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TEST ALERT SERVICE AGAINST VERY LARGE SEP EVENTS

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ABSTRACT

The Aragats Solar Environment Center provides real time monitoring of different components of secondary cosmic ray fluxes. We plan to use this information to establish an early warning alert system against *extreme, very large solar particle events with hard spectra,* dangerous for the satellite electronics and for the crew of the Space Station. Neutron monitors operating at altitude 2000 m and 3200 m are continuously gathering data to detect possible abrupt variations of the particle count rates. Additional high precision detectors measuring muon and electron fluxes along with directional information are under construction on Mt. Aragats. Registered Ground Level Enhancements in neutron and muon fluxes along with correlations between different species of secondary cosmic rays are analyzed to reveal possible correlations with expected times of arrival of dangerous solar energetic particles.

INTRODUCTION

Unpredictable bursts of Solar Energetic Particles (SEP) peaking in 11 year cycles are one of the major constraints on the operation of space systems and further technological utilization of near-Earth space (Tylka, 2001). Some of these bursts produce fluxes of high energy particles which can be harmful to satellite electronics, the Space Station, its crew and to flights over the poles. In the 1999 report on space weather, the US National Security Space Architect finds that during the preceding 20 years about one or two satellites per year have suffered either total or partial mission loss due to space weather (Space Studies Board, 1999). Since our lives depend so heavily on the satellite based technologies, not to mention the value of protecting humans in space and in aircraft, it is becoming increasingly important to have an accurate and reliable forewarning about the arrival of these dangerous particles, so that mitigating action can be taken if necessary.

The use of large-area detectors which can only be accommodated at ground based stations is vital for measuring the low fluxes of high energy particles accelerated during the Solar flares (Sf) and in shock waves driven by the Coronal Mass Ejections (CME). The highest energy particles from the most severe events, arrive to Earth about a half hour earlier than the abundant “killer” medium energy particles, thus providing an opportunity to establish an early warning system to alert the client about the potential damage to satellites, space personnel, and flights scheduled over the poles (Dorman, 1999). Taking into account that only very few of a great number of SEP events produce dangerous ion fluxes, it is not only critical to alert clients about the arrival of the most severe radiation storms, but also to minimize the number of false alarms against events which are not severe enough to cause damage. *We can accomplish both goals by detecting secondary fluxes generated by the high-energy ions in the Earth’s atmosphere by surface detectors located at mountain altitudes and low latitudes.*

Because the high energy ions are so few in number and, because secondary particles are scattered and attenuated in the Earth’s atmosphere, large-area detectors, located at high mountain altitudes are necessary to measure them. The information about primary ion type and energy is mostly smeared during its successive interactions with atmospheric nuclei, therefore, only coherent measurements of all secondary fluxes (neutrons, muons, and electrons) can help to make unambiguous forecasts and estimate the energy spectra of the upcoming dangerous flux. Lev Dorman demonstrated in numerous papers that detecting at least two cosmic ray flux components at one, or better, two stations at different altitudes will make it possible not only to reconstruct the solar ion flux outside the Earth’s atmosphere, but also to estimate the energy spectra of upcoming solar particle fluxes (Dorman et. al., 1993a and 1993b). Multidimensional statistical methods of analysis of the multivariate data and time series as well as timely delivery of the alert are also of utmost importance.

THE STRUCTURE OF THE ARAGATS SPACE ENVIRONMENT CENTER

The Aragats Space Environmental Center (ASEC, Chilingarian et al., 1999a, 2002) consists of two high altitude stations on Mt. Aragats in Armenia (Geographic coordinates: 40°30'N, 44°10'E. Cutoff rigidity: ~7.6 GV, altitude 3200 and 2000 m.). At these stations several monitors are continuously measuring intensity of the secondary cosmic ray fluxes and sending data to the Internet each in real time (see Table 1).

After 50 years of operational experience, neutron monitors continue to be the best instrumentation for measuring intensity variations of cosmic rays starting from threshold values (determined by the rigidity cutoff and attenuation in the atmosphere) of ~1 GV(in Polar Regions) to ~15 GV (Equatorial Regions) (Moraal, 2000). In the 60's Carmichael developed a neutron monitor with statistical accuracy of 0.1% for hourly data in preparation for the Year of Quiet Sun (IQSY), (Carmichael, 1964). This type of neutron monitor is usually designated by the name X-NM-64 where X denotes the number of counters operating in the entire monitor. For more details and for a list of world-wide monitors see (Shea, 2000).

