Aragats space-environmental centre: status and SEP forecasting possibilities

2003 J. Phys. G: Nucl. Part. Phys. 29 939

(http://iopscience.iop.org/0954-3899/29/5/314)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **29** (2003) 939–951 PII: S0954-3899(03)54475-9

Aragats space-environmental centre: status and SEP forecasting possibilities

A Chilingarian[1], **K Avakyan**[1], **V Babayan**[1], **N Bostanjyan**[1],
S Chilingarian[1], **V Eganov**[1], **A Hovhanissyan**[1], **G Karapetyan**[1],
N Gevorgyan[1], **G Gharagyozyan**[1], **S Ghazaryan**[1], **A Garyaka**[1], **V Ivanov**[1],
H Martirosian[1], **R Martirosov**[1], **L Melkumyan**[1], **H Sogoyan**[1],
S Sokhoyan[1], **S Tserunyan**[1], **A Vardanyan**[1], **A Yeremian**[2] **and M Zazyan**[1]

[1] Cosmic Ray Division, Yerevan Physics Institute, Alikhanyan Brothers 2, Yerevan 36, Armenia
[2] Stanfrod Linear Accelerator Center, Stanford, CA 94309, USA

Received 18 September 2002, in final form 23 January 2003
Published 9 April 2003

Abstract

The Aragats Space Environment Center in Armenia provides real-time monitoring of cosmic particle fluxes. Neutron monitors operating at altitudes of 2000 m and 3200 m on Mt Aragats continuously gather data to detect possible abrupt enhancement of the count rates. Additional high precision detectors, measuring muon and electron fluxes, along with directional information have been put in operation on Mt Aragats in the summer of 2002. We plan to use this information to establish an early warning system against *extreme solar energetic particle* (SEP) events which pose danger to the satellite electronics and the space station crew. Solar ion and proton fluxes as measured by space-borne sensors on ACE and GOES satellites are used to derive expected arrival times of highest energy ions at 1 AU. The peaks in the time series detected by Aragats neutron monitors, coincided with these times, demonstrate the possibility of early detection of SEP events using the ground-based detectors.

1. 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 in the vicinity of the Sun due to solar flares (SF) and coronal mass ejections (CME). The high energy particles from the most severe events which can cause damage, arrive at Earth about half an 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, the space station, space personnel and flights scheduled over the poles (Dorman 1999). Taking into account that only very few of a great number of SF and CME 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 using detectors on mountain altitudes and low latitudes to detect secondary fluxes generated by the few high energy ions as they enter the Earth's atmosphere. 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), along with their correlations, can help to make unambiguous forecasts and estimate the energy spectra of the upcoming dangerous flux.

Lev Dorman has demonstrated in numerous papers that detecting at least two or three cosmic ray components at different altitudes and latitudes 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 and Venkatesan 1993a, Dorman *et al* 1993b). Multidimensional statistical methods of analysis of the multivariate time series as well as timely delivery of the alert are also of utmost importance (Chilingarian *et al* 1999b).

2. Particle acceleration at the Sun

Galactic cosmic rays (mostly protons and fully stripped ions) incident on the atmosphere create fluxes of secondary particles reaching the Earth. The intensities of these fluxes, as measured at different geographical positions by various particle detectors, are characterized mostly by geophysical conditions of the site, by the particular phase of solar activity, and by the local time of day. Transient solar events also influence the count rates of particle monitors. In this paper we will examine short-term enhancements of count rates in surface detectors (so called ground level events (GLE)) correlated with the fluxes of relativistic solar ions incident on the Earth's atmosphere.

The first experimental evidence of the GLE was observed in 1942 with ionization chambers at Cheltenham, MD by Forbush (1946). Correlating detected GLEs with large SF, Forbush concluded that the cause of the rise in the detector counts is the flux of charged particles, accelerated during large disturbances on the Sun and reaching Earth.

Established in the 1950s, the worldwide network of neutron monitors (NM) provides more detailed data on GLE. Mutual analysis of the data on GLE detected by NM located at different latitudes leads to the estimation of the energy spectra of the solar proton flux and its time dependence (Meyer *et al* 1956).

In the 1960s satellite detectors measured precise proton energy spectra for energies from 1 MeV up to 500 MeV and helped to establish correlations between increases of particle fluxes at 1 AU with abrupt decreases of surface detector count rates, called Forbush decreases (Fd), and with sudden commencement of the geomagnetic storms (Bryant *et al* 1963).

Starting from the 1970s, with the launch of particle spectrometers, began the continuous monitoring of low and medium energy cosmic rays in space. Time histories of the simultaneously detected x-rays, gamma-rays, electrons and ions of different energy and charge, combined with the detection of the developing flares and CME using coronagraphs, helped to create a comprehensive picture of the major solar events that also include highest energy ions giving rise to GLEs (Reames 1999). 'New instruments on WIND and ACE satellites operating during the 23rd solar cycle, with geometry factors $\sim$100 times larger than those of the previous cycle, have yielded unprecedented observations of temporal evolution in composition and spectra over a wide range of energies and species' (Tylka 2001).

