Forbush decreases and solar events seen in the $10 - 20$ GeV energy range by the Karlsruhe Muon Telescope

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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. A selection of recent events 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.

1. Introduction

The association of solar activity with the cosmic-ray intensity has been studied for various observed effects including Forbush decreases (Forbush, 1954), i.e. a rapid decrease in the observed galactic cosmic-ray intensity, and Ground Level Enhancements, which are connected to large solar flares. They can be related to magnetic disturbances in the heliosphere that create transient cosmic-ray intensity variations (Parker, 1965; Kallenrode, 2003). 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 (Simpson, 2000). 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.

2. 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). The set-up is sketched in Fig. 1, details are given by Engler et al. (1999). Two double layers of scintillation counters are arranged on top of each other, separated by a 16 cm lead absorber, forming a "tower". Each scintillation counter comprises a scintillator (NE 102) with the dimensions $0.6\,\mathrm{m} \times 0.25\,\mathrm{m} \times 0.02\,\mathrm{m}$, read out by a photomultiplier via an adiabatic light guide. A double layer is formed by two scintillation counters arranged parallel to each other and two counters oriented perpendicular to them, forming a 2×2 detector matrix. The lead absorber selects muons with energies larger than 0.8 GeV. Two such towers with a separation of 1.8 m are operated with a veto trigger logic selecting vertical particles and rejecting showers in which more than one particle hits the detector, thus suppressing the hadronic background to about 0.8% of the events (Hörandel, 1994). The
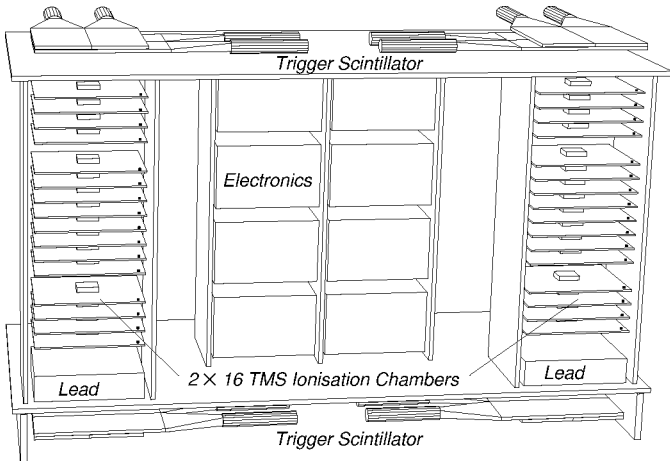
Fig. 1. Sketch of the muon telescope. It consists of two "towers", each comprising two double layers of scintillation counters (arranged in a 2 × 2 matrix), separated by a 16 cm lead absorber.

muon detector is operated in a climatized room at a stable temperature. The towers of the instrument can be used to calibrate up to 32 liquid ionization chambers for the KAS-CADE hadron calorimeter, their data are not included in the present analysis. This analysis includes 80 017 h of data between October 1993 and November 2006.

From simulations with CORSIKA (Heck et al., 1998) and GEANT 3.21 (GEANT, 1993), properties of the primary particles were investigated. The simulations include the physics processes in the atmosphere and the propagation through the building surrounding the detector, as well as the trigger conditions of the muon telescope. It turns out that the muons originate mostly from cosmic-ray protons, of which 95% have zenith angles smaller than 18°. The differential energy spectrum of primary protons triggering the telescope was derived for parameterized primary spectra in different solar activity states (Urch, 1972), taking into account modulation parameters according to Usoskin (2003). The differential trigger rate obtained, in other words the detector response function folded with the primary particle spectrum, is presented in Fig. 2. The maximum occurs at primary energies of about 15 GeV. The expected counting rate difference between the two activity states is 2.5%. The median energy E_M of a detector is defined such that one half of the detected events originate from primary particles below (or above) E_M. The median energy of the Karlsruhe Muon Telescope for both simulated spectra is 40 GeV.

