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On the production of highest energy solar protons at 20 January 2005

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Abstract

On January 20, 2005, 7:02–7:05 UT the Aragats Multidirectional Muon Monitor (AMMM) located at 3200 m a.s.l. registered enhancement of the high energy secondary muon flux (threshold ~5 GeV). The enhancement, lasting for 3 min, has statistical significance of $\sim 4\sigma$ and is related to the X7.1 flare seen by the GOES, and very fast (>2500 km/s) CME seen by SOHO, and the Ground Level Enhancements (GLE) #69 detected by the world-wide network of neutron monitors and muon detectors. The energetic and temporal characteristics of the muon signal from the AMMM are compared with the characteristics of other monitors located at the Aragats Space-Environmental Center (ASEC) and with other neutron and muon detectors. Since secondary muons with energies >5 GeV are corresponding to solar proton primaries with energies 20–30 GeV we conclude that in the episode of the particle acceleration at 7:02–7:05 UT 20 January 2005 solar protons were accelerated up to energies in excess of 20 GeV.
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Keywords: Solar Cosmic Rays; Ground Level Enhancement; Particle detectors

1. Introduction

On January 20, 2005 NOAA reported an X7 importance flare with helio-coordinates (14N, 61W), which started at 6:36 UT with maximal X-ray flux at 7:01 UT. The associated CME had the largest sky-plane speed, exceeding 3000 km (Gopalswamy et al., 2005). The first results on the unleashed Solar Energetic Particle (SEP) event reported by space-born particle spectrometers (Mewaldt et al., 2005) pointed to very hard energy spectra of accelerated protons. It stimulated detailed investigation of the correspondent Ground Level Enhancement (GLE) #69, having one of the goals to estimate the maximum energy of the solar accelerators.

Available experimental data on the Ground Level Enhancements (GLEs) confirm proton acceleration up to 20 GeV (Toptigin, 1983; Dorman, 2004). The stochastic acceleration in the flares (Petrosian, 2006) and shock acceleration in corona and interplanetary space (Gang and Zank, 2003) are the two theories aimed to explain the origin and mechanisms of the particle acceleration at the Sun.

Middle and high-latitude neutron monitors can not be used for the reconstruction of the primary energy spectra above 5 GeV due to very weak fluxes and relatively small sizes of the detectors. Therefore, recent years surface particle detectors measuring Extensive Air Showers (EAS) were implemented for the investigation of the highest energy solar protons and ions (Ryan, 1999; Ding, 2001; Poirier and D'Andrea, 2002; Chilingarian et al., 2003a). Due to their large surface area and solid angle and high efficiency of the registration of the charged particles, these detectors provide valuable information about the solar proton fluxes above 5 GeV.

The *Aragats Multidirectional Muon Monitor* (AMMM) is located at (40.25°N, 44.15°E) and on altitude 3200 m above sea level (ASL) with cutoff rigidity 7.6 GV and relative accuracy of measuring 3-min time series of ~0.17%, more sensitive than the neutron monitor 18NM64, located at the same altitude.

The AMMM consists of 45 (in 2006 enlarged to 100) plastic scintillators with detecting surface of 1 m^2 and

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thickness of 5 cm each. The detector AMMM is located in the underground hall of the ANI experiment (Chilingarian et al., 2003b) under 15 m of soil and concrete, plus 12 cm. of iron bars. Only muons with energies greater than 5 GeV can reach this underground detector. These muons are efficiently produced by primary protons of energy 35–50 GeV if we assume the power-law differential energy spectrum with spectral index of $\gamma = -2.7$ for Galactic Cosmic Rays, and proton energies of ~20–30 GeV if we assume spectral index $\gamma = -4$ to -5 (Chilingarian et al., 2005; Zazyan and Chilingarian, 2006).

During GLE #69 on January 20, 2005 from 7:02 to 7:05 UT, AMMM detects a peak with significance $\sim 4\sigma$. We compare this with observations of the other Aragats Space-Environmental Center (ASEC) monitors (Chilingarian et al., 2006a) and other world-wide monitors, see parameters of the monitors in Table 1, where types, heights above sea level, area, cutoff rigidity and geographic coordinate of monitors are presented. Statistical significance is given for peaks occurred at 7:02 UT.

