Observation of Forbush Degreases and Solar Events in the 10-20 GeV Energy Range with the Karlsruhe Muon Telescope

Isabel Braun*, **Joachim Engler**§, **Jörg R. Hörandel**¶ **and Jens Milke**‖

* *Institute for Particle Physics, ETH Zurich, 8092 Zurich, Switzerland*
§*Institut für Experimentelle Kernphysik, Universiät Karlsruhe, D-76021 Karlsruhe, Germany*
¶*Radboud University Nijmegen, Department of Astrophysics, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands*
‖*Institut für Wissenschaftliches Rechnen, Forschungszentrum Karlsruhe, D-76021 Karlsruhe, Germany*

***Abstract*. Since 1993, a muon telescope located at Forschungszentrum Karlsruhe (Karlsruhe Muon Telescope) has been recording the flux of single muons mostly originating from primary cosmic-ray protons with dominant energies in the 10 - 20 GeV range. The data are used to investigate the influence of solar effects on the flux of cosmic-rays measured at Earth. Non-periodic events like Forbush decreases and ground level enhancements are detected in the registered muon flux. Events of the 23rd solar cycle will be presented and compared to data from the Jungfraujoch neutron monitor. The data of the Karlsruhe Muon Telescope help to extend the knowledge about Forbush decreases and ground level enhancements to energies beyond the neutron monitor regime.**

***Keywords*: Forbush decreases, Ground Level Enhancements, Muon Telescope**

I. Introduction

The association of solar activity with the cosmic-ray intensity has been studied for various observed effects including Forbush decreases [1], i.e. a rapid decrease in the observed galactic cosmic-ray intensity, and Ground Level Enhancements connected to large solar flares. They can be related to magnetic disturbances in the heliosphere that create transient cosmic-ray intensity variations [2], [3]. From the observation of such events with different experiments, an energy dependent description can be obtained. The heliospheric influence is mostly pronounced for primary particles with low rigidity and has been studied mainly using data of the worldwide neutron monitor network [4]. With its unique median primary energy of 40 GeV for protons, the Karlsruhe Muon Telescope fills the energy gap between neutron monitors (from $\approx 11 - 15$ GeV, depending on solar activity state, to ≈ 33 GeV) and other muon telescopes ($\approx 53 - 119$ GV rigidity). In the following, we report on the detection of Forbush decreases and the investigation of Ground Level Enhancements with the Karlsruhe Muon Telescope.

II. Experimental Set-Up

The flux of single muons from the zenith region has been recorded continuously since 1993 with the Karlsruhe Muon Telescope located at Forschungszentrum Karlsruhe, Germany (49.094°N, 8.431°E, 120 m a.s.l). Details on the set-up are given in [5] and [6].

The response of the muon detector has been evaluated with simulations based on the CORSIKA [7] and GEANT 3.21 [8] packages. The median energy of the Karlsruhe Muon Telescope is 40 GeV, the maximum occurs at primary energies of about 15 GeV.

Corrections were applied to the recorded muon rate using the atmospheric pressure measured at the Forschungszentrum Karlsruhe. In addition, balloon ascends at noon and midnight conducted by the German weather service (DWD) in Stuttgart provide the heights of specific pressure layers including the 150 g/cm^2 layer (≈ 13.6 km) which is close to the typical production layer of muons triggering the telescope at 130 g/cm^2, as determined from simulations.

For each year, the muon rate was iteratively corrected for a pressure of 1013 hPa and a nominal height of the 150 g/cm^2 layer of 13.6 km, yielding correction parameters of $d(Rate)/dp = (-0.12 \pm 0.04)$ %/hPa and $d(Rate)/dh = (-3.8 \pm 1.2)$ %/km. This correction eliminates rate variations caused by changing atmospheric conditions from the data-set.

III. Forbush Decreases

The muon data were searched for days where the average rate was significantly lower than that of a background region. The background level was determined from hourly count rates within two times two weeks (14 d before the test region and 14 d afterwards), separated by three days from the tested day. The significances for each day were computed according to [9]. Trial factors were not taken into account.

The Karlsruhe Muon Telescope has detected several significant structures.

