales (> several tens of years) are the subject using indirect methods of CR measurements, based mainly on a cosmogenic nuclide analysis in materials exposed to CR for a long time. These topics, very useful for estimates of e.g. solar activity in the past are not included in the current review. Overviews on that can be found e.g. in papers (Gosse and Phillips, 2001; Ivy-Ochs and Kober, 2008) as well as in the books (Dunai, 2010; Beer *et al.*, 2012).

Important new results on CR were obtained from PAMELA complex instruments as well as by AMS-02 detectors on low altitude orbits. One of them is the precise measurement of CR proton and He spectra at energies from those below the sensitivity of ground based measurements up to very high energies (Adriani *et al.* 2011; Aguilar *et al.* 2015). An upper limit of the antihelium flux in CR is reported by Mayorov *et al.* (2011). The flux of antiprotons in the energy range from 60 MeV to 350 GeV has been obtained too (Adriani *et al.* 2012). Electron and positron fluxes in primary CR have been reported from both experiments, AMS-02 and PAMELA (Aguilar *et al.* 2014; Adriani *et al.*, 2016). Gusev *et al.* (2001), by the study of the nuclear interactions of CR in the atmosphere, suggested a source of positrons with a possibility of their trapping in the magnetosphere. Mikhailov *et al.* (2016) present spatial distributions of trapped, quasi-trapped and short-lived albedo electrons and positrons in the near Earth space according to PAMELA observations.

In the following chapters we present a short review of selected results and scientific activities with references on the ground based measurements (chap.2), the heliospheric modulation of CR (chap. 3), contribution to the CR flux from solar and interplanetary acceleration (chap. 4), short term or transitional CR variations (chap.5), geomagnetic filtering of CR (chap. 6), energetic and suprathermal particles within the magnetosphere of the Earth and near its boundary regions (chap. 7), and, finally, CR relations to selected space weather effects and atmospheric processes (chap.8).

2. Measurements by neutron monitors and muon detectors

After 50 years of measurements by neutron monitors (NM) at different sites, at various altitudes and for different periods of time, the network of those instruments still remains to be an important tool for the study of primary CR variations in the rigidity range between 1 and 15 GV. History of a half of the century of measurements by NMs and of results obtained from them has been the subject of papers collected in a special issue of Advances in Space Research (Storini, 2009).

In recent years new NMs have been put into operation and collection of the data has been updated. In October 2011, an NM64-type NM with a vertical cutoff rigidity of 11.2 GV started the measurements at Daejeon in Korea (Kang *et al.*, 2012). Until 2014, 37 Forbush decreases (FDs) at Daejeon and at the position with a lower geomagnetic cut-off rigidity, namely Oulu have been reported (Kang *et al.*, 2016). The Castilla-La Mancha neutron monitor (CaLMa) in Spain, with a vertical cut-off rigidity of 6.95 GV started its full operation in July 2012 (Medina *et al.*, 2013; Blanco *et al.*, 2015) and observed at least 29 FDs. A new NM with He3 tubes used for CR observatories in Chile is described by (Cordaro *et al.*, 2012). While energy spectra and anisotropy of CR are deduced from many NMs with individual characteristics, the calibrations of NMs producing data over a long time period, is of importance (Krüger and Moraal, 2010; 2013). Semikh *et al.* (2012) report the NM design at Plateau de

Bure, France (2555 m a.s.l., in operation since 2008) and complete a numerical simulation obtaining in detail the NM detection response function for neutrons, muons, protons and pions at that altitude. The NM data processing center in Athens is introduced by Mavromichalaki *et al.* (2009).

In addition to "classical" NMs a new design with a smaller size and weight and with rather high sensitivity, and thus being of importance for inter-calibration of NMs at different positions, namely mini neutron monitors, have been developed in past years and installed in operation (Poluianov *et al.*, 2015; Heber *et al.*, 2015, Krüger *et al.*, 2015). The altitude profile has been obtained recently with a mini NM (Lara *et al.*, 2016).

Assuming different characteristics of NMs from those obtained from cosmogenic nuclides, the use of the 10Be flux to study heliospheric phenomena as an extension of NM records in the past are discussed by (Beer *et al.*, 2013).

Secondary neutrons are of interest since they contribute up to 60% to the dose from CR at flight altitudes and they are important also at high mountain positions (Rühm *et al.*, 2009). Bonner Sphere Spectrometers (BSS) are used for monitoring neutrons at Zugspitze. Comparison with a high mountain NM and with other measurements indicates that BSS measurements could be used to monitor the flux of secondary neutrons from CR if the data are restricted to neutrons $E > 20$ MeV (Rühm *et al.*, 2012). BSS measurements are compared with NM ones also at a high geomagnetic latitude (Pioch *et al.*, 2011). Hubert (2016) described recently new high-altitude platforms operated in the Concordia stations since December 2015. By comparison with Pic-du-Midi, Pico dos Dias and the reference laboratory in Toulouse, the author reports a first neutron network dedicated to study the atmospheric radiation field based on neutron spectrometry. A BSS extended to high energies (HERMEIS) was set up at the summit of the Pic du Midi de Bigorre in the French Pyrenees (2,885 m a.s.l.; geomagnetic cutoff 5.6 GV) in May 2011 (Cheminet *et al.*, 2013). The authors analyzed FDs and derived an analytical model to estimate the atmospheric neutron spectrum at the the site according to primary spectra depending on the solar modulation potential.

Relations between the variability of the primary CR flux and that measured by NMs as well as by muon detectors is of essential interest. In addition to earlier works (e.g. Clem, 2004; Clem and Dorman, 2000; Nagashima *et al.*, 1990; Flückiger *et al.*, 2008 and references therein), the recalculation of the primary CR flux variations above the atmosphere deduced from those measured by NM on the ground has been checked by new computations/simulations of the yield and response functions and compared in some cases with a latitudinal profile of the count rate by NM(s) in past years. Gil *et al.* (2015) verified the new yield function of NM using data from the PAMELA satellite measurements of CR during 2006-2009 and the NM latitude survey in 1994-2007 including intervals with high solar activity. The authors found a very good agreement between the measured count rates of sea level NMs and the modeled ones in different conditions. Maurin *et al.* (2015) discuss the uncertainty for NMs related to the yield function and to other effects. Functions useful for inferring the primary CR variability from ground based NMs and from muon detectors can be found e.g. in papers (Mishev *et al.*, 2013; Caballero-Lopez and Moraal, 2012; Mangeard *et al.*, 2016; Caballero-Lopez, 2016). The surrounding structure of NM is important for the count rate measured. Monte Carlo simulations of the count rate inside and outside the building with NM and the use of the calibration detector provided validation of the model of the yield functions of NMs (Aiemsa-ad *et al.*, 2015).

Lead-free NMs with different sensitivity to energies of the primary CR than usual NMs (e.g. Shah *et al.*, 2010) have been used for measurements over the past period. The paper (Mufti *et al.*, 2016) presents the lead free Gulmarg NM detector design, salient features and a detailed FLUKA – Monte Carlo approach for modelling sensitivity and energy response of that neutron detector. It is seen that a BF3 proportional counter, when surrounded with a hydrogenous moderating medium, extends the useful sensitive energy range of neutrons from thermal to high energies. Solar modulation studies by Gulmarg lead-free NM indicate significant consistency with the data recorded by the Emilio Segre observatory, Israel (ESOI) NM (Darzi *et al.*, 2014). However, the same type of consistency is not observed in the data recorded by the other conventional NMs.

While NMs are used mainly for detection of the temporal variations of the primary CR at longer time scales, the recent paper (Ruffolo *et al.*, 2016) shows that NM (in that case at the highest vertical geomagnetic cut-off rigidity, 16.8 GV, PSNM) can also monitor short-term changes in the GCR spectrum. After atmospheric corrections, a substantial short-term GCR spectral hardening during some but not all FDs in the GCR flux is reported. The data-acquisition system recording the time delays between successive neutron counts at the same tube is working at PSNM. Another similar method has been suggested and started to measure in the NM recording schemes at Lomnický štít (LS, Kollár *et al.*, 2011). Korotkov (2012) describes a method for registration of neutron multiplicities in NM including automatic adjustments with allowance for the effect of coincidence, which is very important for correct obtaining of multiplicities.

Not only are variations of primary CR spectra based on NM examined, but also new instrumentations with high statistical accuracy and good temporal resolution are promising for future studies of CR variability on short term scales. An FD in August 2006 was observed on a satellite with very high time resolution (Mulligan *et al.*, 2009). Regarding high statistical accuracy for the study of transitional effects of the primary CR variability, there have recently been published papers using the scaler mode of the Pierre-Auger project (The Pierre-Auger Collaboration, 2011; Dasso *et al.*, 2012) indicating possibilities of CR solar modulation studies using that mode.

Muon measurements continued in the period reviewed. The Space Environmental Viewing and Analysis Network (SEVAN) has been put into operation in several laboratories. Its description and first results can be found in the paper by Chilingarian (2013). Since March 2014, after tests in Košice, there has been installed one detector system of the type mentioned above (Langer *et al.*, 2010) at LS (altitude 2634 m a.s.l., nominal geomagnetic cutoff 3.84 GV). The complex of the NaI detector network at the Aragats is described by Avakyan *et al.* (2013). Barometric coefficients for the correction of various CR devices at the Aragats center during the start period of solar cycle 24 are summarized by (Chilingarian and Karapetyan, 2011). A muon-neutron telescope has been put into operation at Yangbaijing (described by Zhang *et al.*, 2010). Muon detector recordings (measurements at KACST) have been examined for corrections on the atmospheric depth, the pion production layer height and the temperature (Maghrabi *et al.*, 2015; Maghrabi and Almutayri, 2016). An interesting point is that after usual atmospheric corrections the temperature at the pion production level has a different sign of correlation with muons in spring and winter, and opposite in fall and summer. Seasonal variations of muon recordings are still needed to be examined in the future. CR measurements and checking the temperature with a muon detector is reported by Yun Ho Kim *et al.* (2012).

With improvement of measurements and with data collection from many NMs and muon telescopes (MT), one of the most important activities is that connected with the Neutron Monitor Data Base (NMDB, Steigies, 2009; Klein, 2010; Mavromichalaki *et al.*, 2011). All information can be found at `http://nmdb.eu`. Starting from European NMs, subsequently data from more stations in other continents are included in the data base. Hourly data from many NMs, including those which are not currently in operation, are stored at `http://center.stelab.nagoya-u.ac.jp/WDCCR`. Many data from NMs can be found at `http://cr0.izmiran.ru/common/links.htm`. The data require appropriate processing. Papers by (Dudok de Witt *et al.*, 2009; Sapundjiev *et al.*, 2014; Paschalis and Mavromichalaki, 2012, 2013; Paschalis *et al.*, 2013a) introduce various methods used for correct processing and/or techniques revealing weak transients in NM records. The online method for barometric pressure coefficient calculations for NMDB NMs is introduced by (Paschalis *et al.*, 2013b). Some NMs, especially those situated at high mountains (including LS), have problems in corrections of the snow accumulated above/around NMs and with the strong wind. The first question is discussed and a procedure suggested by Korotkov *et al.* (2013). A useful data base of CR anisotropy considerations is described by Asipenka *et al.* (2009).

As NMs are measuring several tens of years, the question about the long-term stability of the data is a natural question for a correct description of long time variations of CR. Ahluwalia and Ygbuhay (2012) checked the instrumental drift in the counting rate for a couple of NMs and present evidence that some of the high latitude NMs are undergoing long-term drifts in their baselines. The authors argue that there is no physical basis to justify the observed long-term downward trend in the baseline of the South Pole NM. Paper by Oh *et al.*, (2013) examined 15 NM count rates (stations operated for a long time). By checking the changes in sensitivity the authors obtained a consistent picture. Using as a reference 4 NMs in the northern and 4 in the southern hemisphere, all NMs analyzed display a maximum at the recent solar minimum, approximately 3% above the previous one. In Table 3 of the cited paper there is mentioned the excess over the trend line at the beginning of cycle 24. The lowest excess is obtained for two high mountain european NMs, namely Jungfraujoch (1.1%) and LS (1.0%). Also the Rome NM has a relatively low excess (1.2%). This fact should be examined in the future.

3. Heliosphere: modulation of galactic cosmic rays

Parker (1958a,b) showed that the hydrodynamic outflow of gas from the Sun (solar wind) leads to reduction of the CR intensity in the inner solar system. The explanation of the solar cycle activity anticorrelation with CR flux near the Earth ($\sim$ 11 year periodicity) was suggested. Parker also suggested that perhaps the FDs are the result of disordering of the outer magnetic field by the outflowing gas from the Sun. The outward flow of the solar wind results in the radial density gradient of galactic cosmic rays (GCR) in the heliosphere due to diffusion and convection. The inward diffusion, outward convection and drifts of CR (along with adiabatic cooling/heating at plasma discontinuities) in the heliosphere are the main controlling mechanisms for particle transport. In addition the scattering on IMF inhomogenities also influenced the CR flux. Parker (1964) and Krymsky (1964) independently indicated that including a diffusive inward flow, in near balance with the convective radial outward flow, is important for the observed (at that time) amplitude of the diurnal anisotropy. The passage of CR particles and energetic solar particles through interplanetary space and the dynamics of the interplanetary gas and IMF were discussed by Parker (1965a,b). The particle distribution, which is described by Fokker-Planck equation, corresponds to irregularities (IMF) moving with the solar wind speed. The expression for a particle diffusion coefficient was worked out, including scattering in IMF irregularities and systematic pressure drifts. According to magnetometer data in the interplanetary space available for that time, Parker assumed the CR moving more freely along B than across, and estimated the order of the diffusion coefficient. CR density gradient was estimated $\sim 10\,\%/\mathrm{AU}$ at the Earth‘s orbit. As a first approach, the isotropic diffusion of CR in a spherical region was assumed.

