Research Signpost
37/661 (2), Fort P.O.
Trivandrum-695 023
Kerala, India

Advances in Solar and Solar-Terrestrial Physics,2012: 135-161 ISBN: 978-81-308-0483-5
Editors: Georgeta Maris and Crisan Demetrescu

8. The physics of cosmic rays applied to space weather

Helen Mavromichalaki
National & Kapodistrian University of Athens, Faculty of Physics, Nuclear and Particle Physics Section, 15771 Zografos-Athens, Greece

Abstract. The research on cosmic rays provides the required definitions for the understanding of space environment and for the development of appropriate sophisticated models useful for monitoring and eventually prognosis of Space weather. Foreknowledge of cosmic ray intensity, energy and composition has always been a challenge and it is further complicated by the influence of geomagnetic disturbances during their penetration into the magnetosphere.

Proofs of long- and short- term cosmic ray modulation such as the 11- year solar cycle, the Forbush decreases of cosmic ray intensity and the high energy solar particles that are registered at the Earth by neutron monitors, called Ground Level Enhancements, brought to the attention of the scientific community the unique role of the Sun inside the heliosphere, as well as the corresponding use of cosmic rays as a significant tool for Space weather research. Cosmic rays provide a diagnostic mean in order to analyze processes in interplanetary space and at the Sun and serve as indicators of solar variability. On top of which, the need for radiation

Correspondence/Reprint request: Dr. Helen Mavromichalaki, National & Kapodistrian University of Athens, Faculty of Physics, Nuclear and Particle Physics Section, 15771 Zografos-Athens, Greece
E-mail: emavromi@phys.uoa.gr

measurements both at space environment and inside the Earth's atmosphere revealed another aspect of their crucial role for Space weather. This report summarizes the efforts of the cosmic ray community to establish an Alert signal for dangerous particle fluxes heading to the Earth using the worldwide neutron monitor network, as well as to implement various algorithms on phenomena as Ground Level Enhancements, variations of cosmic ray gradient and anisotropy and to successfully measure radiation doses on spacecrafts and aircrafts.

Introduction

The Earth's magnetosphere is sputtered by a nearly isotropic flux of energetic charged particles, the cosmic rays. Galactic cosmic rays (GCR) are primarily protons together with other heavier ions. Their energy extends up to 10^{20} eV with their most effective part recognized between 100s MeV to 20 GeV. The penetration of these GCR into the vicinity of the Earth is influenced by conditions on the Sun. The cosmic ray fluxes are modulated by solar activity, presenting an 11-year period with the highest fluxes occurred at solar minimum and the lowest at solar maximum that means an anti-correlation with solar activity [1]. This modulation is energy or rigidity dependent with low to medium energies (<1GeV/nucleon) showing the most effect. There is also a 22-year modulation induced by the reversal polarity of the polar magnetic field of the Sun. Propagation and time variations of cosmic rays are treated together because long-term solar cycle time variations at the Earth are caused by travelling of the cosmic rays from outside of the heliosphere into it; the simple view is that the expanding solar wind exerts a pressure on the interstellar charged particles, modifying their entry into the heliosphere. The propagation is in fact much more complex being governed by the balance between the three main physical processes of diffusion, convection and adiabatic deceleration. In addition to these long-term temporal changes, there are shorter term fluctuations, called Forbush decreases (FDs) [2], which are thought to be caused by large interplanetary shocks.

The Sun is an additional recurrent source of lower energy particles accelerated during certain solar flares (SF) and coronal mass ejections (CMEs) in the years around solar maximum. These solar particle events last for several days, at a time, and consist of both protons and heavier ions with variable composition from event to event. Energies typically range up to several hundred MeV and have most influence on high inclination or high altitude systems. Occasional events produce particles of several GeV in energy and those are able to reach equatorial latitudes [3]. Earth's atmosphere operates as natural shielding for its surface. At this sense, when primary cosmic rays reach the atmosphere, interact with air nuclei to generate a cascade of secondary particles (pions, muons, neutrons, electrons, positrons and gamma-rays), which shower down through the atmosphere to the surface of the Earth. The number of particles reaching the Earth's surface is related to the energy of the primary cosmic ray particles that reaches the upper atmosphere limit.

In addition to the previous, one should note that when cosmic rays and solar induced particles are impeded from reaching specific locations due to interactions with the Earth's magnetic field and due to the direction in which these particles are travelling, compared to the magnetic latitude of a certain point. To which extent their trajectories are influenced by the Earth's magnetic field is determined by their rigidity R, while the direction's influence depends on the particle's equations of motion. Because of the non-linearity of these equations, an analytical solution can not be achieved. However, Störmer [4] in his classic work on aurora about 50 years ago developed some useful analytic approximations for the minimum value of the cut-off rigidity Rc, which are still used today [5].

On the other hand, the term space weather describes the state of the environment in space near the Earth and the Sun is the main driver of space weather. It refers to conditions on the Sun, in the solar wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space born and ground based technological systems and can endanger human life and health (US National Space Weather Programme, 1995). To this direction, cosmic rays can play a useful role as indicators of abrupt changes at the interplanetary space. A schematic presentation of the physics involved at space weather is given in Fig. 1.

This report summarizes the efforts of the cosmic ray community to contribute to space weather research using an extensive network of ground based reliable detectors around the world, the neutron monitors (NMs) [6,7].

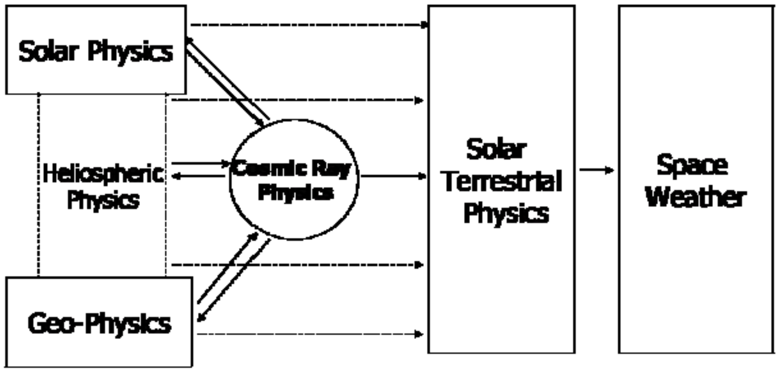


Figure 1. A schematic representation of the physics involved at Space Weather; adjusted from [8].

Correspondingly, aspects of the space environment, the development of special algorithms as well as the physics, the advances and the implementation of an Alert signal originating by neutron monitors, expanding the capabilities of monitoring and eventually space weather prognosis are also discussed.

1. Natural space radiation environment

Natural space radiation environment can be classified into two populations, the particles trapped by planetary magnetospheres in 'belts'-including protons, electrons and heavier ions and transient particles which include protons and heavy ions of all elements of the periodic table.

The transient radiation consists of GCR particles and particles from solar events, such as solar flares and CMEs. The radiation environment research covers a wide range of subjects due to the fact that radiation exists throughout the universe, originating from many sources and with varying intensities. The radiation environment topics are predicated by critical radiation effects and mechanisms from basic science research and methods for quantitative predictions of the environment issues, by new atmospheric and space radiation measurements and by availability of resources to transition new findings (Fig. 2). A complete description of radiation environments can be found in the works [10, 11, 12] and at references within these reports.

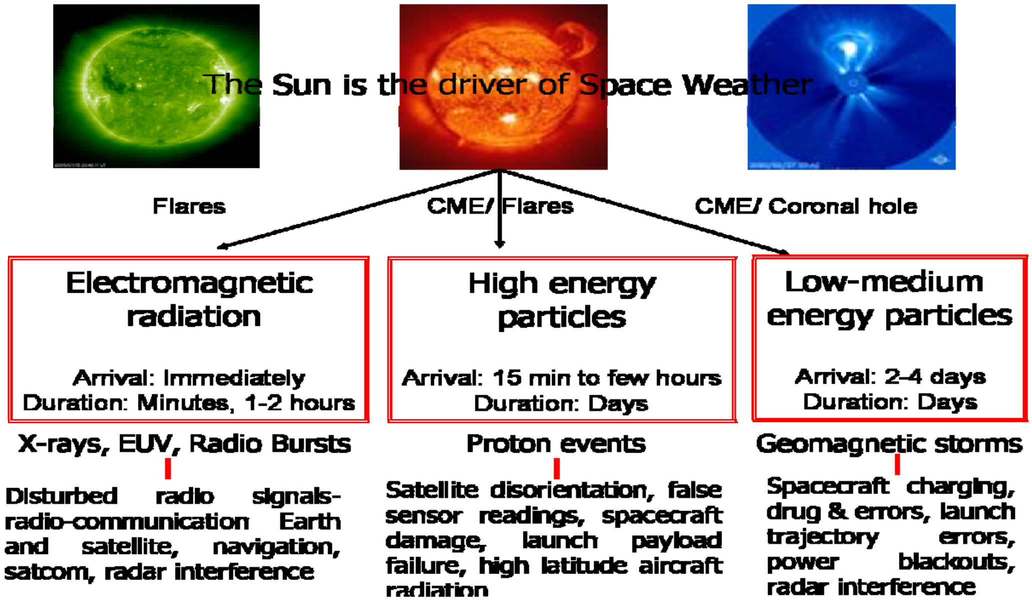


Figure 2. A schematic representation of the Sun's influence at natural radiation and the corresponding Space Weather impact; adjusted from Schwenn [9].

A brief description on particle populations of the space environment together with the ability of monitoring such events is provided underneath:

1.1. Solar energetic particles

Solar flares with a lifetime ranging from hours to tens of seconds, release ultraviolet, X-ray and radio emissions reaching the Earth and producing ionospheric disturbances of minutes to hour's duration. Large flares, known as solar energetic particle events (SEPs) can release very energetic particles (mostly protons) which arrive at Earth's atmosphere within 30 minutes [13]. As it was pointed out earlier, the Earth's magnetic field offers some protection, but these particles are capable to spiral down the magnetic field lines, to enter the atmosphere and to produce additional ionization in the ionosphere. A broad range of phenomenology relating proton events to flares (with some references to related interplanetary disturbances), including correlations of occurrence, intensities, durations and timing of both the particle event and the flare as well as the role of the heliographic location of the designated active region has been investigated by many authors [14, 15] and references within (Fig. 3).

