Cosmic Ray Radiation Effects on Space Environment Associated to Intense Solar and Geomagnetic Activity

H. Mavromichalaki, A. Papaioannou, G. Mariatos, M. Papailiou, A. Belov, E. Eroshenko, V. Yanke, and E. G. Stassinopoulos

***Abstract*—Intense cosmic ray fluxes during Forbush decreases can be responsible for a number of radiation effects in electronics and sensor systems of spacecrafts and aircrafts. Monitoring, modeling and possible prediction, from the real-time database of the Athens Neutron Monitor Data Processing (ANMODAP) Center are being considered. A different kind of cosmic ray events that evolves during a Forbush decrease, as an additional intermediate enhancement and its impact on electronic systems, is also identified.**

***Index Terms*—Cosmic rays, extraterrestrial phenomena, solar radiation, Space weather.**

I. Introduction

As it is known, the radiation environment research cover a wide range of subjects due to the fact that radiation exists throughout the universe, originating from many sources with varying intensities and composition. The 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 galactic cosmic ray (GCR) particles and particles from solar events, such as solar flares (SF) and coronal mass ejections (CMEs). This work is focusing on the impact of GCR on the microelectronics systems of spacecrafts and aircrafts. A complete description of related radiation environments can be found in [1]–[3].

The Earth's magnetosphere is bombarded by a nearly isotropic flux of cosmic rays. The penetration of these very energetic charged particles into the solar system, to the vicinity of the Earth is influenced and modulated by the conditions on the Sun, during the active and quiet phases of the solar cycle. In addition, during the years of solar maximum, the sun is a recurrent source of lower energy particles, accelerated during certain SFs and CMEs. 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/amu and, within the magnetosphere, are more numerous on high inclination and/or high altitude orbits. Occasionally, rare solar events produce particles of several GeV in energy which are able to reach equatorial latitudes [4].

The Earth's atmosphere operates as a natural shield, preventing most cosmic rays from reaching its surface. Specifically, when primary cosmic rays reach the atmosphere, they interact with its constituents, nitrogen and oxygen, generating a cascade of secondary particles. On satellites orbiting outside the magnetosphere, similar interactions of cosmic rays with the spacecraft materials complicate shielding evaluations, due to the generation of multiple daughter products. Similarly, incident electrons produce penetrating X-rays, or bremsstrahlung, as they scatter and slow down, interacting with the spacecraft materials.

Up to now, a list of extreme cosmic ray events harmful to spacecraft, recorded by Earth-based observatories such as neutron monitors (NMs), included events known as ground-level enhancements (GLEs) and Forbush decreases (FDs). In this work, a different kind of extreme event is being analyzed, which evolves during Forbush decreases as an intermediate cosmic ray enhancement (ICRE), that was recently recorded by the neutron monitors network of the Athens University, Athens, Greece.

II. Cosmic Ray Effects on Spacecraft and Aircraft

The GCR population is continuously present, consisting of ions from all elements of the periodic table. The levels of GCR are modulated by the 11-year solar cycle with the peak of the GCRs population occurring near solar minimum. Superimposed on the GCR levels are unexpected sudden rises in the flux levels due to solar energetic particle (SEP) events. Galactic and solar particles have unimpeded access to spacecraft outside the magnetosphere. Those particles that penetrate into the Earth's magnetosphere, reach near-Earth orbiting spacecraft and are particularly hazardous to satellites in polar, highly elliptical and geostationary (GEO) orbits [5].

Hazards to Space systems from cosmic ray particles include the following:

a) radiation damage to spacecraft electronics, solar cells, and materials, from the Earth's trapped radiation belt particles and from solar and galactic energetic particles;
b) single event effects (SEEs) in spacecraft electronics, due to ionization from galactic cosmic rays or solar energetic particles, or due to ionization from secondaries produced from nuclear interactions between the incident heavy ions and the component materials;
c) interference to spacecraft imaging and sensing systems;

Manuscript received October 6, 2006; revised April 4, 2007. This work was supported in part by Greek grand PYTHAGORAS II which is funded by European Social Funds and National Resources.

H. Mavromichalaki, A. Papaioannou, G. Mariatos, and M. Papailiou are with the Nuclear and Particle Physics Section, Department of Physics, National and Kapodistrian University of Athens, Greece (e-mail: emavromi@phys.uoa.gr; atpapaio@phys.uoa.gr; gmphysics@yahoo.com; mpapahl@phys.uoa.gr).

A. Belov, E. Eroshenko, and V. Yanke are with the Institute of Terrestrial Magnetism Ionosphere and Radio wave Propagation (IZMIRAN) 142092, Troitsk, Moscow Region, Russia (e-mail: abelov@izmiran.rssi.ru; erosh@izmiran.ru; yanke@izmiran.rssi.ru)

E. G. Stassinopoulos is with the Radiation Physics Office, Code 561, Applied Engineering and Technology Directorate NASA/Goddard Space Flight Center, Greenbelt, MD 20771 USA (e-mail: estassin@pop100.gsf.nasa.gov).

Digital Object Identifier 10.1109/TNS.2007.897401

0018-9499/$25.00 © 2007 IEEE

d) electrostatic charging from "hot" (∼ keV electron temperatures) plasmas and energetic (∼ MeV) electrons [6].

