

Identification of extreme energy photons with JEM-EUSO

A. D. SUPANITSKY^{1,2}, G. MEDINA-TANCO² FOR THE JEM-EUSO COLLABORATION.

¹ *Instituto de Astronomía y Física del Espacio (IAFE), CONICET-UBA, Argentina.*

² *Departamento de Física de Altas Energías, Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, A. P. 70-543, 04510, México, D. F., México.*

supanitsky@iafe.uba.ar

Abstract: Extensive searches for ultra-high-energy photons have been performed by past and current cosmic-ray observatories. Nevertheless, at present no firm candidates have been found. All candidate events are compatible with proton primaries, which are the principal source of backgrounds for their identification. As a result, several upper limits on their integral photon flux have been obtained. Besides other theoretically possible sources, at least a flux of ultra-high-energy photons is expected as a result of the interactions suffered by cosmic rays during propagation through intergalactic medium. However, current upper limits do not reach the flux expected by the corresponding astrophysical models. Extreme Universe Space Observatory on board Japanese Experimental Module (JEM-EUSO), is an orbital fluorescence telescope intended to observe the most energetic component of cosmic rays ($E \gtrsim 10^{19.7}$ eV), planned to be installed on the International Space Station. By design, the instrument is also sensitive to photons and neutrinos. In this work we study the potential of JEM-EUSO for photon searches. We obtain the upper limits on photon fractions in a total of expected events (under the assumption that there are no photons in the samples) for different combinations of observation time in the Nadir and Tilted modes of the telescope. For the calculation of the upper limits we use a statistical method based on the parameter X_{max} , the atmospheric depth for which the maximum development of the shower of a primary particle is attained.

Keywords: Ultra High Energy Photons, JEM-EUSO.

1 Introduction

Extreme energy photons can originate in different astrophysical contexts. They can be produced as a consequence of the interactions suffered by cosmic rays during their propagation through intergalactic medium, on route to the Earth (see for instance Ref. [1]). These energetic photons are generated by the decay of neutral pions produced by the interactions of cosmic rays with the low energy photons of the radiation field that fills the Universe. Extreme energy photons can also be produced by the interactions of cosmic rays in their acceleration sites. In this case the neutral pions can be produced by the interaction of cosmic rays with intense radiation fields and also with ambient protons present in the acceleration regions [2]. Another possibility is the production of extreme energy photons in the decay of super heavy relic particles or topological defects (see for instance [3]). However, these type of top-down scenarios are disfavored by present data [4]. It is worth noting that at present there is no ultra high energy photon unambiguously identified.

High energy photons can generate extensive air showers when they interact with the molecules of the atmosphere. At the highest energies the characteristics of such air showers are dominated by the Landau and Pomeranchuk [5, 6], Migdal [7] (LPM) effect and pre-showering (i.e., photon splitting) in the Earth's magnetic field (see Ref. [8] for a review). In this work we briefly discuss the characteristics of the longitudinal profiles of the extensive air showers generated by these energetic photons. We also calculate the expected upper limits on the photon fraction in the integral cosmic ray flux, assuming that there is no photon in the samples, expected for the JEM-EUSO mission [9]. We use the atmospheric depth of the maximum development

of the showers, X_{max} , which can be reconstructed from future JEM-EUSO data, as the parameter to discriminate between showers initiated by protons and photons. We use an extension of the method proposed in Refs. [10, 11] to calculate the expected upper limits.

2 Characteristics of photon showers

One of the most sensitive parameters to the nature of primary cosmic rays is the atmospheric depth of the points at which the showers reach the maximum development. It can be reconstructed from data taken by the fluorescence telescopes like JEM-EUSO.

A shower library of protons and photons is generated by using the program CONEX [12] (v2r2.3). It consists of 1.1×10^5 proton showers following a power law energy spectrum of spectral index $\gamma = -1$ in the interval of $[10^{19.7}, 10^{21}]$ eV. The arrival directions of the showers are distributed uniformly. Also 1.5×10^5 photon showers are generated under the same conditions but in this case the impact points of the showers are uniformly distributed over the Earth's surface in order to properly take into account the pre-showering effect in the geomagnetic field. The hadronic interaction model used to generate the showers is QGSJET-II [13].

