MEASUREMENTS OF THE COSMIC MUON FLUX WITH THE WILLI DETECTOR AS A SOURCE OF INFORMATION ABOUT SOLAR EVENTS

A. SAFTOIU[1,*], A. BERCUCI[1], I. M. BRANCUS[1], M. DUMA[1], A. HAUNGS[2], B. MITRICA[1],
M. PETCU[1], H. REBEL[2], O. SIMA[3], G. TOMA[1]

[1]Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
Email[*]: allixme@gmail.com
[2]Institut für Kernphysik, Karlsruher Institut für Technologie, Germany
[3]Department of Physics, University of Bucharest, Romania

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The WILLI detector, set up in the National Institute of Physics and Nuclear Engineering, Bucharest, is a 1 m^2 incident area rotatable system, consisting of 16 scintillator modules (3 cm thickness). WILLI detector measures simultaneously muon events with the muon energy $\geq$ 0.4 GeV and energy between 0.4 $\leq E_\mu \leq$ 0.6 GeV, if the muons are stopped in the detector.

The measurements show a variation of the muon intensity with time which can be correlated with 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. Muon events for a smaller energy range (0.4 - 0.6 GeV) seems to exhibit an aperiodic variation of the muon intensity, which could be correlated with magnetic activity indicated by the planetary K_p index.

1. 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 time scales and with various intensities associated with the solar activity. For solar modulation effects the low energy part of the cosmic rays spectrum is relevant as there the propagation of particles is most influenced by the solar activity.

The atmosphere and magnetic field of the Earth play also an important role. Cosmic particles hitting the atmosphere undergo nuclear interactions, loose energy and generate showers of secondary particles that will continue interacting as they propagate towards ground. Due to their penetrability the muons of such a shower constitute the most abundant component at ground level.

The fact that cosmic rays and the secondary particles, observed at ground level, appear to be associated with the solar activity provides the opportunity to study the solar activity.

The two different types of solar effects that can be observed by use of particle

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detectors at ground level, i.e. the neutron or muon telescopes, are either periodic or sporadic [1–5]. Periodic events are well established to correspond to the solar cycle and to the geometry of the Sun-Earth connection. They do not provide any danger for human life and the fact that we are used to their effects on a daily basis sometimes may cause us to overlook them, but their observation is an important subject for solar physics. Phenomena of solar origin which can affect biological life on Earth are non-periodic and they may be predicted if we study space weather. Particle detectors at ground level may record anomalies in the cosmic rays propagation before dangerous magnetic storms reach the Earth and affect life and sensitive electronic devices.

The present work reports some attempts to use the WILLI (Weakly Ionizing Lead-Lepton Interaction) detector, installed in the National Institute of Physics and Nuclear Engineering, Bucharest, originally designed [7] and extensively used [8] for muon charge ratio measurements, for observations of intensity variations of atmospheric muons and tentative correlations with the solar activity. Such kind of measurements has a long and lively tradition, since S.E. Forbush has discovered in 1954 the influence of the Sun on CR propagation [9]. The more recent paper of I. Braun *et al.* [10] comprises observations of the muon flux recorded over 13 years and highlights the associations of these variations with solar activity induced phenomena. The conclusion the authors draw is very important: non-periodic effects caused by the solar activity are visible at ground level by recording secondary muons.

The present investigation [11] is a feasibility study that addresses the question to which extent WILLI may be used for long term monitoring of the solar activity. One important feature of this set-up is that measurements for different muon energy windows can be performed.

2. SOLAR MODULATION

Solar modulation of cosmic rays takes place within the heliosphere (i.e. a bubble of the solar wind plasma ranging up to 100 AU from Sun) and it is a time variation of cosmic radiation intensity due to solar activity. When entering the heliosphere, galactic cosmic rays (GCR) are influenced by the solar wind and heliospheric magnetic field (HMF). 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 10 GeV/nucleon, i.e. a rigidity of 10 GV for protons and 20 GV for He [12].

The amplitude of this activity is time dependent and manifests periodic as well as aperiodic features on different time scales (see table 1).

Among the periodic effects the strongest, and thus most ’visible’ one is the 11-

Table 1.

CR Intensity variations: extra-terrestrial effects [13]

Type	Amplitude	Nature
Periodic variations		
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
Aperiodic variations		
GLE Ground Level Enhancement	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

year variation of the galactic cosmic rays intensity with the solar cycle, but it needs observation on an extended period of time.

Periodic effects that extend over shorter periods of time are easier to investigate because we consider a feasibility study. Thus, we will restrict our present study only to the shortest of the periodic effects, the diurnal variation.