3. Atmospheric Corrections

Muons loose energy and decay on the way from their production site in the atmosphere to the detector, yielding a dependence of the detected rate on the height of the production layer and the amount of material traversed above the detector. 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
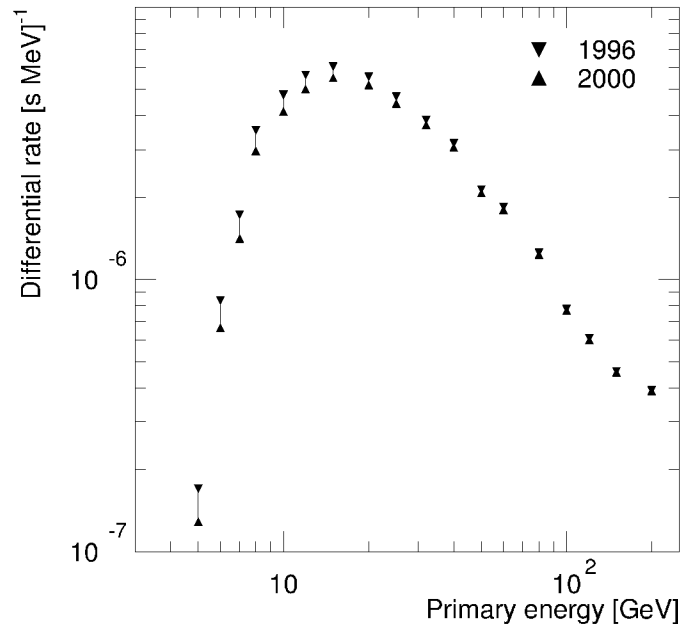

Fig. 2. Simulated differential trigger rate of the Karlsruhe Muon Telescope as a function of primary energy for solar minimum (1996) and maximum (2000).

German weather service (DWD) in Stuttgart provide the heights of specific pressure layers including the 150 g/cm^2 layer ($\approx$ 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 from the data-set, which are caused by changing atmospheric conditions. For a consistency check, a rough estimate of the muon lifetime can be deduced from these values, assuming that all muons are produced with the same energy at the same atmospheric depth. The obtained lifetime of 2 ± 0.5 μs is consistent with the literature value.

4. 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 Li and Ma (1983). 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 1. Shown are a sequential number, the date, the significance and the amplitude A of the minimum rate (r_{FD}) relative to the average rate before the decrease (r_b) computed as

