Study of solar activity by measuring cosmic rays with a water Cherenkov detector

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Abstract. We report on an indirect study of solar activity by using the Forbush effect which consists of the anti-correlation between the intensity of solar activity and the intensity of secondary cosmic radiation detected at ground level at the Earth. We have used a cylindrical water Cherenkov detector to measure the rate of arrival of secondary cosmic rays in Morelia Mich., Mexico, at 1950 m.a.s.l. We describe the analysis required to unfold the effect of atmospheric pressure and the search for Forbush decreases in our data, the latter correspond to more than one year of continuous data collection.

1. Introduction

Many aspects of the emergence of sunspots and coronal mass ejections on the surface of the sun are still under research as well as the details of the interaction of the solar wind with the magnetic field of the Earth. The appearance of sunspots, recorded systematically since 1700, shows an 11-year cyclic variation. The physicist Scott Ellsworth Forbush studied the secondary cosmic radiation at ground level and the rate of occurrence of sunspots in the 1930s; he discovered that there exist transient effects showing a clear of anti-correlation between the intensity of cosmic rays and solar activity, these effects are known today as Forbush decreases [1]. This phenomenon can be explained by the fact that the arrival of electrically charged cosmic rays at ground level on the Earth is directly influenced by the magnetic field carried by the solar wind as it propagates within the Solar System. In turn, the solar wind fed by coronal mass ejections is correlated with solar activity in general, and, in particular, with the rate of occurrence of sunspots.

Forbush decreases of secondary cosmic rays are detected by worldwide networks of monitors of neutron fluxes and, more recently, detectors of fluxes of secondary muons. The Forbush decrease is usually observable at the Earth within a few days after the observation of coronal mass ejection by the Sun; the decrease in the flux of secondary cosmic rays takes place over the course of a few hours.

Neutron monitors are the preferred instruments to monitor Forbush decreases because they respond to lower energy cosmic rays that suffer more heliospheric modulation compared to muon detectors. However, the advantage of muon monitors is that they are cheaper and easier to operate. Since they respond to the same phenomenon, i.e., the detection of secondary cosmic rays on the ground, the data from muon counters can be readily compared with the data from neutron monitors available in real time on the World Wide Web [2]. In this paper we study the sensitivity that can be achieved with a single water Cherenkov detector of small dimensions to monitor Forbush decreases by measuring the flux of secondary muons.

2. Data acquisition system

The propagation of charged particles through a medium with a higher speed than the speed of light in that medium produces the Cherenkov effect, this effect allows us to detect secondary cosmic radiation. The so called Cherenkov light can be detected by a photomultiplier located inside a water Cherenkov detector. The water Cherenkov detector used for this study, see Fig. 1, is a tank of polyethylene 1.3 m of height and 1.15 m of diameter, filled with water up to a height of 1.1 m. The water was contained in a bag of a highly reflective material called tyvek, which has a diffuse reflectivity of about 90 percent in the ultraviolet region of the EM spectrum. A single photomultiplier, EMI 9353KB, of 8 inches was located along the axis of the cylinder looking downwards from the top of the water surface. The photomultiplier signal was transmitted via RG58 coaxial cable to the electronics used to measured the rate of arrival of the secondary cosmic rays, our electronics is based on a a custom-made ADC card working at 100 MS/s controlled by a Field Programmable Gate Array (FPGA) programmed in VHDL, see Fig. 2. Our data acquisition system also has a GPS receiver to set a precise time tag on our data, an atmospheric pressure sensor and a temperature sensor. The atmospheric pressure and the temperature sensors allow us to correct our data to unfold variations in the measured rate of arrival of secondary cosmic rays due to variations in atmospheric pressure and temperature. We measured the rate of arrival of the secondary cosmic rays with four different thresholds on the PMT signals. All these data are transmitted via a RS232 port to a computer for storage; the data are saved in binary format in one file each day; we use off-line Linux tools to convert the data into decimal format and to analyze and plot the data. It is important to note that our discrimination threshold is anchored to the baseline of the signal from the PMT; this baseline is measured every second. In summary, the tasks that our data acquisition system performs are the following:

- Get the pulse-per-second (PPS) signal from the Oncore UT+ GPS receiver.
- Measure the rates in one-second intervals from the ADC board at a threshold of 22 mV which roughly corresponds to a muon deposition energy of 22 MeV or 0.11 VEM (Vertical Equivalent Muon)

Figure 1. The water Cherenkov used in this study, in the left side, located in UMSNH.

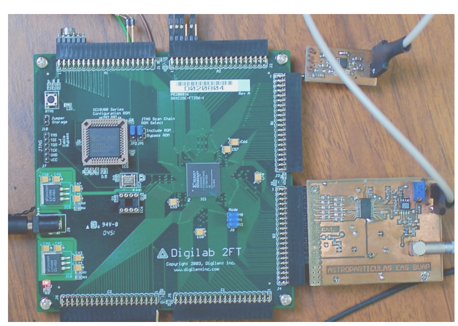

Figure 2. FPGA board and the ADC card.

