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Observations with the Mini Neutron Monitor at Sierra Negra, Mexico

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In this study we analyze the observations with the Mini Neutron Monitor (miniNM) located at Sierra Negra, Mexico. This relatively new cosmic-ray detector is the mobile version of the standard NM64. There are about seven of these instruments around the world. The miniNM at Sierra Negra is the highest located miniNM (≈ 626 *mb*, 4100 m a.s.l.), and with the cutoff rigidity of approximately 7.9 GV. It is in the same place as the HAWC observatory, and has been in operation since September 2014. In this work we applied recently published analysis of the yield function and barometric coefficient for the minNM ([1]; [2]), to model the high altitude cosmic-ray observations at Sierra Negra.

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1. Introduction

Primary cosmic rays arrive at the top of the atmosphere and produce showers of secondary particles such as neutrons, protons, muons, and pions, plus an electromagnetic shower. These secondary particles are detected by instruments inside the atmosphere, mainly on ground level, but also with underground detectors, and high up in the atmosphere with aircraft and balloons. For about 60 years, the neutron monitor network has been recorded the continuous cosmic ray flux at the Earth surface. The analysis of the cosmic ray flux variations is important for understanding not only the solar modulation processes but also the generation and acceleration of solar energetic particles and their interactions with atmospheric atoms.

The Institute of Geophysics of the National Autonomous University of Mexico (UNAM) acquired a miniNM as part of the study and calibration of the response of the High Altitude Water Cherenkov (HAWC) Gamma Ray Observatory to the flux of low energy CRs. The miniNM is similar to the NM64 but smaller, with different spectral response and yield functions (see [3]; [4]; [1]).

The yield function for the miniNM was estimated by [1], and the barometric coeffcient was calculated by [2]. Using both results, in the this analysis we reproduce the montly counting rate observed by the miniNM at Sierra Negra.

2. Method

The counting rate, N, of any neutron monitor (NM) is a function of cutoff rigidity, P_c, atmospheric pressure, x, and time, t, as follow:

$$N(P_c,x,t) = \int_{P_c}^{\infty} (-\frac{dN}{dP})dP = \int_{P_c}^{\infty} S(P,x)\,j(P,t)dP, \tag{2.1}$$

where, $-dN/dP$ is the differential counting rate of the detector, S is the yield function and j is the primary cosmic-ray spectrum at the top of the atmosphere. The sign "-" inside the left integral in (2.1) is due to the fact that $dN/dP \leq 0$ for all rigidities.

However, the counting rate at a given atmospheric altitude can be written in another form (see for instance [5]), through its relation to the counting rate at sea level. This is:

$$N(P_c,x,t) = N(P_c,x_{SL},t)\exp(\beta(x_{SL}-x)). \tag{2.2}$$

Here, $x_{SL} = 1033.23\ mb$ is the atmospheric pressura at sea level and β is the barometric coeffcient, which according to [2] is equal to 0.00729 mb^{-1}. We will use this value here. Comparing 2.1 and 2.2, we can write an expression for the miniNM yield function at atmospheric pressure x as:

$$S_{miniNM}(P,x) = S_{miniNM,SL}(P)\exp(\beta(x_{SL}-x)). \tag{2.3}$$

The function $S_{miniNM,SL}(P)$ is the yield for a mini neutron monitor at see level. In Figure 1 we present the proton yield function for the miniNM at Sierra Negra used for our analysis. We can see that this function is about 1.7 times smaller than the one for the standard 6NM64 detector in

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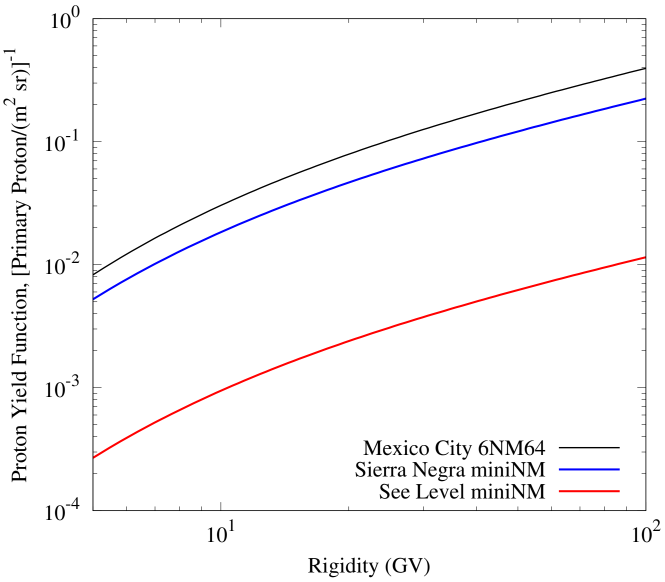

Figure 1: Yield functions for the miniNM at Sierra Negra and See Level, together with the yield for the standard 6NM64 in Mexico City.

Mexico City (≈ 773 *mb*, 2300 m a.s.l.) and about 20 times higher than the yield for the miniNM at see level.

The primary spectrum $j(P,t)$ in 2.1 is calculated from the Force-Field model as described in [5]. In order to obtain the variations in the force-field parameter (respect to March 1987), we used the monthly counting rate from , observed from October 2014 to August 2016 at Sanae, Hermanus and Tsumeb standard NM64.

Using the results in [1] for $S_{miniNM,SL}(P)$, together with the yield function for the standard NM64 and the primary galactic cosmic-ray spectrum in [5], we calculate the monthly counting rate 2.1 for the miniNM at Sierra Negra ($x = 626.0$ *mb*).

