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THE CORRELATIONS BETWEEN GLE FINE STRUCTURE AND PRIMARY ION TYPE

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ABSTRACT

Correlation analysis of satellite detector data and ground based detector data could bring understanding of the different channels of ion acceleration at the Sun and in interplanetary space. A new approach to integrate the data from satellite spectrometers and data from surface detectors, corresponding to higher energy primary ions, is proposed in the present report. Taking as an example the 15 April 2001 event we examine the short-term enhancements of count rates detected by the ground-based Neutron Monitors located at the Mount Aragats Space-Environmental Center in Armenia due to fluxes of high energy ions accelerated by shock waves from Coronal Mass Ejections and within solar flares. We correlate these results with the data for lower energy ion spectra as detected by the Solar Isotope Spectrometer on board of ACE satellite. Correlations of data from the ACE/SIS and SOHO/LASCO instruments allow us to determine the injection location and time near the sun of the different ions.

INTRODUCTION

Galactic cosmic rays interacting with the atmosphere create fluxes of secondary particles. The intensities of these fluxes, as measured at different geographical positions by various particle detectors, are characterized mostly by geophysical conditions of the site, 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 report we will examine short term enhancements of count rates in surface detectors due to the fluxes of high energy ions incident on the Earth's atmosphere. We suppose that these ions were accelerated by Solar flares (Sf) and by shock waves from Coronal Mass Ejections (CME).

The first experimental evidence of Ground Level Enhancement (GLE) of the count rates at ground based detectors due to CME was observed in 1942 with Ionization Chambers at Cheltenham, Maryland by Scott Forbush (Forbush, 1946). Correlating detected GLEs with large solar flares, Forbush concluded that the cause of the rise in the neutron detector counts on earth is the flux of charged particles, accelerated during large disturbances on the Sun, reaching Earth.

Established in the 50's (Carmichael, 1964)**,** the world-wide network of Neutron Monitors (NM) provides more detailed data on GLE. Combined analysis of the GLE detected by NM located at different latitudes (and assuming that the accelerated solar particles were protons) allowed the estimation of the energy spectra of the solar proton flux and it's time dependence, (Meyer, et al., 1956).

In the 60's satellite detectors measured precise proton energy spectra for energies from 1 MeV up to 500 MeV and helped to establish correlation between increases of particle fluxes at 1 AU away from the earth, with Forbush decreases (Fd) on earth, as well as sudden commencement of the geomagnetic storms from the sun (Bryant et al., 1963).

The continuous monitoring of the low and medium energy cosmic rays in space began with the launch of particle spectrometers in space-borne satellites starting from the 70's. Time histories of the simultaneously detected X-rays, gamma-rays, electrons and ions of different energy and charge using space-borne detectors, combined with the detection of the developing flares and coronal mass ejections using coronagraphs on the ground helped to create a comprehensive picture of the major solar events that include the highest energy ions giving rise to GLEs (Reames, 1999). New Instruments on WIND and ACE satellites operating with geometry factors of ~100 times larger than those of previous apparatus, provided detailed data on temporal evolution in composition and spectra over a wide range of energies and species (Tylka, 2001a).

ION ACCELERATION MECHANISMS

Two types of solar events which accelerate particles – impulsive and gradual - were categorized and described in numerous publications, see for example (Mazur, 2000).

