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Observation of ultra-high energy cosmic rays in cloudy conditions by the space-based JEM-EUSO Observatory

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Abstract. JEM-EUSO is a space observatory that will be located on-board the Japanese Experiment Module at the International Space Station. It will observe Extensive Air Showers (EAS) induced by ultra-high energy cosmic rays using the Earth's atmosphere as detector. In addition to clear sky observations, EAS are also observable in cloudy conditions if a sufficiently large part of the EAS development occurs above the cloud. The atmospheric monitoring system plays a fundamental role in our understanding of the atmospheric conditions in the field of view of the telescope.

1. Introduction

It is not known which mechanism can accelerate ultra-high energy cosmic rays (UHECRs) to energies around and above 10^{20}eV [1]. Due to these extremely high energies, trajectories of low mass UHECRs are only little affected by Galactic or extragalactic magnetic fields. Therefore, by back-tracing these trajectories, sources may be identified. UHECRs can be observed through the measurements of extensive air showers (EAS). EAS develop when cosmic rays traverse the atmosphere. The primary energy is shared among secondary particles that interact with atmospheric molecules. Part of the energy goes into the production of nitrogen fluorescence light. A Cherenkov component results from the relativistic velocity of those particles.

JEM-EUSO ("Extreme Universe Space Observatory on-board the Japanese Experiment Module") is a space-based experiment that will be located on-board the International Space Station. Its measurements shall be performed at night. Operating a wide field of view ($\sim 60°$), it will cover an area of order of 10^5 km^2, which is far larger than any ground-based experiment. Its aim is to identify cosmic ray sources by observing UHECRs with large statistics [2, 3].

Ideally, the observations take place in clear sky conditions. However, the space-based observatory has the capability to observe EAS also in certain cloudy conditions. It depends on the fact that certain fraction of EAS develops above the altitude of the typical clouds. Apart from observable EAS, the influence due to cloud presence is needed to be monitored. The

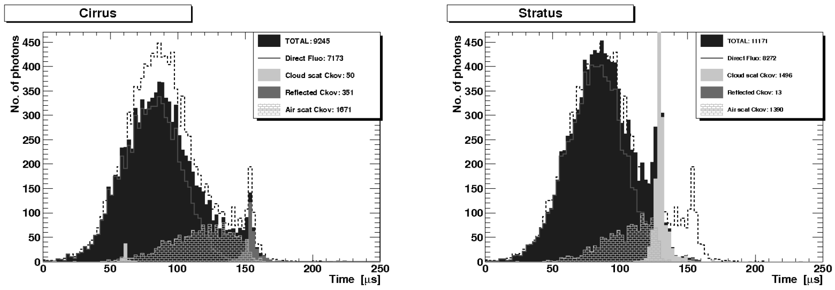

Figure 1. Light curves of EAS for two different kind of clouds. Left and right panels correspond to the cases of cirrus- and stratus- like test clouds, respectively. Total number of photons, Cherenkov and fluorescence components are represented in each panel. For comparison, light curve for clear sky is also drawn (dashed histogram).

key information is the coverage of clouds, the cloud-top altitude distribution and the profile of the optical depths. To comprehend these parameters, JEM-EUSO will accommodate the atmospheric monitoring (AM) system that consists of LIDAR (LIght Detection And Ranging) system and the infrared (IR) camera.

In this contribution, the impact of cloud presence to EAS is briefly reported. The essential ideas on the AM system are summarized, as well as possible techniques to measure the properties of clouds with JEM-EUSO IR camera.

2. EAS observation from space and cloud impact

The EAS development is observed as light spot moving with the velocity of light that is the key information of the arrival direction of the UHECR. Calorimetric fluorescence light that closely traces the energy deposit of EAS particles may be used as a good estimator of UHECR energy. A part of Cherenkov light reflects from Earth's surface or cloud top that helps identify the location of EAS landing.

In Figure 1, arrival time distributions (light curve) of photons from a typical EAS (proton of 10^{20} eV and θ=60°) are shown for the presence of different types of clouds obtained by simulations [4]. Dark most shaded histogram shows the total number of photons as well as one for clear sky for comparison (dashed lines). Fluorescence and Cherenkov components are also displayed.

In the presence of optically thin clouds at high altitudes such as cirrus (left panel), the intensity of light curve suffers from a certain absorption. The energy estimation is feasible at certain level. Information from the atmospheric monitor system will allow correction of the effect of absorption by the clouds.

Clouds with large optical depths at lower altitude such as stratus still allows the measurement of dominant part of light curves (right panel). In addition, Cherenkov light is largely reflected from the cloud-top and helps determine the arrival direction of landing location of EAS even better than the clear sky case.

The occurrence of clouds sorted with the cloud-top altitude and optical depths has been investigated using existing satellite data [5]. The overall cloud impact is studied taking into account the efficiency of the trigger, as well as a cosmic rays flux of E^{-3}. Cloudy events are chosen to be of good quality if, either the X_{max} of the shower is above the cloud top height, or the cloud is optically thin ($\tau \leq 1$). Results show that $\sim$ 70% of the cases are found to be observable [6, 7].