Two 18NM-64 neutron monitors are in operation at Nor-Amberd (2000 m. elevation), and at Aragats (3200 m. elevation) research stations. The monitors are equipped with interface cards, providing time integration of counts from 1 sec up to 1 minute. Real-time data from these monitors is available at URL http://crdlx5.yerphi.am/neutron/index.html.

One of the improvements to the Aragats monitoring facilities includes registration of the variations of the muon flux under different angles of incidence. The Nor-Amberd muon multidirectional monitor (NAMMM) consists of two layers of plastic scintillators above and below the NM installation. The lead filter of the NM will absorb electrons and low energy muons. The threshold energy of the detected muons is estimated to be 350 MeV. NAMMM consists of 6 up and 6 down scintillators, each having the area of 0.5 m^2. The data acquisition system of the NAMMM can register all coincidences of detector signals from the upper and down layers, thus, allowing us to measure the arrival of the muons from different directions. Changes in the relative count rates from different directions will point to the approaching magnetized cloud, allowing the forecasting of geomagnetic storms. The changes in count rate pointed on the Sun will prove the solar origin of Ground Level Enhancement (GLE).

The Solar Neutron Telescope (SNT-1) at the Aragats station is part of a world-wide network coordinated by the Solar-Terrestrial Laboratory of the Nagoya University (Matsubara, 1999, Tsuchiya, 2001). It consists of four 1 m^2, 60 cm thick scintillation blocks with anti-coincidence shielding (consisting of the 5 cm. thick four plastic scintillators with area 1 m^2 each) vetoing near vertical charged flux. An important advantage of the SNT over the NM is its possibility to estimate the energy of detected neutrons. The amplitude of the SNT output signal is discriminated according to 4 threshold values, corresponding approximately to neutron energies of 50, 100, 150 and 200 MeV. The data from the solar neutron telescope is available online at URL http://crdlx5.yerphi.am/solar.html.

At the Aragats high altitude station two surface arrays (MAKET and GAMMA) operate with the main purpose of detecting Extensive Air Showers (EAS) initiated by very high energy primaries $>5\cdot10^{14}$ eV. The EAS installations are triggered 3-5 times per minute by high energy particles incident on the array area. 1 m^2 plastic scintillators overviewed by photomultipliers are used for measuring charged particle densities and arrival times (for the determination of the angles of incidence). The total area of the surface detectors of GAMMA and MAKET installations is about 150 m^2. The spacing between detectors varies from several meters to tens of meters.

In the underground hall originally constructed for the ANI Cosmic Ray experiment (Danilova, 1992) another one hundred fifty of the same type of detectors are located to measure the muon content of the EAS. The absorption in the 6 m thick concrete blocks and 7 m filtered electrons and low energy muons, therefore only muons with energies >5GeV reaches detector location. The high count rates of the charged component (mostly electrons and muons) at mountain altitudes (~ 450 counts/m^2/sec for electrons and ~ 50 counts/m^2/sec for 5 GeV muons) and the large area of the electron and muon detectors on Mt. Aragats are very attractive for establishing a monitoring facility for the investigations of the correlations between short term variations of electron and muon count rates with the enhancing flux of solar ions incident on the Earth's atmosphere or with approaching magnetized cloud of solar plasma.

As with the NAMMM, we will use the coincidence technique to estimate arrival direction of the high energy muons. Scattering of the high energy muons is negligible in the atmosphere, therefore by measuring the incident muon direction we can determine the direction of the coming solar or galactic ions. It will give us additional evidence of the registration of solar particles. The count enhancements of the present ASEC monitors are integrated over all directions. The question arises whether the signal enhancement is due to the solar particles or disturbance of the Earth's magnetic field leading to decrease of the local rigidity threshold (see for example Kudela et. al., 2001). The total count rate of Aragats Multidirectional Muon Monitor (AMMM) due to incident muons registered by the 72 m^2 scintillators is approximately ~200,000 per minute. Thus, the sensitivity of this new monitor reaches record value of ~0.2% for one minute count rates, 3 times better compared to the Aragats NM. Using 27 m^2 scintillation detectors located on the top of the ANI concrete calorimeter, 24 m above the 72 m^2 underground array, we can monitor changing count rates from numerous directions from the Sun. Detectors on the top are grouped in 3, while those in the underground hall are groupd in 8 to provide significant amount of coincidences. We expect from 300 to 500 coincidences in 5 minutes intervals. The geometry of the detector arrangement will allow us to detect directions from the vertical to 60º declination with accuracy of ~5º. Along with the Moscow TEMP muon telescope (V.Borog, 2001) the AMMM could fill the gap in the world-wide network of muon telescopes intended for forecasting of the upcoming severe geomagnetic storms (K.Munakata et al, 2000)

Table 1 The parameters of ASEC Monitors at Mt. Aragats.