Multiwavelength measurements from very sensitive x-ray detectors, high resolution imaging coronagraphs and radiotelescopes now reveal the location and characteristics of the natural accelerators at the Sun and in the interplanetary space in much more details. Given this background information, two types of solar events which accelerate particles—impulsive and gradual—were categorized and described in numerous publications (see, for example, Miroshnichenko (2001)).

Impulsive flare events are believed to accelerate electrons and ions in large structures originating in the magnetic reconfiguration regions. After discovery of the above-the-loop-top hard x-ray source (Masuda *et al* 1994) with the Yohkoh/HXT (Kosugi *et al* 1991) it became apparent that particles are accelerated by the dynamic electromagnetic forces during the reconfiguration of the magnetic fields (Aschwanden *et al* 1996). The most probable acceleration mechanism is the stochastic acceleration, allowing detectable intensities of non-thermal x-ray radiation from locally trapped electrons. Direct hard x-ray detection as well as the application of the time-of-flight technique to the electrons travelling from acceleration site to the chromosphere reveals that the location of the acceleration region is 5000–35 000 km above the top of the soft x-ray-bright flare loop (Ashwanden 2002). The temporal pattern of the chromospheric thick target Bremsstrahlung emission suggests the existence of subsequent acceleration phases and points to the highly spatially fragmented acceleration sites (Aschwanden 2002).

The natural assumption that positively charged protons and ions will be accelerated with the same mechanisms as the electrons is proved by the registration of the lined gamma radiation in coherence with hard x-ray radiation. The time sequence of the Bremsstrahlung radiation peaks produced by accelerated electron beams, interlaced by the nuclear de-excitation lines produced by proton and ion bombarded chromosphere, clearly demonstrates that ions and electrons are accelerated in the same region and nearly simultaneously (Forrest and Chupp 1983).

The efficiency of the stochastic acceleration of ions via the mutual wave–particle interactions depends on the relation between the frequencies of the resonant waves (Alfven waves, magnetosonic waves, sound waves) and ion gyrofrequency. Alfven waves, if fast enough ($\sim$2000 km s^{-1}) can accelerate 20 keV protons up to GeV energies during time scales of 1–10 s (Barbosa 1979, Miller *et al* 1990). If the field above the acceleration region is magnetically open for the out-flowing ions, then the ions will be injected into the interplanetary space and if the flare site is magnetically connected with the Earth, ions will be detected by the orbiting isotope spectrometers at 1 AU. If energetic enough, escaping ions will generate secondary fluxes when interacting with the Earth's atmosphere and cause enhancements detected by surface monitors. High energy neutrons produced by ions interactions in the chromosphere could also escape into interplanetary space and reaching Earth, raise the high altitude monitor count rates (Chupp *et al* 1982, 1987).

Gradual events are associated with CME development in corona and in interplanetary space. CME driven shock should be fast enough (>500 km s^{-1}, Reames 1999) to produce SEP events. Shock acceleration is believed to be one of the major mechanisms in the Universe for accelerating particles to highest energies. Multiple traversals of shock are required for the acceleration of solar ions up to MeV energies. Ambient magnetic turbulence is not sufficient for scattering and trapping ions with such energies. Self-generated Alfven waves effectively scatter energetic ions, providing their trapping near the shock and, therefore, increasing their energy. Maximum attainable energy of accelerated ions is proportional to the rate of re-crosses of the shock; this rate in turn is proportional to the particle trapping time. 'As trapping increases for particles of one rigidity, they are more likely to be accelerated to a higher rigidity, where they again stream out and produce resonant waves, etc' (Reames 2000). Numerical calculations and Monte Carlo simulation prove that solar protons could be accelerated up to energies of 100 GeV during propagation of CME in middle and high corona (Miller *et al* 1990). The same authors examining the 3 June 1982 flare mention that protons were accelerated within 16 s from 30 MeV to ~1 GeV. Krucker and Lin (2000), based on the data from WIND/SST instrument (Lin *et al* 1995), concluded that protons at energies up to 6 MeV are injected simultaneously at heights $\leqslant 10$R.

The maximum energy attainable by the shock acceleration depends on shock speed and height of shock start in the corona. Shock waves as fast as ~1500 km s^{-1} starting below ~5R$_{\text{sun}}$ can accelerate ions up to 10–30 GeV (Tylka *et al* 2001a, 2001b). Numerical modelling by Kallenrode and Wibberenz (1993) also suggested more effective acceleration in the corona compared to acceleration in the interplanetary space. The conclusion from the analysis of the biggest SEP events is that the peak of the proton injection profiles occurs when CME heights reach 5–15R$_{\text{sun}}$ (Kahler 1994).

