Observation of Ultra-High Energy Cosmic Rays in cloudy conditions by the JEM-EUSO Space Observatory

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DOI: 10.7529/ICRC2011/V03/1034

Abstract: Source of Ultra-high Energy Cosmic Rays (several times 10^{19} eV) are still unidentified. Overcoming their extremely small fluxes, a detector with huge observation areas is needed to investigate the energy and arrival direction distribution of EECRs. JEM-EUSO is a unique experiment that will be located in the International Space Station to observe extensive air showers (EAS) by monitoring night part of Earth atmosphere. In addition to clear sky condition, the extensive air showers in cloudy condition are also observable by taking advantage of the certain fraction of EAS develop above the cloud. In the preset work, using Monte Carlo simultions for test clouds, the cloud impact to the trigger efficiency was estimated taking into account the statistics of cloud property.

Keywords: JEM-EUSO, Ultra-High Energy Cosmic Rays, Extensive Air Shower simulation

1 Introduction

Cosmic rays origin is not identified, specially for Ultra-High Energy Cosmic Rays (UHECRs), despite of the limited numbers of astrophysical objects that can accelerate particles to such energies [1]. Properties of the primary UHECR can be measured by the observation of Extensive Air Showers (EAS). These EAS are developed when cosmic rays come through the atmosphere. The primary energy is shared among secondary particles. Most of them are electrons which carry about 90% of the primary energy. These electrons excite nitrogen molecules in the atmosphere that results in fluorescence light through the de-excitation of the molecules. Also Cherenkov component is produced, due to the relativistic velocity of the particles. These components have been measured by ground-based ultra-violet (UV) telescopes. However, with a steep power-law energy spectrum and possible Greisen-Zatsepin-Kuzmin effect, UHECR flux at highest energy (above $\sim 5 \times 10^{19}$ eV) [2, 3] is such small, that their origin cannot be investigated by these ground-based experiments.

JEM-EUSO (Extreme Universe Space Observatory on Japanese Experiment Module) is a new type, space-based experiment that will be launched in 2017, aiming to identify origin sources by detecting UHECRs at large statistics [4, 5]. JEM-EUSO telescope will cover a much larger area than ground-based experiments with a wide field of view (FoV) of 60°. From the orbit on the International Space Station (ISS) an altitude of ~ 400 km, it will search the Earth's atmosphere as a detector for light produced by EAS. In order to determine the energy and arrival direction of the primary particle as well as its composition, the light profile is needed to be measured. This profile depends on atmospheric conditions, such as absorption and scattering. The atmosphere is also the source of UV background such as subsistence airglow and transient luminous events, artificial sources, etc. Therefore, JEM-EUSO will need a dynamical trigger system capable of continuously adapting the triggering requirements [6, 7]. Furthermore, the FoV of JEM-EUSO varies as ISS orbits with sub-satellite speed of ~ 7 km/s and therefore presence and properties of clouds change significantly. To acquire such information, LIDAR (LIght Detection And Ranging) device and an infrared (IR) camera will be installed on JEM-EUSO [8, 9]. The former will measure transmittance as a function of the altitude and the latter will be accommodated to obtain cloud coverage overview and cloud-top altitude (H_C) in JEM-EUSO's FoV that provide data for evaluate exposure of the observation.

In this paper, the impact to the trigger aperture was investigated by Monte Carlo simulation taking into account cloud conditions. The presence of the clouds may affect varying by their altitude and optical depth τ. The effect due to clouds may also depend on the fraction of EAS develops above the typical altitude of cloud over the orbit. Effectively observing such EAS events helps increase the statistics of UHECR events. As conclusion, the cloud impact to the exposure will be presented.

2 Simulations

In this work, ESAF (Euso Simulation and Analysis Framework) [10] was used. It is a software framework to simulate space-based cosmic observations, including showers generation, emission and transport of photons, ray trace of optics, photodetector response and telemetry, as well as reconstruction. Key parts of ESAF were developed in EUSO project [11] and nowadays, it is adapted and optimized for JEM-EUSO instrument [12].

In the ESAF, EAS event is generated along with fluorescence and Cherenkov photons emission and their propagation in the atmosphere. In present work, fluorescence yield, one of uncertainty in energy scale, is assumed by the measurement of Reference [13] from the available options. Even in case of clear sky condition, UV photon propagation through atmosphere severely involves Rayleigh scattering and absorption by ozone in shorter wavelengths ($\sim$ 320 nm). The transmittance of these processes are modeled by LOWTRAN package [14].