Diurnal variation of the cosmic rays activity is known since the early thirties of the last century (see [1]) and has been related to solar effects [2]. The asymptotic cone of acceptance of ground based detectors sweeps daily through the direction containing spatial anisotropies in interplanetary space.

If the periodic variation in the galactic cosmic ray intensity are observed to amount up to $\sim 30\%$ [13], aperiodic effects however may be of unpredictable strength from insignificantly weak to dangerously strong. Sporadic variations include decreases (*e.g.* the well known Forbush decreases) and increases (*e.g.* GLE - ground level enhancement) in the particle flux. A decrease is caused by the deflection of galactic cosmic rays away from the Earth as a result of a solar magnetic disturbance. The increase comes from the addition of solar energetic particles ejected during solar explosions. Eruption in the solar corona cause magnetic storms on Earth, but by measuring how cosmic rays react to the solar activity, these storms can be predicted.

Aperiodic variations are mainly characterized by their relative unpredictability. They are linked to coronal phenomena that usually occur during solar maximum but this is not a rule, and therefore we will investigate the possibility of their occurrence even in a time of solar minimum, 2008-2009. Small intensity variations may also be caused by geomagnetic field perturbations which are usually triggered by the solar activity.

3. THE DETECTOR

The detector WILLI is a sampling calorimeter for atmospheric muons, designed initially for muon charge ratio measurements [7]. It is located in the National Institute for Physics and Nuclear Engineering, at 44^0 21' N, 26^0 E, 75 m above sea level and with 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 and read out by 2 photomultipliers placed at opposite corners of the plate.

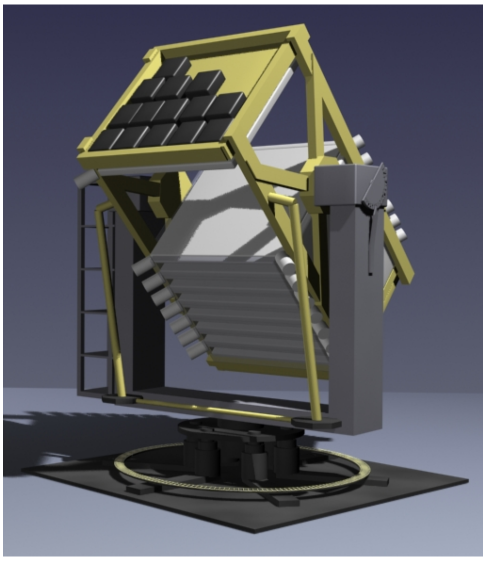

Fig. 1 – The WILLI detector.

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 thresholds. We have performed measurements for energies $\geq$ 0.4 GeV, with the trigger set for the first 2 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 μs. For muons that are stopped in the detector an additional 80 ns time window is reserved for the observation of the delayed electron resulting from the muon decay inside the detector [7], thus increasing the overall dead time.

4. MUON INTENSITY VARIATIONS

After recording muon events we calculate the raw muon count rate. Subsequently we correct the count rate for atmospheric pressure following the procedure described in [12]. The fractional change of muon intensity, $\delta j_\mu / j_\mu$, is related to the pressure change, δp, by:

$$\delta j_\mu / j_\mu = -\alpha_\mu \delta p \tag{1}$$

where α_μ is the *pressure coefficient* of the muonic component, $\alpha_\mu \simeq 0.12\%$ [mm^{-1} Hg] for atmospheric pressure measured in [mm Hg], taken from [12].

Since further information is not available, no additional correction for the atmospheric influence has been made.

4.1. PERIODIC VARIATIONS

Periodic variations in sea level muon intensity have been compiled by other authors [3, 5]. They include data recording on extensive periods of time as well as daily monitoring. With respect to the relatively short period of time WILLI has been taking data, 15 days, only short periodic (daily) variations are considered for the moment.

Registered 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 (i.e. for a time interval of 10 minutes, each point represents the number of muons recorded in that time). Figure 2 shows the pressure corrected count rate for a period of 4 days (June 2009) for muons of E $\geq$ 0.4 GeV, i.e. all muons passing through the detector.

