PROCEEDINGS OF SCIENCE

Solar neutron event recorded by a muon telescope in Mexico City on november 4, 2003

Ortiz E.,[a,*] García R.,[b] Anzorena M.,[c] Valdés-Galicia J.F.,[b] González L.X.,[d] Hurtado A.,[b] Musalem O.,[b] Taylor R.,[b] Morales-Olivares O.G.[a] and Quintanar T.[a]

[a] *Universidad Nacional Autónoma de México, Escuela Nacional de Ciencias de la Tierra, Coyoacán, Ciudad de Méexico, MEXICO*

[b] *Universidad Nacional Autónoma de México, Instituto de Geofísica, Coyoacán, Ciudad de México, MEXICO*

[c] *University of Tokyo, Institute for Cosmic Ray Research, Kashiwa, Chiba 277-8582, JAPAN*

[d] *Universidad Nacional Autónoma de México, Instituto de Geofísica Unidad Michoacán, Morelia, Michoacán, 58089, MEXICO*

E-mail: eortiz@encit.unam.mx, rocio@geofisica.unam.mx, anzorena@icrr.u-tokyo.ac.jp, jfvaldes@igeofisica.unam.mx, xavier@igeofisica.unam.mx, ahurtado@igeofisica.unam.mx, omusalem@geofisica.unam.mx, omorales@encit.unam.mx, tanessi.quintanar@encit.unam.mx

In association with the X28 solar flare on November 4, 2003, the muon telescope Mexico observed a 8.0 σ enhancement of the counting rate between 19:50 and 20:05 UT. Based on a numerical simulation, we found that the entry of a high energy solar neutron flux, with energy range from 0.2 to 2 GeV, is capable of producing muon flux that reach the atmospheric depth of Mexico City. Furthermore, we also found that the expected excess counts are of the same order as the excess counts recorded by the telescope.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

[*] Speaker

PoS(ICRC2023)1309

1. Introduction

The accelerated particles during a solar flare lead a variety of products, interacting with solar material, high energy solar neutrons and gamma rays extending to energies beyond 100 MeV, are signatures of highest energy processes that take place on the Sun [1]. Since neutrons have no electric charge, they travel directly to the Earth not affected by the intense magnetic field at flare site or by the coronal or interplanetary and Earth's magnetic fields. We can obtain infomartion on the time of neutron production at a solar flare from arrival times of solar neutrons, the spectrum of the neutrons at Earth preserves that of the original solar proton. The time variations observed during these events provide important information on the nature of ion acceleration in solar flares, in particular whether the acceleration is impulsive or gradual, or both [3] [2].

When solar neutrons penetrate the Earth's atmosphere, they have nuclear interactions with atmospheric nuclei, which include: production of secondary particles, energy change, scattering and absorption. Among the secondary particles produced are pions, that decay into muons. Therefore, the high energy solar neutrons might be detected not only by neutron detectors, but also by muon detectors [4].

On november 4, 2003, in association with an X28 solar flare, high energy solar neutrons were recorded by the neutron monitors at Haleakala and Mexico City and by the solar neutron telescope at Mauna Kea. This event has already been analyzed and reported by [5] and [6].

2. The muon telescope at Mexico City

The muon telescope is made up of 8 scintillator plastic plates (SPP), organized in 2 layers, an upper and a lower layer, each is made up of 4 SPP in an array of 2x2, see figure 1; the dimensions of each SPP are 1x1 m^2 with a thickness of 5 cm. The telescope time resolution is 5 minutes and the effective area is 0.44 m^2, for more details see [7]. Between the upper and lower layer of SPP a neutron monitor is placed. The lead in the neutron monitor absorbs the soft componet of secondary cosmic rays, assuring that coincidences bewteen the upper and lower contain only muons.

