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SPACE FLUORESCENCE DETECTION OF ULTRA-HIGH ENERGY COSMIC RAYS BASED ON CORSIKA SIMULATION

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Abstract

Using the Earth's atmosphere as a calorimeter, the air fluorescence light observation technique is commonly used in ultra-high energy cosmic ray (UHECR) experiments, in order to reconstruct the shower cascade curve and to estimate the primary particle energy and its arrival direction. With the help of the CORSIKA air shower simulation program, the development of extensive air showers (EASs) initiated by primary particle energy up to 100 EeV and entering the Earth's atmosphere is performed with different combinations of high and low hadronic interaction models. The sensitivity of longitudinal distribution of particles, depth of shower maximum and energy deposited into the air are studied for different simulation parameters. Implications on UHECR experiments are then discussed, especially for a space fluorescence telescope onboard the international space station (ISS). The number of fluorescence photons and the profile of their arrival time to the detector pupil are calculated for typical extreme energy events.

Introduction

Ultra High Energy Cosmic Rays (UHECR) are the most energetic particles observed in nature with (detected) energies up to 3-5.10^{20} eV. The flux of such primary particles reaching Earth is extremely low (1 particule.km^{-2}.century−1). The observations of UHECR are performed nowadays by the Auger observatory in Argentina and Telescope Array (TA) in the USA. The observation of these particles leads to many interesting questions mainly on their nature and origin. JEM-EUSO is a new type of observatory, embarked on the ISS, that uses a huge volume of the Earth's atmosphere as a detector. It observes transient luminous phenomena taking place in the Earth atmosphere caused by particles coming from Space. The sensor is a super wide-field telescope that detects particles with energy above 10^{20} eV.

Methods

Firstly, we have calculated the number of charged particles and energy deposit in the atmosphere for an extensive air shower initiated by a proton and iron primary particles of extreme energy. We have used for this purpose different low and high energy hadronic interaction models available in the CORSIKA package. For the low hadronic interaction model, our results (Fig. 1 and Fig. 2) show a difference less than 5 % between GHEISHA and UrQMD models. So we have chosen GHEISHA because it takes less time in the simulation compared to UrQMD. For the high hadronic interaction model, we have used three models namely QGSJETII-04, EPOS and SYBILL. We have noticed a difference less than 10 % between EPOS and QGSJETII-04 and less than 20 % between QGSJETII-04 and SIBYLL (Fig. 3 and Fig. 4). So we have chosen QGSJETII-04 because it is widely used, takes less computation time and gives relatively close results to those obtained by EPOS.

After selecting the models, QGSJETII-04 for high energy hadronic interactions and GHEISHA for the lower ones, we have tested our method and compared some results to experimental data. For this aim, we have computed X_{max} for a proton and iron with extreme energies and compared our values to those measured by the 1500 m Array of Pierre Auger Observatory (PAO). This comparison is shown in Fig. 5 with an agreement between calculation and experimental data. Also, the deposit energy distribution of the secondary particles in the atmosphere is computed in the same condition as the measured one by PAO. This comparison is shown in Fig. 6 with a relative agreement.

For the fluorescence calculation, one needs to have the fluorescence yield for the US standard atmosphere, between 300 and 430 nm. From the energy deposit and the yield, we can calculate the amount of fluorescence photons produced in the atmosphere and then propagate them to the space telescope. For this work, we have only taken into account the attenuation due to Rayleigh scattering.

The photon yield per meter for an electron in air of energy E written as a function of energy deposit, air density and temperature is given by:

$$FYi(K_C,\rho,T) = \frac{\left(\frac{dE}{dX}\right)}{\left(\frac{dE}{dX}\right)_{K_C}} \times \rho \times \frac{A_i}{1+\rho\times B_i\times\sqrt{T}} \qquad i = 1, 14 \qquad (1)$$

Where $\left(\frac{dE}{dX}\right)_{K_C}$ is the average energy deposit of all particles in the shower and K_c is kinetic energy for an electron of 0,85 MeV. ρ is the air density and T is the temperature. The constants A_i and B_i are calculated and listed by M. Nagano *et al.* for 14 wave bands between 300-430 nm.

The atmospheric transmission T_R uses the optical depth δ for Rayleigh scattering taken from Berat et al. :

$$\delta = \frac{X}{3120\,(g{\cdot}cm^{-2})}\left(\frac{400\ nm}{\lambda}\right)^4\left(1-0{,}0722\left(\frac{400\ nm}{\lambda}\right)^2\right)^{-1} \qquad T_R = e^{-\delta} \qquad (2)$$

The number of photons created per shower length interval and arriving to the detector pupil is transported. At this stage, multiple scattering of light and ozone absorption was ignored. The same applies to Mie scattering which is more relevant below few kilometers, while the EAS develops above this altitude.

