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Solar modulation of cosmic rays in the energy range from 10 to 20 GeV

I. Braun[a,1], J. Engler[a], J.R. Hörandel[a], J. Milke[a]
(a) University and Forschungszentrum Karlsruhe, P.O. Box 3640, 76021 Karlsruhe, Germany
(1) now at Max Planck Institute for Nuclear Physics, P.O. Box 103980, 69029 Heidelberg, Germany
Presenter: J.R. Hörandel (hoerandel@ik.fzk.de), ger-hoerandel-J-abs3-sh34-poster

The flux of single muons with energies above 0.7 GeV has been recorded from 1993 to 2005 using a muon telescope, located in southern Germany. The registered events originate from primary cosmic rays with energies around 10 to 20 GeV, thus extending the energy range covered by neutron monitors to higher energies. Correlations of the time dependence of the muon flux with heliospheric parameters have been analyzed using data from the muon telescope and the worldwide neutron monitor network as well as simulations. Variations on time scales of the solar cycle, the solar rotation, and the Earth's rotation are investigated.

1. Introduction

Galactic cosmic rays traverse the heliosphere and interact with its varying fields yielding a variation of the cosmic-ray flux with solar activity. At energies up to about 10 GeV, the modulation effect is measured in detail by the well established world wide neutron monitor network. The present experiment uses secondary muons corresponding to more energetic cosmic-ray protons that are still modulated by the heliosphere. This allows to study energy dependent differences like in the amplitude of solar modulation. In addition, an annual modulation of cosmic rays can occur due to heliospheric anisotropies. The relative movement of the Earth around the sun and within the interstellar medium generates the Compton-Getting effect. Low energy cosmic-ray particles travel mainly along curved field lines in the heliospheric neutral current sheet (NCS), inward or outward according to the magnetic polarity of the heliosphere. These fields rotate with a period of approximately 27 days and overtake the Earth in its orbit creating a flux variation dependent on local time.

A muon telescope located at Forschungszentrum Karlsruhe, Germany (49°N, 8°E), consisting of two layers of scintillators separated by a lead filter, records the flux of single muons with energies above 0.7 GeV continuously since 1993. The experimental setup is described in detail in [1]. Simulations with CORSIKA (with the hadronic interaction model UrQMD) and GEANT 3.21 using a parametrized cosmic-ray spectrum at the top of the atmosphere [2] ($M = 750$ MV) revealed that the registered events originate from primary cosmic rays with energies around 10 to 20 GeV with a maximum at 15 GeV. 90% of the triggered events are caused by primary protons with zenith angles smaller than $15°$.

The muon rate dN was iteratively corrected for an atmospheric pressure of 1013 hPa and a height of the typical muon production layer of 13.6 km ($\sim$ 150 g/cm^2) for each year, yielding correction parameters of $dn/dp = (-0.12 \pm 0.04)$ %/hPa and $dn/dh = (-3.8 \pm 1.2)$ %/km. 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 expected value.

2. Results

Variability on Timescales of the Solar Cycle

The traditional key parameter to quantify solar activity is the international sunspot number (ISSN), which is provided by the Sunspot Index Data Center [3]. As a measure for the correlation between cosmic-ray intensity

