SIMULATION OF SOLAR NEUTRON FLUX IN THE EARTH'S ATMOSPHERE

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Abstract

We performed simulations of the solar neutron (n_s) fluxes in the atmosphere of the Earth, associated with the X17 flare from September 07, 2005, and with the X1.3 and M3.9 flares from September 07, 2017. The input of the simulations was calculated on the basis of n_s signals, detected on ground level by the Solar Neutron Telescope of Sierra Negra (SNT-SN), and by the FIB scintillator of the Space Environment Data Acquisition-Attached Payload (SEDA-AP) on board of the International Space Station. We used the CORSIKA code and FLUKA subroutines to simulate the particle fluxes, associated with the X17, X1.3 and M3.9 flares. Our analysis suggested that 11-14% of the n_s, released by the X17 flare, could reach the SNT-SN without starting a shower, and that n_s, associated with the X1.3 and M3.9 flares, did not reach the SNT-SN.

Solar neutrons and Earth's atmosphere

Produced by nuclear reactions induced by collisions of protons (p^+) and He nuclei, accelerated at the reconnection site of magnetic field lines after a solar flare.

Relativistic n_s released from the Sun may reach 1 AU, according to their survival probability (P_s), which is a function of n_s energy (E_n) (Fig.1).

The n_s flux is scattered at the Earth's atmosphere. Based on the n_s zenith angle (θ_i), such flux attenuation will become significant. Also, some of these collisions are able to start air showers.

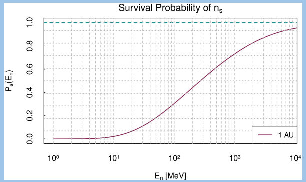

Figure 1. Survival probability of n_s as a function of their kinetic energy, calculated for 1 AU.

Simulation of solar neutron flux with CORSIKA

CORSIKA code is widely used to perform cosmic rays simulations, we integrated the FLUKA interaction model to consider low energy interactions. The main input parameters are:

Observation level: we selected the Sierra Negra volcano (SN) in Mexico.

Spectrum (j): from the spectra obtained by FIB SEDA-AP, we calculated (assuming a power law) j=3.5 for the X1.3 and j=1.9 for the M3.9 flares of 07-09-2017 (Fig. 2), the X17 flare of 07-09-2005 had j=3.

Energy interval: from Fig.2, E_n=0.1-0.8 GeV (X1.3 flare), E_n=0.1-3 GeV (M3.9 flare). According with Fig.1, E_n=0.1-20 GeV for the X17 flare.

Primary flux (F): for the X1.3 and M3.9 flares, we calculated it as the sum of the total events on Fig. 2. For the X17 flare, we used the counting enhancement (ΔN) of the S1_with_anti channel of the SNT-SN (Fig.3), its effective area (S), detection efficiency (ε) and energy interval per time bin (ΔE), according to:

$$F = \Delta N / (S * \Delta E * \varepsilon) \qquad (1)$$

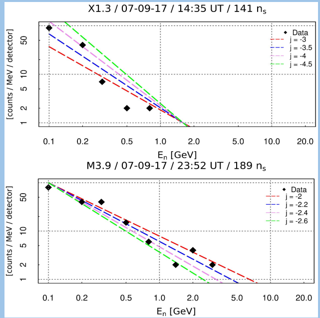

Figure 2. Spectrum of n_s, associated with the X1.3 (top) and M3.9 (bottom) flares.

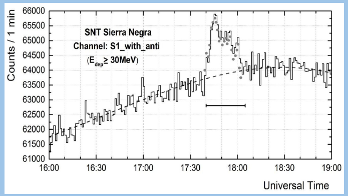

Figure 3. Counting rate (1 min) of the S1_with_anti channel of the SNT-SN for 07-09-2005. The background is calculated as a third order polynomial. An increment, associated with the X17 flare, is observed between 17:40 and 18:05 UT. Taken from González, et al. (2015).

Discussion

For each simulation, we obtained the following results:

Longitudinal Distribution (LD); shows an average of the flux variations due to attenuation and air shower generation.

Longitudinal Energy Distribution (LED); shows the flux average energy variations. The peak corresponds to the first interaction, followed by an exponential decrease. LD's and LED's are plotted as a function of atmospheric depth (X), by bins of 2g/cm^2 for θ_i=0°, 15°, 30°, 60°, (Figs. 4a-4f). For the X1.3 and M3.9 flares, only secondary n arrive at SN (X=624 g/cm^2).

Interactions and multiplicity, as a function of particle energy, for the X17 flare: ~86-89% of interactions and ~93-97% of particle production, take place in a low energy (E) range (Figs. 4h and 4g). This defines a percentage of n_s that reach the SNT-SN without starting a particle shower.

To evaluate our results, we plotted S1_with_anti channel data (5 min counting rate) for 07-09-2017 and fitted the background as a third order polynomial, we also plotted a significance of ±3σ (Fig. 5). No increment, associated with the n_s released by the X1.3 or M3.9 flares, is observed.

Conclusions

Atmospheric attenuation and energy dissipation of n_s are more significant for higher θ_i. The collisions of n_s decreased the E_n by ~ one order of magnitude at the STN-SN level.

Only secondary n arrived at the SNT-SN for the X1.3 and M3.9 flares. This is consistent with SNT-SN data, since no enhancement was observed.

We estimated that ~11-14% of the initial n_s, associated with the X17 flare, reached the SNT-SN. Thus, our results are a theoretical confirmation of the n_s detection of 07-09-2005.

For further validation of our methodology, we need a bigger sample of high energy n_s events. We are looking forward such possibility in the next solar maximum.

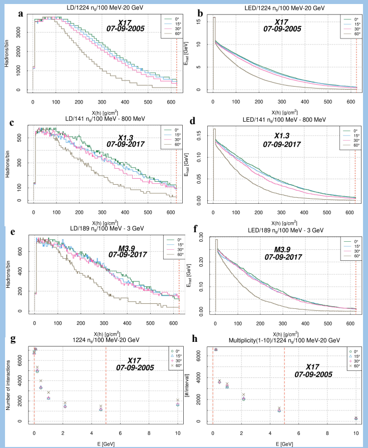

Figure 4. Simulation results for the X17, X1.3 and M3.9 flares. Each input is specified on top of the plots. The LD (a, c, e) and LED (b, d, f) are plotted as a function of X for zenith angles θ_i=0°, 15°, 30°, 60°. The SNT-SN level is indicated with a vertical line. The number of interactions (h) and multiplicity (g), associated with the X17 flare, are plotted as a function of the particle energy. We show the E range of secondary particles between vertical lines.

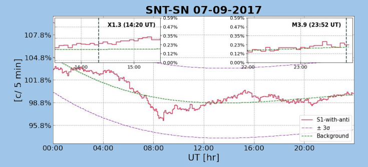

Figure 5. Counting rate (5 min) of the S1_with_anti channel of the SNT-SN for 07-09-2017. The background is calculated as a third order polynomial, we also plotted a significance of ±3σ. The insets show the time of occurrence (vertical dashed line) of the X1.3 and M3.9 flares. No n_s emission is observed.