Results

The comparison of calculation given by different hadronic model at high and low energy are plotted, for primary iron with $E = 10^{19}$ eV and zenithal angle ϑ=60°. This allows us to choose between these models the more useful one. Then we have tested our methods and finally used it to simulate the signal detected by an ideal space detector aboard the ISS.

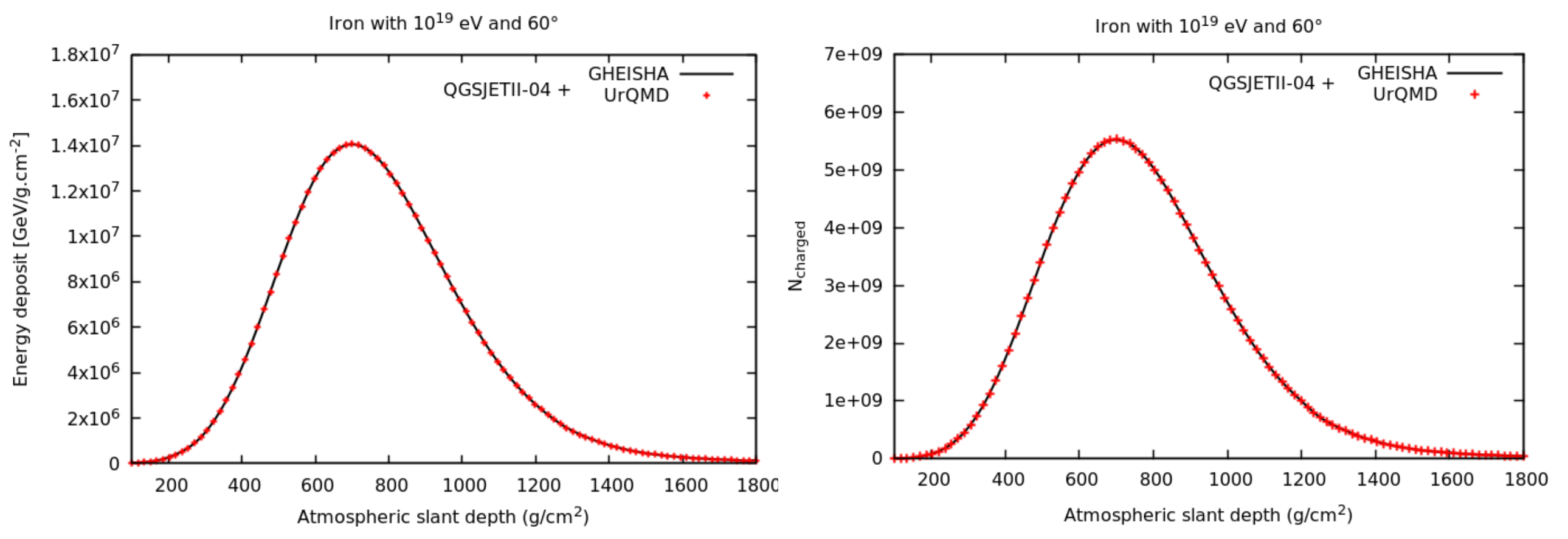


Fig. 1 and **Fig. 2** : GHEISHA vs UrQMD the differences are less than 5% difference.