Detector	Altitude *m*	Surface m^2	Threshold(s) *MeV*	In operation since	Count rate (min^{-1})
Nor-Amberd N M (18NM64)	2000	18		1996	2.7×10^4
Aragats NM (18NM64)	3200	18		2000	6.6×10^4
SNT-1	3200	4	50,100,150,200	1998	6.7×10^4
SNT-2	3200	4	50,100,150,200		3.0×10^4
NAMMM	2000	3+3	350	2002	6.0×10^3
AMMM	3200	72+27	5000	2002	2×10^5

GLE CORRELATIONS WITH SOLAR ENERGETIC ION ARRIVALS TO 1 AU

The arrival times of the ions at 1 AU are estimated by the technique proposed in (Lockwood et. al., 1990, Fluckiger, 1991). In that paper it was proposed to use the registered arrival times and energies of the first ions by the space-born ion spectrometers to deduce spatial-temporal history of the accelerated ions. Extrapolating the obtained dependences to the relativistic particles we can obtain the expected arrival time of the ions that are energetic enough to enter the atmosphere at the Aragats geographical location and produce secondary fluxes reaching the Aragats altitudes. Relativistic ions arriving at 1 AU and generating secondary fluxes in interactions with atmospheric nuclei, are detected by the ASEC monitors, as peaks in 1 or 5 minute count rates.

Rather good correlation between expected arrival times of relativistic ions and peaks detected by Aragats and Nor-Amberd Neutron Monitors (ANM and NANM) is described in (Martirosyan et.al., 2002).

Here we want to compare time of detection of first ions of GLE by ASEC detectors and time of arrival of the bulk of, so-called, "hard" particles with energies greater than 50 MeV. The energy of the "hard" particles is sufficient to cause them to penetrate the walls of manned spacecraft and to result in a harmful or even fatal radiation dose to astronauts. Such intense events also degrade electronic components on unmanned spacecraft. Solar energetic ions can also penetrate deep into the atmosphere over the Earth's magnetic polar regions and produce increased ionization, lowering the ionosphere and disrupting radio communication (HESSI, 1997). In Figures 1-4 the count rates of the ASEC neutron monitors (left Y-axes) are superimposed on the solar hard (40 to 80 Mev) proton intensity rise pattern detected by the GOES satellites (GOES, Internet) spectrometers (right Y-axes).

For all events, the intensity of the dangerous "hard" particles reaches significant values later than the arrival of the first relativistic ions generating GLE, thus detection of the early arriving relativistic ions by measuring the GLE gives us a forewarning on the arrival of the harmful fluxes of solar protons. The peaks in 5 minute monitor counts for all 4 events are well correlated with expected arrival times of solar ions (for details see Martirosyan et.al., 2002). Continuously comparing the well synchronized data streams from ASEC solar monitors it is possible to issue alerts and warnings when abrupt increase in count rates will be detected at all muon and neutron monitors listed in table 1. The alert sent by e-mail to users will be delivered with 5 minutes from start of the abrupt enhancement of the count rate (see Babayan, et.al., 2001), allowing time for satellite operators to take mitigating actions.

