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Great SEP events and space weather: 1. Experience of automatically searching for event beginnings; probabilities of false and missed alerts

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It is well known that in periods of great SEP, fluxes of energetic particles can be so big that memory of computers and other electronics in space may be destroyed. These periods are also dangerous for astronauts on space-ships, and passengers and crew in commercial jets. The problem is how to forecast exactly these dangerous phenomena. We show that exact forecast can be made by using high-energy particles (few GeV/nucleon and higher) for which transportation from the Sun is characterized by much bigger diffusion coefficients than for small and middle energy particles. Therefore, high energy particles come from the Sun much earlier (8-20 minutes after acceleration and escaping into solar wind) than the main part of smaller energy particles, which cause a dangerous situation for electronics (about 30-60 minutes later). We describe here principles and experience of automatically working the program "SEP-Search". The positive result which shows the exact beginning of SEP event on the Emilio Segre' Observatory (2025 m above sea level, R_c = 10.8 GV), is now determined automatically by simultaneously increasing by 2.5 St. Dev. in two sections of the neutron supermonitor. The next 1-min of data the program "SEP-Search" uses for checking if the observed increase reflects the beginning of real great SEP or not. If yes, it automatically starts to work on line the program "SEP-Research". We also determine the probabilities of false and missed alerts. The work of the NM on Mt. Hermon is supported by Israel (Tel Aviv University and ISA) – Italian (UNIRoma-Tre and IFSI-CNR) Collaboration.

1. Data from the past and classification of space weather radiation hazard (NOAA classification and its modernization)

NOAA Space Weather Scale establishes 5 gradations of SEP events, which are called Solar Radiation Storms: from S5 (the highest level of radiation, corresponding to the flux of solar protons with energy >10 MeV about $10^5\, protons.\, cm^{-2}.\sec^{-1}$) up to S1 (the lowest level, the flux about 10 $protons.\, cm^{-2}.\sec^{-1}$ for protons with energy >10 MeV). In our opinion, by ground level CR neutron monitors and muon telescopes it is possible to monitor and forecast (using much higher energy particles than the smaller energy particles that cause the main radiation hazard) SEP events of levels S5, S4 and S3. With the increase of an SEP event's level of radiation, the accuracy of forecasting will increase. We have two comments to the NOAA classification: 1. For satellite damage and influence on people's health and technology, and for communications by HF radio-waves, the total fluency of SEP during the event is more important than the proton flux that is used now in the NOAA Space Weather Scale. 2. The level S5 (corresponding to a flux of $10^5\, protons.cm^{-2}.\sec^{-1}$, or fluency $F \approx 10^9\, protons.cm^{-2}$ for protons with $E_k \geq 10\, MeV$) is not maximal; the maximal level can be much higher, but with much smaller probability than S5. As it was shown in [1], the dependence of event probability on fluency can be prolonged at least up to $F = 2\times 10^{10}\, protons.cm^{-2}$ for protons with $E_k \geq 30\, MeV$, which was observed in SEP of September 1869 according to data of nitrate contents in polar ice. This type of greatly dangerous event is very rarely (about one in a few hundred years). According to [1], it is not excluded that in principle very great SEP events with fluency in 10 and even in 100 times bigger (correspondingly one in few thousand and one in several tens of thousands of years) can occur. So, we suppose to correct the very important classification, developed by NOAA, in two directions: to use fluency F of SEP during all event (in units $protons.cm^{-2}$) instead of flux I, and to add levels of radiation hazard. As result, the modernized classification of SEP events is shown in Table 1.

Table 1. Extended NOAA Space Weather Scale for Solar Radiation Storms

SEP events radiation hazard			**Fluency ≥30MeV protons**	**Frequ-ency**
S7	**Ultra extreme**	**Biological:** Lethal dose for astronauts, for passengers and crew on commercial jets; great influence on people health and gene mutations on the ground **Satellite operations:** very large damages to satellites' electronics and computers' memory, damage to solar panels, loss of many satellites **Other systems**: complete blackout of HF (high frequency) communications through polar and middle-latitude regions, big position errors make navigation operations extremely difficult.	10^{11}	**One in a few thousand years**
S6	**Very extreme**	**Biological:** About lethal dose for astronauts, serious influence on passengers and crew health on commercial jets; possible influence on people health and gene mutations on the ground **Satellite operations:** a big damage to satellites' electronics and computers' memory, damage to solar panels, loss of several satellites **Other systems**: complete blackout of HF communications through polar regions, some position errors make navigation operations very difficult.	10^{10}	**One in a few hundred years**
S5	**Extreme**	**Biological:** unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); high radiation exposure to passengers and crew in commercial jets at high latitudes (approximately 100 chest X-rays) is possible. **Satellite operations:** satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Other systems:** complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^{9}	**One in 20-50 years**
S4	**Severe**		10^{8}	**One in few years**
S3	**Strong**		10^{7}	**One per year**