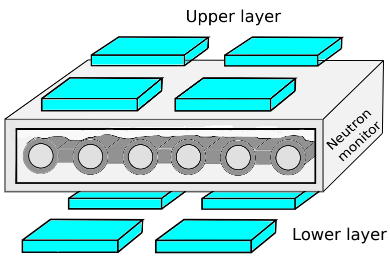

Figure 1: Scheme of muon telescope from Mexico City.

3. Simultaneous observations by neutron monitor and muon telescope.

On november 4, 2003: a) GOES recorded a X28 solar flare in hard X-rays channel, starting at 19:29 UT, reached its maximum at 19:53 UT and end at 20:06 UT [11]; b) SONG instrument onboard the CORONAS-F satellite recorded an increase of gamma ray fluxes in 4-7 MeV and 60-100 MeV channels, starting at 19:42 UT, reached its maximum at 19:44 UT and end at 19:47 UT, this instrument also recorded solar neutrons [6]; c) INTEGRAL recorded an increase of gamma ray fluxes in 4300-4600 keV and 5900-6250 keV channels, starting at 19:43 UT, reached its maximum at 19:45 UT and finish at 19:47 UT, the 2200-2240 keV channel also recorded the increase with the same characteristics but it lasted until 19:50 UT, approximately [5].

Associated with this solar event, high energy solar neutrons were recorded by the neutron monitors at Haleakala and Mexico City and by the solar neutron telescope at Mauna Kea [5], [6].

We present here an analysis of an enhancement in the counting rate recorded by the muon telescope in Mexico City and compare it with the observations of the neutron monitor in the same site.

It is worth mentioning that for this event the direction of the Sun was, 41° south with respect to the local zenith and 33° east with respect to the south direction. This is consistent with the observations, since the enhancement of the counting rate were registered by the south direction channel of the muon telescope. From now on, when we talk about the muon telescope counts, we will refer to those registered by the south direction channel.

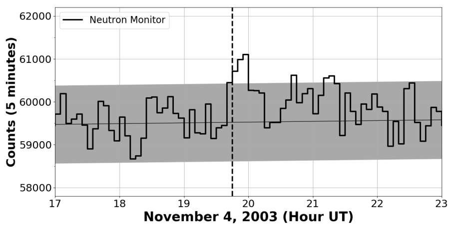

Figure 2: Neutron monitor in Mexico City, 5 minutes counting rate resolution. The vertical dotted line corresponds to the maximum gamma ray flux recorded by INTEGRAL; the shaded areas show ± 2 σ.

In order to establish a baseline and calculate from it the variations of the data recorded by the detectors, we fitted a first degree polynomial to the data between 17:00 and 23:00 UT. In figures 2 and 3, we show the data recorded by neutron monitor and muon telescope, both data with a resolution of 5 minutes; the vertical dotted line indicates the time when INTEGRAL registered the maximum in the gamma ray flux, the shaded areas show ± 2 σ with respect to the baseline.

We found that the neutron monitor recorded an increase in its counting rate of 2.6, 3.2 and 3.4 σ in 3 time bins from 19:45 to 20:00 UT (see figure 2), while, the muon telescope recorded an increase in its counting rate of 2.3, 3.1 and 2.6 σ in 3 time bins from 19:50 to 20:05 UT (see figure 3). Both detectors recorded the most significant increase at the same time, namely, between 19:55 and 20:00 UT. The presented results suggest that solar neutrons when traveling through the atmosphere interact with the nuclei of the atmospheric material producing muons in quantities enough to produce a significant signal in the muon telescope; in the next section we will explore this possibility by means of a numerical simulation.

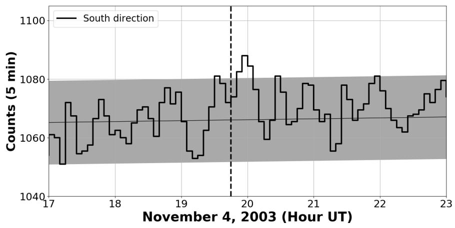

Figure 3: Muon telescope in Mexico City, ordinate axis is scaled down by a factor of 10. The vertical dotted line corresponds to the maximum gamma ray flux recorded by INTEGRAL; the shaded areas show ± 2 σ with respect to the baseline.

