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Variability of Low Energy Cosmic Rays Near Earth

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1. Introduction

Almost a century ago Victor Hess in his balloon experiments discovered cosmic rays (Hess, 1912). The history in understanding the nature, physical mechanisms affecting the temporal and spatial variability of cosmic rays (CR) observed on the ground and within the atmosphere, as well as of the anisotropy of secondary particles due to geomagnetic effects and due to the state of atmosphere is reviewed e.g. in the monographs (Hillas, 1972; Dorman, 2004; 2009; Rossi and Olbert, 1970 and references therein). Progress in clarifying mechanisms controlling the secondary CR flux required the design and construction of new detectors. Production of secondary CRs is reviewed in the books (Grieder, 2001; 2010). Until half of the past century the elementary particle physics was driven mainly by CR studies. With the improvement of the acceleration technique, the domain of CR for subnuclear physics research, was shifted to high energies. Even today the high energy CRs observed by the large ground based detectors remain the only one source of information about the particles of extremal energy. The astroparticle physics aspect of CR is described e.g. in the books (Grupen, 2005; Gaisser, 1990; Hayakawa, 1969). Relations of high energy astrophysics to CR physics include the book (Longair, 1981 and the newer versions).

The important step in CR studies represented the International Geophysical Year in 1957-1958. The new detectors and its networks were built (Simpson 1958; Hatton, 1971; Stoker, 2009 among others) and CR research attracted many scientists, engineers and students. Most important stimulus for the progress in low energy cosmic rays (LECR) was the launch of the first satellites of Earth which meant beginning of the Space Era. Shortly after measurements of radiation on the first satellites, the new populations of energetic particles in space (not providing secondary „signal" on the Earth) have been found. That direction of research was important also for plasma physics. Processes of particle acceleration, transport and losses in the plasma regions in space, where conditions are inimitable for laboratory plasma experiments, brought new knowledge into plasma physics. There are several books and papers summarizing/illustrating in detail CR physics in its history. At low energies to which this chapter is devoted, much more informations can be found e.g. in (Dorman, 1974; Bieber et al., 2001; Vainio et al., 2009; rapporteur papers in the proceedings of ICRCs). Here we mention selected results in the experimental studies related to LECR with empasis to the papers published in the past 2-3 years.

2. LECR variations

Two populations of LECR can be assigned, namely (1) at the energies above, and (2) below the atmospheric threshold (~ 400 MeV for protons). Above that energy the ground based measurements provide the direct information about changes in the flux of primaries. For lower energies the measurements of particles on satellites, space probes, rockets and balloons are most relevant. Two types of experimental devices on the ground are very important for the detection of LECR flux variability above the atmospheric threshold, namely neutron monitors (NM) and muon telescopes (MT) sensitive to different ranges of energy spectra of primaries.

Galactic CRs entering the heliosphere are affected by the interplanetary magnetic field (IMF) which, especially in the inner heliosphere, is controlled by the solar wind plasma having higher energy density than IMF. Concept of field lines frozen in the high conductivity solar wind plasma is often used. CR in the inner heliosphere having lower energy density than the IMF, can be assumed as a specific "autonomous" population of particles. In the outer heliosphere, however, the relations are changing. The heliosphere via the IMF is modulating the CR flux at the low edge of its energy spectra. In addition, it contributes itself to energetic particle populations by acceleration at the Sun as well as at plasma discontinuities in the interplanetary space, and within the magnetospheres of planets with strong magnetic field. Additionally, heliosphere is transparent for access of neutral atoms from outer space. They can be ionized in the heliosphere and subsequently accelerated, which contributes to the suprathermal particle population known as anomalous cosmic rays (Garcia-Munoz et al., 1973). Modulation of CR depends on its primary energy. Solar wind with the embedded IMF flowing outward from the Sun screens the access of primary CR into the heliosphere. The physical framework in which the energetic particles and CR propagate in the heliosphere is also denoted as heliospheric magnetic field, HMS (recent review e.g. by Balogh and Erdös, 2011). Below few hundreds MeV practically no galactic CR enter the inner heliosphere (Jokipii, 1998). The modulation below ~ 10 GeV is present even during solar activity minimum. The main feature of a long term variation of low energy galactic CR (GCR) near Earth is the anticorrelation of the flux with solar activity having about 11 year cyclicity. In addition to ~11 year periodicity, the ~ 22 year modulation cycle in CR flux due to solar magnetic field polarity reversals, is observed (e.g. Webber and Lockwood, 1988). Around the epoch of solar activity maxima there is observed a double-peak structure in many solar activity factors. A distinctive minimum between the peaks is called Gnevyshev gap (Storini et al., 2003 and references therein). In CR this minimum is connected e.g. with decrease of ~27 day quasi-periodicity.

Theory of CR transport, used basically until present with several small modifications, was described first by E.N. Parker (1965). Energetic particles in the interplanetary space walk randomly in irregularities of the large-scale IMF when irregularities are moving with the solar wind velocity. The distribution function determined by a Fokker-Planck equation describes the time evolution of the probability density function of the position and momentum of particle. In addition to the convection and diffusion, CRs experience two additional effects. One of them is the acceleration or deceleration. Solar wind plasma is expanding in free space and compressing at the shocks near the planets or in the interplanetary space. The inhomogenities with different IMF become mutually more distant or more close to each other. This leads to the adiabatic cooling or heating due to multiple interactions of CR with inhomogenities. Modulation of GCR in the inner heliosphere is controlled by convection in solar wind, diffusion, particle drifts and adiabatic energy losses. Using the experimental data from various space missions, an overview of the current understanding of the modulation over the past decade is given by (Potgieter, 2011). At low energies, 10–100 MeV, where the adiabatic cooling plays the primary role, its effect can be best seen in the framework of the force-field approximation (Gleeson & Axford 1968; Fisk et al. 1973). In addition, the curvature and gradB drifts in IMF play role in the modulation. Gyration of particle around the field line is faster than scattering. Thus particles are subject of drift due to large scale spatial structure of the IMF. CR transport and modulation was studied in many papers (e.g. Jokipii, 1966; 1967; Potgieter and Le Roux, 1994; Zank et al., 1998; Cane et al., 1999 among others) and it is examined further along with the new knowledge of CR flux at various points in the heliosphere and near its boundaries. For the transport equation the determination of the coefficients deduced from the measurements at various positions and energies is important. Reviews of transport coefficients for LECR is e.g. in (Palmer, 1982; Valdés-Galicia, 1993). Recently (Kecskeméty et al., 2011) examined the energy spectra of 0.3–100 MeV protons and found, that at the lower energies, the galactic particle spectra are significantly steeper than the $J(E) \sim E$ one, predicted by analytical approximations, such as the force-field model of modulation. Usoskin et al. (2005) provide a long series of a parameter allowing for a quantitative estimate of the average monthly differential energy spectrum of CR near the Earth for long time interval.