The top panel of figure 1 shows the distributions of X_{max} for proton and photon showers with $E \in [10^{19.8}, 10^{20}]$ eV and zenith angle of the shower $\theta \in [30^\circ, 60^\circ]$. It can be seen that the distribution of photons has two components; one corresponds to photons that suffered from photon splitting and the other one corresponds to the photons that do not suffered from photon splitting. Note that the values of X_{max}

for the photons that are converted in the geomagnetic field are smaller and present smaller fluctuations.

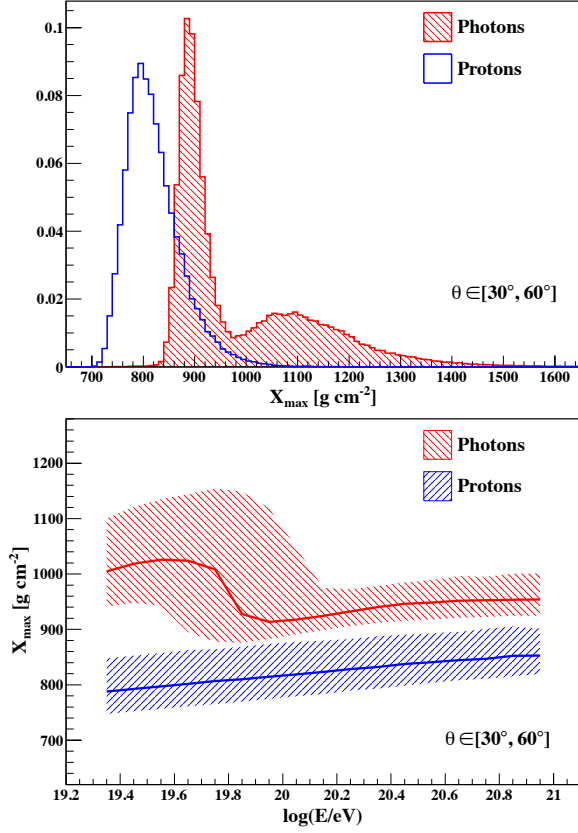


Figure 1: Top panel: X_{max} distributions for proton and photon primaries of $E \in [10^{19.8}, 10^{20}]$ eV and $\theta \in [30^\circ, 60^\circ]$. Bottom panel: Median and region of 68% probability of the X_{max} distributions as a function of the logarithm of the primary energy for protons and photons with $\theta \in [30^\circ, 60^\circ]$.

The bottom panel of figure 1 shows the median and the region of the central 68% probability containment of the X_{max} distribution as a function of the logarithm of primary energy for protons and photons with $\theta \in [30^\circ, 60^\circ]$. It can be seen that for energies below $\sim 10^{19.5}$ eV the LPM effect dominantly affects the X_{max} distribution, i.e. the photon splitting is negligible. From $\sim 10^{19.5}$ eV to $\sim 10^{20.1}$ eV the X_{max} distribution is composed by the two populations of photons, and for energies above $\sim 10^{20.1}$ eV all photons are converted in the geomagnetic field. Note that the discrimination power between protons and photons by the parameter X_{max} increases with primary energy in the region where all photons are converted in the geomagnetic field.