There are still many unanswered questions concerning the details of the CME-SEP and SF-SEP relationship and sometimes both scenarios are claimed to be competitive for acceleration to the highest energies (Klein *et al* 1999, Kahler *et al* 2000, Cane 2000). Nevertheless, although during large SEP events different acceleration processes act at different sites of disturbed solar plasma, we can conclude from the analysis of various events with different methodologies that acceleration to highest energies for all realistic scenarios takes place in the vicinity of the Sun, and that injection of the first ions of all energies is performed within time spans not larger than few tens of seconds. This very strong assumption, supported by the majority of experimental and theoretical works, gives the theoretical possibility of developing an early warning system, based on the obvious fact that high energy particles will reach 1 AU faster than the high flux of medium and low energy ions which cause the damage to satellites and pose radioactive hazard for the space station crew.

3. The Aragats Space Environment Center

The Aragats Space Environmental Center (ASEC) (Chilingarian *et al* 1999) consists of two high altitude stations on Mt Aragats in Armenia (geographic coordinates: 40°30′ N, 44°10′ E; cut-off rigidity: ~7.6 GV, altitudes 3200 and 2000 m). At these stations several monitors continuously measure the intensity of the cosmic ray fluxes and send data to the internet in real time (see table 1 and Chilingarian *et al* (2003a, 2003b) for detailed description of ASEC monitors).

After 50 years of operational experience, neutron monitors with threshold values from ~1 GV (in the polar regions) to ~15 GV (equatorial regions) continue to be the best instrumentation for measuring intensity variations of cosmic rays (Moraal *et al* 2000). In the 1960s Carmichael developed a neutron monitor with statistical accuracy of 0.1% for

Table 1. Parameters of the ASEC monitors at Mt Aragats in Armenia.

Detector	Altitude (m)	Surface (m^2)	Threshold(s) (MeV)	In operation since	Mean count rate (min^{-1})
NANM (18NM64)	2000	18		1996	2.5×10^4
ANM (18NM64)	3200	18		2000	6.2×10^4
SNT-1	3200	4	50, 100, 150, 200	1998	6.7×10^{4}[a]
NAMMM-test operation	2000	5 + 5	350	2002	2.5×10^{4}[b]
AMMM-test operation	3200	15 + 72	5000	2002	2×10^{3}[b]

[a] Count rate for the first threshold; near vertical charged particles are excluded.

[b] Expected total coincidence rate for the near vertical muon flux.

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 of the entire monitor. For more details and for a list of worldwide monitors see Shea and Smart (2000).

Two 18NM-64 neutron monitors are in operation at Nor-Amberd (2000 m elevation) and at Aragats (3200 m elevation) research stations, respectively, called the Nor Ambert neutron monitor (NANM) and the Aragats neutron monitor (ANM). The monitors are equipped with interface cards, providing time integration of counts from 1 s up to 1 min. Real-time data from these monitors is available at URL http://crdlx5.yerphi.am.

The solar neutron telescope (SNT-1) at the Aragats station is part of a worldwide network coordinated by the Solar-Terrestrial Laboratory of the Nagoya University (Matsubara *et al* 1999, Tsuchiya *et al* 2001). An important advantage of the SNT over the NM is its possibility to estimate the energy of detected neutrons. The SNT consists of four 1 m^2, 60 cm thick scintillation blocks with anti-coincidence shielding consisting of four plastic scintillators each having 5 cm thickness and 1 m^2 area, which veto the near vertical charged flux. Incoming neutrons are converted to protons in nuclear interactions inside the thick scintillator target. The energy deposited due to ionization by recoil protons is measured by photomultipliers over the scintillators. The amplitude of the photomultiplier output signals is discriminated according to four threshold values, approximately corresponding to neutron energies of 50, 100, 150 and 200 MeV. The count rate of SNT-1, measuring large amounts of neutrons and inclined muons and electrons is sensitive to transient solar events. We use short-term variations of the SNT count rate along with Aragats and Nor Amberd neutron monitor data to analyse the GLE and Forbush decreases (Babayan *et al* 2001). Data from SNT-1 is available online at URL http://crdlx5.yerphi.am.

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) shown in figure 1 consists of two layers of plastic scintillators above and below one of the three sections of the Nor Amberd NM. The lead (Pb) filter of the NM absorbs electrons and low energy muons. The threshold energy of the detected muons is estimated to be 350 MeV. The NAMMM consists of six up and six down scintillators, each having an area of 0.81 m^2. The distance between layers is $\sim$1 m, and the mean angular accuracy is $\sim 25^\circ$. The data acquisition system of the NAMMM can register all coincidences of detector signals from the upper and lower layers, thus, enabling measurements of the arrival of the muons from different directions.

At the Aragats high altitude station two surface arrays, MAKET (Hovsepyan 1998) and GAMMA (Garyaka *et al* 2002), are in operation for the main purpose of detecting extensive air showers (EAS) initiated by very high energy ($E > 5 \times 10^{14}$ eV) ions and protons.