CR, measured directly by its secondaries at Earth over more than half of century, indicate complicated structure in its temporal behavior. The nucleonic component of primary CR is appropriate to study solar modulation from ground based measurements (e.g. Storini, 1990). CR modulation as observed from the Earth is discussed and reviewed e.g. by (Belov, 2000). Single point measurements are influenced by the large scale structure of IMF over the heliosphere, which, in the given time, in addition to the measured IMF and solar wind e.g. at L1, includes also “memory effect” of solar activity due to relatively slow outward motion of solar wind with the IMF inhomogenieties, if compared to the speed of CR particles. Long term modulation is observed as a series of steplike decreases. Outward propagating diffusion barriers were identified as merged interaction regions, MIRs (Burlaga et al., 1985). A comprehensive review of various CR intensity variations over different time scales that have been conducted over 1970s and 1980s can be found in paper (Venkatesan and Badruddin, 1990) and in references therein. Recently (Strauss et al., 2011) review some of the most prominent CR observations made near Earth, and indicate how these observations can be modelled and what main insights are gained from the modelling approach. Also, discussion on drifts, as one of the main modulation processes, is given as well as how the drift effects manifest in near Earth observations. Specifically, discussion on explanation of the observations during past unusual solar minimum, is included. Siluszyk et al. (2011) developed a two-dimensional (2-D) time dependent model of the long period variation of GCR intensity, where they included the slope of power spectrum density of IMF fluctuations, magnitude of B, tilt angle of heliocentric current sheet and effect of particle drift depending on solar magnetic field polarity. Solar modulation of GCR over the past solar cycles is described and discussed in detail e.g. by (Chowdhury et al., 2011). Recent solar minimum was specific one, unusually long and deep (e.g. Badruddin, 2011). The modulation of CR was minimal for the more than 70-year-long period of direct measurements (Bazilevskaya et al., 2011). In 2009 (Stozhkov et al., 2011) recorded the highest

CR fluxes (particles with energy > 0.2 GeV) in the history of the CR measurements in the stratosphere. An increase of the flux on NMs during that minima was also reported (e.g. Moraal and Stoker, 2010). GCR modulation for solar cycle 24 began at Earth's orbit in January 2010 (Ahluwalia and Ygbuhay, 2011). That paper reports that some NMs are undergoing long-term drifts of unknown origin. Such effects have to be examined in detail because of correct understanding the long term CR variations from the direct measurements. Corrections of data in the NM network are discussed also e.g. by (Dvornikov and Sdobnov, 2008). There are several sources of the data from CR measurements by NMs (recently e.g. NMDB data base at http://nmdb.eu).

Modulation of the low energy component of GCR inside the heliosphere gives us insight on the relevance of solar phenomena that determine the structure and evolution of the heliosphere. Reviews of the advancement in the comprehension of the phenomena controlling the transport of LECR in heliosphere can be found e.g. in (Valdés-Galicia, 2005). Time profiles of CR observed at a given position of NM on the ground are result of superposition of many transitional effects due to the temporary and spatially changing structures of IMF irregularities within the heliosphere, by the rotation of the Earth with detector, by the effects of magnetosphere and by the variable state of the atmosphere. In addition to the network of NMs, the information about the variability of CR at higher energies provide the detectors in relatively new installations. The decription of few of such installations along with the first results are reported e.g. in papers (Augusto et al., 2011; De Mendonca et al., 2011; Maghrabi et al., 2011).

Charge dependent modulation is important point in the CR drift models (e.g. Kóta and Jokipii, 1983; Potgieter and Moraal, 1985). The drift effects have to be marked differently for CR particles with the opposite sign of electric charges during epochs with opposite polarities of the solar magnetic field. Thus the interest to the measurements of positrons and antiprotons is increasing. Important finding was done by PAMELA experiment (Adriani et al., 2009; 2010). The authors present data on the positron abundance in the CR in the energy range 1.5 - 100 GeV with high statistics. The data deviate significantly from predictions of secondary production models, and the authors stress that it may constitute the first indirect evidence of dark matter particle annihilations, or the first observation of positron production from near-by pulsars. The evidence of solar activity affecting the abundance of positrons at low energies is reported too. This result was recently confirmed independently by the observations of FERMI (Ackermann et al., 2011), where the authors report first time measurement of absolute CR positron spectrum above 50 GeV, and indicate that the fraction has been determined above 100 GeV. Increase of positron fraction with energy between 20 and 200 GeV is found. The future measurements with greater sensitivity and energy resolution, such as those by AMS-02, are necessary to distinguish between many possible explanations of this increase. Serpico (2011) summarizes the global picture emerging from the data and recapitulates the main features of different types of explanations proposed. Testing of different scenarios and inferring some astrophysical diagnostics from current/near future experiments is also discussed.

2.1 Irregular variations

Coronal Mass Ejections (CME) are causing changes in CR intensity measured at Earth. Although the decrease in CR coincident with geomagnetic field depression (horizontal component) was first observed by Forbush already in 1937 (in the book Van Allen, 1993, p. 117), this phenomena attracts the CR physicists until present. Forbush decreases are generally correlated with co-rotating interaction regions (CIRs) or with the Earth-directed CMEs from the Sun (e.g. Prasad Subramanian, 2009). The characteristics of CMEs in the inner heliosphere are discussed in detail by (Gopalswamy, 2004). One of the first papers suggesting that the solar cycle dependent modulation of GCR can be explained by CMEs and by related IMF inhomegeneities in the heliosphere was that by (Newkirk et al., 1981). Correlation of CR intensity and CME ocurrence at a single NM with high geomagnetic cut-off is reported e.g. by Mishra et al. (2011) for different solar magnetic field polarities.

The Forbush decrease (FD) or cosmic ray storm is produced as a result of the transient diffusion-convection of CR caused by the passage of IMF shock wave. Nagashima et al. (1992) show that the storm is frequently accompanied by non-diffusion-convection-type phenomena, depending on local time, as precursory decrease of CR at the front of the shock in the morning hours of local time, and a post-shock increase different from the diurnal variation. FDs are analyzed by global spectrographic method using worldwide network of NMs (e.g. Sdobnov, 2011 and references therein). Recently (Dumbovic et al., 2011) performed statistical study of the relationship between characteristics of solar wind disturbances, caused by interplanetary CMEs (ICMEs) and corotating interaction regions, as well as with properties of FDs. It was found that the amplitudes of the CR depression are primarily influenced by the increase in magnetic field strength and fluctuations, and the recovery phase also depends on the magnetic field strength and size of the disturbance. The use of FDs for space weather studies is discussed by (Chauhan et al., 2011). For this application the complexity of relations between the geomagnetic storms and FDs must be assumed. Mustajab and Badruddin (2011) critically analyze the differences in geoeffectiveness due to different structures and features, with distinct plasma/field characteristics. Distinct relations of FDs and geomagnetic activity measured by Dst in different events is reported by (Kudela and Brenkus, 2004; Kane, 2010). Richardson and Cane (2011) analyzed large number of ICMEs and their associated shocks passing the Earth during years 1995 – 2009. They found that magnetic clouds are more likely to participate in the deepest GCR decreases than ICMEs that are not magnetic clouds. Examining simultaneous observations of FD events by different CR stations remains a subject of interest. Variability in the manifestations of FDs demonstrates that there are still open questions in this field (e.g. Okike and Collier, 2011; Pintér et al., 2011). Study (Oh and Yi, 2009) may support the hypothesis that the simultaneous FDs occur when stronger magnetic barriers pass by the Earth, and in contrast that the nonsimultaneous FDs occur only if the less strong magnetic barriers pass the Earth on the dusk side of the magnetosphere. The FDs are observed not only by NMs but also at higher energies of primary CRs (e,g. Braun et al., 2009; Abbrescia et al., 2011; Bertou, 2011) or by a lead free NM (Mufti et al., 2011). Rigidity spectra of FDs and their relations to the index of power spectra density (PSD) of IMF fluctuations in the frequency range in which the interaction of IMF with CR can be efficient, is studied in papers (Alania and Wawrzynczak, 2008; 2011). The theoretically derived relationship between rigidity spectrum exponent (γ) and exponent (ν) of IMF PSD is confirmed. Figure 1 illustrates different relations of FDs to geomagnetic activity.