2. GLE #69 as detected by the ASEC monitors

GLE #69 was detected by several ASEC monitors on January 20, 2005, during the solar flare X7.1. The 1-min time series of the AMMM is presented in Fig. 1. Enhancement of the count rate is seen from 7:02 till 7:04 UT with maximum at 7:03 UT. Three out of the 45 one m^2 scintillators of the AMMM were not operational at the time, therefore only 42 m^2 of muon detectors were in use to measure the high energy muon flux. The estimated mean count rate of the Galactic Cosmic Rays (GCR) as measured by the 42 m^2 of the AMMM detector is 123,818 particles per min. The additional signal at 7:03 UT equals to 863 particles or enhancement of 0.70%. Taking into account that the standard deviation of 1 min data is 352 (0.29%) the significance of the 1 min peak at 7:03 UT is 2.5σ.

To emphasize the peak in the AMMM time series we group the 1 min date in 3-min time-intervals (see Fig. 2). As expected the 3-min time series demonstrates a more pronounced peak of 3.93σ. The mean count rate of GCR equals 371,454 particles per 3 min. The additional signal at 7:02 equals 2394 or enhancement of 0.644%. If we adopt the Poisson standard deviation for the 3-min time series 0.164% (see detailed discussion on the determination of

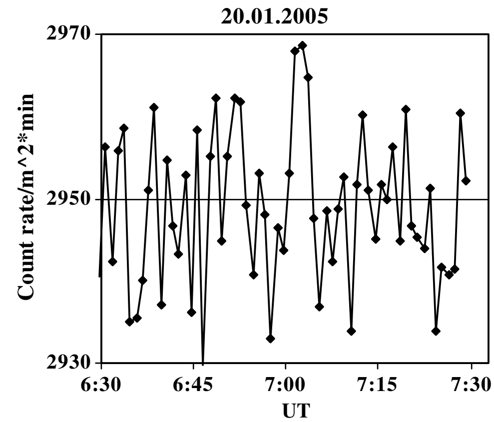

Fig. 1. Time series of the 1 min count rates of secondary muons with energies greater than 5 GeV measured by AMMM. Count rates are normalized to the flux fallen on 1 m^2.

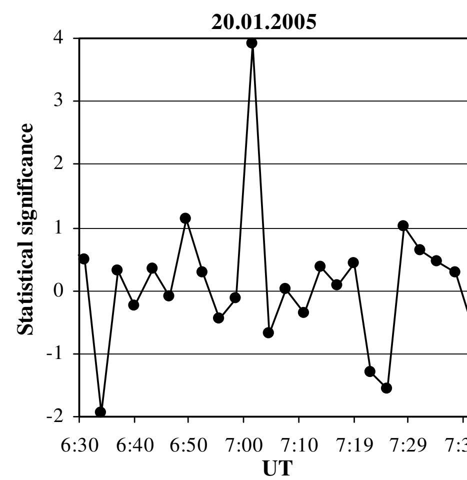

Fig. 2. Time series of the 3 min count rates of secondary muons with energies greater than 5 GeV measured by the AMMM, expressed in the units of the standard deviations. Significance of the peak at 7:02 equals 4σ.

the significance of detected enhancement in Chilingarian et al., 2006b) we come to the significance of 3.93σ for the 3 min peak at 7:02–7:05 UT. The excess count rate registered at AMMM during the interval 7:02–7:05 UT corresponds to the flux $(3.1 \pm 0.8) \times 10^{-5}$ muons/cm^2/s.

Due to the very short enhancement time span no corrections for the atmospheric pressure and temperature variations are necessary.