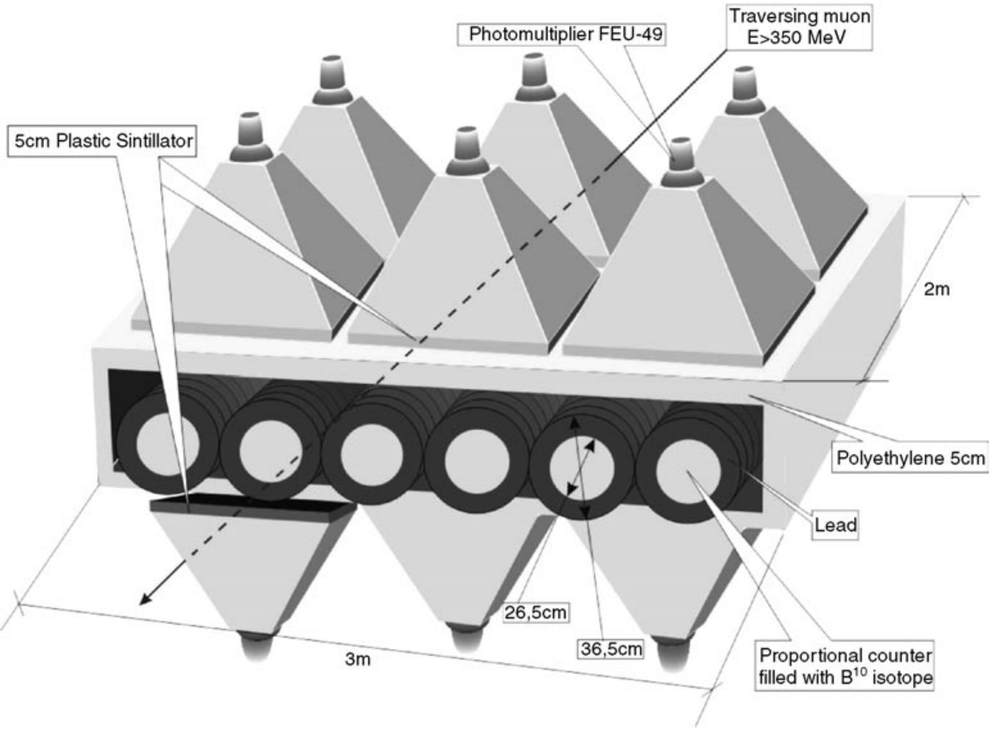

Figure 1. Nor Amberd multidirectional muon monitor installed around the 8-NM-64.

The EAS installations are triggered 3–5 times per min. The plastic scintillator–photomultiplier assemblies, symmetrically distributed over the ground surface, are used to measure charged particle densities and arrival times. The total area of the detectors of GAMMA and MAKET installations is about 150 m^2. The spacing between detectors varies from several metres to tens of metres.

In the underground hall originally constructed for the ANI cosmic ray experiment (Danilova *et al* 1992) another 150 of the same type of detectors are located to measure the muon content of the EAS. The 6 m thick concrete blocks plus 7 m soil filter the electrons and the low energy muons. Thus, only muons with energies >5 GeV reach the detectors. The count rates of the charged components at mountain altitudes are $\sim$420 counts/m^2/s for >10 MeV electrons and $\sim$50 counts/m^2/s for >5 GeV muons. These high count rates combined with the large area of the electron and muon detectors on Mt Aragats are very attractive for establishing a monitoring facility to investigate 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.

The count enhancements of the ASEC neutron monitors are integrated over all directions. In that case the question arises whether the signal enhancement is due to the solar particles or disturbance of the Earth's magnetic field inducing a temporary decrease of the local rigidity threshold (see, for example, Kudela and Storini (2001)). The scattering of the high energy muons in the atmosphere is negligible, therefore by measuring the incident muon direction we can determine the direction of the coming solar and galactic ions. It will give us additional evidence on the registration of solar particles. The Aragats multidirectional muon monitor (AMMM) consists of 15 m^2 scintillation detectors located on the top of the ANI concrete calorimeter and 72 m^2 array of same type detectors 24 m below. Using the coincidence technique we can monitor changing count rates from numerous space directions. Detectors on the top are grouped into three, while those in the underground hall are grouped into eight to provide significant amount of coincidences. The geometry of the detector arrangement will allow us to detect directions from the vertical to 60° declination with accuracy of $\sim 5^\circ$ with very good statistics.

Measuring the intensity deficit of the galactic cosmic rays, it will be possible to determine the loss cone direction and perform 'screening' of approaching magnetized plasma cloud. The worldwide network of the muon monitors covering as much as possible incident directions could be used for the early forecasting of the upcoming severe geomagnetic storm (Munakata *et al* 2000). Along with the Moscow TEMP muon telescope (Borog *et al* 2001) the AMMM could improve sky coverage when combined with present muon detector network.

