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Atmospheric influence on space-based observation of high-energy cosmic rays

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Abstract. High-energy extensive air showers developing in the Earth's atmosphere emit faint UV light that can be detected from space. The impact of varying atmospheric conditions on light emission and transmission has been studied in detail for the space-borne ultra high-energy cosmic ray observatory JEM-EUSO. By these studies, the importance of atmospheric scattering and reflection from ground on the fraction of Cherenkov light as well as fluorescence light received by JEM-EUSO is pointed out. For any telescope measuring UV light from an altitude higher than 40 km, the attenuating influence of the ozone layer cannot be disregarded. Based upon air shower simulation, quantitative numbers of ozone attenuation will be presented.

1. Introduction

The Extreme Universe Space Observatory on board the Japanese Experiment Module (JEM-EUSO) has the capability to explore cosmic rays of energies beyond 50 EeV. On board the International Space Station (ISS), this fluorescence telescope will orbit the Earth in a 90 minutes cycle at an altitude of approximately 400 km. Given a field of view of about 60° , JEM-EUSO will monitor a surface area with a radius of roughly 231 km [1]. JEM-EUSO will observe the night side of the Earth to detect the faint UV light emitted by high-energy air showers. In Figure 1, the observation principle of JEM-EUSO is illustrated. The main signals reaching the telescope are fluorescence photons emitted isotropically along the shower track and scattered Cherenkov light. A significant contribution originates from the reflection of mainly Cherenkov light on the Earth's surface which is visible as characteristic peak in the measured signal (see Figure 1b). For the detection of air showers, knowledge about the state of the Earth's atmosphere is important, since it significantly affects the development of the shower, as well as the UV light emission and transmission. The fluorescence yield as well as the Cherenkov yield are sensitive to changes in the state of the atmosphere [2, 3].

Apart from the Atmospheric Monitoring System (AMS) which will be installed together with JEM-EUSO, data from a Global Atmospheric Model (GAM) will be used as important information at the air shower event reconstruction. The AMS of JEM-EUSO will consist of an IR camera and a LIDAR system to monitor especially the cloud and aerosols in the field of view of the detector [1]. In this work, the Global Data Assimilation System (GDAS) has been chosen as GAM [5]. GDAS provides near real-time atmospheric state functions (pressure, temperature, humidity, etc.) as altitude-dependent profiles on a $1^\circ \times 1^\circ$ global grid. GDAS data have been successfully used for several years in data reconstruction by the Pierre Auger Observatory [6]. For the new studies regarding the effects of the ozone, altitude-dependent ozone data have



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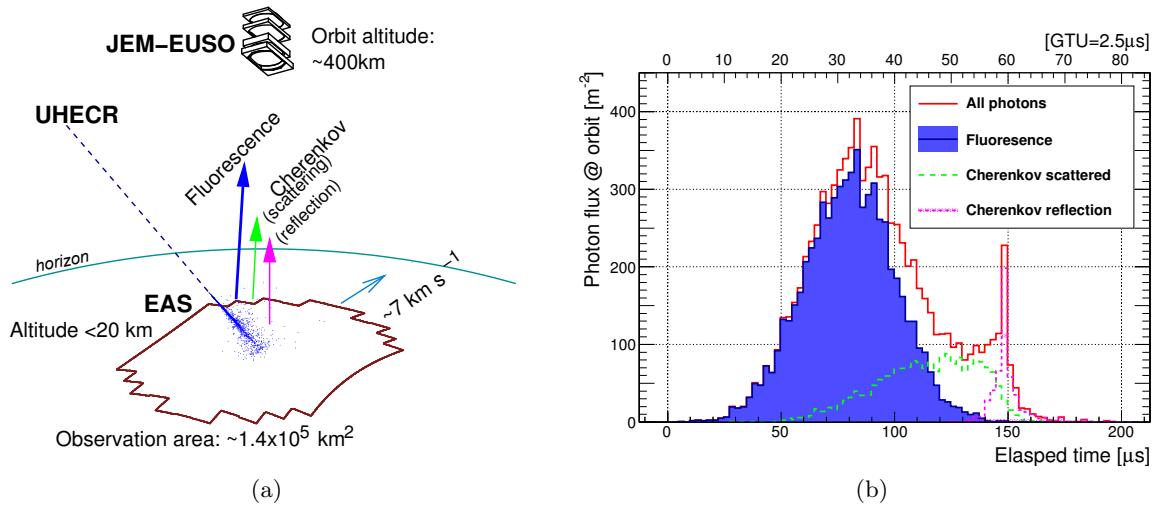