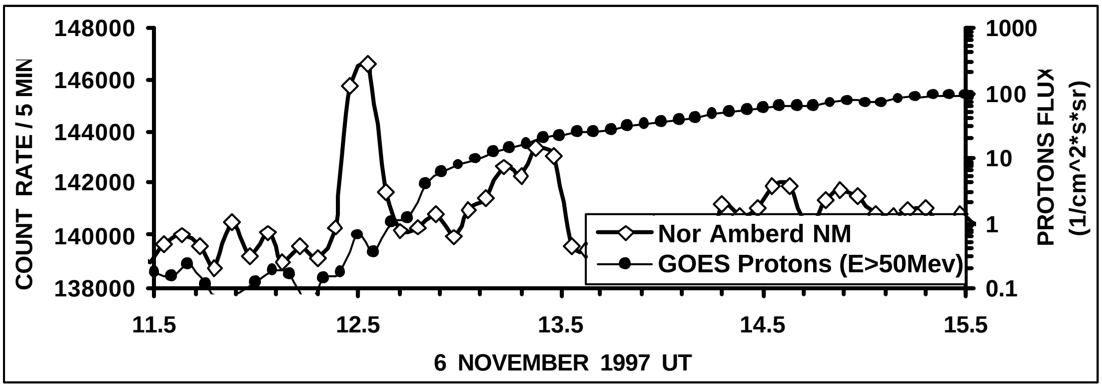

Figure 1. Duration of the X9.4-ray flare 11:41 – 11:53, first O ions reach Earth at 12.30

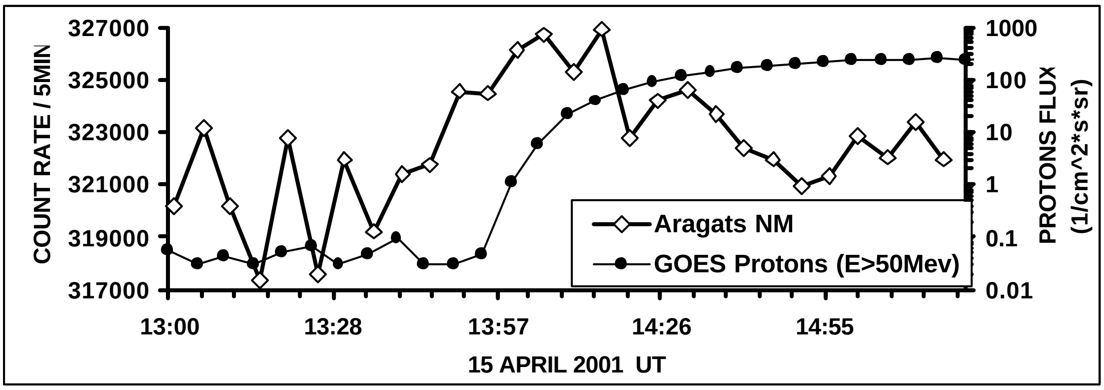

Figure 2. Duration of the X14.4 – X-ray flare 13:11 – 14:47, first Fe ions reach Earth at 13:51

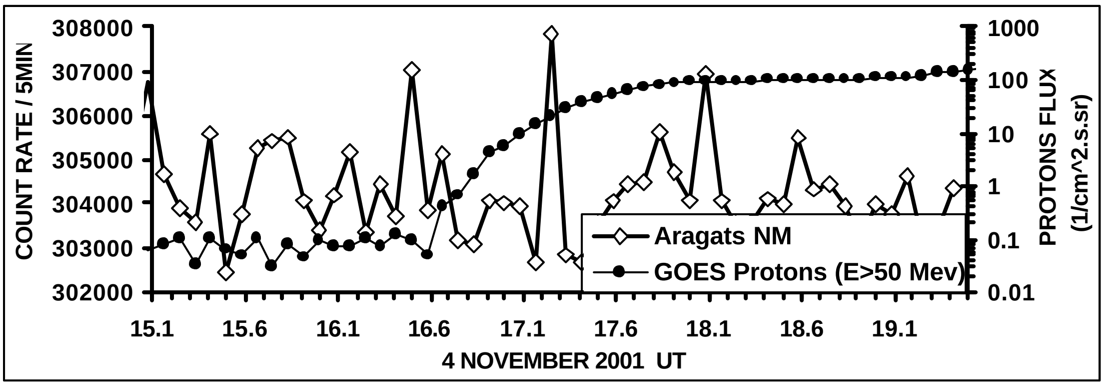

Figure 3. Duration of the X1.0-ray flare 15:55 – 16:49, first protons reach Earth at 16:33