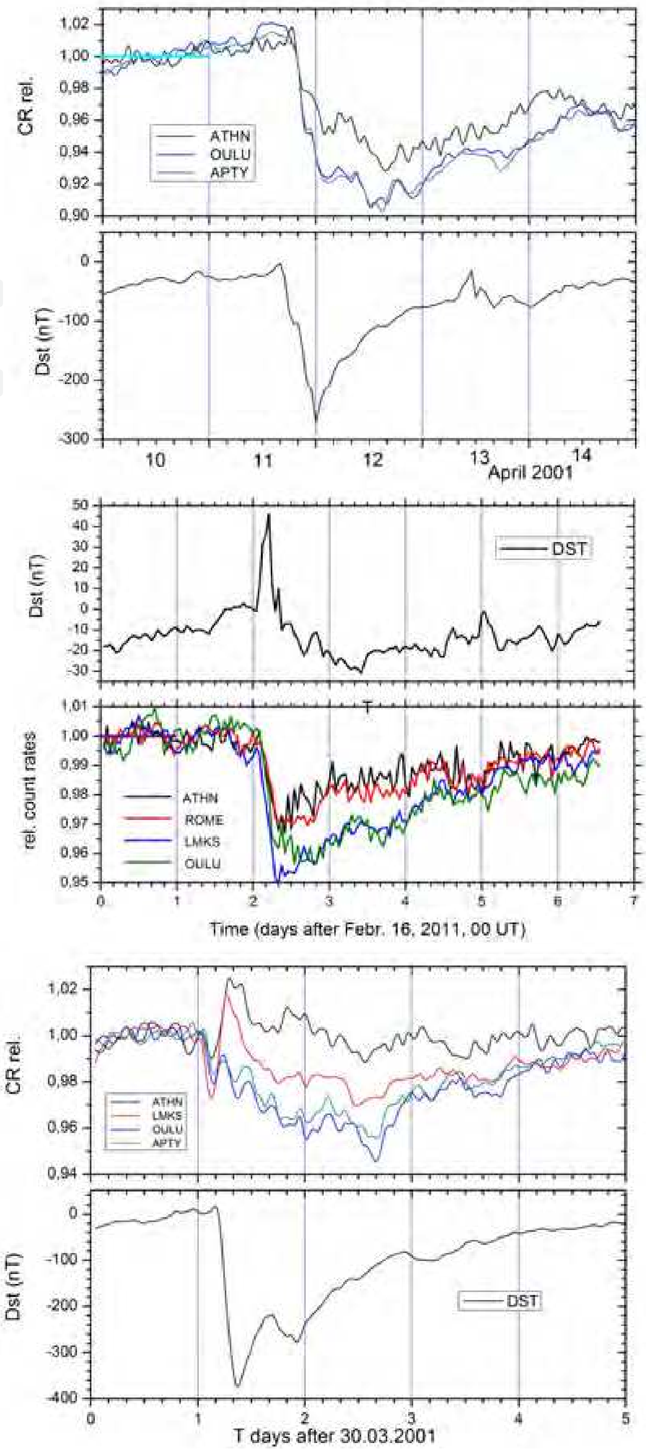

Fig. 1. Three decreases of GCR as measured by NMs (Athens, Oulu, Apatity, Rome, Lomnicky stit) with different relations to geomagnetic activity. Upper panel: CR storm accompanied by Dst depression. FD is better pronounced at low cut-off rigidity NMs (Apatity, Oulu) than at higher one (Athens). Middle panel: FD observed at several european NMs not accompanied by any Dst depression (IMF Bz>0). Lower panel: At low cut-off NMs CR decrease is seen (geomagnetic cut-offs near or below the atmospheric ones), while at middle and high cut-off positions (Lomnicky stit, Athens) an increase is seen due to the improvement of magnetospheric transmissivity.

Analysis of FDs is important for better understanding of the magnetic field structure related to shock waves and fast streams originating at the Sun. Quenby et al. (2008) examined the temporal history of the integral GCR fluence (≥100 MeV) measured by the high-sensitivity telescope (HIST) aboard the Polar spacecraft, along with the solar wind magnetic field and plasma data from the ACE spacecraft during a 40-day period encompassing September 25, 1998 FD. The authors also analyzed FD and energetic storm particle event on October 28, 2003, one of the largests in the past decades. Short-scale GCR depressions during a test period in September through October 1998 did not show correlation with changes in magnetic scattering power or fluctuations in solar wind speed or plasma density. However, IMF and solar wind data during the test period of FD suggest the presence of ICME. Mulligan et al. (2009), using the high resolution energetic particle data from ACE SIS, the Polar high-sensitivity telescope, and INTEGRAL's Ge detector measuring GCR background with a threshold of 200 MeV, show similar, short-period GCR variations in and around the FD. NMs have lower statistics. Earlier paper (Kudela et al., 1995) indicated that the Dst decreases are correlated with the „prehistory“ of CR fluctuations on time scales longer than tens of minutes especially during the years with high solar activity. In the future high temporal resolution data on CR are needed, and the analysis based on combination of NM data with the satellite measurements by detectors having large geometrical factors is important (e.g. Grimani et al., 2011).

Another class of irregular variations of CR intensity observed in the vicinity of Earth are high energy particle populations accelerated in the solar flares or at the discontinuities in interplanetary space. Two types of solar energetic particle (SEP) events, namely impulsive and gradual ones, have been recognized since 1980s (e.g. Lin, 1987). Reames (1999) summarized the knowledge about energetic particle populations coming from solar flares, from shock waves driven outward by CMEs, from magnetospheres of the planets and bow shocks and reviewed various acceleration processes throughout the heliosphere. Miroshnichenko (2001) surveyed in detail the results of solar CR investigations since 1942, with including a large amount of data, obtained during long time period of observations of SEP. The book also covers theoretical models and gives an extensive bibliography. Recently Hudson (2011) reviews the knowledge of solar flares with the focus on their global properties. Flare radiation and CME kinetic energy can have comparable magnitudes, of order 10^{25} J each for an X-class event, with the bulk of the radiant energy in the visible-UV continuum. The author argues that the impulsive phase of the flare dominates the energetics of all of these manifestations, and also points out that energy and momentum in this phase largely reside in the electromagnetic field, not in the observable plasma. Barnard and Lockwood (2011) constructed a database of gradual SEP events for 1976-2006 using mainly data of > 60 MeV protons. Although number of events decreases when solar activity is low, the events during solar minimum are observed with higher fluence. Thus, very strong flares may be more likely at lower solar activity. Ground level events (GLE) are observed by NMs when the energy of accelerated particles in the flare or in interplanetary space exceeds the atmospheric threshold and geomagnetic cut-off rigidity. Characteristics of GLEs for the past solar cycles are summarized and discussed e.g. by (Gopalswamy et al., 2010; Andriopoulou et al., 2011). Moraal and McCracken (2011) analyzed all GLEs for the cycle 23. Three of the 16 GLEs have a double-pulse structure. They are associated with western flares and have good magnetic connection to the Earth. All have fast anisotropic first pulse followed by a smaller, gradual, less anisotropic second pulse. Vashenyuk et al. (2011) present a GLE modeling technique applied for 35 large GLEs for the period 1956 – 2006 and obtained features of prompt and delayed components of relativistic solar particles. Kurt et al. (2011) studied signatures of protons with energy above several hundred of MeV associated with major solar flares and observed by NMs during GLEs. The authors revealed that the delay of the earliest arrival time of high-energy protons at 1 AU with respect to the observed peak time of the solar bursts did not exceed 8 min in 28 events. This indicates that efficient acceleration of protons responsible for the GLE onset is close to the time of the main flare energy release. For the GLE observations are important high altitude NMs due to their high count rate and high statistics. List of GLEs observed at one high mountain NM can be found in (Kudela and Langer, 2008).