- Get the GPS time from the Oncore UT+ GPS receiver
- Read the atmospheric pressure from the HP03D sensor in synchrony with the PPS signal
- Send all the above data in binary format to the PC in synchrony with the PPS signal by using the RS232 port.

3. Analysis and results

Figure 3 shows the rate measured every second for one day (August 1st, 2010) for the second threshold; this was a typical day during a period of low solar activity. Figure 4 shows the correlation between the rates for two of the different thresholds. We have checked that the distribution of these rates is given by a Gaussian distribution with a standard deviation equal to the square root of the mean value; this means that the muon detection is a random process with a constant probability per unit time, i.e., a Poisson process. In turn this constitutes an important test of the stability of the detector.

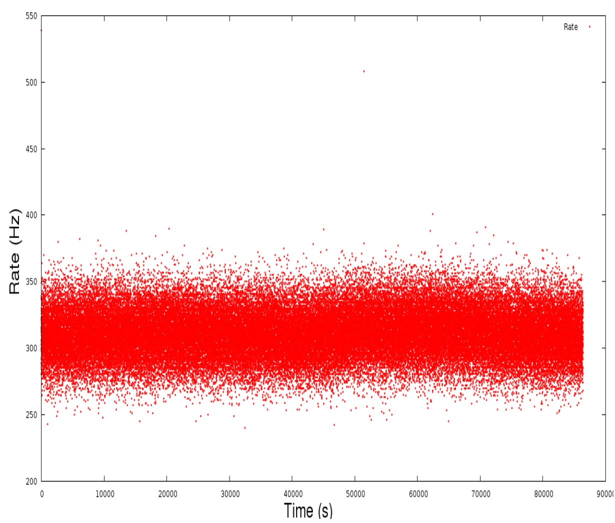

Figure 3. Rate measured per second for one day on August 1, 2010, by using the second threshold.

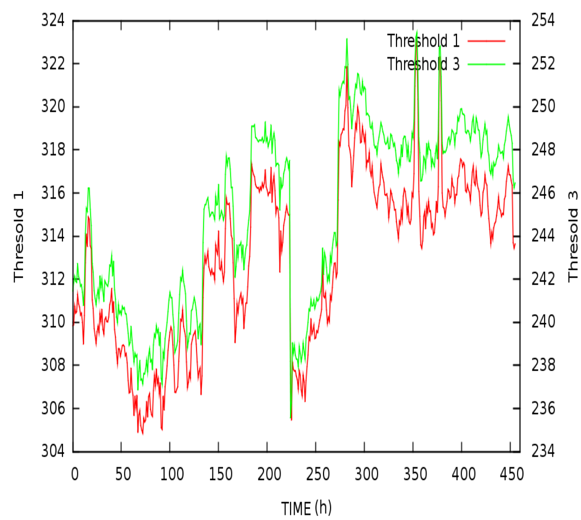

Figure 4. Hourly average rate for two different thresholds, in the period of August 1-19, 2010.

In Figure 5 we see the anti-corelacion between the average of the muon rates over periods of one hour and the atmospheric pressure. The statistical error on the average is equal to the standard deviation of the rate measured every second, roughly equal to the square root of the mean value measured every second, i.e., about 19 Hz, divided by the square root of 3600, i.e., the number of seconds in one hour. Figure 6 shows the scatter plot of the hourly average of the rate (vertical axis) versus the hourly average of the atmospheric pressure (horizontal axis), this also expresses the anti-correlation between atmospheric pressure and rate. The solid line is a least-squares fit with a slope of 0.79657. This anti-correlation is the well-known barometric effect on the flux of secondary cosmic rays; it is due to the larger or smaller mass of air in the path of the secondary cosmic rays when the atmospheric pressure is higher or lower, respectively, giving rise to a higher or smaller attenuation of the secondary muons, i.e., a lower or higher flux at ground level.

Figure 7 shows the comparison of our measurements with data from the McMurdo neutron monitor, taking with same dates. As explained above, these observatories are preferable for the observation of Forbush decreases. This image shows a decrese Forbush, due to solar activity,

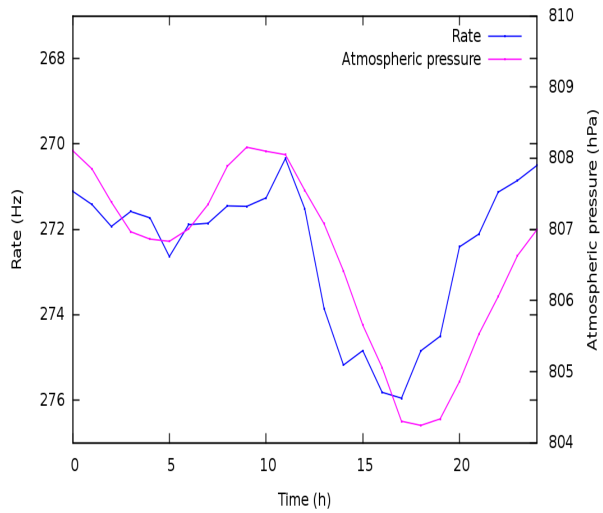

Figure 5. Hourly average of the rate of arrival of secondary muons and of atmospheric pressure, showing a clear anti-correlation between them, note that the Y axis on the left side is inverted.