Most recently, a new catalogue of 1265 solar proton enhancements (SPEs) based on energetic proton measurements obtained from the GOES and IMP-8 satellites as well as from ground based neutron monitors covering the time period 1975 up to May 2004 has been created by the University of Athens [16,17]. A sample of this catalogue is presented in Fig. 4. Unlike the NOAA definition the term SPE has been used in order to refer to proton enhancements with energy >10 MeV and proton flux > 0.1 pfu at the Earth's orbit. The term SPE, has been introduced in order to emphasize the point that a broad range of near-Earth proton flux intensities is being investigated, including flux intensities well below that of the NOAA standard. The statistical

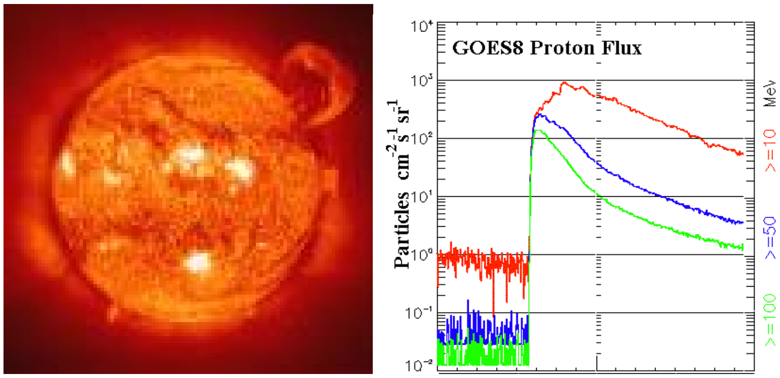
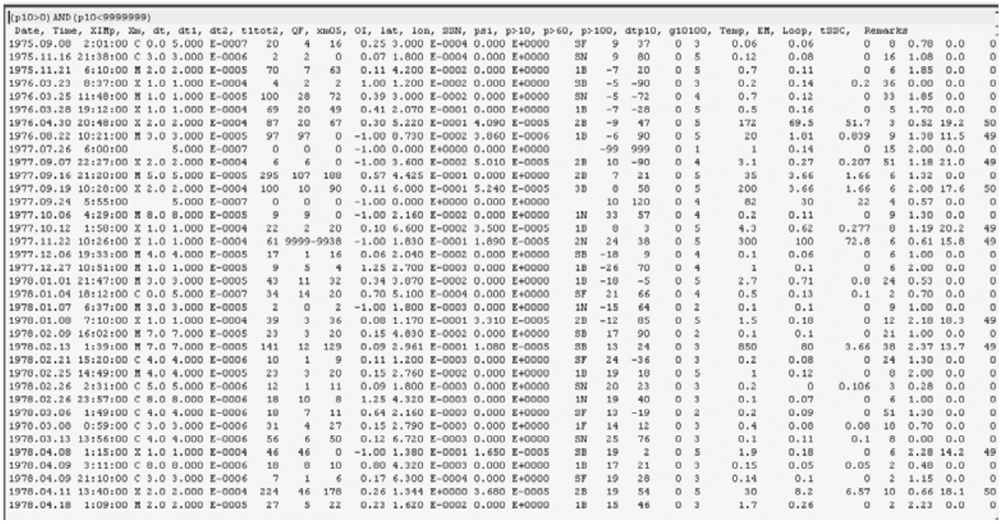


Figure 3. A solar flare and the corresponding SPE event on April 2001.



```
(p10>0) AND (p10<9999999)
 Date, Time, XIMp, Xm, dt, dt1, dt2, t1tot2, QF, xm05, OI, lat, lon, SSN, psi, p>10, p>60, p>100, dtp10, g10100, Temp, EM, Loop, tSSC,  Remarks
1975.09.08  2:01:00 C 0.0 5.000 E-0007    20    4   16   0.25 3.000 E-0004 0.000 E+0000   SF    9   37   0  3   0.06    0.06      0   8 0.78  0.0    0
1975.11.16 21:38:00 C 3.0 3.000 E-0006     2    2    0   0.07 1.800 E-0004 0.000 E+0000   SN    9   80   0  5   0.12    0.08      0  16 1.08  0.0    0
1975.11.21  6:10:00 M 2.0 2.000 E-0005    70    7   63   0.11 4.200 E-0002 0.000 E+0000   1B   -7   20   0  5    0.7    0.11      0   6 1.85  0.0    0
1976.03.23  8:37:00 X 1.0 1.000 E-0004     4    2    2   1.00 1.200 E-0002 0.000 E+0000   SB   -5  -90   0  3    0.2    0.14    0.2  36 0.00  0.0    0
1976.03.25 11:48:00 M 1.0 1.000 E-0005   100   28   72   0.39 3.000 E-0002 0.000 E+0000   SN   -5  -72   0  4    0.7    0.12      0  33 1.85  0.0    0
1976.03.28 19:12:00 X 1.0 1.000 E-0004    69   20   49   0.41 2.070 E-0001 0.000 E+0000   1B   -7  -28   0  5    0.5    0.16      0   5 1.70  0.0    0
1976.04.30 20:48:00 X 2.0 2.000 E-0004    87   20   67   0.30 5.220 E-0001 4.090 E-0005   2B   -9   47   0  5    172    69.5   51.7   3 0.52 19.2   50
1976.08.22 10:21:00 M 3.0 3.000 E-0005    97   97    0  -1.00 8.730 E-0002 3.860 E-0006   1B   -6   90   0  5     20    1.81  0.839   9 1.38 11.5   49
1977.07.26  6:00:00       5.000 E-0007     0    0    0  -1.00 0.000 E+0000 0.000 E+0000       -99  999   0  1      1    0.14      0  15 2.00  0.0    0
1977.09.07 22:27:00 X 2.0 2.000 E-0004     6    6    0  -1.00 3.600 E-0002 5.010 E-0005   2B   10  -90   0  4    3.1    0.27  0.207  51 1.18 21.0   49
1977.09.16 21:20:00 M 5.0 5.000 E-0005   295  107  188   0.57 4.425 E-0001 0.000 E+0000   2B    7   21   0  5     35    3.66   1.66   6 1.32  0.0    0
1977.09.19 10:28:00 X 2.0 2.000 E-0004   100   10   90   0.11 6.000 E-0001 5.240 E-0005   3B    8   58   0  5    200    3.66   1.66   6 2.08 17.6   50
1977.09.24  5:55:00       5.000 E-0007     0    0    0  -1.00 0.000 E+0000 0.000 E+0000         10  120   0  4     82      30     22   4 0.57  0.0    0
1977.10.06  4:29:00 M 8.0 8.000 E-0005     9    9    0  -1.00 2.160 E-0002 0.000 E+0000   1N   33   57   0  4    0.2    0.11      0   9 1.30  0.0    0
1977.10.12  1:58:00 X 1.0 1.000 E-0004    22    2   20   0.10 6.600 E-0002 3.500 E-0005   1B    8    3   0  5    4.3    0.62  0.277   8 1.19 20.2   49
1977.11.22 10:26:00 X 1.0 1.000 E-0004    61 9999-9938  -1.00 1.830 E-0001 1.890 E-0005   2N   24   38   0  5    300     100   72.8   6 0.61 15.8   49
1977.12.06 19:33:00 M 4.0 4.000 E-0005    17    1   16   0.06 2.040 E-0002 0.000 E+0000   SB  -18    9   0  4    0.1    0.06      0   6 1.00  0.0    0
1977.12.27 10:51:00 M 1.0 1.000 E-0005     9    5    4   1.25 2.700 E-0003 0.000 E+0000   1B  -26   70   0  4      1     0.1      0   6 2.00  0.0    0
1978.01.01 21:47:00 M 3.0 3.000 E-0005    43   11   32   0.34 3.870 E-0002 0.000 E+0000   1B  -18   -5   0  5    2.7    0.71    0.8  24 0.53  0.0    0
1978.01.04 18:12:00 C 0.0 5.000 E-0007    34   14   20   0.70 5.100 E-0004 0.000 E+0000   SF   21   66   0  4    0.5    0.13    0.1   2 0.70  0.0    0
1978.01.07  6:37:00 M 3.0 3.000 E-0005     2    0    2  -1.00 1.800 E-0003 0.000 E+0000   1N  -15   64   0  2    0.1     0.1      0   9 1.00  0.0    0
1978.01.08  7:10:00 X 1.0 1.000 E-0004    39    3   36   0.08 1.170 E-0001 3.310 E-0005   2B  -12   85   0  5    1.5    0.18      0  12 2.18 18.3   49
1978.02.09 16:02:00 M 7.0 7.000 E-0005    23    3   20   0.15 4.830 E-0002 0.000 E+0000   SB   17   90   0  2    0.1     0.1      0  21 1.00  0.0    0
1978.02.13  1:39:00 M 7.0 7.000 E-0005   141   12  129   0.09 2.961 E-0001 1.080 E-0005   SB   13   24   0  3    850      80   3.66  38 2.37 13.7   49
1978.02.21 15:20:00 C 4.0 4.000 E-0006    10    1    9   0.11 1.200 E-0003 0.000 E+0000   SF   24  -36   0  3    0.2    0.08      0  24 1.30  0.0    0
1978.02.25 14:49:00 M 4.0 4.000 E-0005    23    3   20   0.15 2.760 E-0002 0.000 E+0000   1B   19   18   0  5      1    0.12      0   8 2.00  0.0    0
1978.02.26  2:31:00 C 5.0 5.000 E-0006    12    1   11   0.09 1.800 E-0003 0.000 E+0000   SN   20   23   0  3    0.2       0  0.106   3 0.28  0.0    0
1978.02.26 23:57:00 C 8.0 8.000 E-0006    18   10    8   1.25 4.320 E-0003 0.000 E+0000   1N   19   40   0  3    0.1    0.07      0   6 1.00  0.0    0
1978.03.06  1:49:00 C 4.0 4.000 E-0006    18    7   11   0.64 2.160 E-0003 0.000 E+0000   SF   13  -19   0  2    0.2    0.09      0  51 1.30  0.0    0
1978.03.08  0:59:00 C 3.0 3.000 E-0006    31    4   27   0.15 2.790 E-0003 0.000 E+0000   1F   14   12   0  3    0.4    0.08   0.08  18 0.70  0.0    0
1978.03.13 13:56:00 C 4.0 4.000 E-0006    56    6   50   0.12 6.720 E-0003 0.000 E+0000   SN   25   76   0  3    0.1    0.11    0.1   8 0.00  0.0    0
1978.04.08  1:15:00 X 1.0 1.000 E-0004    46   46    0  -1.00 1.380 E-0001 1.650 E-0005   SB   19    2   0  5    1.9    0.18      0   6 2.28 14.2   49
1978.04.09  3:11:00 C 8.0 8.000 E-0006    18    8   10   0.80 4.320 E-0003 0.000 E+0000   1B   17   21   0  3   0.15    0.05   0.05   2 0.48  0.0    0
1978.04.09 21:10:00 C 3.0 3.000 E-0006     7    1    6   0.17 6.300 E-0004 0.000 E+0000   SF   19   28   0  3   0.14     0.1      0   2 1.15  0.0    0
1978.04.11 13:40:00 X 2.0 2.000 E-0004   224   46  178   0.26 1.344 E+0000 3.680 E-0005   2B   19   54   0  5     30     8.2   6.57  10 0.66 18.1   50
1978.04.18  1:09:00 M 2.0 2.000 E-0005    27    5   22   0.23 1.620 E-0002 0.000 E+0000   1B   15   46   0  3    1.7    0.26      0   2 2.23  0.0    0
```