The strongest Forbush decreases in the years from 1998 to 2006 are compiled in Table I. Shown are: a sequential number, the date, the significance and the amplitude A of the minimum rate (r_{FD}) relative to the

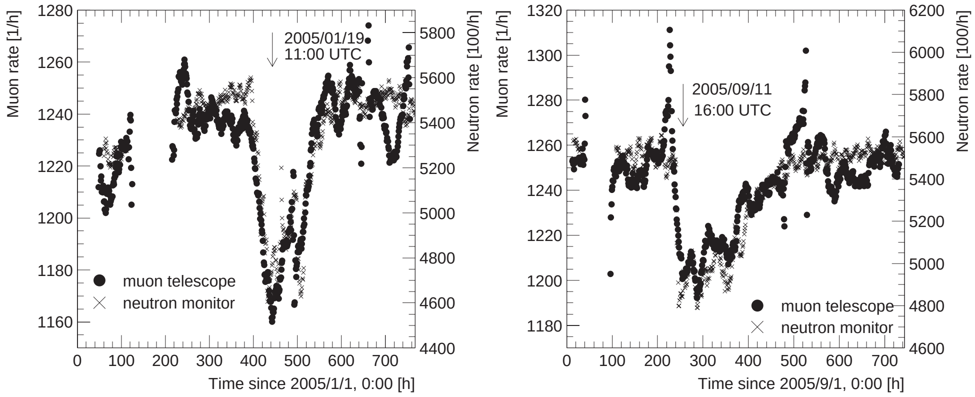


Fig. 1: Count rates of the Karlsruhe Muon Telescope and the Jungfraujoch neutron monitor for the two most recent Forbush decreases. The corresponding dates and times are indicated in the figure. Jungfraujoch data scaled by a factor 100, muon counting rate smoothed over a period of 24 hours.

TABLE I: Very significant Forbush decreases detected since 1998. A sequential number and the dates are listed. Significances are pre-trials, the amplitudes of the Karlsruhe Muon Telescope refer to the hourly data (not smoothed). The fifth column gives the amplitudes detected by the Jungfraujoch neutron monitor. The last column gives an estimate for the energy dependence of the detected amplitudes, expressed in amplitude change per decade in energy.

#	date	significance(μ)	amplitude(μ) [%]	amplitude(n) [%]	amplitude change [% / energy decade]
1	1998/08/26	6.1σ	10.1	7.1	5.7
2	1998/09/25	6.2σ	11.7	5.7	11.5
3	1999/01/23	4.7σ	8.1	7.0	2.1
4	2000/07/15	8.3σ	12.3	10.5	3.5
5	2000/11/10	6.1σ	6.8	1.5	10.2
6	2001/08/03	8.7σ	9.4	1.7	14.8
7	2003/10/30	8.4σ	11.3	17.0	-10.9
8	2004/11/10	5.0σ	10.5	6.6	7.6
9	2005/01/19	10.6σ	13.2	13.2	0.02
10	2005/09/11	5.5σ	8.4	10.4	-3.9

average rate before the decrease (r_b) computed as

$$A = (r_b - r_{FD})/r_b. \quad (1)$$

The amplitudes A_μ and A_n have been calculated according to (1) for the muon telescope (based on hourly rates) and the Jungfraujoch 18-IGY neutron monitor (46.55°N / 7.98°E, 3570 m asl), respectively. The latter has an effective vertical cutoff rigidity of 4.49 GV [10]. It was chosen for this comparison because of its geographic proximity to Karlsruhe. The two most recent detected events compared to the neutron monitor counting rate are depicted in Fig. 1. To display their development, the muon telescope rates are smoothed by a running mean over 24 hours. Attention should be paid to the different scales for the muon rate (left-hand scale) and for the neutron monitor rate (right-hand scale). The apparently significant excesses on 2005/09/09-10 and 2005/09/22 are artefacts of the smoothing and caused by individual high data-points at the boundaries of detector down-time. It is worth to point out that the rate development observed at 4.5 GV (Jungfraujoch) and for the muon telescope (15 GeV) are quite similar, despite of their different energy thresholds. This illustrates that Forbush decreases are clearly detectable with a muon detector with 15 GeV peak energy. Forbush decreases were already detected with the GRAND muon detector [11] at 10 GeV peak energy. With the Karlsruhe Muon Telescope, we push the detection towards higher energies.