3 Expected upper limits

Assuming that the JEM-EUSO exposure is the same as the one for protons [14] it is possible to calculate the expected number of photon events above a given energy threshold. Table 1 shows the expected number of photons with energies above $10^{19.6}$ eV, calculated considering the most optimistic photon flux taken from Ref. [1] (it corresponds to the curve on the top of the shadowed region of Fig. 2). The calculation is done for four cases: The observation of 5 and

10 years in the Nadir mode, 1 year in the Nadir mode and 4 years in the Tilted mode, and 1 year in the Nadir mode and 9 years in the Tilted mode. The tilted angle used for the calculation is 40° . Note that the number of events for the cases including observation in the Tilted mode the expected number of events is slightly smaller than the ones corresponding to observation in the Nadir mode. This is due to the fact that the exposure for 40° of the Tilted angle is smaller than the one corresponding to the Nadir mode for energies higher than $\sim 10^{19.85}$ eV. For higher threshold energies this tendency is inverted.

5 yrs N	10 yrs N	1 yr N+4 yrs T	1 yr N+9 yrs T
88	177	85	168

Table 1: Expected number of photon events for energies larger than $10^{19.6}$ eV. N corresponds to the Nadir mode of observation and T to the Tilted one. The cosmogenic photon flux corresponds to the most optimistic case taken from Ref. [1]. The exposure used for the calculation is the one calculated for proton primaries.

Nevertheless, there are astrophysical models that predict a much smaller flux of cosmogenic photons, specially the ones that includes heavier nuclei in the composition injected by the sources (see for instance [15]). Also, fluctuations of a relatively large flux can still produce a null detection even for a non-null statistical expectation. For these reasons and also to compare with the existing upper limits on photon fractions obtained by different experiments the case in which there are no photons in the samples is studied below.

In an ideal condition where it is known that there are no photons in a given sample of N events the upper limit to the photon fraction can be easily calculated and it is given by [8],

$$\mathcal{F}_\gamma = 1 - (1 - \alpha)^{1/N} \quad (1)$$

where α is the confidence level of rejection. However, in practice, the probability of the existence of photons must be realistically estimated through some observational technique which involves the determination of experimental parameters, like X_{max} , which leads unavoidably to less restrictive upper limits than in the ideal case.

The method used to calculate the upper limits of the photon fraction by using the X_{max} parameter is based on the abundance estimator first introduced in [16],

$$\xi_{X_{max}} = \frac{1}{N} \sum_{i=1}^N \frac{f_\gamma(X_{max}^i)}{f_\gamma(X_{max}^i) + f_{pr}(X_{max}^i)} \quad (2)$$

where $f_\gamma(X_{max})$ and $f_{pr}(X_{max})$ are the distributions of X_{max} for photons and protons, respectively, X_{max}^i are experimental values of X_{max} of the i th event, and N is the sample size.

For samples of a large size it is possible to calculate the upper limit to the photon fraction for the case in which there is no photon in the sample by using the $\xi_{X_{max}}$ parameter analytically [11]. However in this work the Monte Carlo technique is used for the calculations which is valid for samples of any size.

Given a sample of the X_{max} parameter of size N , the upper limit on the photon fraction, $\mathcal{F}_\gamma^\xi$, is obtained as the solution of the following equation,