The top layer of the AMMM can be used separately as the electron and low energy muon monitor with sensitivity of 0.15% for 1 min counts. The short scale variations in the low energy charged particle fluxes are of major interest for correlation analysis with high energy muon and neutron data. The lower layer of the AMMM constitutes a very sensitive high energy muon monitor, robust to local atmospheric conditions due to the rather high energy threshold. Total count rate of the monitor is approximately $\sim 200\,000$ min^{-1}. Thus, the sensitivity of this monitor reaches a record value of $\sim 0.2\%$ for 1 min count rates, three times better compared to that of the Aragats NM. Simultaneous detection of variations in low energy charged particles in neutron and high energy muon fluxes by ASEC monitors, with characteristics given in table 1, will provide new possibilities for investigating the transient solar events and will allow us to classify GLEs according to their origin and physical nature.

4. Calculated arrival times of the relativistic solar ions at 1 AU and enhancements registered by ASEC monitors

The expected arrival times of the SEP relativistic ions at 1 AU are calculated by the technique proposed in Lockwood *et al* (1990) and Fluckiger (1991) and successfully applied by Krucker and Lin (2000) for data analysis from the spectroscopic survey telescopes on board of WIND satellite (Lin *et al* 1995). We apply the same technique to estimate the relativistic particle arrival at the location of ASEC monitors. We use the arrival times and energies of the first ions registered by the solar isotope spectrometer (SIS) on board of the ACE satellite (Stone *et al* 1998), and protons, registered by GOES satellites (GOES, internet). We assume that the first ions of all energies are accelerated in one and the same spatial region and that interplanetary propagation of the high energy ions is essentially scatter free (see Kahler (1994)). It was demonstrated in Krucker and Lin (2000) that the path length of 6 MeV protons at 1 AU is very close to the Parker spiral length. Therefore, the arrival times of the ions of different energies will be linearly correlated with the inverse of their speed. We can extrapolate the velocity–time relationship to calculate the expected arrival times of the first relativistic ions that are energetic enough to enter the atmosphere at the Aragats geographical location and produce secondary fluxes that reach the ASEC monitors. We calculate the threshold values of ion velocities (unique to each ion) for which secondary particles will reach the Aragats monitors. Then we check the correctness of our assumptions by calculating the correlation coefficients of the linear regressions. The reconstructed regression lines for some of the events are shown in figure 2. All correlations are greater than 0.96, thus justifying the validity of the proposed technique to estimate the arrival times of the first ions and protons at the location of the ASEC monitors.

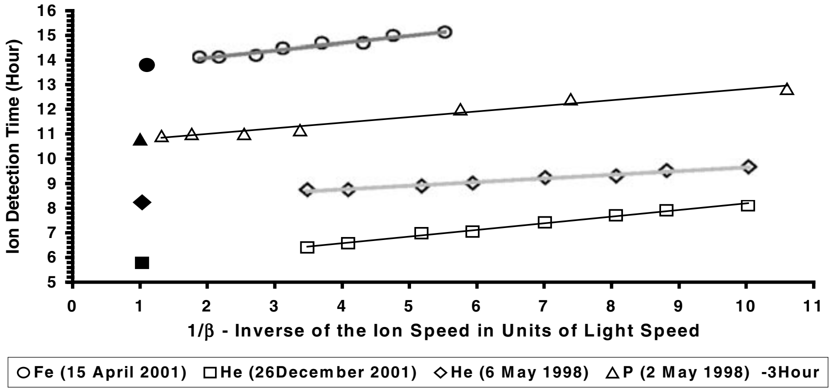

Figure 2. Linear correlation of ion arrival times at 1 AU versus their inverse speed. The filled symbols correspond to the expected arrival times of relativistic ions. The proton event is shifted down by 3 h for better visualization of the regression lines.

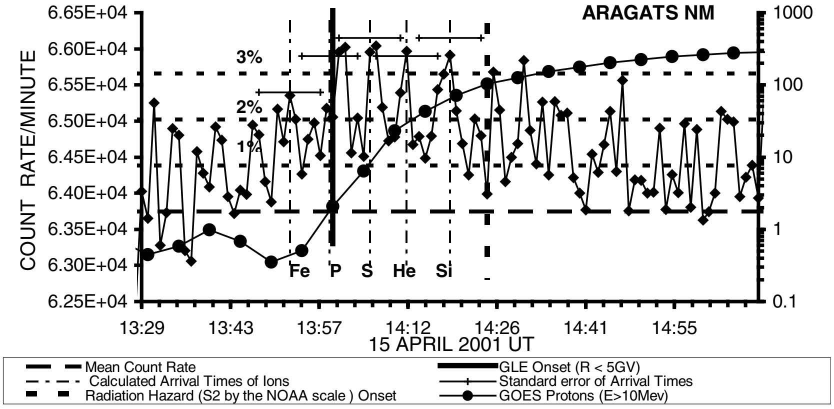

Figure 3. The 15 April 2001 GLE. Estimated arrival times of relativistic ions superimposed on the ANM 1 min time series. Horizontal dashed lines indicate 1, 2 and 3% enhancements relative to mean count rate.