Figure 4. A sample from the catalogues of SPEs which was recently put together at the University of Athens.

analysis indicates that the probability and magnitude of the near-Earth proton enhancement depends critically on the flare's importance and its heliolongitude. The existence of a high correlation between the number of SPEs and major flares with importance ≥M4-M5 may provide a reasonable proxy index for SPE production rate on a scale of months and years. The heliolongitude dependence of protons from 10 MeV to relativistic energies reveals that many SPEs associate with flares located westward of 70°W, i.e., west of the predominant 45°W–70°W sector.

Furthermore, SPE probability of occurrence increases with the duration of the flare. This is especially true for flares of low importance. This correlation becomes less important for more powerful flares, on the prima facie basis that strong flares trend to long duration anyway. Additionally, the SPE probability of occurrence appears to be inversely related to the maximum temperature and directly related to the loop length of the X-ray flare. The physics of solar energetic particle generation, as well as the forecasting models concerned with SPE probability of occurrence, time delay and expected proton flux on the basis of the characteristics of the observed X-ray flare, are very important for SW monitoring. The crucial role of ground based measurements to the determination of SPE characteristics has also been revealed.

1.2. Ground level enhancements

The largest SEP events can cause significant rise in the neutron monitor count rates which are classed as Ground Level Enhancements (GLEs)

[18,19]. These enhancements characterize only one part of the entire solar cosmic ray (SCR) spectrum. A historical beginning of SCR observations was set by the occurrence of the GLEs on Febuary 28, 1942, in July 1946 and November 1949. The greatest GLE of SCR recorded by NMs is the one recorded on January 20, 2005.

Several techniques have been introduced over the years, with the scope of modelling the dynamic behaviour of GLEs. Usually the case is to apply a least square procedure in order to define the parameters that fit the GLE model used at any case. The chosen functions represent the physical processes involved in the particle’s rigidity distribution and propagation as well as the responses of the atmosphere to energetic solar particle fluxes. Over the years, a special method of calculating the NM response during a SPE has been developed and it is described by [20]. The most significant parameter that allowed a better modelling of GLEs was the precise calculations of the effect of the Earth’s magnetic field on the particle arrival [21], with the use of better and more complex representations of the magnetic field [22]. The strategic role of combined NM measurements at several cut-off rigidities and at various asymptotic viewing directions revealed once again at the modelling efforts of GLEs. It was made clear that in order to get the most accurate behaviour of SCR during a GLE event a large number of NM stations were needed.

One of the most recent models on GLEs is the NM-BANGLE model which couples primary solar cosmic rays at the top of the Earth's atmosphere with the secondary ones detected at ground level by NMs during GLEs. It is based on the Coupling Coefficient Method, firstly introduced by Dorman [5]. The NM-BANGLE Model calculates the evolution of several GLE parameters such as the solar cosmic ray spectrum and anisotropy as well as the particle flux distribution, revealing crucial information on the energetic particle propagation and distribution (Fig. 5). The total output of the NM-BANGLE model is a multi-dimensional GLE picture that gives an important contribution to revealing the characteristics of solar energetic particle events recorded at ground level [23].

1.3. The establishment of a real-time GLE-Alert system

The early detection of Earth directed SEP events by NMs provides preventive prognosis of dangerous particle flux and therefore can initiate an Alert with very low probability of false alarm. The method of the Alert establishment is developed in [24, 25]. They used 1-min NM data from a single NM station and managed to predict the spectrum of the approaching particles. It was made clear at that point that a more feasible and statistically proven

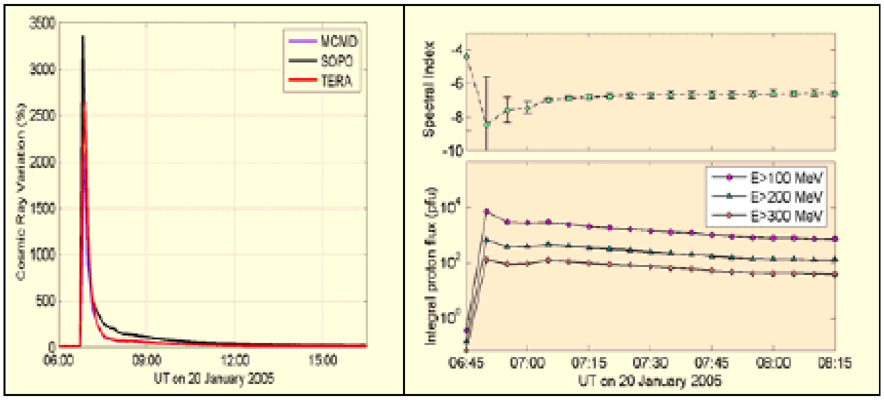


Figure 5. GLE 69 on January 20, 2005. Result from NM-BANGLE mode.

method should be developed and used, using total counts of several NM stations.

In response to the above, the Athens Cosmic Ray Group created a sophisticated algorithm capable of predicting the onset of a GLE providing an Alert. The basic physical ideas are described in [5]. This particle flux cannot be recorded on satellites with enough accuracy because of their small detecting area. However, it can be measured by ground-based NMs with high statistical accuracy (in average, 0.5% for 5 min) as GLE. The Athens GLE-Alert relies at the processing of 1-min data with refresh rate of 1-min, from at least three NM stations (two high latitudinal and one low latitudinal) and two independent satellite channels (e.g. GOES 10 & GOES 12) aiming to the search of the beginning of a GLE. In case an enhancement is marked the software collects data from every NM station contributing as an input to the GLE-Alert and tries to verify the beginning of such an enhancement. If an Alert signal is established, a notification is being provided. In order to be accurate, the software uses different kind of inputs from all available sources. For large events the Alert stage is considered to have about 99% accuracy. An analytical explanation of the Athens GLE-Alert software is provided at [26, 27].

In December 13, 2006 a GLE was recorded by NM stations around the world [28]. This was the first real-time GLE-Alert prognosis signal that was produced by the Athens NM station, proving that cosmic rays and their ground based observatories as NMs can have a significant role at the monitoring and forecasting of such particle fluxes, providing reliable GLE Alert signals. Results are presented in Fig. 6.

1.4. Coronal mass ejections

Explosive release of mass from the Sun’s outer atmosphere over the course of several hours, identified as coronal mass ejections (CMEs), can rapidly

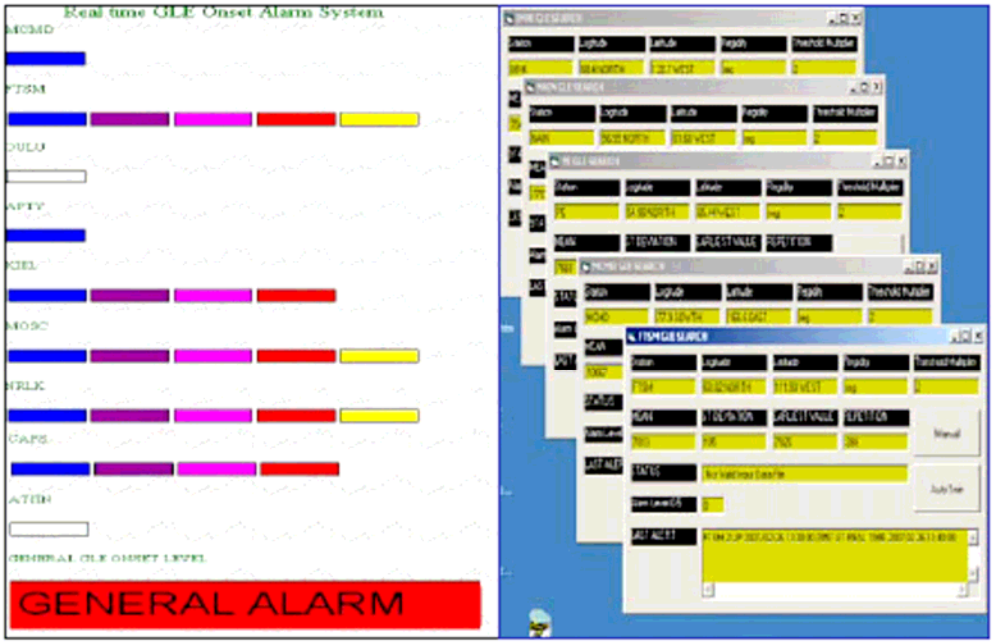


Figure 6. The actual Alert signal displayed at the Athens NM station webpage (left panel) and the scripts that read data from NM stations (right panel).

shower Earth with accelerating energetic particles and cause severe disturbances in the physical characteristics of solar wind (density, composition, magnetic field strength) [29].

The Earth directed events, called halo CMEs are of great importance, as those produce the most severe SW impacts. CMEs, because of their significant role in IMF perturbations, are continuous monitored by space based observatories as the Solar and Heliospheric Observatory (SOHO) [30]. Observations of the solar corona with the Large Angle Spectrometric Coronagraph (LASCO) and the Extreme ultraviolet Imaging Telescope (EIT) instruments on SOHO provided an unprecedented opportunity for continuous real-time monitoring of solar eruptions that effects space weather in a most profound way (Fig. 7).