For humans, 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. More recently, a comprehensive database, using aircraft measurements made by a low-LET-radiation spectrometer to enable a mapping of doses and linear-energy transfer spectra at aviation latitudes was used to generate a detailed description of the cosmic ray induced particle environment and determine the effects from long- and short-term variations [7]. Spurny *et al.* [8] with similar equipment on board of Czech Airlines for a time period of one year (2001) were able to register the solar cosmic ray event GLE60 on April 15, as well as the Forbush decreases on April 12 and November 6, respectively. Experimental studies on air crew exposure to radiation permit the exact estimation of the level of exposure to the galactic cosmic ray component. The results of all previous studies demonstrated quantitative and qualitative influence of cosmic ray events on the radiation situation close to the Earth's surface.

Regarding effects on electronic systems, a paper by Silberberg *et al.*. [9], presented methods for calculating the single events upset (SEU) rate, arising from the secondary neutrons generated by the interactions of cosmic rays with the atmosphere. This work demonstrated the importance of ions at an altitude of greater then about 65 000 feet, although SEUs from neutron interactions dominate lower altitudes. Finally, it was also predicted that SEUs would increase during solar particle events.

From the above it is clear that the estimation of a probability rate, regarding satellite and aviation anomalies, must follow a specific direction. First of all, a global monitoring of all parameters relating to Space and Earth weather must be established. Especially, a search for specific criteria linking anomalies to universal characteristics of the Space and Earth weather is crucial in order to construct models suitable for prediction.

Apart from satellite measurements, a useful tool for this purpose is NMs, because of the fact that they are cost effective, are reliable registration systems that hold complete time series of counts for more than fifty years, and cannot be scrambled by any intense event [10].

III. Athens Neutron Monitor Data Processing Center

In response to the above, and considering the fact that solar relativistic particles, recorded on Earth, provide information on solar and interplanetary conditions much earlier than lower mid-energy particles, a data processing center was established at the Athens neutron monitor station since 2004 (Athens Neutron Monitor Data Processing Center—ANMODAP Center). This center provides real time monitoring of cosmic ray variations and it has been created with the purpose to make feasible the use of the neutron monitor network data in real time for Space weather tasks. The Athens center in synchronization with other centers (IZMIRAN, Bartol University), gathers data to detect possible abrupt changes in the cosmic rays, associated with real solar wind and geomagnetic disturbances.

The physical idea is that early detection of an Earth-directed proton event by NMs offers the opportunity for preventive prognosis of dangerous particle fluxes and can provide an alert with low probability of false alarm. The network of neutron monitors is a unified multidirectional spectrograph/detector characterized by considerable accuracy, providing an important tool of forecasting the arrival of interplanetary disturbances at the Earth [11].

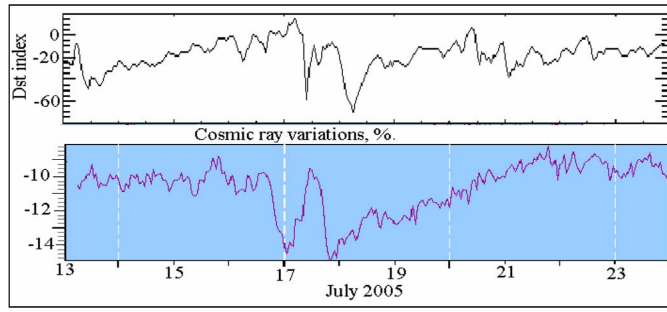


Fig. 1. Dst variations related to cosmic ray counting rate from Athens neutron monitor station in July 2005

The Athens Center provides reliable data using independent programs for simultaneous data collection from twenty-three different stations in a periodic scheme, with a specific time period determined automatically or even manually. This process is a feasible and statistically proven method, using total counts from several stations in real time together with satellite data from the Advanced Composition Explorer (ACE) and the Geostationary Operational Environmental Satellites (GOES) [12].

IV. New Category of Events

Following a powerful CME or a SF, short period disturbances with a significant large range of change of solar wind velocity and of the interplanetary magnetic field (IMF) strength, are usually observed. The variations of the IMF are accompanied by short decreases of the GCRs, the so-called FDs [13].

Whenever an intense and/or an unusual decrease or increase in cosmic rays is recorded, it is essential to analyse the background of the event regarding solar and geomagnetic activity as well as cosmic ray activity and anisotropy [14].

It is clear that a solar blasting event, as a SF or a CME produce significant variations in cosmic ray (CR) intensity. Over the years, a lot of attempts [15]–[17] have been made in order to establish specific criteria on the impact of these phenomena to CR modulation. As a result, it is commonly pointed out that solar extreme events influence CR in a dynamic way.

A. *July 2005 Effect*

An analysis of the solar and interplanetary background has been made for the mid-July 2005. It is characteristic that within one week (July 11–18), solar activity ranged from low to very active. During that time, the number of sunspots decreased until a blank Sun was observed on July 17.