Figure 1: Illustration of the observation principle of JEM-EUSO for a nominal orbit of 400 km [4]. (a) The main signals are fluorescence photons emitted isotropically along the track and (delayed) scattered Cherenkov light; (b) Light components at the aperture of JEM-EUSO as function of time for a simulated EAS of zenith angle 60° and energy 10^{20} eV. The peak from ground or cloud reflected Cherenkov light is visible well.

been selected from the ozone sounding program of the US National Oceanic and Atmospheric Administration (NOAA) [7].

2. Atmospheric transmission

The atmospheric transmission of UV light plays an important role for air shower measurements with the fluorescence as well as the Cherenkov technique. The classical observation from ground level is strongly affected by attenuation due to Rayleigh and Mie scattering of light from its source to the detector. While Rayleigh scattering is caused by the air molecules themselves, Mie scattering is due to aerosols (e.g., dust, fumes, volcanic debris) and hydro meteors (e.g., water droplets). The Mie attenuation length of 53 km within a mixing layer below 3 km has been taken from measurements of the Pierre Auger Observatory [8]. This value corresponds to a *clear* atmospheric condition. The state of the atmosphere is described by the U.S. Standard Atmosphere 1976 (US-StdA 76). Light emission and transmission of an air shower at zenith angle $\theta = 60^\circ$ and primary energy $E = 10^{20}$ eV have been simulated using a version of Offline, the Pierre Auger Observatory analysis and simulation framework, adopted for JEM-EUSO [9]. Two scenarios have been studied. For the *classical observation*, the observer has been placed in 40 km distance to the shower core at ground level (see Figure 2a). A strong attenuation within the detection range ($290 \text{ nm} \leq \lambda \leq 450 \text{ nm}$) is visible. At the main fluorescence emission line of 337 nm, the total attenuation is about 98%. The attenuation is dominated by Rayleigh scattering. For the *space-borne observation* the same parameters have been used, though the observer has been placed in a distance of ~ 400 km above the shower core (see Figure 2b). The total attenuation is much less compared to the classical observation, only 50% at 337 nm. For space-borne observation in a clear atmosphere, attenuation by Mie scattering becomes insignificant compared to Rayleigh scattering.

3. Ozone attenuation

Previous studies have shown that ozone absorption can usually be neglected [10]. To be detected from space, the light emitted by an extensive air shower has to pass the total column of

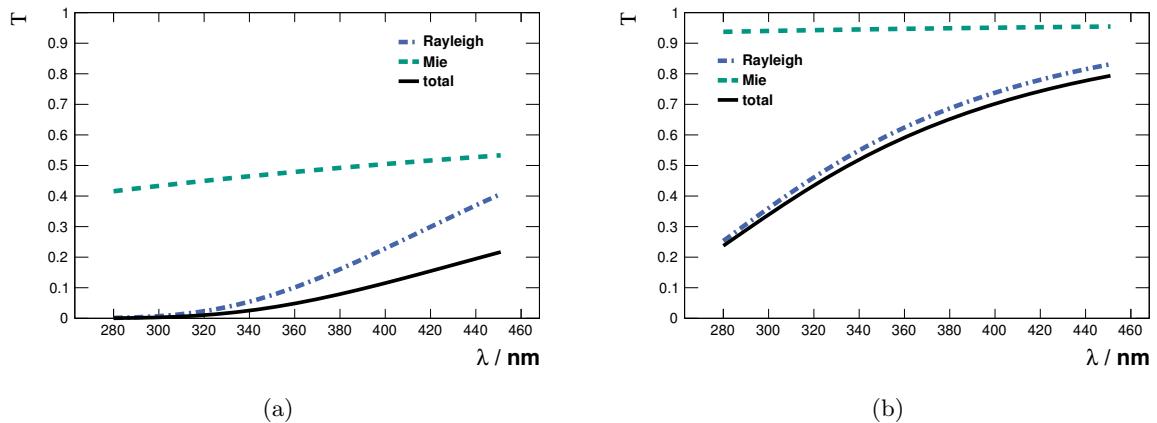


Figure 2: Comparison of the transmission factor T for Mie and Rayleigh scattering. A Mie attenuation length is 53 km in a homogeneous mixing layer below 3 km, taken from measurements of the Pierre Auger Observatory. The Rayleigh attenuation length is computed with respect to the US-StdA 76. The detector was placed (a) in 40 km distance at ground level, (b) at the ISS altitude 400 km above ground.