3. Discussion and Summary

Figure 2 shows the observed monthly counting rate for the miniNM at Sierra Negra (in counts/sec), as well as the normalized counting rate for Sanae, Hermanus and Tsumeb, and the calculated variation in the force-field parameter ($\Delta\phi$) for the period of October 2014 to August 2016. We can see in this figure that temporal variations in all four neutron monitors are in agreement, and as expected, they are anti-correlated with the magnitude of the force-field parameter.

Then, using the method explained in the previous section, we calculated the miniNM counting rate and compared it with the observed one. Figure 3 shows the ratio of calculated to observed monthly counting rate. In average, the calculated values are about 1.016 times higher than the observed. That is because the NMN at Sierra Negra is inside a container, and the roof absorbs about 1.6 % of the counts. It means that if we want to explain the observed counting rate with the miniNM at Sierra Negra, we should take into account this correction factor, similar to that reported in [6] (see their equation 8).

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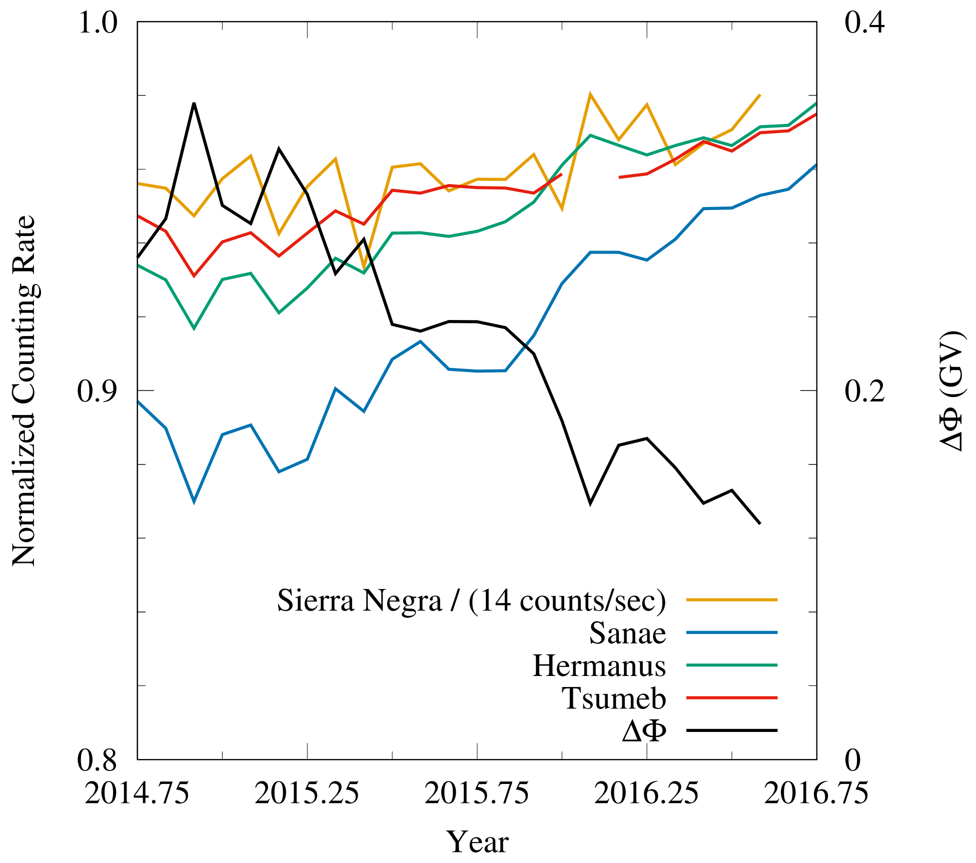

Figure 2: Normalized neutron monitor counting rate. For the miniNM at Sierra Negra, the monthly averages are divided by 14 counts/sec. The counting rate for the standard NM64 is normalized to 100 %, and the Force-Field parameter $\Delta\phi$ is equal to 0, in March 1987 (see [5]).

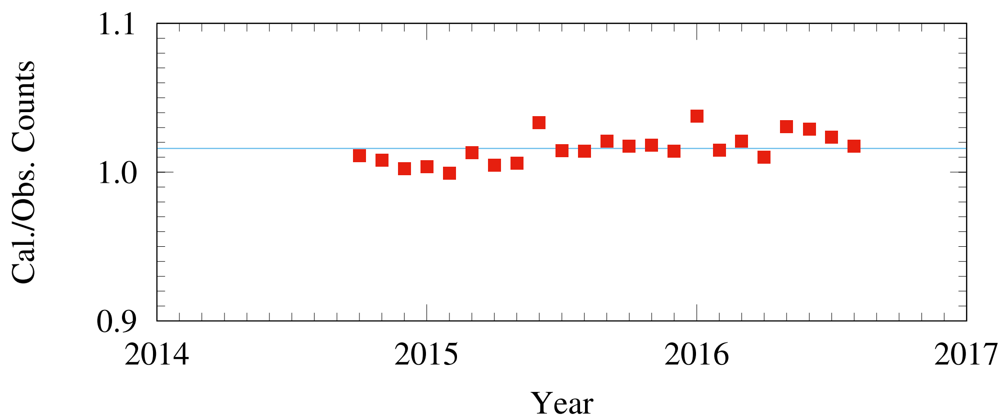

Figure 3: Calculated to observed counting rate ratio for the miniNM at Sierra Negra, Mexico.

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We consider that the yield function for the miniNM shown in Figure 1, allows us to reproduce the observed counting rate and therefore can be applied for future studies. Also, it is useful for the analysis of the observed rate in other mini neutron monitors, like for those located in Antartica ([7]; [8]) and at Doi Inthanon, Thailand [9].

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