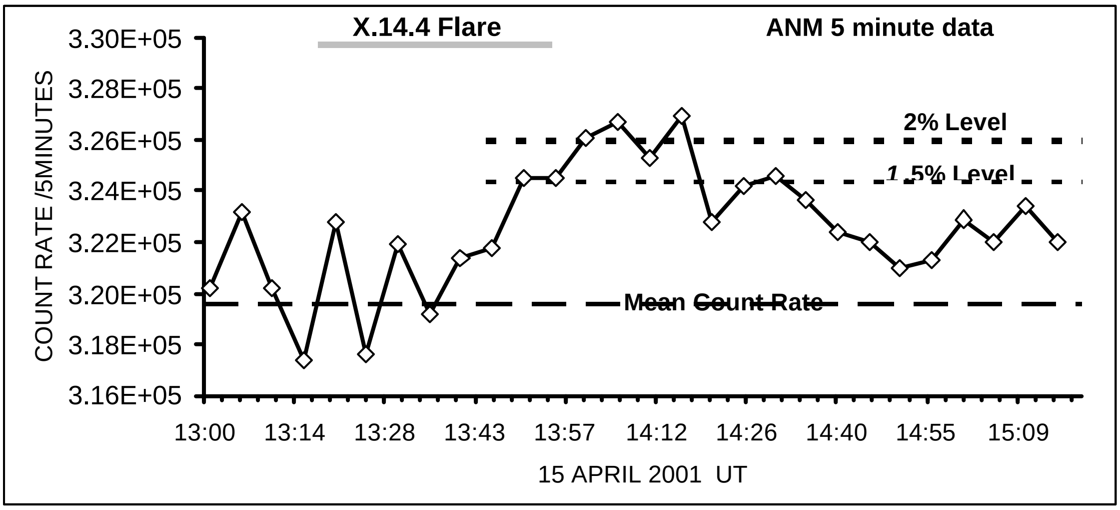
Impulsive flare events are believed to accelerate electrons and ions in very large closed magnetic structures, solar magnetic arcades (loops) with radii 40,000 – 100,000 km. These magnetic structures are created from reconnected magnetic lines previously opened by the CME. The electron beams (10 – 100 KeV) streaming along these magnetic tubes excite the plasma oscillations resulting in specific radio-frequency wave emission, so called fast-drift bursts (type III radio-bursts). Comparison of the time profiles of the type III radio-burst and of the X-ray continuum radiation, implied a low plasma density at the electron acceleration site. This acceleration site is estimated to be ~1.7 times the loop radius (Aschwanden, 1996). Electrons streaming downward generate electromagnetic ion cyclotron waves (Temerin & Roth, 1992), interacting with ambient ions according to their gyrofrequences. Depending on the ion charge-to-mass ratio, several ions will be predominantly accelerated via the ion-wave resonant process. The described mechanism gives a plausible explanation for the detected ion abundances, particularly for the large enhancement of the ^{3}He/^{4}He ratio in "impulsive" events.

The field above the acceleration region is magnetically open for the out-flowing electrons and ions. Ions traveling upward will be injected in the interplanetary space. If the flare site is magnetically connected to Earth, ions will be detected by the orbiting isotope spectrometers at 1 AU. If escaping ions are energetic enough, they will cause major ground level enhancement detected by the surface detectors. Ions moving downstream and reaching dense regions of the chromosphere will generate gamma rays, hard X-rays and neutrons in nuclear reactions. High energy neutrons could escape into interplanetary space and reaching Earth, raise the high altitude large area ground-based monitor count rates (Tsuchiya, 2001).

Gradual events are associated with CME propagation in corona and in the interplanetary space. The stochastic acceleration in shock waves is believed to be one of the major mechanisms in the Universe for accelerating particles to highest energies. Self-generated Alfven waves are believed to effectively trap energetic ions. The 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). The elemental composition of gradual events resembles the corona composition and the charge-states will be significantly less compared to impulsive events due to lower corona temperature ~ 2 million degrees Centigrade, as apposed to up to 10 million degrees Centigrade at flare sites).

The onset of the highest energy ions which reach Earth and produce the GLE will coincide with the maximal CME speed V ($E_{max} \sim V^4$) . Therefore, the onset of highest energy ions is expected to be near the Sun, before the evolving shock speed fades at greater distances. For large Solar Energetic Particle (SEP) events the CME speed reaches values of ~2000 km/sec. For the biggest SEP event ever registered, the so-called Carrington event, CME speed may have reached 5000 km/sec (Carrington, 1859). Passage of the CME in middle and high corona is accompanied with the so-called type II and type IV slow-drift radio-bursts, starting after the onset of type III radio-bursts. (Klein, 2000).