An extensive review of the status of the knowledge on the solar modulation of CR, with the relevant references, is published by Potgieter, 2013. Moraal (2011) provides the survey of mathematical tools needed to describe the modulation of CR in the heliosphere, includes the CR transport equation, and describes its solutions. Kóta (2013), with references therein, surveys the past and future trends in the theory and modeling of GCR in the heliosphere, discusses the theory of diffusive transport, drifts, the force- field approximation, and numerical methods. Special attention is paid to modeling of CR in the heliosheath, to an unusual deep solar minimum 23/24 and to understanding of high rigidity CR anisotropies. Papers by (Jokipii *et al.*, 1977; Jokipii and Levy, 1977, Isenberg and Jokipii, 1978; 1979) were among the first pointing out the importance of drift effects in IMF for the modulation of CR. The role of drifts for particle transport in a wavy heliocentric current sheet is discussed by (Jokipii and Thomas, 1981). The recent paper by Cholis *et al.* (2016), using numerical tracing of CR particle trajectories in the heliosphere for different magnetic polarities of the Sun, indicates the difference for the access of CR from the outer heliosphere due to drift effects being of a different character for opposite polarities. Numerical solutions of the transport equation of CR including drift effects have been presented by Potgieter and Moraal (1985). Recently, the importance of curvature and gradient drifts of CR (different in the oposite solar magnetic polarity) has been shown by Nuntiyakul *et al.* (2014) by the analysis of NM data during 1994 - 2007 series of latitude surveys. The authors confirmed the crossover in energy spectra measured near solar minima during the epochs of different solar magnetic polarity. The contribution of the drift effects to the global GCR modulation has been estimated to be between 30% and 35%, depending on the CR particle energy, according to the analysis done on several NM data (Laurenza *et al.*, 2014). The solar magnetic cycle dependence related to different drift influences in the corotating modulation of GCR is examined by Gupta and Badruddin (2009). Thomas *et al.* (2014) analyzed the behavior of GCRs across heliospheric current sheet (HCS) crossings. By 402 events where the HCS has crossed the Earth, and using a superimposed epoch analysis, the authors by splitting the data by the polarity at each solar polar region, found that the increase in the GCR flux prior to the HCS crossing is primarily from strong compressions in cycles with negative north polar fields due to drift effects.

The theory of GCR transport in the heliosphere and the modulation is quite well developed (e.g. Potgieter (2013)). For practical purposes some parametrization of the energy spectrum of GCR near the Earth is required (e.g., Vainio *et al.*, 2009). For long term variations of CR, a useful parameter is the modulation potential. The GCR spectrum near the Earth is well approximated by the force-field model introduced in papers (Gleeson and Axford, 1968a, b; Caballero-Lopez and Moraal, 2004) with just one parameter – the modulation potential. Monthly means of that parameter, suitable for description of medium time CR variability, is available over the period 1951 – 2004 in the paper by Usoskin *et al.* (2005). Force-free parametrization was shown to describe the energy spectra of GCR also on a short term scale (strong FDs) quite well (Usoskin *et al.* 2015). The solar modulation parameter has been reconstructed from measurements of NMs and ionization chambers for a rather long time period since 1936 (Usoskin *et al.*, 2011). Alanko-Huotari *et al.* (2006) indicate that the combination of the open solar magnetic flux, the tilt angle of HCS and the polarity of heliospheric magnetic field explains a majority of the modulation potential variations over more than a half of century.

The anisotropies of CR measured on the ground have to assume the Compton-Getting effect (Gleeson and Axford, 1968b) similarly as it is the case for lower energy particles inside the magnetosphere and in the near interplanetary space (Ipavich, 1974) for transforming the angular and velocity (energy) distribution from one frame to another one (the solar wind and observations at the Earth).

3-D models of the heliospheric modulation assume diffusive scattering varying smoothly over large spatial scales with at most a dependence on the angle with respect to the solar equatorial plane. The relative importance of this, near isotropic and homogeneous turbulence model, compared with barrier effects are discussed by (Quenby *et al.* 2013) for three events of large amplitude and small scale interplanetary energetic particle gradients observed on a satellite with high temporal resolution. Scattering of CR by IMF turbulence in specific ranges of frequencies relevant for wave-particle interactions and its consequences for long period CR intensity variations are discussed by Alania *et al.* (2010). Differences in the relationship between different solar wind disturbances and CR decrease parameters have been examined by Dumbovic *et al.* (2011; 2012). Effects of high-speed solar-wind streams of different characteristics and origin on the CR modulation is examined by Anand Kumar and Badruddin (2014). Kozlov and Kozlov (2011) suggest to use the so called GCR fluctuation parameter as an indicator of the degree of IMF inhomogeneity, on which CR are scattering.

Since Voyager 1 crossed in August 2012 the heliopause and then started first measurements of CR outside the influence of the heliosphere (Stone *et al.*, 2013; for low energy charged particle measurements see e.g. Decker *et al.*, 2015), the measurements on Voy-1 allowed to compare proton as well as heavier nuclei of CR at lower energies with those provided in the inner heliosphere. For comparison a very useful tool is the GALPROP diffusion model (Strong *et al.* 2007 and later updates in papers by Vladimirov *et al.* 2011 and Moskalenko *et al.* 2011, the code GALPROP at `http://galprop.stanford.edu/`). Bisschoff and Potgieter (2016), by using the GALPROP diffusion model and for inner heliosphere PAMELA data, computed the spectra of CR p, He and C and presented recently new local interstellar spectra, with expressions for the energy range of 3 MeV/n - 100 GeV/n, which is important for solar modulation modeling as well as for practical applications.

By ground-based observations of CR one can analyze the diurnal variation due to the solar wind, and the sidereal variation. Hall *et al.* (1996) reviewed the CR data analysis of solar and sidereal anisotriopies over 60 years. The solar diurnal variation is mentioned more in chap. 5. Using the large area muon telescope multidirectional system GRAPES-3, Kojima *et al.* (2015) evaluated carefully the sidereal time wave (the amplitude of solar diurnal variation is by $\sim$1 order higher than that of sidereal time, the method is described in the cited paper), and estimated the radial density gradient of CR at a rigidity of 77 GV as 0.65% per AU.

Recently, Ahluwalia (2015a) studied a relationship between the north-south excess of the sunspot number (SSN) and the GCR asymmetric solar modulation over a long time period starting in 1963: an asymmetric GCR particle density gradient normal to the ecliptic plane is reported for 1963–2013 and undergoes significant temporal variations unrelated to the ∼11 year (Schwabe) or ∼22 year (Hale) cycle. In another paper Ahluwalia (2015b) examined time variations of yearly radial (A_r) and east–west (A_Φ) components from NM records over four sunspot activity cycles and partly cycle 24. Time variations of the transverse component (A_θ due to off-ecliptic GCR contributions and the GCR radial particle density gradient (Gr) have been computed along with N-S anisotropy (A_θ and checked in relation to SSN, rigidity and solar magnetic field (SMF) polarity. For a positive SMF polarity (GCRs drift from polar regions toward the equatorial plane and out along HCS) the symmetric gradient ($G_{\theta s}$) is pointing away from HCS, while for a negative polarity interval $G_{\theta s}$ points towards HCS (with the local GCR density maximum on HCS). A heliospheric asymmetric density gradient ($G_{\theta a}$) perpendicular to the ecliptic plane is the main contributor to A_θ for the period analyzed. The study by Ahluwalia *et al.* (2015c) confirms the result that the product of the mean free path of CR transport parallel to B and the radial density gradient (G_r) obtained from NM data exhibits a weak ∼11 year, but strong ∼22 year dependence.

There are several reviews published on experimental as well as on theoretical aspects of the heliospheric modulation of GCR as observed on the Earth (e.g. Duldig, 2001; Valdes-Galicia and Gonzalez, 2016 among others).

The main feature of a long term modulation of CR is its ∼ 11 year quasi-periodicity related to the solar driver (e.g. Cliver *et al.*, 2013). Due to effects of the conditions in the heliosphere as a whole, and due to a much slower speed of the solar wind (with IMF structures imbedded) in comparison with that of CR particles, the CR flux observed at the Earth is anticorrelated with solar activity (e.g. with Rz), however, with a time lag of a few months. The time lag is different for different solar magnetic field polarities. Kane (2011) reports that the minimum at the juncture of cycle 23/24 was abnormally long, tens of months instead of a few months as in earlier cycles. Similarities and differences in the modulation of CR during different phases of solar and magnetic activity cycles are analyzed in the paper (Aslam and Badruddin, 2014). Inceoglu *et al.* (2014) modelled the relations between NM count rates and the sunspot number using the hysteresis effect.

While a high energy part of the local interstellar spectrum of galactic CR is well described thanks to measurements in the inner heliosphere and on Voyager missions, the shape of the spectra of CR observed near the Earth is influenced by many local features, and the question "what is the background flux of protons at lower energies" at 1 AU is studied too. Zeldovich *et al.*, 2009, by analyzing satellite data on protons < 10 MeV over cycles 20-23, infer that the acceleration in a multitude of weak solar flares is one of the sources of background fluxes of low energy particles in the interplanetary space.

CR variations during the extremely deep solar activity minimum (∼2009) and during a weak solar activity cycle 24 have been studied in several papers. Aslam and Badruddin (2015) examined the time lag between the CR intensity and various solar and interplanetary parameters separately during different activity phases at the period 2008 – 2013. The authors analyzed the role of various parameters, including the current sheet tilt, in modulating CR intensity during different phases of the period studied. The unusual recovery of GCR in 2009 to the highest level observed in the instrumental era for a variety of energetic charged particle species on the Earth, over a wide range of rigidities, in the context of GCR measurements and solar activity over a long time period, is discussed by Ahluwalia (2014).

At energies below those covered by NMs, the modulation of CR in the heliosphere is studied by satellites and space probes. Kühl *et al.* (2016), based on data from 20 years on SOHO (by EPHIN instrument), studied the modulation of protons up to 1.6 GeV and presented annual GCR spectra for the period 1995 – 2014.

At higher energies, the Global Muon Detector Network provided new information about 3D anisotropy of GCR (Kozai *et al.*, 2014). The authors deduced the variation of radial and latitudinal density gradients and the parallel mean free path for the pitch angle scattering of GCRs in the turbulent IMF and showed the derived density gradient and mean free path varying with the solar activity and with magnetic cycles. Nagashima *et al.* (2010; 2012) studied the sidereal CR anisotropies in relation to the conditions at heliomagnetosphere boundaries.

Studies of relationship between the power-law exponent of the rigidity spectrum of GCR intensity variation and the exponents of the power spectral density (PSD) of the y and z components of IMF (Siluszyk *et al.*, 2014) showed a clear inverse relation between the two, which is an important feature of GCR modulation over the long time period.

Ahluwalia (2011; 2013) examined the long term series of characteristics of solar, interplanetary and geomagnetic activity in relation to the profile of CR records.

Several papers stress the effects of coronal magnetic fields and coronal holes for the heliospheric modulation of CR. Fisk *et al.* (1999) present a model of heliospheric magnetic field in which the field lines execute large excursions in the heliographic latitude. Differential rotation of the photosphere and the non-radial expansion of the solar wind is assumed. The model accounts for the observed ease with which low-rigidity particles propagate in latitude in the solar wind and, it provides an explanation for the time evolution and apparent rigid rotation of polar coronal holes and the differences between the fast and slow solar wind. A long term modulation and its relation to coronal holes is analyzed by Guschina *et al.* (2016). A useful approach to the description of the CR solar modulation and long term variability of the flux near the Earth is by introducing the so called CME-index (Mavromichalaki and Paouris, 2012).

An unusually deep sunspot minimum between solar activity cycles 23 and 24 lead to several studies of CR variability not only within the interval when the CR flux was at its maximum value during the direct observations, but also for the periods before and after, based on ground, satellite and balloon observations (e.g. Moraal and Stoker, 2010; Mishra and Mishra, 2016; McCracken and Beer, 2014; Chowdhury *et al.*, 2011; 2013; Ahluwalia *et al.*, 2010; Ahluwalia and Ygbuhay, 2011; Bazilevskaya *et al.*, 2012; Paouris *et al.*, 2012; Leske *et al.*, 2013; Stozhkov *et al.*, 2013; Guschina *et al.*, 2014; Alania *et al.*, 2014). The record-setting intensities of CR nuclei from C to Fe, have been observed also on ACE in the energy interval from $\sim$70 to $\sim$450 MeV nucleon^{-1}, near the peak in the near-Earth CR spectrum; the intensities of major species from C to Fe were each 20%–26% greater in late 2009 than in previous solar minima of the space age (Mewaldt *et al.*, 2010).

4. Solar energetic particles (SPE), ground level enhancements (GLE)

A review on solar energetic particle research until the end of the last century can be found e.g. in the paper by Ryan *et al.* (2000). Cliver (2009) reviews the history of research on SEP events until 2009. There are other reviews on results of the recent studies on SEPs origin, acceleration and transport at the Sun and in the interplanetary medium, as well as on GCR short- and long-term variations (e.g. Malandraki, 2015). Usoskin (2013) presents an extensive review – history of solar activity over millennia.

GLE events in the 23rd solar cycle and relations to space weather are summarized by Shea and Smart (2012). A catalogue of GLEs in cycles 21-23, with their main characteristics, is presented in the paper (Belov *et al.*, 2010). Moraal and McCracken (2012) systematically investigated GLEs of solar cycle 23, from GLE No 55 on 6 November 1997 to GLE 70 on 13 December 2006, and studied the morphology and pulse structure of the events. Three of these 16 events contain the double-pulse structures. Andriopoulou *et al.* (2011), by the analysis of GLEs over cycles 22 and 23, presented the onset-time calculations, determination of the maximum intensity, and determination of the longitudinal and latitudinal distribution of GLEs. The GLEs are usually classified as "impulsive" or "gradual", e.g. Reames (1999). A recent study (Moraal *et al.*, 2016), in analysis of all 71 GLEs since 1942, found that there is no clear distinction of GLEs in impulsive and gradual classes, but rather a continuous range between these extremes, and that the time profiles of GLEs can be interpreted in a simple point-diffusion model. Caballero-Lopez and Moraal (2016), using two pairs of a standard NM and a lead-free neutron monitor (LFNM), analyzed the extreme GLE of 29 September 1989 and demonstrated the sensitivity of using LFNM along with NM at the same place for determination of the spectral index of GLE (separation of spectral and anisotropy effects). LFNM responds to lower rigidities than the standard NM. Largest of the 71 GLEs measured by more than 50 NMs, namely that of September 29, 1989, is reported to be the event as the best example available of a "classical" GLE that has a gradual increase toward the peak intensity and does not contain two or more distinct peaks as inferred in previous papers (Moraal and Caballero-Lopez, 2014).

