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Calibrating the Milagro Instrument for Measuring Forbush Decreases

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Abstract: The Milagro TeV ground-level γ-ray telescope detects Forbush decreases in several of its data channels. To understand how the instrument responds to Forbush decreases, one must calculate, through simulations, its behavior with respect to a changing galactic cosmic-ray background, as that background is modulated by heliospheric activity. To this end, we have been modeling the response of the instrument as a function of the Gleeson and Axford (1968) heliospheric electrostatic retarding potential. We will present ongoing progress in modeling the October and November 2003 Forbush decreases using several independent data channels. We will compare the results to the predicted response of the Climax neutron monitor in nearby Colorado.

Introduction

The *Milagro* instrument is a ground-based TeV γ-ray telescope, designed and built to measure galactic and extragalactic γ-ray sources, such as quasars and pulsar nebulae. It does this by measuring the spatial and temporal signatures from extensive air showers in a large pond of water, located at 2650 m altitude in the Jemez Mountains near Los Alamos, New Mexico, USA (Fig. 1). However, it is also sensitive to hadronic showers produced by galactic and solar cosmic rays, *i.e.*, protons and alphas. Most applicable here is the fact that it also responds to single penetrating particles and the soft component that accompanies it to the ground. As such, Forbush decreases are registered by the instrument, showing up in several data channels that are energy or rigidity dependent. Within a single instrument, we can measure the precursor, magnitude and recovery time of a decrease at a variety of particle rigidities, ranging from the geomagnetic and atmospheric cutoffs (~4 GV) to as much as 50-100 GV.

The *Milagro* instrument detects muons generated by solar and galactic protons with two layers of photomultipliers submerged in an 8-m deep water pond. The Çerenkov light from the relativistic muon illuminates one or several PMTs triggering them if the light intensity is sufficient. Most threshold triggers are of this type. The basic data channel for recording the effect of modulated galactic cosmic-ray protons is the High Threshold (HT) scaler, in which only a single PMT need trigger in a sub-μs resolving time. Other scaler data are available, including those of external particle detectors (outriggers) and higher levels of PMT multiplicity.

Figure 1: Aerial view of *Milagro*.

Ten such scalers are currently available, but not all of these have been present since the commissioning of the instrument in 1999. The greatest multiplicity requirement is 40 PMTs and the smallest is one. When enough PMTs are triggered the instrument records the individual event. Such events are interpreted as potential γ-ray showers, but with software under construction, they can also be interpreted as muon-related hadronic showers. For either case the incident direction, both in azimuth and elevation can be determined. These events have the highest instrumental threshold and are recorded in detail. They represent high-energy hadrons (or γ rays) and they too exhibit modulation in coincidence with Forbush decreases registered in neutron monitors, albeit at a reduced level.