Important source of the information about protons accelerated near the Sun and about their interactions with residual solar atmosphere are solar gamma-rays and neutrons. Their observation near Earth is not affected by magnetic field as it is in the case of protons GLEs, SEP events. Production of γ -rays and neutrons results from convolution of the nuclear cross-sections with the ion distribution functions in the atmosphere. Recently Vilmer et al. (2011) reviewed the γ-ray and neutron observations with the emphasis on the very detailed RHESSI measurements, namely the high spectral resolution revealing line shapes and fluences, and gamma-ray imaging technique. The authors point out also still open question for the study of high energy neutral emissions from the Sun. Chupp et al. (1973) reported first observations of gamma ray lines from solar flares in August 1972 using data from OSO-7 satellite. Ramaty et al. (1979) reviewed the gamma-ray line emission from the Sun due to nuclear deexcitation of ambient nuclei following the interactions of accelerated particles. Although Biermann et al. (1951) long time ago proposed that high energy neutrons created by nuclear interactions of protons with the atmosphere of the Sun can be observed on Earth's orbit, first direct indication of solar neutrons on the ground was reported from high mountain NMs Jungfraujoch and Lomnický štít in the flare event June 3, 1982 (Debrunner et al., 1983; Efimov et al., 1983) and on satellite by electrons from the neutron decay (Evenson et al., 1983). After that event the interest to detection of solar neutrons increased. Several NMs started to measure with better temporal resolution, and new experimental devices for detection of gamma rays and neutrons both on the ground as well as on the satellites were constructed. High energy gamma rays and neutrons during several solar flares have been observed in the past decade also e.g. on low altitude polar orbiting satellite Coronas-F (Kuznetsov et al., 2006; 2011; Kurt et al., 2010). Review on experimental and theoretical works related to solar neutrons is in (Dorman, 2010a).

2.2 Periodic and quasi-periodic variations

The quasi-periodic and periodic variations in CR intensity observed at Earth are studied for rather long time. The solar diurnal wave, being the fixed one, was checked starting from papers (Forbush, 1937; Singer, 1952; Thompson, 1938; Brunberg and Dattner, 1954; Ahluwalia and Dessler, 1962). Studies of its higher harmonics, namely of semi-diurnal one, can be found in papers since (Ahluwalia, 1962; Nicolson and Sarabhai, 1948) and on the tri-diurnal starting probably from (Mori et al., 1971; Ahluwalia and Singh, 1973). At longer quasi-periodicities first attention was paid to ~ 11 yr, ~22 yr and ~27 d variabilities. The detailed review is in the books (Dorman, 1975; 2004) and references therein.

For the shape of the PSD we examined the long time series of Climax NM, skipping the data influenced by the GLEs, interpolating linearly the gaps, and applying the FFT method. PSD obtained is plotted in Figure 2.

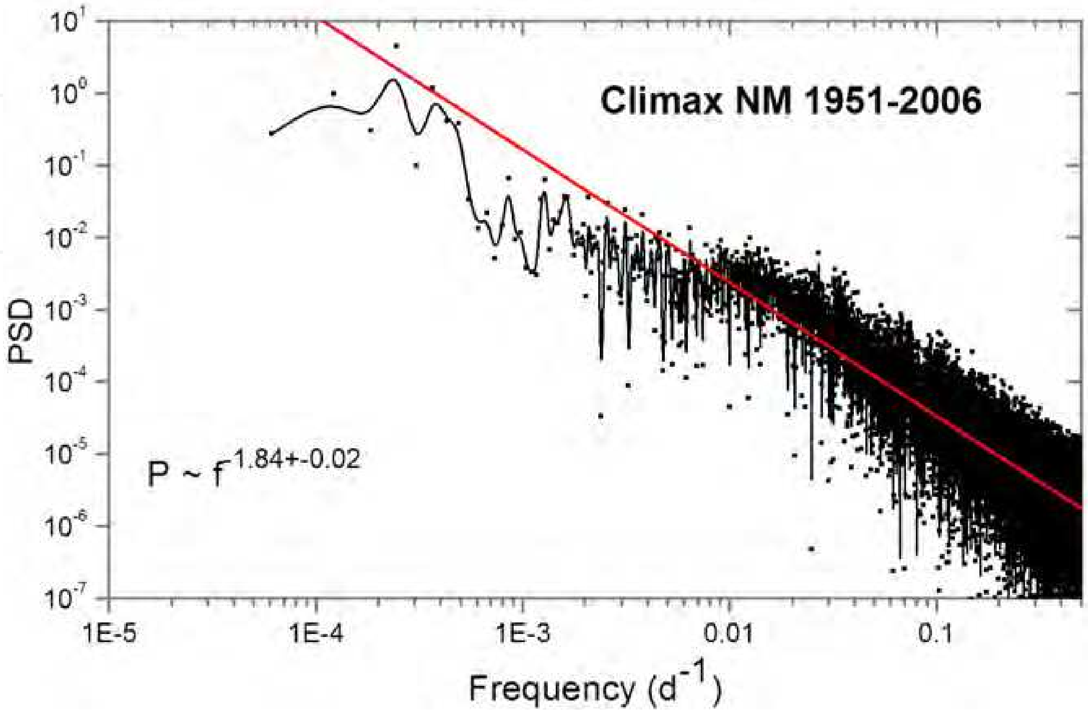

Fig. 2. The power spectrum density (PSD by FFT method) of daily averages of count rate of Climax NM (dots). Data downloaded from ftp://ulysses.sr.unh.edu/NeutronMonitor/DailyAverages.1951-.txt. Line is for the cubic spline connection.

The spectral density at higher frequency ranges is plotted in Figure 3.

At frequencies $f < 5.8 \times 10^{-6}$ Hz (upper panel of Figure 3) the slope is consistent with the theory (Jokipii and Owens, 1974b) where the authors indicate that including the effects of non-field-aligned diffusion, which dominates the power spectrum of NMs at low frequencies ($< 5 \times 10^{-6}$ Hz) produces a spectrum of f^{-2} .The lower panel clearly indicates the presence of the fixed frequencies of the diurnal, semi-diurnal and tri-diurnal waves. Probably the fourth harmonic is present too. Index of the spectra is lower, around -1.5. At $f > 5.10^{-6}$ Hz the theory with field-aligned diffusion is satisfactory for explanation of the shape (Jokipii and Owens, 1974a).

The solar diurnal anisotropy fixed at PSD as a single periodicity is resulting from the co-rotational streaming of particles past Earth (Duldig, 2001). Kudela et al. (2011) indicate the difference in the slopes of PSD at NM Lomnický štít (data at http://neutronmonitor.ta3.sk) for different phases of a solar activity cycle, namely the hardening of the PSD at solar minimum in comparison with the maximum. Similar behavior is found in the spectral analysis of the IMF magnitude B. Such picture is in qualitative agreement with the slopes of IMF measured in different solar cycle phases at large distances (Burlaga and Ness, 1998). El-Borie and Al Thoyaib (2002) studied power spectra of CR in the range 2 – 500 days and found significant differences in the individual spectra of solar maxima for different cycles.

