GLEs as a Warning Tool for Radiation Effects on Electronics and Systems: A New Alert System Based on Real-Time Neutron Monitors

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***Abstract*—Ground level cosmic ray enhancements (GLEs) are the manifestations of short-time solar energetic particles radiation near the Earth causing damage to electronic devices carried on board the satellite platforms. A test alert system based on a real-time ground-level neutron monitor network is proposed in order to protect devices and electronics from space weather radiation effects.**

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

I. Introduction

UNEXPECTED bursts of solar activity producing solar energetic particle (SEP) events can cause major problems in the operation of space systems functioning in the near-Earth space [1]. The U.S. National Security Space Architect report on Space Weather referees that, during the last years, about one or two satellites per year have suffered either total or partial mission loss due to space weather conditions in the near-Earth environment [2]. Electromagnetic fields and radiation are usually the most common factors that influence the satellite operation. Satellites are not protected by the atmosphere and to some extent neither by the magnetosphere. Therefore, their exposure to the variation of several important space parameters can be extremely hazardous for the devices carried above their platforms. High-energy charged particles can even render inoperative the electronic equipment carried on board the satellites. Moreover severe radiation storms can cause memory device impacts, orientation problems, serious noise in image data and permanent damages of solar panels. In addition high frequency radio communications blackouts over high latitude regions as well as increased number of navigation errors over several days are likely to appear.

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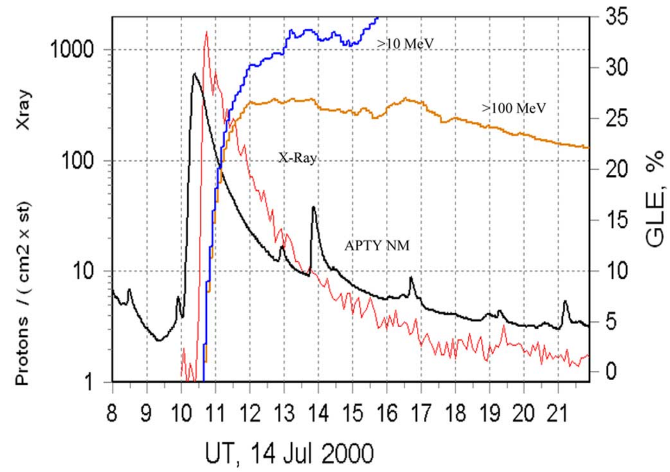

Fig. 1. Illustration of the time delay relatively to the X-ray flare onset (black line) of the GLE (Apatity NM) and of the proton enhancements with energies >10 and >100 MeV for the event of July 14, 2000.

High-energy proton fluxes from solar flares reach gigantic values (>10 000 pfu). Therefore, estimation and prognosis of such fluxes is a practical task of extreme importance. One of the ways to protect devices and electronics from space weather radiation effects is to elaborate accurate prognosis methods for the detection of possible dangerous periods for the near Earth environment. These methods should be built in such way as to allow us to undertake a set of preventive measures for decreasing the probability of space born equipment operation during periods of severe radiation storms. A prognosis and evaluation of the high-energy solar proton flux may be feasible if ground-level enhancements are simultaneously recorded at different points of observation on the Earth. A GLE is a sharp increase in the counting rate of a ground-based cosmic ray detector, caused by solar particles of sufficiently high energies to propagate with the interplanetary magnetic field and reach the Earth surface. A possible solution of such a problem has been considered by [3], [4]. According to this approach, it is possible, during a GLE, to define the high-energy protons spectra on the boundary of magnetosphere using the ground-level neutron monitor data. The duration of a GLE is usually of a few hours—much shorter than that of >10 MeV and >100 MeV energy proton enhancements detected by GOES (Fig. 1). Therefore, after defining the spectra of these particles and calculating their behavior during the proton event, an estimation of the lower energy proton flux, as well as the time of their maximum, will be attainable. The accuracy of this forecasting depends on the accuracy of the spectra obtained. However, in order to run automatically the spectra calculation program, we should first get an alert signal showing the onset of the GLE.