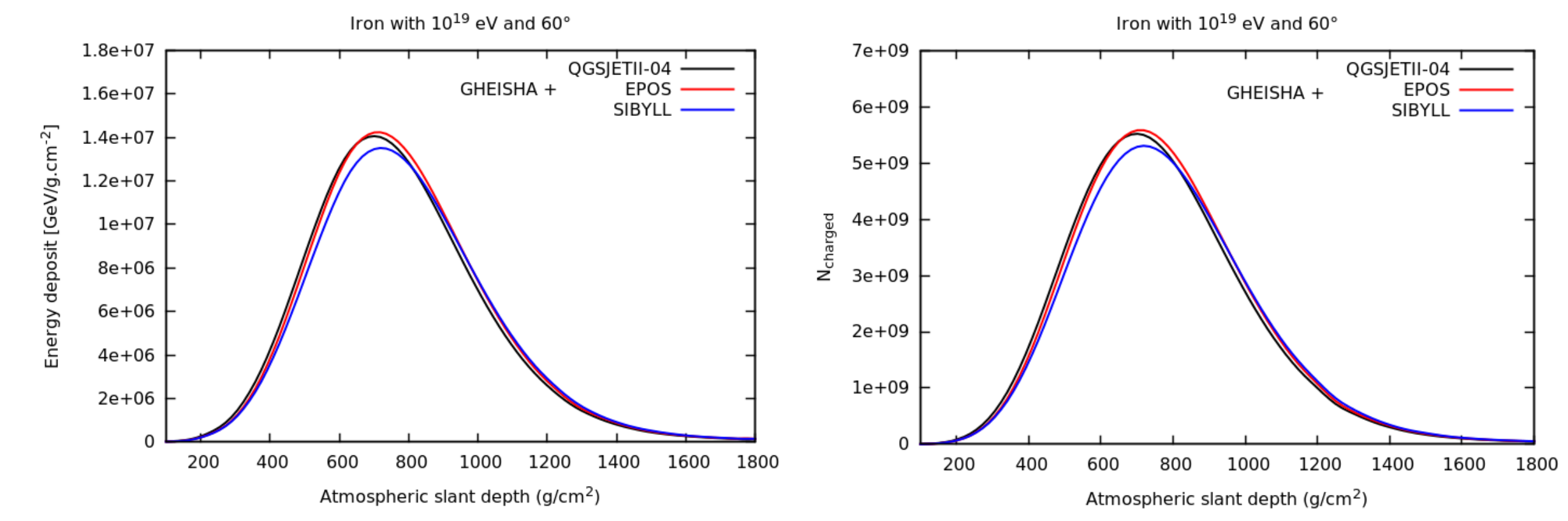
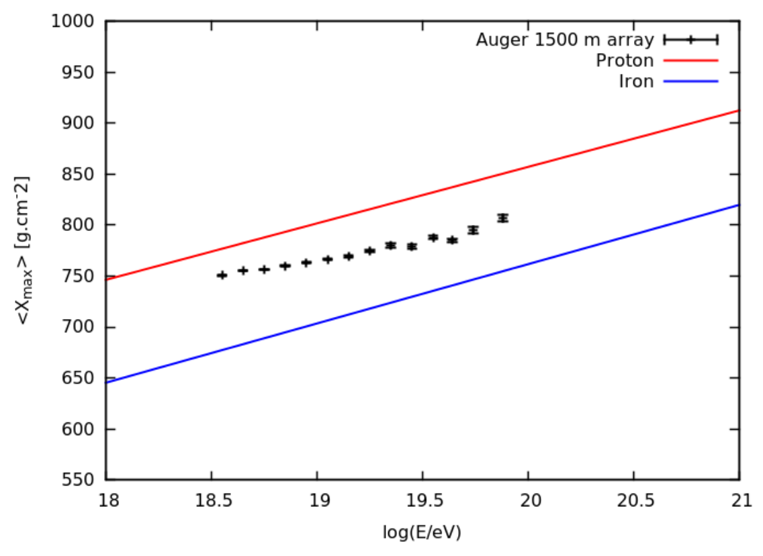


Fig. 3 and **Fig. 4** : Differences are less than 10% for QGSJETII-04 vs EPOS and less 20% for QGSJETII-04 vs SIBYLL.



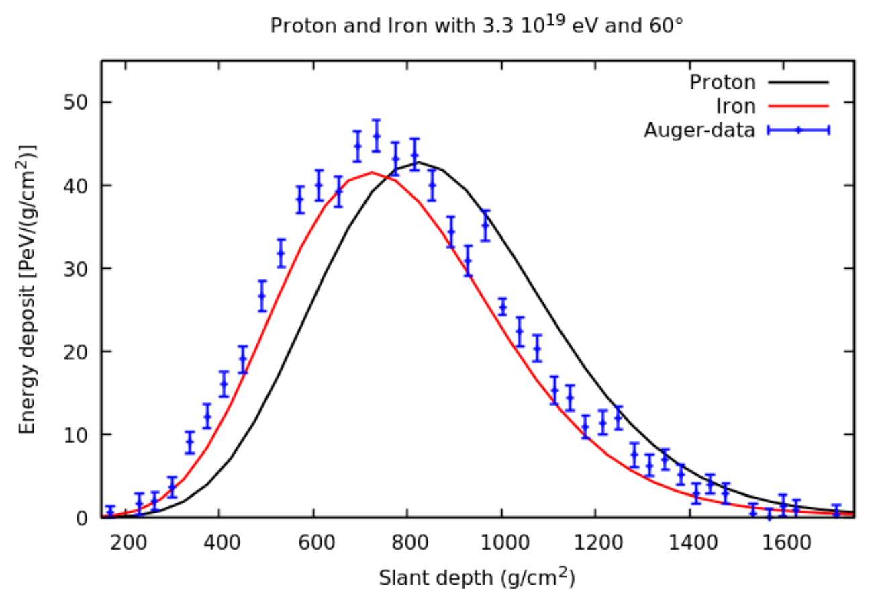


Fig. 5 : The X_{max} distributions have been obtained from simulation of 150 proton and 150 iron primaries for zenith angles 45° and 18 < log (E/eV) <21 compared with data of PAO large area.