On July 16, an intensive Forbush decrease of cosmic rays was observed by the majority of the neutron monitors worldwide. Right after the main phase of the FD, a sharp enhancement of cosmic ray intensity occurred and was followed by a second decrease, within less than 12 h (Fig. 1). The peculiarity of this event owes to the fact that it does not comprise a ground-level

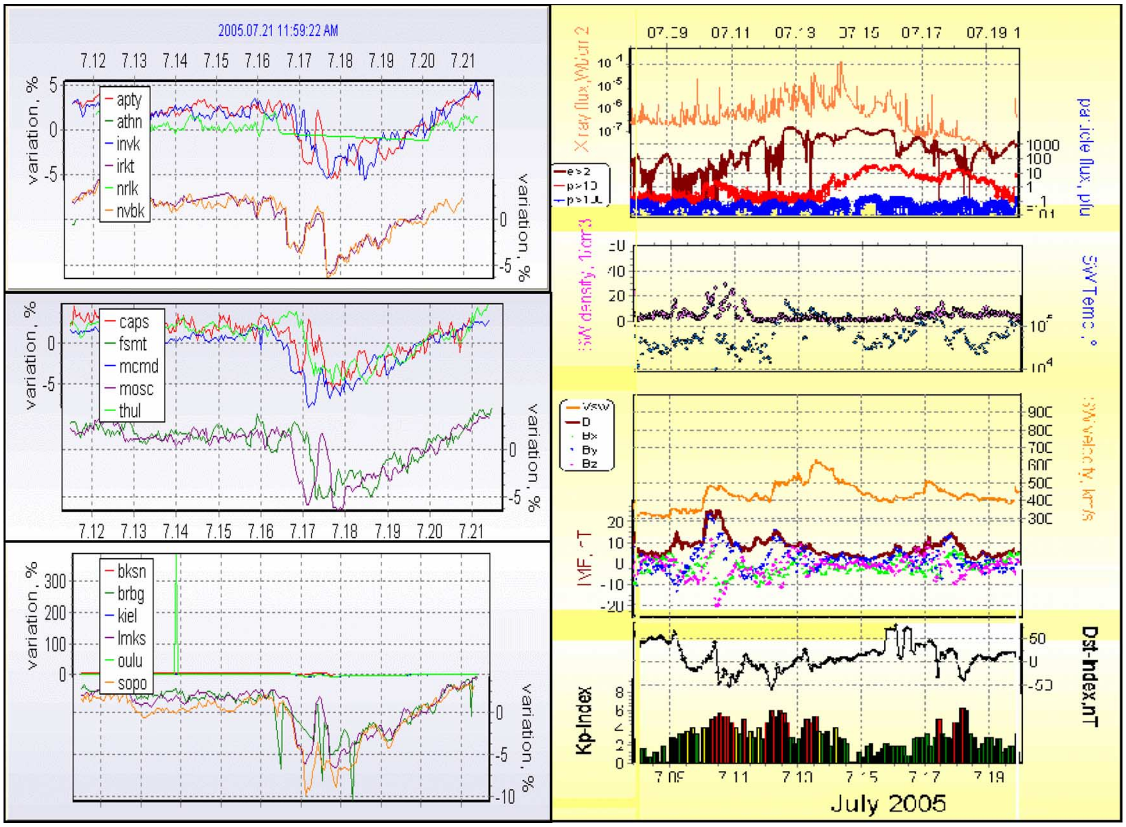


Fig. 2. Neutron monitor data from all real time stations and satellite data from GOES and ACE.

enhancement of solar cosmic rays neither a geomagnetic effect in cosmic rays. Therefore, the July 2005 event can be categorized into a different group of intermediate cosmic ray enhancements (ICRE) events, within an FD.

B. Results From ANMODAP Center (http://cosray.phys.uoa.gr)

The galactic CR density started to drop from July 10 and by July 16 had decreased by $\sim 2\%$, after a series of relatively weak Forbush effects. Most dramatic events occurred on the sixteenth of the month, when in only a few hours the FD reached 8% at several stations. The CR intensity recovered rapidly up to the starting level, but in the middle of the next day, a sharp decrease occurred once again and reached the same 8% at many stations, only to be followed by the classical FE profile. On July 16, the ANMODAP Center received data of a Forbush decrease from 23 neutron monitors in real time around the globe (6% variation in Athens). (See Fig. 2.) The decrease was the result of the solar and geomagnetic activity that has already been described and had a significant signature at almost all stations despite their geographical position.

The Onset program of the ANMODAP Center can determine whether or not the enhancement which was recorded on the 17th of July was a Ground Level event (GLE) or a geomagnetic disturbance [19].

This algorithm makes use of hourly cosmic ray data and although it spotted the sudden enhancement, it responded that this was more gradual, in no case sudden and without an increase in the X-ray or particle channels from GOES. The outcome of the Onset process indicated that it was neither a GLE nor a geomagnetic disturbance. The geomagnetic activity remained in low levels ($\mathrm{Dst} < 80$ nT) and as a result, the enhancement did not present typical characteristics of a GLE.

This series of events appears to be caused by some special structure of interplanetary disturbances in the inner heliosphere. At that time period, Earth crossed the periphery of a giant Forbush effect which originated in the western part of the heliosphere and was correlated to the SF on the July 14, 2005.

Nevertheless, the event was also characterized by unusually high anisotropy of cosmic rays ($\sim$ 7–8%), especially of the equatorial component, with a direction to the western source of this anisotropy.

C. Cosmic Ray Anisotropy Variations

The structure of the evolution of interplanetary disturbances is dominated by anisotropy in a rather complicated way, unlike the flux. The use of the first order anisotropy extends the capabilities to diagnose solar wind structure, although often this is not enough to reach a conclusion about the structure of a disturbance and predict its development.

In order to obtain the variations in the flux and the first harmonic of anisotropy for 10 GV cosmic rays, data from as many stations as possible from the entire global network of neutron monitors (40–45 stations, with their own properties: coupling coefficients and yield functions) should be used.