Fig. 3. Count rates of the Karlsruhe Muon Telescope and the Jungfraujoch neutron monitor for several 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.
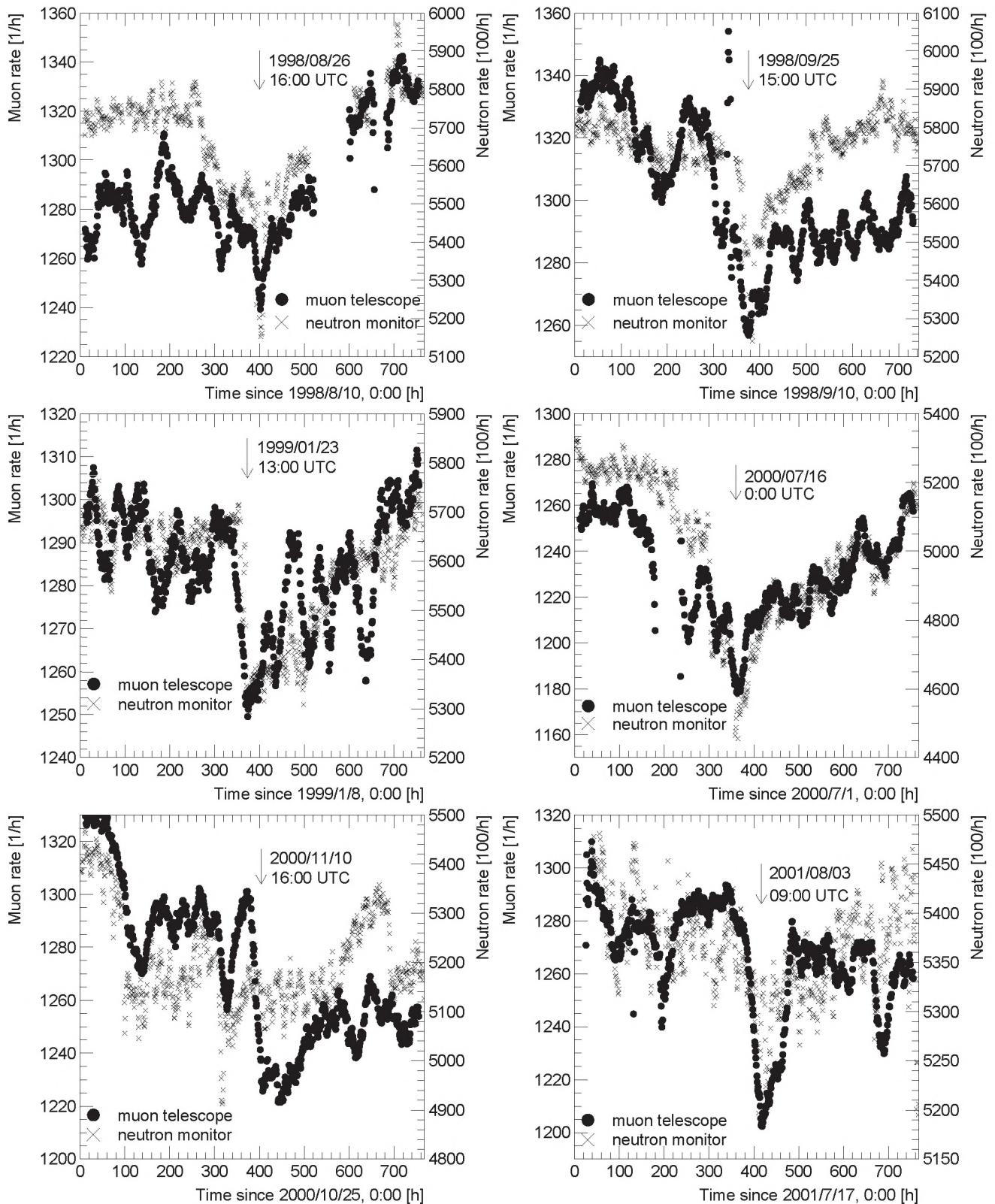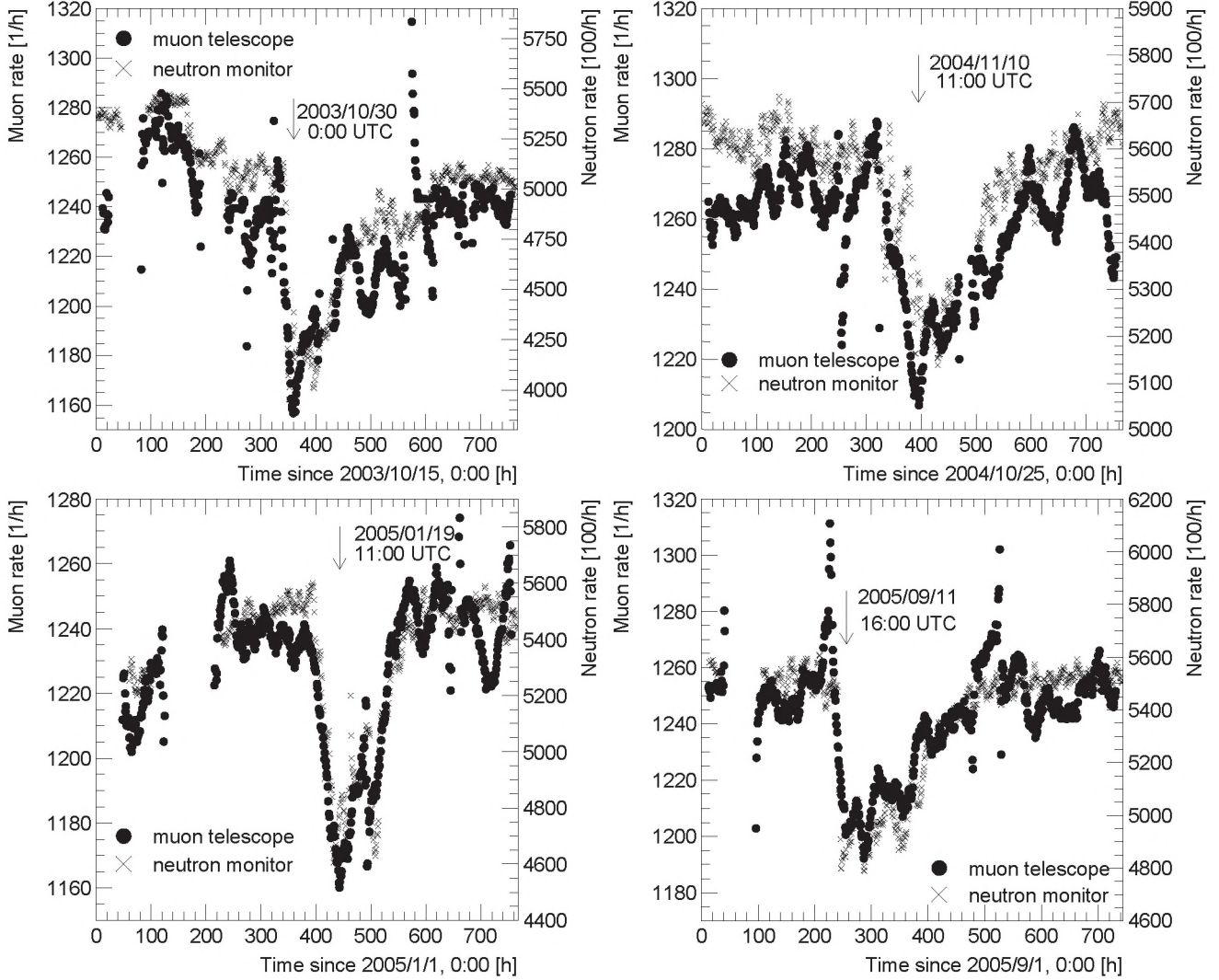
Fig. 4. Count rates of the Karlsruhe Muon Telescope and the Jungfraujoch neutron monitor for several Forbush decreases. The corresponding dates and times are indicated in the figure. Jungfraujoch data scaled by a factor 100, muon counting rate smoothed over a period of 24 hours.