Table 1
Characteristics of the particle detectors registered the GLE #69 at 20 January 2005

Detectors	Altitude (m)	Surface (m^2)	Rigidity GV	Statistical significance	Geographic coordinate
NANM 18NM64	2000	18	7.6	3.7	40.25°N, 44.15°E
ANM 18NM64	3200	18	7.6	1.2	40.25°N, 44.15°E
ASNT-8 channels	3200	4 (60 cm thick)	7.6	0.2	40.25°N, 44.15°E
		4 (5 cm thick)		1.5	
AMMM	3200	42	7.6	3.93	40.25°N, 44.15°E
CARPET/Baksan	1700	196	5.7	19	43.28°N, 42.69°E
Tibet YBJ NM 28NM64	4300	28	14.1	12	30.11N 90.53E

The statistical significance of peaks is calculated by 3-min time series.

The 20 January GLE was detected by several EAS detectors, measuring shower charge particles (mostly muons and electrons) (D'Andrea and Poirier, 2005; Ryan, 2005) and by Tibet YBJ neutron monitor (Miyasaka, 2005); all ensuring registration of highest primary proton energies of 10–15 GeV.

We can see in Fig. 3 rather good agreement of the time series profiles. CARPET and YBJ NM demonstrate high significance peaks in the same time at 7:02, those proving that AMMM $\sim 4\sigma$ peak is not rare fluctuation, but is initiated by the primary protons with energies greater than 20 GeV. Smaller significance values of AMMM comparing with CARPET and YBJ NM is explained by the much higher threshold of AMMM and large index of the proton flux energy spectra $\gamma = -4, -5$ (Bieber et al., 2005; Miyasaka, 2005).

In Figs. 4 and 5 the count rate enhancements measured by the Aragats Neutron Monitor (ANM), located at 3200 m ASL and Nor-Amberd Neutron Monitor (NANM) located at 2000 m ASL are presented (both neutron monitors are 18NM64 type). From the figures we can see that the enhancement at the neutron monitors started ~3 min earlier than the peak detected by the AMMM and in the interval 6:59–7:45 both ANM and NANM show at least two peaks having significance higher than 3σ.

The 5 cm thick plastic scintillators of upper layer of the Aragats Solar Neutron Telescope (ASNT) is sensitive to charged particles with energies greater ~7 MeV. As we can see in Fig. 6 in the same interval of 6:59–7:45 ASNT also detect several significant peaks. Analogous patterns were detected by the neutron monitors from the worldwide network (Flueckiger et al., 2005).

The energies of the primary solar protons giving rise to the secondary neutrons (registered by the neutron monitors) and low energy charged particles (registered by surface scintillator detectors) are smaller than the energies of the primary proton that create the 5 GeV muons in the atmosphere.

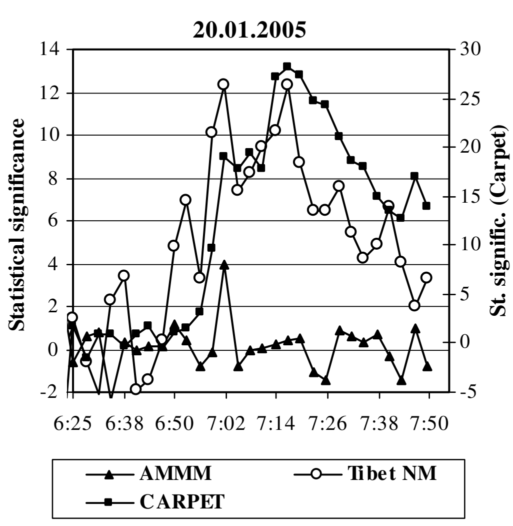

Fig. 3. Comparison of the time series of the particle detector sensitive to the highest energies of solar particles: CARPET (energy range >6 GeV), Tibet NM (>13 GeV) and AMMM (>20 GeV).