The calculation of anisotropy components is being performed by the Global Survey Method (GSM) [21]. Fig. 3 illustrates the

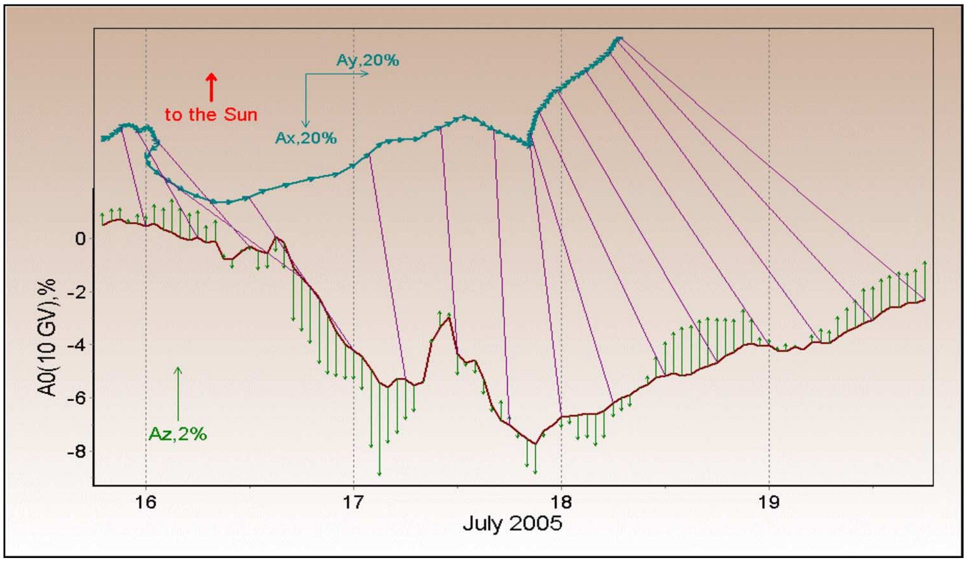


Fig. 3. Variation of 10 GV cosmic ray density and the equatorial first order anisotropy during the unique events of July 2005. The north–south anisotropy is presented by vertical arrows along density curve.

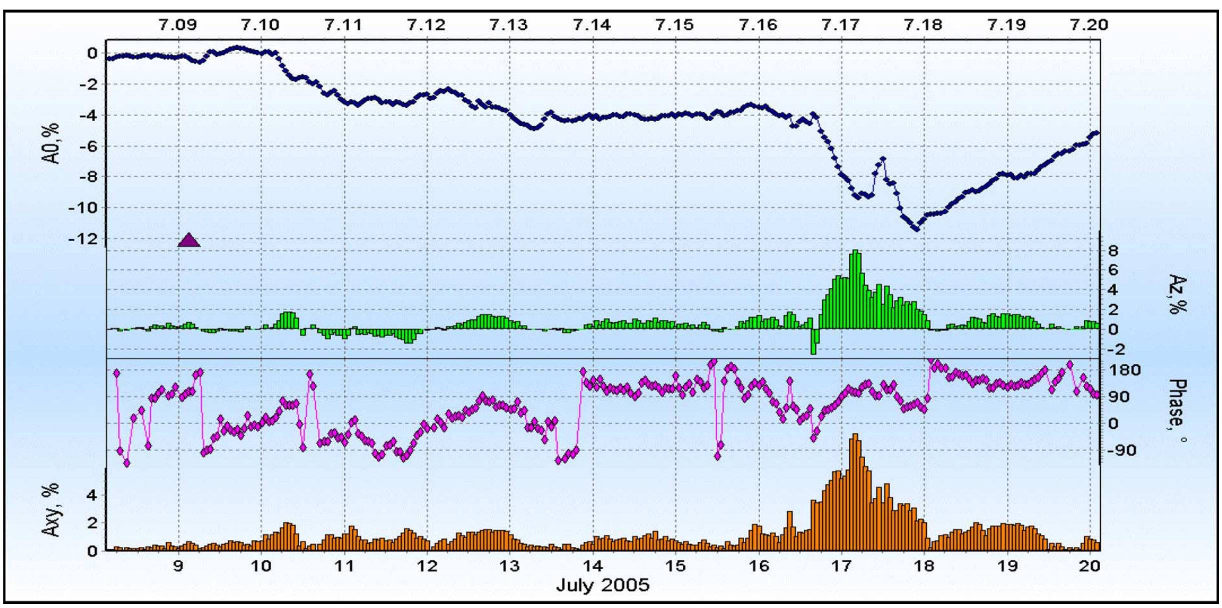


Fig. 4. Behavior of CR density AO (solid line), North–South (Az), and ecliptic components (Axy) of CR anisotropy derived by GSM method from the data of world wide NM network.

north–south component of the anisotropy Az as a series of vertical lines originating from the plot of CR flux as a function of time. The equatorial component of the anisotropy: $A_E = \mathrm{sqr}(A^2x + A^2y)$ is presented by a series of head-to-tail vectors. Thin lines establish time correspondence of the vector and CR density diagram.

As can be observed in Figs. 3 and 4, the anisotropy vector Az increases significantly within the declining phase of the FD on July, and changes its direction in the mid of July 17. This increase of the amplitude and the direction change are typical responses of the first order anisotropy to a shock. A_E is constantly changing its direction and increases, especially during the second FD which followed the sharp enhancement of the mid 17th of the month. Az changes sign from positive to negative throughout this disturbed period [22].

The big equatorial component of CR anisotropy at this time is evidence of an intensive inflow of particle flux from the eastern direction that provided fast recovery of the FD.

All anisotropy components reveal sharp and big changes that occurred on the background of a more or less quiescent interplanetary and geomagnetic condition.