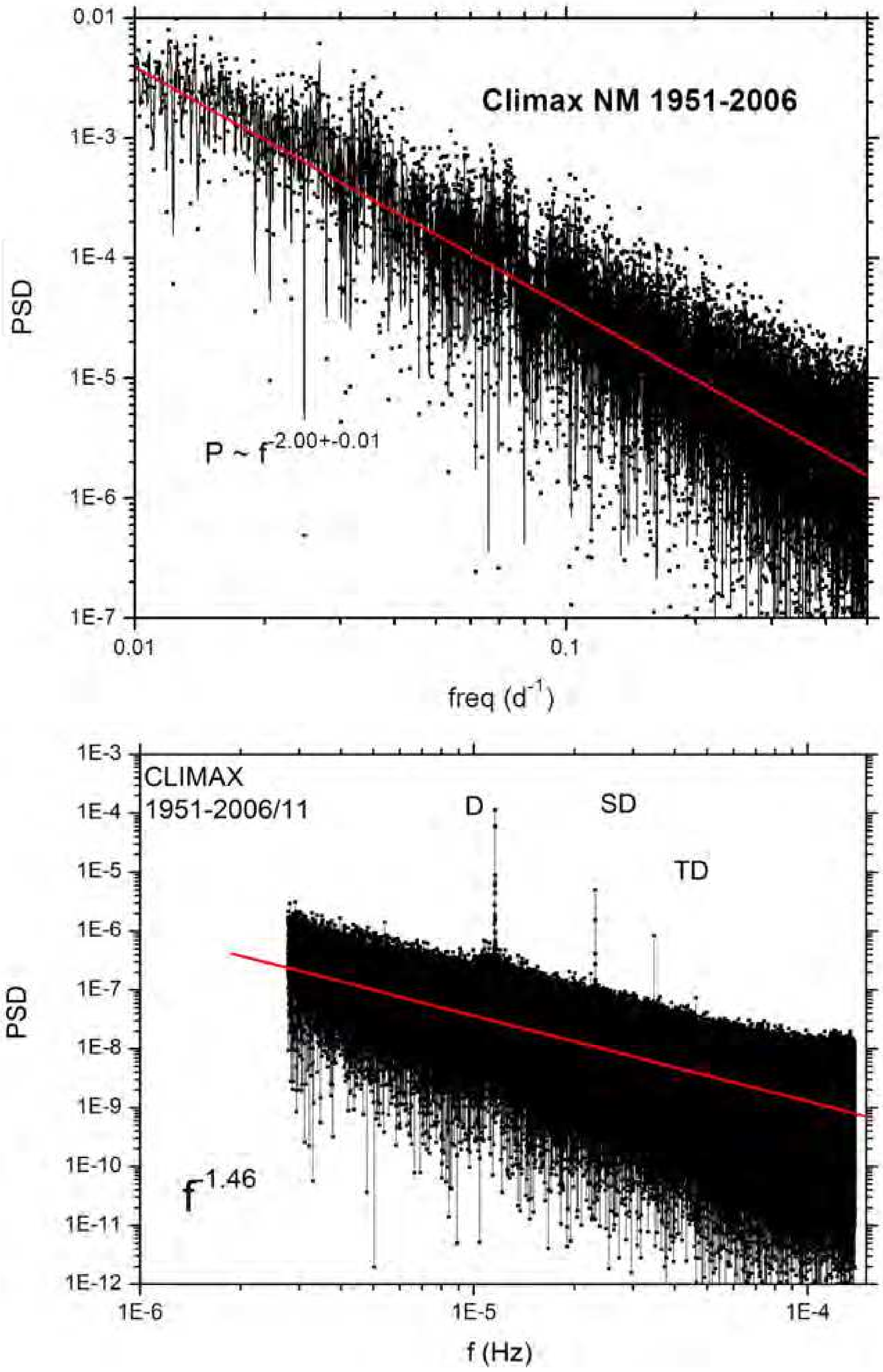

Fig. 3. Power spectrum density of Climax NM data at two ranges of frequencies. For the upper panel the daily means were used, for the lower one the hourly corrected ones. D, SD and TD is foor diurnal, semi-diurnal and tri-diurnal variation. While the amplitude of D has ~11 yr variation, the phase has ~22 yr one.

Spectra in range 2.7 x 10^{-7} – 1.4 x 10^{-4} Hz measured by muon underground detector have been examined by (Sabbah and Duldig, 2007). Flatter spectra having lower power when the interplanetary magnetic field (IMF) is directed away from the Sun above the heliosphercic current sheet (A > 0) than when the IMF is directed toward the Sun above the current sheet (A < 0), are reported.

For the description of the ~27 day variability related to the solar rotation, the daily count rate means of NM Climax was filtered in the frequency range corresponding to the time scale 25 – 33.3 days and the wavelet transform was applied on the data (Figure 4).

The double-peak structure, namely with maxima at ~ 27 days and another at ~ 31 days is found around solar activity maxima, similar to (Dunzlaff et al., 2008) based on data of GCR, EPHIN on SOHO. The structure is more complex during the long time period. Transport models (Gil et al., 2005) and measurements analyzed in paper (Richardson, 2004) suggest the dependence on solar magnetic field polarity. Vivek Gupta and Badruddin, (2009) found that the average behavior of GCR-oscillations during Carrington rotation is different in A > 0 from that in A < 0 epoch. Correlation of solar wind speed with GCR intensity during the course of Carrington rotation is stronger for A > 0 than for A < 0. The amplitudes of GCR-oscillations show somewhat weak dependence on the tilt angle of the heliospheric current sheet. Krymsky et al. (2008) indicate that temporal change of the power spectrum of ~13.5-day and ~27-day variations repeats the power spectrum change of the number of sunspots and tilt angle of the current sheet, and that the dependence of ~ 27-day variation on the polarity of general magnetic field of the Sun is not found. This feature has to be examined in future by wavelet technique in more detail. The ~27 day variation correlates with B, Bz, v, and B(v x B) – (Agarwal et al., 2011a). Similarly to ~27-day variability we examined the vicinity of ~13.5 and ~9 day periodicity contributions. At ~13.5 days we confirm the result by (Filisetti and Mussino, 1982) using ionisation chamber data, indicating the maximum contribution is correlated with the sunspot number. At ~9 days the results can be found in paper (Sabbah and Kudela, 2011).

Rieger et al. (1984) reported 154 day periodicity in solar X-ray and gamma ray flares. Pap et al. (1990) examined various periodicities in solar activity time series. There is no explanation for 150-157 day period found in several data sets. 154-day periodicities in the near-Earth IMF strength, in solar wind speed (Cane et al., 1998) and in solar proton events (Gabriel et al., 1990) have been reported. Hill et al. (2001) using Voyager 1 data, have shown that at anomalous CRs the quasi-periodic variations are in phase, with O, He having periods ~ 151 days, while protons exhibit a period ~ 146 days. Results about quasi-periodicity ~150 days in CR measured on the ground can be found e.g. in papers (Mavromichalaki et al., 2003; Kudela et al., 2010).

Another quasi-periodicity observed in CR is ~1.7 year. It was eported first by (Valdés-Galicia et al., 1996), analyzed by wavelet technique by (Kudela et al., 2002), found also in the outer heliosphere in Voyager data (Kato et al., 2003). Earlier, using NM data Calgary and Deep River, (Kudela et al., 1991) indicated that around ~20 month the change of the shape of PSD occurs. Recently Okhlopkov (2011) reports that length of the quasi-2 year periodicity in even and odd numbered cycles differs by ~2 months. Mendoza et al. (2006) by examining solar magnetic fluxes in the period 1971–1998 found that ~ 1.7 year is the dominant fluctuation for all the types of fluxes analyzed and that it has a strong tendency to appear