Aschwanden (2012) discusses the acceleration of particles to GeV energies in solar flares and GLE events, and the site of acceleration. From the study it appears that the prompt GLE component is consistent with a flare origin in the lower corona, while the delayed gradual GLE component can be produced by both, either by extended acceleration and/or trapping in flare sites, or by particles accelerated in coronal and interplanetary shocks.

NMs in several cases reveal an exponential law energy spectrum for GLEs. Calculations of relativistic proton acceleration in the flare current sheet with magnetic and electric fields found from 3D MHD simulations demonstrate an exponential law spectrum. From comparison of the measured and calculated spectra the rate of reconnection in the event on 14 July 2000 was $\sim 10^7$ cm/s (Podgorny *et al.*, 2010). The delay component of relativistic protons exhibits a power law energy spectrum.

The current (24^{th}) solar activity cycle is rather "poor" in GLEs. The first of the GLEs in this cycle, namely that on May 17, 2012 is analyzed by Mishev *et al.* (2014). From 21 NM data the spectral and angular characteristics of that event are obtained. The angular distribution comprises a focused beam along an IMF line from the Sun and a loss-cone feature around the opposite direction. Technique of a time shifting analysis for the first arriving particles that provides an estimate of the latest possible release time of relativistic protons from the Sun, was applied for that GLE (No 71) by Papaioannou *et al.* (2014) using data from several NMs. Morgado *et al.* (2015), analysing the data from the HISCALE instrument on Ulysses and EPAM on ACE, found that these instruments (dedicated to lower energies than those observed by NM) can be used to measure ions of near relativistic energies, in particular for GLEs. For the May 17, 2012 event the onset times for the EPAM penetrating protons are consistent with the rise seen in NM data at low geomagnetic cut-off positions. Firoz *et al.* (2014a) assume that GLE71 was possibly caused by the energy released from the shock acceleration, which might have been boosted by the energy emanated from a preceding flare. Possibility that the CME-driven shock was capable of producing the GLE71 event is discussed by Firoz *et al.* (2014b). Li *et al.* (2013), by combining multiwavelength imaging data of the prominence eruption and a CME, obtained evidence that GLE 71 protons, with kinetic energy of about 1.12 GeV, are probably accelerated by the CME driven shock when it travels to $\sim$3.07 solar radii. Li *et al.* (2016) report a small GLE appearing on January 6, 2014 according to polar NMs. The authors suggest to interpret that event with the assumption that small GLEs may be produced by shocks associated with CMEs. Three events, namely on January 27, March 7, and March 13, 2012 when a significant increase of the integral proton flux with energy $>$ 100 MeV was recorded by satellite experiments, have been analyzed and they may be considered as candidate(s) of GLEs (Belov *et al.*, 2015). The satellite experiment PAMELA observes since 2006 energetic particles in a wide energy range, including energies lower than the atmospheric threshold limiting NM observations to GLEs. Martucci *et al.* (2014) reports for the first time the shape of the solar proton flux after four SEPs events in 2012, namely January 23, January 27, March 7 as well as May 17 (fits to form similar to those for the bow shock acceleration - the product of $E^{-\gamma}$ and exp(-E/Eo), where E is the kinetic energy) in the energy range from ∼80 MeV/n to ∼400 MeV/n. Augusto *et al.* (2016) discuss the possibility of a new GLE in the current cycle, namely the event on October 29, 2015.

Estimates in the neutron flux which may be experienced at the ground level in CR events of an extreme magnitude over the next century, millennium and ten millennia has been estimated recently based on a long time of NM measurements (Mason, 2015). GLE occurence was assumed as a Poisson process, the magnitude of GLEs was modelled by the Weibull model and a posterior distribution was obtained with the help of an analytical and Markov chain MC Bayesian approach.

An analysis of extreme GLE events during October-November 2003 continued in the past few years. For GLE 65 (Oct. 28, 2003) Krymsky *et al.* (2015) found that the spectrum of solar CR over a very wide energy range is described by a power law with an exponential cutoff at relativistic energies. The authors use a quasilinear theory of the regular acceleration of charged particles by shock waves in the lower corona of the Sun and they show that the acceleration of solar CR on the front of a coronal shock wave in the event under study ended at a distance of not longer than four radii of the Sun. Energy spectra of large solar events (GLEs) are presented and discussed in terms of the impulsive, stochastic, and shock wave acceleration of relativistic protons by Perez-Peraza *et al.* (2009).

Kravtsova and Sdobnov (2015), using a spectrographic global survey method and combining NM data with satellite ones, described in detail the energy (rigidity) spectra and anisotropy during the CR increases attributable to the solar events of June 11 and 15, 1991.

Using 10Be ice core data and NM data, McCracken and Beer (2015), along with estimating the annual CR intensity over a long time period (1391 – 2014), indicate that the occurrence rate for SEP events such as that on February 23, 1956 is about seven per century.

Although the possibility of the production of neutrons as secondary particles at the Sun due to interactions of accelerated protons was proposed already in the middle of the last century (Biermann *et al.*, 1951), the first detection of response from solar neutrons on the ground was identified during the solar flare on June 3, 1982 (Debrunner *et al.*, 1983; Efimov *et al.*, 1983) in coincidence with the satellite observations of hard gamma rays (Chupp *et al.*, 1987). The first observation of solar neutrons on a satellite (SMM) was reported from a flare observed in 1980 (Chupp *et al.*, 1982). The first detection of solar neutrons induced the upgrade of NMs (better temporal resolution, higher statistical accuracy) and implementation of new experimental arrangements, especially at high altitudes (recently e.g. Sasai *et al.*, 2014). Until now altogether 12 solar neutron events have been identified (Xiao Xia Yu *et al.*, 2015). A search for solar neutron signals from other strong solar flares at high mountains provides only the upper limit of the flux (e.g. Lopez and Matsubara, 2015). Watanabe *et al.* (2009) analyzed the response of relativistic solar neutrons by the NMs at mountains, namely Mt. Chacaltaya and Mexico City and by the solar neutron telescopes at Chacaltaya and Mt. Sierra Negra in association with a strong (X17.0) flare on Sep. 7, 2005. The signal was observed for > 20 min with clear statistical significance. At the same time, the intense γ ray emission was also registered by INTEGRAL, and during a decay phase also by RHESSI. The authors indicate that solar neutrons were produced at the same time as the γ ray line emission and that ions were continuously accelerated at the emission site. A review on solar neutron research can be found e.g. in monographs (Dorman, 2010, Miroshnichenko, 2015).

For a correct interpretation of GLEs and those events with solar neutron emissions, the correct recalculation of the observed increases on NMs to the flux of solar particles above the atmosphere is of importance. The paper by Artamonov *et al.* (2016) presents the yield functions computed for solar neutrons observations by NMs.

Studies of high energy gamma rays and possible solar neutrons have been done from measurements on satellites. The SONG device as well as the instrument AVS-F on the low altitude satellite CORONAS-F lead to several new studies and findings related to the production of solar neutrons, gamma rays as well as to indications on the time of solar particle acceleration in several solar flares (Kurt *et al.*, 2010, 2013a; 2013b; Kuznetsov *et al.*, 2011; 2014; Kotov *et al.*, 2014). Background is important to estimate in gamma ray and neutron measurements on low altitude satellites. A background model developed for AVS-F for the October 29, 2003 solar flare is presented in the paper by (Arkhangelskaya *et al.*, 2015).

The measurements on ISS (e.g. Muraki *et al.*, 2012 with references therein) also contributed to solar neutron observations in recent years. Simultaneous observations of solar neutrons on ISS and on high mountain observatories are reported by Muraki *et al.* (2016).

From measurements of the neutron capture γ line 2.23 MeV (photosphere), along with hard X rays during acceleration of particles on the Sun in three large solar flares, as well as on the basis of theoretical estimates, Kichigin *et al.* (2016) substantiated the existence of a skin-layer on the surface of the magnetic flux rope erupted during the flare(s). Earlier Kichigin *et al.* (2014), according to simulation results, indicate that the γ ray source in the excitation lines (4.1–6.7 MeV) should coincide with the region where the accelerated ions interact with the background plasma of the solar atmosphere above the flare-active spot.

SPEs have been studied in detail during the past few years in various papers. Logachev *et al.* (2015) presented a detailed comparison of solar proton activity over cycles 20 – 23. The authors proposed and used a method for estimating the maximum energy of accelerated protons in each event, which is important for checking its dependence on the source parameters and conditions of particle propagation in the interplanetary medium. Systematic long time balloon measurements in the stratosphere over a half of century led to obtaining specific features of SPEs in the stratosphere (Bazilevskaya *et al.*, 2010). The events with >100 MeV proton intensity above a threshold recorded during 1958–2006 are discussed. The experiments made possible to restore the probable number of events in solar cycle 19, which was not properly covered by the observations. SEP event observations are reported also from a new balloon project BARREL (Halford *et al.*, 2016) at high (southern) geomagnetic latitudes. Responses from SEPs electron precipitations as X-rays and gamma rays are observed, namely for the event on Jan. 7, 2014.

The GLE of 2005 January 20 (GLE 69), the second largest on record (and the largest one since that of February 1956), with up to the 4200% count rate enhancement at the sea level, has been analyzed by Bieber *et al.* (2013) using data from the Spaceship Earth network (13 polar neutron NMs) and Polar Bare neutron counters at the South Pole. The proton density, energy spectrum, and 3D directional distribution were obtained. The event was characterized with strong anisotropy. Highest energies detected on the ground during the GLE on January 20, 2005 are reported by Chilingarian (2009). A 3 min enhancement at a muon detector measuring $\sim$5 GeV muons corresponded most probably to primary protons of energy 23-30 GeV. That event was reported to be accompanied by the first clear response to GLE in thermal neutrons' data since 1994 due to its unique character (a high amplitude and anisotropy and a very hard spectrum of initial particle flux) by Sigaeva *et al.* (2009). Matthiä *et al.* (2009a) used data of 28 NMs to approximate the primary solar proton spectra during the first 12 hours of the GLE 69. For altitudes $\sim$12 km the authors estimated the radiation dose range from zero at low latitudes up to almost 2 mSv/h for a very short time in the Antarctic region and about 0.1 mSv/h at high latitudes on the Northern Hemisphere. For the same event, Masson *et al.* (2009) provided a detailed analysis of time profiles by the netwok of NMs with electromagnetic signatures of particle acceleration in the solar corona. Two peaks in the time profile of high energy protons are revealed: the first one corresponds to protons accelerated together with relativistic electrons and pion-decay γ produced by protons, and the second one accompanied by new signatures of particle acceleration in the corona within one solar radii above the photosphere, revealed by hard X-ray and microwave emissions and by radio emission of electron beams and of a coronal shock. Troitskaya *et al.* (2015) studied the flare on January 20, 2005 by methods of the nuclear line analysis. Authors suggest a predominant acceleration of 3He ions in the corona, their subsequent propagation to the low chromosphere and the photosphere where the area of 2.223 MeV (n capture) γ-line effective production is located.

Another strong GLE event studied in the past years was that observed on December 13, 2006 (GLE 70). Grigoryev *et al.* (2009) estimated the energy spectrum of protons from that event based on NM measurements, coupling coefficients and multiplicities, and report that an additional increase of solar protons is also observed in the ionization chamber at Yakutsk. Based on NMs recordings during the two strong GLEs (No 69, 70), Bütikofer *et al.* (2009) determined the characteristics of the solar particle flux near the Earth. For GLE 70, Matthiä *et al.* (2009b) estimated an effective dose at aviation altitudes. At very high latitudes (both hemispheres) the effective dose rates were estimated to reach values of 2530 μSv/h at the atmospheric depth of 200 g.cm^{-2} in the maximum of GLE. Adriani *et al.* (2011) present results of an analysis of the particle flux at lower energies than NMs are sensitive to for the GLE70 using PAMELA satellite data.

Bütikofer and Flückiger (2013) checked the differences in charateristics of GLE 60 (April 15, 2001) as published in various papers and analyzed their consequences on computed radiation dose rates for selected flight paths. Firoz *et al.* (2012) propose that GLE69 is procured with a sufficient possible relativistic energy (similar to 1.6 GeV) by the energy released from particle accelerations in the intensive phases of solar flare components that have been corroborated by the injection time, and that GLE70 is presumably caused by the sum of the energy released mostly from a CME-driven shock and, partially, from preceding flare components.

Models that couple the primary solar CR at the top of the atmosphere with the secondary ones detected at the ground level by NMs in GLE are constructed. This allows to describe the rigidity spectra as well as anisotropy. An NMBANGLE model has been developed, updated and used for several GLE events (Plainaki *et al.*, 2009; 2010; 2014).

At lower energies, the mass-to-charge ratio (A/Z) for SEP events has been recently studied by Reames (2016a). Diffusive transport of ions is described. The abundance enhancements are approximated by power laws of A/Q. Gradual events are selected according to the paper of Reames, (2016b). For gradual SEP events, scattering of ions during transport generates the power-law dependence of abundance enhancements or suppressions on A/Q of the ions which determines the source-plasma temperatures.

An important precondition for responses of relativistic solar particles on NMs are the interplanetary magnetic structures via those the accelerated particles are transported. For 10 GLEs within solar cycle 23 the detailed study of IMF configurations can be found in the paper (Masson *et al.*, 2012). A majority of the events (7 out of 10) are detected in the vicinity of an ICME (an interplanetary coronal mass ejection), and their interplanetary path lengths are longer (1.5–2.6 AU) than those of the two events propagating in the slow solar wind (1.3 AU). The timing of the first impulse on the Earth is mainly determined by the type of the IMF structure during propagation. Initial arrival times are as expected from Parker's model in the slow solar wind, and significantly longer in or near transient structures such as ICMEs. Papers by Firoz *et al.* (2010; 2011) discuss the GLEs associations with solar flares, CMEs, solar energetic particles as well as with interplanetary and geophysical charcteristics.

Techniques for identification of increases on the ground corresponding to solar energetic particles impact on the atmosphere at positions with a higher geomagnetic cut-off rigidity are described by Beisembaev *et al.* (2009), Vargas-Cardenas and Valdes-Galicia (2012). Also the CCD solar images studied at SOHO are reported to be of use for inferring solar cosmic ray flux variations (Oh *et al.*, 2014).

5. Transitional effects, irregular and periodic/quasi-periodic CR variations

Variations of the CR flux near the Earth are influenced not only by the modulation of the heliosphere as a whole, but also via transitional effects driven from the solar surface, and by periodic processes as the solar disc rotation and rotation of the Earth.