V. Particle Fluxes

It is clear that the Space environment is very complex. Therefore, the analysis of every component of this environment can contribute to the clarification of dangers for Space systems.

Particles trapped in the near-Earth environment include energetic protons, electrons, and heavy ions. The transient radiation consists of GCR particles and particles from solar extreme events as CMEs and SFs. It should be noted that in comparison to major solar events, CRs have low level fluxes.

Protons are especially problematic for spacecraft and avionics due to their high energies and notably penetrating power. For some electronic parts, SEEs induced by protons are also a hazard, while finally protons also contribute to the displacement damage.

Low energy electrons are the cause of electrostatic discharging which can be a serious problem for spacecraft in higher altitude orbits (e.g., GEO) where they are exposed to more intense electron populations. High energy electrons can penetrate into the spacecraft and lead to discharges, causing damage to electronics.

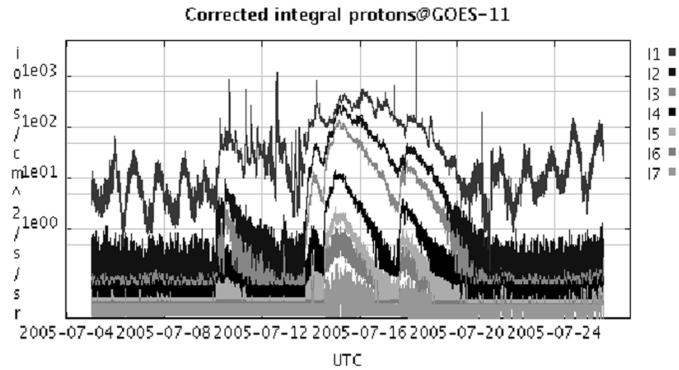
Regarding the effect of July 2005, a slow, gradual rise in the greater then 10 MeV proton flux, followed the M5 SF which had evolved on the fourteenth of the month. The 10 pfu alert threshold was reached the next day, when a large influx of high energy protons followed the X1.2 SF of the previous day. Finally, on July 15, the greater then 10 MeV proton flux presented a peak of 134 pfu, which refers to an S2 moderate magnetic storm [18], and regarding satellite operations it is the cause of infrequent single-event upsets. Nevertheless, the greater then 2 MeV electron flux at geosynchronous orbit was also at high levels.

After the peak, the greater then 10 MeV proton flux dropped, until July 17, when a significant back-sided full halo CME provided an injection of flux, allowing the event to remain in-progress. Eventually, this proton flux began to fail on the eighteenth of the month and ended a few days later, as can be seen by Fig. 5(a) and (b) [23].

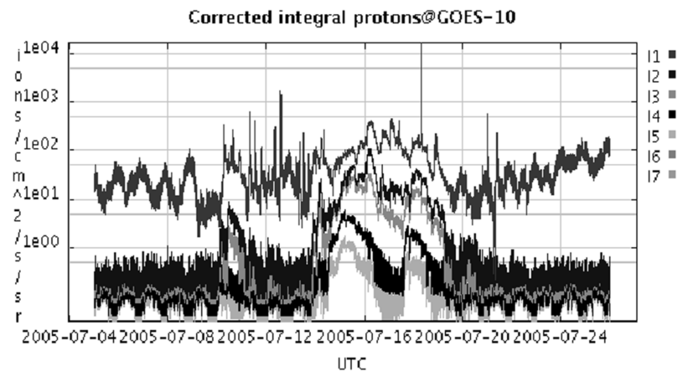
This proton flux, however, may be characterized as moderate. The importance of it lies at the fact that there was no possible indication of such flux from solar or geomagnetic sources. At that time period (July 2005), the Sun had been spotless for a number of days and the interplanetary magnetic field did not induce any notable shifts. The main reason of this flux was the solar activity from July 14 and the long duration of it owes to the back sided full halo CME that registered on July 17.

A. *Cosmic Ray Forbush Effects and Interplanetary Enhancements*

Forbush effects occur when the sun releases an exceptionally large burst of matter and magnetic disturbance. These disturbances typically travel at a speed of 400–1000 km/s, and take two to four days to travel from the sun to the earth. Cosmic ray intensity dips within a few hours, and then slowly recovers over the next few days. Cosmic ray spectral variations during a Forbush decrease are an open research field of scientific interest. Within years of study a lot of researchers concluded that each event is unique and must be treated accordingly. A lot of cases include events where an intermediate increase of cosmic rays has been recorded during a FD. The differences among scientists lies in the explanation of this increase, which in specific cases it is thought to be the result of a magnetic cloud structure or even the result of a shock arrival at Earth [24]. Whatever the case maybe, situations where an increase of CR is intermediate



(a)



(b)

Fig. 5. (a) Proton fluxes from GOES 10 for the July 2005; credit: SPIDR. (b) Proton fluxes from GOES-11 for the July 2005; credit: SPIDR.

within a FD, are common and the special characteristics of each event will categorize these into sub-categories of this significant kind of events. In this work an attempt has been made in order to identify a significant ICRE event (July 2005) within a FD, and its impact on systems.

B. *July 1959 Effect*

An event similar to the July 2005 one was recorded by neutron monitors in July 1959. This latter period was one of the most remarkable in the history of cosmic rays as a lot of strong solar events took place, modulating interplanetary Space and resulting in notable variations at the intensity of CR, which were registered as series of intense Forbush effects.

