

# Correlations between solar events and the cosmic muon flux measured with WILLI detector

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**Abstract.** The WILLI detector, built in IFIN-HH Bucharest in collaboration with FZ Karlsruhe, is a compact rotatable system, with an incident surface of 1 m<sup>2</sup>, consisting of 16 modules, each module having a scintillator layer (3 cm thickness) and Al support (1 cm thickness). The modular system is surrounded by 4 anticoincidence modules. With WILLI detector we can measure simultaneously muon events with energy  $\geq 0.4$  GeV and the muon events with energy lower than 0.6 GeV (corresponding only to events stopped in the detector layers).

The measurements performed with WILLI detector have shown a variation of the muon intensity which can be correlated with the solar effects. Taking into account muon events with energy  $\geq 0.4$  GeV, a modulation of the muon intensity as a diurnal variation is observed.

The analysis of the muon events for a smaller energy range, lower than 0.6 GeV, has shown an aperiodic variation of the muon intensity, which could be correlated with magnetic activity indicated by the planetary K-index.

**Keywords:** low energy atmospheric muons, solar modulation

## I. INTRODUCTION

When galactic cosmic rays enter the heliosphere they enter a region dominated by our Sun. Magnetic fields and processes such as diffusion, convection and drifts affect cosmic particles on different timescales and with various intensities corresponding to the solar activity. For solar modulation surveys the low energy part of the cosmic rays spectrum is relevant as it is the part most influenced by the solar activity. As the particle's energy increases it tends to travel less influenced.

The Earth's atmosphere and magnetic field also play an important role. A cosmic particle hitting the Earth's atmosphere will suffer nuclear interactions, loose energy and generate a shower or secondary particles that will continue interacting as they propagate towards ground. The muons component of such a shower is the most abundant at ground level.

The fact that cosmic rays and the secondary particles that are observed at ground level are linked to the solar

activity gives us the opportunity to investigate the solar activity.

The two different types of solar effects that can be observed using particle detectors at ground level are periodic or sporadic effects, [1], [2], [3], [4], [5], on the flux of neutrons and muons. Periodic events are well connected to the solar cycle and geometry of the Sun-Earth connection and present important subjects for solar studies but do not pose a threat on ourselves. Phenomena that can also affect life on Earth and are of solar origin may be expected if spaceweather is taken into account because particle detectors at ground level can record anomalies in the cosmic rays propagation before dangerous magnetic storms reach and affect us.

## II. THE DETECTOR

The detector, WILLI (Weakly Ionizing Lead-Lepton Interaction), is a sampling calorimeter for atmospheric muons, designed initially for muon charge ratio measurements [6]. It is located in IFIN-HH, at 44° 21' N, 26° E, 75 m above sea level and 5.6 GV rigidity cutoff. It consists of 20 modules 16 plates placed in a stack and 4 as anticounters, fig. 1. All the modules are identical, scintillator plates, 3 cm thick, encased in 1 cm thick aluminium box, read by 2 photomultipliers placed at opposite corners of the plate. The detector has the possibility to rotate both in zenith (up to 45°) and azimuth (no restriction).

The acquisition trigger can be chosen from 1 or 2 different plates in the stack. This means that there exists the possibility to record muons with different energy threshold,  $\geq 0.4$  GeV or  $\geq 0.6$  GeV, if the trigger is set for the first 2 plates or for the first and the last plates in the stack.

Also the detector can register muons stopped inside the detector which gives us the possibility to investigate muons in a small energy range, 0.4-0.6 GeV. The selection for a small range of energies is performed after the acquisition on the usual run when all the incoming muons are recorded. Thus we have access to both types of data, all passing the trigger condition and energy range selection, simultaneously.