Short-term decreases in GCR are observed since the work of Forbush (1937), named as Forbush decreases (FDs). Two types are usually mentioned, namely non-recurrent - CME-related, and High Speed Stream (HSS) -related - recurrent (Cane, 2000). Belov *et al.* (2014) described the correlations of the FD magnitude with the CME initial speed, the ICME transit speed, the maximum solar wind speed and report on comparisons between the features of CMEs (mass, width, velocity) and the characteristics of FDs. FD features for halo, partial halo, and non-halo CMEs are discussed too. An extensive set of FDs (altogeteher 617 events during 2008 – 2013) have been checked for connection with solar activity characteristics recently in the paper by Lingri *et al.* (2016). Out of them three important ones (observed clearly at high cut-off NMs) were checked in detail. Results of a statistical analysis of the amplitude of FDs to solar and geomagnetic parameters have been reported. Kravtsova and Sdobnov (2014) analyzed FDs in March – April 2001 by a global spectrographic method with the use of the NM network. The authors determined the spectral index of the rigidity spectrum of CR during different phases of FDs and found that the spectrum of CR is not described by a power law in a wide energy (rigidity) range. Softer spectra for the March 31 event compared to that of April 11 event are indicated. Jordan *et al.* (2011) discuss the traditional model of FD predicting that the ICME and the corresponding shock decrease the CR intensity in two steps. They analyzed 233 ICMEs that should have created two-step FDs, however, it was the case only in 13 events. A majority of profiles are more complicated and the small-scale IMF structure can contribute to the observed variety of FDs. Caroubalos *et al.* (2009) proposed an interpretation of the unusual FD profile (a sharp enhancement of CR right after the main phase of the FD followed by a 2^{nd} decrease within < 12 h) in July 2005 in terms of a magnetic structure and a succession of interplanetary shocks interacting with the magnetosphere.

Usually FDs are related to CMEs, or to corotating interaction regions (CIRs). However, not all FDs observed by NMs are related to a specific local (near Earth)

IMF and/or solar wind structures. Thomas *et al.* (2015) analyzed such events (called "phantom" FDs). The STEREO mission, providing observations at different heliospheric longitudes, is important for understanding these events. FDs triggered by the passage of shock-driving ICMEs (59 events) have been analyzed by Blanco *et al.* (2013). Authors conclude that ejecta without flux rope topology are the ones less effective in unchaining FDs.

Geoeffectiveness of CMEs and FDs is of importance for relations to space weather. Different relations between relatively large FDs and Dst minimum value as well as between large Dst and FDs for the epoch before 2002 are summarized by Kudela and Brenkus (2004). A big and long lasting ($\sim$6 h) CR pre-decrease ($\sim$2%) is defined before the shock arrival on 15 September 2005 by Papaioannou *et al.* (2009). Gui-Ming Le *et al.* (2016) present results of relations between various types of SPEs and geoeffectiveness. The solar wind structures responsible for the geomagnetic storms associated with SPEs with different intensity-time profiles are discussed. The count rate at CR detectors during the 23^{rd} cycle indicate that an increase during geomagnetic storms occurs coherently (or up to 1 h in advance) with Dst changes (Chilingarian and Bostanjyan, 2009). The increases, observed especially at high nominal cut-off positions, may be due to depression of the geomagnetic cut-off rigidity. Solar wind-magnetosphere coupling during the passage of ICMEs and CIRs in cycle 23 and their relative geoeffectiveness are studied by Badruddin and Falak (2016).

Verma *et al.* (2014) splitting the FDs to U and V shapes, obtained that most of the V shape CR decreases are related to interplanetary shocks and the related shocks are forward shocks. Badruddin and Kumar (2016) studied CR response at the Earth in relation to interplanetary CMEs and to CIRs during solar cycle 23 (1995 – 2009). The authors identified the relative importance of the plasma/field parameters in influencing the amplitude and time profiles of the CR intensity variations during the passage of the ICMEs and CIRs. In agreement with earlier findings, ICMEs are found to be more effective in modulating the GCR intensity when compared to CIRs. Arunbabu *et al.* (2015) studied FD events observed by the GRAPES-3 muon telescope during 2001–2004 and found the importance of the turbulent sheath region between the shock and ICME, as well as the viability of crossfield diffusion through the turbulent CME sheath as the primary mechanism for FDs. Mishra and Agarwal (2010) characterized the influence of four types of CMEs on CR NM. A study by Parnahaj and Kudela (2015) confirms and extends (until 2014) earlier results based on NM data from different geomagnetic cut-off positions and covering earlier periods, namely that FDs associated with halo coronal mass ejections (CMEs) and those related with the shocks correspond to higher amplitudes of FDs than those without the mentioned features.

Raghav *et al.* (2014) checked in detail (43 NM data) the FD on February 14, 1978 and confirmed a physical scenario that the first step of FD is due to a propagating shock barrier and the second step is due to a flux rope of the CME/magnetic cloud. Recently, Bhaskar *et al.* (2016) analyzed 50 FDs at high geomagnetic latitude associated with ICMEs, assuming that events are generally thought to arise due to the shielding of CR by a propagating diffusive barrier and found relations between the profile of FDs, IMF and the solar wind speed for the main and recovery phases of the events. One of the results is that the duration of the FD profile is similar to that of the solar wind speed profile, however it is significantly longer than that of the B profile.

Modulation of CR in the presence of magnetic clouds (MC) has been studied too. In a significant number of events reported in the paper (Belov *et al.*, 2015a) the changes in the CR density inside the MCs are almost symmetrical with a minimum density at the cloud center, suggesting its quasi-cylindrical structure. Belov *et al.* (2015b) indicate that a majority of MCs modulate CR resulting in a reduction of their density. However, there is a group of events (about one fifth of the total sample) in which the CR density in a MC increases. Yu *et al.* (2010) analyzed the influence of MC on FDs in November 2004 and deduced that the sheath region between the shock and MC, especially the enhanced turbulent IMF, results in the scattering of CR, and causes the following FDs. Global simultaneity of the FD is seen. However, in several cases the non-simultaneity of FDs is reported (Oh and Yi, 2009). The mean of CR variation of the main phase of FD is higher for simultaneous than for non-simultaneous FDs (Lee *et al.*, 2015). MC influence on CR in a strongly disturbed period of November 2004 is studied by Yu *et al.* (2010).

Most of the earlier works on FDs analyzed profiles of GCR density. Kozai *et al.* (2016) analyzed the GCR anisotropy using data from the global muon detector network (GMDN) and from NMs. The authors found two distinct modulations of the density of GCR in FDs, one in the sheath region and another in the central region of the CME.

Masías-Meza *et al.* (2016) analyzed ICMEs observed during the period 1998 – 2006 by a superposed method and derived the model describing decrease of CR as a function of the level of magnetic fluctuations and the strength of B. The result is relevant for understanding transport of energetic particles in ICMEs as well as for space weather forecasts.

Models of FDs and results on their rigidity dependences using NM data can be found in papers (Wawrzynczak and Alania, 2010; Alania and Wawrzynczak, 2012, Alania *et al.*, 2013).

Muon detectors (hodoscope(s)) can observe FDs at higher energies of primary CRs (e.g. Angelov *et al.*, 2009; Braun *et al.*, 2009; Barbashina *et al.* 2013, Ampilogov *et al.* 2016). Kalugin and Kabin (2015) analyzed large FDs using phase diagrams of view channels of the Nagoya multidirectional muon telescope and obtained the dependence of the FD amplitude on particle rigidity. Chilingarian and Bostanjyan (2010) examined a relation of FDs detected by various CR detectors of the ASEC system with ICME characteristics over solar cycle 23. FDs are observed also by detectors of thermal neutrons (Alekseenko *et al.*, 2013).

Specific intervals with FDs have been analyzed too. Ahluwalia *et al.* (2009) studied two strong FDs characteristics, namely 22-27 March 1991 and 1-17 June 1991. The decreases were seen propagating in the outer heliosphere (Voyagers 1, 2; Pioneer 10, 11), with the time delays. NM data from both hemispheres, as well as muon telescope underground data (responding to 10 – 300 GV primaries), have been analyzed. Rigidity dependence of the amplitudes of the two FDs in a wide rigidity range was obtained. Papaioannou *et al.* (2010) deduced CR density, anisotropy and density gradients for January 2005 and stress the complexity of CR variations with FDs in that period. Grigoryev *et al.* (2014) examined FDs energy spectra during the growth phase of cycle 24 (2010–2012), based on the measurements performed with the Kuzmin CR spectrograph. A softer spectrum was observed during the growth phase of cycle 24 than during the previous cycle. More turbulent magnetic fields with the predominant diffusion mechanism in the formation of the FDs in CR intensity exist in the 24^{th} cycle. A detailed study of CR intensity variations, including an FD due to a halo CME on May 13, 2005, is done by Ahluwalia *et al.* (2014). Using NMs and muon telescope data the authors obtained the rigidity spectrum in a wide energy range, inferring that the quasi-linear theory of modulation is inconsistent with observations at high rigidities (> 1 GV) and supporting the force field theory of modulation.

Shrivastava *et al.* (2011) studied a longitudinal distribution of solar flares and its relation to CMEs and FDs. Abunina *et al.* (2013a) report on the relation between FDs parameters and heliolongitude of the sources on the Sun.

A high speed solar wind streams effect on the modulation of CR is studied by Anand Kumar and Badruddin (2014). The role of the enhanced and turbulent magnetic field in producing larger amplitude depressions in the GCR intensity, such as FDs, is stressed.

Several papers published in the past 7 years are devoted to quasi-periodic variations of CR intensity. An attempt to survey the current experimental knowledge of selected quasi-periodicities in the CR flux in the energy range above the atmospheric threshold, from direct measurements, is in papers (Kudela and Sabbah, 2015; Kudela and Langer, 2015). Results of various methods used for estimates of the power spectrum density (PSD) of CR can be found in the paper by Vipindas *et al.* (2016). The shape of PSD of CR records by a scaler mode of the Pierre Auger project is presented in the paper (García Canal *et al.*, 2012). Chowdhury *et al.* (2010) evaluated the short and intermediate term periodicities (16 to 500 days) in CR intensity during different phases of cycle 23.

The only "monochromatic" component in the PSD of the CR signal from ground based observations is that of a diurnal wave and its higher harmonics. Oh *et al.* (2010) checked the modulation cycles in the diurnal anisotropy of galactic CR, specifically the phase. All NM stations show mainly the 22-year phase variation controlled by the drift effect due to solar polar magnetic field reversal, and the analysis indicates that the phase variation has two components: $\sim$ 22-year and $\sim$11-year. For higher cut-off rigidity stations a higher contribution from $\sim$11-year cyclicity is controlled by the diffusion effect due to the change in the strength of IMF associated with the sunspot activity cycle. Mohanty *et al.* (2016) analyzed second harmonics of a diurnal wave in pressure, filtered the time series for that, and by the inverse FFT reconstructed the time series of muon and barometric pressure data. The barometric coefficient obtained from those time series is obtained with relatively high accuracy. The amplitude and the phase of the diurnal wave was analyzed by Sabbah (2013) over almost 60 years of measurements by NMs Climax, Deep River, Huancayo/Haleakala and muon detector Nagoya. The phase angle observed with the lower rigidity station depends strongly on the solar magnetic field polarity reversal due to a drift effect. Okpala and Okeke (2011) obtained characteristics of the first four harmonics of the diurnal wave and inferred that the phase reversal is controlled by the solar polar magnetic field reversal associated with the 22 year solar activity cycle rather than the 11 year sunspot cycle. Tiwari *et al.* (2012) analyzed the amplitude and phase of the diurnal wave and its changes during a long time with a different solar magnetic field polarity, and found a significant diurnal phase shift to earlier hours during the ascending periods of odd solar cycles (21 and 23) in comparison to the ascending periods of even solar cycles (20 and 22). The amplitude–phase interrelation of the solar diurnal anisotropy for 1957–2010 is studied in the paper (Abunina *et al.*, 2013b). The obtained CR anisotropy variations agree with the convection–diffusion anisotropy model. Diurnal anisotropy of CR during cycle 23 has been analyzed by Mavromichalaki *et al.* (2016) using data of two NMs at the different geomagnetic cut-off rigidity position. The time of the diurnal variation maximum is shifted to earlier hours than the corotation direction for the period ($qA > 0$) and to later hours for ($qA < 0$). The analysis of NM data done recently (Tezari and Mavromichalaki, 2016) showed a different behaviour in the characteristics of the diurnal anisotropy during the different phases of the solar cycle and the different solar magnetic field polarity. Short term changes as GLEs and FDs/geomagnetic disturbances are pronounced in the diurnal variation.

An analysis of the 3D anisotropy of CR observed with the muon detector Nagoya and with NMs performed over four solar cycles indicated that the phase of the diurnal anisotropy shifts toward earlier hours around solar activity minima in $A > 0$ epochs, due to the reduced anisotropy component parallel to the mean magnetic field. The radial density gradient of GCRs does not depend on the polarity (sign of A) and it is suggested that differences between these parameters in $A > 0$ and $A < 0$ epochs are seriously biased by these long-term trends (Munakata *et al.*, 2014).

Several papers reported peaks in the PSD of CR time series in the range < 1 to 4 years, called quasi-biennal oscillations. A review of results on quasi – periodicities of various characteristics of solar activity can be found e.g. in the paper (Bazilevskaya *et al.* 2014). Bazilevskaya *et al.* (2016) consider the question of the prominent periodicity of CR ($T = 1.6$ years) that has prevailed in CR and in the heliospheric magnetic field for more than 10 years, but was not stable over 60 years of observations. One of the clearest increases in PSD in the above mentioned range of CR periodicities is that of ∼1.6-1.7 years, first reported by Valdes-Galicia *et al.* (1996) and examined later e.g. by others (e.g. Kudela *et al.*, 2002; 2010; Chowdhury *et al.*, 2010). Chowdhury *et al.* (2016), using wavelet technique, indicate the presence of a variety of short- and mid-term periodicities including the well-known Rieger and quasi-biennial periodicities during cycle 24. Richardson *et al.* (2016) report evidence that >25 MeV SEP events show a clustering in time at intervals of ∼ 6 months during the rising and peak phase of cycle 24. This may be related to periodicities of about 150 days reported in various solar and interplanetary phenomena during previous solar cycles. It is close to the Rieger periodicity. Mid-term periodicities in CR have been studied also by El-Borie *et al.* (2011).