Specifically, as is illustrated in Fig. 6, a series of FDs of the GCR initiated on July 11, 1959 when a decrease of about 6% was registered. At that time, the Kp index was 7 and an interplanetary shock reached the Earth. Subsequently, another FD of about 12% recorded on the fifteenth of the month. The decrease lasted almost 12 h and within that time Dst index fell close to -380 nT, while Kp reached value 9. Both indexes provided strong evidence of a geomagnetic storm. Right after the main phase of the decrease, identically to the July 2005 event, an increase of CR was registered. This increase was very sharp, lasted a little less then 48 h and pushed CR back to baseline level. Finally, on July 17, 1959 another strong FD was recorded with amplitude of almost 10%. After this decrease, CR entered into the typical recovery phase. The increase of this situation is due to a geomagnetic effect which evolved at that time.

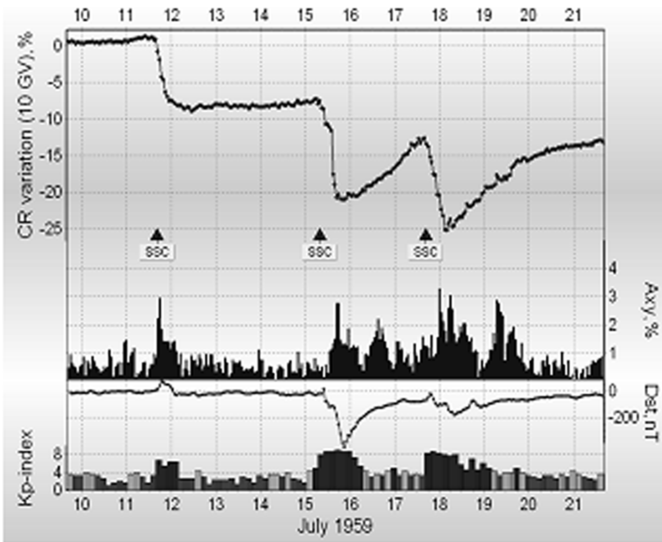


Fig. 6. Remarkable series of Forbush effects that was recorded in July 1959.

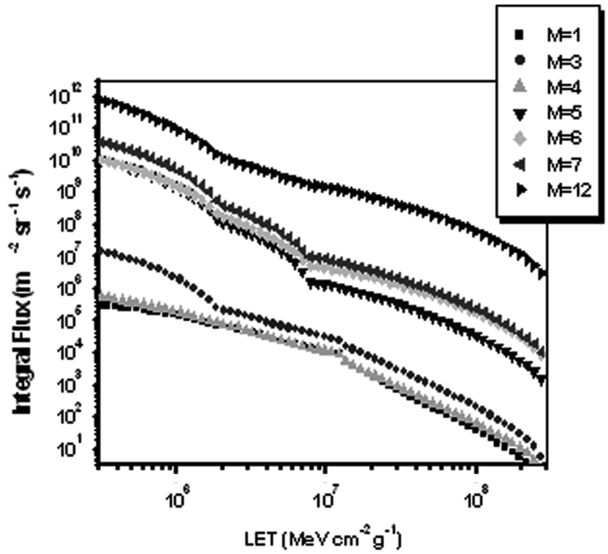


Fig. 7. LET spectrum for the case $M = 1, M = 3, M = 4, M = 5, M = 6, M = 7$, and $M = 12$; credit SPENVIS.

TABLE I
SEU Rates for Different Space Situations

SITUATION	TOTAL SEU RATE (bit^{-1} s^{-1})
M=1	5.3764E-07
M=3	1.3344E-06
M=4	5.3765E-07
M=5	2.2544E-05
M=6	2.2594E-05
M=7	1.3251E-04
M=12	1.4714E-02

Both cases presented almost the same CR features, although evolved at different background situations. As has been pointed out already, the recent event of July 2005 was one of the most difficult to identify because of the fact that there was no prior indication. In contrast, the July 1959 was a severe event with a lot of precursors, as Kp and Dst indices, three registered shocks, and the preceding intense solar activity that portend the extreme event that would follow, as it was finally registered by NMs.

VI. Computer Codes Regarding GCR

The need for understanding the GCR environment was identified early. Especially, when GCRs where held responsible for causing SEEs on spacecraft, the microelectronics community benefited of the work held in the GCR research field. A GCR model predicts flux spectra for all the elements of the periodic table that exist in the GCRs, from Hydrogen to Uranium and for energies varying through 1 to 10 000 MeV/amu. The flux spectra are converted into linear energy transfer (LET) spectra, which are a crucial metric to understand the level of Space environment hazards to microelectronics, as well as, the important key step in order to calculate SEUs [25].

At low-threshold LET devices, GCRs dominate the SEU rates, while in high-threshold LET devices, the anomalous cosmic rays (ACR)—identified as "bumps" in the spectra of certain elements (He, N, O and Ne) at 10 MeV/n [26]—have the leading role on SEU occurrence.

Specifically, ACRs are the dominant part of the LET environment in low-Earth orbits. The reason is that ACR are singly-ionized ions, at least at low energies. This low charge state gives ACRs tremendously enhanced access to low-Earth orbits to which fully stripped GCRs of the same energy are forbidden [26].

Considering solar particle events, those are the main aspect of near-Earth ionization hazard. As it is now known, the high energy long duration particle events—which are important for spacecraft design—are caused by shocks, driven by fast CMEs [27].

The analysis of the complex Space environment and its impact on Space systems led to the development 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 [26], [28], which also lies inside the Space Environment Information System (SPENVIS) interlink, developed by ESA [29]. Both are provided by user-friendly interfaces and can be used via the Internet [29], [30].