There are many unanswered questions concerning the details of the CME-SEP and Flare-SEP relationship. Sometimes both scenarios are claimed to be mutually exclusive for the acceleration of solar particles to the highest energies (Klein, 1999, Kahler, 2000). However, today it is widely accepted that we need more than one mechanism to explain ion acceleration to highest energies (Mazur, 2000). Long awaited direct measurements of the hard X-ray/γ-ray continuum and γ-ray lines by the RHESSI satellite (R.P.Lin et.al, 2000) are now available after the launch of the satellite in February, 2002. Measurements from HESSI will bring the most direct information on the spatial and temporal distributions of the accelerated electrons and ions, but we think that the surface measurements, correlated with ACE/SIS and WIND satellite data will give valuable additional information. This additional information refers to the spectra of the accelerated ions at highest energies. The maximum energy attainable by the shock-wave acceleration depends on the shock-wave speed and the height of the onset of the shock-wave in the corona. Shock waves as fast as ~1500 km sec^{-1} starting below ~5R_{sun} can accelerate ions up to 10-30 GeV (Tylka et.al., 2001b). Ions of these highest energies reaching Earth will generate secondary fluxes of cosmic rays reaching mountain altitudes and generate ground level excesses in neutron, muon, and electron detectors. Similar to the



physics of the galactic cosmic rays, the most important and interesting issue is the detection of the solar accelerated particles of highest energies and the estimation of the energy of the "spectral knee". The determination of the spectral knee energy will also have significant practical importance in forecasting the severity of the radiation hazard to the Space Station crew (Reames, 2000).

Figure 1. Aragats Neutron Monitor 5 minute count rates at 15 April 2001.

The knee energy of the spectra of large solar events can exceed the maximum energies detectable with space-born detectors (< 500 MeV for protons and < 200 MeV/nucleon for ions). Only the joint observation by satellite and surface monitors can provide sufficient information to estimate the energy spectra and fluence of the solar event, and therefore, the expected hazard from the SEP.

Unfortunately, ground based detectors cannot identify the type of the primary ions responsible for the peaks in the count rates. As a result, the universal assumption is made that the initial particles are protons, although some great events have proven that the iron nuclei spectrum is much harder than the proton spectrum (Tylka et al., 2001b). Nevertheless, we will demonstrate that the peak pattern of the GLE in different secondary fluxes is correlated with energetic particles incident on the atmosphere and, if properly analyzed, will provide clues for the identification of the species of the highest energy ions incident on Earth's atmosphere.

EXPECTED ARRIVAL TIMES OF SOLAR IONS AT 1AU AND GLE FROM 15 APRIL 2001

A world-wide network of Neutron Monitors has registered the GLE correlated with the 15 April 2001 X14.4 X-ray flare. The monitors at the Aragats Space-Environmental Center (ASEC, Chilingarian et. al., 2002) in Armenia also detected GLE during this event. Figure 1 shows the characteristics of the flare along with 5-minute counts from the Aragats Neutron Monitor (ANM). The relative statistical variability (r.m.s. deviation devided to the mean) of the ANM 5 minute count rate is σ ~0.5%. The greater than 2% enhancements in 5-minute count rates of ANM apparent from Figure 1 correspond to the significance of peaks more than 4σ. Therefore, we can conclude that the Aragats Neutron Monitors registered GLE in correlation with the X14.4 flare on April 15, 2001.