Figure 3 shows the 15 April 2001 GLE, registered by the ANM and expected arrival times of the various species of ions calculated as in figure 2. The solid vertical line denotes the onset time of the GLE registered by the high latitude neutron monitors with rigidities $R <$ 5 GeV. The vertical dashed line indicates the time of the S2 type radiation storm onset. The estimated expected arrival times of different species of ions (Fe, P, S, He and Si) are denoted by the vertical dashed-dotted lines. Each expected arrival time is associated with an error bar indicated on the graph.

The overall pattern of the peaks seems to fit the expected arrival times of the various species rather well. For more firm inference on the possibility of ‘ion spectroscopy’ with ground-based monitors we also need to register fluxes of the muons and electrons in correlation with the neutrons, now possible and in process at the ASEC since the summer of 2002.

The characteristics of four GLE events are summarized in table 2. Column 5 shows the calculated expected arrival time of the particular ion species at the location of the ASEC monitors. Column 6 shows the time of the first large peak in the Aragats NM time series

Table 2. Characteristics of the GLE detected by ACE/SIS, GOES-8 and ASEC detectors.

Date (order no of GLE)	Flare importance category	First ion type	Correlation coefficient of the linear regression	Calculated arrival time at 1 AU in UT	GLE start at ASEC, in UT	Estimates of significance %	I (E_p>10 MeV) > 100 cm^{-2}.s.sr. S2 onset, UT[a]
02-05-1998 (56)	X1.1	P	0.97	13:43 ± 8.2 min	13:47	2.3 (3.2σ)	15:25
06-05-1998 (57)	X2.7	He	0.98	8:13 ± 4.6 min	8:08	2.4 (3.4σ)	9:15
15-04-2001 (60)	X14.4	Fe	0.96	13:52 ± 6.5 min	13:53	2.5 (3.6σ)	14:25
26-12-2001 (63)	M7.1	He	0.99	5:47 ± 5.4 min	5:52	2.4 (3.4σ)	6:35

[a] NOAA space weather scale for radiation storms.

indicating start of the GLE. Column 7 represents the significance of detected peaks in per cent (relative enhancement) and in the number of standard deviations (relative standard deviation of the ANM, $\sigma \sim 0.7\%$). For all four events the significance of the peak is greater than 3σ, thus the probability that the peak is due to random fluctuation only is very small. The last column shows the time of onset of the S2 type radiation storm during each event represented in figure 2. The S2 type radiation storm is characterized by count rates of >100 counts/cm^2/s for >10 MeV protons. According to the NOAA space weather scales for solar radiation storms (NOAA, SW scales), the intensity of the CR flux during the S2 type radiation storm is high enough to cause considerable difficulties for satellite operation.

5. Discussion

In all four cases of the GLE events described in the previous section, precursors of the S2 type radiation storms could be found in the 1 min time series of the ANM counts, which coincide, within the error bars, with the expected arrival times of the first ions accelerated at Sun. From table 2 we can see that these 'early' ions come about 32 to 67 min prior to the onset of the S2 type radiation storm. Of course, the actual forecasting will be much more difficult than our post-event analysis. Nevertheless, we want to emphasize the feasibility of space weather forecasting based on short-term enhancements of cosmic ray fluxes at mountain altitude. We also want to emphasize the possibility of enhancing the reliability of the prognosis significantly when using data from all the ASEC monitors. We plan to use not only the information about abrupt enhancements in cosmic ray fluxes, but also information contained in the correlation matrix of the measurements of the neutron, muon and electron fluxes. The significance of the information from the different measured components of the particle fluxes and the estimation of the forecasting efficiency versus the frequency of false alarms will be analysed in detail after completing the computer simulations of the various aspects of the Aragats alert service. These include particle propagation in the atmosphere, detector response sensitivity and alternative scenarios of alert triggering.

Here we want to discuss the overall possibilities of forecasting severe radiation storms by various experimental techniques. A variety of measurements of solar activity starting from radio-waves to gamma-rays can be used as precursors of severe radiation storms. Although numerous attempts of modelling the major SEP events have been conducted and this activity is getting more and more support (Boston University 2002), existing models are mostly phenomenological, because the basic knowledge about the consequence of energetic processes on the Sun is still not complete. Formal systems, such as neural network estimators, cannot provide reliable forecasting due to lack of training examples. Among the historically very severe SEPs, only the event from September 1989 was measured and documented well enough to be used for the neural network training.

Correlations between various characteristics of the solar energetic phenomena and spectra of accelerated ions and protons studied on smaller events in the absence of the analysis of data from severe events can be misleading when applied to forecasting of the major event. Only the high enough fluxes of the highest energy particles measured by an ensemble of surface detectors in combination with data from space-borne detectors can predict an upcoming severe radiation storm with any degree of reliability.

Below we present some advantages of using surface detectors at high altitudes and low latitudes in consort with the satellite-based sensors for the SEP forecasting.