An example of using SPENVIS's interface utility, calculations have been performed for LET spectra to represent the Space environment, and for SEU rates, for a GEO orbit for the interval from the July 14–18, 2005, considering the cases of GCR ($M = 1$), 90% worst case cosmic ray level ($M = 3$), GCR and singly ionized anomalous component ($M = 4$), ordinary flare flux and mean composition ($M = 5$), ordinary flare flux and worst case composition ($M = 6$), 10% worst case flare flux and mean composition ($M = 7$) and worst case flare flux and worst case composition ($M = 12$), as can be seen in Fig. 7 and at Table I, respectively.

In order to calculate the SEU rate for each case, a device with dimensions of 5.0 by 5.0 by 5.0 with a critical charge of 0.1 pC is assumed. Table I represents the total SEU rates regarding both direct ionization and proton nuclear interaction effects.

Taking into account the background situation of the July 2005 effect, it can be categorized as an $M = 5$ of the code. From the calculations of SEUs for a GEO orbit for all the above cases it can be seen in Table I that the flux of the July 2005 event was not extensively strong, but as it was pointed out in this analysis, it was difficult to identify an event in that time frame, potentially very hazardous for electronic systems.

It should be noted that the current GCR model is quite acceptable because it predicts the GCR levels over the entire solar cycle within $\pm 15\%$ –25% [25]. Although this code cannot predict a harmful particle flux it is available to simulate possible changes and therefore useful for the evaluation of satellite and aircraft electronics response to heavy ion particle fluxes.

VII. Conclusion

Basic research provides the required definitions for the understanding of radiation effects and for the development of models useful for designing radiation hardened systems. Due to the increasing sensitivity of microelectronics to radiation and the increasing complexity of spacecraft systems, it is more difficult to completely avoid the risk of radiation effects on a system. The goal is to reduce such risk, and the only way to do so is by monitoring every parameter of the radiation environment.

Regarding CR, foreknowledge of CR intensity, energy and composition is a challenge and it is further complicated by the influence of geomagnetic disturbances on their penetration into the magnetosphere, as it was remarked in this analysis.

Intense and short duration events in CR intensity, as those of July 2005 and July 1959, where an intermediate increase of CR occurs during a FD, resulting from special interplanetary conditions, consist a different kind of events, important for Space weather forecasting and with possible radiation effects on Space systems. For the first time an attempt has been made to address a suitable ICRE event category and to define the corresponding features for this different kind of event which will be very helpful for their future identification and their statistical processing. It is clear that in order to be led into preventive prognosis the only approach is by real time monitoring of all dangerous Space weather phenomena.

The physical aspect of the July 2005 effect provides an explanation such as: the cosmic ray intensity behavior on July 16–17 was the result of special interplanetary conditions that evolved at this time. In particular, the CR recorded behavior is the result of the crossing by Earth of a complicated structure from the periphery area of the giant Forbush effect which developed in the western part of the inner heliosphere after the full halo CME released on July 14.

With reference to CR anisotropy, the big equatorial component of CR anisotropy observed at the same time is evidence of an east-opened structure which caused an intensive inflow of particle flux from the eastern direction that provided fast recovery of the FD just after the minimum.

The computer simulation from the SPENVIS interface, pointed out that this was a moderate flux, capable of providing only a minor threat to microelectronic systems in a GEO orbit. And as it was mentioned, SEUs do increase during solar particle events (SEPs), according to the results presented in Table I.

In conclusion it should be pointed out that the ANMODAP Center of the Athens University successfully processed the irregular FD data from twenty three NM stations, together with the satellite data of that time. A further investigation on situations like the July 2005 effect is needed in order to extract solid answers for this category of cosmic ray events, beyond GLEs and classical Forbush decreases.

In summary, the variability of conditions in Space makes an accurate prediction of anomalies in technological systems rather difficult. The need to address that problem, is the primary justification for a strong active program in Space weather modeling, monitoring and prediction with a view to ensure long-life and cost effective systems in Space.

Acknowledgment

The authors are thankful to all collaborations providing continued ground-level monitoring of the cosmic rays, and to all researchers providing the data of satellite measurements via the Internet.

References

[1] E. G. Stassinopoulos, "Microelectronics for the natural radiation environments of Space, chapter I: Radiation environments of Space," presented at the 1990 IEEE NSREC Short Course, Reno, NV, 1990.

[2] J. L. Barth, "Applying computer simulation tools to radiation effects problems, Section II: Modelling Space radiation environments," presented at the 1997 IEEE NSREC Short Course, Snowmass Village, CO, 1997.

[3] C. S. Dyer, "Radiation effects in the new millennium—Old realities and new issues, Section II: Space radiation environment dosimetry," presented at the 1998 IEEE NSREC Short Course, Newport Beach, CA, 1998.

[4] C. S. Dyer and D. J. Rodgers, "Effects on spacecraft and aircraft electronics," in *Proc. ESA WPP-155*, 1998 [Online]. Available: http://esa-spaceweather.net/spweather/workshops/proceedings_w1/proceedings_w1.html

[5] J. L. Barth, C. S. Dyer, and E. G. Stassinopoulos, "Space atmospheric and terrestrial radiation environments," *IEEE Trans. Nucl. Sci.*, vol. 50, no. 3, pp. 466–482, 2003.

[6] E. J. Daly, I. Daglis, Ed., "Outlook on Space weather effects on spacecrafts," *NATO Science Series: Effects of Space Weather on Technology Infrastructure*, vol. 176, pp. 91–108, 2004, Kluwer.