Many structures in these Forbush decreases are visible at both energies. A closer look [6] reveals that for events 7, 8, 9, and 10 (close to the solar minimum), the rates of both detectors follow each other extremely closely. On the other hand, for events 1, 2, 4, and 6 there are systematic differences between the two energies in the behavior before or after the Forbush decrease. For the Forbush decrease in the year of the solar maximum (# 5), the strongest differences between the two rates are observed. It appears as during solar maximum there are significant differences between the fluxes observed at 4.5 GV and 15 GeV, while the fluxes are correlated well during periods of low solar activity.

To study the energy dependence of the amplitudes of a Forbush decrease, the spectral index γ, i.e. the change of amplitude per decade in energy has been calculated according to

$$\gamma = (A_\mu - A_n) \ / \ (log(E_M^\mu) - log(E_M^n)), \quad (2)$$

$E_M^\mu \sim$ 15 GeV and $E_M^n \sim$ 4.5 GeV being the most propable primary energies for the muon telescope and the neutron monitor, respectively. γ is listed in the last column of Table I. No clear correlation between the amplitude change per energy decade and the international sunspot number (taken from [12]) is found [6]. Thus, earlier claims by [13] cannot be confirmed. A study of the energy-dependence of the recovery time of Forbush decreases including data from Karlsruhe Muon Telescope is published elsewhere [14].

IV. Ground Level Enhancements

Due to their relatively short duration, Ground Level Enhancements (GLEs) are difficult to detect with the Karlsruhe Muon Telescope. Therefore, the data were scanned for correlations with all events marked in the GLE database, as provided by the Bartol group [15]. For a detailed list of muon telescope activity at the time of these events see [6].

For GLE 57, no significant excess was observed in the muon counting rate. However, about seven hours before the Ground Level Enhancement a small peak is visible in the registered muon flux. For GLE 58, no significant muon excess has been observed.

GLE 59, the "Bastille day event" on July 14, 2000 has been registered by many detectors, including neutron monitors and space crafts [16], [17]. In particular, the event could be measured for primary cosmic rays with GeV energies [18]. It has been detected by the GRAND muon detector (10 GeV most probable energy) [19], by the L3+C detector at CERN (≈ 40 GeV primary energy) [20] and also by the Karlsruhe Muon Telescope. An excess in the muon counting rate can be recognized a few hours before the event. The significance of this structure is under investigation. If real, it is a possible hint for energy dependent propagation effects or the strongly anisotropic nature of this event.

On Easter day 2001 (April 15), an event occured (GLE 60) which has been observed and discussed by several groups [21], [22], [23], [24], [17]. A muon count excess can be recognized at the time of GLE 60, while no signal is observed from GLE 61. It should also be noted that the Jungfraujoch neutron monitor detects GLE 60 with a large signal. On the other hand, the muon flux is only slightly increased at the time of the event.

Some of the greatest bursts in the 23rd solar cycle occurred on 28/29 October and 2 November 2003 (GLE $65-67$). They are extensively discussed in the literature, e.g. [25], [26], [27], [28]. Unfortunately, the muon telescope was not active during GLEs 65 and 67. At the time of GLE 66, no significant signal is seen in the muon count rate. However, about one day before GLEs 65 and 66 a peak can be recognized in the registered muon flux. It is not clear whether these increases are statistically significant, since there are gaps in the observing time. Thus, it is not obvious whether the detected rate variations are correlated with the Ground Level Enhancements.

V. Conclusions

The Karlsruhe Muon Telescope provides information about effects of solar activity on the cosmic-ray flux observed at Earth since 1993. The recorded muon flux corresponds to 15 GeV peak energy (40 GeV median energy) for primary protons.

Several strong Forbush decreases, i.e. a rapid decrease in the observed galactic cosmic-ray intensity, could be measured with the muon telescope, indicating that these effects can be seen at energies exceeding the typical energies of neutron monitors. Comparing the observed amplitudes to the Jungfraujoch neutron monitor data, the spectral index of the events has been estimated. No dependence of the spectral index on the sunspot number has been found. However, there are significant differences in the timely development of the rates observed at 4.5 GV and 15 GeV for different states of solar activity. For Forbush decreases during solar maximum, the rates of the muon telescope and the neutron monitor behave quite differently, while they are well correlated for periods of low solar activity.