In figure 4, we show the counting rates recorded by the muon telescope in the south, east and west channels; in order to show that the trend of the channels is very similar and that only the south channel registered a significant increase after the solar flare. The counting rates are normalized with the count average registered between 17:00 and 19:00 UT. The north channel is not presented because it was out of operation on this date.

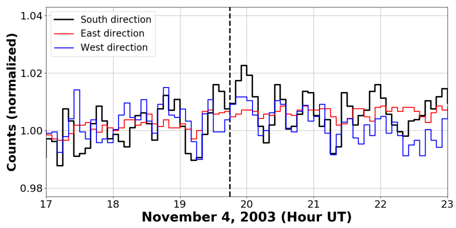

Figure 4: Muon telescope in Mexico City, 5 minutes counting rate resolution. The vertical dotted line corresponds to the maximum gamma ray flux recorded by INTEGRAL; South, east and west channels are normalized to 10,640, 10,430 and 11,970 counts per 5 minutes.

4. Simulation setup

For this simulation we used CORSIKA 7.7410 (COsmic Ray SImulations for KAscade) software, a program for detailed simulation of extensive air showers initiated by high energy cosmic ray particles. Protons, neutrons, light nuclei up to iron, photons, and many other particles may be used as primaries [8] [9].

The main goal of the simulation is to verify if the entry of high energy neutrons into the Earth's atmosphere produces a muon flux at the depth of Mexico City, and to calculate the energy of the produced muons. The main parameters considered in this simulation are: a) an incident flux of $4{\times}10^{10}$ neutrons, we used this initial flux in order to obtain reliable statistical data of secondary particles and the geometric characteristics of the atmospheric shower at the depth of Mexico City, b) atmospheric depth of 1,026 g/cm^2 considering that for this event the direction of the Sun was 41° with respect to the local zenith and, 33° west with respect to the south direction, c) a spectral index of γ = -4, estimated by [5], d) a standard model of the atmosphere and, e) an energy range from 0.2 to 2 GeV, we used this energy range since for this event solar neutrons of up to 1.5 GeV were reported [5]. QGS-JET-II and FLUKA are the models used for high-energy and low-energy processes, respectively.

The results show us that the entry of a neutron flux in the Earth's atmosphere produces an important flux of secondary particles at this depth, among them: gamma rays, electrons and positrons, muons, charged pions (this kind of particles correspond to the lowest flux), neutrons and protons (these species of particles correspond to the highest flux). It is important to mention that the secondary neutron flux is composed of scattered solar neutrons and neutrons generated in the Earth's atmosphere.

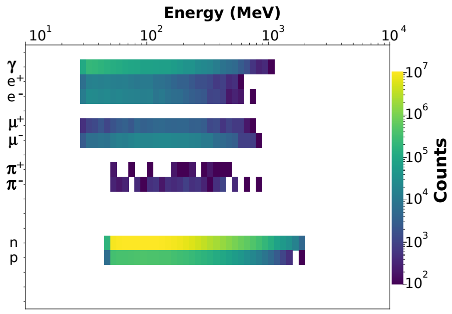

Figure 5: Energy distribution of secondary particles at Mexico City produced by the entry of solar neutrons into the Earth's atmosphere. The total fluxes for each particle species are shown in the table **??**. For more details see the text.

In figure 5, we show the energy distribution of secondary particles at the depth of Mexico City produced by the entry of solar neutrons into the Earth's atmosphere, obtained with the numerical simulation. The left side of the ordinate axis indicates the different species of particles. Considering the muon fluxes for both charges, the total flux for this particle species is 8.13×10^5, of which, $\sim$70% have an energy $\geq$ 100 MeV.