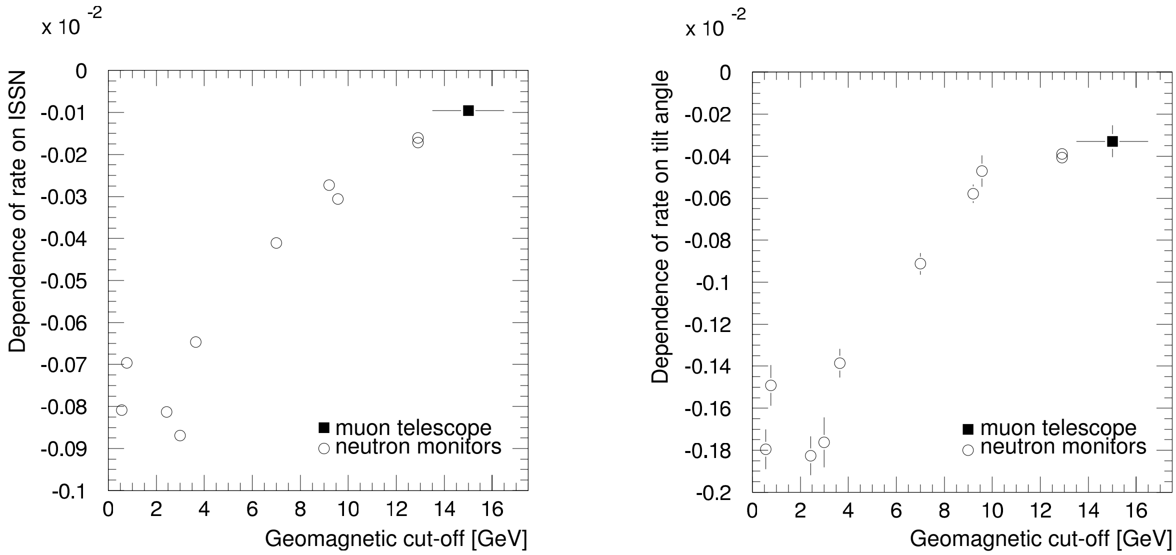

Figure 1. Dependence of neutron and muon count rate on the sunspot number (left) and on the tilt angle of the heliospheric neutral current sheet (right) for different cut-off parameters.

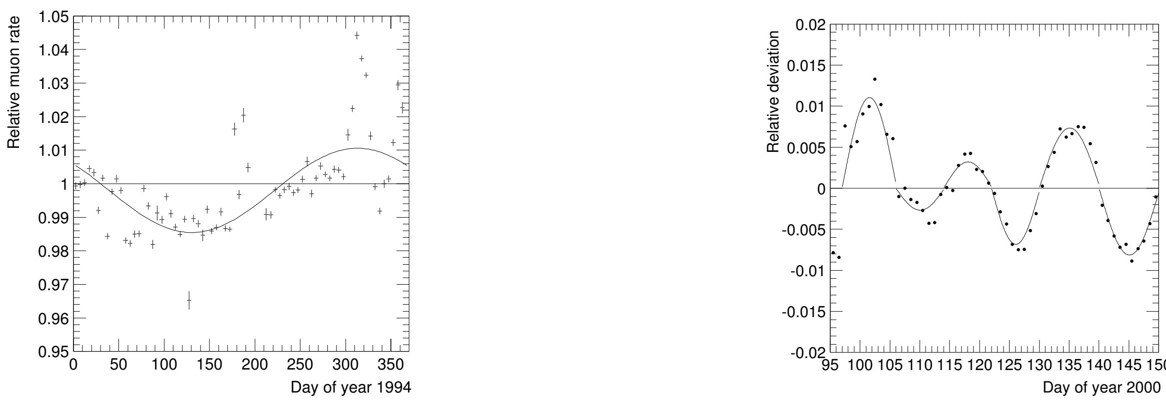

Figure 2. *Left:* Measured annual variation of the muon rate in 1994. *Right:* Example for the difference between the muon rate smoothed over 9 days and the rate smoothed over 29 days. Sine functions have been fitted to the data between subsequent zero crossings.

and solar activity, the slopes of linear fits to the muon and neutron count rates as a function of the sunspot number were used. The same was done for the dependency on the average tilt angle of the NCS over one Carrington rotation [4], which relates to the electromagnetic structure of the heliosphere. Fig. 1 shows the good correlation between both solar modulation parameters and the geomagnetic cut-off rigidity of several neutron monitor sites (open circles). The cut-off rigidity defines the typical energy of the primary particles. For the muon telescope, the typical primary energy has been derived from simulations. Its total flux variability of about $\pm 1.5\%$ over the solar cycle follows the trend of the neutron monitors. It is also consistent with a simulated value of $\pm 2.4\%$ using the spectral sensitivity of the instrument and a parametrized energy spectrum of cosmic rays [2] for modulation parameters obtained from [5].

Annual Variability
The muon flux after atmospheric correction was scanned for annual variation in the years 1994 to 2005. Only for 1994 a significant signal with an amplitude of $\pm 1.2\%$ could be detected (Fig. 2, left). This agrees with a decreasing strength of such a modulation seen in the neutron monitor data as well. The maximum in 1994 occurs on day 313 (November 9th). Averaging over all years we obtain a maximum at day 278 (October 5th) which coincides with the average maximum for the neutron monitors on the same day. The phase of this modulation seems to be nearly independent of energy, while the amplitude decreases with primary energy. For example, in 1993 the modulation amplitude of the neutron rate ranges from about 1.5% at 0.6 GV to 0.3% at 12.9 GV.