II. GLE Alert System

An attempt to create a worldwide data collection system connecting all real time neutron monitor stations in a common real time network, capable of real time data processing and forecasting has been recently made by the Athens and the IZMIRAN cosmic ray groups. The system being developed watches for count rate increases recorded in real time by 21 neutron monitors, and gives an alarm when a GLE is detected. GLEs are sharp increases in the counting rate of ground-base detectors caused by the arrival of solar energetic particles of energy bigger than 500 MeV/nucleon. Their detection is a task of considerable importance for space weather monitoring and forecasting as well as for preventing electronic devices located on board of satellites from increased radiations due to outbursts of solar activity. A GLE event gives an early indication of the arrival of solar energetic particles of relatively lower energy, still very dangerous for human health and electronic devices and systems. Therefore the possibility of detecting GLEs in real-time can provide the scientific as well as the industrial community with crucial information on the timing of a proton flux enhancement.

The technique applied to the GLE-alert program is based on methods developed by [5] and [6] using 1-min NM data from each observatory [4]. In fact, this advanced technique developed by Athens and IZMIRAN cosmic ray groups can be used in order to forecast space weather effects of two categories: a) solar particle events (such as GLEs) and b) magnetic effects (such as Forbush decreases and magnetospheric events). This paper deals with the description of a special GLE-alert program that defines events of the first category. However, the possibility of detecting events of the second category as well also exists.

The early detection of an Earth directed solar energetic particle event by NMs provides a very good chance for preventive prognosis of dangerous particle fluxes. Additionally it can provide an alert with a very low probability of false alarm. In order to create this alarm system the following aims have been followed: 1) utilization of retrospective data (X-Ray radiation, GLE data, solar protons and electron channels from GOES) in order to define the earliest alert GLE signal, 2) use of extended statistical material for investigating the delay of the enhancement onset in case of different kinds of radiation and 3) application of a trustworthy method for producing alert signal, and 4) use of cosmic ray data from a large number of real-time neutron monitors widely distributed around the globe.

As mentioned above, a network of real-time neutron monitors is necessary for providing us with precursors from which we can be led to the prediction of the arrival of solar energetic particles. Such a reliable neutron monitor network, functioning as a data processing center collecting cosmic ray data from ground-based neutron monitors located at various geographical sites as well as satellites, was realized recently in Athens, Greece [7]. The so-called ANMODAP Center (Fig. 2) collects data from 21 real-time stations and elaborates them automatically, in order to set them in a compatible common format. Therefore, the comparison among the high quality data of high rigidity stations can be achieved. Due to their good location in relation with the Earth's magnetospheric field these stations are necessary for a detailed study of cosmic ray variations. The ANMODAP data collection system gathers data from real-time remote stations and represents them to the Internet via FTP or HTTP servers. This system has been designed with the capability to support a large number of stations and therefore its upgrade requires a rather flexible procedure. It is important to outline that the designed collection system has the ability to provide reliable data, based on the issue that there are independent programs collecting simultaneously data from different stations in different ways. In order to produce a continuous upgrade of the developed system a number of algorithms and programs has been developed. In particular a "scheduler" algorithm has the ability to call various types of executable downloader programs. Moreover, a number of special programs such as the Global Survey Method (GSM), the Ring Station Method (RSM)