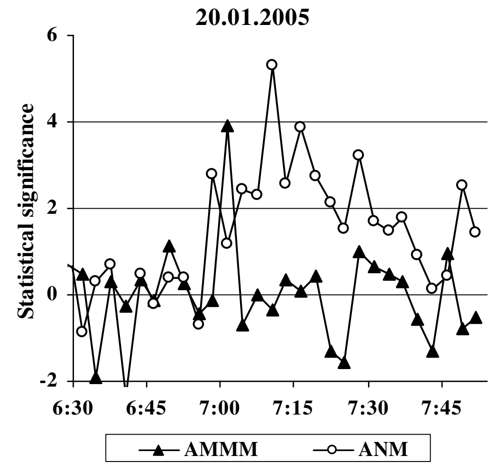

Fig. 4. Comparison of the time series of the 3 min count rates measured by NANM and AMMM detectors expressed in the units of the standard deviations. Duration of the peak measured by AMMM is ~3 min, whereas excess of ANM count rate is much longer ~45 min.

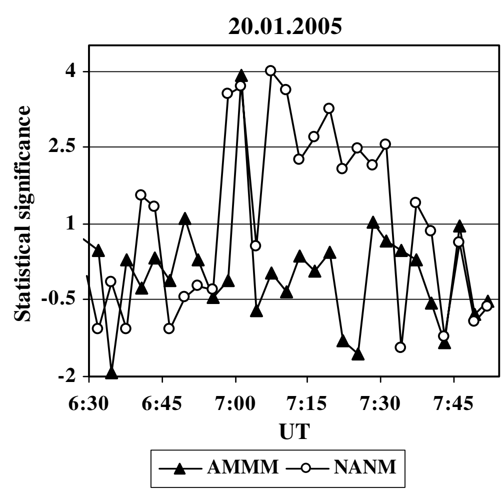

Fig. 5. Comparison of the time series of the 3 min count rates measured by ANM and AMMM detectors expressed in the units of the standard deviations. Duration of the peak measured by AMMM is ~3 min, whereas excess of ANM count rate is much longer ~45 min.

Therefore, we conclude that maximal solar proton energy at 7:12–7:45 was less comparing with 7:02–7:05 when pronounced peak in >5 GeV muon time series was detected. Of course, absence of signal in the AMMM also can be due anisotropic solar protons flux. However, despite the 20 January event was extremely anisotropic at the GLE onset, very soon after onset solar proton flux became rather isotropic (Plainaki et al., 2007; Moraal et al., 2005).

3. Conclusions

As mention A. Tylka in (http://creme96.nrl.navy.mil/20Jan05/) "the January 20, 2005 solar event was in many

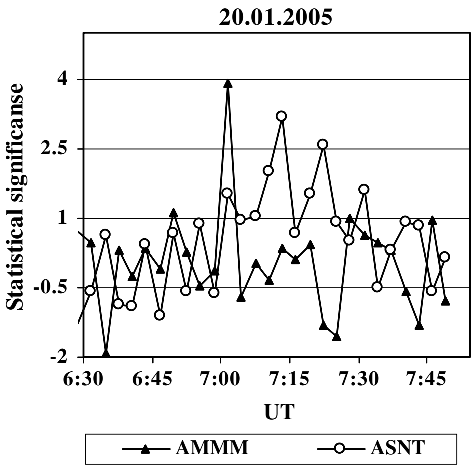

Fig. 6. Comparison of the time series of the 3 min count rates measured by ANM and ASNT detectors expressed in the units of the standard deviations.

ways one of the most spectacular of the Space Age''. Regardless of discussing peculiarities of this event at numerous conferences and workshops the exceptional characteristics of the event are not well understood yet.

Proceeding from the favorable geographical location and high resolution of the AMMM detector at Aragats we add to the corpus of measurements the evidence on the highest proton energies.

On January 20, 2005 at 7:02–7:05 UT the Aragats Multidirectional Muon Monitor registered additional flux of high energy muons equal to $(3.1 \pm 0.8) \times 10^{-5}$ particle/cm^2/s, which corresponds to $\sim 4\sigma$ statistical significance. If we assume that the spectral index of the solar protons at this time equals to ~ -4 to -5, the energy of ''parent'' protons should be 20–30 GeV. Thus we conclude that the protons during this event were accelerated to energies 20–30 GeV.

Particles forming the next peaks of the GLE #69 observed by ASEC monitors at 7:12–7:45 UT has less energy compared with the first peak.

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