The detector dead time is 50  $\mu$ s. For muons that are stopped in the detector an additional 80 ns time window

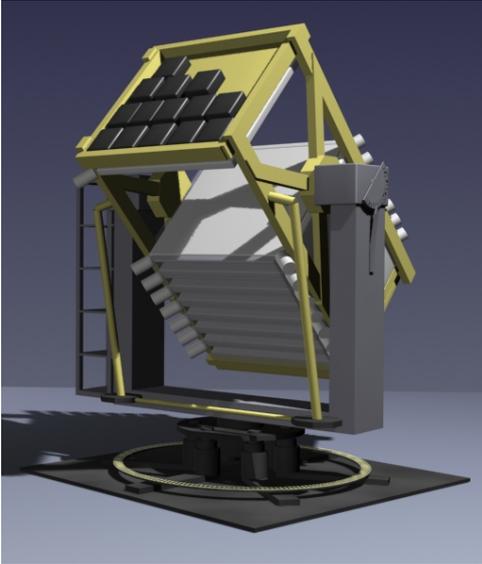


Fig. 1. The WILLI detector.

is reserved for the observation of the delayed electron resulted from the muon decay inside the detector, thus increasing the overall dead time.

### III. SOLAR MODULATION

Solar modulation means time variation of cosmic radiation intensity due to solar activity.

Solar modulation of cosmic rays takes place in the heliosphere (i.e. the region where solar influence is dominant). Galactic cosmic rays are influenced by the solar wind and heliospheric magnetic field (HMF) when entering the heliosphere. The solar activity, through all kinds of magnetic disturbances, affects the shape of the cosmic rays energy spectrum and the direction of particle propagation. The modulation effects decrease with increasing energy and become less significant for particles with rigidities in excess of  $\approx 10$  GeV/nucleon, i.e. a rigidity of 10 GV for protons and 20 GV for He [7].

The amplitude of this activity is time dependent and manifests periodic as well as aperiodic features on different time scales (see table I). In this study we intend to investigate the possibility to observe the types of effects listed in table I.

### IV. MUON INTENSITY VARIATIONS

We have performed measurements of integral vertical muon intensity, computed as below, for various periods of time.

$$I_v(E > E_{th}) = \frac{dN}{dAdtd\Omega} [cm^{-2}s^{-1}sr^{-1}] \quad (1)$$

where  $E_{th}$  is given by the type of acquisition/trigger chosen.

After recording the raw muon count rate we have corrected it for atmospheric pressure, [7]. The fractional

change of muon intensity,  $\delta j_\mu/j_\mu$ , is related to the pressure change,  $\delta p$ , by:

$$\delta j_\mu/j_\mu = -\alpha_\mu \delta p \quad (2)$$

where  $\alpha_\mu$  is the *pressure coefficient* of the muonic component,  $\alpha_\mu \simeq 0.12\%$  [ $mm^{-1}$  Hg] for atmospheric pressure measured in [mm Hg].

So far no additional data, e.g. height of the production layer, are available and therefore no other correction for the atmospheric influence is made.

#### A. Periodic variations

Periodic variations in sea level muon intensity have been documented [3], [5]. They include data recording on extensive periods of time as well as daily monitoring.

Given the short amount of time our detector has been taking data for solar modulation monitoring we will refer only to short period periodic variations, namely the daily variation.

Data sets contain time stamp and PMT signal amplitude information for each individual event. They are divided into user defined time intervals after the acquisition process. Figure 2 shows raw count rate for a period of 3 days for  $E \geq 0.4$  GeV.

For time periods of 24 hours 10-minute rates were normalized to a daily average obtained from data taken 7 days before and fitted with a 24 and 12 hour periodicity function, see figure 3,

$$\begin{aligned} \text{Averaged rate} = & 1 - 0.008 \cdot \sin\left(\frac{2\pi}{12}x - 1.21\right) - \\ & - 0.03 \cdot \sin\left(\frac{2\pi}{24}x - 1.47\right). \end{aligned} \quad (3)$$

The amplitude of the sinusoidal variation relative to the average is  $\sim 3\%$  for the diurnal variation and  $\sim 1\%$  for the semi-diurnal variation. The maximum is around 11 a.m.