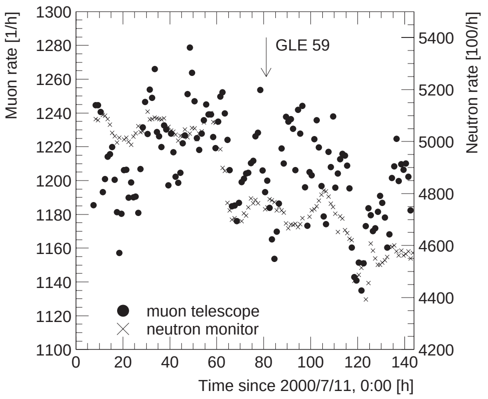
It has been investigated whether Ground Level Enhancements connected to large solar flares, observed between 1997 and 2005 can be detected in the registered muon flux. For the strong Ground Level Enhancements 59 and 60, a clear signal can be seen in the muon count rate at the times of the events. This provides direct evidence for particles being accelerated to energies as high as 15 GeV during solar flares. Indirect evidence has been previously obtained by observations of lines in the gamma ray spectrum measured during solar flares [29], [30]. On the other hand, no signal has been detected for the GLEs 58, 61, 66, 68, and 69. If the underlying physics processes of all Ground Level Enhancements are the same, this means that the energy spectra of GLEs 59 and 60 differ from the spectra of the other GLEs. Another possibility is that the angular distribution of the emitted particles is different for different GLEs, i.e. in cases with highly anisotropic emission no signal was detected in the muon counting rate.

Acknowledgments

We are grateful to Mrs. Heike Bolz for her enthusiastic efforts in continuously operating the Karlsruhe Muon Telescope and to Jürgen Wochele for his help during the construction of the detector. We thank the team operating the Jungfraujoch neutron monitor for making their data publicly available. We acknowledge the help of the Deutscher Wetter-Dienst (DWD) and the Institut für Meteorologie und Klimaforschung of Forschungszentrum Karlsruhe providing atmospheric data.

References

[1] S. E. Forbush, *Worldwide cosmic ray variations*, J. Geophys. Res., 59, 525 - 542, 1954.
[2] E.N. Parker, *The passage of energetic charged particles through interplanetary space*, Planetary and Space Science 13, 9-49, 1965.



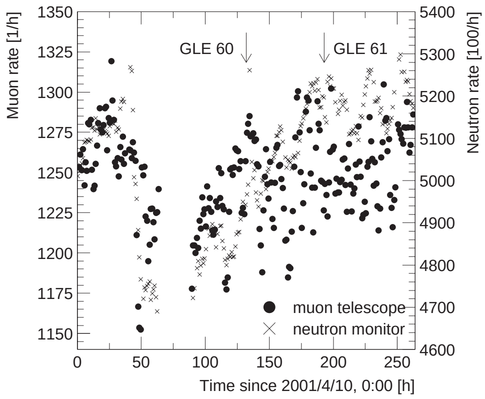


Fig. 2: Hourly count rates registered by the Karlsruhe Muon Telescope and the Jungfraujoch neutron monitor for several Ground Level Enhancements, as marked in the figures, see also [6]. Jungfraujoch data are scaled by factor 100, muon counting rates smoothed over a period of three hours.

[3] M-B. Kallenrode, *Current views on impulsive and gradual solar energetic particle events*, J. Phys. G: Nucl. Part. Phys., 29, 956-981, 2003.

[4] J.A. Simpson, *The cosmic ray nucleonic component: the invention and uses of the neutron monitor*, Space Sci. Rev. 93, 11-32, 2000.

[5] J. Engler, F. Fessler, J.R. Hörandel *et al.* , *A warm-liquid calorimeter for cosmic-ray hadrons*, Nuclear Instruments and Methods A 427, 528-542, 1999.

[6] I. Braun, J. Engler, J.R. Hrandel *et al.* , *Forbush decreases and solar events seen in the* $10-20$ *GeV energy range by the Karlsruhe Muon Telescope*, Advances in Space Research 43, 480-488, 2008.

[7] Heck, D., Knapp, J., Capdevielle, J. *et al.* , *CORSIKA: a Monte Carlo code to simulate extensive air showers*, Report FZKA 6019, Forschungszentrum Karlsruhe, 1998.