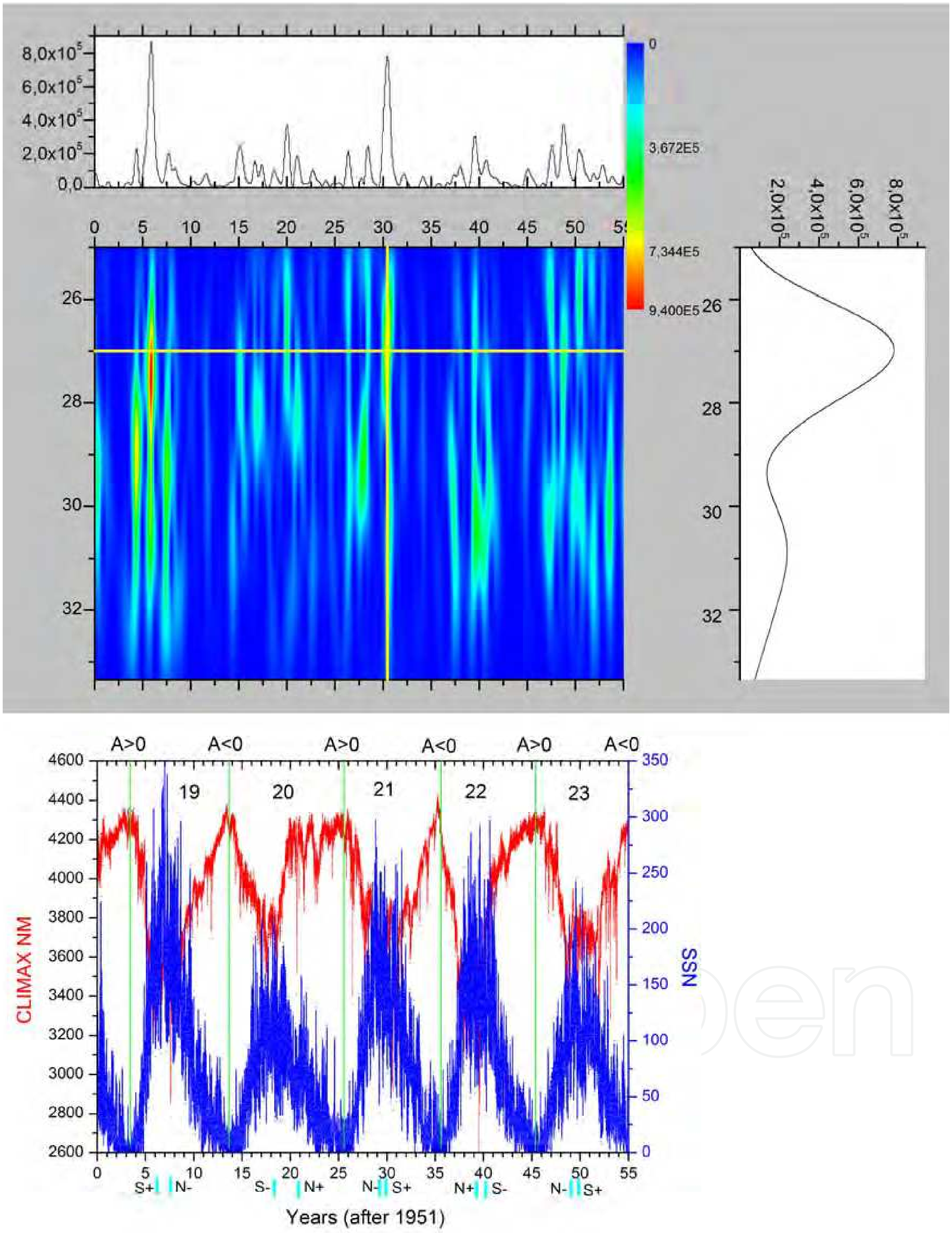

Fig. 4. The wavelet spectrum density (Morlet) of Climax NM daily means (middle panel). The upper panel is cross section of the density at 27 days over long time. Right panel is cross section over periods 25 – 33.3 d for the time of solar maxima ~ 1981. Low panel displays sunspot numbers and CR NM Climax count rates.

during the descending phase of solar activity. Quasi-periodicities of ~1.3 year (observed in solar wind) and ~1.7 years were seen neither often nor prominently in several solar activity indices (Kane, 2005). Rouillard and Lockwood (2004) relate a strong 1.68-year oscillation in GCR fluxes to a corresponding oscillation in the open solar magnetic flux and infer CR propagation paths confirming the predictions of theories in which drift is important in modulating CR flux. Charvátová (2007) indicated an interesting approach to the ~1.6 yr variation. The author calculated the solar motion due to the inner (terrestrial) planets (Mercury, Venus, Earth, Mars) for the years 1868–2030 and found that spectrum of periods shows the dominant periodicity of 1.6 years. Kane et al. (1949) reported that starting with Alfven's original suggestion, it is possible to develop a quantitative equilibrium theory for the trapping of CR in the magnetic field of the Sun, where in addition to the effect of scattering in the geomagnetic field there is also taken into account the direct absorption of the CR by five heavenly bodies Mars, Venus, the Earth, the Sun, and the Moon. This may be one of candidates for finding the link between the result (Charvátová, 2007) and ~ 1.7 year quasi-periodicity observed in CR.

At longer time scales McCracken et al. (2002) identified the presence of ~ 5 year variability in CR over epochs with low solar activity in the past. It is desirable to investigate whether a correlated 5-year signal exists in other geophysical and biological records, and if so, it could provide an additional source of data on the characteristics of the sun at times of low solar activity. El-Borie (2002) studied solar wind speed and density for quasi-periodic cyclicity and found some other long term peridicities. The 9.8, 3.8, and 1.7 – 2.2 year periods are the most significant found in the interplanetary proton flux at 190 – 440 MeV in IMP 8 data (Laurenza et al., 2009). Mavromichalaki et al (2005) reported ~2.3 years periodicity in coronal index calculated using Fe XIV 530.3 nm coronal emission line from ground-based measurements by the worldwide network of coronal stations (Rybanský, 1975). The wavelet analysis at various cut-offs for NM and for muon detector data is required to clarify whether that quasi-periodicity has a cut-off energy and how it is evolved over several tens of years. Figure 5 presents a brief summary of CR quasi-periodicities obtained in long time of measurements by NM.

Most of the quasi-periodicities identified in Figure 5 were reporteded by (Mavromichalaki et al., 2003) in the analysis of the data until 1996. For detailed analysis and for identification of contribution of various quasi-peridicities in the signal over the long time, the wavelet transform technique is suitable to be used in future, along with analysis of data from NMs at different geomagnetic cut-off positions and from muon telescopes sensitive to higher energies. The wavelet technique has been utilized also for checking the presence of other periodicities reported e.g. by (Chowdhury et al., 2010; Agarwal et al., 2011b; Zarrouk and Bennaceur, 2009) and, if used for the same intervals and applied on time series of CR as well as of solar, geomagnetic and interplanetary activity indices, may help in discriminating the links of CR to the atmospheric processes.

3. Geomagnetic effects

At low energies the trajectories of charged particles in the geomagnetic field are usually described with use of guiding center approximation (Roederer, 1970). Three adiabatic invariants connected with the three different cyclic motions, namely with the gyration, bounce and azimuthal (longitudinal) drift, are utilized. This is useful if the phases of the