The expected arrival times of the relativistic ions at 1 AU are estimated by the technique proposed in (Lockwood et. al., 1990). 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 the spatial-temporal history of the accelerated ions. Data from the Solar Isotope Spectrometer (SIS) in the ACE satellite (Stone et al., 1998), was used for joint analysis with the data from the Aragats Neutron Monitor. We assume that the first ions of all energies are accelerated in the spatial region limited by a few Sun radii and that interplanetary propagation of the high energy ions is essentially scatter-free (Lockwood et.al, 1990b and Fluckiger, 1991). Therefore the arrival times of the ions of different energy will be linearly correlated with the inverse of the speed of the ions. Given that the satellite spectrometer maximum detectable energy is at most approximately 500 MeV for protons and less than 200 Mev/n for nuclei, we can extrapolate the velocity-time relationship obtained by the SIS data (8 energy intervals) to calculate the expected arrival time of the ions that are energetic enough to enter the atmosphere at the Aragats geographical location (geomagnetic rigidity 7.6 GV) and produce secondary fluxes that reach the ASEC monitors. We can check the correctness of our assumptions by calculating the correlation coefficient of the linear regression. The reconstructed regression lines for some of the ions are shown in Figure 2. All correlations are greater than 0.9, thus justifying the validity of the proposed technique for estimation of the arrival times of ions at location of ASEC monitors. From figure 2 we can also see that arrival times at 1 AU of the highest energy ions, are grouped into 2 subintervals:

- 13:11-13:47 for the C,N,O,Ne,Mg and Fe ions (coinciding with flare time);
- 14:03-14:20 for He, Si and S (far beyond the flare time).

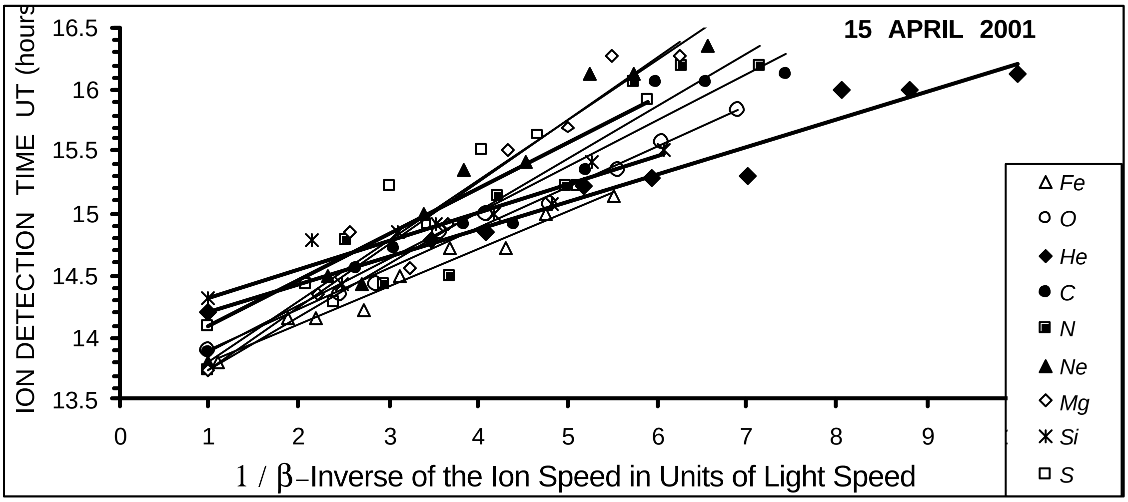


Figure 2. Reconstructed "energy"-time profiles of accelerated ions using data from ACE/SIS and the Aragats Neutron Monitor. 1/β=1 corresponds to the arrival of the speed of light ions to 1 AU from Earth

Taking into account the rigidity cutoff R_c and corresponding energy and velocity cutoffs (E_c , β_c) of ions at different geographical latitudes we can calculate the expected "time span" when particle cascades can reach surface monitors at different geographical locations and induce peaks in count rates. Table 1, shows the calculated time span of the expected arrival times of different ions at low and high latitude Neutron Monitors. It is clear that only monitors located at low enough latitudes, with Magnetic Rigidity R_c > 7GV, are able to correlate the peaks in 1 minute count rates with the arrival of different ions. Thus only detectors at the Mt. Hermon and Mt. Aragats are suited for this purpose. The time span of the high latitude monitors is too large to allow any correlation with expected arrival times of ions.