In consideration of the effect of photon scattering in clouds which consists of droplet below ~ 8 km altitude, Mie scattering is more dominant since the scattering particle size well larger than wavelength. Scattering can be considered as independent of wavelength range of our interest (300-450 nm). The same behavior is observed for cirrus, made of ice crystals [15]. In the software, analytical formulation of scattering process including phase function is modeled and implemented in ESAF [10].

To include clouds in ESAF, there are two different options in its atmospheric model: with TOVS (TIROS Operational Vertical Sounder) database [16] including τ and H_C or as a uniform and homogeneous layer. The database was analysed to understand the global distribution of clouds within the range of the JEM-EUSO orbit and was analyzed in [19]. For the last option, physical parameters considered for the cloud layer are the optical depth τ, that yields transparency by $\exp(-\tau)$, the top altitude of the cloud and its physical thickness. For our study, the latter option was chosen for the discrete test values in τ and H_C.

3 Results

3.1 Shower simulation in cloudy conditions

In Figure 1, light curves (arrival time distribution of photons to the telescope pupil) of typical EAS events with zenith angle of 60° are shown for cirrus- (top panel) and stratus- like test clouds (bottom). Note that the horizontal axis is in unit of GTU (gate time unit = 2.5 μs. In each panel dark most shaded histogram denotes the total number of photons. Other histograms indicate the different components of scattered Cherenkov photons in atmosphere of from cloud or Earth's surface . For comparison, light curve for clear sky for EAS at similar energy is drawn (dashed histogram).

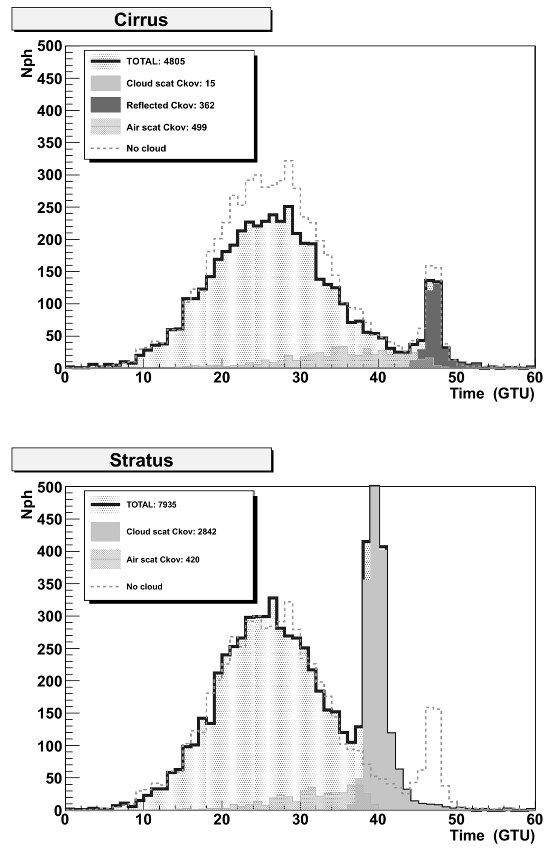

Figure 1: Light curve (arrival time distribution of photons to the telescope pupil) of typical EAS events. Note that the horizontal axis is in unit of GTU (gate time unit) corresponding 2.5 μs. Top and bottom panels correspond to the cases of cirrus- and stratus- like test clouds, respectively. In each panel, dark most shaded histogram denotes the total number of photons. Other histograms indicates the different components of Cherenkov photons. For comparison, light curve for clear sky for EAS at similar energy is drawn (dashed histogram).

For cirrus-like cloud at lower altitudes, signals from EAS are attenuated according to the optical depth, while the shower image and its time evolution will allow the arrival direction analysis. The scattered signals of Cherenkov from the ground is also observed.

For stratus-like clouds with large τ at lower altitudes, most of signals from EAS are observed without attenuation when the altitude of the cloud is well below the altitude of EAS development. Such clouds also produce a very intense reflected Cherenkov signals and the detected signal is even larger, due to higher albedo of clouds, than that for the clear sky case. This may enhance the better capability of triggering for particular case such as low zenith angle event. It is more pronounced in reconstruction of the EAS geometry since the location of the impact on the cloud is more accurately determined.