2. Geomagnetic disturbances

The boundary between interplanetary space and the Earth's magnetosphere is extremely dynamic. One to four days following a significant solar disturbance a closed magnetic structure reaches the Earth, resulting in a geomagnetic storm. The magnitude and the orientation of this magnetic structure when it impacts the magnetopause affect the severity of the storm. It should be stated that even extreme solar events as impulsive SF and

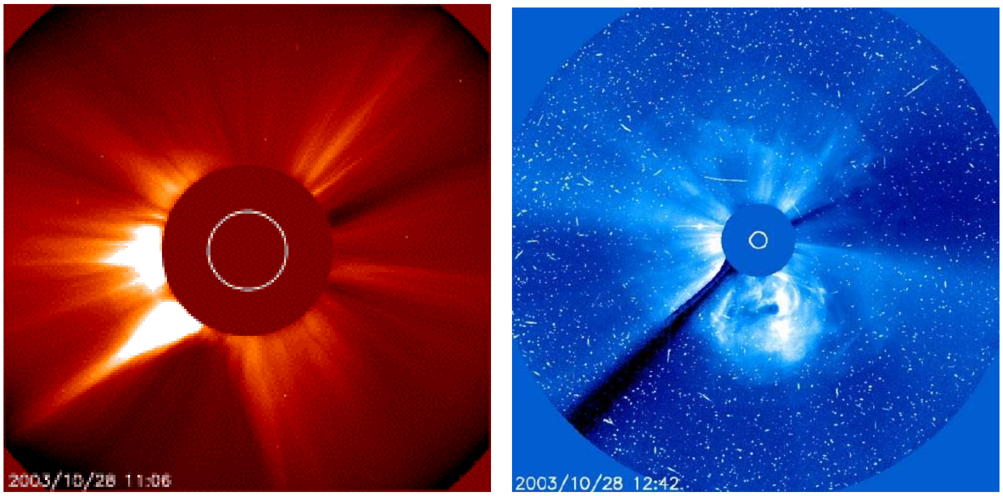


Figure 7. The famous CME on October 28, 2003; Credit: SOHO.

large CMEs are categorized as geoeffective if only the interplanetary magnetic field (IMF) turns southward near 1 AU in order to permit magnetic reconnection in the dayside magnetopause [31]. The need to measure the magnetic perturbations on the Earth's surface resulted into the introduction of the Dst index. This was based on the assumption that the global decrease of the geomagnetic component H is solely due to an external westward electric current system (the ring current), which encircles the Earth symmetrically [32].

2.1. Magnetospheric effects

Cosmic ray variations due to changes in the magnetosphere are of great interest. In [33] the severe magnetic storm on 20 November 2003 was evaluated using data from the worldwide neutron monitor network and the global survey method. From this analysis the changes in the planetary distribution of magnetic cut-off rigidities during this disturbed period were obtained in dependence of latitude. A correlation between *Dst* index and cut-off rigidity variations for each cosmic ray station showed that the maximum changes in cut-off rigidities occurred while *Dst* index was around −472nT. Geomagnetic effect in cosmic ray intensity reached at some stations 6–8% (Fig. 8, left panel) and it seems to be the greatest one over the history of neutron monitor observations. The latitudinal distribution showed a maximum of changes at geomagnetic cut-off rigidities around 7–8 GV (Fig. 8, left panel). This corresponds to unusually low latitudes for maximal effect. Cut-off rigidity variations were also calculated utilizing the last model of Tsyganenko for a disturbed magnetosphere (T01S). A comparison between

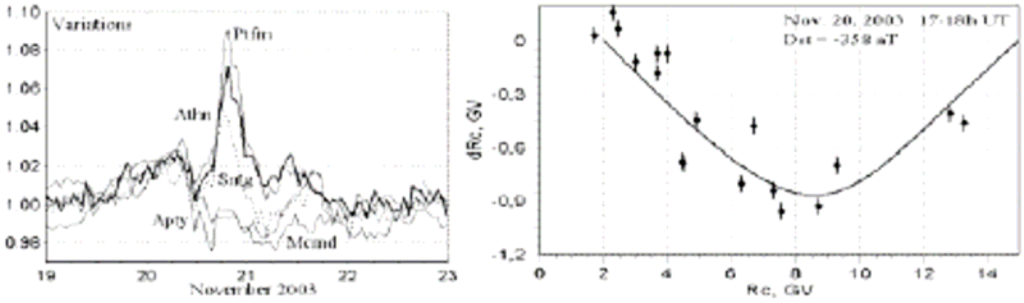


Figure 8. Variation of the cosmic ray intensity (left panel) and of the cut-off rigidity (right panel) of different NMs during the extreme magnetic storm of November 20, 2003.

experimental and modeling results revealed a big discrepancy at cut-off rigidities less than 6 GV. The results on the geomagnetic effect in cosmic rays can be used for validating magnetospheric field models during very severe storms.

2.2. Cosmic rays as precursors of geomagnetic disturbances

Measurements by neutron monitors and the analysis on this data proved the existence of precursors before the arrival of an interplanetary shock to the Earth and before the onset of a Forbush decrease [34]. Therefore these events can be used as reliable indicators of dangerous geomagnetic storms. Forecasting of hazardous geomagnetic storms by means of FD indicators requires data from as many CR stations in real time, as possible. Thus, the need of establishing neutron monitor networks was soon identified. The precursory provided by ground based data is expressed as changes at the pitch angle distribution before shock arrival. A large and long lasted precursor of this kind was first detected at muon data [35, 36]. This is also easy to see at NM data.

Pitch angle distribution changes for more than one day in advance of the arrival of solar wind disturbances in the form of a deep (over 1%) decrease in the cosmic ray intensity close to the interplanetary magnetic field (IMF) direction.

The combination of a narrow decrease with a general increase results in pitch angle distribution dramatically different from the usual one as it has complicated angle dependence with a pronounced minimum at small pitch-angles [37]. Such a distribution is unusual for quiet periods, but typically enough for periods before FDs, thus these can be used as early evidence of approaching disturbances and therefore as predictors of magnetic storms (Fig. 9) [38, 39].

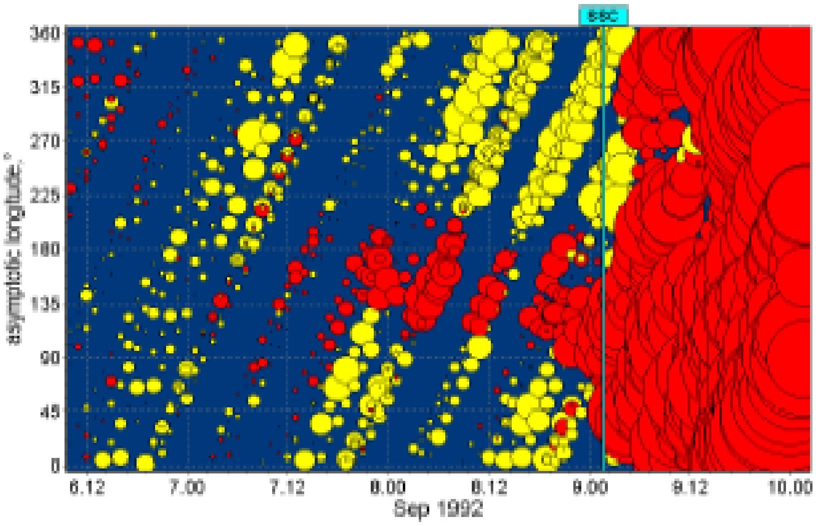


Figure 9. Pre-increases (yellow circles) and pre decreases (red circles) at various asymptotic longitudes during the geomagnetic storm of September 1992. Radii of circles correspond to the amplitude of CR variation [39].

2.3. Onset of radiation hazard events

Particles with energy ranging from several tens to hundreds of MeV are most important for the radiation hazard effects during solar radiation storms: for the electronic element failures on satellites, for the communication, for the biological objects especially in space and at high altitudes [40]. The ground based detectors of CR (at energies above the atmospheric threshold and at locations with various geomagnetic cut-off rigidity, if good temporal resolution and network of several stations is in real time operation), can provide useful alerts ranging from several minutes to tens of minutes in advance of the massive arrival of tens to hundreds MeV particles to the vicinity of Earth.

Systems for short-term radiation hazard forecasting have been suggested by many authors [26, 27]. A large heliospheric storm, indicated by different SW parameters, during which significant variations in CR density and in the first harmonic of the CR anisotropy, derived from ground level observations, occur simultaneously with dramatic changes in the interplanetary and geomagnetic parameters is presented in Fig. 10. The idea introduced regarding the onset of geomagnetic effect lies on the diagnoses of dangerous events heading towards the Earth. In order to do so, simultaneous measurements at several NMs providing real time data with 1 minute resolution or better and with high statistics combined with the reliable measurements of different multiplicities is important [28].

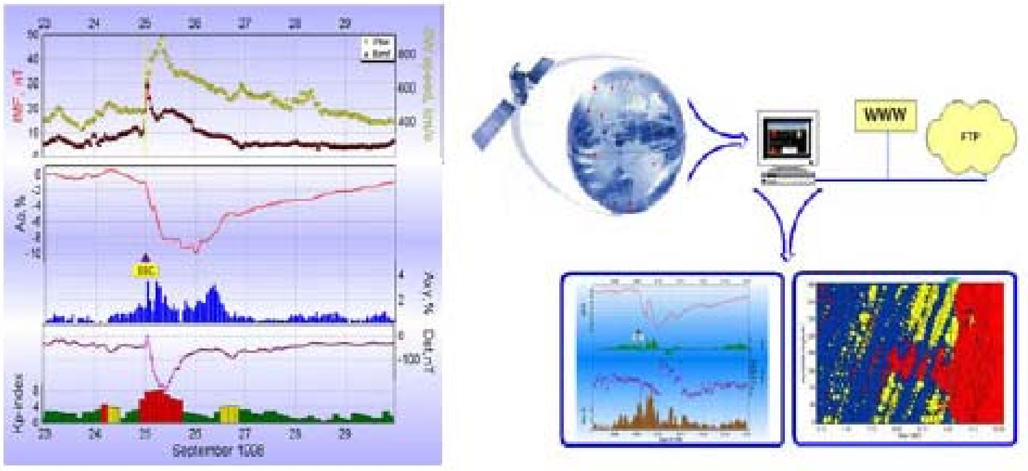


Figure 10. Significant disturbances in CR density, anisotropy and geomagnetic conditions (left panel) and a schematic representation of the method of geomagnetic storms prognosis (right panel).