#### B. Aperiodic variations

Aperiodic variations are mainly characterized by their relative unpredictability. They are linked to the solar activity, therefore a solar maximum period is expected to present more aperiodic events, but this is not a rule. This type of variations can vary both in intensity (see table I) and time scale. Sporadic events have been detected with muon telescopes [9].

Small intensity variations may be caused by geomagnetic field perturbations which are usually linked with the solar activity.

Our detector, being able to 'see' small variations as the daily variation and due to its good counting possibility, can be also used to investigate these aperiodic events.

Low energy muons are mostly produced by low energy primaries which are strongest affected by solar modulation. Because of the stack configuration of the detector we can measure the muon intensity at low energies and for small energy ranges. This enables us to exclude all the high energy muons and measure only the muons most influenced by solar and local

type	amplitude	nature
<b>Periodic variations</b>		
11- and 22-year	up to 30%	Solar modulation of GCR in the heliosphere
27-day	<2%	Long-lived longitudinal asymmetry in HMF of solar wind structure
diurnal	few%	Anisotropy of CR fluxes due to convection by solar wind and diffusion along HMF lines
<b>Aperiodic variations</b>		
GLE	1-300%	Increase of CR intensity due to arrival of solar cosmic rays
Forbush decreases	up to 30%	GCR decrease due to the shielding by an interplanetary shock passing the Earth
increase before Forbush decrease	<2%	CR increase due to "collection" of CR particles in front of the interplanetary shock causing a Forbush decrease
magnetic cloud effect	few%	GCR decrease due to the shielding by a magnetic cloud passing the Earth

TABLE I  
CR INTENSITY VARIATIONS: EXTRA-TERRESTRIAL EFFECTS [8]

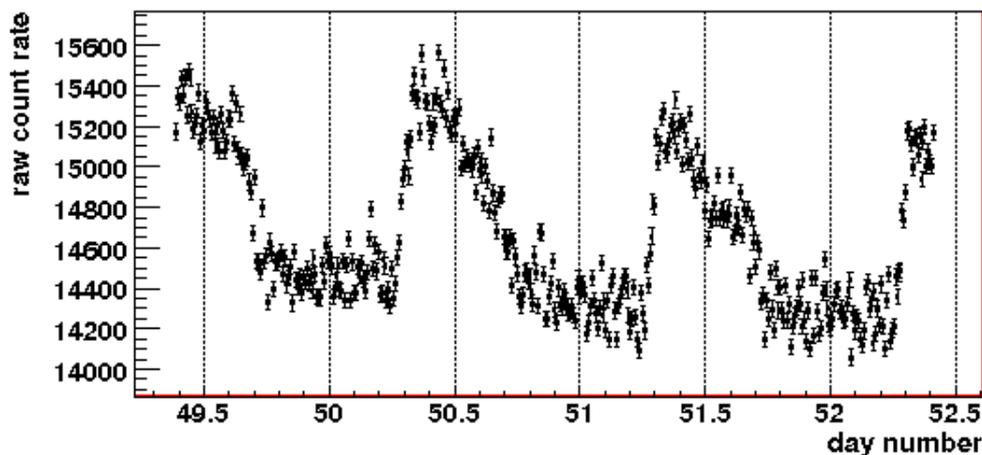


Fig. 2. Raw muon count rate, measured with WILLI, as a function of day number of the year divided into 10 minutes intervals for  $E \geq 0.4$  GeV. Error bars represent statistical errors.

magnetic activities. Such an example is depicted in fig. 4. The figure shows 60-minutes count rates for muons in the energy range 0.4-0.6 GeV. In this energy range a significant decrease is observed that was not significant in the  $E \geq 0.4$  GeV measurements. After investigation, an increase in the  $K_p$  index was found to coincide, as time period during that day, with the observed decrease [10].