Table 1
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	10.3	-0.4
2	1998/09/25	6.2σ	11.7	8.7	5.7
3	1999/01/23	4.7σ	8.1	6.7	2.6
4	2000/07/15	8.3σ	12.3	14.9	-5.0
5	2000/11/10	6.1σ	6.8	2.1	9.0
6	2001/08/03	8.7σ	9.4	3.4	11.7
7	2003/10/30	8.4σ	11.3	23.2	-22.8
8	2004/11/10	5.0σ	10.5	8.9	3.1
9	2005/01/19	10.6σ	13.2	16.8	-6.9
10	2005/09/11	5.5σ	8.4	13.5	-9.8

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

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 (Bern, 2006). It was chosen for this comparison because of its geographic proximity to Karlsruhe. The detected events compared to the neutron monitor counting rate are depicted in Figs. 3 and 4. 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 1998/09/24, 2003/11/08, 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 detected already with the GRAND muon detector (Poirier at al, 2007) 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 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

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

$E_M^\mu \sim 15$ 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 1. To investigate a possible dependence on the solar activity, the amplitude change per energy decade is depicted as function of the international sunspot number (taken from SIDC (2007)) in Fig. 5. No clear correlation between the two quantities can be inferred from the figure. Thus, earlier claims by Ifedili (1996) 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 (Usoskin, 2008).
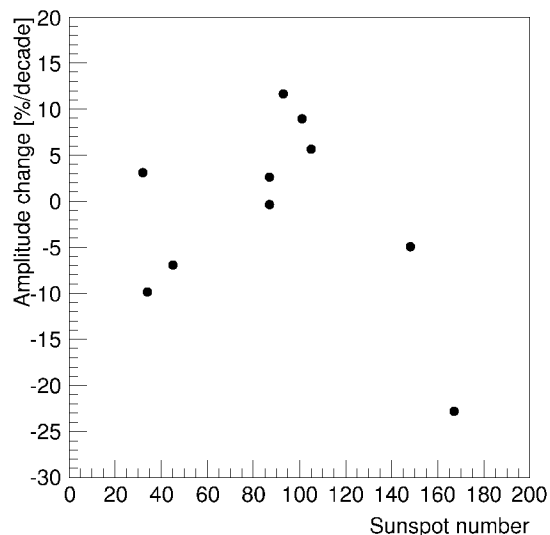

Fig. 5. Energy dependence of the amplitude of the Forbush decreases registered by the Karlsruhe Muon Telescope and the Jungfraujoch neutron monitor (expressed as change in amplitude per energy decade) as function of the sunspot number.

