Cosmic ray radiation effects on space environment associated to intense solar and geomagnetic activity

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Abstract—**Intense cosmic ray fluxes recorded by Neutron Monitors Network during Forbush decreases can be responsible for a number of radiation effects in electronics and sensor systems of spacecrafts and aircrafts. Monitoring, modelling and prediction of them from the real-time Data basis of ANMODAP Center is considered**

Index Terms—**Cosmic Rays, Extraterrestrial Phenomena, Solar Radiation**

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 and with varying intensities. 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 radiation environments can be found in [1], [2].

The Earth's magnetosphere is sputtered by a nearly isotropic flux of energetic charged particles, the cosmic rays (CR). The penetration of these GCR into the vicinity of the Earth is influenced by conditions on the Sun. Specifically, in the years around solar maximum the sun is an additional recurrent source of lower energy particles accelerated during certain SF and CMEs [3].

Earth's atmosphere operates as natural shielding for its surface. At this sense, when primary CR reaches the atmosphere, interact with air nuclei to generate a cascade of secondary particles. Spacecraft shielding is complicated by the production of secondary products. For example, electrons produce penetrating X-radiation, or bremsstrahlung, as they scatter and slow on atomic nuclei.

Up to now, a list of extreme cosmic ray events harmful for spacecrafts 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 another kind of extreme events, which evolve during Forbush decreases and are recorded by the neutron monitors network is being localized.

II. COSMIC RAY EFFECTS ON SPACECRAFTS & AIRCRAFTS

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 [4].

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Space systems most dangerous effects due to cosmic ray particles include radiation damage, single event effects (SEE), interference to spacecraft imaging and sensing systems, electrostatic charging from 'hot' (~keV electron temperatures) plasmas and energetic (~MeV) electrons [5], [6].
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 is 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 during the 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 06, 2001. 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's surface.
From the above it is clear that the estimation of probability rate regarding satellite and aviation anomalies must follow a specific pathway. A global monitoring of all parameters referring to Space and Earth Weather must be established, with a view to extract specific criteria between anomalies and universal characteristics which are crucial in order to construct models suitable for prediction.
Apart from satellite measurements, a useful tool that will suit these necessities is NMs, because of the fact that those are cost effective, reliable registration systems that hold complete time series of counts for more than fifty years and can not be scrambled by any intense event [9].

III. ATHENS NEUTRON MONITOR DATA PROCESSING CENTER

Taking into account the above suggestions, as well as the fact that solar relativistic particles which are registered at Earth have the property to carry information on solar and interplanetary conditions much earlier than low and mid energy particles – which are harmful for spacecrafts and aircrafts – a data processing center has been established in the Athens neutron monitor station since 2004 (Athens Neutron Monitor Data Processing Center - ANMODAP Center) which provides real an alert with low probability of false alarm. 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 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 [10].
The Athens centre provides reliable data using independent programs for simultaneous data collection from twenty-three different NM stations, in a periodic scheme with a specific time period determined automatically or even manually. A feasible and statistically proven method using total counts from several stations in real time together with satellite data from Advanced Composition Explorer (ACE) and Geostationary Operational Environmental Satellite (GOES) [11].

IV. A NEW CATEGORY OF EVENTS

Following a powerful CME or a SF, short period disturbances with a significant large range change of solar wind velocity and the strength of the interplanetary magnetic field (IMF) usually are observed. The variations of the IMF are accompanying by short decreases of the GCR, called Forbush decreases (FDs). It is commonly pointed out that, solar extreme events influence CR in a dynamic way [12].
Whenever an intense or/and 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 [13].

a. The July 2005 effect

An analysis of the solar and interplanetary background has been made for the events of the mid July 2005. It is characteristic that through one week's time (11th to 18th of July) solar activity ranged from low to very active. Sunspots number decreased until a blank Sun revealed on the 17th of July.
On the 16th of July, an intensive Forbush decrease of cosmic rays, 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 hours. The peculiarity of this event owes to the fact that it does not comprise a ground level enhancement of solar cosmic rays neither a geomagnetic effect in cosmic rays.

b. Results from ANMODAP Center (http://cosray.phys.uoa.gr)

Galactic CR density started to fail from the 10th of July and by the 16th, presented a decrease of ~2%, after a series of relatively weak Forbush effects. The most dramatic events occurred on 16th of the month, when FD reached 8% in several stations, only in a few hours. The CR intensity recovered rapidly up to the starting level, but in the mid of the next day a sharp decrease started again and reached the same 8% at many stations, followed by the classical FE profile. At the 16th of July the ANMODAP Center, recorded a Forbush decrease from 23 neutron monitors in real time around the globe (6% variation in Athens). The decrease was the result of the solar and geomagnetic activity that already has been

described and had a significant signature to almost all stations despite their geographical position.
The Onset program of ANMODAP Center 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 nor a GLE or a geomagnetic disturbance [13].