3. Networks – ground based and space born measurements

By the forehanded analysis, it was made clear that in order to provide accurate monitoring, effective modelling of the physical properties and eventually prognosis of SW parameters, a network of NM stations considered as a unique multidimensional spectrograph was needed. This network combined with data from other detectors, either on the ground or at space, provided new perspectives for SW research and application.

One of the first attempts to establish a network of NMs data (two-hourly and then one-hourly) was the World Data Centers: WDC-A (USA, Boulder), WDC-B2 (Russia, Moscow) and WDC-C (Japan, Ibaraki). At that time, data were collected in paper tables with a delay of one to two years. In the 1980's WDC-C made a huge step - they transferred all accumulated data onto magnetic tape, and this was successful up to days when the computer technique started to provide the storage and flexible access to data. Quite recently, another database was created at the Bartol Research Institute (Fig. 6 – left panel), but with different time of updating and only for a limited number (11) of stations. This attempt of realizing a NM network stood on the idea of providing a chain of high latitude NM stations, due to the fact that those are non-sensitive to geomagnetic disturbances, and was called 'Spaceship Earth' [41].

Moreover, particle detectors of the Aragats Space Environmental Center (ASEC) in Armenia combined in a local network [42], focusing mostly at the problem of revealing signal from solar cosmic rays (SCR) against overwhelming background galactic cosmic rays (GCR), which is one of the most complicated in high energy astrophysics.

Another approach on the implementation of a Cosmic Ray Data Processing Center was furnished by the Athens Cosmic Ray group [26, 27], with the scope to provide real-time monitoring of cosmic ray variations from NMs - widely distributed around the globe (at various latitudes and rigidities) - as well as information on the time evolution of several space weather parameters measured by satellites (Fig. 11 – right panel). Thus, the Athens Neutron Monitor Data Processing (ANMODAP) Center made feasible the use of the neutron monitor network data in real time for space weather applications [27].

The latest and more promising approach has been conducted by a European collaboration, under the title: ‘Real-time database for Neutron Monitors-NMDB’ [43]. Under this collaboration 19 NM stations from twelve countries will be able to feed the central database, hosted at the Belgium Institute of Space and Aeronomy (BIRA), with 1-min NM data updated every 1-min. This is truly a remarkable effort, as an old but yet effective registration system will be synchronized, using the state of the art electronic systems and software, resulting into a real-time 1-min database useful for GLE analysis, ionization of the atmosphere analysis and many other applications. Apart from the central database, three mirror databases will be realized

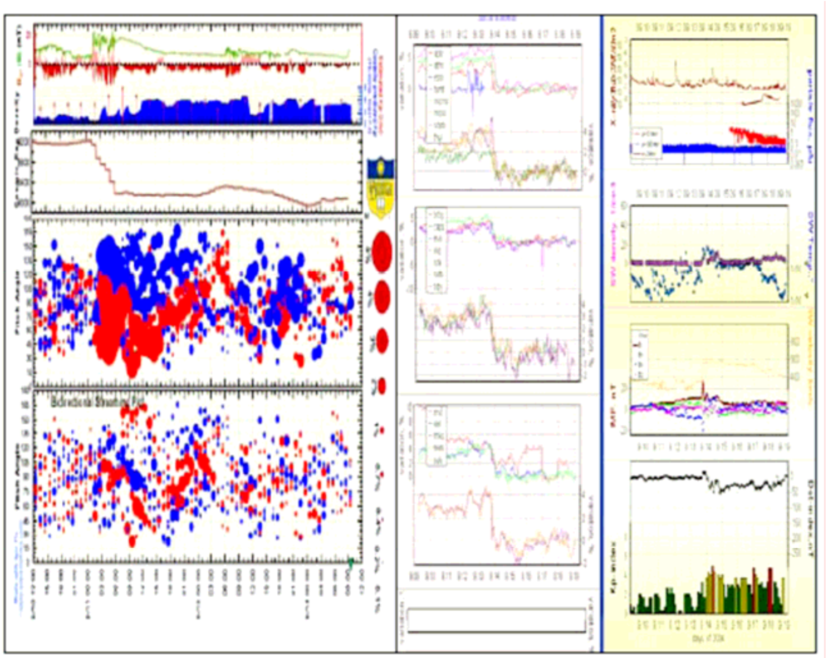


Figure 11. Results from Spaceship Earth (left panel) and the output of the ANMODAP center: both satellite and NM data is being represented (right panel).

in Athens, Kiel and Moscow in order to ensure the flexibility and the progressive usage of the NMDB.

4. Scientific applications of cosmic rays

At this point one should note that basic research on cosmic rays contributes to the understanding of space environment and therefore is part of the explanation of the Space–Earth relation and space weather, in general. In 50 years of continuous observations of CR, a significant number of scientists explored the physical explanations of the mechanisms which dominate interplanetary space.

4.1. Long-term modulation

The cosmic ray intensity, as it is observed from Earth and in Earth's orbit, exhibits an approximate 11-year variation anti-correlated with solar activity, with perhaps some time-lag, firstly studied by [1]. Many research groups have tried to express this long-term variation of the galactic CR intensity through means of appropriate solar indices and geophysical parameters. The modulation of galactic cosmic rays in the heliosphere using theoretical as well as empirical approaches is successful and advanced rapidly [44]. However an adequate description of the effect of the heliosphere on cosmic rays still does not appear to be a simple task. To be adequate, theoretical models should consider the complex shape and dynamics of the heliospheric current sheet, the heliolatitudinal distribution of the solar wind velocity, boundaries between fast and slow solar wind streams, various sporadic and recurrent structures and the role of the termination shock and the heliopause. [45] tried to estimate the magnetic field at the heliospheric termination shock and to study the effects of its temporal variation on the galactic cosmic-ray long-term modulation starting from the Parker's model and using in-ecliptic measurements from different Spacecrafts at 1 AU near the Earth. [46] tried to estimate the size of the heliosphere derived from the long-term modulation of neutron monitor intensities. Using a construction of the open solar magnetic flux from sunspot data as an input to a spherically symmetric quasi-steady state model of the heliosphere, the expected intensity of galactic cosmic rays at the Earth's orbit was calculated in [47]. This calculated cosmic ray intensity is in good agreement with the neutron monitor measurements during the last 50 years.

Particular consideration of the cosmic ray modulation is given to the correlation of long-term cosmic ray variations with different solar-heliospheric parameters and to existing empirical models of cosmic ray intensity, as it is described in the review paper [48]. A method to predict cosmic ray intensity and solar modulation parameters was proposed in [49]. This method gives satisfactory results when applied to prediction of the dose received on-board commercial aeroplane flights. He notes that prediction of the galactic cosmic ray intensity observed at a given station is preferable than prediction of the different potentials such as the modulation potential in terms of sunspot numbers [50]. The importance of this choice is that the cosmic ray intensity is the only variable directly observed. Records of cosmic ray intensity are available, and homogeneous, over a long period, while that is not the case for the data obtained from space observations. Two models were proposed in [51], a quasi-linear and a model assuming a power-law relation between the modulation potential and the magnetic flux during the neutron monitor area 1951-2005 useful for predictions, if the corresponding global heliospheric variables can be independently estimated.

Recently, an empirical relation based on solar and interplanetary parameters was presented by [52] in order to describe the long term modulation of cosmic ray intensity during the last solar cycle. Emphasis was given to the different behaviour of the heliospheric parameters compared with the solar ones regarding interesting properties of the cosmic ray intensity modulation (Fig. 12). These are the hysteresis phenomenon and the correlation of these parameters with the cosmic ray intensity in the three phases of the solar cycle and according to the solar magnetic field polarity as well. This model has been so far applied to four solar cycles (nos. 20, 21, 22 and 23) and can be considered as a useful tool for understanding cosmic ray modulation [53]. The proposed model can be extended backward in time or used for predictions, as it has practical implications for planning solar observations and forecasting space weather phenomena.

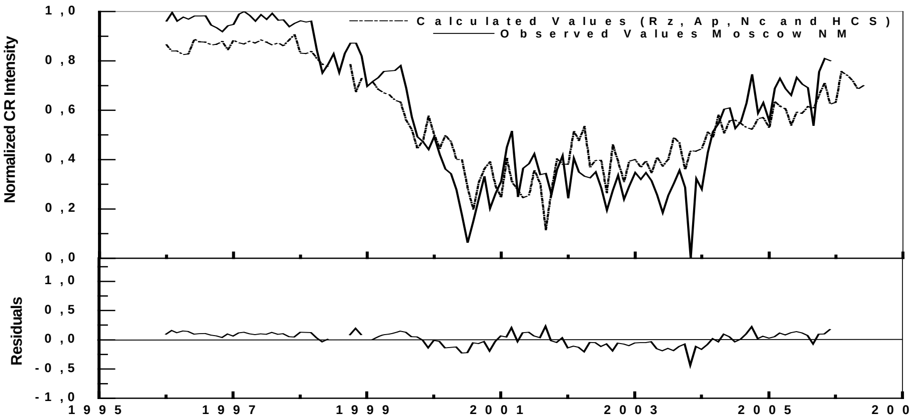


Figure 12. Empirical modulation model of cosmic ray intensity for solar cycle 23 [52].