Table 2
Solar Ground Level Enhancements according to the Bartol group database (Bartol, 2007). The last column denotes the status of the Karlsruhe Muon Telescope: a: active, i: inactive, +: GLE detected.

GLE number	event date	status
55	1997/11/06	i
56	1998/05/02	i
57	1998/05/06	a (+)
58	1998/08/24	a
59	2000/07/14	a +
60	2001/04/15	a +
61	2001/04/18	a
62	2001/11/04	i
63	2001/12/26	i
64	2002/08/24	i
65	2003/10/28	i
66	2003/10/29	a
67	2003/11/02	i
68	2005/01/17	a
69	2005/01/20	a

5. 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 (Bartol, 2007) and listed in Table 2. The muon flux was recorded for events marked with an "a". During events marked with "i" the muon telescope was not active. The hourly rates for GLEs 56 to 67 as registered by the Karlsruhe Muon Telescope and the Jungfrau-
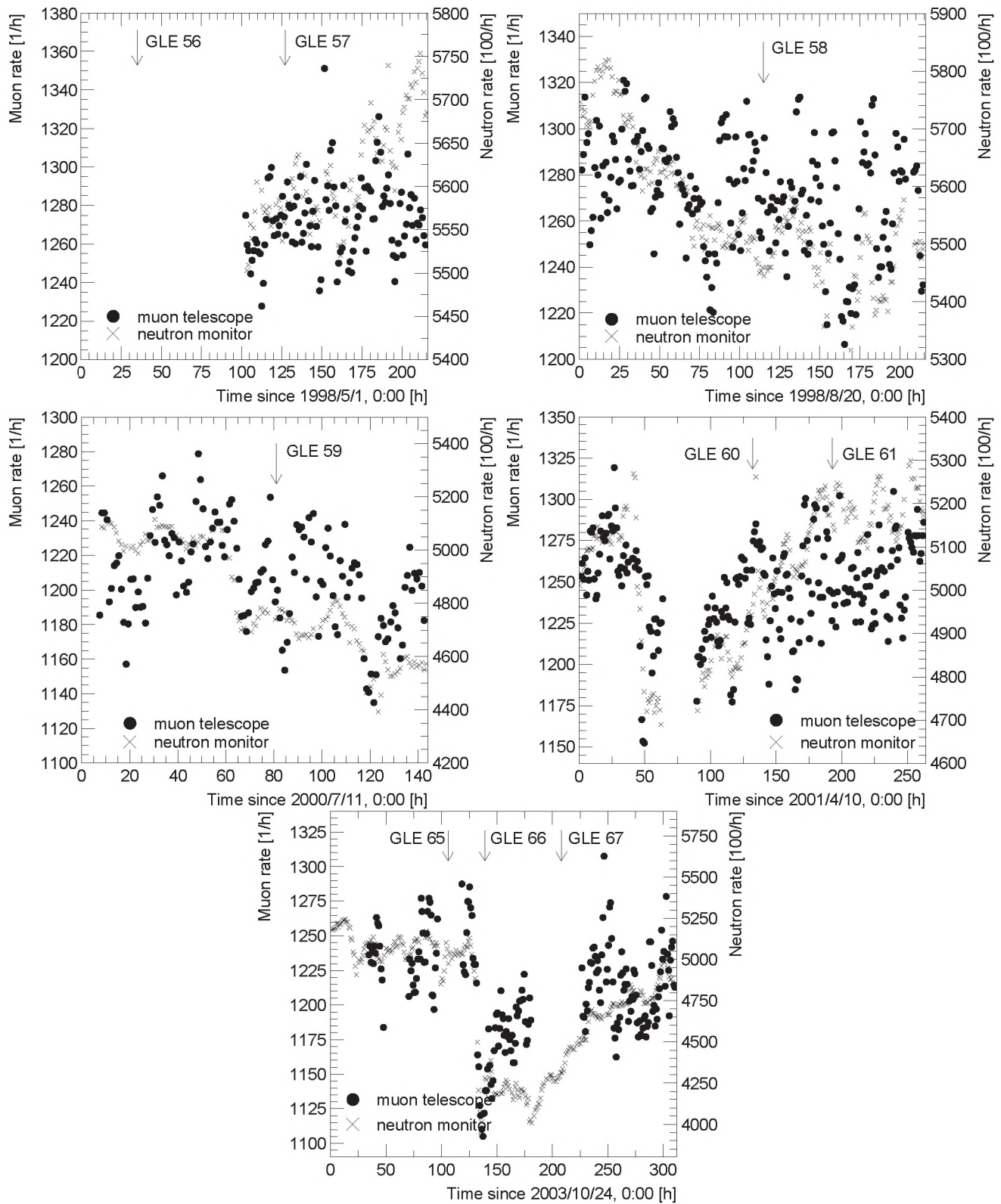
Fig. 6. Hourly count rates registered by the Karlsruhe Muon Telescope and the Jungfraujoch neutron monitor for several Ground Level Enhancements, as marked in the figures, see also Table 2. Jungfraujoch data are scaled by factor 100, muon counting rates smoothed over a period of three hours.
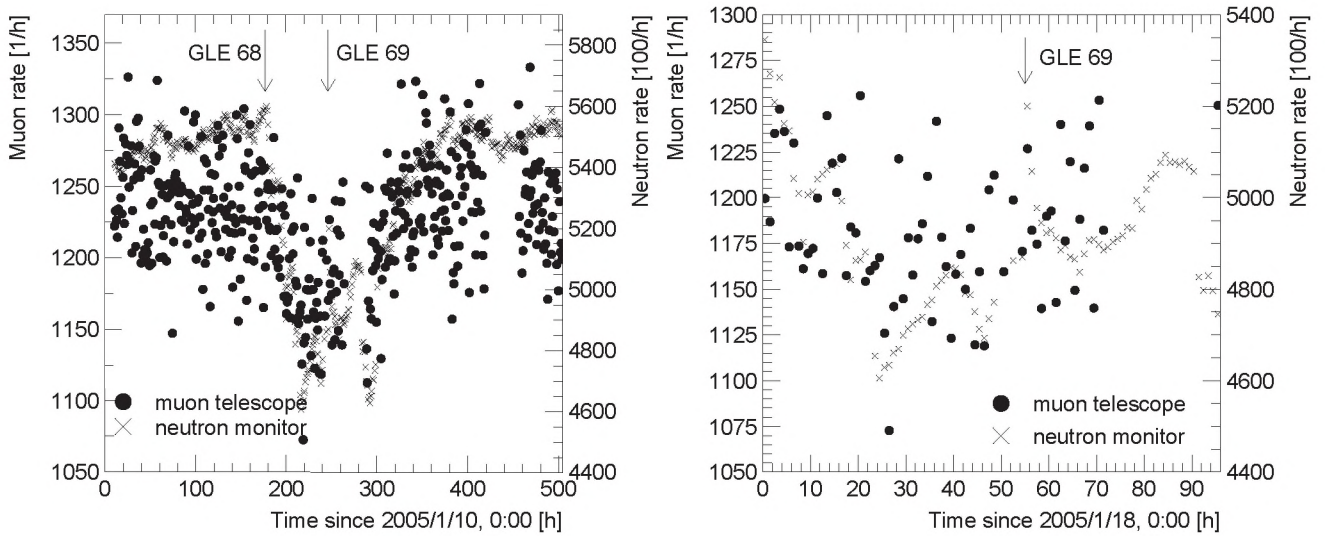
Fig. 7. Count rates of the Karlsruhe Muon Telescope and the Jungfraujoch neutron monitor for the Forbush Decrease on January 19th, 2005. Jungfraujoch data scaled by a factor 100, hourly (unsmoothed) muon counting rate. The arrows indicate the positions of GLEs 68 and 69. *Right:* zoom into the region around GLE 69.

joch neutron monitor are depicted in Fig. 6. Jungfraujoch data are scaled by a factor 100 and the muon counting rates are smoothed over a period of three hours.