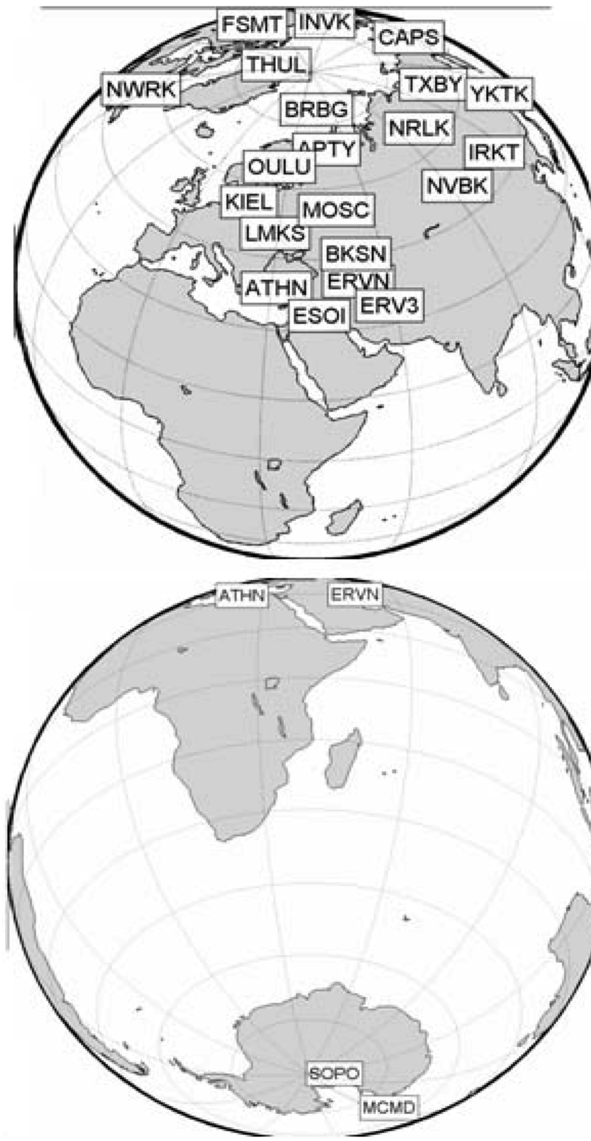

Fig. 2. ANMODAP Center processes data from 21 real-time neutron monitor stations.

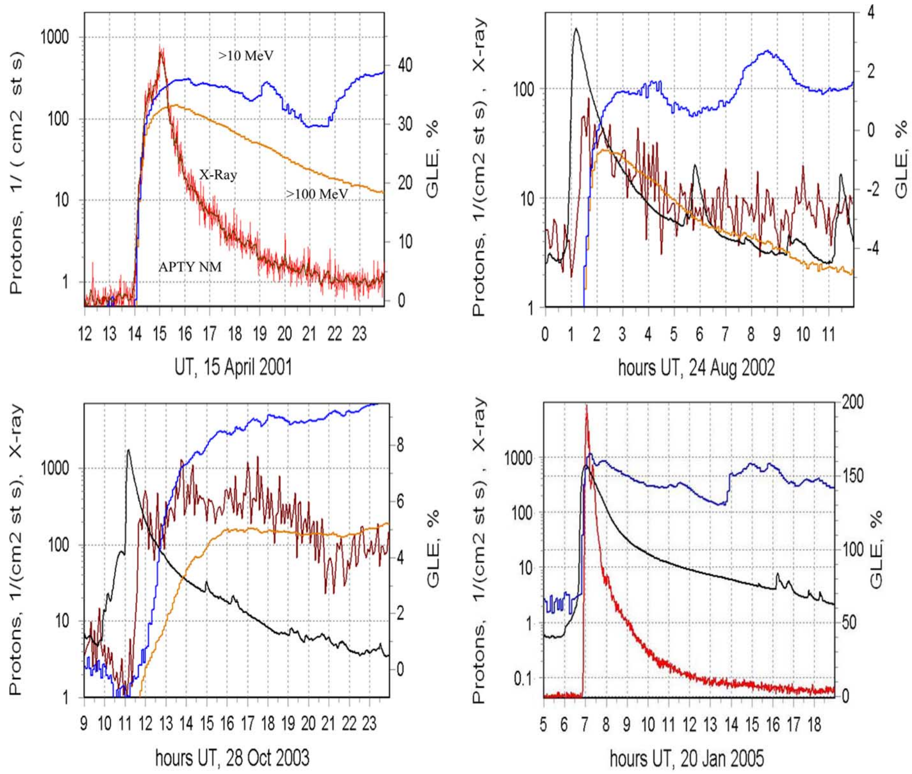

Fig. 3. Illustration of the time delay relatively to the flare onset in X-ray enhancement of the GLE (Apatity NM, red color) and of the proton enhancements with energies >10 and >100 MeV for four GLE events.