2. The method of automatically searching for the start of great SEP events

Let us consider the problem of automatically searching for the start of great SEP events. Of course, the patrol of the Sun and forecast of great solar flares are very important, but not enough; only a very small fraction of great solar flares produce dangerous SEP events. As we mentioned in the Abstract, this forecast can be made by using high-energy particles (few *GeV/nucleon* and higher) whose transportation from the Sun is characterized by much bigger diffusion coefficients than for small and middle energy particles. Therefore high-energy particles arrive from the Sun much earlier (8-20 minutes after acceleration and escaping into solar wind) than the lower energy particles that cause the dangerous situations in space and in the atmosphere. The flux of high-energy particles is very small and they are not dangerous for people and electronics. The problem is that this very small flux is very difficult to measure with enough accuracy on satellites used for forecasting (it needs a very large effective surface for the detector and a very large weight). On the other hand, high-energy particles of galactic or solar origin are measured continuously by ground-based neutron monitors, ionization chambers and muon telescopes with very large effective surface areas (many square meters) that provide very small statistical errors. We show on the basis of data in periods of great historical SEP events that one-minute on-line data of high energy particles could be used for the forecasting of incoming dangerous fluxes of particles with much smaller energy. Let us describe the principles and on-line operation of programs "SEP-Search-1 min", "SEP-Search-2 min", and so on, developed and checked in the Emilio Segre' Observatory of ICRC. The determination of increasing flux is made by comparison with intensity averaged from 120 to 61 minutes before the present Z-th one-minute data. For each Z minute data, start the program "SEP-Search-1 min". The program for each Z-th minute determines the values

$$D_{A1Z} = \left[\ln(I_{AZ}) - \sum_{k=Z-120}^{k=Z-60} \ln(I_{Ak})/60 \right] \Big/ \sigma_1 \,, \tag{1}$$

$$D_{B1Z} = \left[\ln(I_{BZ}) - \sum_{k=Z-120}^{k=Z-60} \ln(I_{Bk})/60 \right] \Big/ \sigma_1 \,, \tag{2}$$

where I_{Ak} and I_{Bk} are one-minute total intensities in the sections of neutron super- monitor *A* and *B*.
If simultaneously

$$D_{A1Z} \geq 2.5,\ D_{B1Z} \geq 2.5, \tag{3}$$

the program "SEP-Search-1 min" repeats the calculation for the next Z+1-th minute and if Eq. 3 is satisfied again, the onset of great SEP is determined and program "SEP-Research/Spectrum" starts.
If Eq. 3 is not satisfied, the program "SEP-Search-2 min" searches for the start of an increase by using two-min data characterized by $\sigma_2 = \sigma_1/\sqrt{2}$. In this case, the program "SEP-Search-2 min" will calculate values

$$D_{A2Z} = \left[\left(\ln(I_{AZ}) + \ln(I_{A,Z-1})\right) \Big/ 2 - \sum_{k=Z-120}^{k=Z-60} \ln(I_{Ak}) \Big/ 60 \right] \Big/ \sigma_2 \,, \tag{4}$$

$$D_{B2Z} = \left[\left(\ln(I_{BZ}) + \ln(I_{B,Z-1})\right) \Big/ 2 - \sum_{k=Z-120}^{k=Z-60} \ln(I_{Bk}) \Big/ 60 \right] \Big/ \sigma_2 \,, \tag{5}$$

If the result is negative (no simultaneous increase in both channels of total intensity $\geq 2.5\,\sigma_2$, i.e. the condition $D_{A2Z} \geq 2.5,\ D_{B2Z} \geq 2.5$ fails), then "SEP-Search-3 min" uses the average of three minutes Z-2, Z-1 and Z with $\sigma_3 = \sigma_1/\sqrt{3}$. If this program also gives a negative result, then the program "SEP-Search-5 min" uses the average of five minutes Z-4, Z-3, Z-2, Z-1 and Z with $\sigma_5 = \sigma_1/\sqrt{5}$. If this program also gives negative result, i.e. all programs "SEP-Search-*K* min"(where *K* = 1, 2, 3, 5) give negative result for the Z-th minute, it means that in the next 30-60 minutes there will be no radiation hazard from small energy particles (for this minute in our website appears: **Alert – NO**). After obtaining this negative result, the procedure repeats for the next, Z+1-th minute, and so on. If any positive result is obtained for some Z=Z', the "SEP-Search" programs checked the next Z'+1-th minute data. If the result is again positive, then for this minute in our website appears: **Alert – YES**, and the program "SEP-Research/Spectrum" starts.