The information on temporal variability of CR on much longer time scales than that allowed by the direct ground based measurement of CR (e.g. by NMs), is based on radionuclides, like 10Be and 14C (e.g. McCracken *et al.*, 2005). A long time before that type of studies Peters (1955) proposed that cosmogenic isotopes are produced in the atmosphere of the Earth. The isotopes are stored in terrestrial archives and their checking allows to deduce variability of CR prior to their direct measurements. Modulation of the GCR over the past 1150 years is investigated using 10Be data from Greenland and the South Pole in the paper by (McCracken *et al.*, 2004). Another isotope with a much shorter lifetime produced by CR in the atmosphere, namely 7Be, is studied in connection e.g. with seasonal and meteorological variations (e.g. Yoshimori, 2005).

Recurrent CR modulation near the ecliptic can arise from latitudinal CR density gradients arranged about a tilted HCS (e.g. Badruddin *et al.* 1985 among others). In a recent paper by Yeeram and Saengdokmai (2015) the enhanced diurnal anisotropy of GCR during 2010 observed by NM at a high nominal geomagnetic cut-off position (16.8 GV) is analyzed. Recurrent trains of enhanced anisotropy have been observed during the A-sector rather than during the T-sector. Gil and Alania (2010; 2011), computing rigidity spectra of the 1^{st} and 2^{nd} harmonics of the 27-day variation of CR intensity from Kiel and Rome NMs in the period of 1965–2002, found that they change in the same way; the rigidity spectrum is hard in the maximum phase and soft in the minimum one. Rigidity spectra of amplitudes in 27-day variations are approximated as $R^{-\gamma}$. A 3-D model of the 27-day variation of the CR intensity for various phases of the solar activity cycle was presented in the paper (Gil and Alania, 2013). The model provides values of γ for minimum and maximum activity. Dependence of the 27-day variation of CR on the global magnetic field of the Sun can be found in the paper (Modzelewska and Alania, 2012) stressing that a higher range of the heliolongitudinal asymmetry of the solar wind speed in the positive polarity period ($A > 0$) than in the negative polarity period ($A < 0$) is an important reason for differences in amplitudes of ∼27 day waves for solar cycles of the opposite polarity. Imprint of the solar magnetic activity cycle on the corotating modulation of CR is discussed by Gupta and Badruddin (2009). Gil and Alania (2016) studied temporal changes of the energy spectrum of the first three harmonics of the 27-day variation and indicate that the energy spectrum of amplitudes of the recurrent variation of the CR intensity is hard in the maximum epochs and is soft in the minimum epochs during Solar Cycles 20 – 24, but with peculiarities during the deep minimum 23/24 (rigidity spectrum of the amplitudes of the 1^{st} harmonic of the recurrent variation of CR behaves similar to previous epochs, the spectra of amplitudes of the 2^{nd} and 3^{rd} harmonics are softer). Appearance of the third harmonic of ∼27 day variation was examined by Sabbah and Kudela (2011). Recurrent (repeating after ∼27 day) trains of the enhanced diurnal variation of CR are identified by Yeeram *et al.* (2014). The authors conclude that the gradient anisotropy is a source of temporary changes in the CR diurnal anisotropy under solar minimum conditions, and that the latitudinal CR gradient can sometimes be explained by the coronal hole morphology. Guo and Florinski (2014), analyzing the ∼27 day wave in CR during the cycle 23/24 solar minimum, show that the CIR forward/reverse shock pairs or compression/rarefaction regions play important roles in the transport of CR and directly control the observed 27 day wave observed in CR.

In the records of NMs there appear in some periods the "wave trains" with the enhanced amplitude of diurnal variation in subsequent series of days. Singh *et al.* (2010) studied high (HAE) and low (LAE) amplitude wave trains events during cycle 23 using a single NM data and compared their occurence during different phases of the solar cycle. Mishra and Agarwal (2009) analyzed the first three harmonics of HAE wave trains of the CR intensity in 1981-1994 and reported that all the three harmonics, except the amplitude of second one, have no significant correlation with geomagnetic indices. Diurnal variations have been analyzed also from other measurements (e.g Mailyan and Chilingarian, 2010; Oh and Kang, 2013; Mufti *et al.*, 2011).

A specific type of secondary CR variations is reported in connection with a total lunar eclipse, based on measurements done by the NaI (Tl) scintillation detector with an energy threshold of 200 keV (Raghav *et al.*, 2013).

Wavelet technique is a very useful tool for examination of the occurrence of quasi-periodicities. For solar wind and geomagnetic field parameters the comprehensive studies are done e.g. in papers (Katsavrias *et al.* 2012; 2016). In identifying the driver(s) of quasi-periodicities in various characteristics of the chain of solar-terrestrial physics, the study of phase relations between different parameters is important.

Out of longer quasi-periodicities in CR one with the length ∼30-34 years (or three solar cycle one) is discussed in some papers (e.g. Ahluwalia, 1977, Perez-Peraza *et al.*, 2012; Kudela, 2013).

Qin *et al.* (2012) present an algorithm useful for despiking both satellite and ground based data of CR measurements. Using that algorithm for a lower energy CR flux from satellite data, the authors get both 11 year and 27 day period cycles comparable to the much higher energy GCR flux data measured by NMs. Such type of techniques is important for clarification of both regular (periodic) or irregular CR variations at low energies.

6. Magnetospheric transmissivity for cosmic rays

Geomagnetic field and the Earth's body cause a rather complicated system of trajectories (allowed, forbidden, quasi-trapped) for low energy CR particles coming from the interplanetary space (the terminology in the paper Cooke *et al.*, 1991). For estimates of CR transmissivity both the computation schemes used for trajectory tracing (e.g. Shea *et al.*, 1965; Shea and Smart, 1970; in recent years e.g. Herbst *et al.* 2013; Gvozdevsky *et al.*, 2016 among many others) as well as geomagnetic field models (e.g. Smart *et al.*, 2000, Desorgher *et al.*, 2009) are important. During geomagnetic storms the cut-offs and asymptotic directions are changing and transmissivity depends on the geomagnetic field model used, especially on its external current sources involved (e.g. Flückiger *et al.*, 1986; Kudela *et al.*, 2008; Tyasto *et al.*, 2013a,b; Parnahaj *et al.*, 2015; Kravtsova and Sdobnov, 2016; Chu and Qin, 2016). Geomagnetic cut-off variations are important also for SEP and GLE events (Kress *et al.*, 2010). The cut-offs have also long term variability (e.g. Storini *et al.* 1999; Smart and Shea, 2003; Kudela and Bobik, 2004). A review on effects of filtering CR in various magnetospheres can be found in the book (Dorman, 2009).

Possible effects of the South Atlantic Anomaly (SAA) region on secondary CR have been discussed in the past couple of years. Augusto *et al.* (2010) reported two different origins of muons detected in that region at distinct altitudes: precipitation of particles in the SAA (lowest energies) and the GCR component (high energy). Cordaro *et al.* (2016), analyzing data from Chilean CR and magnetometer stations, report that although the magnetometric data indicate the magnetic reconnection for the Chilean region, there is no direct influence from the SAA other than a lower rigidity cut-off that leads to an increased count rate of muon and NM records.

New measurements of CR provided onboard of low altitude satellites with a high inclination orbit, PAMELA as well as AMS-02 (with selected results mentioned in chap. 1, 4), require for their correct interpretation to compute precisely the geomagnetic field filtering, which is especially the case of GLE and SEP events (e.g. Adriani *et al.* (2015)). This is important also for correct assuming of the modulation effects (chap. 3).

Correct assumptions on viewing directions for GLE events are also important. E.g. Plainaki *et al.* (2009) present results of such computations for GLE on December 13, 2006.

Bieber *et al.* (2013) analyze the specifically continuing long time decline in the counting rate of NM South Pole. The authors deduced that neutrons of approximately 100 MeV, at the South Pole over past 50 years systematically decline and that this decline is continuing. The question about geomagnetic effects neglecting for all high latitude monitors (the geomagnetic cutoff lower than the atmospheric one) is discussed. Low rigidity particles with steep spectra (e.g. GLEs or SPEs), particles arriving at higher angles of incidence can be ignored because the cascades from these particles can barely penetrate to the surface for near vertical incidence. Contribution of the obliquely incident CR to the counting rate of NMs is described in the paper (Clem *et al.*, 1997). Trajectory computations are usually starting (the reverse velocity and the sign of charge) from 20 km. The full maps published by Bieber *et al.* (2013) show in some directions near the horizon that the cutoff is very high and a differential map also shows significant changes between 1969 and 2005. Thus for a harder CR energy (rigidity) spectrum the oblique directions, even at a low nominal geomagnetic (vertical) cut-off rigidity, the situation may be more complicated due to highly oblique asymptotic directions and changes in allowed, forbidden trajectories structure in the changing geomagnetic field over a long time. The authors indicate that increase in the area of a high cutoff will clearly reduce the secondary CR at the South Pole, but whether the change could be large enough to account for the observed decline is not at all obvious. Thus a detailed investigation of a geomagnetic cutoff change at the South Pole, and its influence on the radiation environment, may be of importance.

Kalugin and Kabin (2015) discussed posible definitions of the average effective rigidity for the Nagoya muon detector assuming individual channel acceptance of particles. The authors developed a new approach for estimate of a power law index of CR spectra at energies to which the muon detector is sensitive, and calculated the index γ for quiet and disturbed conditions (12 FDs).

7. Energetic particles in the Earth's surrounding

An increasing number of measurements of energetic particles trapped in the geomagnetic field on board of the first satellites led to introduction of the magnetic shell parameter L (McIlwain, 1961; 1966) and data were organized in the (L,B) space. There are detailed reviews and/or books on suprathermal/high energy particles observed in the vicinity of the Earth and on description of their sources, transport within the magnetosphere of the Earth, dynamics, and losses (just as examples Roederer, 1967, 1970; Williams 1971; Schulz and Lanzerotti, 1974, Paulikas and Blake, 1982; Lyons and Williams, 1984; Vernov *et al.*, 1967, Tverskoy 1968; Walt, 1994). Hapgood *et al.* (2011), in description of the proposed CrossScale mission, stress that suprathermal (30 keV-1 MeV) measurements are essential to fully characterise particle distributions.

Populations of suprathermal particles in the magnetosphere are described e.g. by Vasyliunas (1971). Suprathermal and sub-cosmic rays in the interplanetary space are reviewed e.g. in papers (Lin *et al.*, 1995; Lazar *et al.*, 2012).

The motion of the charged energetic particles in geomagnetic field is usually described in terms of three adiabatic invariants (Northrop and Teller, 1960). The approach is valid when the three periodicities (gyration around the field line, bouncing between the mirror points, azimuthal drifting around the Earth) are strongly differing. During perturbations in the magnetosphere on the scale comparable to the periodicities, the adiabatic invariants are not conserved. Such situation appears, e.g., during geomagnetic disturbances. The dynamics of the trapped (and also quasi-trapped – trapped just during one azimuthal drift period, and precipitating into the atmosphere) particles is the subject of study since the beginning of the space era. We mention just few examples of results from such studies obtained during the past few years. One of the problems is rather strong dynamics of energetic electrons during magnetic storms – decrease of the electron flux during the main phase of the storm and reappearance of the fluxes during the recovery phase. Regarding that at least two mechanisms are proposed, namely (i) increase of the rate of pitch angle diffusion of electrons at higher L shells due to their interactions with VLF waves and with electromagnetic ion cyclotron waves (EMICS) occuring during substorms and consequently scattering high energy electrons (e.g. Friedel *et al.*, 2002; Shprits *et al.*, 2008), and (ii) the magnetopause shadowing – periods when magnetic field is decreasing inside the inner magnetosphere and electrons are transferred from initially closed drift orbits to the open ones when scattered at the magnetopause (e.g. Ukhorskiy *et al.*, 2006). Lazutin (2016a) analyzed the dawn-dusk asymmetry of the belt of electrons during the geomagnetic storm at the end of August 2004 using data from the low altitude polar orbit satellite SERVIS-1 and showed that the effect observed can be explained by the adiabatic transformation of a particle trajectory during each magnetic drift orbit and by the Dst change.

If the trapped electron population is sufficiently anisotropic, this situation will itself lead to generation of whistler waves which will scatter the electrons and subsequently electrons are precipitating. This is related to the limit of stably trapped particles in the magnetosphere found by Kennel and Petchek (1966). Summers *et al.* (2009) reexamined the Kennel-Petschek concept and derive relativistic formulae for the limiting electron fluxes for planetary radiation belts (RBs) at a given L shell, and compared the theoretical limits on the trapped flux with the observed electron fluxes at the Earth, Jupiter, and Uranus. A new relativistic formulae for the self-limiting electron integral and differential fluxes in a planetary RB is presented by Summers *et al.* (2011). It is a generalization of the Kennel-Petschek limit assuming an extreme electron flux in the nonlinear regime of interactions.

Energetic electron precipitation from the magnetosphere is an important complex of effects in "transfer" of solar activity (variability) to the upper atmoshere. An extensive survey ($>$ 9 years of data from low altitude satellites for different phases of geomagnetic storms) of energetic electron precipitation from the outer RB is published in the paper by Horne *et al.* (2009). Specifically, the storm time variations and region of SAA are discussed. Meredith *et al.* (2011) studied in detail (by a superposed epoch analysis) the characteristics of energetic electrons observed by the NOAA POES spacecraft during 42 high-speed solar wind stream (HSS) to determine the temporal evolution and global distribution of the precipitating flux of electrons. The authors found that HSS-driven storms lead to increases in precipitation of energetic electrons, and that the flux of trapped and precipitating E $>$ 30 keV electrons increases immediately following the storm onset and remains elevated during the passage of the HSS.

A primary scientific objective of the Balloon Array for RBSP Relativistic Electron Losses (BARREL) is to understand the processes responsible for scattering relativistic electrons into the Earth's atmosphere (Millan *et al.*, 2011). The authors present results of X ray measurements for a January 21, 2005 duskside precipitation event observed by three MINIS balloons, comparison with THEMIS data, and a precipitation pattern observed during a weak geomagnetic storm illustrating abilities of the mission. Since the array will typically consist of 4–5 balloons below L=7, spread over 150° of geographic longitude (6 h of MLT at this location), with separations just over an hour of MLT, and conjunctions with the RBSP spacecraft is assumed, the data from the mission are important for progress in clarification of the questions related with electron precipitation.