4.2. Spectral behaviour of cosmic ray intensity

Detailed analysis of the time series of cosmic ray intensity observations at the Earth and particularly their spectral characteristics in various frequency domains is important for determining both the large- and small-scale behaviour of magnetic fields in the heliosphere. At the low frequency of the spectrum the dominant quasi-periodic variations in cosmic ray intensity observed at the time scales of 11 and 22 years have been attributed to the solar activity and magnetic polarity reversal cycles, respectively. At higher frequencies the diurnal and the 27-day variations are dominant and are caused by corotation of cosmic ray particles in the interplanetary magnetic field [54, 55]. Within these two extreme frequency ranges a wide range of frequencies of cosmic ray intensity variations exists, although a clear and stable periodicity has not been established so far [56, 57]. It was noted that there are two distinct regions of cosmic ray periods with respect to the underlying physical mechanisms, and that the barrier is located around 20 months [58]. The large scale variations are caused by the solar dynamics, whereas transient effects in the interplanetary space cause the short-scale variations that have a different probability of occurrence in different epochs, as it is illustrated in Fig. 13 [59]. [60] reported on a short-time variation of 1.68 year in the cosmic ray intensity observed at the Earth at the neutron monitor energies (several GeV) that might appear as a consequence of phenomena rooted in the solar interior and could help to the understanding the origin of the solar magnetic cycle. This cosmic ray variation is also appeared at the top of flare- producing regions as well as in the long duration event (LDE)-type of flares which precede the formation of coronal holes [61, 62]. Common periodicities in cosmic ray intensity time series analyzing into trigonometric series and in the solar flare index are also determined during

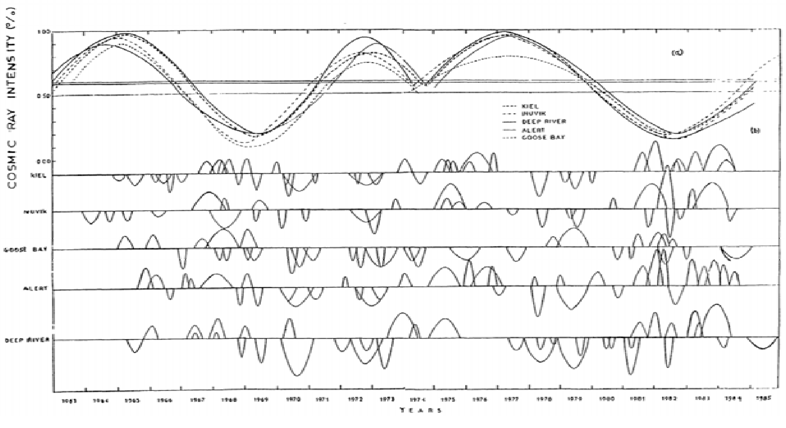


Figure 13. Long-term and short-term periodicities, 1963-1985 [59].

the maximum phase of cycles 21 and 22 [63]. Results from these studies support the argument regarding the differences in the solar activity between even and odd solar cycles [56].

It is interesting to note that there are similarities in quasi-periodicities of cosmic ray time series with those reported in chronobiology [64]. Alignment of various data on health (physiological, heart rate frequency, etc) with the variations of cosmic rays and the geomagnetic activity suggests the possibility of links among these environmental variations and health risks [65, 66]. Recently, a special study of the diurnal anisotropy of cosmic rays and the heart rate variations of healthy persons gives a close behaviour of these two parameters [66].

4.3. Fast solar wind streams - sector boundaries

It is known that one of the most dynamical interplanetary phenomena of solar terrestrial physics is definitely the passage of solar wind streams near the Earth environment. Studies of various aspects of the solar wind velocity variability with time in the ecliptic plane revealed a solar wind tendency to be organised as stream structures (e.g. [67, 68] among others). In particular, the characteristics and the long-term variations in the occurrence rate of high-speed streams for solar cycles 20, 21 and 22 have been studied in [69, 70, 71]. Recently, a new catalogue for the high speed streams in solar wind during solar cycle 23 has been presented by [72]. Reference catalogues of high-speed solar wind streams observed near the Earth have been produced, considering two possible solar sources, coronal holes and active regions emitting solar flares. Apart from these, these catalogues contains the dominant polarity of the interplanetary magnetic field (either away or toward the Sun) for the stream duration. The above are very useful for the study of the solar wind stream distribution as a function of Bartels rotation days for various categories [73, 74]. It was resulted that the interplanetary magnetic field associated with fast solar wind streams in Bartels rotation days, presents generally a four-sector structure. This phenomenon is stronger in fast streams with positive IMF polarity, while for the streams with negative polarity there seems to appear a tendency for a two-sector structure. These studies give evidence for the behaviour of the sector structured magnetic field and make it possible to infer the nature of the warp in the heliospheric current sheet during different epochs. Specific features of the high-speed plasma stream cycles are presented in [75].

4.4. Cosmic ray variations – Forbush decreases

Cosmic ray variations recorded by NMs can be defined as the temporal changes in the intensity of the component of the cosmic radiation originating outside the solar system. Hence, this work refers to the galactic cosmic radiation. The solar controlled modulation is well established over the years as the intensity of cosmic rays arriving at the earth varies in anti-correlation with the overall solar activity. The long-term modulation of galactic cosmic rays (CRs) has been recorded by neutron monitors for more then two 22-year cycles providing crucial information on comic ray variations.

Shorter term decreases in the cosmic ray intensity, called Forbush decreases (FD), are generally correlated with co-rotating interaction regions (CIRs) or with earth-directed CMEs from the sun. Some contemporary reviews of Forbush decreases can be found in [76] and [77]. The first observations of a FD was made in 1938 by [78] and since then these decreases are characterized as large sudden asymmetrical depressions in the cosmic radiation lasting for several days. They are world wide in extent and consequently must be attributed to either extensive changes in the geomagnetic field or variations in the interplanetary magnetic field. Usually, FDs have a rapid rate of decrease and a slow recovery. The major portion of the decrease phase is completed within 12-24 h, while the recovery phase extends to a number of days [2].

A wider definition of this comic ray intensity decreases was delivered in 2001 by [37]. According to that Forbush phenomena are also observed under rather quiet geomagnetic conditions, in contradiction to the definition provided by [2] and thus a more complete definition should include FDs as part of the whole phenomenon. Thus, it was suggested that most decreases of the cosmic ray intensity should be categorized as Forbush effects (FE) while only a certain number of them could be referred as Forbush decreases (FD), providing significant coupling to geomagnetic perturbations [38].

Over the years sophisticated algorithms attempted to extrapolate the complex physical mechanisms that produces CR variations and the formation of FDs. On the CR variations issue the most reliable and well established approach is the convection-diffusion (CDM). This treatment was introduced by [79] and was developed in several works [80, 81, 82]. CDM offers a wide and clear picture of the density gradient variations of CR and in that sense provides information on the formation of the interplanetary magnetic field which reflects in the propagation of cosmic rays. On the FDs issue, a recent contribution was the treatment proposed by [83] which relies on the method of coupling coefficients of primary to secondary cosmic rays. An addition to this approach is the Forbush Decrease (FORD) Model which uses an analytical expression of the coupling coefficients [84] instead of pre-calculated empirical values and resolves the optimization problem through the Gauss-Newton-Levenberg-Marquardt algorithm [23]. Results are given in Fig. 14. This latter approach is still under development by the Athens cosmic ray group, but until today it has provided satisfactory results.

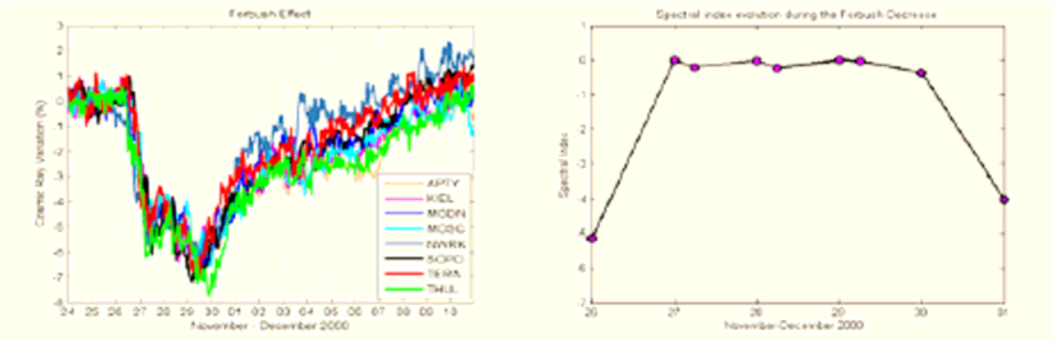


Figure 14. Results from the FORD model. Representation of the FD on November 26, 2000 (left panel) and the evolution of the spectral index for the same FD (right panel).

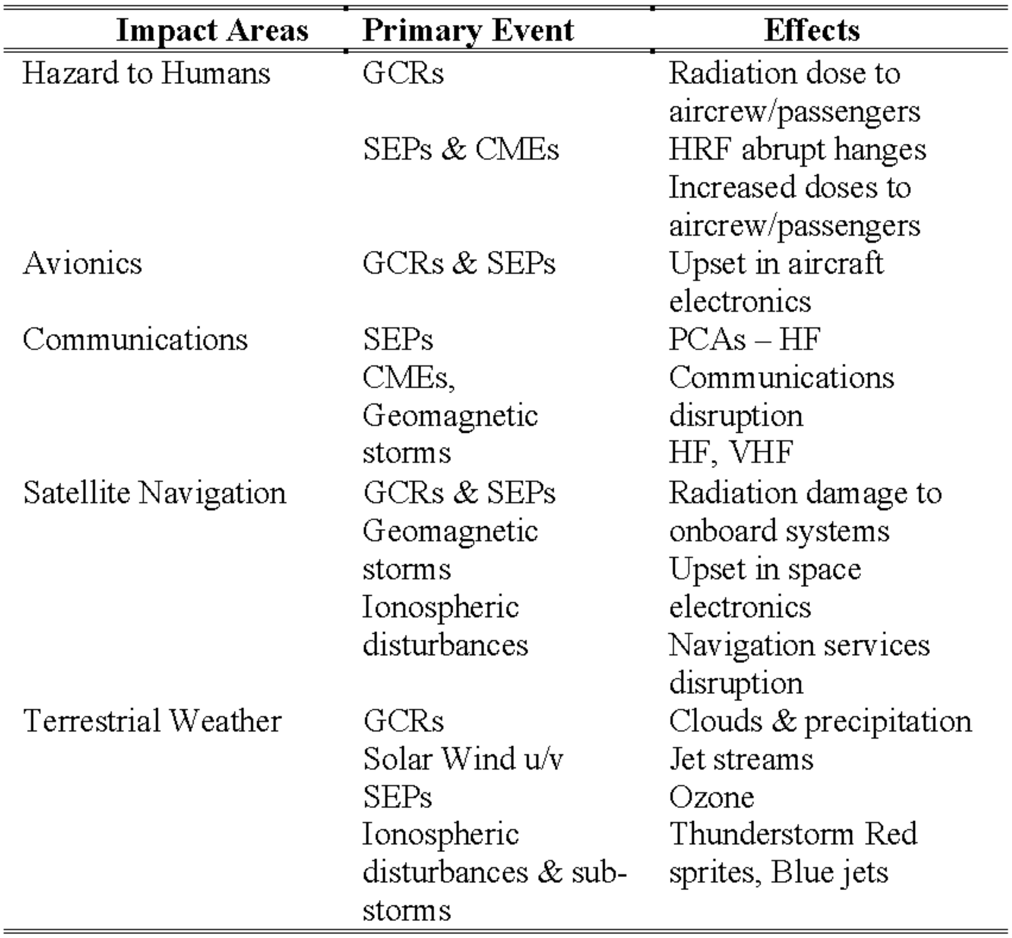
5. Cosmic ray effects on materials & humans

Galactic and solar particles have free access to spacecrafts outside the magnetosphere. Considering the fact that these particles penetrate into the Earth's magnetosphere, those are able to reach near-Earth orbiting spacecrafts and are particularly hazardous to satellites in polar, highly elliptical and geostationary (GEO) orbits. On top of which, the electronics components of aircraft avionics are susceptible to damage from highly ionizing interactions of GCR, SCR and secondary particles generated in the atmosphere [40] .