Table 1. Calculated time spans of expected arrival times of different ions for low and high latitude NM

Neutron Monitor	Rigidity Cutoff R_c GV	He (Z=2)		O (Z=8)		Fe (Z=15)	
		E_c Mev/n	Δ? min	E_c Mev/n	ΔT min	E_c Mev/n	Δ? min
Mt. Hermon, Israel	10.80	4543	**0.20**	4543	**0.29**	2102	**0.92**
Mt. Aragats, Armenia	7.58	2966	**0.40**	2966	**0.59**	1298	**1.78**
Jungfraujoch, Swiss	4.61	1550	**1.07**	1550	**1.58**	612	**4.52**

Moscow Russia	2.43	597	**3.51**	597	**5.19**	204	**13.30**
Oulu, Finland	0.78	78	**21.43**	78	**31.67**	23	**64.02**

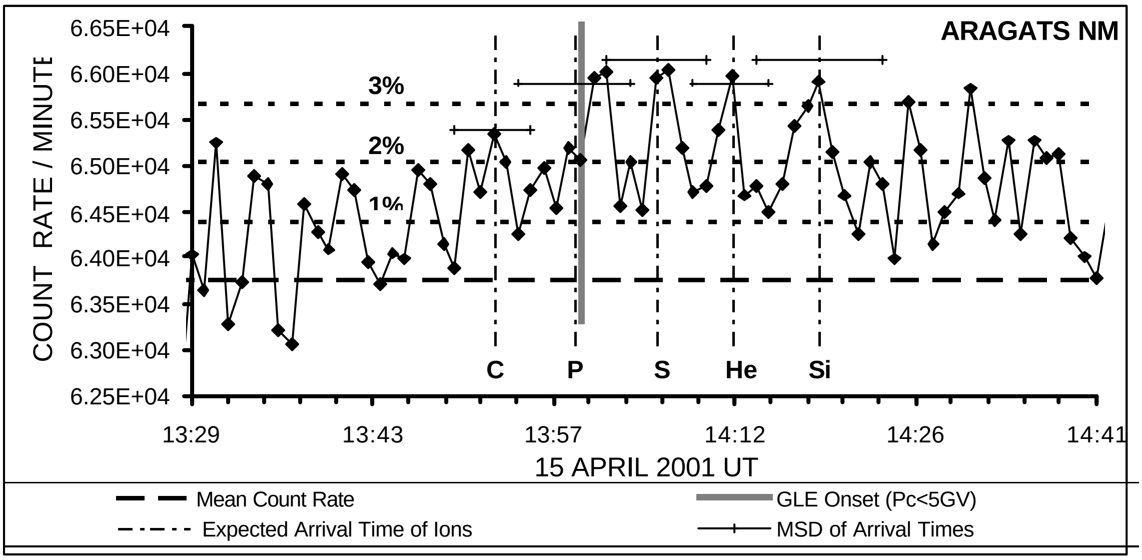


Figure 3. Estimated arrival times of ions superimposed on the Aragats NM 1 minute count rate.

Figure 3 shows the Aragats Neutron Monitor (ANM) count rates in 1 minute intervals and expected arrival times of the various species of ions calculated as in Figure 2. The estimated arrival times of different species ions are denoted by the vertical dashed lines with the error bars in the expected arrival times of C, P, S, He, and Si. One can see the correlation between expected times and the peaks in the time series of the ANM count rate. More than 3% enhancements in 1 minute count rates correspond to more that 4σ significance. The variability of 1 minute count rates is ~0.7. Thus, we have significant peaks in the regions of the expected ion. Of course, the error bars are too large and we cannot prove that a particular 1 minute peak is due to the ion of a definite type arriving at 1 AU and giving rise to secondary particle in the atmosphere. However, 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 need to also register fluxes of the muons and electrons in correlation with neutrons, now possible and in process at ASEC.