3. The probability of false alarms

Because the probability function $\Phi(2.5) = 0.9876$, the probability of an accidental increase with amplitude more than 2.5σ in one channel will be $(1 - \Phi(2.5))/2 = 0.0062\,\text{min}^{-1}$, or one in 161.3 minutes (in one day we expect 8.93 accidental increases in one channel). The probability of accidental increases simultaneously in both channels will be $((1-\Phi(2.5))/2)^2 = 3.845\times10^{-5}\ \mathrm{min}^{-1}$, or one in 26007 minutes ≈ 18 days. The probability that the increases of 2.5σ will be accidental in both channels in two successive minutes is equal to $((1-\Phi(2.5))/2)^4 = 1.478\times10^{-9}\ \mathrm{min}^{-1}$ that means one in 6.76×10^8 minutes ≈1286 years. If this false alarm (one in about 1300 years) is sent, it is not dangerous, because the first alarm is preliminary and can be cancelled if in the third successive minute is no increase in both channels bigger than 2.5σ (it is not excluded that in the third minute there will be also an accidental increase, but the probability of this false alarm is negligible: $((1-\Phi(2.5))/2)^6 = 5.685\times10^{-14}\ \mathrm{min}^{-1}$ that means one in 3.34×10^7 years). Let us note that the false alarm can also be sent in the case of a solar neutron event (which really is not dangerous for electronics in spacecrafts or for astronauts' health), but this event usually is very short (only few minutes) and this alarm will be automatically canceled in the successive minute after the end of a solar neutron event.

4. The probability of missed triggers

The probability of missed triggers depends very strongly on the amplitude of the increase. Let us suppose for example that we have a real increase of 7σ (that for ESO corresponds to an increase of about 9.8 %). The trigger will be missed if in either of both channels and in either of both successive minutes if as a result of statistical fluctuations the increase of intensity is less than 2.5σ. For this the statistical fluctuation must be negative with amplitude more than 4.5σ. The probability of this negative fluctuation in one channel in one minute is equal $(1-\Phi(4.5))/2 = 3.39\times10^{-6}\ \mathrm{min}^{-1}$, and the probability of missed trigger for two successive minutes of observation simultaneously in two channels is 4 times larger: 1.36×10^{-5}. This means that a missed trigger is expected only one per about 70000 events. In Table 2 probabilities P_{mt} of missed triggers for ESO (where the standard deviation for one channel for one minute σ=1.4%) are listed as a function of the amplitude of increase *A*.

Table 2. Probabilities P_{mt} of missed triggers as a function of amplitude of increase *A* (in % and in σ)

A, %	4.9	5.6	6.3	7.0	7.7	8.4	9.1	9.8	10.5
A, σ	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5
P_{mt}	6.3×10^{-1}	2.7×10^{-1}	9.1×10^{-2}	2.5×10^{-2}	5.4×10^{-3}	9.3×10^{-4}	1.3×10^{-4}	1.4×10^{-5}	1.1×10^{-6}

5. Discussion and conclusion

Obtained results show that the considered method of automatically searching for the onset of great, dangerous SEP on the basis of one-minute NM data practically does not give false alarms (the probability of false preliminary alarm is one in about 1300 years, and for false final alarm one in years). Non-dangerous solar neutron events also can be separated automatically. We also estimated the probability of missed triggers; it was shown that for events with amplitude of increase of more than 10% the probability of a missed trigger for successive two minutes of NM data is smaller than 1.36×10^{-5} (this probability decreases sufficiently with increased amplitude *A* of the SEP increase, as shown in Table 2). Historical ground SEP events show very fast increase of amplitude in the start of event. For example, in great SEP event of February 23, 1956 amplitudes of increase in the Chicago NM were at 3.51 UT - 1%, at 3.52 UT – 35%, at 3.53 UT – 180%, at 3.54 UT – 280 %. In this case the missed trigger can be only for the first minute at 3.51 UT. The described method can be used in many CR Observatories where one-minute data are detected. Since the frequency of ground SEP events increases with decreasing cutoff rigidity, it will be important to introduce the described method in high latitude Observatories. For low latitude CR Observatories the SEP increase starts earlier and the increase is much faster; this is very important for forecasting of dangerous situation caused by great SEP events.

References

[1] K.G. McCracken et al., *Proc. 27th ICRC*, Hamburg, **8**, 3209 (2001).