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 (Bieber et al., 2002; Vashenyuk et al., 2007). In particular, the event could be measured for primary cosmic rays with GeV energies (Wang, 2006). It has been detected by the GRAND muon detector (10 GeV most probable energy) (Poirier et al., 2001), by the L3+C detector at CERN ($\approx$ 40 GeV primary energy) (L3, 2006), 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 (Shea et al., 2001; D'Andrea et al., 2003; Bieber et al., 2004; Tylka et al., 2005; Vashenyuk et al., 2007). 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, (Watanabe et al., 2006; Liu et al., 2006; Hurford et al.,

2006; Eroshenko et al., 2004, e.g.). 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 if these increases are statistically significant, since there are gaps in the observing time. Thus, it is not obvious if the detected rate variations are correlated with the Ground Level Enhancements.

Unsmoothed hourly count rates of the Karlsruhe Muon Telescope compared to the Jungfraujoch neutron monitor data during the Forbush Decrease in January 2005 are depicted in Fig. 7. For comparison the reader may refer to Fig. 4 for the smoothed counting rate of the same event. In the interval shown, two Ground Level Enhancements (GLE 68 and 69) have been observed, the corresponding times are marked in the figure. GLE 69 occoured on January 20, 2005 and was the second largest GLE in fifty years (Vashenyuk et al., 2005a,b, 2006, 2007). Measurements of the Aragats multidirectional muon monitor indicate that protons were accelerated at the Sun up to energies of 20 GeV in this GLE (Bostanjyan et al., 2007). Protons accelerated during the main phase have a softer energy spectrum than during the initial phase of the event. It is assumed that protons were accelerated in a process or processes directly related to a solar flare (Simnett, 2006). The right-hand panel of Fig. 7 shows the region around GLE 69. No indication for a significant increase in the muon rate associated with GLE 69 can be seen in the figure. The Aragats data indicate that the time interval of solar proton flux with very high energies was only very short, this could explain why nothing is seen in the Karlsruhe Muon Telescope data. In addition, the solar cosmic-ray flux during the initial phase was very anisotropic, another potential reason for the non-observation in the muon rate.

6. 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, which are 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 obtained previously by observations of lines in the gamma ray spectrum measured during solar flares (Rieger, 1989; Fletcher, 2002). 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.

References

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

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

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.

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.

N.K. Bostanjyan, A.A. Chilingarian, V.S. Eganov, et al., On the production of highest energy solar protons at 20 January 2005, Advances in Space Research 39, 1454-1457, 2007.

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.

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.

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.

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

S. E. Forbush, Worldwide cosmic ray variations, J. Geophys. Res., 59, 525 - 542, 1954.

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

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

J.R. Hörandel, Kalibration von TMS-Ionisationskammern mit Myonen der Höhenstrahlung und Messung des Myon-flusses, Report KfK 5320, Kernforschungszentrum Karlsruhe ISSN 0303-4003, 1994.

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.

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

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

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

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

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.

E.N. Parker, The passage of energetic charged particles through interplanetary space, Planetary and Space Science 13, 9-49, 1965.

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.

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.

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

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.

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

G.M. Simnett, The timing of relativistic proton acceleration in the 20 January 2005 flare, Astronomy and Astrophysics 445, 715-724, 2006.

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

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.

I.H. Urch and L.J. Gleason, Galactic cosmic ray modulation from 1965-1970, Astronom. Space Sci., 17(2), 426-446, 1972.

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

I.G.Usoskin, G. A. Kovaltsov, K. Mursula, et al., Long-term cosmic ray modulation by heliospheric parameters: non-linear relations, Proceedings 28th International Cosmic Ray Conference, Tsukuba 3803-3806, 2003.

E.V. Vashenyuk, Y.V. Balabin, B.B. Gvozdevsky, Super GLE of January 20, 2005, Physics of Auroral Phenomena, Proc. XXVIII Annual Seminar, Apaty, 149-152, 2005.

E.V. Vashenyuk, Y.V. Balabin, B.B. Gvozdevsky, et al., Relativistic solar cosmic rays in January 20, 2005 event on the ground based observations, Proc. 29th Int. Cosmic Ray Conf., Pune 1, 209-212, 2005.

E.V. Vashenyuk, Y.V. Balabin, J. Perez-Peraza, et al., Some features of the sources of relativistic particles at the Sun in the solar cycles 21 - 23, Advances in Space Research 38, 411-417, 2006.

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.

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

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