- Low latitude monitors with high cut-off rigidities have the advantage over high latitude monitors, because the enhanced signal-to-noise ratio minimizes the 'false-alarm' rate increasing the possibility of early detection of low fluxes of highest energy ions. These ions can go undetected by the high latitude monitors, because their signal can be overwhelmed by the large background of galactic cosmic rays of lower energies at high latitude locations.
- The advantage of an alert service which utilizes data from the ground-based detectors over services which use satellite-based detectors only lies in the possibility of detecting ions of the highest energies. No instrument exists and nor has been envisioned for the flight that can measure high energy ions in SEP events (Reames 2000). Also it is worth mentioning that high intensity radiation has the potential of blinding the very system that warns against the SEP events.
- ASEC monitors provide precise information on short-term variations of three species of cosmic ray flux (electrons, muons and neutrons). Simultaneously detected abrupt changes of all three types of species count rates from the ASEC monitors will significantly improve reliability of forecasting.
- Directional information provided by the ASEC muon monitors will further enhance the signal-to-noise ratio and further improve the quality of forecasting.
- Along with count rates the correlation matrices of all ASEC measuring channels are calculated online as well, providing additional information on the nature and strength of the detected SEP.
- Measuring CR fluxes at two altitudes of 3200 m and 2000 m, gives additional information to estimate the spectra of SEP particles at highest energies and the 'knee' position of the spectra, most important for the calculation of expected radiation doze (Reames 2000).

The mentioned advantages of the SEP forecasting using surface detectors in addition to satellite-based instruments point to the necessity of improving the existing worldwide networks for measuring different species of cosmic ray fluxes along with the directional information. The detectors of the type presented in figure 1 distributed along different Earth longitudes and latitudes, preferably at high altitudes, connected with space-borne sensors via interplanetary internet connections will highly improve existing warning services.

6. Conclusion

Our analysis, based on the SEPs unleashing S2 type radiation storms, demonstrates that the large area ground-based neutron monitors on Mt Aragats in Armenia can detect the early arriving highest energy particles released near the Sun 30 to 70 min in advance of the arrival of the lower energy higher flux particles which can cause the damage to the satellites and humans in space. We have also designed detectors to measure directional information about the arriving radiation, which helps to enhance the signal-to-noise ratio. One of the very attractive features of the ASEC is its ideal geographical location—latitude and altitude—to maximize the signal-to-noise ratio. Finally, the variety of the types of monitors which allow us to measure all three species of cosmic radiation (electrons, muons and neutrons) simultaneously is a very important tool to increase the reliability of accurate forecasting and decrease the number of false alarms. Information from the ASEC ground-based detectors is an essential element to add to the information available from satellites for engineering an accurate and reliable early warning forecast of the most severe irruptions on the Sun directed towards Earth.

The influence of solar radiation on humans and orbiting technological system has been summarized in the Public Documents of the ESA Space Weather Programme Studies as follows: *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). These effects, as they are sporadic, are of major concern for space weather. Some of them are permanent, either directly (e.g., latchup, burnout) or indirectly (e.g., changes in permanent program memory).*

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 tumour induction. They can also induce cell mutation that can have effects on the genetics. Energetic ions and electrons locally increase dark currents in detectors. This effect is clearly visible from images on board Earth or Sun observatories. Energetic ions and electrons also produce atom displacements in solar cells, decreasing the output power. Energetic electrons as they penetrate inside the spacecraft produce internal charging and electrostatic discharges. The effect of discharges can be direct destruction but normally they create electromagnetic pulses which produce signals interpreted as false commands by onboard computers (Horne 2001, Koskinen *et al* 2001a, 2001b).

In 2001, Tylka stated the following: ‘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).

Nevertheless, we can optimistically look to the future. More and more of the measurements from worldwide network of ground-based neutron monitors are posted on the internet in real time. Soft x-ray, hard x-ray and gamma radiation detections by space-borne detectors are also posted on the internet in real time. There are plans to put the real-time Sun images from EIT and LASCO instruments of 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 from LASCO and EIT satellites will provide additional valuable information for forecasting the danger from the energetic solar events. The joint multidimensional multidetector analysis of all relevant information from space-borne and ground-based detectors, including the full complement of large ground-based detectors at ASEC, will minimize the number of false alarms and will maximize the reliability and timeliness of forecasting the arrival of the dangerous SEP.

Acknowledgments

The authors wish to thank the GOES and ACE groups for posting the data on the internet. Useful discussions with L Dorman of Israel Cosmic Ray Center, Y Muraki of Solar-Terrestrial

Laboratory, Nagoya University and M Panasyuk from Moscow State University, are highly appreciated. The work resulting in this paper was supported by the ISTC A216 and A757 projects and project number 1465 of the Republic of Armenia.