3.2 Trigger efficiency in cloudy conditions

In order to evaluate the impact of clouds in FoV into trigger efficiency, shower simulations for different cloudy cases were made. To characterize the test cloud property, four altitudes have been considered ($H_C = 2.5$ km, 5 km, 7.5 km and 10 km), as well as four optical depths (τ= 0.05, 0.5, 1.5 and 5). For each of the sixteen cases, incident angles from 0° to 90° and energies of the primary particles (protons) with energies of $\log E = 19.5$ to 21 have been considered. For comparison, simulation for clear sky case was also made.

In this paper, 'trigger efficiency' $\epsilon(E)$ is referred to the ratio to the trigger aperture at energy E in comparison to the nominal semi-saturated aperture. The semi-saturated aperture is meant to be the product of solid angle (π for $\theta = 0^\circ - 90^\circ$) and observation area determined by the result of the optical ray trace simulations [17, 18]. Note that the efficiency can be slightly higher than 1 since some EAS that cross a part of FOV may trigger. To quantitatively estimate the effect of clouds, we first calculate the ratio ϵ of given cloudy condition to that of clear sky case. The ratio, to be called 'cloud impact' hereafter that represents the ratio of the number of events in comparison to the one expected for clear sky condition. For a given cloud condition (H_0, τ), the average cloud impact $\epsilon(E; H_0, \tau)/\epsilon(E; \mathrm{clear})$ is defined taking into account the assumed UHECR flux.

In Table 1, the average cloud impacts are summarized for the different tested clouds with different energy thresholds of 5×10^{19} (top) and 7×10^{19} eV (bottom) with an assumed differential spectrum of $dN/dE \propto E^{-3}$.

In case of optically thick clouds with $\tau \geq 1$, the presence of clouds affect the trigger efficiency depending on H_C. Especially high-altitude clouds absorb EAS signals emitted beneath the cloud that significantly result in lowering the trigger efficiency. In the middle altitudes such as ~ 5 km, the influence of the clouds are limited to EAS from lower zenith angles, which develop even lower altitudes.

In the presence of similarly high clouds but with $\tau < 1$, signal from EAS below such clouds is only attenuated by a factor of $\exp(-\tau)$ and the effect to the trigger efficiency is limited.

If H_C is well below the altitudes where EAS develops, the clouds do not attenuate the EAS signals.

Comparing different energy thresholds, the difference of the cloud impact slowly increases with energy, while it stays marginal in the energy of interest.

Table 1: Average cloud impact for different types of clouds for energy ranges above 5×10^{19} eV (top) and 7×10^{19} eV eV (bottom). In each case, a differential spectrum of $dN/dE \propto E^{-3}$ was assumed.

	H_C			
$E > 5 \times 10^{19}$ eV	2.5 km	5 km	7.5 km	10 km
$\tau = 5$	88%	66%	37%	18%
$\tau = 1.5$	89%	69%	43%	26%
$\tau = 0.5$	88%	82%	74%	70%
$\tau = 0.05$	90%	89%	89%	90%

	H_C			
$E > 7 \times 10^{19}$ eV	2.5 km	5 km	7.5 km	10 km
$\tau = 5$	98%	77%	44%	21%
$\tau = 1.5$	99%	83%	54%	39%
$\tau = 0.5$	100%	95%	88%	84%
$\tau = 0.05$	99%	100%	100%	99%

Table 2: Statistical distribution of clouds for τ and H_C from TOVS database [16] analyzed taking in account JEM-EUSO orbit [19].

	H_C			
τ	< 3 km	3–7 km	7–10 km	> 10 km
> 2	17.2%	5.2%	6.4%	6.1%
$1 - 2$	5.9%	2.9%	3.5%	3.1%
$0.1 - 1$	6.4%	2.4%	3.7%	6.8%
< 0.1	29.8%	0.03%	0.01%	1.2%

4 Discussion

In order to estimate the overall impact due to clouds, one needs to take into account how often the different types of clouds appear in FoV. From the TOVS data analysis for JEM-EUSO orbit, statistical distribution of clouds is summarized in Table 2 (see [19] for further details). The undesired clouds such as one with $\tau > 1$ and $H_C > 7$ km accounts for 20%, while $\sim 60\%$ cases are only low altitude clouds with $H_C < 3$ km whose influence to EAS is limited.