### V. CONCLUSIONS

In this study we investigated the possibility to detect solar modulation of cosmic rays, both periodic and aperiodic effects, with our detector, WILLI, a sampling calorimeter for atmospheric muons.

Due to the configuration of our detector we can perform various types of measurements, selecting only a small energy range, 0.4-0.6 GeV, or all the muons passing through the detector which sets an energy lower limit.

Our detector is capable of recording variations in the muon count rate that are of the same order as those expected for solar modulation effects. A few examples stand to prove it.

### VI. ACKNOWLEDGEMENTS

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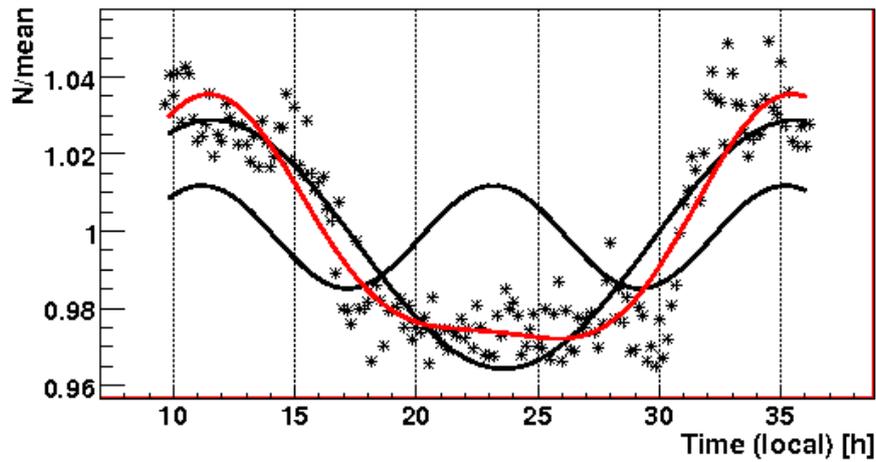


Fig. 3. Daily variation of muon count rate for  $E \geq 0.4$  GeV as a function of local time averaged with a daily mean and fitted with 12 and 24 hour periodicity functions. The third curve represents the fit with the sum of the 2 sine functions.

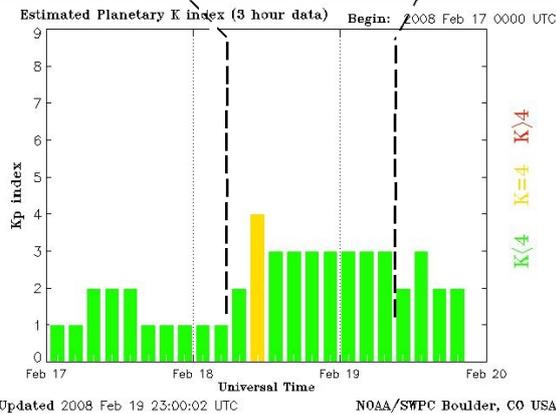
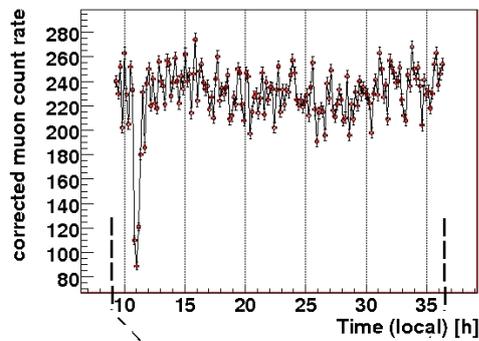


Fig. 4. Upper panel: variation of 60 minutes count rate, measured with WILLI, for an aperiodic decrease registered around 10 a.m. local time on February 2008; the line connecting the points is only meant to help the eye. Lower panel: planetary  $K_p$  index indicating an unsettled magnetic field around the same period of time that the decrease was observed, [10].

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