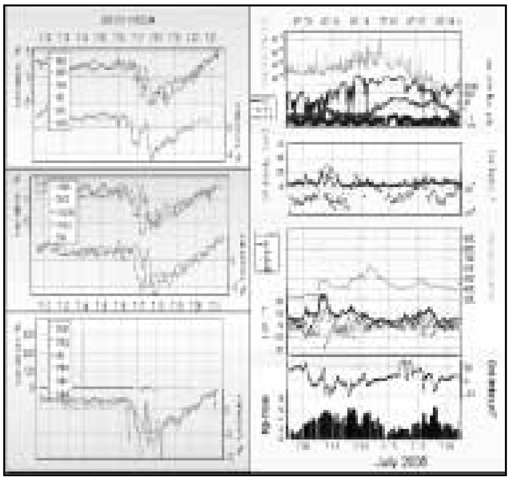

Fig. 1: Neutron Monitor data from all real time stations and satellite data from GOES and ACE

This series of events appears to be caused by some special structure of interplanetary disturbances in the inner heliosphere at that time period when the Earth crossed a periphery of a giant Forbush effect started in the western part of the heliosphere after the flare on 14th of July 2005.

c. *Cosmic Ray Anisotropy Variations*

The calculation of anisotropy components is being performed by Global Survey Method (GSM) using 40-45 NM stations from all over the world [15]. Fig.2 illustrates the north-south component of the anisotropy Az as a series of vertical lines

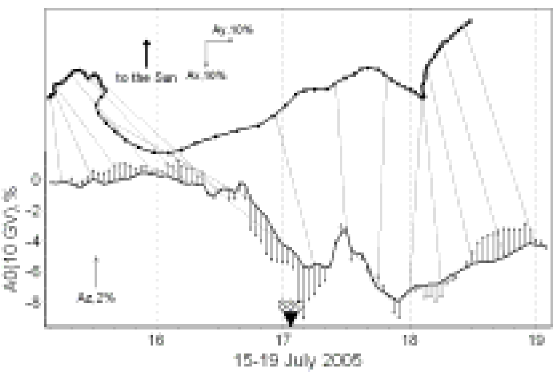

Fig.2: Variation of 10GV cosmic ray density and the equatorial first order anisotropy during the unique events of July 2005. The north-south anisotropy is presented by vertical arrows along density curve

originating from the plot of CR flux as a function of time. The equatorial component of the anisotropy: $A_E = \text{sqr}(A^2x + A^2y)$ is presented by a series of head to tail vectors. Thin lines establish time correspondence of the vector and CR density diagram.The anisotropy vector Az increases significantly within the declining phase the FD on the 16th to 17th of July and changes its direction in the mid of 17th of July. 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 [16].

V. PARTICLE FLUXES

Regarding the effect of July 2005, a slow, gradual rise in the greater then 10 MeV protons followed the M5 SF which was evolved on the 14th 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 the 15th of July, the greater then 10 MeV proton flux presented a peak of 134 pfu, which refers to an S2 moderate magnetic storm [17], and regarding satellite operations it is the cause of 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 underwent, until the 17th of July, where 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 18th of the month and ended a few days later.
This proton flux may be characterized as moderate however, the importance of it lies at the fact that there was no possible indication from solar or geomagnetic sources of such a flux. At this 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 the 14th of July and the long duration of it owes to the back sided full halo CME that registered on the 17th of the month.

VI. OCCURRENCE RATE

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 difference among scientists is the explanation of this increase, were in specific cases this increase is thought to be the result of a magnetic cloud structure or even the result of a shock arrival to the Earth [18]. Whatever the case maybe, situations where an increase of CR is intermediate within a FD are common and the special characteristics of each event will categorize these into sub-categories of this significant new kind of events.

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

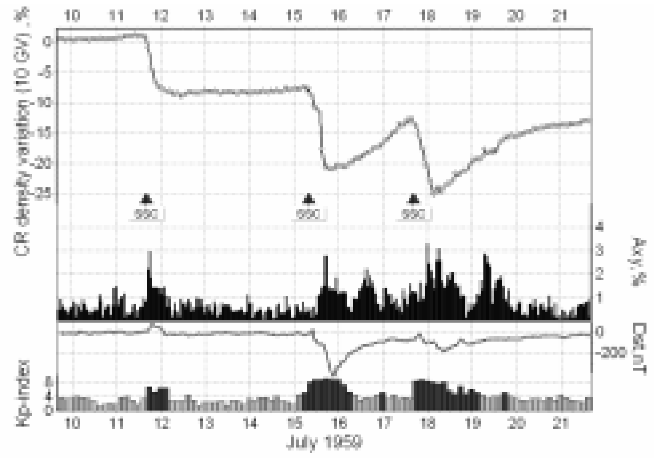

Fig.3: The series of the Forbush effects that were recorded in July 1959

VII. CONCLUSIONS

Basic research science provides the required definitions for the understanding of radiation effects and for the developing models useful for designing radiation hardened systems. 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 to 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, resulted by special interplanetary conditions, consist a new kind of events important for space weather forecasting and with possible radiation effects

The physical aspect of the July 2005 effect provides an explanation such as: the CR intensity behaviour on the 16^{th} - 17^{th} of July was 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 the 14^{th} of July. 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.

Finally, the ANMODAP Center, successfully recorded the irregular FD from 23 stations, as well as from satellite data of that time. Further investigation on situations - like the July 2005 effect - is needed in order to extract solid answers for this new category of events.

In a whole, the variability of conditions in Space makes an accurate prediction of anomalies in technological systems rather difficult. That is the primary justification of a strong need for an active program in Space Weather modelling, monitoring and prediction with a view to ensure long-life, cost effective systems in space.

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