In figure 6, we show the neutron flux distribution at the depth of Mexico City obtained with the numerical simulation. This flux is composed of scattered solar neutrons and secondary neutrons generated in the Earth's atmosphere. The vertical axis points to the south-north direction. In this figure we can see the asymmetry of the angular distribution due to the inclination with which the solar neutrons enter the Earth's atmosphere, coupled with the refraction effect that produces an asymetry in the particle distribution [10]. In addition, we can see that these particles are distributed in an area of 10×10 km^2, approximately.

In figure 7, we show the muon flux distribution at the depth of Mexico City obtained with the numerical simulation. The horizontal axis points to the south-north direction. In this figure we can see that the muon flux present an asymmetry in its angular distribution very similar to that presented by neutrons (in south-north direction); this is due to the fact that the solar neutrons inherit both, the inclination with which they enter the Earth's atmosphere and the refraction effect to the muons. This result is an argument to justify that only the south channel of the muon telescope registered a significant increase. In addition, we can see that these particles are distributed in a smaller area than the area where of neutrons are distributed.

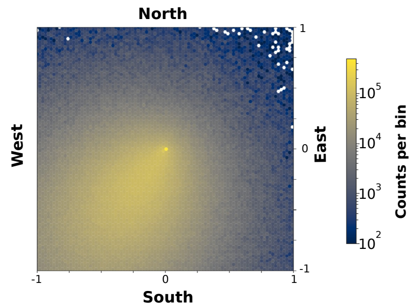

Figure 6: Scattered solar neutron and secondary neutrons flux distribution at the depth of Mexico City, generated with the CORSIKA software. Both axes are normalized to 10 km. See details in the text.

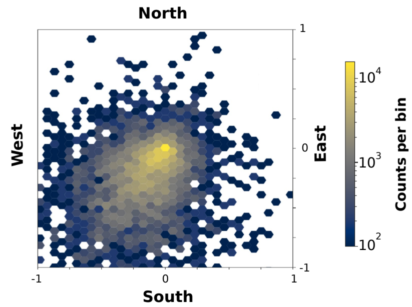

Figure 7: Muon flux distribution at the depth of Mexico City, generated with the CORSIKA software. Both axes are normalized to 10 km. See details in the text.

5. Results

According to our analysis presented in previous sections, the neutron monitor recorded a significant increase in its counting rate of 2.6, 3.2 and 3.4 σ in 3 time bins, with σ = 452 counts, recorded an excess of 4,158 counts. The muon telescope recorded a significant increase in its counting rate of 2.3, 3.1 and 2.6 σ in 3 time bins, with σ = 71, recorded an excess of 568 counts.

In figures 6 and 7, we can see that the neutron flux at the depth of Mexico City composed of scattered solar neutrons and secondary neutrons generated in the Earth's atmosphere are distributed over a larger area (10×10 km^2), while, the muons are distributed in a smaller area (5×5 km^2); this allows us to determine that any solar neutron beam whose direction of incidence is within a radius of 2 km with respect to the muon telescope, generates a flux of muons that may be recorded by the detector.

Considering the energy spectrum for solar neutrons reported by [5] with spectral index γ = -4, we calculate that at a distance of 1 AU the neutron flux was ~4×10^{13}, calculated for a circular area with a radius of 2 km at the top of the atmosphere and, producing average fluxes at the depth of Mexico City of $\sim 1 \times 10^3 neutrons/m^2$ and $\sim 2 \times 10^1 muons/m^2$, enough to produce significant counting rates in the neutron monitor and the muon telescope.

6. Conclusions

Based on a numerical simulation, we found that the entry of solar neutrons to the Earth's atmosphere with energies between 0.2 and 2 GeV and with a spectral index of γ = -4 is capable of generating a muon flux that reach the depth of Mexico City. We also found that solar neutrons upon entering the Earth's atmosphere experience a refraction effect, an effect that is inherited to the muon flux.