stratospheric ozone which peak at about 40 km altitude is known as *ozone layer*. To analyze the impact of UV absorption by ozone on the space-borne measurement of air showers, several simulation studies have been conducted. Since GDAS does not provide altitude-dependent ozone profiles, ozone sounding data of the Ozone and Water Vapor Group (OZWV) of the global monitoring division of NOAA have been used [7]. The transmittance T_{O_3} is computed based on an ozone cross-section parametrization [11]. For wavelengths above 320 nm, the transmission is above 90%, below 320 nm the transmission drops rapidly. This applies to about 26% of the generated fluorescence light. The impact on the transmission has been studied for example air showers ($\theta = 60^\circ$, $E = 10^{20}$ eV) using US-StdA 76 and different ozone profiles. Average profiles for each month have been computed for three selected sounding locations. Boulder is located in the state of Colorado (USA), Hilo is located on the state of Hawaii (USA) and Pago Pago on American Samoa which is on the southern hemisphere. They represent continental ozone and different maritime concentrations. In Figure 3, the result is shown as relative difference of the number of photons at the JEM-EUSO aperture $\Delta N_\gamma = N_\gamma - N_\gamma^{\text{WOO}}$ and number of photons without considering ozone absorption N_γ^{WOO} . The total amount of light at the aperture decreases on average by 8 – 10%. The typical annual change in ozone concentration is reflected by the transmission ratio. The amount of ozone in the stratosphere decreases in the course of summer and recovers in winter [12]. Therefore, the transmission in summer is higher compared to winter. The strongest decrease is seen for Boulder, for the ozone concentration is higher at higher geographical latitudes and lower close to the equator. The monthly variation as well as the difference between the average annual transmission is of the order of $\pm 1\%$. It is shown by these studies that ozone has to be taken into consideration for air shower reconstruction in case of space-borne observation.

4. Impact of varying atmospheric conditions

The influence of varying atmospheric conditions and albedo on the amount of UV light at the aperture of JEM-EUSO has been studied for nine example locations. Atmospheric data from GDAS have been used to compute average profiles for temperature, pressure, and humidity. For each, 100 showers have been processed using Offline. An average UV albedo of 2% has been assumed and a Lambertian phase function has been used. In Figure 4a, the resulting

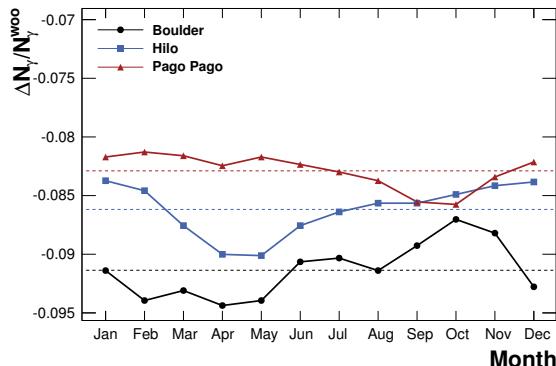


Figure 3: Monthly change of light transmission due to ozone absorption as relative difference $\Delta N_\gamma = N_\gamma - N_\gamma^{\text{WOO}}$ and number of photons without ozone absorption N_γ^{WOO} . The dashed lines indicate the annual sample for the three locations Boulder, Hilo, and Pago Pago.

mean relative deviation from the average of all locations is depicted. The maximum deviation in summer are +2%, -3%, and in winter +4%, -6%. The further away from the equator (Aléutian islands, Timmins (Canada), Boulder (USA), Malargüe (Argentina)), the less light is emitted/transmitted. The closer to the equator (remaining locations), the more light is emitted/transmitted. The most extreme difference is seen for the Aléutian islands which are located at 52° geographical latitude. If the local atmospheric conditions are not addressed properly the energy reconstruction of JEM-EUSO will be significantly biased.