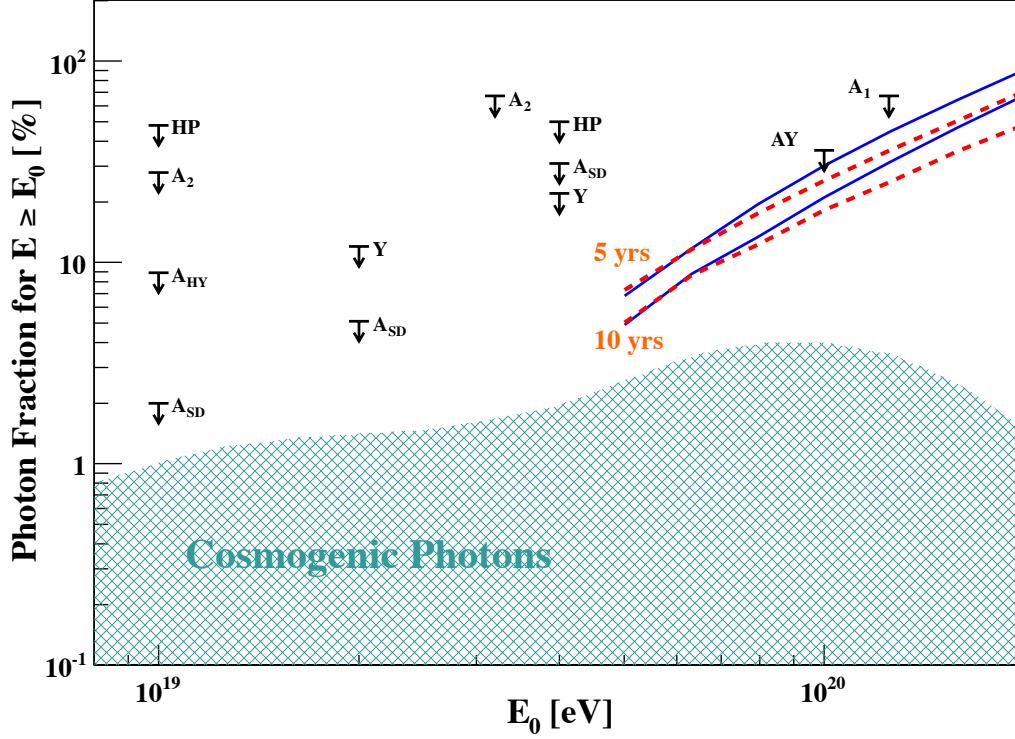


Figure 2: Upper limits on the fraction of photons in the integral cosmic ray flux at 95% confidence level as a function of primary energy. Solid lines correspond to the expected upper limits, $\mathcal{F}_\gamma^\xi(E_0)$, obtained by using the $\xi_{X_{max}}$ method for JEM-EUSO in the Nadir mode and dot-dash-dot lines correspond to a combination between the Nadir and Tilted modes (see text). A Gaussian uncertainty on the determination of the X_{max} parameter of 100 g cm^{-2} is assumed for calculations. The shadow region is the prediction for the cosmogenic photons [1]. Black arrows are experimental limits, HP: Haverah Park [19]; A₁, A₂: AGASA [20, 21]; A_{HY}, A_{SD}: Auger [22, 4]; AY: AGASA-Yakutsk [23]; Y: Yakutsk [24].

$$\int_{\text{med}(\xi_{X_{max}}^{pr}(N))}^1 d\xi P(\xi|\mathcal{F}_\gamma^\xi, N) = \alpha \quad (3)$$

where $\text{med}(\xi_{X_{max}}^{pr}(N))$ is the median of $\xi_{X_{max}}$ assuming that there are only protons in the sample, $P(\xi|\mathcal{F}_\gamma^\xi, N)$ is the distribution function of $\xi_{X_{max}}$ for a photon abundance $c_\gamma = \mathcal{F}_\gamma^\xi$, and α is the rejection probability.

The distribution function $P(\xi|c_\gamma, N)$ is obtained by means of a Monte Carlo simulation. Given the sample size N and the photon abundance c_γ a large number of X_{max} samples is used to estimate the distribution function. The number of photons in a sample, N_γ , is obtained by sampling a binomial distribution of probability c_γ and total number of events N . Then, N_γ values of X_{max} are taken at random from the X_{max} distribution of photons and $N_{pr} = N - N_\gamma$ values of X_{max} are also taken at random from that of protons. The value of $\xi_{X_{max}}$ in a given sample is obtained by using the Eq. (2). The distribution functions needed to calculate $\xi_{X_{max}}$ are obtained from the simulated data by using the non-parametric method of kernel superposition with adaptive bandwidth [17, 16]. The number of events expected above a given energy threshold are calculated by using the broken-power law fit of the Auger energy spectrum [18] and the exposure of JEM-EUSO [14].