allow the derivation of CR density, anisotropy and pitch angle distribution at any moment, using as many neutron monitors as possible. The use of all stations as a unified multidirectional detector, made the accuracy of the measurements substantially higher ($<$ 0.1% for hourly data). One of the most interesting aspects of this program is the presentation of data. The neutron monitor recording system transfers one minute and hourly data to their server and refreshes the database every hour. A special program included in a scheduler creates a graphical file once per hour which is displaced on the website of the station. An advanced processing system of 1, 5, 15, and 60 min refreshes the database which is operating in a number of stations providing both graphical and digital form of the measurements. At the same plots satellite data from GOES and ACE are presented on line. The ANMODAP center provides data in real time, in digital and/or graphical form.

The prognosis method is based on the fact that the maximal flux of low energy protons reaches the Earth several hours after the occurrence of the event on the Sun. High energy particles from the solar proton event reach the Earth with a velocity close to that of light. The flux can not be accurately measured by satellites because of their small detector area while ground-based NMs do measure the flux with highly statistical accuracy (in average 0.5% for 5 min) as GLEs. In that way, we are in a position to develop methods in order to extract dependable forecast signals. In Fig. 3, the time delay between solar flare onset (X-ray) and beginning of the enhancement in different particle channels (NM, and protons of >10 and >100 MeV energies) is illustrated for different proton events. It is clearly seen that in the vicinity of the Earth, the first notification of the existence of the event is obtained from X-ray radiation data. Significantly later, the effect starts to appear in the high energy particle arrival at Earth, causing the onset of a GLE. Solar protons of lower energy (>10 and >100 MeV) have more complicated trajectories due to their influence from the interplanetary magnetic field. This leads to bigger delays relatively to the flare onset.

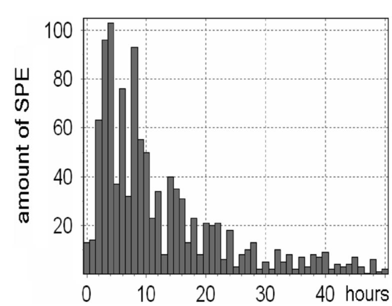

Fig. 4. Distribution of the time delay of the proton enhancements (>10 MeV) relatively to the onset of the associated X-ray flares.

As one can see from the figures presented above, the behavior of particles with different energy during the powerful solar energetic particle events clearly declares that high-energy particle profiles recorded at the Earth had ended well before the main development of the low-energy particle profiles. The distribution of the time delay between maxima in X-rays and in >10 MeV protons obtained from [8] on the large statistical material, is plotted in Fig. 4. The main maximum of this distribution corresponds to a time delay of 3–4 h, but there are also seen other clusters of events with significantly larger time of delay. The width of the time delay distribution is caused, first of all, by different longitudinal location of the solar sources. However, even in the case of simultaneous onsets (as, for example, in the case of the event of January 20, 2005, Fig. 3) the ground-level observations give a clear chance to evaluate and predict a behavior of lower energy particles and their fluencies during some later hours due to the fact that GLE profile is completely finished well before the enhancement evolving in the lower energies.

The method of prognosis consists of four steps.

1) Data from at least three ground-level NM stations and two independent satellite channels, for example X-ray on GOES10 and GOES12, are processed to search for the start of ground-level enhancement. If it is found, our computer elaborates an alert signal. From about 30 considered events, only one signal was elaborated as false alert.
2) The obtained by such a way alert signal is sent by e-mail, while simultaneously a system of minute data collection from the whole NM network is running. In this case it is very important that neutron monitor data are updated not rarer than every 5 min. The number of necessary stations to be used should be about 10 to 20.
3) A program for deriving the proton spectrum operates simultaneously with the 1-min neutron monitor data collection. The accuracy on the derivation of the proton spectrum is being improved with time.
4) Parameters of GLE spectrum from the NM network obtained are being used for the calculation different characteristics: diffusion coefficient, fluxes at different levels above the magnetosphere, possible fluencies for different energy particles and behavior dangerous part of proton radiation during the next hours, providing some kind of forecasting for proton fluxes. In a whole, it allows prognosis time behavior of non-relativistic solar protons up to 10–15 hours.