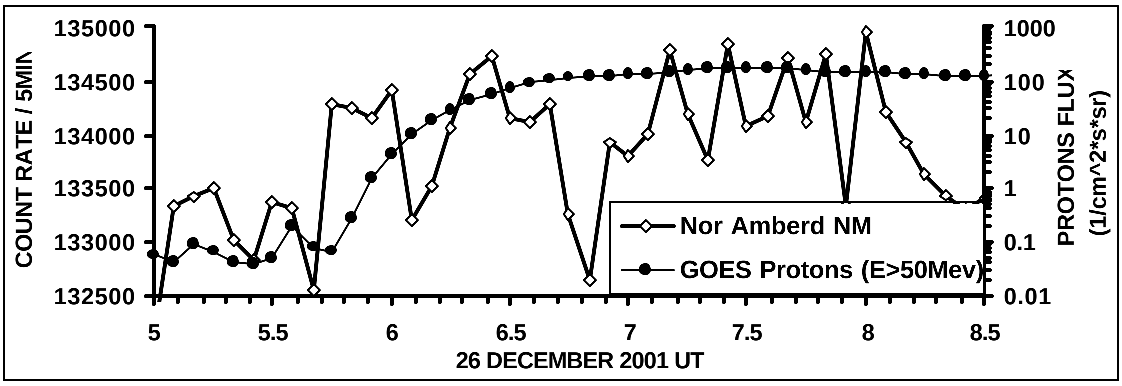

Figure 4. Duration of the M7.14 X-ray flare 4:24 – 6:39, first He ions reach Earth at 5:47

CONCLUSION

The influence of solar radiation on humans and orbiting technological systems was summarized in the public documents of the ESA Space Weather Programme Studies as follows (Horne, 2001).

Energetic ions from SEP arriving to 1 AU can produce Single Event Effects (SEEs) in satellite electronics (single hard errors, single event upsets, latchups, burnouts, gate and dielectric ruptures). These effects are normally due to heavy ions, but particles as light as protons or neutrons can produce the same effects as heavy ions through nuclear reactions with silicon inside the electronics (in the future, due to increasing miniaturization, protons may be able to directly induce SEEs);

The radiation effects on human beings are similar to the effects on electronics. Dose effects affect all cells, especially those, which are not renewed or at least not rapidly renewed. Single energetic particles can also break the DNA chain in the cell nucleus, producing chromosome aberrations, translocations and tumor induction. They can induce also cell mutation that can have effects on the genetics

A. J. Tylka made the following conclusion based on his analysis of the observations by sensors on the WIND and ACE satellites: “at present SEP events are not predictable in any meaningful sense”. “We cannot give a reliable prediction of when such event will occur, nor can say, once an event has started, what its characteristics will be, even a few hours in advance” (Tylka, 2001).

However, events of the September 29, 1989 and November 6, 1997 unambiguously indicate solar ions well above NM cutoff rigidities. Combining the neutron GLE data with precise monitoring of the secondary muon flux by the directionally sensitive large ground-based muon detectors provides good perspectives to partly overcome difficulties mentioned by A.J.Tylka.

Simultaneous monitoring of the different secondary particle fluxes at 2 different altitudes and in different energy bandwidths along with directional information will allow not only the forecasting of the upcoming very severe radiation storm, but also to estimate the energy spectra of different ions and e-folding of the spectra, thus giving us the possibility to estimate the arrival time and fluence of “hard” ions.

The forecast and alert sending can be done at least 30 minute prior to the arrival of the “killer” particles. The advantage of the ASEC alerts compared with NASA and NOAA services is in the possibility of detecting ions of the highest energies, thus improving both the timing and the information content. However, for 24 hour coverage similar detectors must be located at 2 or 3 more locations around the perimeter of the earth. The information from ASEC will be complimentary to the information from the space-born sensors. Most of the measurements of the flare and CME characteristics from satellites and ASEC are posted on the internet. Soft X-ray, hard X-ray, and gamma radiation detections by space borne detectors are posted on the Internet in real-time. There are plans to put the real time Sun images from EIT and LASCO Instruments on the SOHO satellite on the Internet (Berghmans, 2001). The real time information about the CME, its magnitude and the direction in which it is headed measured by the LASCO and EIT combined with data from ASEC will provide additional valuable information for forecasting of the danger from the solar event.

The joint multidimensional multidetector analysis (see Chilingarian et.al., 1999b) of all relevant information will minimize the number of false alarms and will maximize the reliability and timeliness of forecasting the arrival of dangerous SEP. The operating facilities at ASEC provide a test Space Weather Early Warning service using solar monitors equipped with all the necessary components to collect, store, analyze and send data to the Internet.

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