The wide field of view of JEM-EUSO covers at least 5° in geographical latitude/longitude. This does not only include different states of the atmosphere, but also various ground and cloud scenarios. Exemplarily, the position of the detector has been assumed above Malargüe (Argentina). To compare the significance of the different states, data of four surrounding GDAS grid points have been chosen one and two degree to the east and west ($\Delta\Phi$). Cloud has been neglected. The corresponding albedo has been estimated by the local vegetation based on UV albedo values on natural surfaces [13]. For Malargüe and the two locations towards the east this refers to an albedo of 2%. Towards the west one may first encounter a high altitude glacier or snow on top the Andes ($\Delta\Phi = -1^\circ\text{E}$; 68% albedo) and forest on the western slope of the mountains ($\Delta\Phi = -2^\circ\text{E}$; 7% albedo). The simulation results are depicted relative to the total amount of light at the aperture in Figure 4b. For the locations to the east, the total amount of light varies only by about 1% which is of the same order of magnitude as the statistical uncertainty of the simulation. The largest divergence is found for the Andes, where the surface altitude is above 3 km. While the total number of photons increases by 120% due to the high snow albedo, the number of fluorescence photons decreases by about 6%. A significant fraction of light originates from reflection. The assumed albedo is important for reconstruction of air shower events observed from space and will have to be addressed in the future in more detail.

5. Conclusion

The UV attenuation for a space-borne observatory is much less compared to ground-based observatories. In the space-borne scenario, the attenuation ranges from about 75% at 280 nm to 20% at 450 nm (50% at the main fluorescence line of 337 nm). The maximum attenuation that may occur in case of a ground-based observatory on the horizontal line of sight ranges from almost 100% at 280 nm to 78% at 450 nm. The UV absorption by ozone over the total wavelength range (280-450 nm) becomes significant. For the total amount of light at the JEM-EUSO detector aperture, an absorption of 8 – 10% has been computed. Finally, the influence of varying atmospheric conditions on emission/transmission amounts to ∼ 6%.

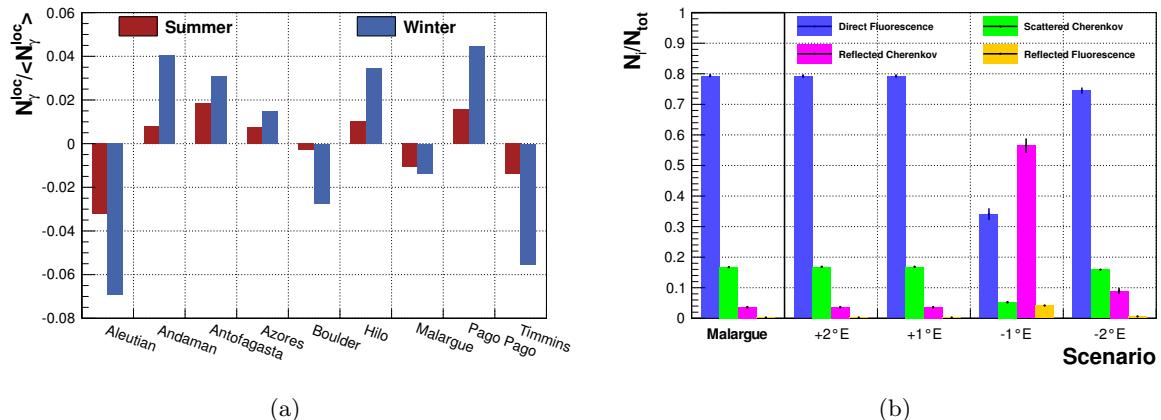


Figure 4: The ratio of light at aperture for different atmospheric conditions. (a) Mean relative deviation from average of light at aperture. The albedo had been set to Savannah in all cases. Ozone profiles of Hilo, Boulder, and Pago Pago have been used according to month and location. Winter refers to January on northern hemisphere, July on southern, summer vice versa. (b) Malargüe, November 2009, the May ozone profile of Boulder data has been used.

Acknowledgments

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