[8] GEANT 3.15, *Detector Description and Simulation Tool*, CERN Program Library Long Writeup W5013, CERN, 1993.

[9] T.-P. Li and Y.-Q. Ma, *Analysis methods for results in gamma-ray astronomy*, Astrophysical Journal, 272, 317-324, 1983.

[10] Bern Cosmic Ray Group, Physikalisches Institut, University of Bern http://cosray.unibe.ch.

[11] J. Poirier, M. Herrera, P. Hemphill, *et al.* , *A study of the Forbush decrease event of September 11, 2005 with GRAND*, Proceedings 30th International Cosmic Ray Conference, Merida, 2007.

[12] SIDC: Sunspot Index Data Center, Royal Observatory of Belgium, http://sidc.oma.be

[13] S.O. Ifedili, *Spacecraft measurement of forbush decreases in the cosmic radiation*, Solar Physics 168, 195-203, 1996.

[14] I.G.Usoskin, I. Braun, O.G. Gladysheva *et al.* , *Forbush decreases of cosmic rays: Energy dependence of the recovery phase*, Journal of Geophysical Research, 2008.

[15] Bartol Research Institute neutron monitor program, http://neutronm.bartol.udel.edu.

[16] J.W. Bieber, W. Dröge, P.A. Evenson *et al.* , *Energetic Particle Observations during the 2000 July 14 solar event*, Astrophysical Journal 567, 622-634, 2002.

[17] E.V. Vashenyuk, Y.V. Balabin, P.H. Stoker, *Response to solar cosmic rays of neutron monitors of a various design*, Advances in Space Research 40, 331-337, 2007.

[18] R. Wang and J. Wang, *Spectra and solar energetic protons over 20 GeV in Bastille Day event*, Astroparticle Physics 25, 41-46, 2006.

[19] J. Poirier, C. D'Andrea, M. Dunford, *A project GRAND study of the GLE of July 14, 2000*, Proceedings 27th International Cosmic Ray Conference, Hamburg, 3557-3559, 2001.

[20] L3 Collaboration, *et al.* , *The solar flare of the 14th of July 2000 (L3+C detector results)*, Astronomy and Astrophysics 456, 351-357, 2006.

[21] M.A. Shea and D.F. Smart, *Solar proton and GLE event frequency: 1955 - 2000*, Proc. 27th Int. Cosmic Ray Conf., Hamburg 3401-3404, 2001.

[22] C. D'Andrea and J. Poirier, *A study of the ground level event of April 15, 2001 with GRAND*, Proc. 28th Int. Cosmic Ray Conference, Tsukuba, 3423-3426, 2003.

[23] J.W. Bieber, P. Evenson, W. Dröge *et al.* , *Spaceship Earth observations of the Easter 2001 solar particle event*, Astrophysical Journal 601, L103-106, 2004.

[24] A.J. Tylka, C.M.S. Cohen, W.F. Dietrich, *et al.* , *Shock geometry, seed populations, and the origin of variable elemental composition at high energies in large gradual solar particle events*, Astrophysical Journal 625, 474-495, 2005.

[25] K. Watanabe, M. Gros, P.H. Stoker *et al.* , *Solar Neutron Events of 2003 OctoberNovember*, Astrophysical Journal 636, 1135-1144, 2006.

[26] Y. Liu and K. Hayashi, *The 2003 October-November fast halo coronal mass ejections and the large-scale magnetic field structures*, Astrophysical Journal 640, 1135-1141, 2006.

[27] G.J. Hurford, S. Krucker, R.P. Lin *et al.* , *Gamma-ray imaging of the 2003 October/November solar flares*, Astrophysical Journal 644, L93-96, 2006.

[28] E. Eroshenko, A. Belov, H. Mavromichalaki *et al.* , *Cosmic-ray variations during the two greatest bursts of solar activity in the 23rd solar circle*, Solar Physics 224, 345-358, 2004.

[29] E. Rieger, *Solar flares: high-energy radiation and particles*, Solar Physics 121, 323-345 1989.

[30] L. Fletcher, *Energetic particles in the solar atmosphere*, Proc. 10th European Solar Physics Meeting, Prague, Czech Republic, ESA SP-506, 223-232, 2002.