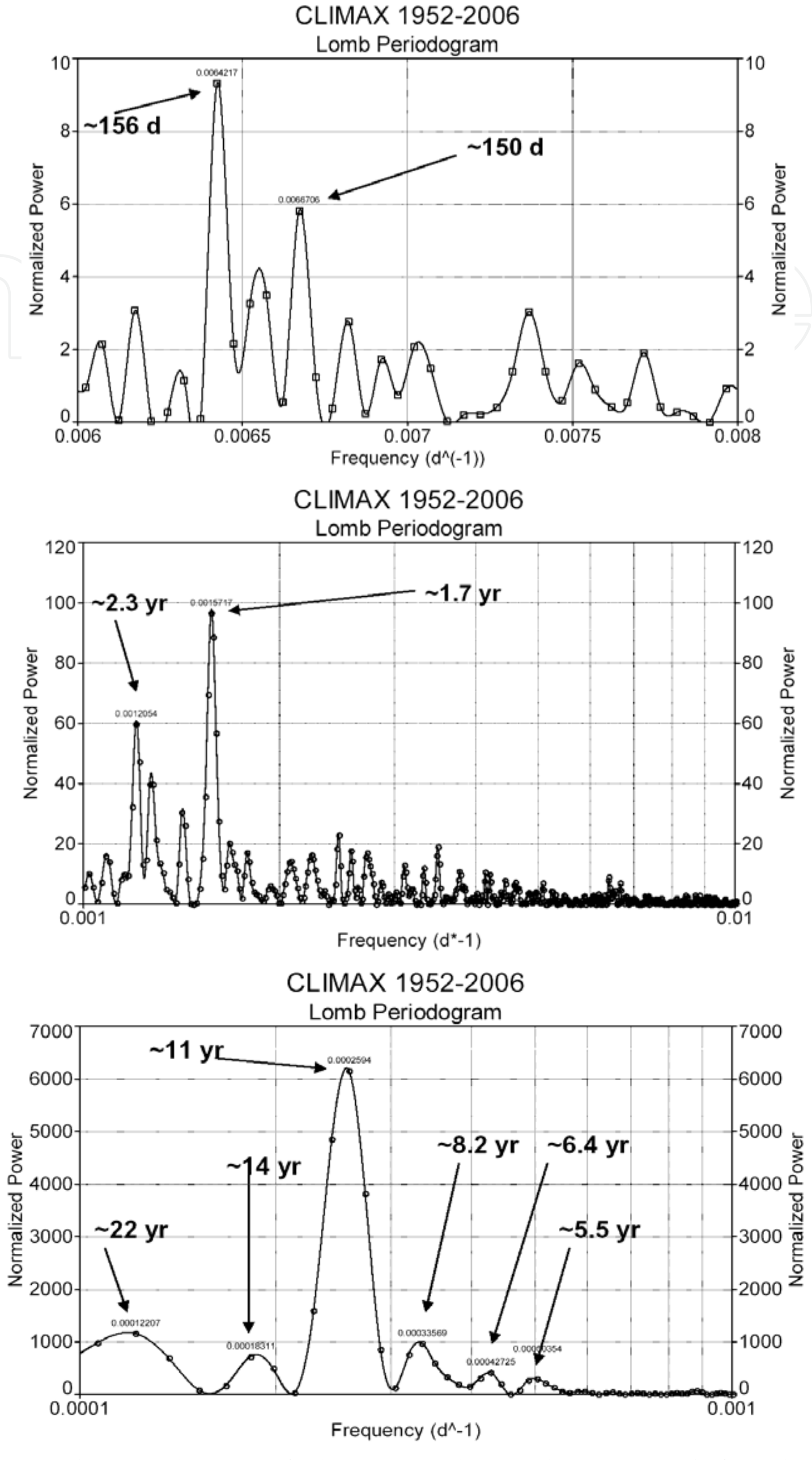

Fig. 5. Lomb-Scargle periodogram of Climax NM data at three intervals for which the filter was used. Upper panel shows the double structure with significant peaks at ~156 and ~150 days. Middle panel: in addition to ~1.7 yr variation also ~2.3 yr is statistically significant (0.99). For that level only ~11 yr variability is significant at lower plot.

motions are not of importance. Such approach is frequently used for trapped particle populations since the discovery of radiation belts. This approximation is valid if the three periodicities are very distinct. For given type of particle (proton, electron) the frequencies corresponding to the three types of motions in a dipole field depend on McIlwain's L parameter and kinetic energy (Schulz and Lanzerotti, 1974, Figure 6). The approximation becomes inapplicable when the periodicities are comparable. This is the case of higher energies in outer magnetosphere. Such particles from the point of view of magnetosphere can be assigned as CR. Detailed review of CR in the magnetospheres of planets is in (Dorman, 2009).

Trajectory description for CR particles in the Earth's magnetosphere is possible only by numerical solution of the equation of motion in given geomagnetic field model. The trajectory of particle with opposite sign of charge and velocity vector is traced starting from the point above the detector and continuing either up to the magnetosphere boundary (if the trajectory is allowed) or to the point on the ground (forbidden trajectory). For allowed trajectories the asymptotic directions are obtained. System of forbidden and allowed trajectories determines the geomagnetic cut-off rigidity. Cooke et al. (1991) summarize the definitions of the characteristics relevant for the cut-offs. Such procedure is used for long time, its history with relevant references is in the paper (Smart and Shea, 2009). Crucial for the results is the geomagnetic field model. Earlier the IGRF model was used, later the models with external current systems were introduced. Desorgher et al. (2009) discuss the geomagnetic field models used for the CR trajectory tracing. Usually for given position of NM the geomagnetic cut-off rigidity is computed for the vertical incidence of particles.

Due to geomagnetic field evolution on long time scale the geomagnetic cut-off rigidities at given point of the Earth's surface are changing (e.g. Smart and Shea, 2003; Kudela and Bobík, 2004). During the geomagnetic storms the contribution of external current systems in magnetosphere is important for the transmissivity function, asymptotic directions and geomagnetic cut-offs. Procedure that allows to determine the cut-off rigidity and asymptotic direction changes during geomagnetically active periods from measurements of magnetic field variations is presented in (Flückiger et al., 1986). Different transmissivity of CR through the Earth's magnetosphere for different empirical geomagnetic field models during strong geomagnetic storms is expected (Kudela et al., 2008). The correlations of cut-offs estimated from the global network of NMs and from trajectory tracing in one model of the field during a disturbed period, is discussed by Tyasto et al. (2011). Penetration boundary of SEP into magnetosphere is a specific tool for checking the validity of geomagnetic field models (e.g. Lazutin et al., 2011).

Recently, experiment PAMELA has shown that antiprotons produced due to nuclear interactions with the residual atmosphere are trapped in the geomagnetic field and observed at the altitude of several hundreds km (Adriani et al., 2011). Theoretical works published earlier have shown such possibility (Pugacheva et al., 2003; Gusev et al., 2008).

4. LECR, space weather and atmospheric effects

Space Weather is a relatively new discipline of science and CR play a role in this study in both aspects, namely in (a) direct one – irradiation of materials in space, in atmosphere and on the ground with various consequences for the technological systems and for the people, and (b) as one of the precursors due to changes of LECR anisotropy several hours before the onset of geomagnetic storm when CME arrives to the vicinity of Earth. LECR provide for that "remote" information about CME propagation in interplanetary space (alert for geoeffective events). There are several books and reviews on space weather effects and its possible forecasting (e.g. Song et al, 2001; Goodman, 2005; Bothmer and Daglis, 2007; Moldwin 2008; Lilensten et al., 2008), and on relations between cosmic rays, energetic particles in space and space weather (e.g. Kudela et al., 2000; 2009; Daglis (ed) 2004; Lilensten and Bornarel, 2006, Flückiger, 2007) as well as on physics behind (e.g. Scherer et al., 2005; Dorman 2010; Kallenrode, 2004; Hanslmeier, 2007; Kamide and Chian, 2007 among others). Singh et al. (2011) and Siingh (2011) reviewed CR effects on terrestrial processes such as electrical phenomena, lightning discharges cloud formation and cloud coverage, temperature variation, space weather phenomena, Earth's climate and the effects of GCRs on human health. The paper includes the new results and the authors point out many basic phenomena which require further study as well as new and long data sets.

Ions accelerated to several tens to hundreds of MeV are most important for the radiation hazard effects during solar radiation storms with electronic element failures on satellites, communication and biological consequences. Before their massive arrival, NM, if good temporal resolution and network by many stations is in real time operation, can provide useful alerts several minutes to tens minutes in advance. Kuwabara et al. (2006) report a system that detects count rate increases recorded in real time by eight NMs and triggers an alarm when GLE is detected. The GLE alert precedes the earliest indication from GOES (100 MeV or 10 MeV protons) by ~10–30 minutes. Oh el al. (2010) studied characteristics of SPE connected with GLEs.