In the light of all the evidence presented in this work; the coincidence between observations and the numerical simulation performed, confirms that the statistically significant increase observed in the muon telescope at the time of a solar neutron event in the Mexico City neutron monitor, corresponds to muons generated by solar neutrons.

7. Acknowledgments

This work was partially supported by AEM-2018-01-A3-S-63804 Fondo Sectorial CONACYT-AEM. It was also partially supported by Programa Espacial Universitario, Universidad Nacional Autónoma de México.

References

[1] Murphy R.J., Dermer C.D., and Ramaty R. (1987). High-energy processes in solar flares. The Astrophysical Journal Supplement Series, 63:721-748.

[2] Shibata S. (1994). Propagation of solar neutrons through the atmosphere of the Earth. Journal of Geophysical Research. Vol. 99, No. A4, 6651-6665.

[3] Koi T., Muraki Y., Masuda K., Matsubara Y., Sako T., Murata T., Tsuchiya H., Shibata S., Munakata Y., Hatanaka K., Wakasa T., and Sakai H. (2001). Attenuation of neutrons in the atmosphere and a thick carbon target. Nuclear Instruments and Methods in Physics Research A, 469, 63-69.

[4] Dorman L. (2010). Solar neutrons and related phenomena. Astrophysics and Space Science Library. Chapter 5, pp. 71-73. Springer Science+Business Media B.V.

[5] Watanabe K., Gros M., Stoker P.H., Kudela K., Lopate C., Valdés-Galicia J.F., Hurtado A., Musalem O., Ogasawara R., Mizumoto Y., Nakagiri M., Miyashita A., Matsubara Y., Sako T., Muraki Y., Sakai T., and Shibata S. (2006). Solar neutron events of 2003 october-november. The Astrophysical Journal, 636: 1135-1144.

[6] Kuznetsov S.N., Kurt V.G., Myagkova I.N., Yushkov B.Yu., and Kudela K. (2006). Gamma-ray emission and neutrons from solar flares recorded by the SONG instrument in 2001-2004. Solar System Research, Vol. 40, No. 2, 104-110.

[7] Alvarez-Castillo J. and Valdés-Galicia J.F. (2010). Signatures of thunderstorms in the variations of the secondary cosmic rays registered in Mexico City. J. Atmos. Sol.-Terr. Phys. 72, 38-50.

[8] CORSIKA software. http://www.iap.kit.edu/corsika/

[9] Heck D., Knapp J., Capdevielle J.N., Schatz G., Thouw T, and Forschungszentrum Karlsruhe GmbH Karlsruhe. (1998). CORSIKA: a Monte Carlo code to simulate extensive air showers. V + 90 p., TIB Hannover, D-30167 Hannover (Germany).

[10] Dorman L.I., Valdés-Galicia J.F., and Dorman I.V. (1999). Numerical simulation and analytical description of solar neutron transport in the Earth's atmosphere. Journal of Geophysical Research, Vol. 104, No. A10, 22417-22426.

[11] National Oceanic and Atmospheric Administration. https://www.swpc.noaa.gov/products/goes-x-ray-flux

[12] Muraki Y., Lopez D., Koga K., Kakimoto F., Goka T., González L.X., Masuda S., Matsubara Y., Matsumoto H., Miranda P., Okudaira O., Obara T., Salinas J., Sako T., Shibata S., Ticona R., Tsunesada Y., Valdés-Galicia J.F., Watanabe K., and Yamamoto T. (2016). Simultaneous Observation of Solar Neutrons from the International Space Station and High Mountain Observatories in Association with a Flare on July 8, 2014. Solar Phys.

[13] Flükinger E.O., Moser M.R., Pirard B., Bütikofer R., and Desorgher L. (2007). A parameterized neutron monitor yield function for space weather applications. Proceedings of the 30th International Cosmic Ray Conference, Mexico.