Energetic ion precipitation peculiarities in the position equatorward of the isotropic boundary of their fluxes during a very strong geomagnetic storm have been analyzed by Yahnina and Yahnin (2014) using NOAA satellite data. A new type of precipitation is distinguished, which is observed on the dayside at relatively high latitudes and authors suggest that this type of precipitation is associated with development of an ion-cyclotron instability in the equatorial magnetosphere.

An analysis of particle data from the low-altitude CORONAS-F satellite contributed to description of the fluxes of sub-cosmic rays (<100 MeV) in the magnetosphere. Lazutin (2016b) reports dynamics of the latitudinal profiles, dependence on particle energy and on magnetic activity of the solar protons penetrating to the orbit of that satellite using data from several energetic particle experiments. As a result of the magnetic field asymmetry, isotropic protons from the night side position may arrive to the dayside trapping region with a decreased precipitation flux. The earthward shift of the nighttime proton profiles may be observed before the beginning of the main phase caused by the rise of the solar wind pressure. Myagkova *et al.* (2010) performed an analysis of enhancements in the fluxes of electrons $>$ 300 keV onboard of the CORONAS-F satellite in the polar regions at the boundary of the outer RB. The analysis of data from CORONAS-F and SERVIS-1 satellites shows how during magnetospheric substorms the outer boundary of the electron belt is shifted to higher latitudes (Lazutin, 2014). Bursts of electrons can be generated by the substorm at high latitudes. Relaxation of electron and proton RBs after strong magnetic storms in July and November 2004, observed by two satellites mentioned above, indicates that predictions of the theory about the rate of pitch-angle diffusion are not always correct (Lazutin *et al.*, 2012). Early, in the beginning of the space era in 1964, during flights of the ELECTRON satellites the narrow belts of energetic electrons ($E_e \approx 6$MeV) were discovered in the Earth's magnetosphere at L $\approx$ 2.75. The same structures approximately at the same magnetic shells were found in 2004 by the CORONAS-F and SERVIS-1 satellites (Logachev and Lazutin, 2012). The additional narrow belts of energetic electrons occur after intense magnetic storms (Dst $<$ -100 nT), and have a double-triple structure.

Another low altitude satellite, CORONAS-Photon, measured energetic particle fluxes during very low solar activity in 2009. Using a detector with a high geometrical factor (STEP-F) and combining data with another instrument measuring X rays, Dudnik *et al.* (2012) indicate during weak geomagnetic activity appearance of the additional peaks in the profile of the electron flux at low L shells. One of the complex of the instruments on the Vernov satellite (sun-synchronous, apogee and perigee 830 km and 640 km, respectively, inclination 98,4°) described by Panasyuk *et al.* (2016) provided information about electron flux variations in the second half of 2014 (Myagkova *et al.*, 2016).

Kozelova and Kozelov (2013), analyzing in detail the explosive local magnetic field line stretching just before dipolarization, observed by one of THEMIS satellites during the pseudo-breakup followed by a local substorm of 6 January 2008, indicate that penetration of the hot electron plasma sheet to the region of trapped energetic ion is a precondition for the substorm onset in the premidnight sector. A few minutes before the substorm onset, simultaneously with an intensification of the auroral arc in the same longitudinal sector, the oscillations of the fields and particles with a period of $\sim$ 50–60 s start near this convection boundary.

Penetration of solar protons (during SPE or GLE events), as well as features of outer RB electrons, can be used as a tool for diagnostics of the magnetosphere (a review by Tverskaya, 2011; Lazutin *et al.*, 2011).

Study of energetic electrons during a strong storm on March 17, 2015 (Dst min = − 223 nT) by Van Allen Probes done recently and the simulations show that the radial, pitch angle and the energy diffusion by chorus and hiss reproduce the observed electron dynamics well. Thus quasi-linear diffusion theory is reasonable for RB electron dynamics during this big storm (Li *et al.*, 2016). Comparison of data obtained from measurements on the Colorado Student Space Weather Experiment (CSSWE) at a low altitude orbit with REPT and MagEIS observations aboard Van Allen Probes (a low inclination (10°) geo-transfer-like orbit) during a geomagnetic storm in October 2012 provides an example of how CubeSats can be used to complement larger missions by providing additional data points and types of measurements in aspects of the study source, loss and energization processes of particles in the magnetosphere (Li *et al.*, 2013). The study by Zhenxia Zhang and Xinqiao Li (2016), using 5 years of data of energetic particle measurements on the DEMETER satellite, indicates that the electron energy region influenced by the strong geomagnetic storms is opposite in the inner and outer RB and different electron injection mechanisms and accelerating processes responsible for spectral index variations in different L regions during geomagnetic storms are stressed.

For the formation of RBs, as well as for the losses and transport of energetic particles in the magnetosphere, there are important wave-particle interactions (e.g. Thorne, 2010). For checking the theoretical descriptions of the dynamics of energetic particles, their lifetime in the trapping region is an important parameter. The analytical estimates of energetic electron lifetimes in the RBs have been compared extensively with full numerical simulations assuming the quasi-linear pitch-angle diffusion by whistler-mode waves e.g. by Artemyev *et al.* (2013). Demekhov *et al.* (2009) estimate the efficiency of energetic electron cyclotron acceleration in the Earth's magnetosphere in different regimes of the resonant interaction with parallel propagating whistler mode waves of a variable frequency, specifically, with chorus ELF–VLF emissions. A considerable fraction (several tens of percent) of the chorus element energy can be absorbed by electrons accelerated in the trapping regime during a single interaction. Results of test particle simulations of non linear interactions of energetic electrons with whistler mode chorus emissions are published by Omura *et al.* (2015). The authors found that the energetic electrons are accelerated effectively by relativistic turning acceleration (a very efficient relativistic electron acceleration mechanism by a long-time whistler mode wave packet, in which electrons are accelerated to a few MeV through a single resonant trapping process – described by Omura *et al.*, 2007) and ultrarelativistic acceleration through nonlinear trapping by chorus emissions. These processes result in the rapid formation of a distribution of highly relativistic electrons within a few minutes after the onset of the continuous injection of 10–30 keV electrons. The numerical method is the first long-timescale modeling of the relativistic electron flux in the RBs that takes into account specific nonlinear mechanisms. A new type of resonant interaction between suprathermal ions and specific wave packets of ion cyclotron waves (ICW) in which a spatially dependent wave frequency is close to the local ion cyclotron frequency, while the magnitude of the wave vector at a local point increases linearly with time, is investigated by Shklyar and Kuzichev (2014). The interaction suggested provides a continual and efficient mechanism of ion energization in the low-altitude magnetosphere and it insures the damping of ICW excited by lightnings.

A new efficient mechanism of the ion acceleration by electric field pulses in the inner magnetosphere is described by Artemyev *et al.* (2015). The authors used THEMIS observations during a substorm and the test particle modeling and show that at $L = 7$–9 such pulses can effectively accelerate ions with tens of keV initial energy to hundreds of keV. Grigorenko *et al.* (2015) studied the energetic spectra of H+, He+, and O+ ion fluxes in the energy range $\geq$130 keV measured by Cluster RAPID instruments during 37 intervals of the tailward bulk flow propagation in the near-Earth tail (at X $\leq$19 Re). Plasmoid-like structures were associated with the enhancements of energetic ion fluxes and the hardening of energy spectra in a majority of cases. Factors favorable for the ion energization are: the spatial scale of a plasmoid should exceed the thermal gyroradius of a given ion component in the neutral plane inside the plasmoid and the PSD of magnetic fluctuations near the gyrofrequency of a particular ion component should exceed the threshold value (different for different ions).

Injection of particles from various source regions has been discussed in several papers during the past few years. Lazutin *et al.* (2013) analyzed a connection between rapid increases in the electron (>0.3MeV) intensity and magnetospheric substorms using measurements on SERVIS-1. In addition to the radial diffusion occurring at the recovery phase, the increases during a short time period (< 1.5 h) at the main phase of six magnetic storms were observed. The injection of electrons by a pulse electric field induced during substorm activations is suggested as an explanation. Energetic particles are injected into the regions of trapping not only during the storms. Park *et al.* (2010) report, according to STSAT-1 low altitude satellite measurements, that during a quiet period the slot between the outer and inner belt was populated by quasi-trapped electrons (0.1 – 0.4 MeV) and lasted for several hours. The event was observed also by POES. This is the first observation of a slot-region electron injection that did not occur during a geomagnetic storm. Based on an analysis of the THEMIS satellites data and ground magnetometr observations, Kozelova and Kozelov (2015) studied particle injections in the morning sector for a January 6, 2008 substorm. Substorm injections of particles with energies >100 keV, observed by the spatially separated satellites, correspond to the large-scale ground magnetic perturbations. During an injection event of suprathermal electrons observed on THEMIS (0.1 to 30 keV) the whistler mode chorus intensification on the nightside is analyzed by Li *et al.* (2009). Distributions of various charge states of energetic ions on different L shells in the magnetosphere provide an insight into the injection and energization of ionospheric oxygen, as well as solar wind ions inside the magnetosphere. Recently, Allen *et al.* (2016) expand on these early results using observations from the Polar spacecraft. The authors show a charge state distribution of various oxygen ions in dependence on L, on geomagnetic indices and on the product of solar wind velocity and the Bz component of IMF (characteristics of the solar wind-magnetosphere coupling). From these results, it is now possible to develop an empirical model for oxygen charge state abundances in the global magnetosphere as a function of the parameters mentioned above.

The exterior cusp is also populated by energetic electrons. The cusp is a location suitable for the most direct entry for the solar wind plasma into the magnetosphere. Walsh *et al.* (2010) present a case study to test the role different sources may play in populating it with ($E > 40$ keV) electrons. From observations it is likely that local acceleration is the primary source. Fritz *et al.* (2012), discussing the observations made by the Polar, Cluster, and ISEE satellites, suggest that the cusp source appears to be capable of providing energetic ions and electrons to the magnetosphere, which form the source population of the subsequent radial diffusion and formation of the RBs.

Among the most important regions for particle accelerations are the magnetotail and the aurora. The review about acceleration processes, discussions about the models and references can be found in the paper by Birn *et al.* (2012). Birn *et al.* (2013) present results of a MHD simulation of magnetotail reconnection, flow bursts and dipolarization, and investigate the acceleration of test particles to suprathermal energies.

The phase space densities of electrons (PSDe), corresponding to measurements in the energy range $\sim$25 – 800 keV inside and outside RB, are compared by Lui *et al.* (2014). The authors analyze the energetic particle and magnetic field data from instruments onboard Van Allen Probes and THEMIS and PSDe for equatorially mirroring electrons at three values of the first adiabatic invariant are assumed. PSDes at the outer RB boundary are 1-3 orders higher than inside RB; substorms leads to the PSDe increase inside L=5.5 in t<1 h; progressive inward transport of enhanced PSDes is reported, and variations of PSDes at L=3.5 – 6 occur rapidly in 2-3 hours. The authors deduce that continual replenishments are required to maintain a high level of PSDes and that inward radial transport of electrons occurs fast (on a scale of few hours). An extensive statistical analysis of outer RB electron and proton fluxes at the geosynchronous orbit (8 spacecraft) over two solar cycles was done by Borovsky *et al.* (2016). A detailed description of the outer RB in terms of the density number and temperature is provided. Influence of SPEs, changes due to high speed solar wind events, and dependences on local time and on solar activity are presented. Importance of the substorm during the strong stretching phase of the storm is stressed. Outer relativistic electron RB onboard GLONASS (altitude 20.000 km, incl. 65°) is examined for the period from 2006 to 2010 by Tverskaya *et al.* (2012). The authors report about minimum of the 23^{rd} solar cycle. Significant degeneration of the outer RB of electrons during the 23^{rd} solar cycle is reported. Semiannual electron fluxes and daily radiation doses decreased in 2009 by more than an order of magnitude in comparison with the levels observed in 2007. Ripoll *et al.* (2015) studied electron lifetimes in the vicinity of the slot region according to High Earth Orbiting (HEO3) satellites measurements over years 1998 – 2007. Long decay periods of electrons, in the vicinity of the slot region are found and discussed in comparison with timescales previously observed from SAMPEX and CRRES. Turner *et al.* (2014) examined in detail an electron flux dropout during a main phase of a strong storm using 8 spacecraft THEMIS, Van Allen Probes and GOES. The PSDe in adiabatic invariant coordinates revealed that loss processes during the dropout were >90% effective throughout the majority of the outer RB. At L>4 the loss due to magnetopause shadowing and the subsequent rapid outward radial transport is reported, which is not the explanation for L<4.

The mission Van Allen Probes following their launch on August 30, 2012 provided a series of new results on RB dynamics. Spence *et al.* (2013) present science objectives of the RBSP-ECT instruments of energetic particle measurements on the Van Allen Probe spacecraft within the context of the overall mission objectives. One of them is the discovery of a long-lived relativistic electron storage ring embedded in the outer RB, or the third Van Allen belt (Baker *et al.*, 2013). The observations revealed an isolated third ring, or a torus, of relativistic (>2 MeV) electron population formed on 2 September 2012 and persisted in the radial range from 3.0 to 3.5 Earth radii for more than 4 weeks. Shprits *et al.* (2013) showed that ultrarelativistic electrons can stay trapped in the outer zone and remain unaffected by the VLF plasma waves for a very long time owing to a lack of scattering into the atmosphere. Mann *et al.* (2016) provided an explanation of the ultra-relativistic third Van Allen belt. The authors show for the first time how the third radiation belt is established as a consequence of the storm-time extremely fast outward ULF wave transport. High frequency wave-particle scattering loss into the atmosphere is not needed in that case.

For practical reasons the models of trapped particle populations are important. Li *et al.* (2015) analyzed the high-quality measurements from the Relativistic Electron and Proton Telescope on board Van Allen Probes, in a geo-transfer-like orbit. Their study provides, for the first time, quantified upper limits on MeV electron fluxes in various energy ranges in the inner belt. These upper limits are rather different from flux levels in the AE8 and AE9 models (older data sources). An overview of models of RB and plasma, the model architecture, data reduction methods, statistics algorithms, user application and initial validation is presented in the paper by Ginet *et al.* (2013). For a geostationary orbit the model of electron fluxes, which can be used online at `http://www.ssg.group.shef.ac.uk/USSW/UOSSW.html`, is described by Boynton *et al.* (2015).