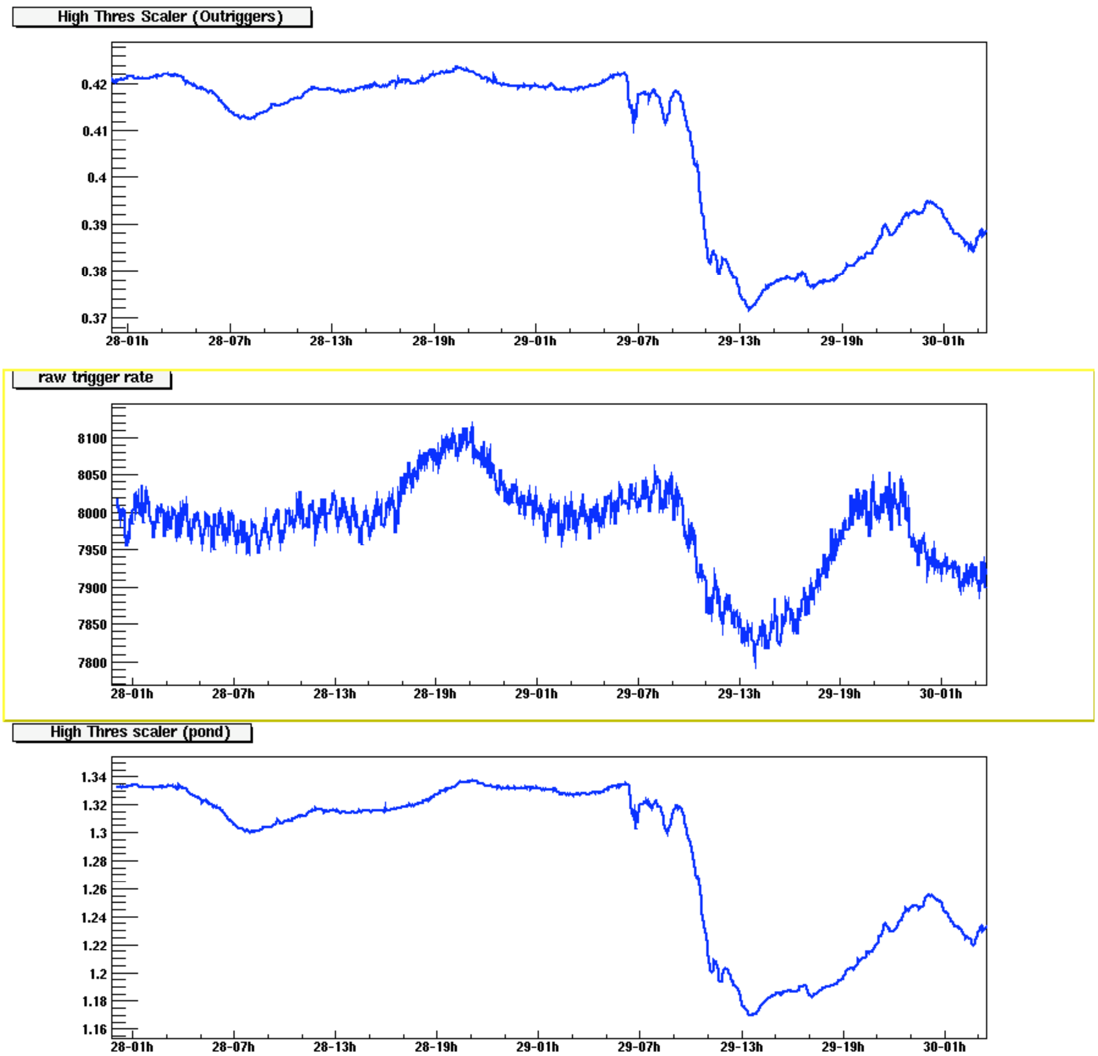

Figure 2: From top to bottom, the HT (outrigger) scaler rate, the triggered event rate and HT (pond)

As shown below, a Forbush decrease is smaller in the *Milagro* instrument than in a neutron monitor of similar geomagnetic cutoff, *i.e.*, Climax. By examining the decrease magnitude in different channels (with different thresholds), we can study the uniformity of the modulation as a function of energy. The *Milagro* data allow us to examine this effect well above the highest threshold neutron monitor, *i.e.*, $\gg$20 GV.

However, we must calibrate the signature of a Forbush decrease in the different data channels. To do this we will use simulations of the *Milagro* instrument, adjusting the input cosmic-ray spectrum and recording the magnitude of the decrease as we have calculated.

Forbush Decrease Observations

Raw *Milagro* rates for the period of 28-30 October 2003 are shown in Fig. 2. The upper panel and the lower panel show the rates in the outrigger Çerenkov detectors and the High Threshold (HT) scaler in the pond, respectively. The two behaviors are similar in all respects. The middle panel shows the raw trigger rate of individually analyzable events in the pond. The threshold for such an event trigger is of order 50 GeV.

During the time period shown barometric variations are small. It shows that the Forbush decrease is registered in the highest and lowest threshold channels, and thus all data channels. The recovery in the raw trigger rate may be corrupted by barometric changes, but for this case, the decrease occurs when the pressure is almost constant. Comparing the decrease as registered with Climax over a three-week period around this time, we note that Climax (~280 km from *Milagro*) registers an initial decrease on 22 October 2003 4× larger than that registered in the *Milagro* HT. The large decrease on 29 October 2003 as shown in Fig. 2 was (not shown) for Climax as for *Milagro* HT (26% vs. 13%). The smaller decreases for *Milagro* are to be expected because its effective cutoff is ~5 GV. We would also expect the *Milagro* recovery to be quicker, and we may be witnessing this in the raw trigger rate (~50 GeV) as shown in the middle panel of Fig. 2.