For time periods of 24 hours, 10-minute pressure corrected count rates were normalized to a daily average obtained from averaging data taken 7 days before, a day which we consider did not present any aperiodic events. The rate was then fitted with a 24 and 12 hour periodicity function (parameters from the fit).

$$\text{Averaged rate} = 1 - 0.008 \cdot sin(\frac{2\pi}{12}x - 1.21) - 0.03 \cdot sin(\frac{2\pi}{24}x - 1.47). \tag{2}$$

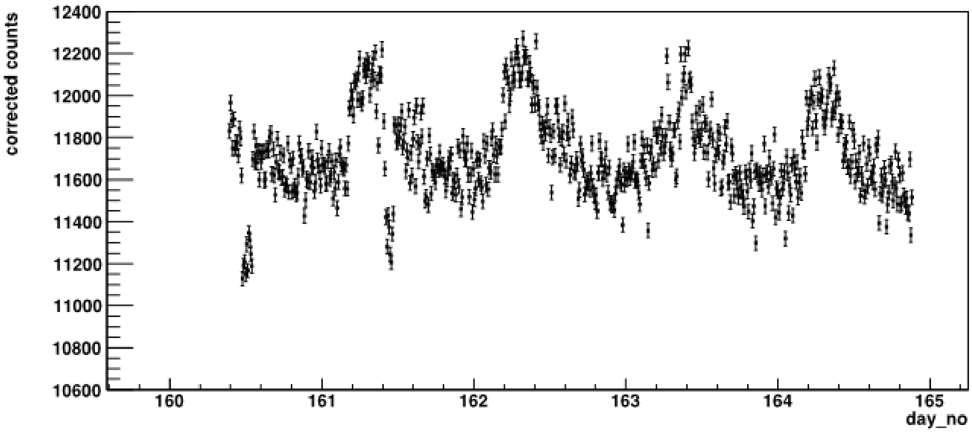

Fig. 2 – Muon count rate as a function of day number of the year 2009 divided into 10 minutes intervals, for $E \geq 0.4$ GeV. Error bars represent statistical errors.

An example for a period of one day is displayed in figure 3. The amplitude of the sinusoidal time variation (x being the time parameter) relative to the average is $\sim 2\%$ for the diurnal variation and $\sim 0.5\%$ for the semi-diurnal variation. The maximum is around 11 a.m. local time (EET). This trend is visible in the entire observation time of 14 days.

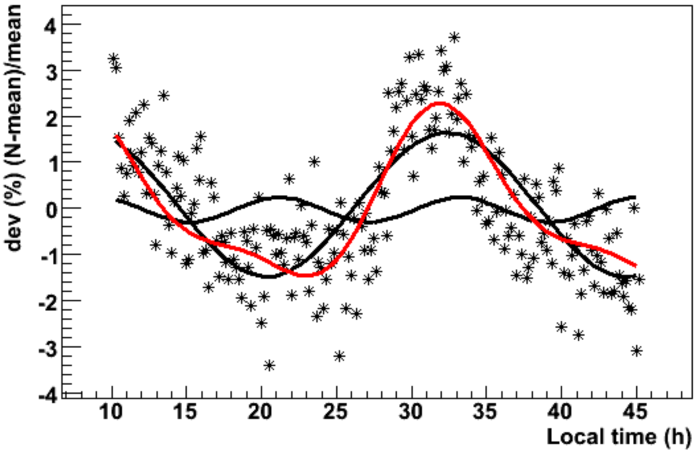

Fig. 3 – Variation of muon count rate over the period of one day (one of the days from figure 2), expressed as percentage of deviation from a daily mean, for E ≥ 0.4 GeV, as a function of local time, fitted with 12 and 24 hour periodicity functions. The red line is a sum of the 2 functions.

The sinusoidal variation maps the known solar diurnal variation which is related to spatial anisotropies outside the influence of the Earth's atmosphere and geomagnetic field (see the discussion in [1]). In a recent paper [14] Mailyan and Chilingarian report impressively on similar variations of the neutron and muon flux observed with the detectors of the Aragats Space-Environmental Center in Armenia.

4.2. APERIODIC VARIATIONS

Aperiodic variations are relatively unpredictable. In general, a solar maximum period is expected to present frequent aperiodic events, but this is not a strict rule. Small intensity variations may also arise because of geomagnetic field perturbations.

WILLI is able to register the daily variation of the muon flux and can be also used for aperiodic events, in particular for low energy muons (see sect. 3), which are most influenced by solar and local magnetic activities. Figure 4 shows the 10-minutes corrected count rate for muons in the energy range 0.4-0.6 GeV (upper panel). In this energy range a significant decrease is observed that was not significant for the E $\geq$ 0.4 GeV measurements.