III. Data and Method

Data of solar radiation of different kinds (X-ray, proton fluxes) have been used from the archive of minute data enhancement [9] from 1986 to 2005. One-minute real time data of X-ray and protons have been taken from updated sources [10] and [11]. Different GLE neutron monitor data have been used from the archive source [12]. Alert signal determining the beginning of the proton event (in our case, the GLE event) can be obtained from ground-level observation data, sometimes jointly with the data of >10 MeV and >100 MeV protons [13]. The methods and preliminary algorithms for elaborating such a signal were described in [3], [4], and [14]. In this work, special attention was paid to choosing the baseline period as well as the selection criteria of the GLE beginning. The aim was to minimize a probability of a false Alarm. Obtaining alert signal for the onset of the event gives a start for running a special program for collecting and processing data from NM network to calculate the GLE spectrum and evaluate the behavior as well as the fluencies of the lower energy, however more dangerous, and the fluxes of solar protons. At present in the ANMODAP Center in the Athens University, Athens, Greece, jointly with IZMIRAN Cosmic Ray group, essential efforts are being applied in order to elaborate this alert forecasting program.

TABLE I
PRELIMINARY GLE-ALERT RESULTS

	STATION ALERT (UT)
15 April 2001	
Oulu	14: 03
Kiel	14: 04
Apatity	14: 07
Moscow	14: 09
Norilsk	14:16
General Alert	**14:07**
18 April 2001	
Oulu	2: 45
Kiel	2: 51
Apatity	3: 01
Moscow	2:44
Norilsk	2: 56
General Alert	**2:51**
28 October 2003	
Oulu	11:04
Kiel	11:25
Apatity	11: 04
Moscow	11: 18
Norilsk	11: 18
General Alert	**11:18**
29 October 2003	
Oulu	18: 01
Kiel	21: 08
Apatity	10: 04
Moscow	-
Norilsk	21:09
General Alert	**failure**
2 November 2003	
Oulu	17: 46
Kiel	18: 00
Apatity	17: 52
Moscow	17: 40
Norilsk	17:43
General Alert	**17:46**

On the basis of a very close method in [15] a creation of software of automatically sending out the alert signal is planned. Combination of two or more independent sources of alert signal will allow to get the signal on GLE onset with high accuracy and run corresponding procedures for the automatic spectra estimation and the calculation of the expected fluxes of >10 MeV or >100 MeV protons.

IV. Preliminary Results

The results obtained after having applied the GLE-alert program on historical data from five different events are demonstrated in Table I. The recent GLEs of 2001 (on April 15 and 18) and 2004 (On October 28 and 29 and November 2) were used as test cases in order to define the reliability of our GLE-alert program. It should be noticed though that our testing took place off-line meaning that possible problems such as the synchronization of the different NMs used as well as data anomalies due to malfunction of the detectors have not been taken into account. However the GLE-alert system is designed with the capability of giving an alarm with 95% accuracy at approximately 5 to 10 min before the maximum of the event. Moreover in case of big events the forecasting is scheduled to be about 99% accurate. As it is clearly seen in Table I, the GLE-alert

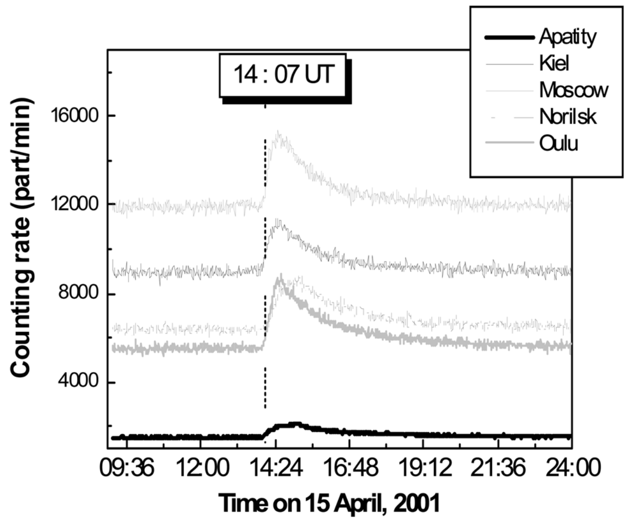

Fig. 5. Ground level enhancement onsets at five NM stations recording the event of April 15, 2001.