By the convolution of $\epsilon(E; H_C, \tau)$ with such information of cloud property distribution, the expected cloud impact on the trigger efficiency is obtained. In presence of cloud, however, the triggered events are needed to be selected with proper criteria of quality cut. In this work, we assumed observed EAS as 'quality event' if its maximum of development lies above the cloud-top altitude. In the case of clouds with $\tau < 1$, all triggered events are also accepted since the the maximum of development is measurable even with attenuated EAS signals. In such a case, angular reconstruction is little affected since it is based on the angular speed of moving spot corresponding to EAS track.

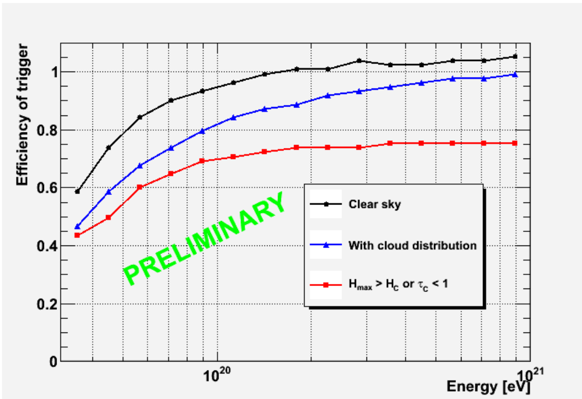

Figure 2: Preliminary trigger efficiency vs energy. The clear sky case is denoted by circles. Cloud-statistics average case is shown by triangles. The case for quality event is indicated by squares.

In Figure 2, the trigger efficiency is shown as a function of energy. For cloudy cases, all triggered events as cloud-statistics average is shown by triangles. The case of selection of quality event into those triggered events is also indicated by squares. For comparison, the clear sky case is shown by the circles.

For all triggered events, the efficiency increases with energy and approaches that of clear sky case at highest energies. For quality events, it increases up to $\sim 10^{20}$ eV and becomes almost constant at higher energies. This is because a certain fraction of the clouds with $\tau > 1$ exists at higher altitudes. From Table 2, for example, such clouds with $H_C > 7$ km accounts for 20%. Therefore a part of EAS develops below such type of clouds. The cloud impact for overall cloud-statistics is estimated to $\sim 70\%$ above $\sim 3 \times 10^{19}$ eV. This value is an important factor when one estimates the effective exposure over the mission (see [18, 20]). Similar estimate was carried out in EUSO mission and this result is in fair agreement apart from detailed difference in selection criterion. Currently, detailed study on reconstruction is in progress to take into account configuration of the JEM-EUSO mission. It should be mentioned that the main telescope of JEM-EUSO will be operated along with AM system. Utilization of these subsystem is investigated in parallel [8, 9].

5 Summary

In this work, the impact of the clouds in observation of UHECRs by the JEM-EUSO mission is investigated using ESAF simulation package with a test cloud assumption. The light curves for typical EAS with a stratus-test cloud shows the intense scattered signals of Cherenkov photons from the cloud-top. In the case of cirrus-like test cloud, there is attenuation of EAS signals that are emitted or scattered below the test cloud corresponding to the transmittance determined by the cloud's optical depth. For various cases, the trigger efficiency was estimated and compared with that of clear sky case. In the case of optically thick and high cloud, EAS signals are generally attenuated that results in smaller trigger efficiency. For optically thin ($\tau < 1$) cloud, a part of EAS does not trigger, while it keeps good visibility of EAS maximum. For the low altitude cloud, the influence is limited especially at higher energies. Taking into account the statistics of cloud property and the observability of the EAS maximum, the cloud impact to trigger aperture is $\sim 70\%$ above 3×10^{19} eV. The results herein are preliminary and further detailed studies are in progress along with utilization of the atmospheric monitoring system.

Acknowledgements

Sáez Cano thanks to University of Tübingen and RIKEN for their kind hospitality during her research stays. This work is supported by MICINN under projects AYA2009-06037-E/AYA, AYA-ESP 2010-19082, CSD2009-00064 (Consolider MULTIDARK) & AYA2011-29489-C03-01 and by Comunidad de Madrid under project S2009/ESP-1496. For computation, SPAS-UAH cluster was used.

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