Human health is always exposed to ionising radiation. This radiation is measured in terms of absorbed dose, the energy deposited per unit mass. Equal absorbed doses of different types of radiation cause biological effects of different magnitude, depending on the sensitivity of different tissues of the body. The total effective dose is measured in Sieverts (Sv) over the whole body. Apart from the radiation impact on humans, as it was also pointed out in 5.2, recently scientists have been also focusing on the relation of CR variations to various parameters of the human physiological parameters as myocardial infarctions, brain strokes, cardiac arrhythmias etc [85, 86, 87]. A new field, called 'Clinical Cosmobiology', is under development and due to that, several groups are focusing on the relation of CRs to human physiology. A summary of most recorded effects of cosmic rays and other energetic particles together with their triggering for specific areas is being displayed in Table 1.

The usage of NM data for the calculation of radiation at space environment and at different altitudes within the atmosphere, has recently been promoted to the scientific community as NMs provide key information about the interactions of the GCR radiation with the plasmas and magnetic fields

Table 1. A summary of all possible impacts of CRs & energetic particles to various areas of interest.



Impact Areas	Primary Event	Effects
Hazard to Humans	GCRs	Radiation dose to aircrew/passengers
	SEPs & CMEs	HRF abrupt hanges Increased doses to aircrew/passengers
Avionics	GCRs & SEPs	Upset in aircraft electronics
Communications	SEPs CMEs, Geomagnetic storms	PCAs – HF Communications disruption HF, VHF
Satellite Navigation	GCRs & SEPs Geomagnetic storms Ionospheric disturbances	Radiation damage to onboard systems Upset in space electronics Navigation services disruption
Terrestrial Weather	GCRs Solar Wind u/v SEPs Ionospheric disturbances & sub-storms	Clouds & precipitation Jet streams Ozone Thunderstorm Red sprites, Blue jets

in the heliosphere and contrary to satellites, the functionality of them is not influenced by intense events.

5.1. Radiation effects in space – simulations

Most dangerous effects in space systems include: a) Radiation damage to spacecraft electronics, solar cells and materials from Earth’s radiation belt particles and solar energetic particles; b) Single event effects (SEE) in spacecraft electronics due to ionisation tracks from galactic cosmic ray or solar energetic particle ions or due to ionisation products of nuclear interactions between radiation belts or solar protons and component materials; c) Interference to spacecraft imaging and sensing systems; d) Electrostatic charging from ‘hot’ (~keV electron temperatures) plasmas and energetic (~MeV) electrons [40].

The analysis of the complex space environment and its impact on space systems led to the developing of empirical or quasi-empirical models by different organizations, often independently of one another. Regarding cosmic rays the most well known and used operating model is the Cosmic Ray Effects on Micro-Electronics (CREME), developed by NASA which also lies inside the Space Environment Information System (SPENVIS) interlink, developed by ESA. Both are provided by user-friendly interfaces and can be used via internet [88].

5.2. Radiation effects in the atmosphere – simulations

The International Commission on Radiological Protection (ICRP), in 1990, recommended that the radiation exposure due to cosmic rays at high altitudes must be taken into account as part of occupational exposure to radiation. Results of experimental studies of air crew exposure regularly compared with the results of transport codes permit the estimation of the level of exposure due to galactic cosmic ray component. The results of previous studies demonstrated quantitative and qualitative influence of cosmic ray events on the radiation situation close to the Earth.

Lately, the MAGNETOCOSMICS Geant4 application which was developed by the University of Bern [89] allowed the computation of the propagation of charged cosmic rays through different magnetic field models of the Earth's magnetosphere at several altitudes within the atmosphere. It also permits the computation of cut-off rigidities and asymptotic directions of incidence. Different models are available in MAGNETOCOMICS for the geomagnetic field and for the external magnetospheric field, these include IGRF/DGRF, Tsyganenko89, Tsyganenko96 and Tsyganenko2001.

5.3. CR effect on human health – present knowledge

As it was pointed out in the introduction of chapter 6, the CR effect on human health presents at least two major aspects. The first one refers to the radiation that we are exposed at. It is a new topic of interest especially due to increasing airplane use and space travelling plans. The most important result of all the analyses referring to radiation risks from CRs (galactic and solar) is that the absorbed radiation doses increases with altitude and latitude [90]. Hence, people who are frequently flying at long-distance (high altitude) journeys are in great danger [91], especially if during this journey a solar extreme event occur, resulting at increasing the particle populations within the atmosphere. The second one is the alignment of various data on health (epidemiological, physiological etc) with the variations of CR, geomagnetic activity and atmospheric pressure, suggesting the possibility of links among these environmental variations and health risks, such as myocardial infarctions and ischemic strokes, among others [87].

Regarding the radiation risk issue, extensive studies has been performed and revealed the ways in which CR affect human health. Due to the increasing use of airplanes it is impossible to completely avoid the risk of radiation effects. The goal is to reduce such risk and the only way to do so is by monitoring every parameter of particle populations inside the space environment. Regarding the epidemiological issue and the exact ways in which CR affect human health, one should note that most of the studies on this subject are statistical. The processes involved depend on many parameters, and both the clear causality as well as the mechanisms behind these, are not completely and satisfactorily clarified yet, although this is a new and exciting scientific field on CR research.

6. Discussion and concluding remarks

The term ‘Space weather’ is now a popular scientific one including a lot of concept. Effects of solar induced disturbances on our space environment ranging from degradations in spacecraft operations to disruptions of electrical power grids have been documented many years. Today, more than 50 years after the initiation of ground based monitoring with neutron monitors and muon telescopes, it is clear that real-time ground level measurements in combination with satellite / space born calculations can provide a useful tool for space weather prognosis. The results from this approach are very satisfactory.

- The GLE-Alert system which is operating at several groups in real-time mode provided the first ever GLE-Alarm signal in December 2006.
- The corresponding developed algorithms on physical phenomena as Ground Level Enhancements (GLEs) and Forbush decreases (FORD) render reliable results which realistically reconstruct and foresee the course of such events.
- The implementation of several NM networks (IZMIRAN, Spaceship Earth, ANMODAP Center), provided new insight at space weather monitoring, which resulted into a new very promising European collaboration: ‘NMDB’.
- The scientific exploration of space extended the informational limit of cosmic rays into a new level which resulted in a scientific stride with many new results.

Advances in our understanding of cosmic rays and their impact on space weather continue to come at a rapid rate. The field remains healthy because we have excellent data for long-time series, and innovative new ideas from experimental and theoretical groups. However, there is an obvious need for more accurate space weather prognosis which will result through, new advanced modelling. Cosmic rays will have a key-role to the exploration of space environment parameters providing major advantages to the scientific calibration of Space Weather.

Acknowledgements

The author apologizes for including only a limited number of papers relevant to the title. There are so many interesting works concerning cosmic rays and space weather. In this work I tried to present some of the research activities of the Athens Cosmic ray Group that is greatly acknowledged. Especially I am grateful to my colleagues A. Papaioannou and M. Papahliou for their valuable help in writing this article. The Research Committee of the University of Athens and the PYTHAGORAS II project (70/3/7979) funded by European funds and National resources are acknowledged as well.

References

1. Forbush, S.E. 1958, *J. Geophys. Res.*, **63**, 651.
2. Lockwood, J. 1971, *Space Science Reviews*, **12**, 658.
3. Dyer, C., and Rodgers, D. 1998, Proceedings ESA WPP – 155.
4. Störmer, C. 1955, Clarendon Press, Oxford.
5. Dorman, L.I. 2004, Cosmic rays in the Earth’s atmosphere and underground, Kluwer Academic Publishers, The Netherlands.
6. Simpson, J. 2000, *Space Sci. Rev.*, **93**, 11.
7. Mavromichalaki, H., Sarlanis, C., Souvatzoglou, G., Tatsis, S., Belov, A., Eroshenko, E., Yanke, V., and Pchelkin, A. 2001, Proc. 27th ICRC, 4099.
8. Kudela, K., Storini, M., Hofer, M., and Belov, A. 2000, *Space Sci. Rev.*, **93**, 153.
9. Schwenn, R. Max-Plank Institut fur Aeronomic Germany.
10. Stassinopoulos, E. 1990, Reno, NV, Proc. 1990 IEEE NSREC Short Course.
11. Barth, J. 1997, Snowmass Village, CO, IEEE NSREC Short Course.
12. Dyer, C. 1998, Newport Beach, CA, Proc. 1998, IEEE NSREC Short Course.
13. Belov, A.V., Garcia, H., Kurt, V., Mavromichalaki, H., and Gerontidou, M. 2005, *Solar Physics*, **229**,135.
14. Nymmik, R.A. 2005, Proc. 2nd Inter. Symposium SEE – 2005, 25.
15. Garcia, H. 1994, *Astrophys. J.*, **420**, 422.
16. Gerontidou, M. 2007, PhD Thesis, University of Athens.