Fig. 6 : The energy deposit obtained by simulation of 500 events for each proton and iron primaries. The zenith angles was 60°and the energy was $3 \times 10^{19} eV$, Compared PAO event data.

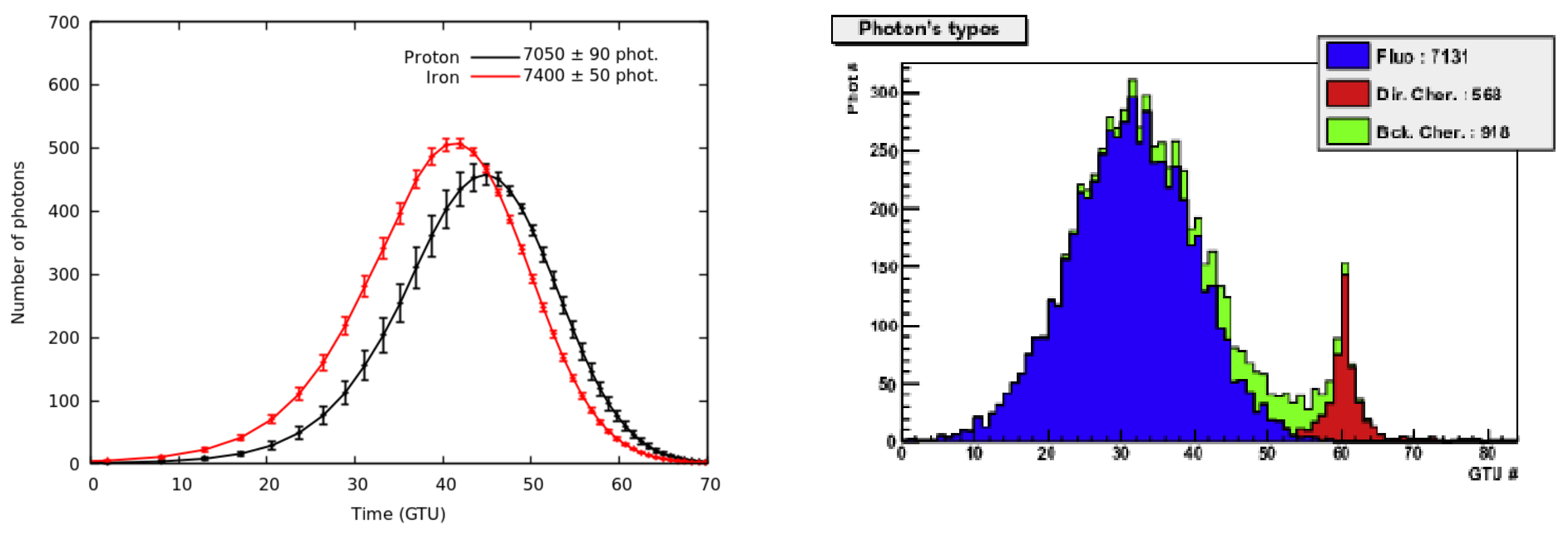


FIG. 7 and FIG. 8 : Our simulation of the number of fluorescence photon arriving at the detector pupil and those done by Bertaina *et al.*

The fluorescence photon arriving to an ideal space detector and their time distribution is plotted in Fig. 7. For comparison, the Fig. 8 is a calculation done by Bertaina with ESAF software.

Conclusion

We have performed a calculation of the amount of fluorescence photons arriving at a space detector pupil. The shower is initiated by a primary proton and iron with an energy and a zenith angle respectively equal to 10^{20} eV and 60°. Our calculation gives 7050 ± 90 (for proton) and 7400 ± 50 (for iron) fluorescence photons reaching a space detector aboard the ISS. This is in a good agreement with a calculation done by M. Bertaina using the ESAF software that has given 7131 fluorescence photons detected. Primary particle discrimination between light and heavy nuclei is possible but high statistics and quality measurements required.

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