UV fluorescence detection of extreme energy cosmic rays by the JEM-EUSO experiment

Zohra Bouhali¹, Taoufik Djemil¹² and Khaoula Sassane¹

¹ Laboratoire de Physique des Rayonnements, Badji Mokhtar University, Annaba, Algeria.
² Faculté de Médecine, Badji Mokhtar University, Annaba, Algeria.
E-mail: bouhali_zohra@yahoo.fr

Abstract. The Extreme Universe Space Observatory on the Japanese Experiment Module (JEM-EUSO) is a new experiment, based on an international collaboration of 16 countries, including Algeria. With the help of a space telescope embarked on the International Space Station (ISS), this experiment aims to observe extreme energy cosmic rays (EECR), above $5 \cdot 10^{19}$ eV. Due to their very low flux, the study of these EECR is carried out indirectly by observing from space the extensive air showers (EAS) generated by the interaction of a primary particle with the upper atmosphere. The characteristics of these EAS allow us to go back to the characteristics of the primary particle, such as energy and arrival direction, by measuring the amount of fluorescence light emitted along their development. For this purpose, we have used an analytical method to estimate the amount of fluorescence photons detected by the JEM-EUSO space telescope for an incident proton of $10^{20}$ eV and a zenithal angle of 60°. Our results are compared to a more precise calculation using the EUSO Analysis and Simulation System (ESAF).

1. Introduction
Ultra High Energy Cosmic Rays (UHECR) are the most energetic particles observed in nature with (detected) energies up to $3 - 5 \cdot 10^{20}$ eV. The flux of such particles reaching Earth is extremely low (1 particle·km$^{-2}$·century$^{-1}$). The experimental observations of UHECR are performed nowadays by the Auger observatory in Argentina and Telescope Array (TA) observatory 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 the whole Earth as a detector. It observes transient luminous phenomena taking place in the Earth atmosphere caused by particles coming from Space. JEM-EUSO focuses its science case on the most energetic of those events, at $E = 10^{20}$ eV, often referred to as extreme energy cosmic rays (EECR) [1].

2. Methods
The number of fluorescence photons produced along the track of an extensive air shower (EAS) is proportional to the number of charged particles, essentially electrons and positrons. For this purpose, we have used two analytical models based on respectively the Greisen Iljina Linsley and Gaisser Hillas parametrisations. After that, each particle will produce a certain number of fluorescence photons according to a measured fluorescence yield.
2.1. Greisen Iljina Linsley equation
The Greisen Iljina Linsley (GIL) formula is used to describe the longitudinal profile of hadron-initiated EAS in the range \( E > 10^{19} \text{ eV} \) [2]. Based on the GIL function that is derived from the QGSJET model [3], the number of charged particles \( N_{\text{charged}}(t) \) is given by:

\[
N_{\text{charged}}(t) = \frac{E^{1.45} \text{ GeV}}{e^{f(t)}}
\]

where \( E \) is the incoming particle energy in GeV, and \( t \) is the slant depth in atmospheric units of mean interaction length \( X_0 = 37.15 \text{ g/cm}^2 \) after the first interaction depth \( X_1 \) and given by:

\[
t = \frac{X - X_1}{X_0}
\]

The function \( N_{\text{charged}}(t) \) reaches its maximum point at \( t_{\text{max}} \) where \( f(t) = 0 \), which in turn is defined by:

\[
f(t) = t - t_{\text{max}} - 2t \ln \left( \frac{2}{1 + \frac{t_{\text{max}}}{t}} \right)
\]

and \( t_{\text{max}} \) is a function of the primary energy \( E \) and the atomic number \( A \), given by :

\[
t_{\text{max}} = 1.70 + 0.76 \left( \ln \frac{E}{81 \text{ GeV}} - \ln A \right)
\]

2.2. Gaisser-Hillas equation
The Gaisser-Hillas (GH) function fits well the longitudinal profile of the shower, providing also an a posteriori an estimation of the fundamental parameters: the depth of first interaction \( X_1 \), the depth of the shower maximum \( X_{\text{max}} \) and the number of charged particles at the maximum of the shower development \( N_{\text{max}} \). The number of charged particles \( N_{\text{charged}}(X) \) at the slant depth \( X \) using GH equation is given by [4]:

\[
N_{\text{charged}}(X) = N_{\text{max}} \cdot \left( \frac{X - X_1}{X_R} \right)^{X_R} \cdot e^{(X_R + X_1 + X)}
\]

where \( N_{\text{max}} = \kappa E, \kappa = 0.6 \text{ GeV}^{-1} \) [5] and \( E \) is the incoming particle energy, \( \Lambda = 65 \text{ g/cm}^2 \), \( X_R = (X_{\text{max}} - X_1) \) and finally \( X_{\text{max}} = 875.54 \text{ g/cm}^2 \), taken from a simulation done with CORSIKA program[6].