Subbotin *et al.* (2011) performed a long-term radiation belt simulation for 100 days with the 3-D Versatile Electron Radiation Belt (VERB) code and compared the results with the electron fluxes observed by the Combined Release and Radiation Effects Satellite (CRRES) and made comparison of PSDe with multisatellite data from observations CRRES, Geosynchronous orbit, GPS and Akebono. The authors obtained good agreement with the data. That code include the radial, energy, and pitch angle diffusion and the mixed energy and pitch angle diffusion driven by electromagnetic waves inside the magnetosphere with losses to the atmosphere with boundary conditions account for the convective source of electrons and loss to the magnetopause. It is driven only by Kp and variations of the seed electron population around the geosynchronous orbit.

Miyake *et al.* (2014) studied the solar cell output at the Akebono satellite (an elliptical orbit with the inclination of 75.1° and with initial apogee and perigee of 10,482 and 272 km respectively) related to the proton RB. After removing the temperature effect, the authors deduced another variation component due to the solar cell degradation by energetic protons in the RB. They found that the annual degradation rate fluctuates more largely than expected from the model calculation using the NASA's AP8 model.

While the planetary rotation effect on the RB strucure for particle acceleration at Jupiter and Saturn due to the electric field produced in the inner magnetosphere has been considered important, the effect of the Earth's rotation was usually neglected. Ukhorskiy *et al.* (2014) report that the distributions of energetic electrons across the extent of the Earth's inner RB are organized in regular, highly structured stripes even for low solar activity. Patterns are produced by the Earth's rotation. RB electrons are trapped in the Earth's dipole-like magnetic field, they undergo slow motion around the planet because of the gradient and curvature drift. Rotation of the Earth induces diurnal variations of magnetic and electric fields. They can resonant with electrons having a drift period close to 24 h, and regular patterns composed of multiple stripes in RB occur.

Kanekal *et al.* (2010) discuss the seasonal dependence of relativistic electron fluxes in the Earth's outer RB with the help of 11 years of data from SAMPEX. The relativistic electron fluxes show a strong semiannual modulation. However, the highest electron fluxes occur at times well away from the nominal equinoxes, lagging them by about 30 days. The observed asymmetry of the peak fluxes during the ascending phase of the solar cycle remains a puzzle and requires observations over more solar cycles.

Kalegaev and Vlasova (2015) studied the magnetosphere response to the interplanetary medium conditions in January 2005 and in December 2006 based on data from several satellites and report similar dynamics of the trapped, quasi-trapped, and precipitating particle population during the storms and the main sources caused ring current (RC) build-up have been determined for both storms. The fluxes and ionizing effect of quasi-trapped electrons with the energy ranging from 10 to 300 keV (measurements by NOAA/POES satellites) observed in the so-called forbidden zone (FEE, Suvorova and Dmitriev, 2015) are analyzed for the initial phase of the storm of December 2006 and connection to increases in the total electron content (TEC) are discussed in paper by Suvorova *et al.* (2016). The question how much the modeled RC depends on the representations of magnetic and electric fields and boundary conditions used in simulations, is discussed by Ganushkina *et al.* (2012).

The magnetopause is an important region for energetic particle dynamics in the magnetosphere. The study by Klida and Fritz (2009), based on observations on the POLAR satellite analyzes the energetic ions as functions of both the pitch angle and location. The study indicates that the magnetopause can act simultaneously as a sink for high energy ions and electrons with pitch angles near 90° via magnetopause shadowing, and as a source for ions with pitch angles near 90° for energy < 60 keV. A detailed analysis of the pitch angle distribution of electrons on the POLAR satellite allowing much of the inner equatorial magnetosphere to be observed, combined with the electron paths computations of varied pitch angles in a magnetospheric model is presented in the paper by Klida and Fritz (2013). Results indicate that magnetopause shadowing does play a significant role in the loss of equatorially drifting electrons from the outer regions of the inner magnetosphere. The escape of energetic particles across the magnetopause is studied by Mauk *et al.* (2016). The authors report that even with the relatively simple model developed, energetic particles can completely escape across the boundary for a wide range of conditions. Model also predicts specific pitch angle evolution signatures.

Omidi *et al.* (2010) employ simulations treating ions kinetically and electrons as a massless fluid to study the formation and properties of a new structure named the foreshock bubble upstream from the bow shock. Foreshock bubbles (FB) are found to be highly effective sites for the ion reflection and acceleration to high energies via 1^{st} and 2^{nd} order Fermi acceleration. The interaction of the foreshock bubble with the bow shock results in the release of energetic ions into the magnetosheath, and part of them are subsequently injected into the cusp. Energetic (suprathermal) particles are probably important for FBs: if foreshock ions pass through approaching solar wind discontinuities, they may get concentrated upstream of the discontinuities and form FBs. Different conditions leading to the formation of FBs and hot flow anomalies (HFAs) are discussed by Liu *et al.* (2016). A new type of variability in the foreshock and magnetosheath is revealed with the recent energetic particle experiments monitor of electrons and protons (MEP) onboard the Spectr-R spacecraft and a solid-state telescope onboard the THEMIS spacecraft with high time resolution (Petrukovich *et al.*, 2015a). Oscillations of ion fluxes are observed in the broad energy range $\sim$4–400 keV, with periods of 10–30 s, often a rather monochromatic waveform and accompanied with magnetic oscillations. Energetic ion leakage from the magnetosphere into the magnetosheath remains an important subject of interaction of the solar wind with the magnetosphere. Earlier the measurements e.g. on Prognoz-10 and Interball contributed to the topic (e.g. Kudela, *et al.* 1992). Recently, Westlake *et al.* (2016), using sophisticated instrumentation from two spacecraft (RBSPICE on the van Allen Probes and EIS on the MMS) spaced uniquely near and outside the dayside magnetopause, determined the escape mechanisms for large gyroradii O ions and much smaller gyroradii H and He ions.

Also PAMELA satellite measurements contributed significantly to the description of trapped particles in the magnetosphere. The paper by Adriani *et al.* (2011) reports the discovery of an antiproton radiation belt around the Earth. The trapped antiproton energy spectrum in the SAA region has been measured by the PAMELA experiment for the kinetic energy range 60–750 MeV. The antiproton flux in the SAA exceeds CR antiproton flux by three orders of magnitude, and exceeds the sub-cutoff antiproton flux outside RB by four orders.

Energetic particles play an important role in magnetospheric-ionospheric relations (e.g. a review of the characteristics of plasma-wave perturbations produced by wave-particle interactions in the magnetosphere-ionosphere system by Petrukovich *et al.*, 2015b).

8. Cosmic Rays, atmosphere and selected space weather effects

Secondary CRs have been studied since the discovery of CR in balloon experiments by Victor F. Hess a century ago (Hess, 1912). The extensive review of various secondary components of CR, their distribution with the altitude, the geomagnetic latitude as well as their energy spectra and the angular resolution of its fluxes is published in the book by Grieder (2001). A summary of measurement results and processes of the creation of secondary CR in the atmosphere is also in the book by Dorman (2004). Most probably the longest data set (since 1957) of the charged particle fluxes in the atmosphere at various depths up to $\sim$ 40 km is collected from stratospheric balloon investigations launched regularly by scientists in the Lebedev Physical Institute in Moscow (Stozhkov and Bazilevskaya, 2010).

For calculations of the secondary particle production at various altitudes in the atmosphere the important information include the models of primary CR, high energy particles within the magnetosphere and probabilistic models of solar particles. A review of models of the near-Earth space radiation environment with references is presented in the paper by Xapsos (2013). The Updated Trapped Radiation Environment and its effects on the ISS Dosimetric Measurements have been recently presented by Badavi (2016).

The atmosphere is not only influencing the variability of the flux of secondary CR as measured by ground based detectors (via meteorological conditions above the instruments), however it also plays an important role in physical and chemical processes in the atmosphere. The reviews on the role of CR in the atmosphere can be found e.g. in papers (Stozhkov, 2002; Siingh and Singh, 2010).

Radiation in the atmosphere, especially at high altitudes, is a dangerous factor for people as well as for the stability and reliability of electronic components. The effect of naturally occurring CR on airplane crews and space flight personnel is a subject of several studies. We mention here just a fragment of them. Bramlitt and Shonka (2015) discuss contributions of various CR species for dose at airplanes, especially on solar protons on polar flights and indicate that proton occasions are seven times more frequent than generally believed. An overview of the subject can be found e.g. in paper by Shea and Smart (2000). Increase of commercial airplane activities led to increasing interest in radiation dose studies not only for applications with respect to aircrew personnel, but also to possible negative effects on electronics used for aviation (e.g. Dyer and Truscott, 1999; Stassinopoulos *et al.*, 2003; papers in the book edited by Schrimpf and Fleetwood, 2004). Tobiska *et al.* (2015) stress that active international effort toward observing the weather of atmospheric radiation must occur to make progress in mitigating radiation exposure risks. The correlation of dose measurements on airplanes with that on the ground is studied especially in connection with strong GLEs and FDs (e.g. Spurný and Dachev, 2001; Spurný *et al.* 2004 among many others). For adjusting the models of radiation dose the NM measurements are used (e.g. Mertens *et al.*, 2012). Radiation dose at the airplane altitudes is not clearly corresponding to that on the Earth. Kim, Yun Ho *et al.* (2013) performed an analysis of the dose variation observed on aircraft with data of NM in Daejong. Lee *et al.* (2015) indicated changes in dose over a flight time of 5-7 h without a strong correlation to the CR variability observed on the ground.

CR are investigated also in connection to environmental radioactivity. For that purpose especially high mountain observations are relevant. Autran *et al.* (2015) summarize results of the ASTEP project, launched in 2005 (Plateau de Bure (Dévoluy, France), 2552 m asl). That project produced a large amount of original data concerning not only the real-time testing of soft errors in electronic circuits subjected to terrestrial CR, but also concerning the extensive characterization of the natural radiation environment using various particle detectors. A review on soft-error rates (SER) experiments at various locations and at various altitudes in the field of natural radiation, including the secondary CR, is in the papers (Autran *et al.*, 2009a, b). Advantages and limitations of the approach (measurements of SER in the natural environment) and comparison with accelerated tests using intense particle beams or sources are discussed. A review on SER measurements can be found in the paper (Autran *et al.*, 2014). For similar purposes the long-term dosimetric measurements at high mountains is of relevance. Possibilities as well as limitations of dosimetric measurements with a small dosimeter of type LIULIN (used mainly for estimates of radiation doses at airplanes and on satellites, e.g. Dachev *et al.* 2011 and references therein) at mountain altitudes, namely at Lomnický štít and Jungfraujoch, are summarized by (Kubančák *et al.*, 2015a). For the high mountain altitudes a model for estimate of the effective dose due to secondary CRs produced by GCR is presented by Mishev (2016). The model is in agreement with data observed on Moussala. During GLEs the radiation environment is strongly changed in the troposphere and the radiation of aircrew is increasing in comparison with a quiet period and effects of only GCR. For three strong GLEs Mishev (2014) computed the absorbed dose by a simulation of the atmospheric cascade due to solar particles and obtained contribution of various secondary CR particles. Mishev and Usoskin (2015) present a numerical model for assessment of the effective dose and ambient dose equivalent produced by secondary CR, both of galactic and solar origin, at commercial aircraft altitudes. The authors apply the method for computation of the effective dose rate at a flight altitude during a GLE of 13 December 2006. The computation is using data from NMs and considers the pitch angle anisotropy. Doses at airplane altitudes for three GLEs using the cascade simulations with the PLANETOCOSMICS code (Desorgher *et al.* 2005) have been reported by Mishev *et al.* (2015). Aircrew radiation dose estimates during recent SPEs and effects of anisotropy of the particle flux are presented by Al Anid *et al.* (2014).

In recent years several papers deal with radiation effects on electronics at satellites. Bentoutou and Bensikaddour (2015) report a long-term study on radiation effects in non-hardened high density memory devices operating within the main on-board computer system of Alsat-1 in LEO during 2002 – 2010. SEU rate's correlation with a solar cycle and solar events is found in consistence with expectations. The paper by Suparta (2014) discusses the effects of radiation on a low orbiting spacecraft (LEO) in the equatorial region and indicates importance of assuming that for the design and testing devices for equatorial missions to protect the system from serious damages.

Computations of the production of secondary CR in the atmosphere, especially neutrons, have been conducted and models produced (e.g. Sato, 2015).

A relatively simple dosimetric device, as LIULIN is, is useful not only for aircraft measurements, but also for satellite observations (Dachev *et al.*, 2015). There are many instruments measuring the dose at low orbital satellites and an extensive review on that subject requires a better summary than what is provided here. Thus we mention only selected points here. For a correct evaluation the important point is the calibration of the LIULIN detector described e.g. by Kyselová *et al.* (2015) and comparison of various detectors on aircraft (Kubančák *et al.*, 2015b). Measurements by that detector on aircraft are analyzed e.g. in papers (Ploc and Spurný 2007; Ploc *et al.*, 2013a; Meier *et al.*, 2016). Other measurements have been performed on dose at aircraft with plastic detectors (e.g. a neutron dose equivalent by Vukovic *et al.* (2010)); with personal dosimeters (Takada *et al.*, 2012); neutron dose onboard a polar route flight was studied in detail (Yasuda *et al.* 2011) and dose observations on balloons and rockets (e.g. Moeller *et al.* 2011; Zábori *et al.* 2016) are done. Responses of specific monitors of neutrons to CR at aviation altitudes were studied by Yasuda *et al.* (2009).

Granja *et al.* (2016a, b) present new approach to dosimetric measurements based on quantum imaging detectors of the type Timepix. One of that instruments named SATRAM (The Space Application of Timepix based Radiation Monitor) measures radiation on board the Proba-V satellite launched in an 820 km altitude low Earth orbit in 2013. A timepix chip with a 300 μm Si sensor, a signal threshold of 8 keV/pixel, and a wide range of event count rates is used. The single quantum sensitivity combined with per-pixel spectrometry and a micro-scale pattern recognition analysis of single particle tracks enables to study the composition (particle type) and spectral characterization (energy loss) in the mixed radiation fields. Timepix devices have wide potential applications. Description of particle detection by those types of detectors can be found e.g. in the book by Leroy and Rancoita, 2016, where the interactions of a particle with matter as well as various detectors including those of importance for space studies is included in detail with many references. There are several measurements of the dose at ISS and other low altitude satellites, reviews and future projects proposed (e.g. Benton and Benton, 2001; Berger, 2008; Onishi, 2016; Pálfalvi and Sajó-Bohus, 2015; Nagamatsu *et al.*, 2015; Zábori and Hirn, 2012) as well as simulations related to those experiments (e.g. Ploc *et al.*, 2013b). Sihver *et al.* (2015) present a review on the radiation environment at aviation altitudes and in space.