This finding is tentatively correlated with an increase of the K_p index period during the day when the decrease was observed [15]. The planetary K_p index quantifies magnetic disturbances by a 3 hour average of a number of 13 stations situated all over the world measuring the horizontal component of the Earth's magnetic field; a higher index shows a more disturbed magnetic field, *e.g.* a value below 3 shows a quiet field, a value between 3 or 4 shows an active magnetic field, a value between 4 and 9 means a magnetic storm is present and a value larger than 9 means that the storm is severe. A disturbed and stronger magnetic field than a quiet one may cause deflection of low energy incoming particles and thus a decrease in ground level muon intensity. The information on K_p is taken from a public archive which uses NOAA, Space Weather Prediction Center data [15].

5. CONCLUSIONS

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

Thanks to the configuration of our detector various types of measurements could be performed, either selecting only a small energy range, 0.4-0.6 GeV, or for all muons traversing the detector with E $\geq$ 0,4 GeV.

Differently from [3] the studies here are concentrated on the short term variations observed in periods of days. We observe the modulation of the muon flux due to solar diurnal variation, considered to be caused by spatial asymmetries of the impinging low energy CR flux, and we could reveal a case of aperiodic variation by

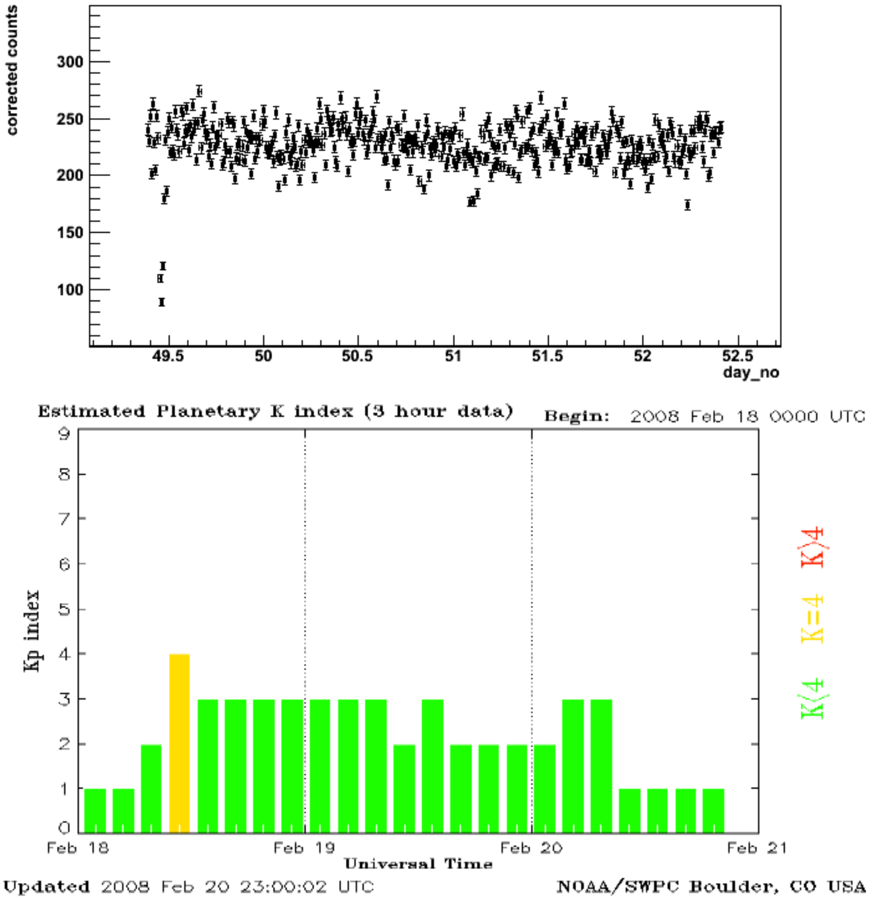

Fig. 4 – Upper panel: variation of 10 minutes count rate for an aperiodic decrease registered around 10 a.m. local time (EET) on February, 18, 2008; the x axis is expressed in day number of the year. Lower panel: planetary K_p index indicating an unsettled magnetic field around the same period of time that the decrease was observed, [15].

correlating with the planetary K_p index. The topic needs further attention.

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Figure 1. The cosmic muon and gamma-ray detector. The configuration shown is for measuring muon flux as the detector is pointed to the sky at a given angle (90 o with respect to the vertical here). v. External Pulse Counter The external pulse counter, although not required, allows the CR detector greater flexibility.Â Cosmic-Ray Muons The PMTs are very sensitive and generate their own noise. This is largely due to thermal energy causing an electron to be ejected, which then excites several other electrons in the neighboring plates, triggering a false signal.Â The procedure was done while looking for coincidence events, which revealed a plateau range around one volt without major disruption in the number of counts between different control voltages.