Next step is to use the fluorescence yield, which describes the number of UV photons created each meter by a charged particle in the shower. The fluorescence yield in the UV range 300-430 nm, generated by EAS in the Earth’s atmosphere for one charged particle is equal to \( 4.23 \pm 0.21 \) photons/m, taken from the work of G. Lefeuvre [7]. Then, The number of UV fluorescence photons created per shower length interval is given by:

\[
dN_{\text{ph}} = Y \cdot \eta \cdot N_{\text{ch}}(t) \cdot dl
\]

where \( \eta \) is the atmospheric transmittance, \( Y \) the measured fluorescence yield and \( N_{\text{ch}}(t) \) represents the number of charged particles in the shower according to the GIL and GH parametrizations, that approximate the longitudinal shower profile analytically. In this work we have used a full atmospheric transmittance \( \eta = 1 \). The number of photons per shower length interval arriving at the detector pupil is given by:

\[
dN_{\text{det}}^{\text{ph}} = \frac{\Delta \Omega}{4\pi} \cdot Y \cdot \eta \cdot N_{\text{ch}}(t) \cdot dl
\]
where ΔΩ is the detector solid angle. In the flat Earth approximation (θ ≤ 70°), the relation between the altitude \( h \) above the Earth surface and the distance \( d\ell \) measured along a straight line, with zenith angle \( \theta \), is given by:

\[
d\ell = \frac{h}{\cos \theta}
\]  

Eq. 8

We have then to rewrite \( N_{ch}(t) \) in function of altitude, replace \( d\ell \) by \( \frac{h}{\cos \theta} \) and proceed to the integral of the Eq. 6 from 0 to 48000 m which is the altitude of the first interaction. To perform this, the altitude dependence of the atmospheric vertical depth \( X \) was taken from [5] and given by:

\[
\ln X = 5.26 \cdot \ln((44.34 - h)/11.86) = (45.5 - h)/6.34
\]

Eq. 9

\[
= 13.78 - 1.67 \times (68.47 - 1.2 \times (48.63 - h))^{0.5}
\]

Eq. 10

where Eq. 9 is for the troposphere, from ground to 11 km. The Eq. 10 refers to the tropopause, from 11 km to 25 km. At higher altitude above 25 km, the Eq. 11 is modelling the stratosphere. In the flat Earth approximation, one can scale the slant depth as \( X \cos \theta \).

3. Results

The number of charged particles has been calculated using GIL and GH equations. The Fig. 1 shows the number of charged particles created by an incident proton with a primary energy \( E = 10^{20} \) eV, as a function of atmospheric depth. The GIL and GH equations give the same results relatively, as we can see on the left of Fig. 1. But if we plot the GIL and GH equations with a different manner, on the right of Fig. 1, we can see that GIL equation gives more charged particles than the GH one. When we draw the graph of the number of charged particles in function of altitude \( h \), we have also found larger differences between the two equations as shown in Fig. 2. The difference appears at low atmospheric depths, i.e., high altitudes.

Detailed Monte carlo simulations done with Corsika program for an incoming proton with extreme energy \( E = 10^{20} \) eV were compared to GIL analytical formula. The authors concluded that GIL formula and Corsika simulation predict longitudinal profiles with the same behaviour.
Figure 2. Number of charged particle as a function of altitude given by GIL and GH equation.

for EECR [8]. We have then chosen the GIL equation and used it for our fluorescence photon calculation. The integral of Eq. 6, from ground to first interaction altitude, gives $3.12 \times 10^{15}$ fluorescence photons emitted in $4\pi$ steradian. The detector surface is equal to $4.5 \, m^2$ orbiting at 400 km. The distance from the middle of the shower to the detector is around 375 km. So the solid angle to the detector is $s/r^2 = 3.2 \times 10^{-11} \, sr$.

Finally, our analytical calculation has given 7935 ± 394 fluorescence photons arriving at the detector. We have compared our results to those obtained by Bertaina et al. [9]. They have calculated the Number of fluorescence photons created by an EAS initiated by a primary proton of $E = 10^{20} \, eV$ and a zenith angle of 60° interacting with the atmosphere, using the EUSO Simulation and Analysis Framework (ESAF). Their calculation has given 7131 fluorescence photons arriving at the detector pupil, and their value was given without the uncertainty bars. Since we have assumed a full atmospheric transmission for the UV photons, our value is larger.

4. Conclusion
We have performed an analytical calculation of the amount of fluorescence photons arriving at the pupil of the JEM-EUSO detector. We have used the GIL equation to estimate the number of charged particles in an EAS initiated by a primary proton with an energy of $10^{20} \, eV$ and a zenith angle of 60°. Our method was based on the fluorescence yield of a charged particle per unit length. The amount of fluorescence photons reaching the detector was estimated to 7935 ± 394. This is very consistent with a more precise calculation done by M. Bertaina [9].

References
[1] M. Casolino et al, Astrophysics and Space Science Transactions 7,477-482, 2011
[2] J. Linsley (2001). In: 27th ICRC. Hamburg
[3] D. Naumov, SLAST, Shower Light Attenuated to the Space Telescope.
[4] T.K. Gaisser and A.M. Hillas, 15th ICRC, 8 1977.
[5] T. Stanev, Hitgh energy cosmic rays, 2nd edition, Springer 2010.
[6] C.L. Pryke, Astroparticle Physics, 14 (2001).
[7] G. Lefeuvre et al. Nucl. Inst. Meth. Phys. Res. A 578 2007.
[8] O. Catalano et al. 27th ICRC, Hambourg, Germany, (2001).
[9] M. Bertaina et al. Adv. Space Res. 53 (2014).