Figure 2 shows the upper limits on the photon fraction in the integral flux at 95% confidence level. The zenith angle of the showers is in the interval $[45^\circ, 90^\circ]$ and a Gaussian uncertainty on the determination of X_{max} of 100 g

cm^{-2} is assumed for the calculation. Note that the uncertainty on the determination of X_{max} considered is a conservative value (perhaps overestimated) for the resolution expected for the JEM-EUSO mission. The solid lines show the expected upper limits for the cases in which the observation is done in the Nadir mode during 5 and 10 years. The dashed lines correspond to the observation of one year in the Nadir mode and 4 and 9 years in the Tilted mode for 5 and 10 years of the total observation time, respectively. The tilted angle used for the calculation is 40° . The arrows correspond to the upper limits obtained for several experiments and the shadowed region corresponds to the expectation for the cosmogenic photons taken from Ref. [1]. The expected photon fraction obtained in Ref. [1] is calculated assuming a power law energy spectrum of nucleons at injection, a uniform distribution of sources in the universe and no evolution of the sources with redshift. The normalization of the spectrum is obtained by fitting the Hires data (see Ref. [1] for details).

The expected upper limits are more restrictive for increasing values of the number of events. The number of events collected by observing in the Tilted mode increases at the highest energies and decreases at lower energies comparing with the observation in the Nadir mode. For 40° of the tilted angle the number of events detected in one year of observation in the Nadir mode is compatible with that in the Tilted mode for an energy of $\sim 10^{19.85} \text{ eV}$. For energies higher than that the difference in the number of events increases. This difference in the number of observed events is responsible for the improvement on the expected upper

limits obtained when the observation in the Tilted mode is considered.

In order to compare the expected upper limits of the photon fraction in the integral cosmic ray flux obtained by using the $\xi_{X_{max}}$ method with the ideal case in which it is known that there is no photon in the samples, the following parameter is defined,

$$R(E_0) = \frac{\mathcal{F}_\gamma^\xi(E_0)}{\mathcal{F}_\gamma(E_0)}, \quad (4)$$

where $\mathcal{F}_\gamma(E_0)$ is given by Eq. (1).

Figure 3 shows R as a function of the logarithm of primary energy for the four cases considered. Note that all curves decrease with primary energy because the discrimination power between protons and photons of the parameter X_{max} increases with primary energy (see bottom panel of figure 1). It can also be seen that for a given energy, R is larger for samples with larger number of events. This is due to the fact that the upper limits obtained for the ideal case decrease faster as a function of the number of events than the ones corresponding to the realistic case which is caused by the limited discrimination power of X_{max} to separate protons from photons.

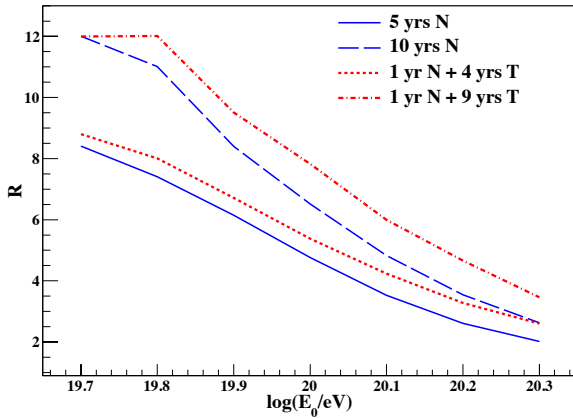


Figure 3: Ratio between the expected upper limits of the photon fractions considering experimental configurations and that in the ideal case (see text).

Note that improving the methods to discriminate between protons and photons more stringent upper limits can be obtained. More sophisticated techniques are under development at present to make progress in this direction.

4 Conclusions

In this work we have studied the characteristics of the photon showers in the energy range relevant to the JEM-EUSO mission, which is important for the development of methods for photon identification. We have also presented the attainable upper limits on the photon fraction in the integral cosmic ray flux by using an extension of a method developed earlier. We have shown that for 5 and 10 years of observation it is possible to obtain more stringent upper limits than the existing ones at present. Comparing with the ideal case in which it is known that there is no photon in the samples we have shown that there is still room for improvement which is at present work in progress.

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