CR and energetic particles in the surrounding of the Earth play an important role in several atmospheric processes. We shortly mention just two aspects of that, namely (a) lightning, TGF (terrestrial gamma ray flashes) and TGE (thunderstorm ground enhancement) effects; and (b) relation of CR to cloud cover.

Wilson (1924) already predicted the existence of short-lived light flashes over large thunderstorm clouds. A review on planetary atmospheric electricity can be found e.g. in the paper by Yair *et al.* (2008). Short pulses of γ rays with hard energy spectra consistent with bremsstrahlung and related to atmospheric electrical discharges, have been first reported by Fishman *et al.* (1994) on a satellite. Corresponding flashes originate at an altitude of > 30 km and the idea was proposed that energetic electrons are related to rare types of high altitude discharges above thunderstorm regions. Nowadays there are more satellite measurements (CGRO, RHESSI, FERMI, AGILE) of TGF and papers discussing the mechanisms of their production (e.g. Smith *et al.* 2005; Dwyer *et al.* 2008; Dwyer *et al.* 2012; Connaughton *et al.* 2013 among many others) and projects under preparation for their studies (e.g. Lefeuvre *et al.* 2008) or suggestions to measure TGF on other missions under preparation (e.g. Kudela and Blecki, 2015). Lightning induced hard X ray enhancement was observed probably on the CORONAS-F satellite during strong lightning activity in geomagnetically conjugated region (Bučík *et al.*, 2006).

TGFs must be created > 30 km to escape absorption in the atmosphere. Within the few past years there have been observations of counterparts? of lightning induced TGFs at high altitudes - the TGEs on the ground (Chilingarian *et al.*, 2011, 2013a, b, 2014; Kollarik *et al.*, 2016). Chilingarian *et al.* (2016a, b) indicate that relativistic runaway electron avalanches (RREAs) observed on Mount Aragats in Armenia during the strongest thunderstorms and simultaneous measurements of TGE electron and gamma ray energy spectra proved that RREAs are a robust and realistic mechanism for electron acceleration. There are links between atmospheric processes and secondary CR. These processes, however, occur at lower altitudes and are observed on the ground. Recently Hare *et al.* (2016) report on a TGF coincident with an altitude-triggered lightning. The TGF was observed by a ground-level network of gamma ray, close electric field, distant magnetic field, Lightning Mapping Array (LMA), optical, and radar measurements. TGFs are sometimes marked as "gamma ray glow". It should be mentioned that gamma ray glows are fundamentally distinct from TGFs, since gamma ray glows occur on time scales of seconds to tens of minutes, while TGFs occur on time scales of tens to hundreds of microseconds. Furthermore, TGFs are observed in correlation with lightning flashes, particularly intracloud flashes raising the negative charge (Hare *et al.*, 2016). Modeling provided by Dwyer (2012) shows how TGFs could be directly initiated by lightning flashes, whereas glows are not correlated with lightning flashes and tend to be terminated by lightning flashes.

The first experimental evidence that neutrons are generated in lightning discharges, with 10^7-10^{10} neutrons per stroke, has been reported by Shah *et al.* (1985). The evidence of detecting the neutrons correlated with the natural atmospheric lightning discharges (NALD) was obtained with the Lead-Free Gulmarg Neutron Monitor (LFGNM) operating at the High Altitude Research Laboratory, Gulmarg, Kashmir, India. Results obtained from the upgraded version of the system observing bursts of neutrons (improving time resolution) reconfirmed recently the production of neutrons in an NALD (Ishtiaq *et al.*, 2016). Gurevich *et al.* (2015) report that neutrons are observed during atmospheric discharges as short 0.2-0.4 ms bursts (Tian Shan high mountain observatory). Also other authors indicate the relations between the atmospheric discharge and short time increases of neutrons (including thermal ones) at the same site (e.g. Antonova *et al.*, 2009; Martin and Alves 2010; Tsuchiya *et al.*, 2012; Starodubtsev *et al.* 2012; Babich *et al.*, 2013; Kozlov *et al.*, 2013). In addition, the effects of the thunderstorm electric field on intensity of CR muons is reported too (Wang *et al.*, 2012, abstract).

The discussion of the possible influence of CR on cloudiness is continuing for a rather long time. Svensmark & Friis-Christensen (1997) reported a correlation between the GCR flux and cloud cover. Data on clouds have been taken from satellite measurements and CR data from ground based ones, namely NM.

Krahenbuhl (2015) investigated the product called the North American Regional Reanalysis which provides high-resolution, low, mid-level, high, and total cloud cover data over the northern hemisphere. He found that for the low cloud cover over the North American continental interior and for regions of the mid-latitude oceans exhibited a positive correlation with the CR flux. In regard to the solar forcing of the climate system, the results of this investigation suggest that with the assumption that solar forcing does impact cloud cover, measurements of solar activity exhibit a slightly higher correlation than GCRs. The correlations of cloud cover and CR are variable and most probably depending on the site of measurement. The empirical study of the relations between the cloud cover and CR intensity as observed at the same high mountain site (2634 m a.s.l.) indicates no strong binding between the two data sets over the interval covering almost three solar activity cycles (Kancírová and Kudela, 2014). Importance of barometric pressure and CR corrections for this type of study at the mountain site is mentioned by Kancírová *et al.* (2016).

For comparison between cloud cover and CR there are used mainly data from ground based observations of CR by NMs. Harrison *et al.* (2014) analyzed an atmospheric ion production rate obtained during 2013-2014 by Geiger counters on a series of meteorological radiosondes up to $\sim$27 km. Above $\sim$10 km, the ionisation rate correlates with the NM data time profile, while below $\sim$5 km the correspondence with NM is poor. Short-term CR variations like FDs clearly observed by NMs may not provide a good parameter used for characterisation of the actual atmospheric short-term ionisation changes at the levels of cloud formations. A probably longest time series of ionisation measurements on balloons is that provided by FIAN, Moscow (e.g. Bazilevskaya *et al.*, 1994). Such type of data are of interest for checking relations between cloudiness and ionisation at various altitudes and time petriods. For clarification of the role of CR by ionisation in the cloud formation simultaneous measurements of the ionisation on tropospheric balloons at different sites and at NMs of different positions will be useful.

Solovyev and Kozlov (2009) report a positive correlation of the cloud cover change with the FDs in the case of the auroral activity index AE $>$ 300 nT and an anticorrelation in the case of smaller FDs (for AE $<$ 300 nT). The comparison is done over northern Asia. On the other hand, several studies found no statistically significant signal during or following FDs (Sloan and Wolfendale, 2008; Calogovic *et al.* 2010). Rohs *et al.* (2010) used for the analysis extinction data, the occurrence frequency and cloud index data from the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS), and they indicate that a positive correlation between clouds (cloud index) and Climax NM data prevails and that this correlation is especially pronounced at 9 km. Harrison and Ambaum (2008) discuss enhancement of the cloud formation by droplet charging. They say that because a vertical air–earth conduction current is present globally, the abundance of stratiform clouds implies extensive regions globally where cloud edge droplet charges may influence haze activation and modulate the cloud base. Such regions would experience a cloud edge modulation from global atmospheric electrical circuit changes and CR. One possibility to discriminate between the influence of CR and solar activity on clouds, is checking the variability – periodicities differently imprinted in the two characteristics. Harrison (2008) discusses discrimination between CR and solar irradiance effects on clouds. Harrison *et al.* (2011), checking the cloud base height and CR, conclude that the data support the idea of propagation of heliospheric variability into layer clouds, through the global atmospheric electric circuit. Didebulidze and Todua (2015; 2016) studied inter-annual variations and long-term trends of cloudless days and cloudless nights in 1957–1993 from Abastumani (41.75N, 42.82E), at different geomagnetic conditions and corresponding CR flux changes. The authors show possible influence of cosmic factors on cloud covering processes and, thus, on the climate change.

Papers (Eroshenko *et al.* 2010; Germanenko *et al.*, 2013) provide information about influence of precipitation/rains on various secondary CR measured on the ground.

The aerosols are assumed to be important for radiative forcing the climate. Kirkby *et al.* (2016) report the atmospheric particle formation solely from biogenic vapours. The data are obtained at the CERN CLOUD chamber. Authors present evidence for the formation of aerosol particles from highly oxidized biogenic vapours in the absence of sulfuric acid in a large chamber under atmospheric conditions, and they found that ions from GCR increase the nucleation rate by one to two orders of magnitude compared with neutral nucleation. Svensmark *et al.* (2016) discuss the response of clouds and aerosols to CR decreases. The authors report that total solar irradiance has a relative decrease in connection with FDs of the order of 10^{-3} (too small for thermodynamic impact on timescales of a few days) and indicate that there is a real influence of FDs on clouds probably through ions.

SEPs and GLEs influence the atmosphere. Tropospheric response is observed even in non-GLE events at middle latitudes. During an SEP event associated with a solar flare on April 11, 2013, the vertical ionization rate profile obtained using a balloon-borne detector showed enhanced ionization with a 26% increase at 20 km, over Reading, UK (Nicoll and Harrison, 2014, a balloon experiment). An epoch of the extremely low solar activity between cycles 23 and 24 and the corresponding enhanced ∼27 day variation of CR allowed to obtain phase synchronous electrical variations in the terrestrial lower atmosphere in the southern UK, including an increase in the vertical conduction current density of fair weather atmospheric electricity during increases in the CR NM count rate at the surface (Harrison *et al.* 2013).

There are various relations between the space weather effects and CR including high energetic magnetospheric particles (e.g. Kudela *et al.*, 2000; Lilensten and Bornarel 2006; Dorman 2010; Kudela 2013; Lilensten *et al.* 2014). For solar cycle 23, Shea and Smart (2012) overview the GLEs in relation to various space weather effects. The effects include communication and navigation systems, spacecraft electronics and operations, space power systems, manned space missions, and commercial aircraft operations. The extreme effects of the unusually increasing solar, interplanetary and geomagnetic activity in October and November 2003 are highlighted. The lower ionosphere is influenced by particles from GLEs subsequently changing the electron density and plasma frequency and thus the conditions for VLF waves are changing too. Usoskin *et al.* (2011), using solar proton spectra for 58 out of 66 GLEs recorded by NMs since 1956, evaluated possible ionization effects in the low and middle atmosphere. The authors report that the direct ionization effect is negligible or even negative, due to the accompanying FDs at low and middle-latitudes, and the ionization effect is important only in the polar atmosphere, where it can be strong above 30 km during major GLE events. The paper by Žigman *et al.* (2014) presents an example of changing the phase and amplitude of the VLF wave during GLE 70 when the largest portion of the path traversed the night side of the Earth and thus high energy photons from the Sun have a negligible effect. For the same event, Mishev and Velinov (2013) computed the enhanced ionization of the atmosphere due to high energy protons. High energy electrons precipitating from RB may have influence on the middle atmosphere ozone chemistry. A detailed study of these effects during a geomagnetic storm in September 2005 is done by Rodger *et al.* (2010). Ground based subionospheric radio wave observations are used to estimate electron precipitation fluxes at L = 3.2. Applying a specific ion and neutral chemistry model, and refining the quantification of the electron precipitation flux into the atmosphere by using a time varying energy spectrum determined from the DEMETER satellite, the authors show that the large increases in odd nitrogen (NOx) and odd hydrogen (HOx) caused by the electron precipitation do not lead to a significant in situ ozone depletion in September in the Northern Hemisphere. However, if a similar precipitation is deposited into the polar winter atmosphere, it would have led to >20% in situ decreases in O3 at 65–80 km altitudes, with a possible additional stratospheric O3 depletion from descending NOx beyond the model simulation period.

In the past 7 years there have been published papers on short and medium term alerts of space weather effects using CR measurements. The NM network can provide alerts of GLE (e.g. Souvatzoglou *et al.*, 2009, 2014; Mavromichalaki *et al.*, 2006). For a short term prediction of the strong flux of energetic particles related to solar and/or interplanetary acceleration, which are dangerous for correct functionality of technological systems on satellites and aviation, there are used schemes based on measurements by NMs with high temporal resolution and high statistical accuracy, using data from several points (e.g. Dorman and Zuckerman, 2003; Dorman *et al.*, 2006; Mavromichalaki *et al.*, 2010 among others).

Regarding the probability of the occurrence of GLEs on a longer time scale, recently the paper by Perez-Peraza and Juarez-Zuniga (2015) reports that by means of the wavelet spectral analysis combined with fuzzy logic tools, the previous known GLE events have been reproduced. The authors present results for eventual future events.

Kojima *et al.* (2015), using high statistics muon data of six years (2000–2005) from the large GRAPES-3 muon telescope, and minimizing the contribution of various unrelated solar phenomena (periodic and transient (FD and GLE) events identified by a NM), found a strong anticorrelation between the variations in the solar wind speed and CR intensity at a very high significance level.

Petukhov and Petukhov (2012) determined (via calculations) the dynamics of CR before the geomagnetic storms onset caused by an interplanetary shock and obtained good comparison with the event Sep. 9, 1992 decreases. The method can be used for space weather studies - dynamics of the solar wind disturbances by precursors in CR. Papailiou *et al.* (2013) checked large FDs and large geomagnetic disturbance events (Kp>5) related to the western parent solar flare positions, and concluded that in 60% of the events the precursors of CR variation are observed in the plot asymptotic longitude versus time. Precursors of FDs are studied in papers (Papailiou *et al.*, 2012a, 2012b). Using the wavelet analysis of CR intensity is reported for a prediction of great geomagnetic storms in the paper by Zhu Xiao-Lu *et al.* (2015, abstract).

There were published also papers relating CR variability (probably via the variations of the physical parameters in the chain Sun – Earth) to health and activity of people (e.g. Papailiou *et al.* 2009, 2012c; Stoupel *et al.*, 2009; Caswell *et al.*, 2016 among others).

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1. Introduction

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