program produced 4 alarms in five cases of GLEs. It should be noticed that the only false alarm produced for the GLE event on October 29, 2003 was rather due to unreliable cosmic ray data than to the program itself. In fact this specific GLE on October 29, 2003 is very complicated also because of the magnetically disturbed conditions in the interplanetary space and a magnetospheric effect taking place almost simultaneously with the proton enhancement [16]. According to the algorithm applied in the GLE-alert program, an alert (if found) is defined separately for each NM station. In the off-line application, we have set as general alert the local-time of the third NM to record the beginning of the enhancement. In real-time, however, the general alert definition is a little different. In that case the general alert will be given as the exact moment that the main server (located in ANMODAP Center) "sees" the third onset in NM enhancement. In other words, the general alert will be the local-time of the ANMODAP Center the moment a simultaneous enhancement is recorded at three neutron monitors at least. A graphic representation of the alert signal observed at five different NMs, described above, is demonstrated in Fig. 5.

Although the preliminary alert results seem quite satisfying, our statistics are currently poor because of the continuous upgrades of the forecasting source code of the program. It is possible that very soon we will present a full analysis of all more GLE data. It is well known that GLEs accompany only small fractions of strong solar proton events and also that not all proton events result in ground enhancements as well. However, a technique for calculating the relative flux increases using the data of high latitude stations eliminates the possibility of loosing an event. An improved version of the GLE-alert program will be soon available via a link from the main page of the Athens Neutron Monitor station visualizing all the forecasted events in real time.

V. A Generalized GLE-Model

The creation of a GLE model that will take into account the physics taking place under extreme solar conditions as well as cosmic ray data from the worldwide network of neutron monitors is a task of considerable importance for space weather monitoring and forecasting. A GLE model can reveal information on particle flux on the top of the atmosphere as well as possible enhancements that can affect electronic devices and systems. Such a model has been recently developed [17] on the basis of the coupling function method [18]. A combination of the so-called NM-BANGLE model with the GLE-alert, functioning in real-time, will give the possibility for a reliable space weather prognosis and energetic particle arrival dangerous for human health and electronic components and systems.

The distribution of the solar energetic particle intensity observed at the vicinity of the Earth depends on the source site, acceleration mechanism, coronal transport and the ejection profile as well as on the transport of accelerated particles through the interplanetary magnetic field (IMF). The problem of determining the variations in the solar cosmic ray flux distribution outside the magnetosphere using the neutron monitor ground-level observations presents considerable difficulties. To solve this problem one requires adequate assumptions about the form of the energetic particle intensity distribution as well as knowledge of particle trajectories in the magnetosphere and the atmospheric interactions that create the secondary particles observed by ground-based stations.

Possible time variation of the intensity of any cosmic ray component of type i during a GLE can be defined by the coupling function method [18]. Count rate variations recorded by a ground-level detector during a GLE can be written as follows:

$$\frac{\Delta N(R_c,h,t,t_0)}{N_0(R_c,h,t_0)} = \frac{\int_{R_c}^{R_u} W(R,h,t_0)\frac{\Delta I(R,t)}{D_0(R)}(t,R)dR}{\int_{R_C}^{R_u} W(R,h,t_0)dR} \quad (1)$$

where $\Delta I(R,t)$ is the differential rigidity spectrum of solar cosmic rays at the top of the atmosphere, $N_0(R_c,h,t_0)$ is the background of the galactic cosmic ray variation, recorded at ground level and $W(R,h,t_0)$ is the coupling function between secondary CR of type i and primary CR arriving at the top of the atmosphere. Solar cosmic ray differential flux can be written as a product, as follows:

$$\Delta I(\Omega,R,t) = \Delta D(R,t)\cdot\Psi(\Omega,R,t) \quad (2)$$

where $\Psi(\Omega,R,t)$ is the anisotropy function reflecting the angular dependence of the flux for particles with rigidity R coming from asymptotic direction Ω, and $\Delta D(R,t)$ is the rigidity dependent differential SCR spectrum. Anisotropy function represents the distribution of solar cosmic ray particles at the top of the atmosphere during a GLE, revealing information on the way these particles propagated in the interplanetary magnetic field and finally arrived at the vicinity of the Earth. The form of $\Psi(\Omega,R,t)$ is a crucial point in the GLE analysis, since it characterizes in the most significant way the anisotropic GLE model that is being applied.

Application of the NM-BANGLE model for the case of the GLE on January 20, 2005 (Fig. 3) gave detailed information on integral particle flux as well as anisotropy during this extreme solar particle event. The event of January 20, 2005 appeared to have a complex structure with two maxima. The time evolution of the rigidity spectrum has a rather complicated behavior. In the beginning of the event it appears hard meaning that a great amount of very energetic solar particles reached the vicinity of the Earth. Lower energy particles came 20 min later after the onset detected by neutron monitors. The spectrum softened abruptly in the second time-interval it and then it hardened again. During the later phases the spectral index varied between -6.6 and -7.6.

Solar particles seemed to have arrived in the form of extremely intensive narrow beams of solar relativistic particles arriving at the Earth during the time interval 6:50 UT–6:55 UT had a width that did not exceed 10°–40°. This result can be proved extremely important since it points out the most dangerous area (i.e., area of maximum flux) for satellites. These initially narrow particle beams widened with time resulting in big enhancements recorded by all other high latitude NMs. Anisotropy remained in relatively high levels during the first hour of the event. The source of anisotropic flux was located in southern hemisphere. The position of the anisotropy source changed with time, moving to more northern locations. The estimation of the integral flux for particles with energy >100 MeV on the basis of our model is in good agreement with the satellite observations. Moreover, it ranks this event among the largest proton enhancements ever recorded.

The results of the modelling of the January 2005 event are satisfactory enough since proton fluxes obtained from our model using ground-level neutron monitor data are very much consistent with the real fluxes recorded by space instruments. This result can be utilized in means of the space weather monitoring and/or prognosis. Application of this model in real-time to as many GLEs as possible is of great importance in order to reveal the characteristics of the solar proton flux distribution and magnitude in the vicinity of the Earth in as many cases as possible. Of course, this requires the use of a worldwide network of real-time neutron monitors such as the ANMODAP Center in Athens. Interpretation of possible common characteristics can also outcome from the utilization of data from different types of observing instruments (e.g., muon detectors, neutron telescopes, etc.). Incorporation of data from satellite particle detectors can also provide important information on particles of the lower rigidity range as well as on the X-ray flux. Therefore, an extended integrated analysis combining all the above mentioned potentials and the already developed GLE-alert program may drive our current knowledge to a point that the forecasting of solar extreme phenomena will be attainable. One should mention, however, that other institutes, such as the Bartol Research Institute have made similar efforts for space weather prognosis (http://neutronm.bartol.udel.edu/spaceweather).

VI. Conclusion

After having obtained the first preliminary results of the GLE-alert program and having applied the NM-BANGLE model to the extreme case of the event of January 20, 2005, we may conclude the following.

1) A new GLE-alert system is being developed in order to predict the low energy part of the SEP events near Earth by the ground-based cosmic ray measurements.
2) The new Athens Neutron Monitor Data Processing Centre (ANMODAP), based on the activity of the cosmic ray group in Athens University, provides real time monitoring of cosmic ray variations.
3) A new GLE model (NM BANGLE model) has being developed on order to calculate characteristics of solar energetic particles during GLEs (Anisotropy, integral fluxes, rigidity spectrum).
4) NM-BANGLE model was tested for GLE 69. Results of the proton flux calculations agree with the observations.
5) Combination of NM-BANGLE model with GLE-alert system, functioning in real-time, will give the possibility for a reliable space weather prognosis and energetic particle arrival dangerous for human health and electronic components and systems.

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