DETERMINATION OF THE ION INJECTION LOCATION NEAR THE SUN

To verify our conclusions on the two distinct groups of ions accelerated near the Sun, we reconstruct the expected injection location using the energy-time dependences according to the CME propagation in the Sun corona registered by the SOHO/LASCO instrument (LASCO, Internet). We interpolate the CME trajectory in the corona by the quadratic equation. Assuming that particle injection occurs on the CME trajectory, as well as relying on the times of different ion injections from the regression lines in figure2, we can determine the location of the injection of different species ions in units of Sun radii (R_{sun}) from the center of the sun, as shown in figure 4. Thus, we can categorize the injection location of the different species particles as follows:

- "flare zone" at 1 to 1.3 R_{sun} – for C, O and Fe ions; injection time 13:31- 13:34 UT ± 5min The injection times of these ions overlap with the type III radio burst duration (13:36 – 13.38 UT) and precede the type II and IV radio bursts;

- "shock zone" at 2.5 to 5 R_{sun} – for He at 13:43 ± 11 min., S at13:59 ± 9 min., and Si at 14.06 ± 10 min. injection times. The injection of these ions occurs after the flare process (13:11 – 13.47 UT) and after the start of the radio bursts of II and IV type

CONCLUSION

Comparing the results presented in Figures 1 to 4 we can conclude the following:

- The pattern of ANM count rates on April 15, 2001 demonstrates that the peaks in ANM time series are correlated with the expected arrival times of specific ion species, thus opening the possibility to "mass-spectroscopy" using low latitude and high altitude ground based solar monitors;
- On 15 April 2001 the acceleration of the ions took pla ce in the flare itself and during the shock propagation in the middle and high corona.
- The acceleration of ions by the shock wave took place in different space-temporal regions in the vicinity of the Sun, thus pointing to selective ion acceleration.

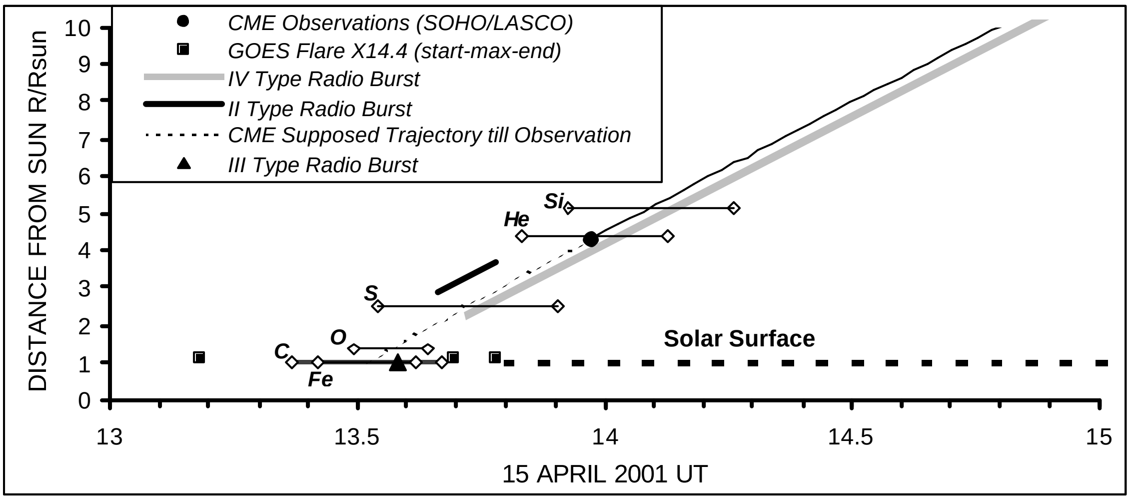


Figure 4. Calculated first ion injection locations from center of the Sun

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