[7] E. G. Stassinopoulos, C. Stauffer, and G. Brucker:, "A systematic global mapping of the radiation field at aviation altitudes," *Space Weather*, vol. 1, pp. 13–21, 2003.

[8] F. Spurny, K. Kudela, and T. Dashev, "Airplane radiation dose decrease during a strong Forbush decrease," *Space Weather 2*, p. S05001, 2004.

[9] R. Silberberg, C. H. Tsao, and J. R. Letaw, "Neutron generated single event upsets," *IEEE Trans. Nucl. Sci.*, vol. 31, pp. 1183–1185, 1984.

[10] C. J. Dyer, F. Lei, A. Hands, and P. Truscott, "Solar particle events in the qinetiq atmospheric radiation model," in *Proc. RADECS 2006 Workshop* [Online]. Available: http://www.radecs2006workshop.gr

[11] H. Mavromichalaki, G. Souvatzoglou, C. Sarlanis, G. Mariatos, M. Gerontidou, A. Papaioannou, C. Plainaki, S. Tatsis, A. Belov, E. Eroshenko, and V. Yanke:, "The new Athens centre on data processing from the neutron monitor network in real time," *Annales Geophys.*, vol. 23, pp. 1–8, 2005.

[12] H. Mavromichalaki, M. Gerontidou, G. Mariatos, C. Plainaki, A. Papaioannou, C. Sarlanis, G. Souvatzoglou, A. Belov., E. Eroshenko, V. Yanke, and S. Tsitomeneas, "Space weather forecasting at the new Athens center: The recent events of January 2005," *IEEE Trans. Nucl. Sci.*, vol. 52, no. 6, pp. 2307–2312, 2005.

[13] A. Wawrzynczak and M. V. Alania, "Peculiarities of galactic cosmic ray Forbush effects during October–November 2003," *Adv. Space Res.*, vol. 35, pp. 682–686, 2005.

[14] A. Belov., E. Eroshenko, V. Oleneva, A. Struminsky, and V. Yanke, "What determines the magnitude of Forbush decreases?," *Adv. Space Res.*, vol. 27, pp. 625–630, 2001.

[15] H. Cane, "Coronal mass ejections and Forbush decreases," *Space Science Rev.*, vol. 93, pp. 55–77, 2000.

[16] R. Harrison, "The nature of solar-flares associated with coronal mass ejection," *Astron. @ Astrophys*, vol. 304, pp. 585–594, 1995.

[17] J. Hundhausen, , K. T. Strong, J. L. Saba, B. H. Haisch, and J. T. Schmelz, Eds., "Coronal mass Ejections," in *The Many Faces of the Sun: A Summary of the Results From NASA's Solar Maximum Mission*. New York: Springer, 1999, p. 143.

[18] *NOAA*, [Online]. Available: http://noaa.gov

[19] G. Mariatos, G. Souvatzoglou, C. Sarlanis, and H. Mavromichalaki, "Alert systems for ground level cosmic ray enhancements prediction at the Athens neutron monitor network in real time," *J. Mod. Phys. A*, vol. 20, pp. 6711–6714, 2005.

[20] P. N. Mayaud, "Derivation, meaning and use of Geomagnetic indices," in *Geophysical Monograph*. Washington, DC: Amer. Geophysical Union, 1980, p. 22.

[21] J. Chen and W. Bieber, "Cosmic ray anisotropies and gradients in three dimensions," *Astrophys. J.*, vol. 405, pp. 375–389, 1993.

[22] A. Belov, L. Baisultanova L., E. Eroshenko, H. Mavromichalaki, V. Yanke, V. Pchelkin, C. Plainaki, and G. Mariatos, "Magnetospheric effects in cosmic rays during the uniquemagnetic storm on November 2003," *J. Geophys. Res.—Space Phys.*, vol. 110, no. 9, p. A09S20, 2005.

[23] *SPIDR*, [Online]. Available: http://spidr.ngdc.noaa.gov/spidr/index.jsp

[24] M. Hofer and E. O. Flueckiger:, "Cosmic ray spectral variations and anisotropy near earth during the March 24, 1991 Forbush decrease," *J. Geophys. Res.*, vol. 105, no. A10, pp. 23085–23097, 2000.

[25] J. L. Barth, I. Daglis, Ed., "Prevention of spacecraft anomalies—The role of Space climate and Space weather models," *NATO Science Series: Effects of Space Weather on Technology Infrastructure*, vol. 176, pp. 123–145, 2004, Kluwer.

[26] A. J. Tylka, J. H. Adams Jr., P. R. Boberg, B. Brownstein, W. F. Dietrich, E. O. Flueckiger, E. L. Petersen, M. A. Shea, D. F. Smart, and E. C. Smith, "CREME96: A revision of the cosmic ray effects on microelectronics," *IEEE Trans. Nucl. Sci.*, vol. 44, no. 6, pp. 2150–2160, 1997.

[27] J. T. Gosling, "The solar flare myth," *J. Geophys. Res.*, vol. 99, p. 4259, 1994.

[28] J. H. Adams Jr., R. Silberberg, and C. H. Tsao, "Cosmic ray effects on microelectronics, Part I: The near-earth particle environment," *NRL Memo. Rep.*, p. 4506, 1981.

[29] *SPENVIS*, [Online]. Available: http://spenvis.oma.be/spenvis

[30] *CREME*, [Online]. Available: http://crsp3.nrl.navy.mil/creme96