The decrease as seen in the triggered event rate on 2003 October 29 is of order 2.5%, smaller as one would expect for the higher threshold of this data channel.

Simulated Decreases

To estimate the effect of a Forbush decrease, we employ the formalism of Gleeson and Axford [1] to characterize the effect. That is, the cosmic-ray spectrum at Earth suffers a uniform decrease in particle energy during the transport from beyond the heliosphere to the vicinity of Earth. The uniform decrease in particle energy is couched in terms of a retarding electrostatic potential ϕ. Thus, the cosmic-ray intensity at energy E_{geo} at Earth is the same as that measured outside the heliosphere at energy $E_{geo} + \phi$. This implies, with a decreasing spectrum ($E^{-2.7}$), that the intensity has been diminished after passing through the potential gap. We can apply a variable retarding potential to the galactic cosmic-ray spectrum to compute the count rate in different *Milagro* channels. Although this formalism applies to the steady state and isotropic distribution, it provides a basis for understanding the variation seen in the count rates. One should not expect to treat dynamic situations such as recovery times or anisotropies introduced by the interplanetary disturbances with this technique.

To estimate the magnitude of the effect, we first compute via simulations the cutoff energy for a given channel. The cutoff energy in the presence of the interplanetary disturbance is (E_{Th} + ϕ), where E_{Th} is the threshold energy for that channel. One must integrate the cosmic-ray spectrum from (E_{Th} + ϕ) to infinity and compare that number to the integrated CR spectrum from the unmodulated cutoff E_{Th} .

Shown in Fig. 3 is the effective area of *Milagro* in several scaler channels. These simulations were computed assuming a hemispherical flux of cosmic rays distributed over a planar atmosphere of area 100 km^2 above the instrument. In Fig. 4 is a subset of those channel areas weighted by a cosmic-ray spectrum of $E^{-2.7}$.

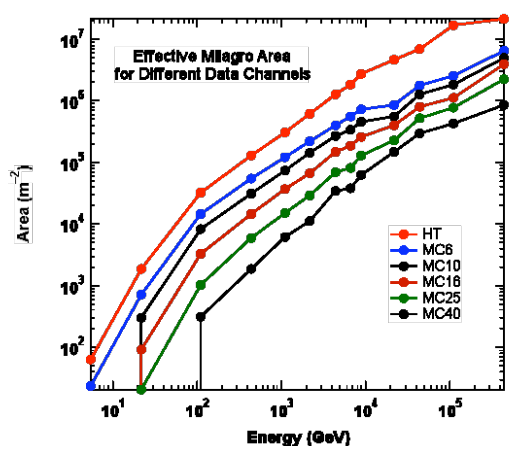

Figure 3: Effective area plots for different Milagro data channels.

Because the maximum contribution always occurs at threshold, a simple linear approximation to the effect of a retarding potential gives a reasonable estimate to the magnitude observed (Fig. 2).

A retarding potential of order 1000 MV provides the correct order of magnitude observed in Fig. 2. More careful calculations are underway and will be presented.

Although the Gleeson and Axford [1] formalism applies to a quasi-static environment, we should only apply this to the initial decrease and not the recovery where differential recovery rates may apply.

Another complicating effect would be any anisotropy introduced by the passing CME responsible for the decrease. Detailed examination of the individual high-energy events may shed some light on the magnitude of this effect.

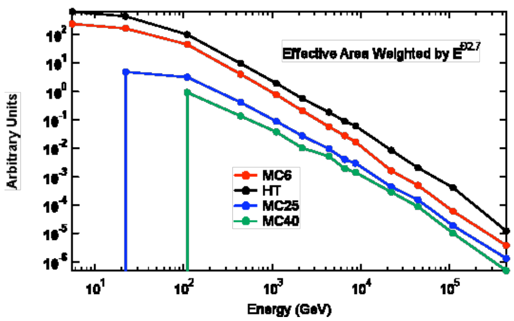

Figure 4: Spectrum weighted effective areas of Milagro.

References

[1] L. Gleeson and W.I. Axford. Solar Modulation of Galactic Cosmic Rays. *Astrophysical Journal*, 154:1011-1026.