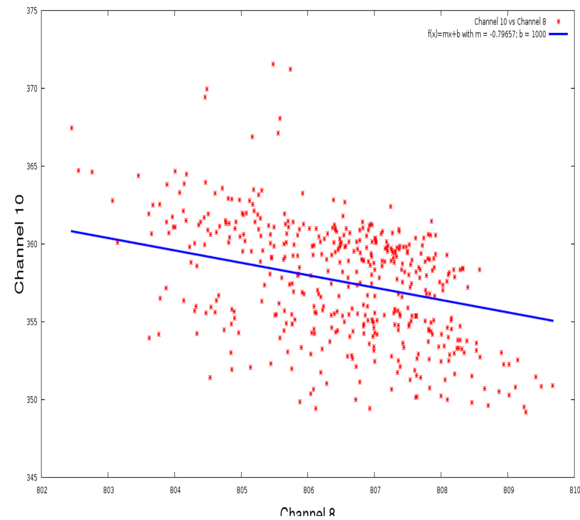

Figure 6. Hourly average of the rate (Y axis) and the hourly average of the atmospheric pressure (X axis). The solid line is the least-squares fit with a slope of -0.79657.

detected by both arrays. In red we show the hourly average rate obtained in the period August 1-19, 2010 corrected, to remove the effect due to changes in atmospheric pressure, and normalized. In blue we show data from the McMurdo neutron monitor [3] also corrected to remove the effect due to changes in atmospheric pressure. Both lines show a Forbush decrease in coincidence during August 3rd., 2010. The horizontal axis denotes the time in hours. The second decrease shown in red, our data, which does not correspond to the graph of the McMurdo data may be due to a failure in the electronics. The daily variations in the corrected rate are in part due to the temperature variations and in part due to the rotation of the Earth, which allows the detector to successively view regions of greater or lesser cosmic ray activity.

4. Conclusions

We conclude that a single water Cherenkov detector of 1.1 m of diameter filled with purified water up a height of 1.1 m has been shown to possess sufficient sensitivity to observe variations greater than 2% in the muon rate averaged over periods of one hour. Forbush decreases as big as 4% have been observed with muon detectors located at similar magnetic rigidity compared to Morelia. The data obtained from this work are available on line [4].

Acknowledgments

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References

[1] http://astronomy.swin.edu.au/cms/astro/cosmos/F/Forbush+Decrease
[2] See for instance the on-line data from the neutron monitor of UNAM, Mexico, at http://www.geofisica.unam.mx/infra/observ.html
[3] ftp://ftp.bartol.udel.edu/pyle/BRIData/BRI2010B.txt
[4] http://www.fismat.umich.mx/~abahena/tesis/Datos_Completos_2010.

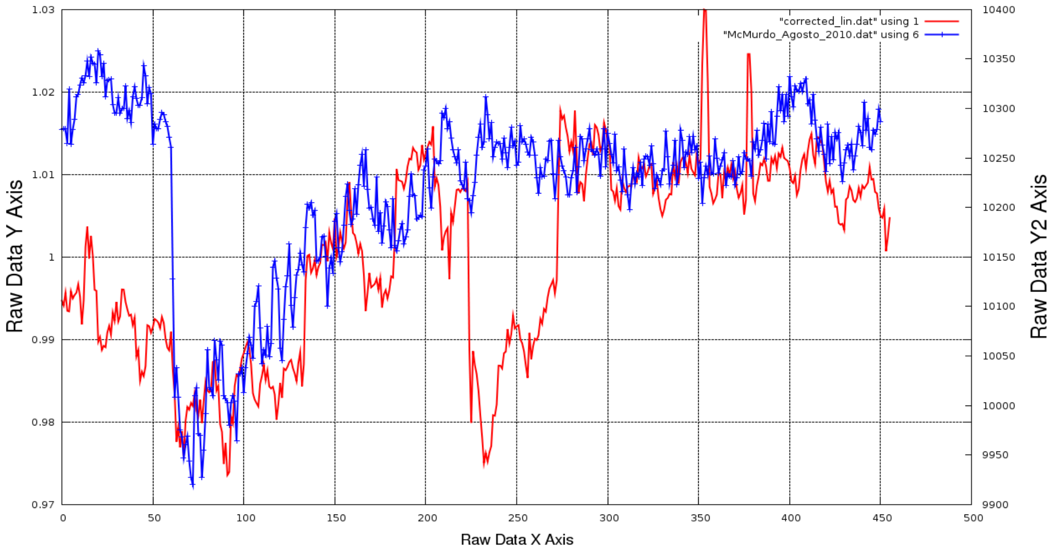

Figure 7. Comparison of our data with data from the McMurdo observatory, in the period August 1-19, 2010.