Important point stressed by the recent papers is requirement of global detector network operating in real time with good statistical resolution is essential for space weather applications using ground based measurements. One of such systmes using neutron monitors is described by Mavromichalaki et al. (2006). At higher energies the Global Muon Detector Network is important source of the precursory information for geomagnetic storms (e.g. Rockenbach et al., 2011) and for sounding of CME geometry before its arrival to Earth (Kuwabara et al., 2004). Precursor signatures of SSC at the beginning of relatively small geomagnetic storm was also observed (Braga et al., 2011). Recently (Agarwal et al., 2011b) studied the cosmic ray, geomagnetic and interplanetary plasma/field data to understand the physical mechanism responsible for Forbush decrease and geomagnetic storm that can be used as a signature to forecast space weather and stressed the importance of change of geomagnetic cutoff rigidity.

Cosmic rays and energetic particles of lower energy interact with the material of the satellites, airplanes, atmosphere and may cause the failures. There is variety of effects with consequences on the reliability of the electronic elements. The energy deposition in materials resulting in permanent damage in silicon semiconductor devices and the single event effects due to the individual events caused by interaction of particles inside the active volume of silicon devices, along with the review of processes of electromagnetic interaction, nuclear interaction with matter is described in detail e.g. in the book (Leroy and Rancoita, 2009). The memory circuits are also partially affected by CR and its secondary products. Autran et al. (2010) review recent (2005–2010) experiments and modeling-simulation work dedicated to the evaluation of natural radiation-induced soft errors in advanced static memory (SRAM) technologies. The impact on the chip soft-error rate (SER) of both terrestrial neutrons induced by CR and alpha particle emitters, generated from traces of radioactive contaminants in CMOS process or packaging materials, has been experimentally investigated by life (i.e. real-time) testing performed at ground level on the Altitude Single-event Effect Test European Platform (ASTEP) and underground at the underground laboratory. Soft errors are caused by CR striking sensitive regions in electronic devices. Paper (Wang and Agrawal, 2010) illustrates how soft errors are a reliability concern for computer servers, and indicates a possible soft error rate (SER) reduction method that considers the CR striking angle to redesign the circuit board layout.

Miroshnichenko (2003) provides phenomenological picture of the radiation environment of Earth, summarizes observational data and theoretical findings related to main sources of energetic particles in space as well as surveys the methods of prediction of radiation risk on spacecraft. Dartnell (2011) reviews in detail the influence of ionizing radiation including CR on the emergence and persistence of life. Not only effects of ionizing radiation on organisms and the complex molecules of life are discussed, but also pointed out that ionizing radiation performs many crucial functions in the generation of habitable planetary environments and the origins of life. There are reports on the effects of short time increases of LECR on the dose within the atmosphere (airplanes, eg. Spurný et al., 2001; 2004; Felsberger et al., 2009) as well as in outer space (important for planned missions to the planets both for humans and for reliability of electronic systems); the changes of the status of the ionosphere with consequences on navigation. LECR and its measurement is important not only for monitoring radiation and its temporal and spatial variability (significant for preparing models), but its systematic measurement with good temporal resolution by many ground based devices has a potential to be one of the elements for schemes of space weather effects prediction.

Variability of CR with the aim of deducing the features useful in search of correlation between CR and atmospheric processes is described and discussed by (Bazilevskaya, 2000). Studies on relation of CR to the atmospheric processes (started probably from Svensmark and Friis-Christensen, 1997 and references therein) and references therein, recent paper reporting results of CLOUD experiment (Kirkby et al., 2011), as well as the availability of long term series of CR measurements from various NM and muon detectors until now, motivate to describe in detail LECR variability. Harrison et al. (2011) report cloud base height distributions for low cloud (<800 m) measured at the Lerwick Observatory, Shetland, UK, is varying with CR conditions. 27 day and 1.68 year periodicities characteristic of cosmic ray variations are present, weakly, in the cloud base height data of stratiform clouds, when such periodicities are present in neutron monitor CR data. Papers (Sloan and Wolfendale, 2008; Erlykin et al., 2009a,b) do not indicate that the large portion of the clouds is related to CR. No response of global cloud cover to Forbush decreases at any altitude nor latitude is reported by (Calogovic et al., 2010). Fichtner et al. (2006) point out that presence of a 22-year periodicity can not only be understood on well-known physical grounds, but must be expected if CR play a role in climate driving. The test of whether 22-year periodicities in climate indicators are present or not is a promising tool to bring the presently intensely led debate to a satisfactory conclusion. Discussion is continuing. For the purposes of checking long term variations of CR with atmospheric characteristics it is suitable to use indirectly estimated time profile of CR for the past. Usoskin et al. (2002) used the reconstructed magnetic flux as an input to a spherically symmetric quasi-steady state model of the heliosphere, and calculated the expected intensity of GCR at Earth position since 1610.

In recent decade the relations of CR to the atmospheric electricity has been studied extensively. When studying the intensity variations of secondary CR during thunderstorms (Lidvansky, 2003; Lidvansky and Khaerdinov, 2011) with the Carpet shower array of the Baksan Neutrino Observatory it was found that, in addition to regular variations correlating with the near-ground electric field, there existed considerable transient changes of the intensity. Chilingarian et al. (2010) presented the energy spectra of electrons and gamma rays from the particle avalanches produced in the thunderstorm atmosphere, reaching the Earth's surface. Paper by (Ermakov et al., 2009) shows that the main parameters of atmospheric electricity are related to CR. The mechanisms of solar forcing of the climate and long term climate change is summarized, and the role of energetic charged particles (including CR) on cloud formation and their effect on climate is discussed in (Siingh et al., 2010; 2011). Results of spectral analysis of surface atmospheric electricity data (42 years of Potential Gradient, PG at Nagycenk, Hungary) showed ~1.7 year quasi-periodicity (Harrison and Märcz, 2007). ~1.7 year periodicity in the PG data is present 1978 – 1990, but absent in 1963 – 1977. It is of interest to continue checking the occurrence of that quasi-periodicity in CR and in the data of atmospheric electricity after 1990.

Lightning is connected with the short time increases of the high energy photon flux in the atmosphere. Terrestrial Gamma−ray Flash (TGF) is a brief (<1ms) pulse of γ−rays with energies extending up to around 40 MeV, and average energy ~2 MeV (Smith et al., 2005) observed on low altitude satellites. TGFs exhibit both spatial and temporal correlations with lightning activity (e.g. Fishman et al., 1994). Study based on RHESSI data shows that on average the TGFs were found to precede the associated lightning events, with a mean delay of -0.77 ms (Collier et al., 2011). Spatial coincidence of the location of the lightning flashes with conjugate X-ray enhancements, and their simultaneity, was reported by (Bučík et al., 2006).

Cosmic ray characteristics along with the geomagnetic and solar activity are discussed also in connection with hurricanes (e.g. Kavlakov et al., 2008; Mendoza and Pazos, 2009 Perez-Peraza et al., 2008; Kane, 2006). This topic is reviewed in detail by (Mendoza, 2011).

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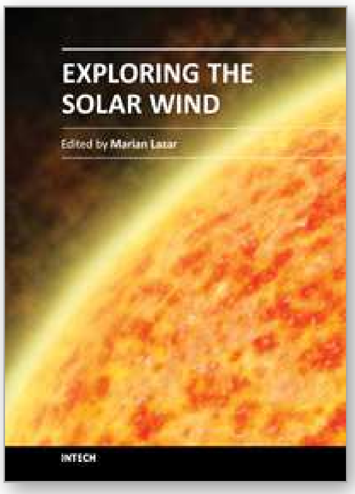

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This book consists of a selection of original papers of the leading scientists in the fields of Space and Planetary Physics, Solar and Space Plasma Physics with important contributions to the theory, modeling and experimental techniques of the solar wind exploration. Its purpose is to provide the means for interested readers to become familiar with the current knowledge of the solar wind formation and elemental composition, the interplanetary dynamical evolution and acceleration of the charged plasma particles, and the guiding magnetic field that connects to the magnetospheric field lines and adjusts the effects of the solar wind on Earth. I am convinced that most of the research scientists actively working in these fields will find in this book many new and interesting ideas.

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