References

Aschwanden M J *et al* 1996 *Astrophys. J.* **468** 398
Aschwanden M J 2002 *Space Sci. Rev.* **101** 2
Babayan V Kh *et al* 2001 *Proc. 27th ICRC (Hamburg)* vol 9 p 3541
Barbosa D D 1979 *Astron. J.* **425** 383
Berghmans D 2001 *ESA Space Science News*, 2 December p 8
Borog V V *et al* 2001 *Proc. Russian Academy of Science (Physics Series vol 65)* p 381
Boston University 2002 *News Release* 19 Sept.
Bryant D A *et al* 1963 *Phys. Rev. Lett.* **11** 144
Cane H V 2000 *Highlight Talk, 27 ICRC (Hamburg)* ed R Schlickeiser p 311
Carmichael H 1964 *Cosmic Rays, IQSY Instruction Manual* (London)
Chilingarian A A *et al* 1999 *Proc. 26th ICRC (Salt Lake City)* vol 6 p 460
Chilingarian A A *et al* 2003a *Nucl. Instrum. Methods* A at press
Chilinagarian A A *et al* 2003b *Adv. Space Res.* at press
Chilingarian A A, Roth M and Vardanyan A A (KASCADE Collaboration) 1999b *Nucl. Phys.* B **75A** 302
Chupp E L *et al* 1982 *Astron. J. Lett.* **263** L95
Chupp E L *et al* 1987 *Astron. J.* **318** 913
Danilova T V *et al* 1992 *Nucl. Instrum. Methods* A **323** 104–7
Dorman L I and Venkatesan D 1993a *Space Sci. Rev.* **64** 183
Dorman L I, Iucci N and Villoresi G 1993b *Astrophys. Space Sci.* **208** 55
Dorman L I 1999 *Proc. 26th ICRC (Salt Lake City)* vol 6 p 382
Fluckiger E O 1991 Solar cosmic rays *Nucl. Phys.* B **22B** 1–20
Forbush S E 1946 Tree unusual cosmic ray increases possibly due to charge particles from the sun *Phys. Rev.* **70** 771
Forrest D J and Chupp E L 1983 *Nature* **305** 291
Garyaka A P *et al* 2002 *J. Phys. G: Nucl. Phys.* **28** 2317
GOES, NOAA geostationary satellite Webpage http://www.goes.noaa.gov
Horne R B 2001 ESA space weather programme study *Alcatel Consortium Benefits of a Space Weather Programme* Alcatel Consortium, British Antarctic Survey, Cambridge, UK
Hovsepyan G G 1998 *Proc. of Workshop ANI98 (Nor Amberd, 1998)* ed A Chilingarian p 45 (*WZK Preprint* N 6215)
Kahler S 1994 *Astron. J.* **428** 837
Kahler S W, McAllister A H and Cane H V 2000 *Astron. J.* **553** 1063
Kallenrode M-B and Wibberenz G 1997 *J. Geophys. Res* **102** 22311
Klein K-L *et al* 1999 Flare-associated energetic particles in the corona and at 1 AU *Astron. Astrophys.* **348** 271
Koskinen H *et al* 2001a *Space Weather Effects Catalogue* ESWS-FMI-RP-0001 Issue 2.2 January 2
Koskinen H *et al* 2001b *Rationale for a European Space Weather Programme* ESWS-FMI-RP-0002 Issue 2.3 March 30
Kosugi T *et al* 1991 *Sol. Phys.* **136** 17
Krucker S and Lin R P 2000 *Astron. J.* **542** L61
Kudela K and Storini M 2001 *Proc. SOLPA (Vico Equense, Italy)* p 289
Lin R P *et al* 1995 *Sol. Phys.* **71** 125
Lockwood J A, Debrunner H and Fluckiger E O 1990 *J. Geophys. Res.* **95** 4187
Masuda S *et al* 1994 *Nature* **371** 495
Matsubara Y *et al* 1999 *Proc. of 26th ICRC (Salt Lake City)* vol 6 p 42
Meyer P, Parker E N and Simpson J A 1956 *Phys. Rev.* **104** 768
Miller J A, Guessoum N and Ramaty R 1990 *Astron. J.* **361** 701
Miroshnichenko L I 2001 *Solar Cosmic Rays* (Dordrecht: Kluwer)
Moraal H, Belov A and Clem J M 2000 *Space Sci. Rev.* **93** 285–303
Munakata K *et al* 2000 Bartol Research Institute *Preprint* BA-00-11
NOAA SW scales Webpage http://sel.noaa.gov/NOAAscales
Reames D V 1999 *Space Sci. Rev.* **90** 413
Reames D V 2000 SEPs: space weather hazard in interplanetary space *Space Weather (Geophysical Monograph 125)* ed P Song and H J Singer (Washington, DC: American Geophysical Union) p 101

Shea M A and Smart D F 2000 *Space Sci. Rev.* **93** 229–62
Space Studies Board 1999 *Radiation and the International Space Station* (Washington, DC: National Academy Press) p 7, 21
Stone E C *et al* 1998 *Space Sci. Rev.* **86** 357
Tsuchiya H *et al* 2001 *Proc. 27 ICRC (Hamburg)* vol 8 pp 3040–3
Tylka A J *et al* 2001a *Proc. 27 ICRC (Hamburg)*
Tylka A J, Dietrich W F, Lopate C and Reames D V 2001b *Proc. 27 ICRC (Hamburg)*
Tylka A J 2001 AGU publication N 2000JA004028