Solar Rotation
Effects following the solar rotation are expected to have time scales of approximately 25.7 to 33.5 days, depending on the heliospheric latitude of their origin. Half that periodicity is expected for disturbances symmetric to the solar rotation axis. In addition to irregular events on the solar surface, NCS crossings (the magnetic polarity surrounding the Earth) can cause variations on both time scales. Instead of a harmonical analysis, a more flexible method was used: a running mean over 29 days was subtracted from a running mean over nine days to eliminate effects on shorter and longer time scales. Between zero crossings, a sine-function was fitted to the data as indicated in Fig. 2, right. Amplitudes in the order of $0.5 - 3\%$ were detected throughout the data, apparently with larger amplitudes when mayor drops in the NCS tilt angle occurred during the phase of rising solar activity. The average variation period of 22.0 days is shorter than expected.

Diurnal Variation
The hourly muon rates were normalized to a daily average and added up from October 1993 to May 2005. The sum of two sine-functions with twelve and 24 hour periodicity was fitted to analyze the dependence on local time. As seen in Fig. 3, the data are described well by the function $dN = 0.15\% \cdot \cos(2\pi/24 \cdot (h - 14.4)) + 0.05\% \cdot \cos(2\pi/12 \cdot (h - 0.2))$, where h is the local time. When separating the data into subsets of different heliospheric sectors according to [6], phase and amplitude of the diurnal variation stay the same within errors, while the semidiurnal component in the Toward-sector is stronger than in the Away-sector by a factor of three.

Individual Events
The high energy threshold of the muon telescope usually impedes direct detection of solar protons, but extremely energetic events as well as magnetic field disturbances could be detected as a drop in the muon rate. The strongest solar activity period so far occurred from October 19th to November 4th, 2003. The measured muon rate in comparison with the rate registered by the Climax neutron monitor is shown in Fig. 3 (right). Both instruments observe similar variations as a function of time, in particular a coincident drop in the rate on October 29th, 2003. This indicates the strength of this event, which influenced the proton flux even above 10 GeV.

3. Conclusion

Effects of solar modulation have been studied using neutron monitors with geomagnetic cut-off energies between 0.6 and 12.9 GV. The results were compared to data from a muon telescope sensitive to primary cosmic rays with energies from 10 to 20 GeV. For various observables the variations of the muon data follow the energy dependence indicated by the neutron monitors. This demonstrates that muon telescope data can be used to complement neutron monitor observations at high energies.

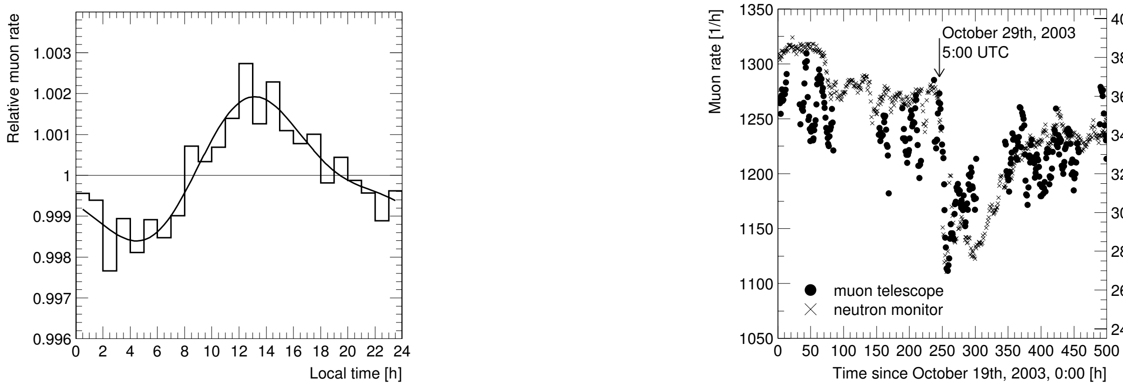

Figure 3. *Left:* Average diurnal variation of the muon rate after atmospheric correction and normalization to the daily average. *Right:* Muon rate (counts/hour) smoothed over 5 hours from October 19th to November 8th, 2003 compared to the Climax neutron monitor rate (counts/hour/100).

4. Acknowledgments

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