The data analysis scheme for cloudy conditions has been investigated [2] and the work for further improving is in progress.

3. Atmospheric monitoring system

3.1. LIDAR system

The LIDAR system will measure the optical depth profiles of the atmosphere in selected directions. The laser pulse energy will be 20 mJ.The laser beam will be able to repoint in any direction within JEM-EUSO FoV.The pointing will be done with the help of a tilting mirror pointing system. The pointing system will receive information about the last triggered EAS candidate event, determine the set of directions for the LIDAR shots, re-point the mirror and send a command to the laser to shoot.

The laser back-scatter signal will be received by the main JEM-EUSO telescope [8]. The power of the laser pulse is adjusted in such a way that the LIDAR signal will trigger the JEM-EUSO telescope in the same way as the air shower event, so that no special trigger mode is needed. The return signals from laser will allow to detect cloud/aerosol layers with optical depth 0.15 at 355 nm wavelength [8]. The LIDAR measurements will also provide a complementary measurement for the cloud-top altitude obtained by the cloud temperature measured by the infrared camera data.

The beam will have 2 mrad divergence matching the angular size of JEM-EUSO pixels. The size of the footprint of the laser beam on the ground will be about 800 m. With such a footprint, the laser beam energy density on the ground will be many orders of magnitude below the limits imposed by the standard laser safety requirements.

3.2. Infrared camera

The IR camera will be used to detect the presence of clouds. It will measure cloud coverage and cloud top altitude during JEM-EUSO observation period. The FoV of the IR camera is 60°, the same as JEM-EUSO main telescope FoV. The observed radiation is related to the cloud temperature and emissivity [9], which can be used to estimate the height of the cloud. Data analysis for the IR camera to get cloud heights could be performed by using stereo vision techniques or radiometric algorithms based on the radiance measured in one or several spectral channels (with split-window techniques).

The atmosphere between the emitter and the sensor absorbs and emits energy. Therefore, some algorithms are needed to infer the cloud temperature from temperature detected by the IR camera. In order to obtain the brightness temperatures measured by the IR camera, a radiative model of the cloud scenario has been considered, that consists of an atmospheric model, with the Earth's surface emitting at 300 K and a cloud at a certain height.

Two options lead to two different IR camera designs:
a) a monoband camera with spectral range between 10 and 12 μm (TIR).
b) a bi-spectral camera with two 1μm-width bands centered at 10.8 and 12 μm (B1 and B2).

3.2.1. Results of the one-band analysis Although for one band analysis the effect of the temperature vertical profiles is not significant, the effect of water vapor vertical profile it is indeed of importance, when low-level clouds and atmospheres with high water vapor concentrations are present. Also, the effect of thin clouds (cirrus) cannot be neglected, since errors in retrieved temperatures are higher than 3 K for low and medium-level clouds. Therefore, temperatures retrieved by only one band are not accurate enough.

3.2.2. Results of the two-band analysis A Split-Window Algorithm (SWA) [10] has to be applied to the brightness temperatures retrieved from B1 and B2 bands, to overcome the effect of the atmosphere. These algorithms are based on linearization of Planck's law and on the Radiative Transfer Equation (RTE). For blackbody clouds (emissivity = 1), the coefficients only depend on the atmospheric transmittance. However, for real cases, the transmittance is not always known and, for this reason, different algorithms have been developed.

Some simulations have been done to find out what happens if there is a cirrus between the cloud top altitude and the IR camera. The results show that the one-band option temperature retrievals have larger uncertainties than SWA option, although accuracy is still not good enough. Therefore, still open points remain to be adressed in order to retrieve top-cloud temperatures accurately.

3.3. Global Atmospheric Models
The AM system of JEM-EUSO will also include the real time global atmospheric models which provide information on the vertical profiles of the atmospheric parameters and information on the cloud coverage.This information will be used in the analysis of the LIDAR and IR camera data. It will be also directly taken into account in the analysis of the cosmic ray data.

4. Summary
The origin of UHECRs is still an open question and high-statistics observation is essential to solve it. JEM-EUSO observatory will measure the UHECR-initiated EAS over very wide area and also during cloudy conditions. The results of the simulations show the capability of such measurement for particular types of clouds such as cirrus and stratus. The atmospheric condition in the FoV will be monitored by AM system consisting of LIDAR and IR camera.

JEM-EUSO LIDAR, that is composed of the laser and the main telescope as the receiver, will allow us to retrieve the optical depth profile, namely transparency of the atmosphere, by analyzing the back-scattered laser signals.

To obtain the cloud temperature from the brightness temperature and cloud coverage, IR camera device will be installed in JEM-EUSO. Two possible configurations are being studied (based on either one or two spectral channels). Cloud top height retrieval can be performed using either stereo vision algorithms or accurate radiometric information

Furthermore, the analyses will be supplemented by taking into account altitude-dependent profiles of the main atmospheric state variables. Currently, there are on-going investigations to provide these data with sufficient spatial and temporal resolution for the trajectory of the ISS.

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