17. Belov, A., Kurt, V., Mavromichalaki, H., and Gerontidou, M. 2007, *Solar Phys.*, **246**, 457.
18. Shea, M.A., Smart, G.F. 1993, National Oceanic and Atmospheric Administration, Environmental Research Laboratories, 48.
19. Storini, M. and Laurenza, M. 2003, *Mem. Soc. Astron. Ital.*, **74**, 774.
20. Cramp, J.L., Duldig, M.L., Flueckiger, E.O., Humble, J.E., Shea, M.A., and Smart, D.F. 1997, *J. Geophys. Res.*, **102**, 24237.
21. Flueckiger, E.O., and Kobel, E. 1990, *J. Geomagn. Geoelect.*, **42**, 1123.
22. Tsyganenko, N.A. 1989, *Planet. Space Sci.*, **37**, 5.
23. Plainaki, C., Belov, A., Eroshenko, E., Mavromichalaki, H., and Yanke, V. 2007, *J. Geophys. Res.-Space Phys.*, **112**, A04102, doi:10.1029/2006JA011926.
24. Villoressi, G., Dorman, L.I., Iucci, N., and Ptitsyna, N.G. 2000, *J. Geophys. Res.*, **105**, A9, 21025.
25. Stoker, P.H., Dorman, L.I., and Clem, J.M. 2000, *Space Sci. Rev.*, **93**, 361.
26. Mavromichalaki, H., Sarlanis, C., Souvatzoglou, G., Mariatos, G., Gerontidou, M., Papaioannou, A., Plainaki, C., Belov, A., Eroshenko, E., and Yanke, V. 2005, IEEE TNS, 52, 2307.
27. Mavromichalaki, H., Gerontidou, M., Mariatos, G., Plainaki, C., Papaioannou, A., Sarlanis, C., Souvatzoglou, G., Belov, A., Eroshenko, E., Yanke, V., and Tsitomeneas, S. 2005, *Annales Geophys.*, **23**, 3103.
28. Souvatzoglou, G., Mavromichalaki, H., Sarlanis, C., Mariatos, G., Belov, A., Eroshenko, E., and Yanke, V. 2007, Solar Extreme Events Intern. Symp., Athens, 87.
29. Gopalswamy, N., Nunes, S., Yashiro, S., and Howard, R. 2004, *Adv. Space Res.*, **34**, 391.
30. Brekke, P., Chaloupy, M., Fleck, B., Haugan, S., and van Overbeek, T. 2004, Effects of Space Weather on Technology Infrastructure, NATO Science Series, Kluwer Academic Press, 176, 109.
31. Daglis, I. 2004, Effects of Space Weather on Technology Infrastructure, NATO Science Series, Kluwer Academic Press, 176, 27.
32. Akasofu, S.-I., and Chapman, S. 1961, *J. Geophys. Res.*, **66**, 1321.
33. Belov, A., Baisultanova Belov, A., Baisultanova, L., Eroshenko, E., Mavromichalaki, H., Yanke, V, Pchelkin, V, Plainaki, C., and Mariatos, G. 2005, *J. Geophys. Res. - Space Physics*, **110**, 9, A09S20,doi:10.1029/2005JA011067.
34. Kudela, K. 2007, 30th ICRC, Merida – Mexico.
35. Nagashima, K., Sakakibara, S., Fujimoto, K., Fujii, Z., and Ueno, H. 1993, Proc. 23rd Inter. Cosmic Ray Conf., 3, 711.
36. Munakata, K., Bieber, J., Yasue, S., Kato, C., Koyama, M., Akahane, S., Fujimoto, K., Fujii, Z., Humble, J., and Duldig, M. 2000, *J. Geophs. Res.*, **105**, 27, 457.
37. Belov, A.V., Eroshenko, E.A., Oleneva, V.A., and Yanke, V.G. 2001, Proc. 27th ICRC, 8, 3552.
38. Belov, A., Bieber, J., Eroshenko, E., Everson, P., Pyle, R., and Yanke, V. 2003, *Adv. Space Res.*, **31**, 919.
39. Dorman, L. 2005, *Ann. Geophys.*, **23**, 2997.
40. Daly, E. 2004, Effects of Space Weather on Technology Infrastructure, NATO Science Series, Kluwer Academic Press, 176, 91.

41. Bieber, J.W., and Evenson, P. 1995, Proc. 24th ICRC, Rome, 4, 1316.
42. Chilingarian, A.A., and Raymers, A.E. 2007, *Astroparticle Phys*., **27**, 465.
43. Steigies, C. 2008, Geophysical Research Abstracts, 10, EGU2008 – A
44. Potgieter, M.S. 1998, *Space Sci. Rev*., **83**, 147.
45. Exarhos, G., and Moussas, X. 1999, *Solar Phys*., **187**, 157.
46. Morishita, I., and Sakukibara, S. 1999, Proc. 28th ICRC, 7, 87.
47. Usoskin, I.G., Mursula, K., Solanki, S.K., Schüssler, M., Kovaltsov, and Gennady A. 2002, *J. Geophys. Res*., **107**, doi: 10.1029/2002JA009343.
48. Belov, A. 2000, *Space Sci. Rev*., **93**, 79.
49. Lantos, P. 2005, *Solar Phys*., **229**, 373.
50. Badhwar, G.D., and O'Neil, P.M. 1993, Proc. 23rd ICRC 3, 535.
51. Alanko-Huotari, K., Mursula, K., Usoskin, I.G., and Kovaltsov, G.A. 2006*, Solar Phys*., **238**, 391.
52. Mavromichalaki, H., Paouris, E., and Karalidi, T. 2007, Solar Phys., 245, 369.
53. Mavromichalaki, H., Belehaki, A., and Rafios, X. 1998, A @ A, 330, 764.
54. Axford, W.I. 1965, *Plan. Space Sci.* **13**, 115.
55. Mavromichalaki, H. 1989, *Earth, Moon and Planets*, **47**, 161.
56. Mavromichalaki, H., Preka-Papadima, P., Petropoulos, B., Tsagouri, I., Georgakopoulos, S., and Polygiannakis, J. 2003, *Annales Geophys*., **21**, 1681.
57. Mavromichalaki, H., Preka-Papadima, P., Liritzis, I., Petropoulos, B., and Kurt, V. 2003, *New Astronomy*, **8**, 777.
58. Kudela, K., Ananth, A.G., and Venkatesan, D. 1991, *J. Geophys. Res*., **96**, 15871.
59. Xanthakis, J., Mavromichalaki, H., and Petropoulos, B. 1989, *Solar Phys*., **122**, 345.
60. Valdes-Galicia, J.F., and Mendoza, B. 1998, *Solar Phys*., **178**, 183.
61. Antalova, A. 1994, *Adv. Space Sci*., **14**, 721.
62. Mavromichalaki, H., Preka-Papadima, P., Liritzis, I., Petropoulos, B., and Kurt, V. 2000, Proc. 4th Astron. Conf. (Samos), 273.
63. Mavromichalaki, H., Preka-Papadima, P., Petropoulos, B., Vassilaki, A., and Tsagouri, I. 2003, *J. Atm. Solar Terr. Phys*., **65**, 1021.
64. Halberg, F., Cornelissen, G., Otsuka, K., Watanabe, Y., Katinas, G.S., Burioka, N., Delyukov, A., Gorgo, Y., Zhao, Z.Y., Weydahl, A., Sothern, R.B., Siegelova, J., Fiser, B., Dusek, J., Syutkina, E.V., Perfetto, F., Tarquini, R., Singh, R.B., Rhees, B., Lofstrom, D., Lofstrom, P., Johnson, P.W.C., and Schwartzkopff, O. 2000, *Neuroendocrinology Letters*, **21**, 233.
65. Cornelissen, G., Halberg, F., Breus, T., Syytkina, E., Baevsky, R., Weydahl, A., Watanabe, Y., Otsuka, K., Siegelova, J., Fiser, B., and Bakken, E. 2002, *J. Atm. Solar Terr. Phys*., **64**, 707.
66. Petropoulos, B., Mavromichalaki, H., Papailiou, M., Kelesidis, K., and Mertzanos, G. 2006, *Proc. Academy of Athens*, **81**, 51.
67. Burlaga, L.R. 1979, *Space Sci. Rev*., **17**, 327.
68. Iucci, N., Parisi, M., Storini, M., and Villoresi, G. 1979, *Nuovo Cimento* 2C, 421.
69. Lindblad, B.A., and Lundstedt, H. 1981, *Solar Phys*., **74**, 197.
70. Mavromichalaki, H., Vassilaki, A, and Marmatsouri, E. 1988, *Solar Phys*., **115**, 345.
71. Mavromichalaki, H., and Vassilaki, A. 1998, *Solar Phys*., **183**, 181.
72. Maris, O., and Maris, D. 2007, ESWW4, Nov. 2007, Brussels.
73. Rangarajan and Mavromichalaki, 1989, *Solar Phys*., **122**, 187.

74. Mavromichalaki, H., Vassilaki, A., and Tsagouri, I. 1999, *Solar Phys*., **189**, 199.
75. Maris, O., and Maris, G. 2005, *Adv. Space Res*., **35**, 2129.
76. Cane, H. 2000, *Space Sci. Rev*., **93**, 55.
77. Venkatesan, D., and Badruddin 1990, *Space Sci. Rev*., **52**, 121.
78. Forbush, S.E. 1938, *Terrest. Mag*., **43**, 203.
79. Krymsky, G.F. 1964, *Geomagn. & Aeronomy*, **4**, 977.
80. Forman, M.A., and Gleeson, L.J. 1975, *Astrophys. Space Sci*., **32**, 77.
81. Belov, A.V. 1987, Proc. 17th Int. Cosmic Ray Conf., 4, 119.
82. Chen, J., and Bieber, W.J. 1993, *Astrophys. Journal*, **405**, 375.
83. Wawrzynczak, A., and Alania, M. 2005, *Acta Physica Polinica*, B, 36, 5, 184.
84. Clem, J.M., and Dorman, L.I. 2003, *Space Sci Rev*., **93**, 335.
85. Babayev, E.S., and Allahverdiyeva, A.A. 2007, *Adv. Space Research*, **40**, 1941.
86. Dimitrova, S., Stoilova, I., and Cholakov, I. 2004, Bioelectromagnetics, 25, 408.
87. Papailiou, M., Mavromichalaki, H., Vassilaki, A., Kelesidis, K. M., Mertzanos, G.A., and Petropoulos, B. 2009, *Adv. Space Res*., **43**, 253. .
88. Mavromichalaki, H., Papaioannou, A., Mariatos, G., Papailiou, M., Belov, A., Eroshenko, E., Yanke, V., and Stassinopoulos, E.G. 2007, IEEE TNS, 54, 1089.
89. Desorgher, L. 2004, http://reat.space.qinetiq.com/septimess/magcos/.
90. Shea, M.A., and Smart, G.F. 2000, *Space Sci. Rev*., **93**, 187.
91. Bentley, B. 2006, Summer School Lecture at the ICTP.